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"Pyne is the world's leading authority on the history of fire, and his erudition is phenomenal. He offers us a broad panorama of ecological and human history in a framework of geology and geography. He shows what a great impact fire has had in shaping landscapes, flora, and fauna all over the world, and how in the late Pleistocene humans have, as it were, joined forces with fire by learning to manipulate it."—*Science*

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"An excellent overview of why the history of humanity cannot be told without the history of fire. . . . An excellent book and strongly recommended for all audiences, especially those with interests in anthropology, geography, history, natural sciences, or the humanities."—*Choice*

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"Stephen J. Pyne writes about fire as if he were on fire, with searing, consuming heat and light. When he looks at fire he sees not biological catastrophe but social illumination and natural renewal."—*Seattle Times*

FIRE

A BRIEF HISTORY

Second Edition

Stephen J. Pyne

Foreword by William Cronon

UNIVERSITY OF WASHINGTON PRESS
Seattle

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COVER IMAGE: 2013 photograph of the Alder Fire in Yellowstone National Park. Photograph by Mike Lewelling, National Park Service.

To Sonja, Lydia, Molly
who have watched it come full circle—twice

CONTENTS

ACKNOWLEDGMENTS

The grand cycle of fire on Earth: that is the big subject of this small book. It is also, in lesser form, its context, for it is my hope that *Fire: A Brief History* will bring, if not final closure, at least a degree of condensation to the Cycle of Fire suite. In truth, this slim volume can pretend to be little more than a candle to the historical firestorm that it introduces. Probably, too, it would be easier to square a circle than to tweak the Cycle's many bulky narratives into the triangular three-fires conceit of *Fire: A Brief History.* Yet the conceit does have a kind of natural logic. If we can reduce fire to the chemistry of a mere three factors, we should be allowed to do no less for its history.

The publication of the Cycle suite began with discussions about this volume. When William Cronon approached me about contributing to the Weyerhaeuser Environmental Books series, an introductory book on fire was the first project he proposed. We agreed that *Vestal Fire*, which I was rabid to write, would precede the projected *Fire*, while my previous publications on fire would be reprinted over a period of several years. Bill possesses an unmatched blend of intellectual vigor and editorial tolerance. My itch to evoke rather than explain has exasperated him more than once; and with regard to this long-delayed volume, he has shown almost preternatural patience. This time I have tried to emulate his passion for clarity and his empathy for the taught audience, although I cannot hope to equal him on such matters. He has my deep gratitude.

As do Julidta Tarver and the staff of the University of Washington Press. At times our correspondence has piled to the point of seeming self-detonation, yet Julidta remained ever pointed, pragmatic, and unfailingly cheerful. No writer could ask for a better editor.

The list of long-sufferers, however, must begin and end with my family. More than once they have asked when this project might conclude. The answer is clear: it won't. But the greatest of the cycles it tells is the

one we have collectively lived. Lydia, our first-born, arrived while I was at the National Humanities Center writing *Fire in America*; she has now helped me edit *Fire: A Brief History*, while Molly is ready for a child of her own. The hearth fire has never burned brighter.

In the two decades since the first edition was written, fire research has expanded exponentially, the media has placed fire into its annual almanac of worthy events, the management of combustion has become a matter for politics, and alarm over fire in all its manifestations has propagated into public discourse. Fire is widely recognized as a defining presence on Earth and an informing principle of the Anthropocene. A young generation seems eager to convert its heat into light. I am grateful for the opportunity to revisit and refresh the text and to add a chapter. I designed the original text to have an integral argument and coherent narrative that needed the end I gave it. Adding another chapter upsets that design, so I decided to keep the original text as it was, editing lightly to correct some rough spots and update evidence. The new chapter looks to the future instead of surveying the past, and reflects on some new organizing themes the original did not have. In this way I think it can stand alone without distorting the prior text or seeming freakishly out of place.

Special thanks go to Il Saggiatore for rekindling my interest and for urging me to add a chapter to update the text, and to the University of Washington Press for granting the reborn text a welcome hearth to burn in.

FOREWORD:
SMALL BOOK, BIG STORY
William Cronon

For me, one of the chief pleasures and privileges of serving as general editor of Weyerhaeuser Environmental Books has been the opportunity to introduce each volume in the series with a brief essay that shares with readers my own enthusiasm for the work of its author. Because Stephen Pyne is the most prolific of our writers, I've had the chance to introduce no fewer than six of the books in which he has taken on the daunting task of narrating the entire human history of fire on Earth. I cannot claim to have anything like Steve's depth of knowledge or consuming passion for the subject of fire, so I've occasionally worried whether I might eventually run out of things to say in reflecting on the scholarly achievement these works represent. But quite the opposite is true of the small book you now hold in your hands. Although it is the slenderest volume we have published in Steve's Cycle of Fire series, it is also among the most remarkable. Indeed, I feel a special pride of vicarious authorship about it, for reasons I'd like to explain in this foreword.

When I first learned that I would be editing the Weyerhaeuser series, I began casting about for books and authors that might be ideally suited to publish in it. Steve Pyne was among the very first who occurred to me, and I therefore approached him to see whether he might be interested in writing a book which, frankly and selfishly, I had long wanted to read and which only he could write. My reasons for this had much to do with the qualities that make Steve such an unusual figure in the field of environmental history. His defining virtue as a scholar is of course his extraordinarily encyclopedic knowledge of fire and the many ways that human beings have interacted with it since our hominin ancestors first discovered the trick of capturing its lightninglike magic and turning it toward their own ends. No one has ever known or cared more about this subject, surely, than Steve Pyne, and he has made a lifework of sharing what he knows in print. His subject is so vast that he has leapt around the world, century by century and continent by continent, in pursuit of his quarry, filling literally thousands of pages in the process. So expansive is his oeuvre, and so intricate the fine-grained textures and patterns he reveals to readers, that I long ago began to suspect that many of those readers might welcome a road map to help them navigate the vast intellectual landscape that Steve lays out before them.

This book is that road map.

The idea for *Fire: A Brief History* as I first proposed it to Steve was something very different from the five monumental volumes, collectively entitled Cycle of Fire, in which he has devoted hundreds of pages each to the fire histories of the United States, Eurasia, Australia, and elsewhere. In those magisterial books, God and the Devil are both in the details, so that keeping track of trees and forest together is both the challenge and the reward that readers face. Cycle of Fire is, in effect, an enormous intellectual mansion with many, many rooms, covering so much territory under one roof that inexperienced readers can be forgiven for occasionally losing their bearings while wandering its corridors—not because its author is a confusing guide, but because his subject is so demanding, and so unfamiliar to most of us. I suggested to Steve that readers might find their way more easily through his other books if they had on hand a much shorter volume offering a bird's-eye view of the whole. What readers needed, to combine the metaphors, was a blueprint of the mansion, and a way to survey the surrounding countryside by stepping back from the individual trees so as to grasp the shape of the immense forest that contains them.

The result is this little book. Although it is certainly the shortest volume in the Cycle of Fire sequence, it is also, arguably, the most ambitious. Never before has Steve Pyne narrated the entire story of earthly fire in so few pages. Never before has he sought to distill his scholarly insights into a handful of core defining observations. Never before have the intricacies of fire history—world-wide and through the whole sweep of human history—been revealed in such stunning relief. The book is a triumph not of abridgement but of concentrated distillation. What I have said before about Steve's other books is even more true of this one: for those willing to gaze through the unusual lens it offers our eyes, it can change the way we see and understand the world.

At the center of *Fire: A Brief History* is an unfolding narrative structure that divides fire's human history into a series of overlapping epic chapters.

In the beginning was nature's flame, the almost irresistible chemical tendency toward oxidation that has defined all life on Earth since the moment photosynthesizing plants began to produce the profoundly unstable oxygen-rich atmosphere that has ever since been among the most defining features of this peculiar planet. When early hominins learned to carry and build this fire at will, making it their own, they began the long process whereby human beings have transformed the Earth by redirecting the complex routes that flames have burned across it.

