Introduction to Wildland Fire

Second Edition

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To Sonja, Lydia, Molly
who prove that the western pines are indeed fire-tolerant
— S.J.P.

To Howard, Jed, and Ryan
who gave me the gift of time
— P.L.A.

To Marta
— R.L.

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CONVERSION FACTORS

To Convert	To	Multiply By	To Convert	To	Multiply By
Acres	Hectares	0.4047	Kilograms/ square meter	Tonnes/hectare	10.0
Btu	Kilojoules	1.055	Kilograms/ square meter	Tons/acre	4.461
Calories	Joules	4.186	Kilojoules	Btu	0.9480
Calories	Kilojoules	0.004186	Kilojoules	Calories	238.9
Centimeters	Inches	0.3937	Meters	Feet	3.281
Cubic feet	Cubic meters	0.02832	Pounds	Kilograms	0.4535
Cubic feet/acre	Cubic meters/ hectare	0.06998	Pounds/square foot	Kilograms/ square meter	4.883
Cubic meters	Cubic feet	35.31	Pounds/square foot	Tons/acre	21.78
Cubic meters/ hectare	Cubic feet/acre	14.29	Tonnes	Tons	1.023
Feet	Meters	0.3048	Tonnes/hectare	Kilograms/ square meter	0.1
Grams/square centimeter	Kilograms/ square meter	10.0	Tonnes/hectare	Pounds/square foot	0.02048
Grams/square meter	Kilograms/ square meter	0.001	Tonnes/hectare	Tons/acre	0.4460
Hectares	Acres	2.471	Tons	Tonnes	1.102
Inches	Centimeters	2.540	Tons/acre	Kilograms/ square meter	0.2243
Joules	Calories	0.2389	Tons/acre	Pounds/square foot	0.04591
Kilograms	Pounds	2.205	Tons/acre	Tonnes/hectare	2.242
Kilograms/ square meter	Grams/square centimeter	0.1			
Kilograms/ square meter	Pounds/square foot	0.2048			

Source: Martin et al. (1979).

Abbreviations Used in Text

ACA	area command authority
AFS	Alaska Fire Service
AFS	Alberta Forest Service
AID	Agency for International Development
ALDS	automated lightning detection systems
AMLICA	Alaska National Interest Land and Conservation Act
AQCR	air quality control regions
AQMA	air quality maintenance areas
AS	ammonium sulfate
ATMU	air transportable mobile units
AVHRR	advanced very high resolution radiometer
BI	burning index
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
Btu	British thermal unit
BUI	buildup index
C + NVC	cost plus net value change
CCC	Civilian Conservation Corps
CCFFM	Canadian Committee on Forest Fire Management
CDF	California Department of Forestry and Fire Protection
CFC	chlorofluorocarbon
CFP	Cooperative Fire Program
CG	cloud to ground
CIFFC	Canadian Interagency Forest Fire Center
CSIRO	Commonwealth Scientific and Industrial Research Organization

DAID	delayed action ignition device
DAP	diammonium phosphate
DASP	Disaster Assistance Support Program
DC	drought code
DMC	duff moisture code
DoD	Department of Defense
DSC	differential scanning calorimetry
DTG	thermal gravimetry derivatives
ECE	Economic Commission for Europe
EF	emission factor
EFF	emergency firefighter
EFSA	escaped fire situation analysis
EMC	equilibrium moisture content
ENSO	El Niño—Southern Oscillation
ERC	energy release component
FAM	Fire and Aviation Management
FAO	United Nations Food and Agriculture Organization
FBP	Canadian fire behavior prediction system
FEMA	Federal Emergency Management Agency
FFASR	Forest Fire and Atmospheric Sciences Research
FFAST	forest fire advanced system technology
FFF	firefighting fund
FFMC	fine fuel moisture code
FIMS	Firescope information management system
FMA	fire management area
FMF	fire management fund
FMO	fire management officer
FMU	fire management unit
FMZ	fire management zone
FWI	fire weather index
FWS	Fish and Wildlife Service
GIS	geographic information system
GYA	Great Yellowstone Area
IAMS	initial attack management system
IBAMA	Instituto Brasileiro do Meio Ambiente dos Recursos Naturais Renovaveis
IC	incident commander
ICS	incident command system
IGAC	International Global Atmospheric Chemistry
IGBP	International Geosphere-Biosphere Program
IHC	interagency hotshot crew
INPE	National Space Science Institute (Brazil)
IR	infrared
IRFS	interregional fire suppression
ISI	initial spread index

IUFRO	International Union of Forest Research Organizations
KBDI	Keetch–Byram drought index
LCPL	least-cost-plus-loss theory
LFO	large fire organization
LST	local standard time
LTER	long-term ecological research
MAB	Man and Biosphere
MAC	multi-agency coordination
MACS	multiagency coordination system
MAFFS	modular airborne fire fighting system
MEDC	Missoula Equipment Development Center
MOS	marine observatory satellite
NARTC	National Advanced Resources Technology Center
NBS	National Bureau of Standards
NDVI	normalized difference vegetation index
NEPA	National Environmental Policy Act
NFDRS	national fire danger rating system
NFMAS	national fire management analysis system
NFPA	National Fire Protection Association
NIFQS	national interagency fire qualifications system
NIIMS	national interagency incident management system
NPS	National Park Service
NSF	National Science Foundation
NVC	net value change
NWCG	National Wildfire Coordinating Group
NWS	National Weather Service
OC	operations coordination centers
OCD	Office of Civil Defense
OES	Office of Emergency Services
PM	particulate matter
PSD	prevention of significant deterioration
RAWS	remote automated weather station
RIGS	remote interactive graphics systems
ROS	rate of spread
SBW	Selway–Bitterroot Wilderness
SC	spread component
SCOPE	Scientific Committee on Problems of the Environment
SDEDC	San Dimas Equipment Development Center
SIPS	state implementation plan
SPOT	Systeme Probatoire d'Observation de la Terre
SRV	Snake River Valley
SWFFF	Southwest Forest Fire Fighters
TAPAS	topographic air pollution analysis system
TG	thermal gravimetry
TSP	total suspended particulates

UNEP	United Nations Environment Program
WFCA	Western Forestry and Conservation Association
WIMS	weather information management system
WMO	World Meteorological Organization

Preface

We are uniquely fire creatures on a uniquely fire planet. To study fire is to inquire into one of the informing processes of the earth; to manage fire is to perform one of the defining acts of human beings. That, distilled, is the sufficient and necessary reason to understand fire.

Within our solar system the earth, and probably the earth alone, is a fire planet. Only on earth are combined the essential components of combustion. With lightning, it has a ready source of ignition; with atmospheric oxygen, an abundant oxidizing agent; and with organic matter, a fuel. Jupiter and Venus, and possibly Saturn, Uranus, and Neptune, have lightning, Mars has traces of free oxygen, and some moons of the outer planets have atmospheres rich in flammable hydrocarbons. But only the earth contains all the essential constituents, the processes needed to mix them, and a suitable environment for their interaction. To complement its ignition source, moreover, the earth also has an extinguishing agent, water. The earth can start fire, sustain fire, and suppress fire. The things that make earth unique among the planets have made it hospitable to fire. And fire, in return, has had much to do with shaping the natural history of the planet.

The process of acquiring fire began with lightning. Not only did lightning make ignition possible, but it may have also catalyzed the evolution of life. Life provided the other two essentials for combustion: atmospheric oxygen and fuel. As terrestrial life expanded, so did fire. Fire is everywhere dependent on life. It is equally true, however, that fire has, over geologic time and across nearly all lands, influenced the evolution and ecology of living communities. In some environments fire occurs infrequently, while in others it comes often; in some it is a dominant presence, and in others, only one process among many; in some biotas it is resisted, in some tolerated, and in some encouraged—but almost nowhere can it be ignored.

The capture of fire by early hominids changed forever the natural and human history of the planet. Humans assumed control over the start, spread, and suppression of fire, and are the only creatures known to have possessed this power. Humans could manipulate fire in new ways and shape the fire environment to new effects. Fire was removed from areas where it had previously ranged and introduced to landscapes that had not formerly known it. Humanity became the keeper of the flame for all the biological communities of which they were a part; the fire regimes of the planet have become, by and large, shaped by anthropogenic fire. The process dates back to *Homo erectus*, perhaps as long ago as 1.5 million years BP. Fire management became a defining attribute of *Homo sapiens'* heritage as a species.

Humanity's pact with fire forged an awesome alliance. It empowered hominids. It gave them a unique ecological role, access to virtually every biota on earth, and an instrument of great subtlety and strength. Suitably positioned, the torch could move continents. Domesticating fire allowed early humans to begin reshaping the planet. That saga commenced with their own domestication, for as fire became enfolded into human society, it changed not only its own character but that of humans. Controlled fire redefined social roles, diets, hunting, tool-making, foraging, and what did and did not constitute a natural resource—the whole relationship between humans and the natural world, and that among humans themselves. A family shared a fireside; a tribe shared a communal fire; a nation shared a vestal flame. Fire and humanity coevolved, like the bonded strands of a DNA molecule.

With great power came also great responsibility. Humans were genetically disposed to handle fire but they did not come programmed knowing how to use it. That had to be learned, which meant it was subject to scholarship, folklore, superstition, social beliefs and community values, philosophy, misinformation, the appeal to authority, and simple misunderstanding and ignorance; it could also be lost, misinterpreted, or forgotten. The management of fire thus belongs with politics, institutions of economics and law, bureaucracies and tribal codes—in brief, the whole social world that guides human behavior, and that far murkier moral universe within which humans must live and make decisions regarding a contingent world about which they have incomplete knowledge. Viewed comprehensively, fire management far transcends the technician's craft, the scientist's experiment, or the bureaucrat's handbook. Its context is much richer.

Just as natural fire amalgamates the complexity of its sustaining biota, so anthropogenic fire expresses the maddening complexity of human existence. The acquisition of fire did not come to humans with an operating manual or engraved on stone tablets. In the mythology of most cultures, it was stolen—a forbidden flame that brought immense power. If humanity wanted fire, it would have to discover and invent its own prescriptions for appropriate use, and it had to do so on behalf of the biotas that equally shared their fire environments. If fire defined a unique niche, it also proposed a unique dilemma. It is not too much to claim that anthropogenic fire could well be the paradigm for all of humanity's relationship to the natural world. That is why fire management is so difficult—and why it is so important.

It is the intention of this book to show how wildland fire is conceptualized and how, in the United States, it is managed . We seek to identify, clarify, and consolidate the concepts and the literature of fire studies, particularly the fire sciences; to explain the general principles and actual practices of fire management, and the institutional environment that sustains them; and to create a context for further reading in the literature and for further learning in the field or office. The book's intended audience includes students, practitioners, administrators, and the simply curious—anyone who wishes a concise survey about a topic of immense interest and complexity.

Several principles have guided the design of this book. The first is to keep fire central. Fire alone holds together the many disciplines, skills, and environments that it touches. A second principle is to reconcile the general with the particular, to convey generic principles through specific events and activities. A third is to integrate the cultural with the natural. Wildland fire studies and wildland fire management are meaningless without reference to human society, and must be understood within their particular cultural context. Lastly, the book seeks to do what books do best. Only a fraction of the knowledge necessary to manage fire is lodged in books; only a small part of what a practitioner needs to acquire by way of skills and know-how can come through reading. All these points are worth some elaboration.

Keep Fire Central As a subject of study fire is inherently interdisciplinary, and as a phenomenon it is wildly diverse in its manifestations. Only by insisting that *fire* remain at the core can the center hold. Wildland fire is a synthetic subject, and fire management a syncretic art. To understand fire requires an understanding of physics, chemistry, meteorology, ecology, economics, politics, anthropology, and history, among other disciplines; fire integrates them all. Equally, fire can serve as a means to better analyze these subjects. To explain combustion is to firm up the explanatory power of chemistry overall. To model the aerodynamics of a flaming front is to improve the conceptual foundations of physics. To track the history of anthropogenic fire is to appreciate better the peculiar character of humanity.

Accordingly this book begins with fire as a phenomenon, then progresses into fire management. What holds its many topics together is fire. Understand fire and you can appreciate the essence in each of its endless expressions.

Reconcile the General With the Particular There are, of course, general principles of combustion, fire behavior, fire weather, fire ecology, economics, anthropology, fire suppression, and prescribed burning. But not all of these principles are known with sufficient rigor. Many are probabilistic, and their manifestation can take extraordinarily complex forms. They express themselves not as clear statements, logically derived from universal axioms, but as specific events acted out at local levels, an empirical zoo of real-world diversity.

Fire does not work in one way only, but in many, heavily nuanced by particular circumstances. A fire in sawgrass burns differently than a crown fire in lodgepole pine or a surface fire through hardwood leaf litter; the general principles that govern fire behavior are of limited use without knowledge of their specific context. So also in fire ecology: In some environments, fire is essential; in some, common; in others, intrusive. In a given environment a burn can yield one consequence in the spring, another in summer, and another still in autumn. Fire can replace biotas, sustain them, reshape them. It catalyzes, animates, kills. It takes on the character of the environment in which it burns, even as it helps to fashion that environment. Its causes are many, its behavior multiple, its effects varied. Fire's reality does not reside in putative general laws but in fire's many particular expressions. As the American philosopher of pragmatism William James reminds us, "truth *happens* to an idea."

This book, then, tries to communicate both the general and the particular. For each major topic it proposes principles, to the extent that they are known or articulated, then it offers examples selected according to region, biota, agency, lessons, and where relevant, historical period. Americans manage fire for many purposes, in many landscapes, and through many social institutions. American fire cannot be understood without reference to that pluralism. Those fires are, in fact, a perfect expression of the unities and contradictions of the American civilization that contains them. To enunciate principles alone would convey a false clarity, like retelling American history by only reproducing the Constitution. But to record examples alone would also be a disservice, like explaining American law by reproducing court transcripts without reference to legal precedent or codes. Reality does not reside in a mythical "middle ground" between principle and event but in their vigorous fusion.

Integrate the Cultural With the Natural Fire management is a human activity. It may be argued that the manipulation of fire was the first distinctively human activity and the only ecologically unique task performed by early hominids, that humanity has become the keeper of the flame for the planet. Certainly the geography of fire today is coextensive with human settlement, and the character of fire is an expression of human will and technology. In a sense, millennia ago humanity and fire made a pact. Humans got fire, and through fire access to the world's biota; that biota, in turn, got a new regimen of fire, one transfigured by passage through human society. Fire science is a product of the human mind; fire management, an expression of human society; fire regimes, a symbiosis between nature and culture. Abstract humans from fire studies and the result is an imaginary world. Even where wildfire rages, it does so in defiance of human wishes, or because of human malfeasance, or with the encouragement of land managers who see such fires as advancing their larger, humanly determined missions. Often fire misbehavior is an expression of human misbehavior.

This book aspires to retain that ancient interdependence. If general principles have meaning only as they are expressed through local conditions, then those particular circumstances must also include the cultural environment. Fire responds to laws, political institutions, social values, recreational trends, religious beliefs, and scientific theories as well as to wind, slope, and fuel loads. Fire history describes a long coevolution between human inhabitants and their natural surroundings. Fire management has its parameters set by social institutions, and its landscape dictated by human boundaries, particularly by nation states.

This is another reason, if any additional justification is necessary, to focus on the United States. By concentrating on the fuel types, fire climates, institutions, and fire history of the United States, it is possible to give the topic a significant degree of unity in subject, style, and voice. But to understand American fire fully, one should understand its comparative position in the world. American fires share a common evolutionary history with fire everywhere; they share a global commons, their by-products cycling through a planetary biosphere and atmosphere; they reflect a global history that saw peoples, flora, and fauna, along with ideas and institutions, transferred among continents; they have in turn become a vital source of information and examples to other peoples. The United States has formal treaties with neighboring nations for mutual assistance in fire suppression, and it maintains an active program of international collaboration and aid in fire research and fire management. It is increasingly likely, moreover, that international conventions will influence fire management in the United States, as elsewhere. Concern over global environmental change, in particular, will probably establish new criteria for judging what fires are good and what are bad, which fire practices are appropriate and which are not. These norms will help shape the future conduct of American fire management.

It is clear that American fire managers need to know more about fire management beyond their national borders. This book provides a preliminary survey. But it is hoped also that the description of American fire can serve students from other nations, as they seek to understand their own fire scene better. Excepting the tropics, the fire biotas of the United States encompass most of those typical of the world. The fire history of the United States includes most practices of fire use and control found throughout the world, from hunting and foraging societies to agricultural economies to an industrial order. American fire history records an illuminating chronicle of a developing country that successfully accommodated technology transfer. Together with Canada, the United States created a North American style of fire management that has influenced global thinking and an outpouring of fire research that dominates the world literature. It is important not merely to identify that legacy but to appreciate its sources, liabilities, assumptions, and strengths.

Perhaps the present volume could serve as a model for other national surveys.

To Let a Book Do What a Book Does Best No one learns how to fell a flaming snag, cut fireline through windfall, operate a sling psychrometer, direct an air tanker drop, or fill out a fire report by reading alone. These skills are learned by demonstration, by example, by repetition on the job, and in recent years by video. Operating manuals, guides, reference handbooks, and the like can only supplement such learning, not substitute for it. But a book can do more. A book can communicate ideas, render accessible the written record of what is known about fire, and convey this information in concise form and in memorable language.

Fire management demands many kinds of knowledge, only some of which have ever been written about or need be written about. Wildland fire was used before it was understood; it was acquired from nature, not invented in a laboratory; and the necessity to physically manipulate fire has dominated much of the thinking about it. Scholarship has followed from practice, and the two are not fully integrated.

There are, in a sense, two cultures: a high culture of scholarship, particularly of science, and a vernacular culture of practitioners. Each culture has its own characteristics and language. Each describes the range of fire phenomena fully. But each preserves and transmits its knowledge differently. The vernacular relies on oral methods, examples, and apprenticeship; scholarship relies on writing. Both cultures, of course, have limitations. Books cannot replace practice, and field experience cannot substitute for that special learning preserved in the written literature. Field experience remains, and for the identifiable future must remain, the basis for practical operations, but the trend is to resolve more and more vernacular knowledge into formal scholarship, especially into modern science and quantitative descriptions.

In one sense, this exchange is merely a process of translation. What the vernacular might describe as a "hot" fire, science might restate as a propagating front with a fireline intensity of 800 Btu/ft sec. But in another sense, the process also involves transformations. Unlike folklore, high culture has the power to progress. Knowledge can be created in the laboratory or sieved from records; fires can be manufactured expressly for study, quite independent of the opportunities presented by nature; information can grow exponentially. And for all its flaws, the drive to express fire knowledge in terms of basic scientific concepts can only accelerate. Yearly such concepts are interpenetrating fire management overall, reformulating folklore into the language of science, and refashioning practice within the conceptual framework of formal scholarship—a trend boosted dramatically by the advent of modern computers.

By coupling fire to the high culture of scientific disciplines, research acquires tools of greater analytical power and concepts of larger synthetic scope. It joins fire studies to a larger realm of scholarship—ideas that are lifelines to the general culture—a matter of considerable importance whenever fire management must address issues beyond the domain of field technicians. Without those linkages fire management cannot speak with power or eloquence to its sustaining society and cannot seriously enter discussions about politics, values, and beliefs that will ultimately determine fire policies.

American fire management proposes to eliminate bad fires and promote good ones. But what criteria determine which fires are good and bad? What groups control that decision process? By what means are good fires prescribed and bad ones suppressed? Hotshot crew superintendents, laboratory technicians, dispatchers, district fire officers—none control this discourse. What are the purposes of fire management? What are suitable methods by which to achieve them? At what costs? Debates about the appropriate ends and means of fire management are no longer—never have been, really—solely under the control of the fire community.

Instead the management of wildland fire pivots around a social compact, a working concensus that addresses many publics. Fire science must connect with all of science, as science. Fire officers must relate to land use and to the welter of values those uses manifest. Fire management must join to the rest of American society, must engage other social institutions, national traditions, and cultural values, in all their variety and confusion. Publics include atmospheric chemists, wildlife biologists, the Audubon Society, journalists, artists, the Nature Conservancy, wilderness advocates, logging companies, recreational businesses, backpackers, summer home owners, county supervisors, novelists, media critics, urban fire services, and politicians, among others. Debates parade through the *New York Times*, *Newsweek*, *Natural History*, and *BioScience*, as well as the *International Journal of Wildland Fire* or *International Forest Fire News* or interdepartmental memoranda. American fire management must engage all of this.

And more. Increasingly, American fire is not even contained within the boundaries of the United States. Atmospheric emissions from burning transcend national borders. Fire research, as "big science," has its agenda set partially by international programs and the transnational character of science. An emerging environmental ethos is proposing for nature what the concept of human rights has argued for societies, that a common standard of basic behavior exists that should govern how humans relate to the natural world. Already some of these ideas have entered into political conventions; almost certainly these ideas will influence how Americans manage fire. Why, for example, is a million acres of crown fire at Yellowstone National Park good, and the burning of a million acres of African savanna or Amazonian forest bad?

The relationship between fire and the public is reciprocal, however. Fire management has a responsibility to communicate its job and the complex nature of wildland fire to the larger society. A book can do this. No single book, of course—certainly not this book—can capture all of what needs to be said. No book can explain American civilization to fire management, or the practical intricacies of fire operations to that mosaic of autonomous, often competing constituencies that makes up the American public. Besides, some of what researchers would like to know is not yet known; some of what students would like to have explained is not yet explicable, or can be conveyed only through vast simplifications; much of what practitioners would like to acquire by way of skills cannot be learned from writings. The reality is that nature is messy, technology defective, ideas flawed, and humans fallible. Like books.

Twelve years have passed since the senior author wrote the original edition of *Introduction to Wildland Fire*. The reasons for a revision are many and obvious. But three are outstanding: to purge the text of errors and antiquated statements, to expand and update its examples and coverage, and to reposition American fire management within a global context. The addition of two additional authors, Patricia L. Andrews and Richard Laven, makes all these ambitions possible.

The 1980s were an eventful decade. After a succession of wet years, drought returned and revived big-time fire suppression. The Yellowstone conflagration of 1988 vaporized an era of wilderness fire. The Berkeley Hills fire of 1991 and the Malibu fires of 1993 branded into American consciousness a new era in which the wild and the urban mix in unstable compounds. Fire research nurtured the BEHAVE program into common practice, then saw it propagated, like sparks from a torching fir, across the world. The incident command system banished earlier fire organization principles into the archives. Alarm over nuclear winter restored the demonology of fire as a hostile presence, a biospheric incubus. Colossal burning in Amazonia ignited environmental activism on a global scale and made fire a symbol of nature's approaching apocalypse. What was fresh has grown stale. Events have overtaken and made irrelevant what once seemed indispensable. Much has been learned, and much done; knowledge, like biotas, is dynamic, and a book that seeks to describe the state of knowledge must also adapt.

This second edition embodies several new editorial decisions. First, since the early 1980s the United States has retreated from a commitment to adopt the metric (SI) system. This book must do likewise. It includes a table of formulas by which to convert between English and SI units, but to clutter the text with dual sets of numbers is pointless. In practice the country is binumerate: Field operations rely on English measurements, scientists on SI units. The text will follow suit. Those chapters that draw primarily on the scientific literature will use SI, and those that pertain to practitioners and the public will continue to speak in English. The mixture is an absurd reality of American life and no book will abolish it.

Second, the decision to avoid mathematical exposition, if it had merit originally, has less justification now. To abolish mathematics from scientific explanation is like banning poetry from literature. Whatever difficulties it imposes, mathematics more than compensates by clarity, rigor, and conciseness. No less important, the universal use of computer programs to predict fire behavior and effects requires that the mathematical fire models around which that software builds must be something more than a black box if practitioners are to understand the tools they exploit, if they are to use the computer and not be used by it. Accordingly, the book appeals to mathematical expressions where appropriate.

Third, the dramatic globalization of fire science and fire management has argued for an additional chapter that would position the United States within a planetary context—a daunting task, for which "Global Fire" can claim to be little more than a prolegomenon.

We have divided the tasks among ourselves as follows. Patricia Andrews wrote Chapters 1–4, Richard Laven wrote Chapter 5, and I wrote the remainder. We have made no effort to homogenize our writing styles or to impose a common interpretation. Each of us has spoken from our strengths, out of the traditions of our own disciplines, and in our own voices.

Fire studies, like fire management, are pluralistic and often particularized. This book reflects that reality without, we trust, succumbing to what literary critics call the imitative fallacy. Consider the outcome a kind of capture-and-release scholarship.

STEVE PYNE

Glendale, Arizona

Part One

Fire Environment

1

Wildland Fire Fundamentals

We begin our study of wildland fire with the basic principles and mechanisms of the combustion process—*fire fundamentals.* In the next chapter we look at wildland fire as an event. *Fire behavior* is what a fire does, the dynamics of the fire event. In later chapters we move up the scale to *fire on the landscape*, and in the final chapter, *global fire.* Figure 1.1 illustrates this expanding view of wildland fire.

At the fire fundamentals scale, combustion processes, fluid dynamics, and fuel chemistry dominate. At a larger scale, fire behavior, the configuration of the fire as a whole and its environment are driving forces. At a still larger scale, landscape, the relationship of areas to each other must be considered—subdivisions, proximity of logging slash areas to one another, extent of wildlife habitat. Other fire influences are at a global scale, the effect of emissions from prescribed and wildfires on the atmosphere, for example.

An understanding of the fundamentals of wildland fire is important for some very practical reasons. The combustion process can be manipulated to some extent: Retardants can be applied to affect the combustion process; fuel arrangement can be altered for hazard reduction; and appropriate environmental conditions can be chosen for prescribed fire to reduce smoke impacts, achieve desired fuel reduction, and still retain control of the fire.

The need to understand wildland fire fundamentals is even more pressing than it was in the past. In earlier times the focus was on describing the aspects of fire that are important to suppression efforts. That continues to be high priority. In addition, there is now increasing emphasis on characterizing fire for its effect on vegetation and for the smoke it produces.

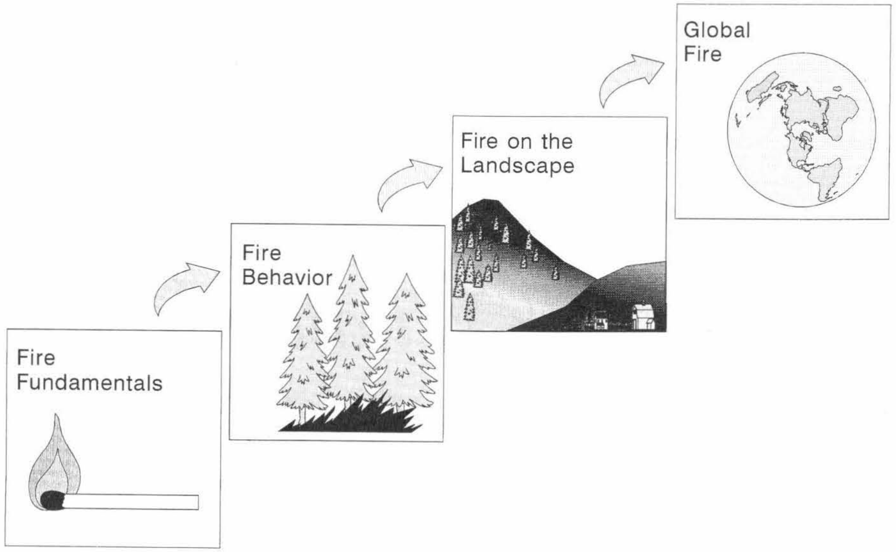


Figure 1.1. *Expanding view of wildland fire. The dominating influence factors change with the scale.*

In addition to practical considerations, wildland fire continues to present interesting and challenging academic problems. Although combustion obeys general principles of physics and chemistry, the study of wildland fire is not an exact science. There have been significant advances in wildland fire science. The fire phenomenon in the wildland setting, however, has not been and may never be explained to the level of first principles. There is much yet to be learned.

Other types of combustion are better understood—automotive engines, jet turbines, coal combustion. When gaseous fuel is metered to a burner, for example, there is no difficulty in describing thermochemical properties of the fuel since they are under the control of the experimenter. When fire burns through wildland fuel, the process is affected by a multitude of factors including turbulence and nonuniformity. Variability even exists in a well-controlled combustion laboratory experiment (Figure 1.2). At the scale of a burning twig, there are complexities due to the molecular arrangement and chemical components of wood and bark. Combustion is a complex subject that involves chemistry, physics, and fluid mechanics. We restrict our discussion to those factors that have a direct bearing on wildland fire.

1.1 COMBUSTION PROCESS OVERVIEW

The plant material that burns in a wildland fire is produced by the process of photosynthesis, the chemical process by which carbon dioxide, water, and the sun's energy are combined to produce cellulose, lignin, and other chemical components. Both decay and fire reverse that process. Decay is a slow process, with a barely noticeable release of heat over a long period of time. Fire, on the other hand, is a rapid release of the heat energy stored by photosynthesis.

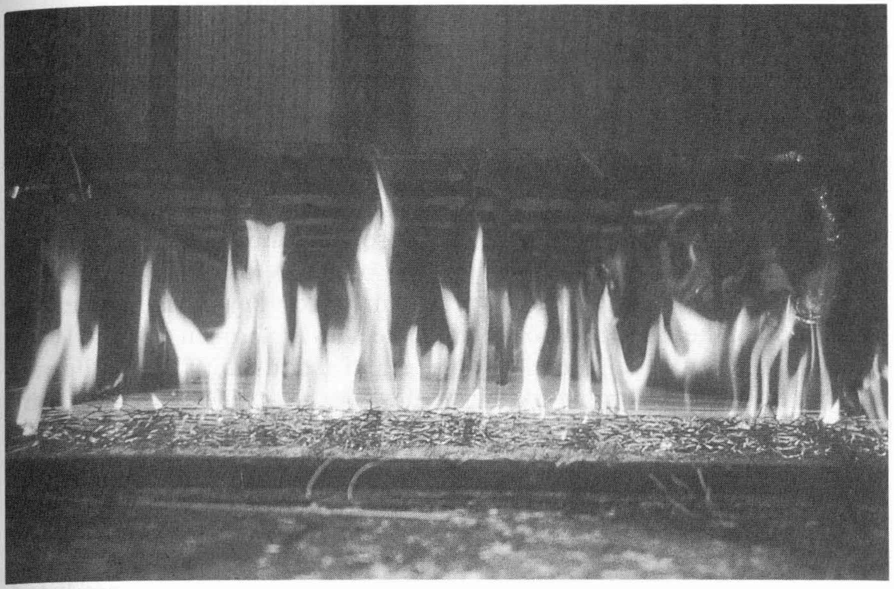


Figure 1.2. *There is significant variability even in a controlled laboratory fire.* Photo courtesy of USDA Forest Service.

Radiant energy from the sun is transformed by the process of photosynthesis to stored chemical energy in vegetation. When the vegetation is burned, the chemical energy is transformed to thermal energy, radiant energy, and the kinetic energy in the rising air in the convection column over the fire. The relationship between photosynthesis and combustion can be visualized by comparison of very much simplified formulae for the two:

Photosynthesis:

$$CO_2 + H_2O + \text{solar energy} \rightarrow (C_6H_{10}O_5)_n + O$$

Combustion:

$$(C_6H_{10}O_5)_n + O + \text{ignition temperature} \rightarrow CO_2 + H_2O + \text{heat}$$

We often think of flames at the mention of fire; that is definitely the aspect of fire that attracts the attention of news crews. There is, however, much more to fire than flame. *Fire* is a manifestation of a chemical reaction; *flame* is a gas phase phenomenon, only part of the process.

Burning begins with endothermic reactions that absorb energy and ends with exothermic reactions that release energy. The endothermic reactions are known as *preignition*, the exothermic reactions as *combustion*, and the point of transition as *ignition*.

During the *preignition* phase the fuel is brought to kindling or ignition temperature. There is generally a pilot source of ignition, but spontaneous ignition is also possible. The initial effect of increasing temperature on the fuel is a *dehydration* process in which the free and absorbed water in the fuel is driven off. The heat also causes the volatilization of waxes, oils, and other compounds. At higher temperatures this is accompanied by *pyrolysis*, the thermal degradation of the fuel. Long polymeric molecules are broken down to lower molecular weight gases and semi-volatile *tar* and a solid *char*. The volatile products are involved in flaming combustion, while char may oxidize (burn) by glowing combustion.

Ignition is the transition between preignition and combustion, the temperature at which a pilot source of heat is no longer required. Once ignited, the heat generated by the combustion brings other fuel to ignition, continuing the cycle.

Combustion may or may not involve a flame. The volatiles that are produced in the preheating phase ignite to form a visible flame. After flaming combustion has ignited and burned most of the volatiles, the remaining carbon may burn as a solid by surface oxidation called smoldering or glowing combustion. Glowing differs from smoldering combustion only in that thermal degradation of the parent fuel does not occur, nor is it required; the pyrolysis zone is replaced by a simple preheat zone. The terms smoldering and glowing are generally used interchangably.

Combustion efficiency varies. If combustion is not complete, some of the volatile products will remain suspended as very small droplets of liquid. These plus residual carbonized particles that float in the air are smoke. Water vapor from dehydration and combustion may also condense giving smoke its whitish appearance.

Extinction is the termination of combustion. It occurs when not enough heat is available to sustain the combustion process without a pilot source of heat.

The *fire triangle* has been used to describe the interacting factors involved in fire fundamentals (Figure 1.3). Fire requires all three legs: the appropriate fuel, adequate oxygen, and enough heat. Fuels burn under appropriate conditions, reacting with oxygen from the air, generating combustion products, and releasing heat. The fuel leg of the triangle refers to the material that burns—type, chemical composition, density, moisture content. Heat refers to pilot source heat, enough to reach ignition point, and to the heat release, which must be enough to sustain combustion. Oxygen is required for combustion and is affected by fuel arrangement. When the fuel is gone, when the pilot heat source is not available, or if not enough heat is generated to continue the process, if ash builds up or dirt is thrown on the fuel limiting oxygen supply then a leg of the triangle is broken and the fire goes out.

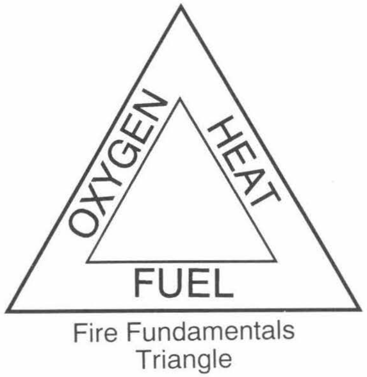


***Figure** 1.3. Fire fundamentals triangle. Oxygen, heat, and fuel must be present for fire to exist.*

The combustion process is illustrated in Figure 1.4 by means of the familiar camp fire.

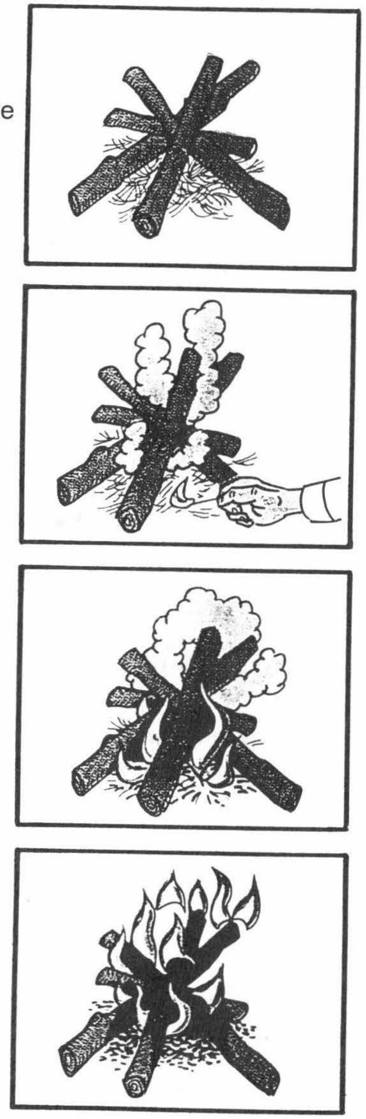
1.2 INTRINSIC FUEL PROPERTIES

We examine wildland fuel by separating the discussion according to those properties that are intrinsic to the fuel and those that are extrinsic. Intrinsic fuel properties are those that delineate the plant parts, including fuel chemistry, density, and heat content. Extrinsic fuel properties include relative abundances of various sizes of fuel components, fraction dead, and compactness of the fuel bed. Intrinsic properties are the dominant fuel factors at the fire fundamentals scale, while extrinsic fuel properties must be considered at the fire behavior scale.

The extrinsic properties of fuel will be covered in Chapter 3. Here we discuss the physical and chemical properties of fuel that are important in a study of the combustion process and of emissions, the products of combustion.

Wildland fuel consists of the cell wall polysaccharides, i.e., cellulose and hemicelluloses, which are readily pyrolyzed; lignin, which mainly forms char; extractives, particularly the terpenoid hydrocarbons, and lipids, which provide a ready source of combustible volatiles; and ash content, which exerts a suppressing effect. Other properties that are intrinsic to the fuel are density, heat content or heat of combustion, and thermal conductivity of the material.

Most plant material consists of polymeric organic compounds. Plant tissue is approximately 50% carbon, 44% oxygen, and 5% hydrogen by weight. The content of most wood varies between 41 and 53% cellulose, 15 and 25% hemicellulose, and 16 and 33% lignin. Lignin content is much higher (up to 65%) in decaying (punky) wood, in which the cell wall polysaccharides are partially removed by biological degradation.



1. Campfire fuel is a mixture of dry fine and heavy fuel. It is placed on mineral soil to eliminate the possibility of smoldering ground fire.

2. The pilot heat preheats the fine fuel. Moisture is boiled off. Tars appear as visible smoke. A cloud of combustible gases is formed.

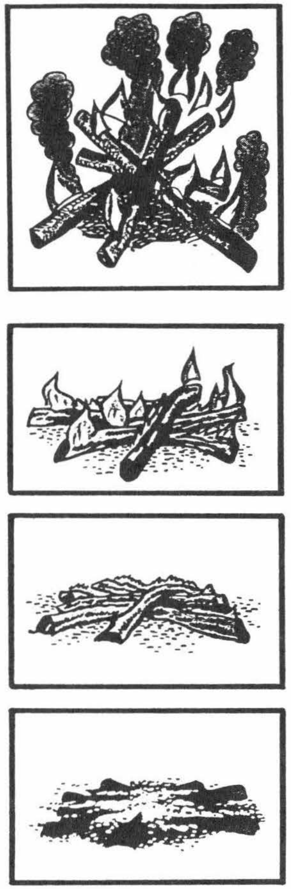
3. The pilot heat ignites the combustible gases. Flames from fine fuel preheat larger fuel. Gases from larger fuel ignite.

4. Fine fuel begins to burn by glowing combustion. Ash is formed.

Figure 1.4. *The combustion process illustrated by means of a camp fire.* Based on Cottrell (1989).

Woody fuels are high in cellulose and lignin, but low in extractives. Green vegetation has a higher extractive content. The chemical diversity found in plant material affects the rate of burning and the amount and type of emissions produced.

Cellulose, the principal constituent of all higher plants, is a condensation polymer of the hexose sugar D-glucose, and adopts a linear structure. This configuration allows the molecules to align themselves into bundles (microfibrils), which provide the structural strength and rigidity of the cell wall. The microfibrils are bound together during the process of lignification when the hemicellulose and lignin are laid down in the growing plant. The molecular weight varies from 300,000 to 500,000. Cellulosic materials are a major contributor of combustible volatiles.



5. Preignition, ignition, and flaming and glowing combustion are occurring in different parts of the fire. Smoke results from incomplete combustion.