The next chapter in this process of fire's coevolution with humanity was the invention of agriculture and the very different fire dynamics it necessarily entails: fire to clear fields, fire to change the composition of wild and domesticated vegetation, fire alternately bound and released in cycles that sometimes seemed increasingly under human control, and sometimes, devastatingly, not. The fires that have burned under this second, agricultural regime have brought a complex remapping of the Earth's surface, extending fire's reach in some regions and habitats while suppressing it in others. The consequences of this human manipulation of terrestrial fire ecology have been so subtle and profound that we are only now beginning to understand them.

Finally, we come to industrial fire, which has been increasingly dominant across ever greater portions of the Earth's surface for the past three centuries, even as natural and agricultural fires have persisted alongside it. Industrial fire has been characterized by two tendencies: it burns in carefully controlled spaces from which energy and motive power can be extracted, and its source is drawn not from the immediate flux of calories emanating from the sun but rather from buried fossil fuels that make it possible for sunlight hundreds of millions of years old to shine on Earth once again. Industrial fire has tremendously increased the human power to manipulate the planet for good or ill, augmenting to an astonishing degree our powers of production while at the same time giving us terrifying new tools for rendering into dust that which we wish to destroy. This is the era in which we now live, whose ending we cannot know but whose fate we cannot help but share. What we *can* know is that the fate of humanity, like the fate of the Earth, is tied to the fires that have made the world as we know it—the fires whose history is told as well in this book as it has ever been told before.

Steve Pyne is a historian, not a prophet, and this small book cannot solve the riddle of fire's future: it cannot predict what forms of fuel might avert future energy crises any more than it can predict what forms of burning might avert future global warming. What it can do is help explain why things like energy crises and global warming—to say nothing of rural and urban land use, human food supplies, forest management, industrial production, and the ever-present threat of wildfire—are bound not just to the history of humanity but to the history of fire as well. Indeed, the great insight of this book is that the two are so inextricably bound to one another that it finally makes no sense to tell their stories separately. No other book in Steve Pyne's Cycle of Fire has made this point more persuasively. The fire that has burned in humanity's hearth from the beginning, the fire with which we have remade the world, is a profoundly double-edged symbol both of our Promethean power to control the Earth . . . and of the frustratingly unexpected limits we repeatedly encounter in our exercise of that power. If one wants to understand just how completely the story of the human past is also the story of fire on Earth, there is no better place to start than this small book.

INTRODUCTION: KINDLING

There was a time when the Earth did not burn, when oxygen did not soak its atmosphere, when plants did not encrust its lands. But for more than 400 million years the planet has burned. In some places and times, fire has trimmed and pruned flora; in others, it has hewn whole biotas; for virtually all it has simply been there like floods and earthquakes, like the winds, droughts, seasons, browsers, and lightning with which it is associated. For almost all the span of terrestrial life, fire has continued, to varying degrees, as an environmental presence, an ecological process, and an evolutionary force. Fuel, oxygen, heat—that is fire's triangle. At various times the play of fire's triangle has been cyclic, singular, evolutionary, but once created it has always endured.

Even on a planet as distinctive as ours, fire's story is special. Fire is unique to Earth and our seizure of it unique to humanity. Although space exploration has revealed that other planets hold some of the components for combustion, none have all of them or the context by which to mingle fuels, oxygen, and spark into the explosive reaction we call fire. So, too, while all species modify the places in which they live and many can modify fire's environment, only humans can, within limits, start and stop fire at will. Other organisms can trash forests, uproot shrubs, denude grasses, promote seedlings, choose one plant rather than another. Some organisms breed in fresh charcoal, some forage among ash and hunt along flame's flank and through clouds of smoke, some self-immolate with a vigor that bestows upon them a selective advantage in comparison with less fire-prone neighbors, some like Philippine tarsiers may even grasp embers in their claws or like Australian kites seize the embers in their talons and redeposit them elsewhere, probably by accident, perhaps by intent. Nicotine-addicted chimps will toy with burning cigarettes. But only humans can kindle fire, sustain it, and spread it beyond its natural habitats. Only humanity has become, for the biosphere, the keeper of the vital flame. Fire's story is a story of the Earth and, as myths emphatically insist, a story of ourselves. For fire we are the keystone species.

The narrative for fire has an intrinsic logic. The first movement involves the creation of combustion, a reaction which, simply put, takes apart what photosynthesis brings together. With an atmosphere fluffed by oxygen and lands lathered in plants, combustion could leave cells and burn where wind and fuel could take it. At that point one can speak of fire. The earliest charcoal preserved in the geologic record dates back to the Devonian.

But fire is a catalyst, it takes on the character of its context, it synthesizes its surroundings. The fires of the Paleozoic were undoubtedly different from those of recent times. Probably much of the early Earth lacked fire altogether and other parts had it in spasms. Certainly immense stocks of biomass failed to burn and were simply buried. Parts of the Earth continue to combust from strictly natural causes, though little of that burning now occurs in completely natural ways.

All this changed profoundly when early hominins captured fire and then devised ways to kindle it on demand. Fire became a species monopoly: it flourished as a unique power humans would never willingly share with other creatures. But, again, fire can burn only what its surroundings furnish. Some landscapes could be burned easily, some not at all. Anthropogenic fire could thrive only where nature fed it. This left chunks of Earth unburned, and other chunks that burned according to various regimens.

To leverage their fire power further, humans needed to manipulate fuel as they did ignition. From the perspective of fire history, this is the meaning of agriculture. Fuel could be created by slashing or browsing, grown by planting and fallowing, burned according to the rhythms of field and pasture. The dominion of fire expanded enormously. Only the most formidable lands remained outside its reach. The greatest extent of open flame resulted from the far-flung colonizings of agriculture, of farming and herding, most of which involved some rotation by which fuels were fashioned and then burned.

Still, human fire power was only as great as the stocks of fuel that nature, with human contrivance, could be made to provide. Serious limits remained: only so much biomass could result from cutting, planting, and fallowing. These barriers fell when, outfitted with combusting machines, people reached into the geologic past and exhumed fossil biomass. For fire history, this marks the moment of industrialization. The limitations on fire reside no longer in its sources—ignition and fuel—but in the sinks such as the atmosphere and ocean that must receive combustion's unbounded byproducts.

All three fires thrive today. How industrial combustion plays against natural fire and the variants of anthropogenic fire is, in particular, the unsettled story of fire's current geography. While the three groupings of fire compete, each with the others, they also coexist. What endures is fire in one form or another. What endures, too, is the unique status of humanity as the keeper of those flames. Fire tracks, as perhaps no other index can, the awesome, stumbling, unexpected, implacable, fascinating course of humanity's ecological agency. The story of one cannot be told without the other.

FIRE

A BRIEF HISTORY

Every man's work shall be made manifest: for the day shall declare it, because it shall be revealed by fire; and the fire shall try every man's work of what sort it is.—1 Corinthians 3:13

Chapter One

Fire and Earth

CREATING COMBUSTION

According to many myths, we became truly human only when we acquired fire. So it is natural to assume a parallel awakening for the place we inhabit. Rather, the Earth likely simmered through more than four billion years before its biotic broth boiled over. Some of fire's components the ancient Earth acquired only after long eons. Even more critically, those ingredients needed a durable context in which to mingle. The parts had to combine and do so consistently. Combustion has its creation story. Fire has its history.