6. Wood collapses due to heat -weakened cellulose.

7. Gray mineral ash coats the fuel surface. Ash must be knocked off to prevent smothering.

8. Fire is out. Most of the cellulose fuel has reacted with oxygen to form carbon dioxide and water.

Figure 1.4 (Continued)

Hemicelluloses are carbohydrate polysaccharides with shorter chain lengths than cellulose, found in association with cellulose in the cell wall of plants. The structure of hemicelluloses are similar to cellulose, based on pentose and hexose sugars, but that of lignin is vastly more complex.

Lignin is the material that gives wood its stiffness. It is an aromatic polymer of wood, consisting of four or more phenylpropane monomers per molecule. Since cellulose is degraded more easily than lignin, dead fuels have progressively higher lignin contents as they age. If lignin is heated to temperatures in excess of 400–450°C (750–840°F), only about 50% volatilizes; the balance of the mass remains as char residue. Lignin is more stable than the cellulosic or extractive components when heated and produces considerable carbaceous char. Char formation is required for glowing combustion.

Extractives are a class of compounds consisting of aliphatic and aromatic hydrocarbons, alcohols, aldehydes, gums, and sugars. Other extractives are a complex mixture of terpenes, fats, waxes, and oils. Ether extractives constitute a smaller fraction than cellulose and lignin, but extractives have special properties. Their high heat of combustion, volatility, and lower limits of flammability in air influence the way that the fuel burns.

Shafizadeh and others (1977) investigated the ether and benzene–ethanol extractives of several plant species. They found that the total amount of extractives varies substantially for broadleaf species, ranging from 45% for gallberry to 13% for saw palmetto, based on dry, unextracted sample weight. Manzanita is 26% extractives and ponderosa pine is 31%. A study by Burgan and Susott (1991) examined the extractives throughout a season. There is some indication that total volatiles evolved up to 500°C (932°F) do have a seasonal trend, particularly in the case of gallberry which has a relatively high volatile content. At 500°C (932°F) (Figure 1.5), gallberry shows a seasonal fluctuation of almost 25%. There is no apparent correlation between the quantity of volatiles and the occurrence of frost.

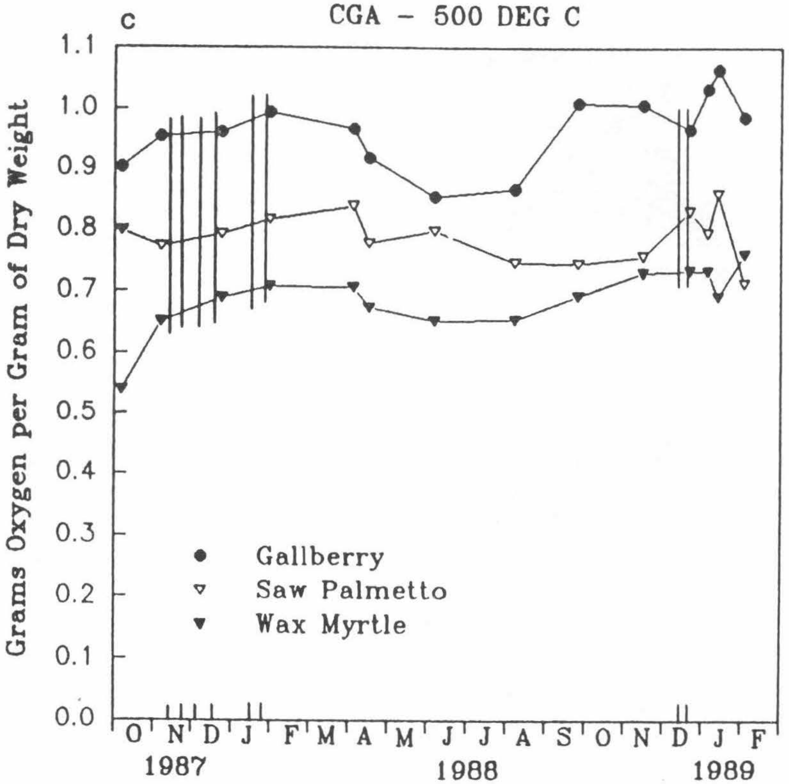


Figure 1.5. *Combustible gas analysis (CGA) for freeze-dried samples of gallberry, saw-palmetto, and wax myrtle at 500°C (932°F). Vertical lines indicate those dates when minimum temperatures were less than 0°C (32°F).* From Burgan and Susott (1991).

Mineral or *ash content* can retard flaming combustion by promoting low-temperature pyrolysis to tar and char. The pyrolysis of cellulose can be altered by the presence of inorganic materials that act as catalysts promoting the formation of char at the expense of flammable volatiles.

Philpot (1970) observed that the changes in pyrolysis found in plant materials with differing ash content are very similar to those that occur when cellulose is treated with increasing amounts of flame-retarding compounds. In plant materials with higher ash contents, maximum volatilization rate decreases, residue increases, and active pyrolysis begins at a lower temperature, and the volatilization rate at that temperature increases. In plant materials having ash contents exceeding 12% the effect was not proportionately increased; the effect noticeably leveled off at 5 to 7%.

Susott (1980b) measured the ash content for 40 fuels: pure cellulose is 0.1% ash; wood samples were 0.6% or less; foliage ranged from 1.6% for slash pine foliage to 7.7% for big sagebrush; Interior tundra (the top layer of black spruce understory) was 33% ash.

1.3 HEAT AND HEAT TRANSFER

The *temperature* of a substance is a function of the kinetic energy of the motion of its molecules, measured in degrees. Although the temperature of a fire is one of its noticeable features (fire is hot), a temperature value alone does little to characterize the fire. More valuable is quantification of time–temperature relationships or heat flux.

Heat is a form of energy, often referred to as thermal energy. When heat is applied to a substance, the molecular activity increases and the temperature rises. Heat is the energy of molecular motion. It is one of the elements in the fire triangle (see Figure 1.3), one of the ingredients that are essential for a wildland fire to start and continue to burn.

Heat of preignition is the total heat required to raise the temperature of a unit mass of fuel to the ignition temperature, usually taken to be 320°C (600°F).

Heat of combustion is the energy that maintains the chain reaction of combustion, and is sometimes known as *heat value* or *heat content*. It is the total amount of heat released when a unit quantity of a fuel is oxidized completely. Heat of combustion can be measured for any particular fuel, but does not vary widely in forest fuels. A value of 18,620 KJ/kg (8000 Btu/lb) is often used.

Heat flux, also called *heat release rate* or *intensity*, is the amount of heat produced per unit of fuel consumed per unit of time, or energy per unit area. It is not a property of the fuel, but rather of the energy transfer process. Heat flux is not an easily measured value.

Heat Transfer: Conduction, Convection, Radiation

Heat is energy in transit as the result of a temperature difference. *Heat transfer* is the process or mechanism by which the energy is moved from one source to another. Heat transfer occurs whenever there is a temperature difference in a medium or between media. An understanding of heat transfer is essential to the study of fire. The mere presence of a heat source does not necessarily mean that a fire will start. Heat must be transferred in some way to the fuel. And if the fire is to continue to burn and grow, heat must be transferred to the unburned fuel around the fire. The way a fire burns and behaves is closely related to the manner and rate of heat transfer.

The three basic mechanisms of heat transfer are radiation, convection, and conduction. All three contribute to the combustion process, but in different ways. The dominant heat transfer mechanism depends on the fuel arrangement, the speed of the wind acting on the fire, the slope of the terrain, and the direction the fire is spreading with respect to wind direction and slope.

Conduction is the transfer of heat by molecular activity from one part of a substance to another part, or between substances in contact, without appreciable movement or displacement of the substance as a whole. The sun heats the earth's surface and this heat is conducted to deeper layers of soil and water during the day and back to the surface at night. The varying ability of different soils and of water to absorb and conduct heat has a profound effect on local and worldwide weather and climate.

Thermal conductivity expresses the quantity of heat transferred per unit of area per unit time per degree of temperature gradient. Copper conducts heat more than 15,000 times better than air, 6500 times better than water, and 2500 better than wood. The thermal conductivity of wildland fuels becomes greater as the density of the fuel increases. Because heat capacity of the fuels also increases with density, high-density fuels usually require more heat for ignition than do low-density fuels. Heat can be conducted more rapidly into deeper layers of the high-density fuels, thus slowing the temperature rise at the surface so that more heat is required to raise the surface temperature to the ignition point. More heat is also required to raise the temperature of the surface layer because the dense fuel has greater heat capacity. This difference in heat requirements for ignition is one of the reasons that fuel like decayed wood can often be ignited with a spark, but solid and dense wood requires a larger firebrand.

Radiation and convection can transfer heat only to the fuel surface. The only way that heat can get into the interior of opaque materials is by conduction. Hence, conduction of heat is of major importance in the combustion process, particularly for larger fuels and organic ground fuels.

Convection is the transfer of heat by the movement of a gas or liquid. Heat is transferred from a hot-air furnace into the interior of a house by convection. Currents of hot air tend to move vertically upward unless a wind or slope causes some degree of lateral movement. Convection currents are primarily responsible for the preheating of the higher shrub layers and crown canopy. Convection is also of vital importance to humans working near a wildland fire.

Radiation is a form of energy called radiant energy, existing as electromagnetic waves that travel at the speed of light. Essentially all materials on earth are radiating energy. Radiant energy travels outward in all directions from the emitting substance until it encounters something capable of absorbing it. An example is the heating of the earth by the sun or the type of energy that one feels when sitting across the room from a stove or fireplace.

There need be no direct contact between a source of radiation and a body it may affect. Radiation accounts for most of the preheating of fuels ahead of a fire front. Radiation is proportional to the absolute temperature of the emitting body raised to the fourth power. A change in the source temperature from 800 to 1000 K will result in a doubling of radiant energy emitted.

For a point source of radiation, the radiation intensity decreases inversely as the square of the distance. This means that the radiation intensity 10 m from the source is only one-fourth that at 5 m. As the distance from the source increases, the same total amount of radiation is spread over a greater area, hence the amount received per unit of area is less. Waves move only along straight paths. Hence, the intensity of radiation received depends on the angle of the incoming radiation and the distance from the source. Radiation perpendicular to the receiving surface is most intense. Wildland fire, however, is not a point source; flames usually have considerable surface area. Because so many points are producing radiant energy, the decrease in intensity with distance from a flame source is much less than that from a point source.

Different kinds of substances vary greatly in capability to emit and to absorb thermal radiation. The ideal radiator is one capable of emitting and absorbing all thermal radiation. Since black surfaces most often approach this capability, a perfect radiator is called a "black body." Thick flames in a wildland fire can come as close to emitting thermal radiation as a blackbody.

Only a perfect blackbody can absorb all the thermal radiation that reaches it; other substances absorb only part of the radiation. In opaque materials, such as wildland fuels, the conversion of radiant to thermal energy takes place in a very thin layer at the surface. Heating of deeper layers is accomplished by conduction.

Heat Transfer Equations

A summary of the basic equations of heat transfer is taken from Drysdale (1985). *Conduction* is the flow of heat from a region of high temperature to one of low temperature; the flow can be expressed as a heat flux, which in one direction is given by

$$\dot{q}''_x = -k \frac{\Delta T}{\Delta x}$$

where ΔT is the temperature difference over a distance Δx. In differential form this is known as Fourier's Law of Heat Conduction. The constant k is the thermal conductivity and has units of W/m·K, where $\dot{q}''$ is in W/m^2, T is in °C (or K), and x is in m.

Convection is that mode of heat transfer to or from a solid involving movement of a surrounding fluid. The empirical relationship first discussed by Newton is

$$\dot{q}'' = h\Delta T \quad \mathrm{W/m^2}$$

where h is known as the convective heat transfer coefficient. This equation defines h, which, unlike thermal conductivity, is not a material constant. It depends on the characteristics of the system, the geometry of the solid, and the properties of the fluid including the flow parameters; it is also a function of ΔT. The evaluation of h for different situations has been one of the major problems in heat transfer and fluid dynamics.

Radiation involves transfer of heat by electromagnetic waves confined to a relatively narrow "window" in the electromagnetic spectrum. It incorporates visible light and extends toward the far infrared. According to the Stefan–Boltzmann equations, the total energy emitted by a body is proportional to T^4, where T is the temperature in Kelvin. The total emissive power is

$$E = \varepsilon\sigma T^4 \quad \mathrm{W/m^2}$$

where σ is the Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^{-4}), and ε is a measure of the efficiency of the surface as a radiator, known as the emissivity. The perfect emitter, the black body, has an emissivity of unity. The intensity of radiant energy ($\dot{q}''$) falling on a surface remote from the emitter can be found by using the appropriate "configuration factor" ϕ, which takes into account the geometrical relationship between the emitter and the receiver:

$$\dot{q}'' = \phi\varepsilon\sigma T^4$$

1.4 PHASES OF COMBUSTION

In this section we examine in more detail four phases involved in the combustion process: preignition, ignition, combustion, and extinction. Figure 1.6 is a diagram of combustion characteristics in the presence of wind.

Preignition

The *preignition* phase includes endothermic reactions by which the temperature of the fuel is raised to the point where the free water evaporates and the volatiles are released. Heated vegetation fuels produce combustible gases as products of pyrolysis and by volatilization of waxes, oils, and other compounds in the vegetation.

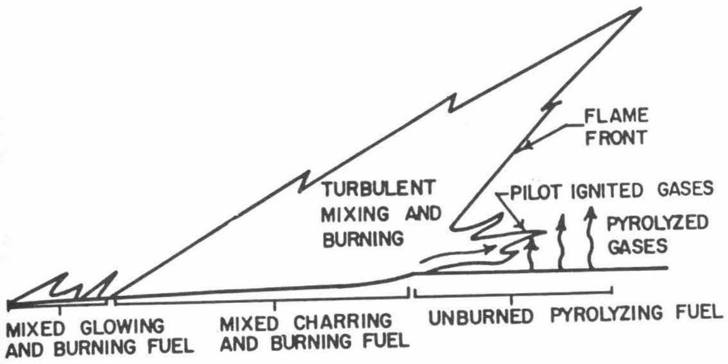


Figure 1.6. *Flaming zone combustion characteristics in the presence of wind.* From Rothermel and Anderson (1966).

Dehydration removes volatiles by the distillation of water and extractives. Preheating acts first on low-temperature volatiles. Even a warm day is enough to evaporate some extractives, thus the characteristic smell of a forest. Continued preheating then operates on any adsorbed water within the fuel particle—its fuel moisture. Fuel moisture content is highly variable. Dead fuel can range from 1 to 300% while live fuel can be 300% or more moisture content (on a dry weight basis). Adsorbed water must be driven off before the heating of the particle proper can begin. Water is volatilized around 100°C (212°F). Because ignition temperature is far above the boiling point of water, any moisture in the vegetation is driven off, at least from near-surface layers of the fuel, before ignition occurs. More water per unit mass of dry matter requires more heat to vaporize it before the fuel can be ignited. If the desiccation process demands too much energy or too much time, the burning that follows ignition may not be able to satisfy the demand.

Pyrolysis is the *thermal degradation* of molecules or polymers prior to combustion; it is chemical decomposition through the application of heat. The word *pyrolysis*, in fact, means "heat divided." The pyrolysis of plant material produces the volatiles that support combustion. Pyrolysis of wildland fuels yields combinations of volatiles, tars, carbonaceous char, and mineral ash. Two general reaction pathways of cellulose degradation are recognized (Figure 1.7): One leads to char and water, while the other leads to tar and volatiles. High temperatures favor the evolution of volatiles—flammable gases known as pyrolysates—whereas low temperatures promote the production of tar and char.

Extractives, such as lipids and terpenoid hydrocarbons, will volatilize at low temperatures and yield gases with a high heat of combustion. Cellulose shows thermal stability until particle temperatures of 250°C (480°F) are reached. At 325°C (620°F) it breaks down rapidly, evolving large quantities of

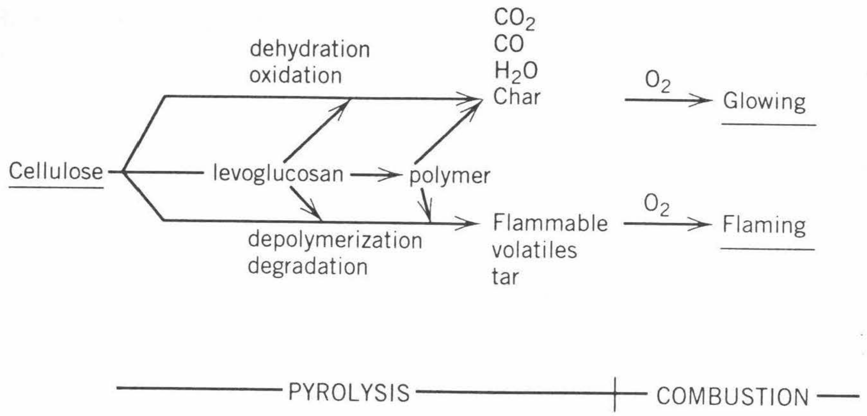


Figure 1.7. *Pathways for the pyrolysis of cellulose.* From Philpot (1971).

flammable gases. Lignin resists thermal decomposition, leaving it more prone to char as a product and glowing combustion as a process. Mineral constituents can retard flaming combustion by promoting low-temperature pyrolysis to tar and char.

Thermal gravimetric (TG) analysis methods have been used to evaluate the evolution of pyrolysis gases from solid fuels as a function of temperature. The peaks using this technique exhibit a spectrum reflecting the thermal stability of the fuel components, as shown in Figure 1.8. Each component released can have a different molecular weight and chemical form, which can have significant implications regarding the formation of emissions. For wildland fuels there are a great number of complex pyrolytic reactions involved in volatile production.

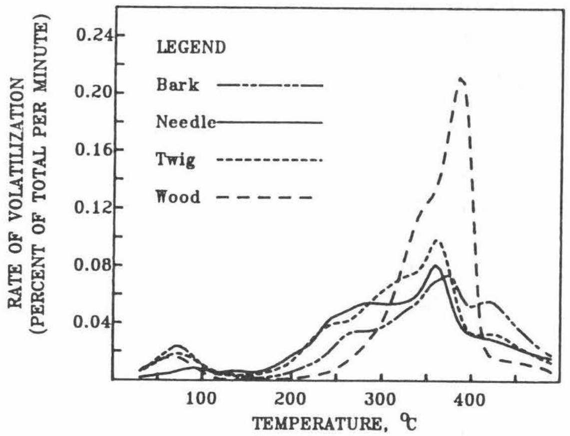
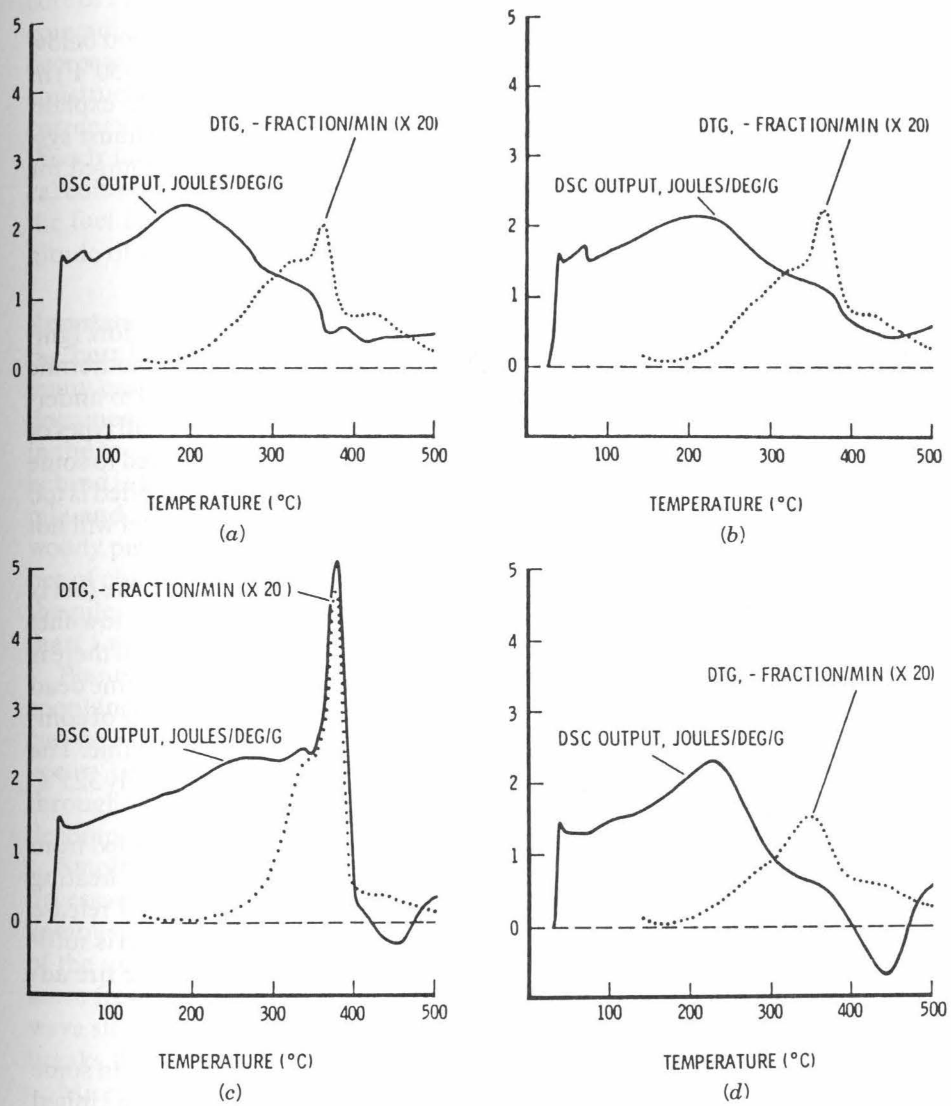


Figure 1.8. *Examples of different rates of fuel volatilization as a function of temperature.* From Ward (1990).