Of fire's three essential elements, only the heat of ignition thrived on the early Earth. Oxygen did not begin to collect until the last two billion years, and did not approach modern quantities until roughly 500 million years ago. Land plants suitable to carry combustion did not become abundant until 400 million years ago. Before that time the Earth lacked the means to burn regularly or vigorously. It is possible that aquatic biomass might have burned, if a lagoon or marsh dried or storms hurled kelp or algal mats into deep berms where they dried, met lightning or lava, and combusted. But such burns, if they occurred, would little resemble modern fires, and are ecological freaks, never absorbed or ordered within a biological community. Earth's original fires—its colonizing fires—demanded land plants. Probably these consisted of primordial moors, a matrix of near-shore organic peat and reeds. Fires probably first flickered during the early Devonian, roughly 420 million years ago. The most ancient fossil charcoal dates from that epoch.

Since then, fire's evolution has been unending if uneven. Each of combustion's components has existed more or less distinctly from the others, colliding from time to time with a fizz of oxidation or a brilliant burst of burning. But combustion could survive only if it had a consistent and durable context. Over time, fire became itself a synthesizing process, a kind of biochemical flywheel that has helped to balance its separate parts into a coherent whole. It has affected the chemistry of the atmosphere. It has influenced, perhaps profoundly, the character of life. Progressively, the biosphere has absorbed fire and tweaked it to fit a system of biological checks and balances. This was easiest with oxygen and fuel, both the products of life. The absorption of ignition proved more vexing, and had to await the arrival of creatures who could make sparks and heat as easily as they could drill bone and chip flint. Those creatures, of course, were ourselves.

How Fire Came to Be

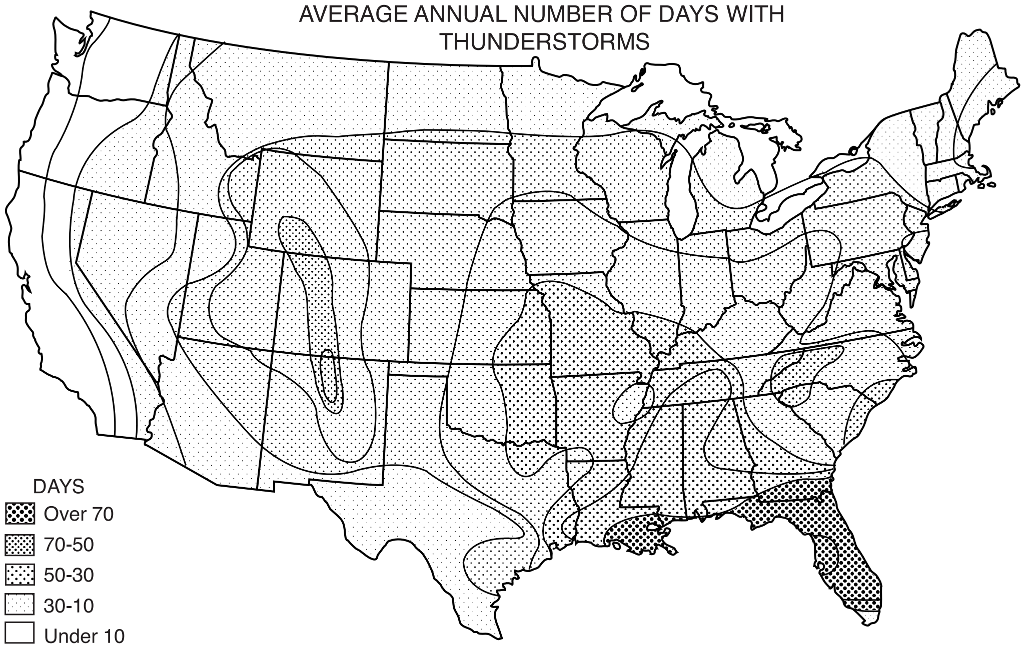
Casting Sparks

Combustion requires a spark. It needs a jolt of energy to unpack photosynthesized matter, to set off a chain reaction that can release enough surplus energy through oxidation to continue. The early Earth offered several sources: falling rocks, volcanic discharges, extraterrestrial impacts, and lightning. After dead biomass collected in heaps, spontaneous combustion was selectively possible, and after fossil fuels were exposed, coalfields, petroleum seeps, and oil shales could take fire and hold it for centuries, even millennia. But of this geophysical exotica, only lightning is sufficiently consistent and universal to account for the natural history of fire.

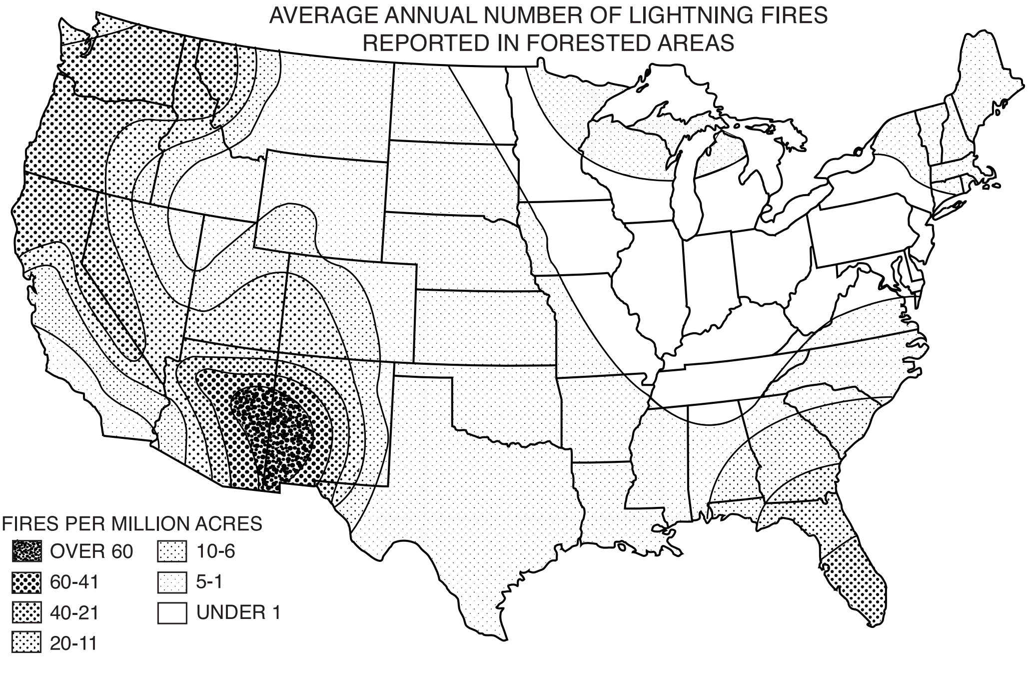
Volcanoes are a faux fire, but they have the capacity to kindle real ones. Flowing lava instantly burns what it touches; eruptions often spawn thunderstorms, which hurl down lightning like volcanic bombs. But while

FIGURE 1. The wet and the dry. Patterns of wetting and drying shape ignition as well as fuels. Areas without lightning lack natural fires because there is no spark; but spark alone is not sufficient if heavy rain accompanies it. The geography of lightning is not identical to the geography of lightning-caused fire.

Consider the United States. A map of thunderstorm days (top) shows a concentration of lightning in the Southeast. A map of lightning-kindled forest fires (bottom), however, highlights the West. In particular, the Southwest boasts an ideal formula for fire. A long droughty spring ends in a “monsoon” announced by sporadic summer thunderstorms, beginning in early July. In their first surge, the storms are scattered, some towering over superheated deserts or more commonly over isolated mountains and high rims. Often these thunderstorms are so dry that the rain evaporates before it reaches the ground or soon afterward. There is enough moisture to power a storm but not enough to saturate the surface fuels. As the rainy season progresses, more fires start but fewer become large as the grasses green up and the woody stems flush. (Sources: Schroeder and Buck 1970, and *Yearbook of Agriculture* 1941, both redrawn by the University of Wisconsin Cartographic Lab)



AVERAGE ANNUAL NUMBER OF DAYS WITH THUNDERSTORMS



AVERAGE ANNUAL NUMBER OF LIGHTNING FIRES REPORTED IN FORESTED AREAS widespread across geologic time, volcanoes are fixed in geographic space. Moreover, volcanic-kindled fires burn locally; lava or ash covers the burns, as often as not; and one way or another the overall disturbance of the volcano smothers the effects of the fire. In brief, volcanoes are too few, too small, too rare to account for the near-universal realm of fire. Most of the burning Earth is far removed from spark-casting volcanoes.

That leaves lightning. Not every place experiences lightning, and not every lightning-blasted place knows fire. The natural history of lightning fire is lumpy: the fires come in bursts, they crowd in time, they bunch in space. Some years have many, some have few. Although a few places never know them, some feel them annually, or until climate reshuffles the deck of places wetted and dried. But its longevity, geography, and concentrated heat mean that lightning clearly accounts for the fact that fire is geologically old and geographically extensive.

Even so, only a tiny fraction of lightning kindles fire. Only one bolt in four reaches the ground. Most of those strike rock or sea, or slam into fuels too wet or shattered or misarranged to burn. Of those that hit something combustible, only one in five has the right properties to convert electrical charge into combustion, the "hot" lightning with high amperage and low voltage. (High-voltage "cold" lightning tends to blast without burning.) Moreover, the storm that looses lightning also dumps rain. What the first can start, the second can stop. The geography of lightning thus overlaps only lightly with the geography of fire. Rather, fire burns along the margins—with the first storms after a long drought or dry season, or from dry storms whose veils of rain evaporate before reaching the ground, or in regions prone to severe swings of wet and dry conditions. However often lightning rolls the dice, the house odds remain against fire.

Yet ignition occurs often enough to render lightning fire the vestal flame of the ancient Earth. In some landscapes it is fickle if powerful, rather like hurricanes. In America, for example, dry thunderstorms can charge whole regions with fire. Between 1946 and 1973, "fire busts" in the Northern Rockies splattered the national forests with more than 100 fires a day on 25 occasions, and five times the total exceeded 200 fires. On July 17, 1940, there were 335 fires; over a ten-day period this same storm kindled 1,488 fires. Between 1960 and 1974, in the national forests of the Southwest five times lightning kindled in excess of 500 fires over a ten-day period. The region averages roughly 2,000 such fires a year. In California between August 5 and September 5, 1987, lightning started 1,244 fires; in 2008, on June 20 and 21, over 2,000 fires. Lightning fire can be as much a chronic presence as storm and sunlight. But wherever it occurs the biota adjusts. Some trees are struck more often than others; curiously, these tend to be species best adapted to survive fire. The lightning bolts that relentlessly restore electrical equilibrium to the Earth also maintain its biological equilibrium.

Yet they do so in peculiar ways. While trees may adapt to lightning, lightning does not adapt to trees. It knows no biological feedback. If lightning has, over geologic time, been the most persistent of fire's elements, it is also the most inflexible. It obeys a geophysical logic, a cold spark without biological control. It matters not to lightning whether it strikes granite or lodgepole pine, a lake or a barn, a sodden log or a snag as parched as kiln-dried lumber. Lightning rips through Jupiter's atmosphere as much as Earth's.

Oxygen and biomass could not ignore the biosphere: life created them. They would have to interact, and combustion would coevolve along with them. But fire's primordial instrument of ignition could exist on its own, leaving fire without a biological means for regulating spark as it did fuel and oxygen. Or rather, it lacked such means until hominins wrested ignition away from lightning's virtual monopoly. From that moment on, the most rigid element of fire's combustion triangle became the most pliant; and a process that had depended on an electrical charge—its bolts as precise as a rifle shot and as random as storm winds—became a global spark as common as grass and as universal as humanity's restless hand and roving mind.

Making Oxygen

Lightning can spark a reaction, but it cannot sustain one. For the act of kindling to yield to self-sustaining fire, free oxygen has to flow into the combustion zone. Yet only in the last two billion years has the Earth succeeded in filling its atmosphere with oxygen on any scale. For several hundred million years thereafter, the atmosphere's oxygen content waxed and waned. During the Carboniferous and Permian, it swelled to perhaps 35 percent, which made possible a general giantism—beetles the size of puppies and dragonflies as big as ravens. By 150 million years ago it stabilized at 21 percent. For this immense shift, without which fire could not exist, the evolution of life is responsible. Organisms pumped out more oxygen than the early Earth could absorb.

That early Earth produced some oxygen by splitting volcanically outgassed molecules of water and carbon dioxide. Such photolysis, along with the chemical weathering of metallic oxides, spewed out packets of free oxygen. But the early Earth's atmosphere was a reducing one. Whatever oxygen that photolysis could produce was quickly absorbed as the freed molecules bonded to carbon, hydrogen, iron, and sulfur—all of them ravenous scavengers of free oxygen. The earliest life (perhaps around 3.5 billion years ago) emerged without oxygen. The first photosynthesizers (roughly 3.1 billion years ago) were also anaerobic. The chemical avidity of free oxygen probably threatened them and likely proved toxic.

The shift from an atmosphere empty of oxygen to one rich in it occurred when oxygen sources increased and oxygen sinks diminished. A critical moment came about 2.3 billion years ago when the earliest photosynthesizing prokaryotes appeared in the form of seaborne blue-green algae. They bolstered oxygen's sources on a large scale by releasing it as a byproduct; yet what algae pumped out, rocks soaked up. Vast quantities of iron, sulfur, and especially carbon were oxidizing and settling into the sedimentary lakes of geologic time. By 1.8 billion years ago, oxidized iron had become abundant in the geologic record, followed by carbonates. In the beginning, carbon dioxide had dominated the Earth's atmosphere; but after eons of lithic burial in forms like limestone, it was becoming a mere trace element, replaced in bulk by the more inert nitrogen. Eventually oxygen's sinks began reaching full capacity and free oxygen flooded the atmosphere. The living world, like the geologic, had to accommodate it. Gradually, organisms transformed a threat into an opportunity. Around 1.3 billion years ago, aerobic photosynthesis emerged, further soaking the Earth's air. About 600 million years ago, select organisms learned to exploit the oxygen that surrounded them to split apart what photosynthesis had joined. Aerobic respiration became common, and a chemical poison evolved into a biochemical necessity.

The chemistry of respiration is a chemistry of combustion. When photosynthesized hydrocarbons are jarred by the right shock, they break apart into carbon dioxide, water, and released energy—what we might term "slow" combustion. In brief, outfitted with special enzymes and antioxidants, organisms so accommodated an oxidizing atmosphere that they neutralized a potentially ruinous reaction and then absorbed and redirected it to their own ends. That, by analogy, is what terrestrial life also did when it found itself steeped in oxygen and blasted by lightning—a process of "fast" combustion we call fire.

There is more. Just as fuels exist within a larger biological context, so oxygen exists within an atmosphere. Fire responds to the air mass as a whole as well as to its chemical parts. Of course without oxygen the atmosphere would be fire neutral or even a retardant. But other properties of an air mass can shape how a fire behaves. How does oxygen enter the combustion zone? Can flames expand freely upward? Will they spread in one direction rather than another? What fuels are dry? The larger properties of the air mass—its layering and stability, its winds, and its moisture (as relative humidity or storm-dropped precipitation)—will help decide. The structure of air is as vital as its chemistry, and the history of climate as relevant as the history of how the atmosphere evolved.

The question arises then whether fire has influenced the atmosphere within which it burns. Is free-burning fire a vital process in the global oxygen cycle, or simply a geochemical afterthought? Since fire and life have coevolved, have fire and the Earth's atmosphere as well? Surely combustion mediates the exchange of gases between plants and the atmosphere. It frees carbon from plants and it buries carbon as charcoal. But how much? And by regulating carbon, has fire also regulated oxygen?