Susott (1982b) used differential scanning calorimetry (DSC) to measure the total pyrolysis energy required for selected forest fuels. In addition, thermal gravimetric analysis was used to record weight loss. The derivatives of the TG curves (DTG) were calculated from the digitized data. Figure 1.9 shows DSC



(*a*) (*b*) (*c*) (*d*)

Figure 1.9. *Differential scanning calorimetry (DSC) and derivatives of thermogravimetry (DTG) plots for (a) green ponderosa pine needles, (b) cured ponderosa pine needles, (c) sound Douglas fir wood, and (d) rotten Douglas fir wood.* From Susott (1982b).

and DTG curies for green and cured ponderosa pine needles and for sound and rotten Douglas-fir wood. A comparison of the results from green and cured ponderosa pine foliage indicates that it is doubtful that the thermodynamics of pyrolysis or variations caused by extractives can explain differences in fire behavior between live and dead foliage. The extractives in green foliage do not appear to lower the total heat required for pyrolysis. Although there are minor differences between DSC curves for green and cured ponderosa pine needles, it is unlikely these differences significantly affect burning behavior.

Rotten wood gives a specific heat comparable to that of sound wood below 150°C (300°F). The large exothermic peak from 300 to 400°C (570 to 750°F) in sound wood is completely missing from rotten wood. This may help explain the ease of ignition of rotten wood by lightning or sparks from exhaust systems. Less energy is required to produce the combustible gases required for ignition of rotten wood.

Ignition

Ignition is a transition between preheating (preignition) and combustion. Ignition is defined by Drysdale (1985) as that process by which a rapid, exothermic reaction is initiated, which then propagates and causes the material to undergo change, producing temperatures greatly in excess of ambient. In all types of combustion, fuel ignition requires that the fuel temperature be raised to some minimum level by the application of heat. If the time the heat is applied is too short, the necessary quantity of heat cannot be supplied, and the fuel will not ignite regardless of the temperature of the heat source.

Ignition temperature depends on the stage of pyrolysis at which the fuel is considered to be actually ignited. Charring can begin at relatively low fuel temperatures, and once started can continue by glowing combustion if there is little heat loss. This is most likely to occur in deep layers of compact, fine dead fuel. The attachment of a flame to a solid particle occurs when the rate of combustible gas generation by the particle is sufficient to maintain a flame. The temperature for flame attachment, or piloted ignition, is approximately 325°C (620°F) for wildland fuels.

Spreading fire can be considered a series of ignitions. Heat is supplied from the fire to the potential fuel, the surface is dehydrated, and further heating raises the surface temperature until the fuel begins to pyrolyse and release combustible gases. When the gas evolution rate from the potential fuel is sufficient to support combustion, the gas is ignited by the flame and the fire advances to a new position (see Figure 1.6).

Ignition by Lightning Lightning is the dominant cause of forest fire in some parts of the world. Approximately two-thirds of the fires in the Western United States are lightning caused. The earth experiences perhaps 1800 storms per hour, or 44,000 per day. Collectively these storms produce 100 cloud-to-ground discharges per second, or better than 8 million per day globally. Obviously, all of those strikes do not cause fires. Whether or not a lightning strike results in ignition depends on the character of the bolt and the character of the material that it strikes. Over a 5-year period examined by Fuquay (1962) only 0.01 to less than 0.001 of the cloud-to-ground (CG) lightning strikes started a wildfire that was detected and required suppression action.

The lightning channel consists of a central core surrounded by a much larger corona sheath. During the first few microseconds of a return stroke, the core of 1 to 2 cm (about 0.5 in) radius is heated to a maximum of about 30,000 K, coinciding with the peak current surge. In a hybrid flash, the current will then decrease to the sustained level of several hundred amperes. Latham (1980) constructed a model that predicts the core temperature of the continuing current to be between 6000 and 12,000 K with a core diameter of 1.4 cm (0.5 in). Woody fuels at the surface are exposed to high temperatures within a cylindrical column of hot gases for the duration of the flash. The degree of heating of the fuel is a function of the current duration and independent of the magnitude of current flow.

Spontaneous Ignition Spontaneous ignition of large piles of hay is one of the best known manifestations of the phenomenon. There have also been many cases in chip and sawdust piles near wood processing plants. But as documented by Frandsen (1993), spontaneous ignition is also being observed in the forest after harvesting because logging residue that was previously left behind is being utilized. Residue from stripping and chipping is shoved into a pile and left in the forest for later retrieval. Logging slash piles with larger woody pieces do not lead to spontaneous ignition. A combination of properties of chip piles can lead to spontaneous ignition: fresh chips and foliage in the pile, moisture content of wood in the pile greater than 20%, pile greater than 1 m (3 ft) high, and soil mixed into the pile.

Plant material can ignite as a result of internal pile heating, which occurs spontaneously if there is an exothermic process liberating heat faster than it can be lost to the surroundings. Two main factors are necessary for this to occur: The material must be sufficiently porous to allow oxygen to permeate throughout the mass and it must yield a rigid char when undergoing thermal decomposition.

Smoldering involves surface oxidation of the char, which provides the heat necessary to cause further thermal degradation of the neighboring layer of combustible material. Successful propagation requires continuous pyrolysis of the unburned woody material ahead of the combustion zone to produce more fresh char and heat for further propagation. The resulting smoldering wave slowly moves outward, possibly leading to flaming combustion when it breaks through to the surface.

Microbial activity is capable of raising the temperature at a location within the stack or pile to about 70°C (160°F). Chemical oxidation then takes over, although reactions involved in these relatively low temperatures appear to be aided by moisture. The initial heating stage requires a relatively high moisture content for vigorous bacterial growth (63–92% by weight). Respiration is an oxidative process that releases carbon dioxide, water, and heat. If wood chips are fresh, respiration of the living plant cells also contributes to self-heating. Foliage in the piles is an important element of self-heating through respiration of its live plant cells.

Smaller, better ventilated piles are less likely to spontaneously ignite. Increased void space in slash piles would allow more ventilation, reducing their ability to store heat. Ventilation in slash piles also enhances drying, which leads to an unfavorable environment for the existence of microorganisms. Smaller piles increase heat transfer from the hot core to the environment.

Combustion

Flaming and smoldering or glowing combustion involve different processes and are quite different in appearance. Flaming combustion dominates during the startup phase, with the fine fuels and surface materials supplying the volatile fuel required for the rapid oxidation reactions to be sustained in a flaming environment. Once carbon begins to build up on the solid fuel surfaces, the pyrolytic reactions no longer produce sufficient fuel gases to maintain the flame envelope. For combustion to continue, oxygen must diffuse to the surface of the fuel, allowing oxidation to take place at the solid fuel surface and providing for heat feedback to accelerate the pyrolytic reactions and volatilization of the fuel gases from the solid fuel.

Flaming Combustion The flame from a spreading fire in wildland fuels can be classified technically as a free, turbulent, diffusion flame. The structure of such flames depends on the properties of the gaseous fuel being burned, the size and shape of the gas-emitting area, the rate of flow of the gaseous fuel, and the flow field of the air into which the volatized fuel is introduced.

An unstructured flame is highly variable, certainly in the field and even in the controlled conditions of the laboratory (see Figure 1.2). However, flame is the aspect of fire that can be most easily observed and the part that people can relate to. The size and shape of flames can be useful in describing the character of the fire and in predicting or describing fire behavior and effects. The severity of a surface fire in terms of its resistance to control can be keyed to flame length, and flame height can be related to the height of lethal scorching of tree foliage. Flame height has also been related to the likelihood of crowning; and flame height, along with flame gas density and velocity, are needed to estimate the firebrand lofting capability of flames. So the structure of the flame from a surface fire in wildland fuel provides much information about the fire in terms of its behavior and its possible effects.

The principal characteristic of the diffusion flame is that the fuel and the oxidizer (air) are initially separate and combustion occurs in the zone where the gases mix. Flames are not attached directly to the wood surface, but are separated from it by a thin layer of vapor or gas. This can be observed by looking closely at a lighted match. Solid organic materials do not burn in flaming combustion directly, but must first be decomposed or pyrolyzed by heat and chemical reactions into various gases, some combustible and some not. The combustible gases do not contain enough oxygen to burn when emitted from the fuel, and must first mix with the surrounding air before a flammable mixture is produced. If the pyrolysis is slow, not much gas is generated and the flames are short and intermittent. But when large amounts of fuel are burning rapidly, the volume of gas is large and some of that gas must move a considerable distance from the fuel before enough oxygen is available and the mixture becomes flammable. Long and massive flames are produced in this process.

A stationary fire, such as a burning pile of forest debris, typically exhibits three phases of burning: (1) a period of time during which the vigor of burning steadily increases, as more fuel becomes involved through fire spread within the pile or through the heating of larger pieces to pyrolysis temperature; (2) a period of steady burning during which the rate of fuel consumption is near constant; and (3) a period of decreasing flame production as the fuel elements are converted to char, collapse, and contribute to a glowing ember bed (see Figure 1.4). Burning rate is increased by wind because, in almost every case, the fuel components in such a stationary fire are so compactly arranged that there is not a sufficient supply of oxygen to the interior fuel accumulation to burn the pyrozylate locally. Thus these fires exhibit tall, free flames in the absence of wind. It is a common experience during a gust of wind for a campfire flame to shrink abruptly in height and the interior of the fire to become suddenly brighter and hotter. Natural fuels, however, are seldomly so compactly arranged.

Fuel burning in the reaction zone of the flame yields a blue color. The orange color of flames is due to the radiation from an abundance of small solid particles. The characteristic yellow luminosity is the net effect of emission from minute carbonaceous particles (of diameters of the order of 10–100 nm) that are formed within the flame, mainly on the fuel side of the reaction zone. These may be consumed when they pass into oxidative regions of the flames, but otherwise they will react and interact further to yield smoke. While within the flame, they will attain high temperatures and each one will act as a minute blackbody or "gray" body. The emission spectrum is continuous. The net emissive power of the flame will depend on the concentration of these particles and on the "thickness," or mean beam length of the flame.

As the temperature of the fuel continues to rise, combustible gases are produced more rapidly and the chemical reactions become more strongly exothermic, reaching a peak about 320°C (600°F). Although combustible gases are generated at temperatures above 200°C (400°F), they will not flame even when mixed with air until their temperature reaches 425 to 480°C (800° to 900°F). The maximum temperature that can be produced by the burning of gases generated from wildland fuels is believed to be between 1900 and 2200°C (3500 and 4000°F) with an ideal mixture of gas and air; this can be attained only in carefully controlled laboratory flames. Temperatures exceeding 1650°C (3000°F) have been measured in exceptionally intense fires. The ideal mixture of gas and air is not likely to occur during most wildland fires, and there is usually considerable cooling of the flames by mixing with cooler air. Thus flame temperature of 700 to 980°C (1300 to 1800°F) are more common. This is well above the temperature needed to ignite the gases, so once flaming starts, it continues as long as sufficient gas is produced.

Smoldering or Glowing Smoldering or glowing combustion, although not as visually dramatic as flaming combustion, is an important component of wildland fires. Surface fires frequently ignite smoldering ground fires. If surface fires initiate ground fire in the organic soil horizons, smoldering may continue for months or even years. Smoldering ground fire is important in suppression and prescribed fire control activities in that it has the potential for reigniting surface fire long after the main front has passed. A large portion of smoke production can come from smoldering combustion. And the effect of the heat from smoldering fire on roots, organisms, and tree cambium can be significant.

Smoldering generally occurs in fuel arrays that are more tightly packed than those that sustain flaming combustion. Forest duff which has packing ratios greater than 10%, exhibits smoldering, while litter, with packing ratios less than 10%, exhibits flaming combustion. Decomposing plant matter tends to smolder because biological degradation removes some cellulose cell wall material leaving a higher lignin content.

The steady smoldering combustion wave has three distinct regions, as shown in Figure 1.10: a pyrolysis zone in which there is a steep temperature rise and an outflow of visible airborne products from the parent material; a charred zone where the temperature reaches a maximum, the evolution of the visible products stops, and glowing occurs; a zone of very porous residual char and/or ash that is no longer glowing and whose temperature is falling slowly.

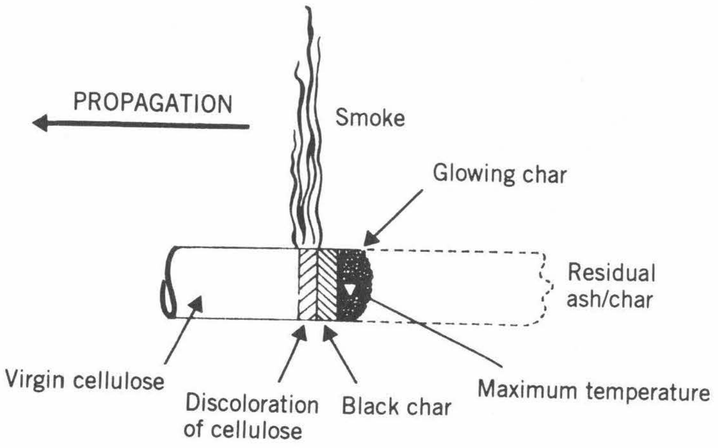


Figure 1.10. *Representation of steady smoldering along a horizontal cellulose rod.* From Moussa and others (1977).

The volatile degradation products that are driven out from the pyrolysis zone are not oxidized significantly. They represent the gaseous fuel that in flaming combustion would burn as a flame above the surface of the fuel. They are released ahead of the zone of active combustion and comprise a complex mixture of products including high boiling point liquids and tars that condense to form an aerosol, quite different from smoke produced in flaming combustion.

Duff can present an effective barrier to the transfer of heat to the mineral soil, during passage of a surface fire. However, if the duff is ignited, the resultant smoldering fire is likely to be brought into direct contact with the mineral soil raising its temperature above 300°C (570°F) for several hours. Flora and fauna of the duff are consumed along with roots and seeds. Organic material in the upper portion of the mineral soil is oxidized, and roots, seeds, and soil organisms necessary for recycling nutrients are killed and possibly consumed.

Smoldering ground fires spread slowly, about 3 cm/h (1 in/h). They can raise mineral soil temperatures above 300°C (570°F) for several hours with peak temperatures near 600°C (1100°F) resulting in decomposition of organic material and the death of soil organisms. Although these are considerably lower than temperatures associated with flaming combustion which generally range from 800 to 1200°C (1500 to 2000°F), the duration of the heat at a point is much longer.

Figure 1.11 shows the time–temperature profiles in the litter and soil for two burns in slash fuel over moist duff and one in litter fuel over dry duff. The most notable feature is the difference in the duration of heating to temperatures above 100°C (212°F) in the duff. Fires of sufficient intensity to consume slash fuels and shrubs and produce flame lengths adequate to scorch tree crowns appeared "hot" but produced little heating in the mineral soil when the duff layer was not completely consumed. In contrast, a very low-intensity surface fire spread through the forest floor litter and ignited the duff, which slowly burned as a ground fire, appearing "cool" but actually producing considerable heating of the soil.

Extinction

Conceptually, extinction can be regarded as the obverse of pilot ignition and may be treated in a similar fashion, as a limiting condition or transition point. Smoldering combustion in duff is limited by inorganic content and moisture content (Figure 1.12). If heat from the smoldering combustion wave is not sufficient to overcome the heat of vaporization required by moist fuel, smoldering must cease. Furthermore, inorganic materials within the fuel matrix can absorb heat but not oxidize to produce more heat. Thus the amount of heat produced per unit volume is reduced. Both moisture and inorganic content reduce the effectiveness of the available heat to propagate the smoldering fire.

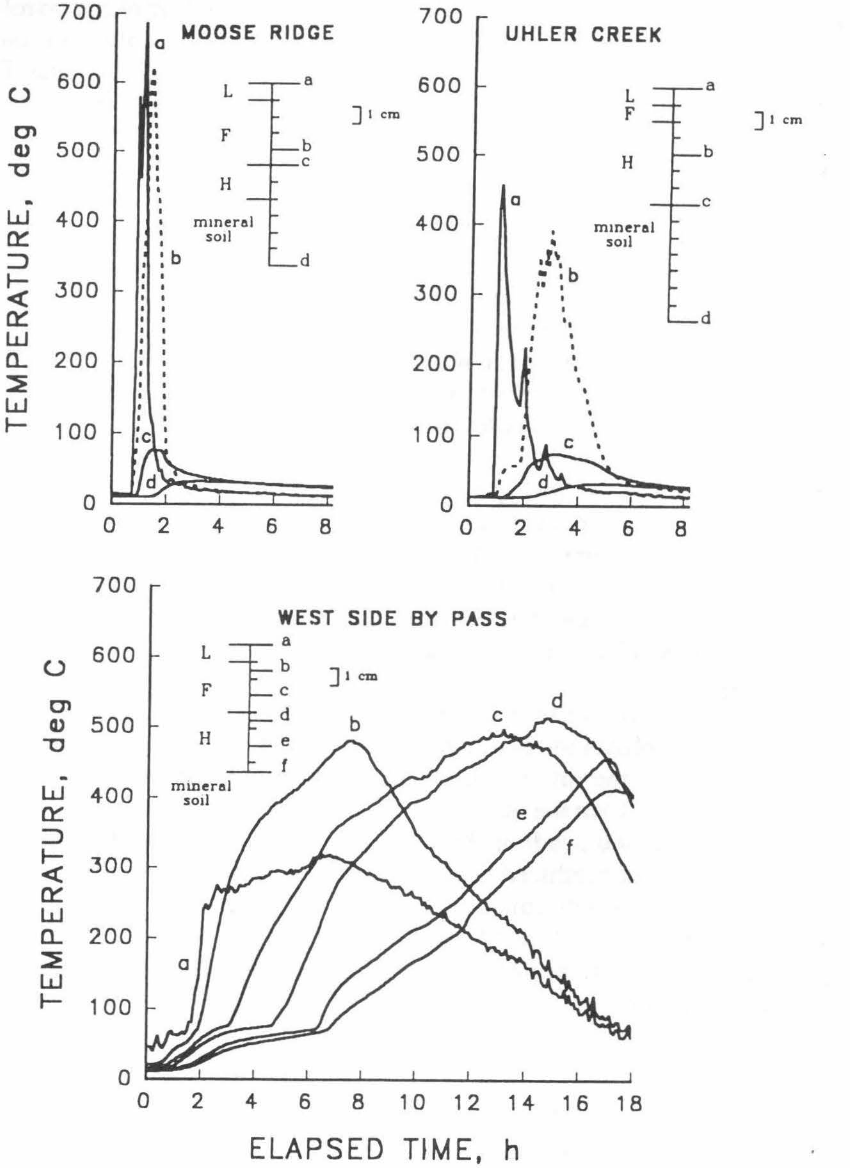


Figure 1.11. Temperature histories in the litter (L), fermentation (F), humus (H), and mineral soil. Insets show vertical placement of temperature sensors relative to the forest floor profile. The fires were in northern Idaho and western Montana. The Moose Ridge and Uhler Creek were in slash; the West Side By-pass fire was in litter. From Hartford and Frandsen (1992).