Almost certainly, much as it has done with carbon dioxide. Rather as the Earth swings between icehouse and greenhouse climates, so it has swayed between low-fire and high-fire eras. Prior to 350 million years ago the amount of fire was limited by the character of vegetation, low and sparse. Then both biomass and oxygen rose and fire rose with them. There were immense stocks of vegetation, much of which burned, much of which was buried. It is possible there were giant fires to match the Paleozoic's giant mosquitoes. Still, spark and oxygen had to act through organic matter.

In nature, what is most important are the overall characteristics of the surrounding air and those of the fuels. The size and shape of individual particles, their chemistry, their compactness and arrangement in ways that allow oxygen to flow over their surfaces, and above all their moisture content determine whether a fire spreads from one kindled particle to another, whether combustion flames or smolders, and whether fuel burns as a surface flash or a deep-burrowing glow. Oxygen content would have to rise significantly for large, wet boles to burn, and it would have to drop hugely to prevent ignition in small, dry grasses. By whatever feedback fire shapes the atmosphere, it seems to do so through fuels. After all, the photosynthesizing plants that pump oxygen into the air are the same ones that stoke free-burning fire.

Evolving Fuels

Once stabilized, atmospheric oxygen has remained relatively uniform, much more so than ignition. Throughout the known history of fire, oxygen has persisted, a combustion constant. No surface fire has self-extinguished due to its absence. That fact has made fuels the prime biotic controller of fire. The history of combustibles, however, is nothing less than the evolution of terrestrial life.

Life had first to send its spores and extend its tendrils to land. That move exposed its photosynthesized hydrocarbons to oxygen and spark, and removed them, at least fitfully, from the smothering and cooling baths of water. Life's surge onto land injected burnable biomass into an otherwise empty combustion chamber. About the same time that vascular plants began seriously colonizing the Earth, the first evidence of fire appears in the geologic record. Yet if fire could not exist without fuel, neither would fuels—the planet's vegetative cover—exist without the evolutionary and ecological presence of fire. Each has directly shaped the other.

Follow the fuels. A field guide to fire would be largely a thesaurus of fuel types. Fire has acquired the vigor, subtlety, and endless variety of the organic world. The biochemistry of metabolism determines the chemistry of combustion; the ecology of biotas establishes the ecology of fire; and the evolution of new organisms shapes the evolution of fire regimes. But the reverse has also been true. Over and again fire has synthesized fuel, oxygen, and spark. Those species that could not accept this fact, like those that could not accommodate oxygen and retired to anaerobic niches, were doomed to occupy the apyric environments of the Earth.

Yet many places and periods probably did escape fire. Fire is a particularized event: it appears patchily in space and time. It is not enough that the atmosphere is marinated in oxygen and that fuels bulk large on the landscape, because while all fuel is biomass not all biomass is available as fuel, only that fraction with the right physical and chemical properties.

Any fire begins best with fine particles, since the exchange of heat and moisture occurs on the surface. The fuels must be dry or else the heat of ignition will be wasted in boiling off the held water. They must be organized in such a way that the combustion zone can spread. Fuels—even dead fuels—still flourish within a complex biological system. Their availability depends on competition with decomposers and browsers and rival species; on the climatic choreography of sun and wind, drought and rain; and on the crude timing of lightning with seasonal and secular cycles that green up and cure surface plants. It would be easy for a particular place to miss fire for a while.

Locally, yes; everywhere, no. Fire demanded only certain chemical conditions, and whenever they met, it could spring into being. It could, for a while, ecologically expire, then revive. It could vanish for perhaps long eons, then return. Steadily, however, its critical parts began to interact in ways that rendered fire less random, that made its appearance and absence less like the roll of a roulette wheel and more like the give-and-take of prey and predator. It mattered not to lightning if fire happened, and most likely it mattered only marginally to oxygen. But terrestrial life would evolve with fire. Because fuels were alive, they could influence the character of fire in ways the pure chemistry of oxygen and the pure physics of lightning could not. By means both coarse and delicate, fire could shape the world that shaped it.

A Prehistory for Fire

Sometime between 450 and 400 million years ago, the pieces snapped together with enough force to burn and keep burning. Before that moment, fire did not exist; afterwards, it became almost impossible for it not to. The eccentric ecology of fire has since evolved along with the often lurching evolution of its parts. While the raw chemistry of combustion has remained more or less constant, fire has no more abided unchanged than has climate or life. First Fire's behavior and habitats likely looked different from today's. Triassic fires were probably as distinct as Triassic fauna and the flora they browsed and shaped. Fire's regimes during the Carboniferous, lacking grass, little resembled those typical of the Holocene, loaded with grasslands and grazers.

What were ancient fires like? Simply put, they were like the fuels on which they fed, which makes a reconstruction all the more difficult because so little is known about the range of ancient plants and how they covered the primordial Earth. The mystery is worse for the fine fuels. Small particles of combustibles—pine needles, grasses, small twigs—respond to heat and moisture more quickly than large ones do. They dry and wet faster, ignite and flare more readily. For a propagating fire, logs and peat are combustion sinks rather than sources; they may burn for a long time and release masses of carbon byproducts, but the flaming front rushes along with the small and the quick. Drop a handful of dry needles into a campfire and it will flash. Drop a thick, leafy branch and it will smolder and may go out. So, too, a spreading fire surges and sags with the tempo of the fine fuels. But what were the fine fuels during the Pennsylvanian, or the Jurassic? Long-needled gymnosperms did not evolve until the late Paleozoic, deciduous angiosperms until the late Cretaceous, and grasses not until the Miocene. The pine needles, oak leaves, and bunch grass that carry fire today did not exist.

What then supported fire? If the preserved record is a guide—and it favors the big and the tough rather than the tiny and the volatile—early fires burned amid reedlike psilophytes and pteridophytes, within once-sodden swamps of rotting debris, biomes later enriched with horsetails, woody and soft-leaved ferns, lepidodendroid trees, proto-gymnosperms, and by the Carboniferous fanlike ferns, towering lycopods, and *Calamites* trees with branches that whorled like a maypole. All probably could combust under the proper conditions, and some perhaps could sustain spreading flame. Analogues that exist today burn nicely: palms shrug off fires like raindrops, bracken fern carries flame with the wind, and swamps, drained by drought, readily refill with smoldering ash. Yet, although they undoubtedly combusted, such ancient biotas probably bear no more relation to recognizable wildfires of today than do lepidodendroids to lodgepole pine, or psilophytes to tallgrass prairie.

Did combustion propagate or just burn in favorable pockets? Did it reach the crowns of the taller woody plants? Did it flame or smolder along the surface? How often did it return, how frequently did it invade swamps, what kind of chemical cocktail did its smoke transport to the sky? No one knows. But the complexities are even greater, for adaptations to fire are rarely singular. Each trait typically supports several needs. Other species compete with fire for biomass, and what they don't consume they can reshape. Heavy grazing can redistribute or even ruin the surface fuels and halt a spreading fire. Browsers can force plants to elevate their crowns, lofting sensitive tissue away from flames. Plants, animals, and fire quickly make for an ecological three-body problem that is most likely insoluble in its details. To what extent was fire a selective force in evolution? What regimens of fire might have existed? Which components carried fire? All are, at present, unanswerable except by analogy.

The paleontology of fire is a vastly inexact study, and fire's prehistory an act of informed speculation. Reconstructing the dynamics of paleofires from the mineral char of *Pteridium* is like reconstructing the physiology of a dinosaur from a preserved femur, or more to the point, like imagining the biota within which that boned dinosaur lived. Were such fires cold-blooded or hot? Did they normally flame or smolder? Did fire regimes consist of ground fires or crown fires? Jurassic fires may resemble modern ones as much, or as little, as a pteranodon does a condor.

Yet fires there were. Fusain (fossil charcoal) exists as their geologic record. Charcoal is nearly immune to further decomposition: it not only preserves fire, fire preserves it. For the Pennsylvanian period, fusain or semifusain comprises 2 to 13 percent of extant coal, a number that seems to decline over the era. Yet the fire cycle was, by today's standards, out of balance. Fuel sources far exceeded fire sinks; producers raced ahead of decomposers; and fuels piled up faster than fires could remove them. During the Mesozoic, conifers as well as ferns burned. Both have left charcoal residues that preserve the structure of leaves and woody cells. Such fossils testify to the combustion of both dried and green wood. In the marine deposits of the North Sea, charcoal is regarded as "the most common form of fossil plant preservation." But there is far less residue than in previous eras. The epoch ended with a bang, and perhaps a burn. The famous boundary between the Cretaceous and the Tertiary eras—a time of mass extinctions, one of the most vivid breaks in the geologic record—was also evidently a time of mass combustion. Atop the K/T boundary's meteoritic-spawned layer of iridium rests a zone of charcoal that could only have resulted from sustained burning, almost certainly continued long after the geophysical tremors of the impact had passed, probably gorging on the mass-killed woods left as biotic berm. By the Tertiary period, the fusain fraction has fallen to less than 1 percent.

Fire is a reaction: it synthesizes its surroundings. It resembles a driverless car, creeping and sweeping over landscapes, integrating everything around it, and because no single factor dominates, its historical record is uneven.

To change metaphors, the Earth's combustion economy had no invisible hand that balanced fuel and flame, that assured an equilibrium of constant combustion. The market for fire boomed and crashed. The Carboniferous and Mesozoic were times of saving; the present, a time of spending. Despite the heaps of fusain it deposited, the Carboniferous piled even greater stocks of unburned fuel. Why burning apparently diminished during the Mesozoic is unclear. Fluctuations in oxygen, large-rhythm climatic changes, rearranged continents, a quickening of lignin-rich (and combustion-poor) plants, a proliferation of browsers and of browser-hungry carnivores, the flukes of the preserved record itself—the options are many. Still, a general trend is apparent. As the Earth evolved, the great fire imbalances of the early epochs tended to dampen. The coupling between biomass produced and biomass consumed sharpened. Fire apparently became both more common and less eruptive.

What is clear, however, is that a biologic chasm has existed between what might burn and what did burn. Perhaps the biomass was simply unavailable—matter, not fuel—because the climate lacked the proper wet-dry rhythms to crack open and dry out the vegetation, or because the right animals did not exist to munch and crunch biomes into burnable states, or because so much lay in swampy environs beyond oxidizing (and fire). A no less likely explanation is that ignition was too random and fire too geograpically specialized. Fuels could hide in wet nooks and seasonal crannies from the predatory flames. The Earth lacked a fire broker, a creature capable of reconciling fuel's supply and flame's demand. The epoch's colossal stockpiling of carbon tracks a fire deficit so vast it had implications for the global climate, as much as its fire-catalyzed release does today.

The simplest explanation may be that not all the elements of First Fire's informing triangle had been brought under biological control. Until that happened, fire could synthesize fuel and oxygen only spottily, if brilliantly. Those historic gaps ended with the arrival of fire-wielding hominins, who first made spark as steadfast as air and then readied fuels for the flame, and in fact did not limit their quest to fuel-foraging but planted and slashed what they wanted to burn and even ripped additional combustibles out of ancient rocks. Although carbon continues to recycle—charcoal from free-burning fire is one of the few mechanisms for shifting black carbon from the biosphere directly into the lithosphere—the dominant story today is the reverse: not storage but removal. Humans have exhumed fossil biomass and are burning it on such an immense scale that combustion and fire regimes now extend across geologic time. What failed to burn in the old Earth is burning in the modern. The limits on fire have increasingly become only those imposed by human will.

Fire and Life

Life can exist without fire. The oceans prove that. But fire cannot exist without the living world. The chemistry of combustion has progressively embedded itself within a biology of burning. As life has evolved, so has flame: fire's history shows the same directions, drifts, and quirks as terrestrial life overall. Fire has prowled through the landscape of Earth history as a bear might search out berries, grubs, and fish; roaming or hibernating with the seasons, growing fat and thin with the yearly offerings.

The mere fact that fire exists has meant that life has had to accommodate it. Those organisms that could not adapt have suffered, those that could tolerate it have survived, and those that have discovered relative advantages in a burned site have found themselves oddly dependent on fire's regular return. In brief, fire has become a selective force and an ecological factor that guides evolution, organizes biotas, and bonds the physical world to the biological. It is as specific as the geotrophic orchids at the Cape of Good Hope that blossom within 48 hours after a burn and the Swedish beetles equipped with infrared-sensing organs that search out smoking stumps as nests. And it is as universal as the planetary cycling of carbon and the greenhouse gases sprung from combusted wood. Like storms and earthquakes, it disturbs sites; like fungi and termites, it recycles dead biomass; like sun and rain, birds and beetles, it is simply there as cause, consequence, and catalyst.

How Life Accommodated Fire

Fire ecology is far from being a laboratory science. Control over the swarm of variables is weak, and field trials often fail to reproduce precisely the same results. The arguments for adaptation to fire largely belong in the realm of common sense and philosophy: an accommodation had to occur. The science of fire ecology is still struggling to document how this has happened. While these are serious qualms for fire sciences, they are less so for a brief history of fire. What matters are a few principles to guide our interpretation of what fire's history means.

First, fire does biologically what human ceremonies have unfailingly declared it to do: it promotes and it purges. It shakes and bakes. Around its flames revolves an ecological triangle, a circulation of biochemicals, species, and communities. It stirs molecules, organisms, landscapes. It kills plants, breaks down ecological structures, sets molecules adrift, shuffles species, opens up niches, and for a time rewires the flow of energy and nutrients. Fire upsets, shreds, reorganizes, revives, and quickens.

Second, plants and animals "adapt" not to fire as a principle but to particular patterns of fires. Even a single place may experience a variety of burns—a surface fire in the spring that lightly brushes off a veneer of needles, a wrenching crown fire in the late summer that guts a conifer forest. A biota can respond to a single event; it adapts to recurring ones. Over time, just such a pattern typically emerges, a mix and rhythm of burning that warrants the term *fire regime*. Organisms adapt to those regimes.

Third, adaptation rarely takes the form of a single trait. Because fire occurs within contexts—a chemical environment that governs combustion, a physical environment that directs its behavior, a biological environment that shapes its ecology—adaptation is also relative to that complex. There are, to be sure, organisms that display traits that are apparently, and spectacularly, specific to fire. But more typical is a suite of traits that adapt the plant or animal to the range of conditions within which fire occurs. In brief, fire is one of the Earth's great interactive biotechnologies. A trait that serves one purpose may serve equally well for others.

Fourth, fire is as ecologically powerful removed as applied. If fire is a biological presence as important as sun and rain, then halting it has the same force as blocking off sunlight or shutting down rainfall. A biota that knows a rainfall regime of 30 inches a year will suffer if it gets only 5, and that in a handful of downpours. So it is with fire regimes. Adaptations good for one set of circumstances become worthless, even harmful, if those circumstances change. What this means for fire history is that there is no ecologically neutral position possible. Not having fire is no more natural or benign than having it. For humanity, whose biological identity derives from "keeping the flame," there is no way to avoid fire. Deciding to apply fire, remove it, or change its rhythms, all have biological consequences.

More on Adaptations

How do organisms relate to fire? To simplify matters, these accommodations take two general forms: those that protect against fires and those that promote (or exploit) fire as a means to help the organism survive competitively.

Protective traits. The easiest features to identify are those that shield an organism from fire's passage. Thick bark shelters a larch's cambium layer from girdling by heat. Fat, succulent leaves guard the reproductive organs of aloes and proteas. Lignotubers store nutrients and even water from which mallee may resprout after fire has removed its crown. So, likewise, buried bulbs thrust upward after a liberating burn and an aspen's belowground rhizomal trunk sends up new shoots. In fact, the same feature may serve several needs. The native grasses of American prairies store most of their biomass in underground roots, ready to blast upward when conditions warrant—traits equally well suited to survive drought, grazing, and fire. Not all grasslands know this full complement; far northern grasses may spend their dormant season under snow. But most will be grazed, undergo a period of curing and drying, and will sooner or later burn. For prairie fauna, the presence of underground burrows may lead them to roots and away from surface aridity and flame.