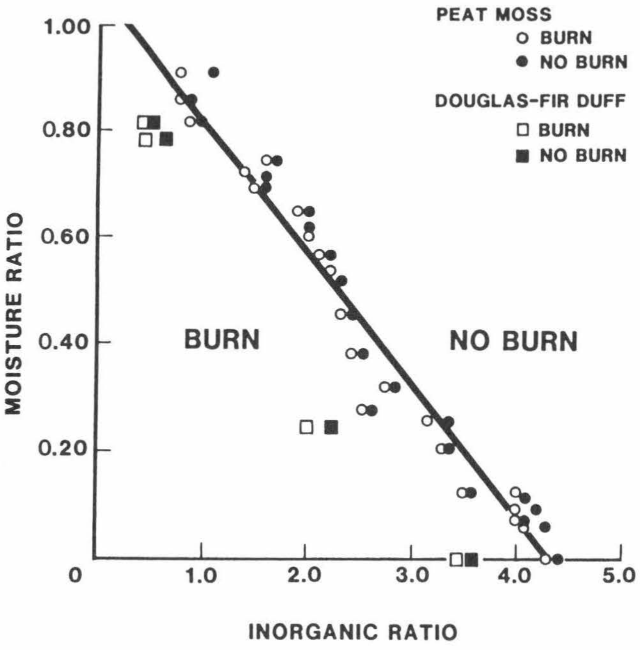


Figure 1.12. *Linear estimate of smoldering limits of smoldering forest duff.* From Frandsen (1987).

The extinction point of spreading surface and crown fires is difficult to define. Dead grass will seldom support a spreading fire when the moisture content of the grass is above 15 to 20%, nor will forest litter if it contains more than about 30% moisture. Yet stands of chaparral composed predominantly of live foliage and stems and timber stands can burn with great vigor at a foliar moisture content of 100%. Attempts to relate differences in flammability to intrinsic chemical properties of fuels have failed to explain the sensitivities to moisture content.

Wilson (1985) presented a methodology to describe fire extinction as an energy balance phenomenon. He examined the probability that a surface fire will burn, not burn, or burn in some defined marginal state. The marginal burning probabilities for two fuel types are shown in Figure 1.13. P_0 is the probability that the fire does not go out; P_s is the probability of a "steady state" fire with 100% contiguous flame front.

1.5 FUEL CONSUMPTION

Fuel is always consumed in a fire. During combustion, fuel is converted to heat, with some of the mass being released in the form of smoke. Fine fuels,

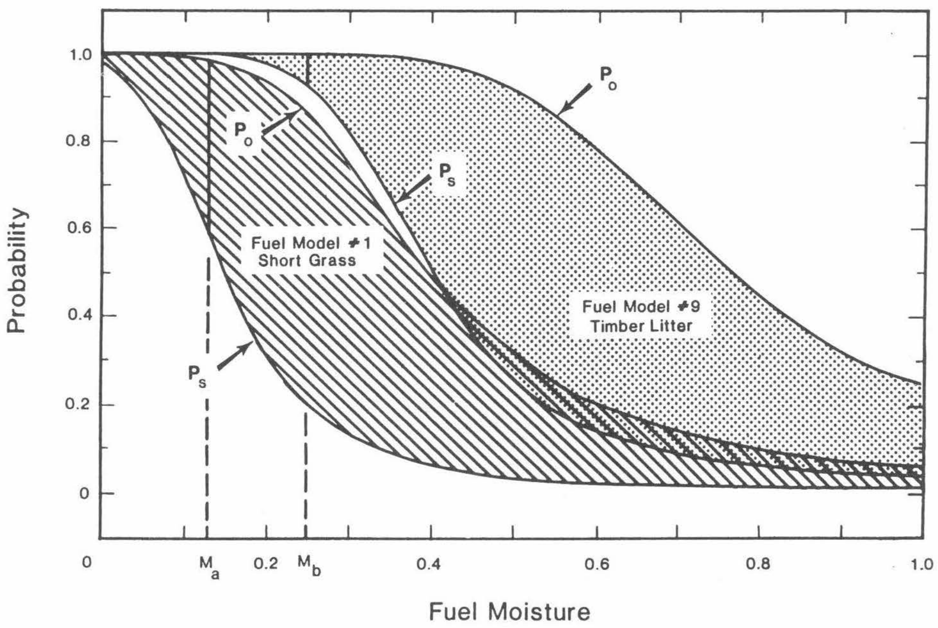


Figure 1.13. *Comparison of marginal burning zones for two stylized fuel models. P_o is the probability that the fire will go out; P_s is the probability of a "steady-state" fire with 100% continuous flame front. $M_a = 0.12$ is the often used moisture of extinction for short grass; $M_b = 0.25$ is used for timber litter. From Wilson (1985).*

such as dead grass, needles, and small twigs, are mostly consumed in the flaming fire front. Dead branchwood from .6 to 7.6 cm ($\frac{1}{4}$ to 3 inches) in diameter is largely consumed. Other components of the fuel complex burn after the flaming front has passed, some flaming, some smoldering or glowing. Consumption of large dead and down fuel and of the duff is important in evaluating smoke production, fire intensity and suppression considerations, and fire effects.

Increased emphasis on smoke production and site protection have created a need to better understand woody fuel and duff consumption. Duff and associated downed woody fuel are removed with prescribed fire to reduce fire hazard, prepare seedbeds, kill selected vegetation, and stimulate desired plants. On the other hand, retention of duff and woody material may be needed to protect sites from sun and erosion, enhance microbial activity, and provide small animal habitat.

The consumption of downed woody fuels affects the amount of duff consumed and consequently the amount of mineral soil exposed. Woody fuel consumption also determines many secondary effects. Other things being equal, the more fuel consumed the greater the heat impact on the site. The amount of heat transmitted downward to the duff and soil often governs the extent to which on-site plants will revegetate the burned area, and thus impacts postfire

species composition and wildlife habitat. Logging slash removal also facilitates big game passage through the area.

Managers may wish to limit consumption of duff and large woody fuel in order to limit the production of smoke from the prescribed burn, protect the site from erosion, provide protection for planted trees, and maintain long-term site productivity and nutrient cycling. Erosion is reduced by retaining an organic mantle and large woody pieces on site. Duff is important in storing nitrogen and absorbing cations. Large woody material is important because it is a site for nitrogen fixation and the source of future soil wood—an important soil component.

Duff

Duff is an inclusive term that refers to organic forest horizons (fermentation and humus layers) that accumulate above mineral soil. Organic soils (often generically called peat) are classified based on organic carbon content and depth. These soils often have a root mat at the surface over horizons of highly decomposed sapric (muck) material or less decomposed fibric (peat) material.

Forest floor materials such as litter and duff on top of mineral soil, and organic soils may be ignited during fire events. These ignitions may develop into smoldering ground fires that burn for days or even months, consume large amounts of duff or organic soil, and result in significant ecological and landscape changes. Moisture is a prominent factor in discouraging ignition of ground fires because of moisture's latent heat of vaporization. Inorganic material plays a similar role by absorbing heat that contributes to the combustion process.

Duff consumption is often expressed in three ways: depth reduction, percentage depth reduction, and percentage mineral soil exposed. For evaluating smoke emissions and nutrient capital, depth reduction is the appropriate expression because it describes actual amounts and can be converted to weight if bulk density is known.

The process of smoldering and the resulting consumption of duff or peat soil is not well understood. However, a conceptual picture of development of burn holes has been provided by Hungerford and others (1995) (Figure 1.14). Ignition of a spot or a number of spots may be initiated by fire brands or by the passage of a fire front from a surface fire or crown fire, if conditions are suitable. Smoldering in duff or peat soils may be initiated at the ground surface, in a crack or depression, or in woody material that burns down into the organic soil. Once ignition occurs the fire begins to burn downward and laterally, if conditions are favorable for sustained smoldering. As smoldering progresses, a basin configuration is created. Lateral spread (often below the surface) becomes the dominant form of spread as vertical spread reaches mineral soil or smoldering moisture limits. Moisture can change markedly over short distances in the lateral direction, e.g., passing through the drip line from under

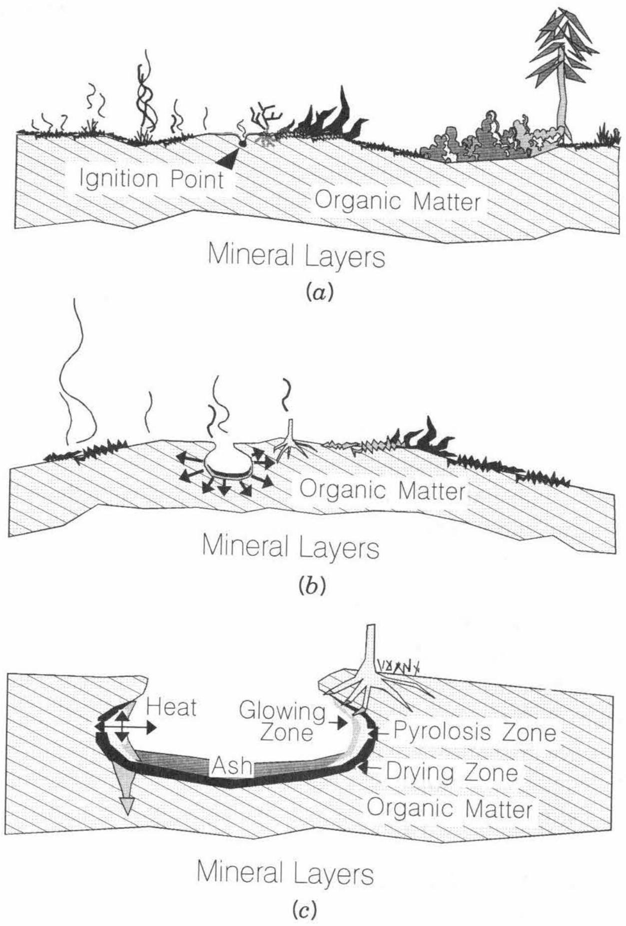


Figure 1.14. *Schematic diagram of the smoldering process. (a) initial ignition point of smoldering initiated by a passing surface fire. (b) Concentric spread of the burn hole from the initial point. (c) Pyrolysis zone and drying zone ahead of the slowing zone in a fully developed burn hole. Heat generated at the glowing zone flows in all directions; some sustains the glowing zone, some moves downward, heating unburned horizons, and some is lost to the atmosphere.* From Hungerford and others (1995).

tree cover. Inorganic content does not change as dramatically. Consequently, lateral spread is modified by lateral changes in the moisture content. Near the surface the front will not spread as rapidly because of heat losses, and an overhang of unburned material will develop over burned out peat. Horizontally spreading fires may leave a thin unburned top crust that will cave in under a person's weight. As smoldering continues, the burn hole develops in a concentric fashion as long as conditions are uniform. Lateral spread continues unless the front reaches noncombustibles. In the downward direction the front may encounter conditions not suitable for ignition (high moisture content, mineral soil, etc.) so the bottom glowing zone is extinguished. The bottom of the burn hole flattens out and continued smoldering is limited to lateral spread. As the smoldering front moves through the peat it creates a drying zone caused by heat from the glowing zone. Pyrolysis occurs between the drying zone and the glowing zone where organics are charred and gases are produced. Soil temperature profiles depth and magnitude of heating) are related to duration of heating and the amount of organic material consumed.

Large Woody Fuel

While alive, limbs and boles of trees or woody shrubs seldom burn in a wildland fire. But when they are dead and arranged in accumulations on the surface, they can burn vigorously. Heavy concentrations of dead large-fuel components can arise from windthrow or avalanche, breakage and cull during timber harvest, or mechanical clearing of shrublands.

Large woody fuels (larger than a 7.6 cm (3-in.) diameter) can sustain fires of relatively high intensity for a prolonged period of time, defying direct suppression efforts and serving as potential sources of spot fires. The amount of heat generated per unit area varies as the total fuel loading burned. And as heat per unit area increases, so does the depth to which it penetrates into the underlying soil and the higher the peak temperature at any soil depth. Intensity history and ultimate fuel consumption depend on the type, quantity, degree of rot, moisture content, and arrangement of the fuels.

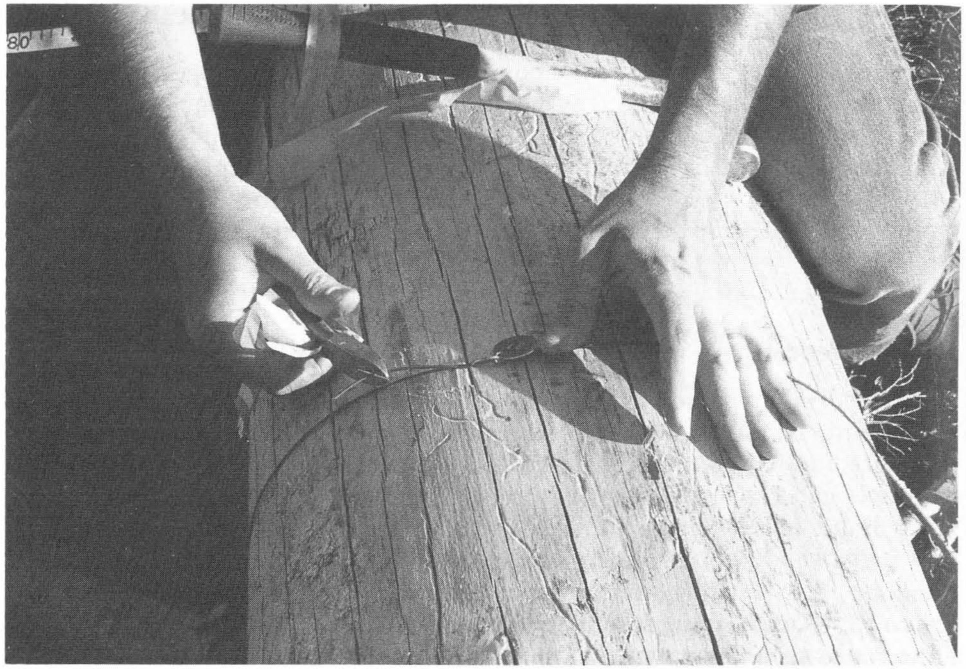
Consumption of woody fuel is often described as percentage of preburn fuel quantities consumed, especially for evaluating prescribed fire effects and designing fire prescriptions. It may be predicted initially as average diameter reduction of woody pieces and then converted to percentage volume reduction or fuel loading reduction.

Much of the work on consumption of large fuel has been empirical, based on field observations. Figure 1.15 shows the results of a fuel consumption study reported by Reinhardt and others (1991).

1.6 PRODUCTS OF COMBUSTION

The direct and indirect effects of smoke emissions from wildfires and prescribed fires receive scrutiny from both the political and scientific communities at the local, regional, and global levels. Smoke can degrade ambient air quality, impair visibility, and worsen regional haze. There are concerns about the effect of smoke on human health. And long-term or indirect effects may be important from the standpoint of contributions to the buildup of "greenhouse gases" and the effect those gases have on the chemistry of the atmosphere.

Wildland fires emit a complex mixture of particles and gases into the atmosphere. The diversity of composition of combustion products results from



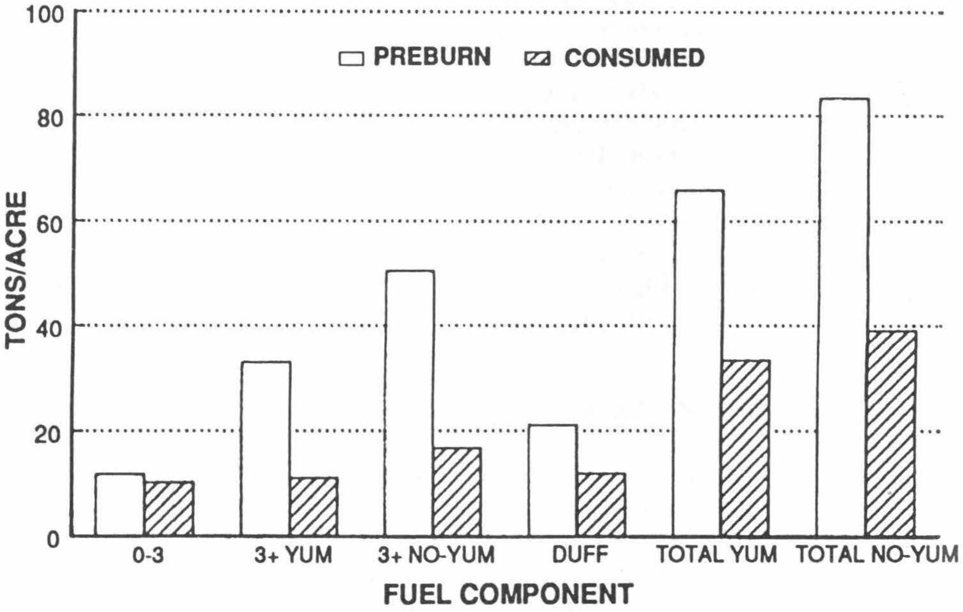


Figure 1.15. *Log being wired for diameter-reduction sampling. Average preburn fuel loadings and fuel consumption for sampled logging units in Northern Idaho. In 12 of the clearcut units a YUM (yarding of unmerchantable material) treatment was applied: Unmerchantable material greater than 6 inches in diameter was yarded to the tops of the units and made available to firewood cutters, resulting in lighter woody fuel loadings and additional duff and soil disturbance.* From Reinhardt and others (1991).

wide ranges in fuel types, fuel chemistry, and fire behavior. When forest and rangeland fuels are burned, carbon is released in the form of particulate matter, carbon dioxide, carbon monoxide, hydrocarbons, and other substances in decreasing abundance (Figure 1.16). Hydrogen is released mostly as water. Other minor constituents, such as nitrogen, phosphorous, and sulfur, affect the mix of pollutants generated by burning plant tissues.

Combustion efficiency is never 100% for wildland fire; it generally ranges from 50 to 95%. A measurement of *combustion efficiency* is the ratio of the actual carbon contained in the emissions of carbon dioxide compared to that theoretically possible if all of the carbon were released as carbon dioxide, i.e., the ratio of carbon released as CO_2. Generally combustion efficiency is lowest for smoldering combustion and highest for fires with good ventilation and vigorous flaming combustion. Smoldering combustion produces high emissions of particulate matter and carbon monoxide. Fires of very low intensity (those in which the flaming combustion phase is barely sustained) produce high emissions of particulate matter.