Organisms also possess many traits that fit them to particular fire regimes. The ponderosa pine has thick bark, can withstand fire-excavated cavities in its bole, and prunes away lower branches as it matures, lofting its needles not only above competitors for sunlight but away from surface flames, an ideal growth scenario for a country full of frequent underburns. By contrast, jack pine grows in gregarious throngs, whole swaths of even-aged trees mottling the landscape on a huge scale. The close packing of the canopy makes each patch vulnerable to crown fire under the right conditions. When the site burns, as it eventually will, massive seeding in receptive ash ensures that the succeeding forest will regrow its predecessor.

And so it goes. Some long-lived trees like coastal Douglas-fir and Australian mountain ash have fire intervals on a scale of 400 to 700 years. Some grasses like African sourveld and American tallgrass prairie thrive under a regimen of near-annual firing. Most plants tolerate a mix of burning, or if fires fall outside their adaptive range, yield to those that can. Or, more provocatively, they evolve features that encourage the kind of fire to which they are best adapted. They move from self-protection against fire to a fiery self-promotion.

Promotional traits. This is an elusive concept, an awkward argument. Geotrophic orchids, cheat grasses, bracken, an infinity of fireweeds—all seize sites purged of competitors by fire. They are opportunists, avid to seed and sprout before others, quick to claim any opening. But they cannot hold as well as they can grasp. After a few years they may be crowded out of a recovering burn. So questions arise. Does their adaptation go further than taking what is presented to them? Have they so evolved that they begin actively shaping those sites and fire regimes to their own advantage? Do plants adopt growth habits and chemical properties that encourage fire—fires that give the plant some selective edge over its neighbors because they need a particular kind of fire to flourish preferentially?

The Earth tantalizes with possible examples. If lodgepole pine often requires heating in order to melt the wax that seals its serotinous cones, has it also grown in such a way that crown fires recur? Has the Australian grasstree, which flowers after being burned, evolved such that it makes that obligatory fire more likely? Is the peculiar evolution of flammability in chamise, a Southern California shrub, a biotic preparation to self-immolation? (As the plant ages, the chemistry of its leaves veers to a higher proportion of volatiles, the ratio of dead to live branches increases, woody debris collects at the base, the ventilation of the waxy scrub reaches an ideal. When it burns, it incinerates not only its surface self but everything around it; and then it resprouts, splendid in its selfish isolation.) And what about the regeneration of Big Tree sequoias, seemingly dependent on sites scoured by the slow deep burns that consume fallen boles? Is the chemistry of its combustion somehow tied to the physiology of its seeds, linked by cycles of fire?

The argument is hard to prove. But then it is equally hard to disprove, for the concept of "adaptation" can be viciously circular. There is no necessary reason why organisms could not have evolved traits to stimulate fire, however; and the exquisite choreography that seems to link high-intensity burning, in particular, with preferential reseeding suggests strongly that it has. These relationships are not the outcome of mechanical causes and effects—a fiery chisel sculpting a marble biota—but a long evolutionary give-and-take in which fire is a vital catalyst. What is clear is that organisms can live with fire, that not a few seem to thrive amid it, and that some will suffer from its absence.

How to Think about Fire Regimes

Flame flickers through space and time. Fire regimes are as lumpy as the biomass that stokes them. The land is a quilt of burnable biomass, some patches vast, some tiny, much of that organic matter available for burning, some not. Those patches vary over time, some changing according to predictable scenarios, some not. Places have their histories, and these are as fitful as their geographies. What matters is that fires burn within these patches and within more or less regular rhythms. If they burn through several patches, they assume the characteristics of each one in turn as they spread, and if they burn at different times, each event exhibits distinctive traits. Yet some patterns do emerge.

The simplest means to reveal a fire's regime (its size, frequency, seasonality, and intensity) is to consider the distribution of water within a patch's biomass. Living or dead, fuels exchange moisture with their surroundings. If they are too wet, they won't burn. A fuel's moisture content—hence that portion of its biomass that is available as fuel—changes with the daily wave of temperature and relative humidity, with the weekly passage of air masses through the region, with seasonal or monsoonal shifts in aridity, and with the long rhythms of drought or deluge on the order of decades or centuries. Severe droughts may crumble even rainforests into burnable fuels. Unusual rains may grow forbs and grasses in normally fireproof deserts, now flush with fine fuels and ready for flame. Long-term fire records around the Pacific Ocean trace nicely the pulses of the El Niño–Southern Oscillation (ENSO). And all these rhythms, of course, ride on the deep swells of climate change, as the Earth slides into and out of glacial ages. Whole biomes may arise and disappear or migrate across continents in the process. Fire will rise, fall, and travel with them.

These wet-dry rhythms set the ecological cadence for fire regimes. A place must be sufficiently wet to grow fuels and sufficiently dry to allow them to burn. Each day thus shows a preferred burning period, each year has its fire season. South-facing slopes make fuels available differently than north-facing ones do; wetlands burn on different cycles than do wind-swept plateaus. Patterns of wetting and drying, not the totals, are what matter—peaks and pulses, not averages; a seasonality of precipitation, not temperature. If the rhythms of wetting and drying are regular, so are fires. If they appear erratically, so will fire. Still, places assume patterns of burning. Just as they synthesize mixed storms into climates, so they amalgamate mixed fires into regimes.

Like all concepts it has its flaws. It stamps a statistical mean onto what in nature is highly variable, and it tends to ignore the exceptional and the unpredictable, which (as with weather) are the events that yield the greatest effects. Fire burns living biomass as its fuel, and thus shares the diversity, exuberance, and randomness of life. Free-burning fire is not encased in the boiler of a steam engine, driving ecological gears with mechanical regularity. Natural fire does not rekindle with the metronomic precision of an automotive spark plug. For all its tangled skeins, however, First Fire is in some ways simpler to unravel than Second Fire. Once fire bonded with humanity, it had also to respond to ideas, institutions, beliefs, trade, and taste as much as to winds and ravines. Anthropogenic fire has had to understand itself in ways natural fire never has.

First Fire Today

Humans have so thoroughly restructured fire on Earth that it is difficult to find truly natural fire regimes. Everywhere we have remade fuel and recast spark, and thus reordered fire. Even landscapes now empty of people bear the marks of our former tenancy, sometimes having coexisted if not coevolved with anthropogenic fire from their very origins. Experiments to restore a pure, lightning-driven regime have generally proved few and frustrating or have failed outright because the legacy of human history cannot be wiped away and rekindled on first principles alone. Even "pristine" landscapes exist through an act of human will. The concept of natural is itself a human invention. It is not "natural" for humans to vacate a landscape. It is not "natural" for humans not to burn. Since at least the Holocene, it has not been "natural" for lightning-caused fire to burn, as the saying goes, wild and free.

Fire Islands

Yet some uninhabited islands do exist. Some sites relatively uninfluenced by direct human meddling have appeared over the past decades, and some landscapes (like portions of the boreal forest), while subject to human-kindled fire, remain under the larger influence of fuels and climate and retain a substantial fraction of their primordial fire identity. They bear witness to the power and inevitability of natural fire. And they suggest, by both contrast and competition, how anthropogenic fire has worked its own alchemy.

There are true islands that exhibit lightning-driven regimes—isles in northern Swedish lakes, sandy patches of Scots pine amid the cold swamp that covers much of western Siberia, forested mesas in Utah and Arizona. The larger Swedish isles show more fire than their adjacent smaller ones, probably by virtue of offering a larger target and sporting lightning-favored trees rather than brush. Still, the frequency of fire is small, measured in centuries. The Siberian pine patches suggest a fire interval of 60 to 70 years, which is still more frequent than the spruce-fir regime in surrounding areas. Remote basins—the biota-filled cavities of old cirque glaciers—in the Sierra Nevada and Rocky Mountains experience fire in splendid granitic isolation. A 1937 expedition to Shiva Temple, a 300-acre mesa in the heart of the Grand Canyon, noted "trees scarred by lightning and evidence of forest fires which had not done much damage." Here frequent surface burns had fashioned a classic pine savanna.

Those scenes simply confirm the obvious: that fire exists independently of humanity, that biomes and lightning fire reach some sort of accommodation. It is not a simple task to extrapolate further. Such sites suffer the liabilities of island biology, a serious concern because fires, like migratory species, move. Most places burn not because lightning has ignited a tree on that precise site but because fires burn into them or across them. Islands, particularly small islands, prevent this. They remove from the scene the most dynamic of fire's properties, its capacity to propagate. This fact accounts also for much of the fire problems associated with "biotic islands" such as nature reserves. Fires aren't allowed in, and are controlled before they can move out. If the reserve lies on a mountain, the effect is worsened because the site is cut off from fires that would, historically, have climbed into it from the lower, drier, sooner-available fuels in valleys below.

First Fire's Reserves

Bigger reserves generally overcome this difficulty, though not completely. Scale alone is not decisive: no place is large enough to capture all possible fires, and none probably large enough to absorb the very biggest burns. But fire size is only part of what shapes a fire regime. Inviolate reserves, in particular, often deny a place's fire history. They pretend that anthropogenic fire was unimportant or that lightning can find a quick equilibrium in a system that humans have long sculpted either by starting fires or by putting them out. In removing people, nature reserves have remade fire's context in often unpredictable ways. It may take decades or centuries for an "equilibrium" to emerge, if that term has any meaning over such long spans of time and a robust Anthropocene.

Still, a growing body of evidence suggests how natural fire regimes can work. The best documentation comes from the United States, where reforms in fire policy from 1968 to 1980 created conditions to reinstate fire where possible, and in wilderness areas and parks, natural fire.

The earliest experiments occurred in California at Yosemite and Sequoia-Kings Canyon National Parks. In the Illilouette Creek basin all fires were suppressed from the 1890s until 1970. Then lightning fires were allowed under certain ("prescribed") conditions. All were surface fires, save for occasional torching and patchy blowouts. Their number and size increased until by 2000 they had filled the basin and were reburning old sites. Each burn scar affected the behavior of future fires, and multiple burns compounded. Gradually the regime and its allied ecology returned to something closer to what it had been, fashioning a landscape more resilient to the fires that were sure to power through under a changing climate.

In 1972 the U.S. Forest Service started an experimental program in the Selway-Bitterroot Wilderness. Here fires were more prone to burn into and through crowns; they were more intense, their effects more lasting than surface fires skipping through montane forests. Each burn scar helped to check future burns in what resembled a mobile jigsaw puzzle. Each burn helped make future burns easier to manage. The acres piled up. Meanwhile, the Gila National Forest in the Southwest, equipped with two wilderness areas and expansive montane forests, used a mix of prescribed fire and natural fire to reinstate a facsimile of the regime that existed prior to logging and overgrazing. The widespread prescribed burns in ponderosa pine helped to cordon off the wilderness areas and make possible natural fires even in the mixed-conifer of the rugged mountains. Over the years, the fires built one against another, one atop the next, a jigsaw puzzle in time as well as space. Even as conditions for burning worsened, enough burning had occurred that the land absorbed the new fires far better than it would have otherwise. Both the Selway-Bitterroot and the Gila examples showed the power of landscape burning, not just patchy set-pieces but free-ranging fires whose current behavior reflected the past history of fires on the land.

Even grander in scale is the interior of Alaska. Legislation in 1980 transferred vast extents of land to nature preserves—this in a boreal forest to which fire was integral. All the interested parties crafted a plan that would concentrate suppression where fires might threaten people and property; elsewhere, the fires were subject to “modified” or “limited” control, which in practice meant monitoring and selective intervention where necessary. Fire control itself relied on widespread burning from natural barriers. Forty years later interior Alaska came as close to a pre-settlement fire regime as anywhere in America. Once completed, the plan seemed not only successful but obvious, and the experience left observers wondering what it would take to extend those practices elsewhere.

Yet even these examples may be an artifact of human history. While the role of anthropogenic fire remains ambiguous, the pre-European peoples practiced an aboriginal economy for which fire was vital. They controlled ignition, which in these kinds of fire regimes is enough, for it is possible for people to seize mastery with little more than firesticks. By keeping fire constantly on the landscape, however, they have left climate as the principal variable. Climate looms exceptionally large in the record,

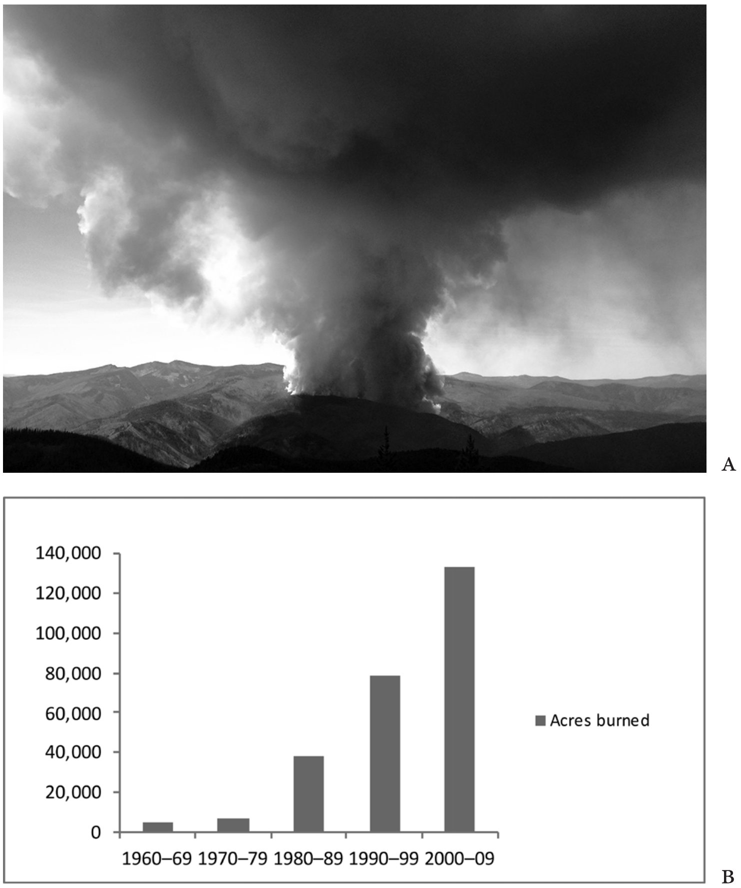


FIGURE 2. Reinstating natural fire. (a) Smoke plume from a 2013 fire in the Selway-Bitterroot Wilderness (SBW), Northern Rockies, USA. Photo courtesy U.S. Forest Service. (b) Area burned from fire restoration programs at the SBW and the adjacent Frank Church River of No Return Wilderness.

and its changes are notably important, because the spark is always there. End that unquenchable flame and the historical record might look different. In fact, the 20th century has removed those torches (along with much of the grassy understory that carried flame), and as a result, fire history reflects the political economy of logging, ranching, and forestry as much as it does the spasms of ENSO. (Oddly, those who argue that the record of fire-scarred trees tracks only natural fire grant humanity's capacity to alter those regimes by suppressing flame, which is difficult, but not by starting it, which is easy.)

In sum, even apart from anthropogenic climate change, what we see today is not wholly natural. How could it be? What we have, however, suggests powerfully how First Fire works and what its regimes might look like.