The formation of particulate matter results primarily from two processes: the agglomeration of condensed hydrocarbons and tar materials, and mechanical processes that entrain fragments of vegetation and ash. If the temperature in the interior of the flame zone is appropriate (>800°C (<1500°F)), rapid formation of particles and accretion of carbonaceous organic particles will occur. Consumption of the particles requires prolonged exposure at high

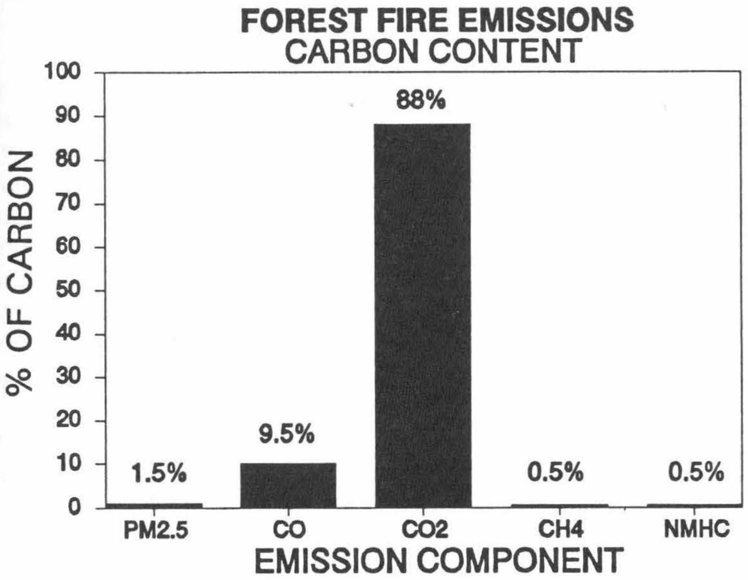


Figure 1.16. *The average percentage of total carbon released by biomass burning in the United States in the form of CO, CO_2, and hydrocarbons. PM2.5 is particulate matter less than 2.5 μm diameter.* From Ward (1990).

temperatures (>800°C (>1500°F)) in a zone with near-ambient (21%) concentration of oxygen.

The size and content of smoke particles have significant health implications. Small-diameter particles (fine particles less than 2.5 μm in diameter) may be drawn deep into the human lung and are defined as the respirable fraction. The respirable fraction contains particles of a diameter that also has a maximum effect on visibility and radiation transfer in the atmosphere.

The results of studies where smoke particles were measured using aircraft suggest a very pronounced concentration peak at a diameter of 0.15 μm. The volume distribution, which for a first approximation represents the mass distribution, shows a bimodal distribution with peaks at 0.5 μm and greater than 43 μm (Figure 1.17). The mass of particulate matter between 1 and 10 μm makes up less than 10% of the total mass.

The trace elements for samples of particles less than 2.5 μm in diameter (PM2.5) are shown in Figure 1.18 as a percentage of the PM2.5 by combustion phase and weighted for the entire fire. All the samples of the trace elements are from broadcast burns of logging slash from coniferous species. The sulfur, chlorine, and potassium components of PM2.5 are high during the higher temperature flaming phase of the fire. Generally, as the combustion efficiency increases, more of the carbon is consumed, thus increasing the percentage of mass reported as trace elements.

Generally, temperatures within flame structures of forest fires do not exceed 1000°C (1800°F), which suggests that molecular nitrogen gas (N_2) from the atmosphere is not disassociated to combine with free radicals within the combustion zone. The production of oxides of nitrogen increases and is highly dependent on the nitrogen content of the fuel burned. Ozone is not a by-product of combustion of biomass, but forms as a product of secondary chemical reactions once the combustion products enter the atmosphere.

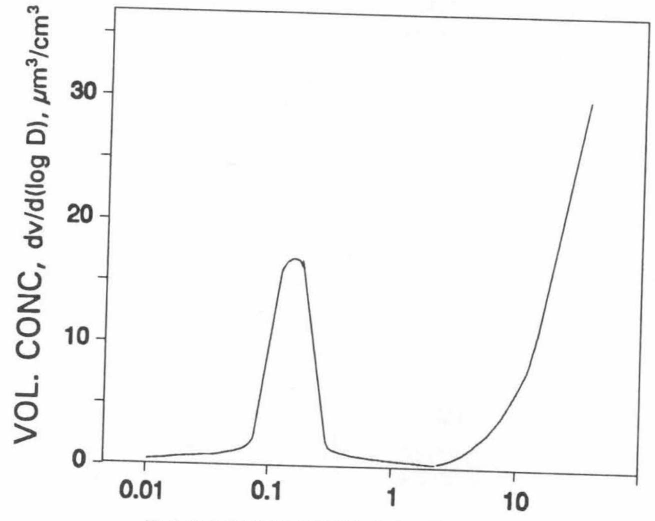


Figure 1.17. *Volume by particle size fractions measured for prescribed fires of logging slash in the Western United States from an airborne sampling platform.* From Radke and others (1990).

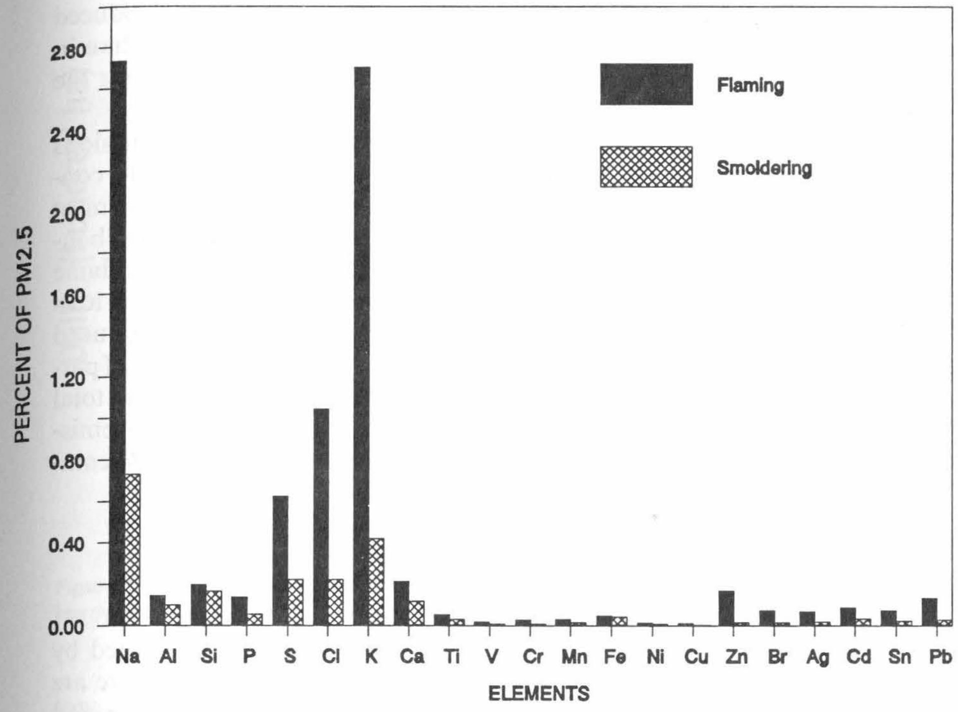


Figure 1.18. *Percentage composition of particulate matter less than 2.5 μm diameter in smoke from logging slash fires in Western United States.* From Ward (1990).

Along with nitrogen, sulfur is one of the essential nutrients required in the synthesis of plant amino acids and other physiologically important substances. Hence, the concern over the volatilization and loss of these important nutrients is of interest in sustaining the productivity of forest and range lands. Nitrogen can be replaced through symbiotic N fixation; sulfur is replenished mainly through atmospheric deposition. Little work has been done to identify the form of the sulfur- or nitrogen-containing emissions released during wildland fires.

Methyl chloride has been suggested as a natural tracer unique to the combustion of wildland fuels. It is produced in much greater quantities in the smoldering combustion phase than in the flaming phase. Emission factors for methyl chloride are inversely proportional to the rate of heat release. Carbon monoxide is the second most abundant carbon-containing gas produced. Combustion efficiency is nearly perfectly correlated with the ratio of the production of carbon monoxide relative to carbon dioxide. Methane is produced in much larger quantities during the smoldering combustion phase than in the flaming phase. Emisson factors are about 2 to 3 times greater for the smoldering phase.

Ward and Hardy (1984) found that for a number of fuel types (1) emissions of particulate matter range over a factor of 10, depending on fire and fuel conditions that affect combustion efficiency; (2) brushy areas produce the most smoke per ton of fuel consumed and have higher rates of production of benzo[*a*]pyrene than nonbrushy areas; (3) fires of higher intensity (long flame lengths) produce proportionately larger particles than are found in low-intensity and smoldering combustion fires; (4) CO is abundantly produced from open fires and, generally, on a mass basis exceeds the production of particles by a factor of 10; (5) hydrocarbon gases are a small part of the total amount of carbon released from the combustion of forest fuels; and (6) emission factors for particles released from fires tend to increase inversely to combustion efficiency.

1.7 SELECTED EXAMPLES

Principles of fire fundamentals covered in this chapter are illustrated by means of two examples. Calculation of emissions from the Silver Fire are based on field observations and relationships among fuel, fire behavior, and combustion efficiency. The Rothermel fire spread model, on the other hand, is based on laboratory experiments and fire fundamentals.

Emissions From the Silver Fire, 1987

The Silver Fire in southwestern Oregon was the largest and longest burning of over 1600 fires started by lightning on 30 August 1987. The fire burned more than 38,000 hectares (94,000 acres) in 72 days. Daily burned area for the first 58 days of the fire are plotted in Figure 1.19.

Hardy, Ward, and Einfeld (1993) estimated daily rates and total mass of PM2.5 production from the fire using a geographic information system (GIS) and compared the results with airborne measurements of smoke production from the same fire. The GIS analysis was performed using empirical data on the area burned daily, intensity of the fire, several vegetation classes, and PM2.5 emissions from prescribed burning.

Digital data ("map layers") were used in a raster-based GIS to derive daily PM2.5 emissions and ratios of flaming-to-smoldering combustion. The spatial resolution of each map layer was approximately 2.17 hectares per grid cell. Four empirically developed map layers formed the baseline data set: (1) burn date, developed from daily perimeter maps; (2) vegetation classification, coded from prefire field examinations, photogrammetric interpretation, and remote sensing prior to the fire; (3) fire intensity, a qualitative index (no burn, low, medium, and high) derived from photogrammetric interpretation of images acquired after the fire; and (4) elevation zone.

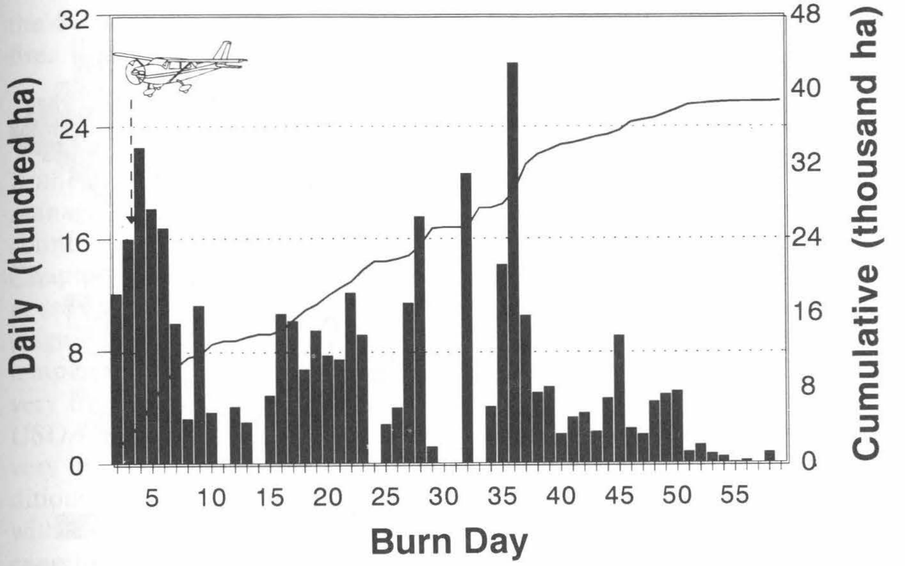


Figure 1.19. *Daily burned area for 58 days of the 1987 Silver fire in southwest Oregon.* From Hardy and others (1993).

Daily fuel consumption was calculated from each grid cell from vegetation classification, fire intensity, and burn day. Both flaming and smoldering fuel consumption were then estimated for each vegetation class. The sum of the products of fuel consumption for each combustion phase and respective emission factor is the total mass of emission produced.

An average combustion efficiency of 90% was estimated for flaming combustion, yielding an emission factor for PM2.5 (EF__PM2.5) of 7.3 g/kg. A smoldering combustion efficiency of 75% yields an EF__PM2.5 of 17.3 g/kg. These combustion phase-specific emission factors and the fuel consumption data were used to calculate total mass of PM2.5 produced for each grid cell.

Three 4-h burning periods for day 3 (3 September) were modeled to improve the temporal compatibility with aircraft data (Figure 1.20). Fire growth was determined from terrain data, knowledge of fire behavior, and anecdotal evidence. The percentage of each interpolated area where flaming combustion was dominant allows the three time periods on day 3 to be compared to all of day 3 (3 September) and also to the entire 58-day analysis period.

The results from this study demonstrate the influence fire growth and fire intensity have on the source strength of fine particulate matter production from wildfires. The observed and modeled data presented in Figure 1.21 provide support for consideration of combustion efficiency and fire behavior in

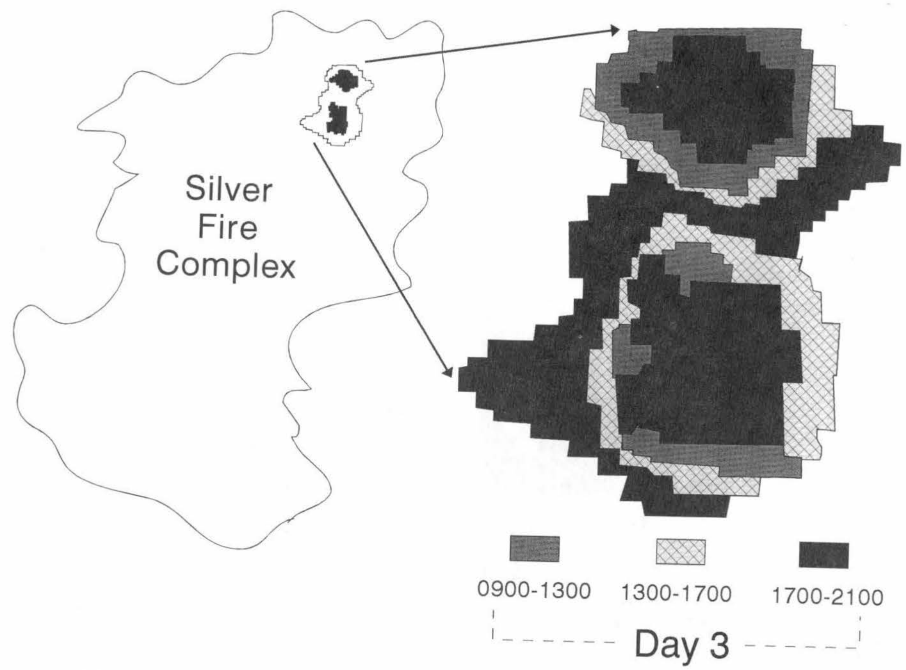


Figure 1.20. *Day 3 of the fire broken into three 4-h burning periods.* From Hardy and others (1993).

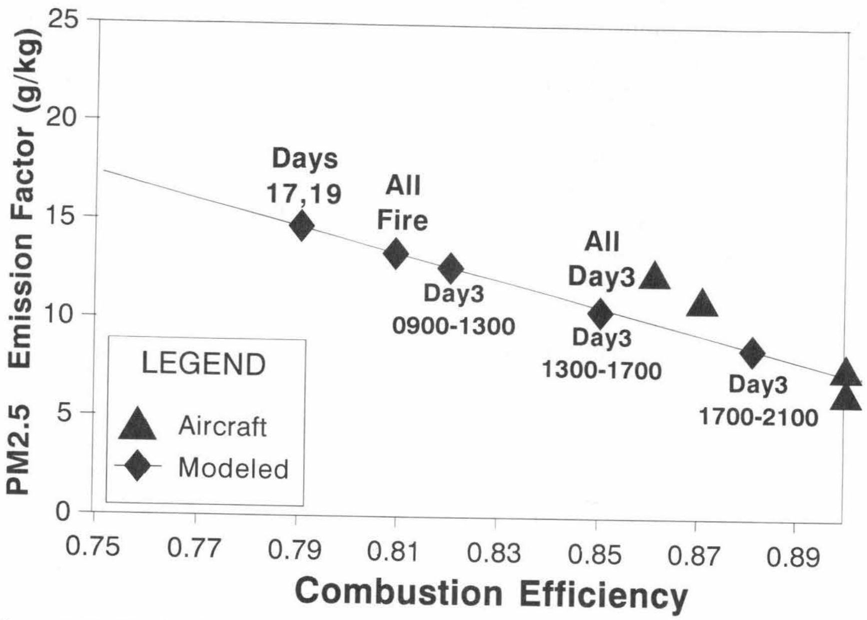


Figure 1.21. *Modeled and observed data for EF_PM2.5 and combustion efficiency.* From Hardy and others (1993).

the determination of an appropriate emission factor to represent wildland fire.

Rothermel's Fire Spread Model

Rothermel's fire spread model (1972) is the basis for most computer-based fire management applications in the United States, with significant use in other countries. Application of the model for fire behavior prediction is described in Chapter 2. The fire model is based on fundamental principles as much as possible, supplemented by laboratory experiments in combustion facilities (Figure 1.22). In the laboratory setting, it is possible to control conditions—temperature, relative humidity, fuel moisture, fuel arrangement and size, and, very importantly, windspeed and direction. Earlier fire spread studies by USDA Forest Service Research were primarily done outdoors. Although some very important results have been obtained in this way, variability in conditions, particularly windspeed, results in complexities that are hard to deal with. In addition there are problems with applying results obtained in field experiments to fuel and weather conditions other than that in which the data were collected.

Rothermel's model was developed from a strong theoretical base in order to make its application as wide as possible. This base was provided by Frandsen (1971) who applied the conservation of energy principle to a unit volume of fuel ahead of an advancing fire in a homogeneous fuel bed. In his analysis, the fuel-reaction zone is viewed as fixed and the unit volume moves as a constant depth toward the interface. The unit volume ignites at the interface. Rate of spread is then a ratio between the heat flux received from the source and the heat required for ignition by the potential fuel. Frandsen's equation could not be solved analytically because it contained heat flux terms for which the mechanisms of heat transfer were not known. To solve the equation, it was necessary to use experimental and analytical methods of evaluation for each term. The final form of the rate of spread equation as derived by Rothermel (1972) with minor adjustments by Albini (1976a) is

$$R = \frac{I_R \xi (1 + \phi_W + \phi_S)}{\rho_b \varepsilon Q_{ig}}$$

where

R is rate of spread of the flaming front (ft/min)

I_R is reaction intensity, the energy release rate per unit area of fire front (Btu/ft^2·min)

ξ is the propagating flux ratio, the proportion of the reaction intensity that heats adjacent fuel particles to ignition

ϕ_W is a dimensionless multiplier that accounts for the effect of wind in increasing the propagating flux ratio

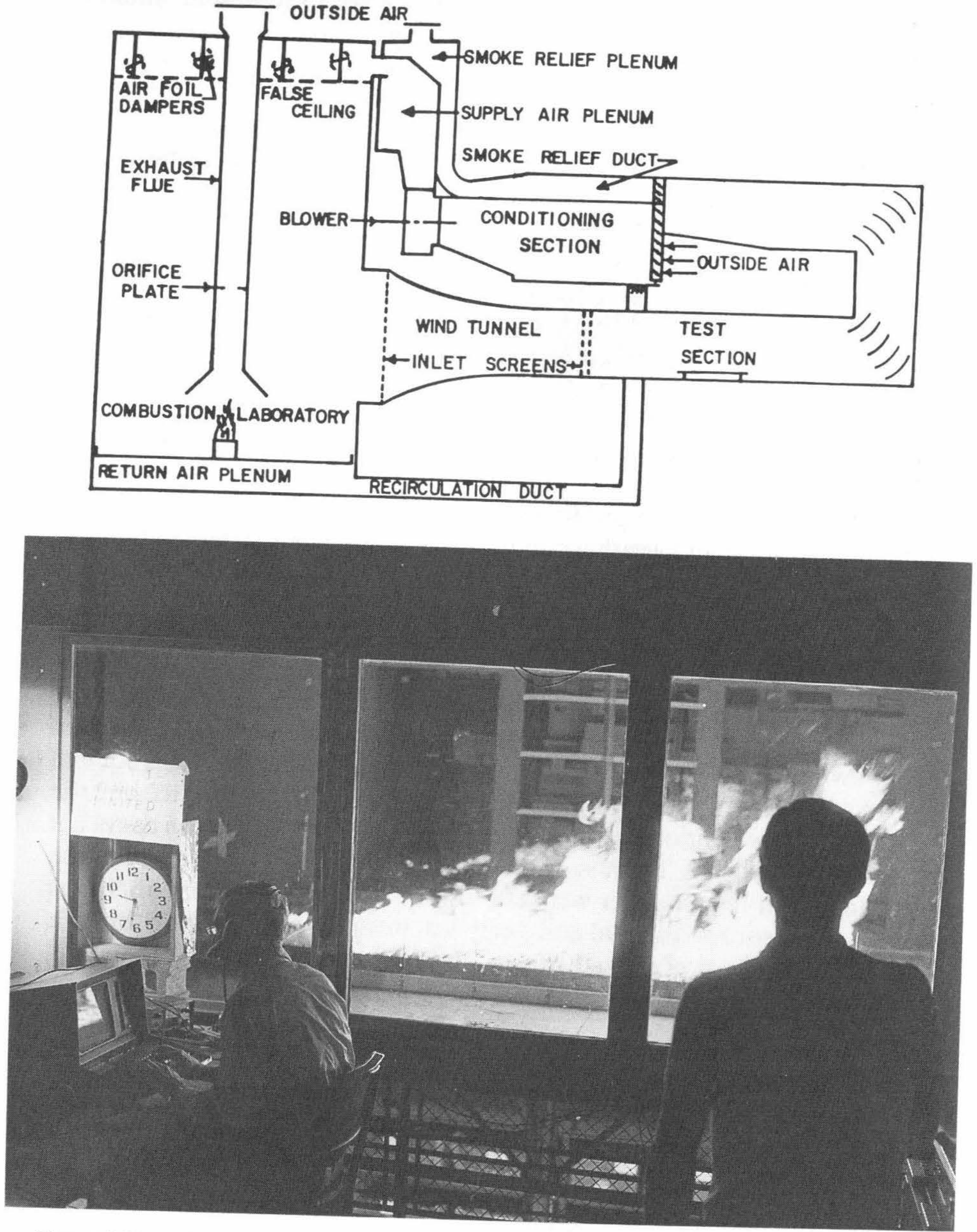


Figure 1.22. *Laboratory conditions can be used for controlled experiments.* Diagram from Rothermel and Anderson (1966). Photograph courtesy of USDA Forest Service.

ϕ_S is a dimensionless multiplier that accounts for the effect of slope in increasing the propagating flux ratio

ρ_b is bulk density, the amount of ovendry fuel per cubic foot of fuel bed (lb/ft^3)

ε is the effective heating number, the proportion of a fuel particle that is heated to ignition temperature at the time flaming combustion starts

Q_{ig} is the heat of preignition, the amount of heat required to ignite one pound of fuel (Btu/lb)

Figures 1.23 and 1.24 give the input values and the equations required to solve the equation above. Figure 1.25 shows which inputs are used in the calculation of each of the variables in the basic equation. The tables are both English and metric. Rothermel used English units in development of the model; we therefore, use English units in the text.

The model was designed so that rate of spread could be calculated from conditions that can be known before the fact. The input in Figure 1.23 can be grouped as follows: *fuel particle properties*—heat content, mineral content, particle density; *fuel array arrangement*—loading by size class for live and dead fuel, mean size within each class as measured by surface-area-to-volume ratio, mean depth of fuel; and *environmental related values*—wind velocity, fuel moisture content, slope.

If fire is thought of as a series of ignitions, it will progress through a fuel bed at the rate at which adjacent potential fuel can be heated to ignition temperature. The rate of spread equation is the heat received by the potential fuel ahead of the fire divided by the heat required to ignite this fuel.

		Units	
Symbol	Paramater	English	Metric
w_0	oven-dry fuel loading	lb/ft^2	kg/m^2
h	low heat content	Btu/lb	kJ/kg
ρ_p	oven-dry particle density	lb/ft^3	kg/m^3
σ	surface-area-to-volume ratio	ft^2/ft^3	cm^2/cm^3
δ	fuel depth	ft	m
M_f	moisture content, wt. moist/wt. ovendry wood	fraction	fraction
S_T	total mineral content, wt. minerals/wt. ovendry wood	fraction	fraction
S_E	effective mineral content, wt. silica-free minerals/wt. ovendry wood	fraction	fraction
U	wind velocity at midflame height	ft/min	m/min
$\tan \phi$	slope, vertical rise/horizontal dist.	fraction	fraction
M_x	fuel moisture of extinction, wt. moist/ wt. ovendry wood	fraction	fraction

Figure 1.23. *Input parameters for basic equations.* Based on Rothermel (1972).

	English		Metric	
Element	Equation	Units	Equation	Units
Rate of spread	$R = \dfrac{I_R\xi(1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$	ft/min	$R = \dfrac{I_R\xi(1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$	m/min
Reaction intensity	$I_R = \Gamma' w_n h \eta_M \eta_s$	Btu/ft^2 · min	$I_R = \Gamma' w_n h \eta_M \eta_s$	kJ/m^2 · min
Optimum reaction velocity	$\Gamma' = \Gamma'_{max}(\beta/\beta_{op})^A \exp[A(1 - \beta/\beta_{op})]$	min^{-1}	$\Gamma' = \Gamma'_{max}(\beta/\beta_{op})^A \exp[A(1 - \beta/\beta_{op})]$	min^{-1}
Maximum reaction velocity	$\Gamma'_{max} = \sigma^{1.5}(495 + 0.0594\sigma^{1.5})^{-1}$	min^{-1}	$\Gamma'_{max} = (0.0591 + 2.926\sigma^{-1.5})^{-1}$	min^{-1}
Optimum packing ratio	$\beta_{op} = 3.348\sigma^{-0.8189}$		$\beta_{op} = 0.20395\sigma^{-0.8189}$	
	$A = 133\sigma^{-0.7913}$		$A = 8.9033\sigma^{-0.7913}$	
Moisture damping coefficient	$\eta_M = 1 - 2.59 \dfrac{M_f}{M_x} + 5.11\left(\dfrac{M_f}{M_x}\right)^2 - 3.52\left(\dfrac{M_f}{M_x}\right)^3$		$\eta_M = 1 - 2.59 \dfrac{M_f}{M_x} + 5.11\left(\dfrac{M_f}{M_x}\right)^2 - 3.52\left(\dfrac{M_f}{M_x}\right)^3$	
Mineral damping coefficient	$\eta_s = 0.174S_e^{-0.19}$ (max = 1.0)		$\eta_s = 0.174s_e^{-0.19}$	
Propagating flux ratio	$\xi = (192 + 0.2595\sigma)^{-1}\exp[(0.792 + 0.681\sigma^{0.5})(\beta + 0.1)]$		$\xi = (192 + 7.9095\sigma)^{-1}\exp[(0.792 + 3.7597\sigma^{0.5})(\beta + 0.1)]$	
Wind factor	$\phi_W = CU^B\left(\dfrac{\beta}{\beta_{op}}\right)^{-E}$ $C = 7.47\exp(-0.133\sigma^{0.55})$ $B = 0.02526\sigma^{0.54}$ $E = 0.715\exp(-3.59 \times 10^{-4}\sigma)$		$\phi_W = C(3.281U)^B\left(\dfrac{\beta}{\beta_{op}}\right)^{-E}$ $C = 7.47\exp(-0.8711\sigma^{0.55})$ $B = 0.15988\sigma^{0.54}$ $E = 0.715\exp(-0.01094\sigma)$	
Net fuel loading	$w_n = w_0(1 - S_T)$	lb/ft^2	$w_n = w_0(1 - S_T)$	kg/m^2
Slope factor	$\phi_S = 5.275\beta^{-0.3}(\tan\phi)^2$		$\phi_S = 5.275\beta^{-0.3}(\tan\phi)^2$	
Oven-dry bulk density	$\rho_b = w_0/\delta$	lb/ft^3	$\rho_b = w_0/\delta$	kg/m^3
Effective heating number	$\varepsilon = \exp(-138/\sigma)$		$\varepsilon = \exp(-4.528/\sigma)$	
Heat of preignition	$Q_{ig} = 250 + 1116M_f$	Btu/lb	$Q_{ig} = 581 + 2594M_f$	kJ/kg
Packing ratio	$\beta = \dfrac{\rho_b}{\rho_p}$		$\beta = \dfrac{\rho_b}{\rho_p}$	

Figure 1.24. *Fire spread equations.* English units from Rothermel (1972) and Albini (1976a). SI equations from Wilson (1980).

Input variable	Term in basic spread equation						
	I_R	ξ	ϕ_W	ϕ_S	ρ_b	ε	Q_{ig}
w_0	x	x	x	x	x		
h	x						
ρ_p	x	x	x	x			
σ	x	x	x			x	
δ	x	x	x	x	x		
M_f	x						x
S_T	x						
S_E	x						
U			x				
$\tan\phi$				x			
M_x	x						

Figure 1.25. *Input parameters used for each equation term.*

The numerator of the rate of spread equation is the propagating flux I_p, the heat release rate from a fire to the fuel ahead of the fire. It is the propagating flux for a fire burning on flat ground with no wind $(I_p)_0$ multiplied by a factor that adjusts for the wind and slope effects. The heat source is then

$$I_P = (I_p)_0(1 + \phi_W + \phi_S) \quad \text{Btu/ft}^2\cdot\text{min}$$

Wind and slope change the propagating flux by exposing the potential fuel to additional convective and radiant heat. The factors ϕ_W and ϕ_S were developed from an evaluation of experimental data. The propagating flux is composed of the horizontal flux and the gradient of the vertical flux as shown in Figure 1.26. As indicated in the figures, the vertical flux is more significant during wind-driven and upslope fires because the flame tilts over the potential fuel, thereby increasing radiation, but more significantly causing direct flame contact and convective heat transfer to the potential fuel. The propagating flux occurs at the front of the fire, therefore I_p is closely related to the fire intensity of the front.

Reaction intensity I_R is the total heat release rate per unit area of fire front, and includes heat convected, conducted, and radiated in all directions, not just in the direction of the adjacent potential fuel. The propagating flux ratio ξ is the proportion of the total reaction intensity that actually heats adjacent fuel particles to ignition. The no-wind, no-slope propagating flux is then

$$(I_P)_0 = I_R\xi$$

The energy release rate of the fire front is produced by burning gases released from the organic matter in the fuels. Therefore, the rate of change in

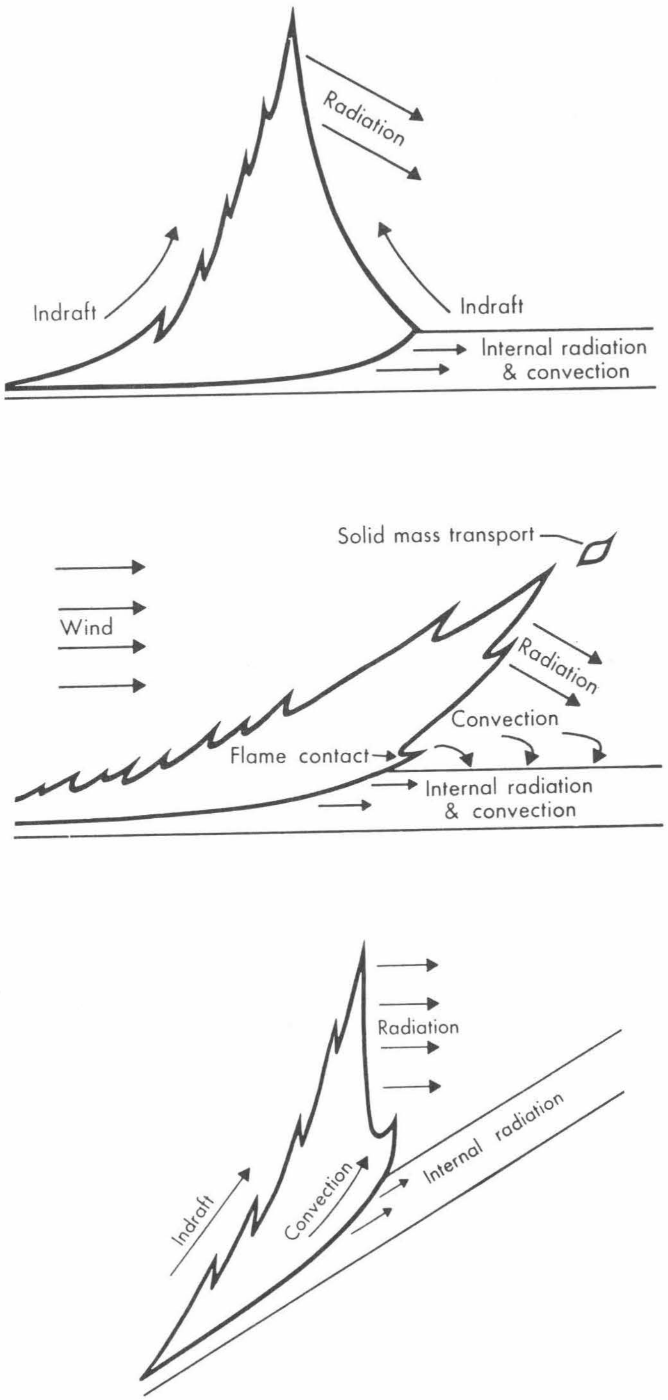


Figure 1.26. *Schematic of no-wind, wind-driven, and upslope fires.* From Rothermel (1972).

this organic matter from a solid to a gas is a good approximation of the subsequent heat release rate of the fire. Reaction intensity was derived from a series of experiments that recorded the weight loss of a portion of the fuel bed during fire spread.

Reaction intensity is calculated from reaction velocity Γ multiplied by the net fuel loading w_n times the heat content of the fuel h:

$$I_R = \Gamma w_n h$$

The reaction velocity indicates the completeness and rate of fuel consumption. It is defined as the ratio of the reaction zone efficiency to the reaction time. The fuel parameters considered to have a major effect on the reaction velocity are moisture content, mineral content, particle size, and fuel bed bulk density.

The presence of moisture and minerals reduces the reaction velocity below its potential value. The potential reaction velocity Γ' is the reaction velocity that would exist if the fuel were free of moisture and contained minerals at the same reaction concentration as α-cellulose. Potential reaction velocity is multiplied by moisture and mineral damping coefficients:

$$\Gamma = \Gamma' \eta_M \eta_S$$

The denominator of the rate of spread equation is the heat required for ignition. It is dependent on the ignition temperature, moisture content of the fuel, and the amount of fuel involved in the ignition process. The heat sink is the product of the effective bulk density $\rho_b \varepsilon$ and the heat of preignition Q_{ig}:

$$\text{Heat sink} = \rho_b \varepsilon Q_{ig}$$

Q_{ig} is the heat of preignition, the energy per unit mass required for ignition. It was evaluated analytically for cellulosic fuels by considering the change in specific heat from ambient to ignition temperature and the latent heat of vaporization of the moisture. The temperature to ignition was assumed to range from 20 to 320°C (68 to 600°F) and boiling temperature to be at 100°C (212°F):

$$Q_{ig} = 250 + 1116 M_f \quad \text{Btu/lb}$$

Moisture is the independent variable in the evaluation of Q_{ig}, but Rothermel noted that other parameters might eventually be included in this evaluation: heating rate, inorganic impurities, and nonpyrolytic volatiles.

The amount of fuel involved in the ignition process is the effective bulk density $\rho_b \varepsilon$. The effective heating number ε is a dimensionless number that is near unity for fine fuels and decreases toward zero as fuel size increases.

Fuel bed compactness and fuel particle size have significant effect on combustibility, but effects were not separated and quantified. The compactness of the fuel bed is quantified by the packing ratio, which is defined as the fraction of the fuel array volume that is occupied by fuel. It is the ratio of the fuel array bulk density to the fuel particle density:

$$\beta + \rho_b / \rho_p$$

The equations in Figure 1.24 have to be modified to accept fuels composed of heterogeneous mixtures of particle sizes and of dead and live fuel. For the model, various size fuels are assumed to be uniformly distributed within the fuel array. Larger fuels have a negligible effect on fire spread and are essentially eliminated from consideration. Input parameters are mathematically weighted by surface-area-to-volume ratio as described by Rothermel (1972).

FURTHER READING

Drysdale's *An Introduction to Fire Dynamics* (1985) and Cotrell's *The Book of Fire* (1989) are both excellent texts on fire fundamentals, although written for different audiences. *Fire Dynamics* gives a solid, technical foundation for all aspects of fire (not just wildland fire). *The Book of Fire* can be used by school children, but also by anyone who wants a well-illustrated explanation of wildland fire from the molecular to the forest level. Albini (1980) describes principles of flame structure in "Thermochemical Properties of Flame Gases From Fine Wildland Fuels." Albini's "Dynamics and Modeling of Vegetation Fires: Observations" is among several good overview papers in *Fire in the Environment: Its Ecological, Atmospheric, and Climatic Importance of Vegetation Fires*, edited by Crutzen and Goldammer (1993). André and others (1992) provide a review of state of the art of research on forest fire physics; they include an extensive bibliography.

"Ignition and Burning Characteristics of Organic Soils" by Hungerford, Frandsen, and Ryan (1995) is a thorough review of available information on the topic; the paper includes a good reference list.

Principles of duff and large, woody fuel consumption and the results of specific studies are covered in "Woody Fuel and Duff Comsumption by Prescribed Fire in Northern Idaho Mixed Confer Logging Slash" by Reinhardt and others (1991).

Overview of the principles of emissions from wildland fire is given by Ward and Hardy (1991) in "Smoke Emissions from Wildland Fires" and by Ward (1990) in "Factors Influencing the Emissions of Gases and Particulate Matter From Biomass Burning."

2

Fire Behavior

As we move from the discussion of *fire fundamentals* in Chapter 1 to *fire behavior* in this chapter, we adjust our point of view as illustrated in Figure 1.1. In Chapter 1 we examined the physical and chemical properties of fuel. Now we look at the whole complex, including such factors as the arrangement and mixture of size classes. We move from an examination of the effect of slope angle on heat transfer to the effect of the lay of the land on fire behavior. And we examine the effects of weather elements, not just the availability of oxygen to the combustion process. Because of the many variable forces influencing fire behavior, no two fires are alike. But much is known about influencing factors and their probable effect on the fire. Some relationships can be described and recognized, others can also be scientifically analyzed and modeled.

The beginning firefighter quickly becomes aware that a fire burning upslope behaves differently from one burning downslope under the same weather and fuel conditions, that windspeed and direction can quickly affect the rate and direction fire spread, and that a fire in logging debris differs from a grass fire. But many variations in the fire environment and their effects on fire are not so obvious, and skill in recognizing them comes from training and experience.

Wildland fire exhibits a tremendous range of fire behavior—from quiet smoldering in duff under a snow bank, to slow moving flames through litter and grass under a pine stand, to a blazing conflagration moving through the tops of trees. The three basic types of fire behavior are named according to the vegetation layer in which the fire is burning: ground, surface, and crown fire (Figure 2.1).

Surface fires spread by flaming combustion through fuels at or near the surface—grass, shrubs, dead and down limbs, forest needle and leaf litter, or

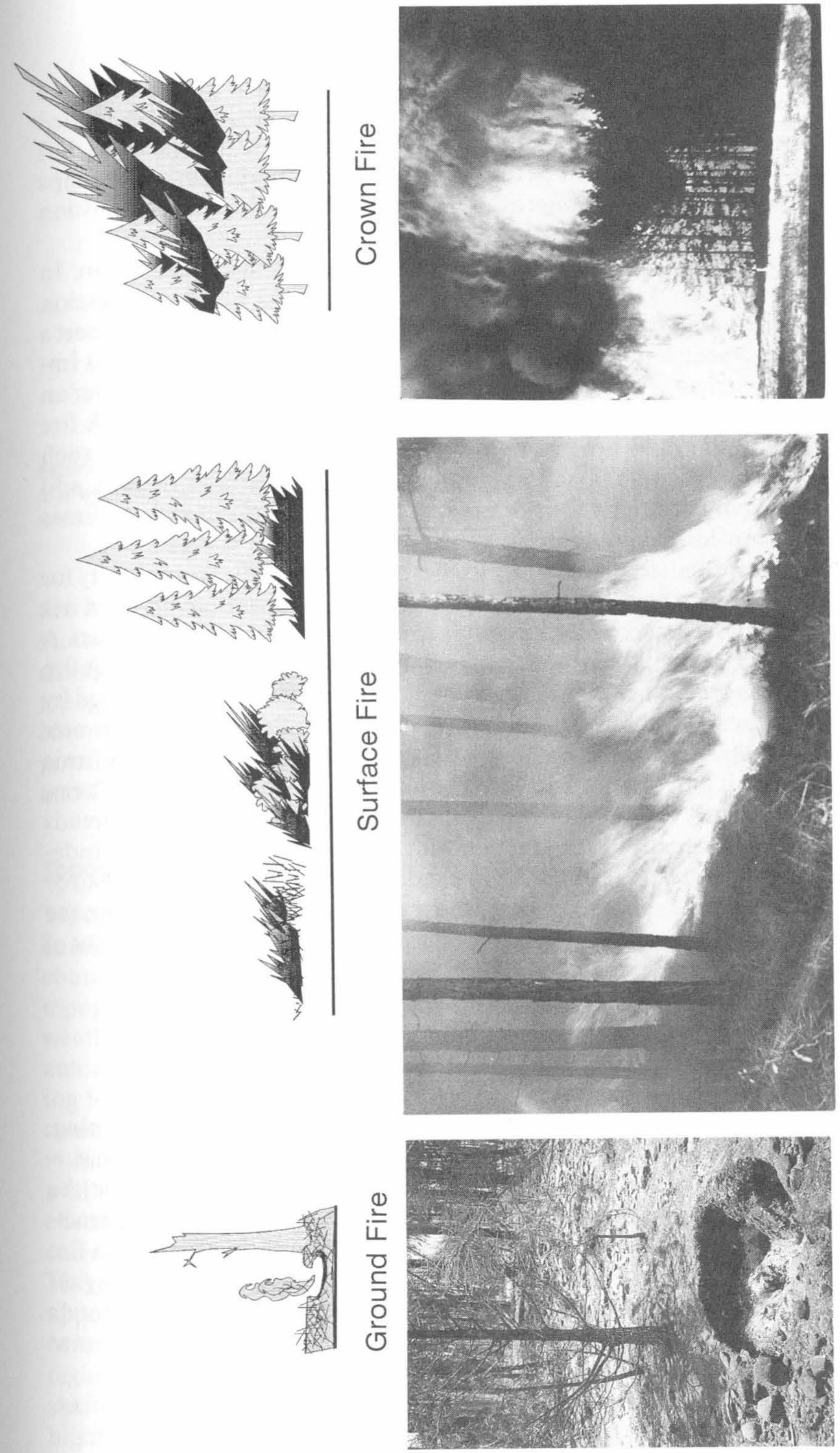


Figure 2.1. The three basic types of fire behavior are named according to the vegetation layer in which they are burning-- ground, surface and crown fire. Ground fire photograph from Dude Fire, Arizona, 1990. Photos courtesy of USDA Forest Service.

debris from harvesting or land clearing. *Crown fires* burn through the tree crowns. They are often dependent on surface fires and are invariably ignited by surface fires. *Ground fires* are fires in subsurface organic fuels, such as duff layers under forest stands, Arctic tundra or taiga, and organic soils of swamps or bogs. Ground fires burn underneath the surface by smoldering combustion and are most often ignited by surface fires.

Fires are also categorized according to human management action. In current United States terminology, *wildfires* are those on which suppression action is taken. *Management ignited prescribed fires* are ignited in order to meet a land management objective such as debris removal or wildlife habitat improvement. *Prescribed natural fires* are those that are allowed to burn under an approved plan to preserve the natural role of fire in the ecosystem. A fire management plan and prescription define acceptable conditions for such elements as time of year, location, drought condition, weather pattern, and other fire activity. If criteria for a prescribed natural fire are not met, the fire is designated a wildfire and appropriate suppression action is taken.

There is a specialized vocabulary used by the wildland fire community for describing different types of fire behavior. A fire is said to be *running* when it is spreading rapidly. It is *creeping* when it is spreading slowly with low flames. A fire is *smoldering* when it burns without a flame and is barely spreading. A fire is said to be *spotting* when it is producing sparks or embers that are carried by the wind or by the combustion column caused by the fire and that start new fires beyond the main fire. The new ignition points are called *spot fires*. A fire is *torching* when it moves from a surface fire into the crowns of individual trees, but not necessarily from one crown to another. It is *crowning* when it spreads from tree to tree, usually in conjunction with, but sometimes completely independent of, the surface fire. A *flareup* is a sudden acceleration of fire spread or intensity, of relatively short duration for a portion of the fire. A *blowup*, on the other hand, is a dramatic change in the behavior of the whole fire, the point of rapid transition to a severe fire.

2.1 THE FIRE ENVIRONMENT

Fire behavior is a product of the environment in which the fire is burning. Countryman (1972) presented the concept of the fire environment—the surrounding conditions, influences, and modifying forces that determine the behavior of a fire. Topography, fuel, weather, and the fire itself are the interacting influences that make up the fire environment. This is illustrated as a fire environment triangle with the fire in the center (Figure 2.2). While the *fire fundamentals triangle* in Chapter 1 shows the major factors in fire fundamentals (fuel, oxygen, and heat), the *fire environment triangle* shows the major factors at the fire behavior scale of our examination of fire.

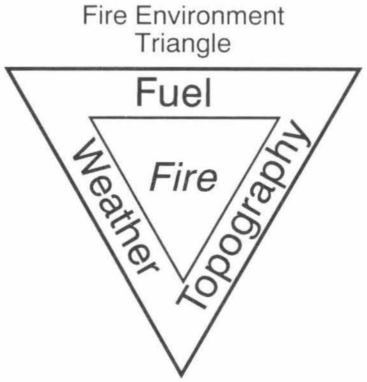


Figure 2.2. The fire environment triangle illustrates the influencing forces on fire behavior: fuel, weather, and topography. The fire in the center signifies that the fire itself can influence the fire environment. Based on Countryman (1972).

The changing states of each of the environmental components—fuel, topography, and weather—and their interaction with each other and with the fire itself determine the characteristics and behavior of a fire at any given moment. Changes in fire behavior in space and time occur in relation to changes in the environmental components. From a wildland fire standpoint, topography does not vary with time, but can vary greatly in space. The fuel component varies in both space and time. Weather is the most variable component, changing rapidly in both space and time. Chapter 3 is devoted to fuel and Chapter 4 to weather.

Topography

Topography includes the elements of slope steepness, aspect, elevation, and configuration of the land. Variations in topography can cause dramatic changes in fire behavior as a fire progresses over the terrain. Although topography may not change in time, it affects the way in which fuel and weather change. The fire environment triangle symbolizes this interaction among the elements. Topography modifies general weather patterns, producing localized weather conditions that in turn affect fuel type and moisture content.

Elevation above sea level influences general climate and thereby affects fuel availability. Length of fire season and fuel vary with elevation due to differences in amount of precipitation received, snow melt dates, and greenup and curing dates. Temperature and relative humidity vary with *position on the slope*. There can be significant difference between valley bottoms, midslope, and upper slopes. The *thermal belt* is a relatively warm area at midslope where the inversion layer contacts the mountain slopes. At night, the temperature of this region can be warmer than that on the slopes above or below. The thermal belt area typically experiences the least variation in daily temperature, has the highest average temperature, and has the lowest average relative humidity.

This is significant because while areas above or below may be relatively quiet, there may be active burning in the thermal belt during the night.

Aspect is the direction a slope is facing. Aspect affects fire behavior through variations in the amount of solar radiation and wind that different aspects receive. In general, in the northern hemisphere, south and southwest aspects are most favorable for fire start and spread. These aspects receive more sunshine and therefore have lower humidities and higher fuel temperatures.

Solar radiation intensity is greatest when the slope is perpendicular to the sun angle (Figure 2.3). In the northern hemisphere, fuels on slopes with an easterly aspect will dry out earlier in the day, but not become as dry as those on slopes with a westerly aspect. Slope steepness also affects the radiation intensity and fuel moisture. The slopes where the fuel will be the driest vary with time of year, time of day, and latitude. Thus, as a fire moves over the landscape its behavior can be expected to change with time of day and topographic characteristics because of the variations brought about by the different amounts and intensity of the solar radiation received.

During the day, sunlight moves across different aspects, and air temperature, relative humidity, fuel moisture, and fuel temperature all change. An inactive surface fire on a southwest aspect in the early morning may become an active crown fire that afternoon. After the sun sets, the same fire may again become a surface fire with fire intensities that allow successful suppression action.

Slope reversal refers to fire crossing onto a slope of opposite aspect, as when a fire runs to the top of a ridge and begins to back down on the opposite slope, or when a fire backs down a slope, crosses a drainage, and begins to run up the next ridge.

Slope reversal affects rate of spread and intensity as well as airflow. Commonly, as a fire runs to the ridgetop, it encounters an opposing upslope airflow from the other side of the ridge. This effect can slow the fire spread and limit the spotting problem on the opposite slope. Conversely, the effect of erratic winds converging at the ridgetop can contribute to spotting. A wildland fire burning near the top of the windward slope can spot across the ridgetop and onto the other slope.

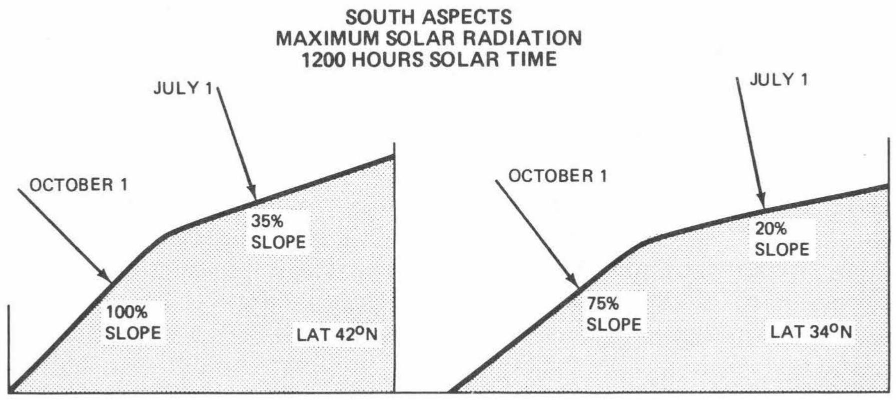


Figure 2.3. *Solar radiation is affected by aspect, slope steepness, and date. Maximum solar radiation for 1 October and 1 July for two latitudes.* From Countryman (1978).

Narrow canyons or ravines can affect fire behavior in several ways. A fire burning on one slope radiates a great deal of energy toward the opposite slope. This radiation can dry the fuel and preheat it enough to make it highly susceptible to ignition from sparks and embers. Occasionally, the whole slope, or a large part of it, will ignite in a matter of a few minutes. Such crossings can occur progressively, at multiple points, creating a hazardous situation for crews.

When a fire is burning in a canyon under an inversion or stable air conditions, the fire is slowly drying out fuels. When the inversion breaks, winds will increase into the canyon, and likewise fire activity will increase.

Barriers, both natural or artificial, are important terrain features. Barriers to fire spread include rocks or bare soil; lakes, streams, and moist soil situations; roads, trails, and other improvements; changes in fuel type and fuel moisture conditions; and previously burned areas. Suppression action often creates barriers by removing fuel, by line construction or by burnout. Sometimes a narrow line scratched in the litter is enough to stop fire spread; other times highways, rivers, and even lakes are not enough.

The "*chimney effect*" has claimed the lives of firefighters. A chimney, as the name suggests, depicts the topographic features of a steep narrow chute with three walls, similar to a box canyon. Normal upslope air flow is rapid and funneled to the chimney's shape. Because of upslope preheating and cross-canyon radiation, these chimneys draft a fire, much like an actual stove chimney. The chimney effect occurs when unstable air conditions at the surface create a convection current through the canyon, drawing air in at the base of the canyon and exhausting it at the top (Figure 2.4).

Slope steepness has a direct effect on flame length and rate of spread of a surface fire. Whether the wind or slope has the greatest effect depends on their relative force. A strong wind can push a fire downslope.

When a fire burns up a steep slope the convection column sometimes becomes "trapped," flowing upward along the slope for a considerable distance (Figure 2.5). At other times, the column separates from the slope at or very near the fire edge. Attachment of the flame to the slope will reduce the scorch height in trees from what would be expected on level ground where the flames stand vertically. But further up the slope at a ridge line where the convection column breaks from the surface and rises, the concentration of hot gases will result in higher scorch than expected on the flat.

Fuel

The influence of fuel on fire behavior is so important that Chapter 3 is devoted to the subject. In Chapter 1 we examined intrinsic fuel parameters and their role in the combustion process. When looking at the behavior of wildland fire, we examine other features of the fuel: the mixture of live and dead fuel, the

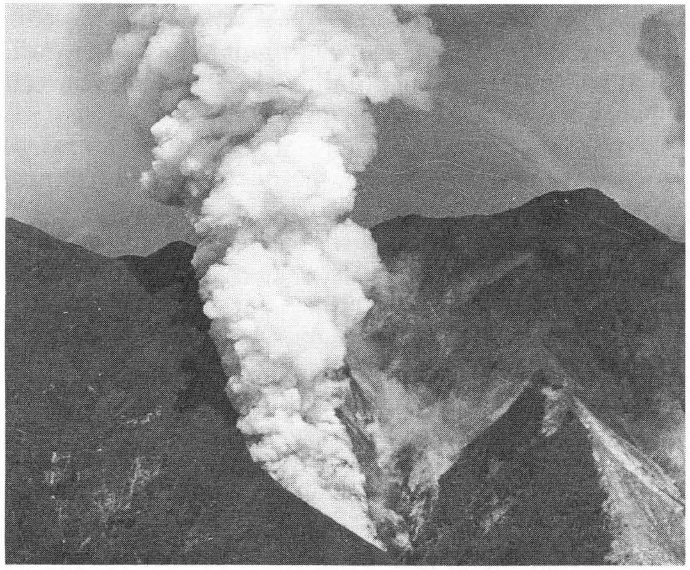


Figure 2.4. *Chimney effect on a fire in Southern California.* Courtesy of USDA Forest Service.

arrangement and size of fuel particles, and fuel moisture. As we move from fire fundamentals to the fire behavior scale we look at the whole fuel complex, which includes ground, surface, and crown fuels.

Fuel can be described in terms of both fuel state and fuel type. Fuel state refers to the moisture content of the fuel and whether it is live or dead. A description of fuel type includes horizontal and vertical continuity of the fuel, size and shape of components, compactness, and so on.

Weather

Weather influences are discussed throughout this chapter and as a separate topic in Chapter 4. Temperature, relative humidity, and precipitation affect fuel moisture. Wind is a dominant influence on fire behavior. It is also one of the hardest elements to predict due to variability of windspeed and direction and the influences of topography, vegetation, and local heating and cooling.

Wind is measured and forecasted at 20 ft above the vegetation in the United States (10 m in most of the rest of the world). The wind on a surface fire can be considerably less, as shown by the wind profile in Figure 2.6. A table of wind adjustment factors has been prepared to adjust 20-ft wind to the wind that influences a surface fire, called midflame wind. The adjustment factors account for the decrease in windspeed according to the wind profile as well as the effect of topography and sheltering by the overstory.

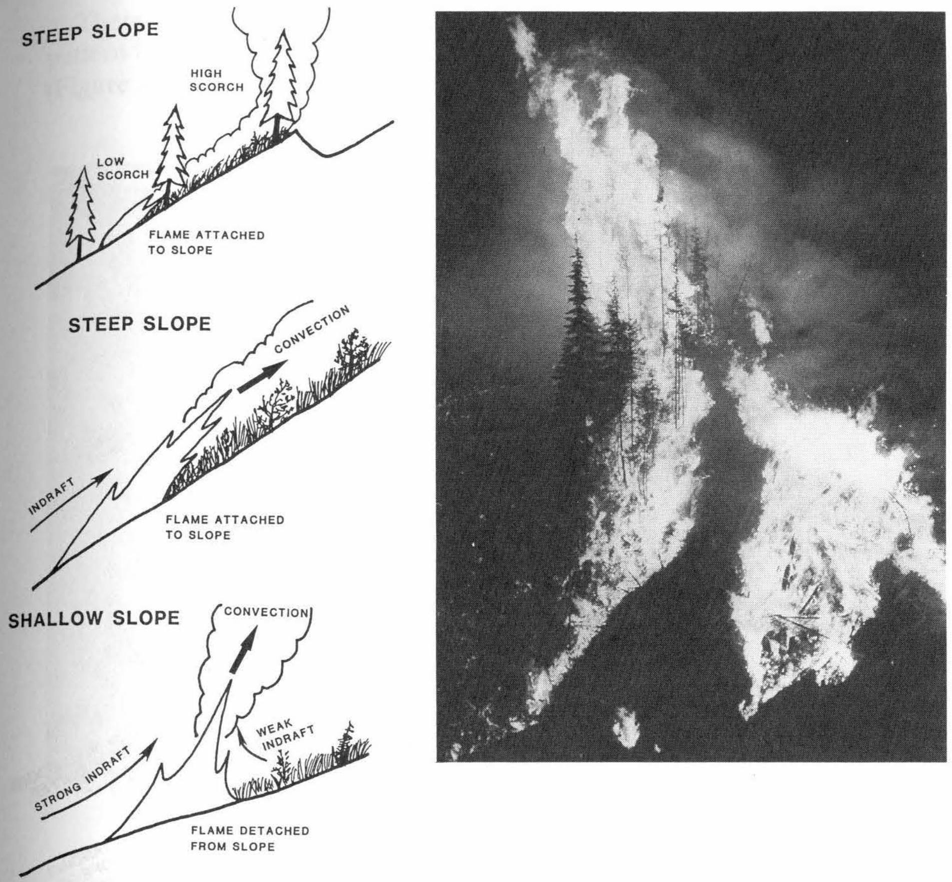
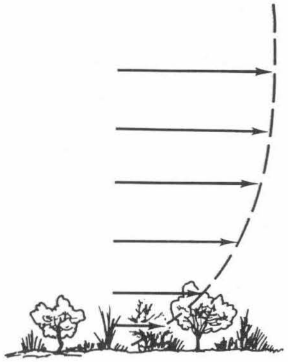


Figure 2.5. *Slope steepness affects fire behavior. Flames detached from a shallow slope and attached to a steep slope. Scorching conditions can be higher at the top of a steep slope.* From Rothermel (1985). Photo by Roberta A. Hartford, USDA Forest Service.

Fire Interaction With the Environment

The fire in the center of the fire environment triangle (Figure 2.2) symbolizes the interaction between the fire and the environment. Fire behavior is generally determined by the fuel, weather, and topography. But in some cases the fire itself influences the environment and thus the fire behavior, a feedback loop. Heating from the fire can modify or produce local winds, contribute to atmospheric instability, and cause cumulus cloud development. At the extreme, a combustion column can build to the point where it can generate lightning, rain, and dangerous downbursts.

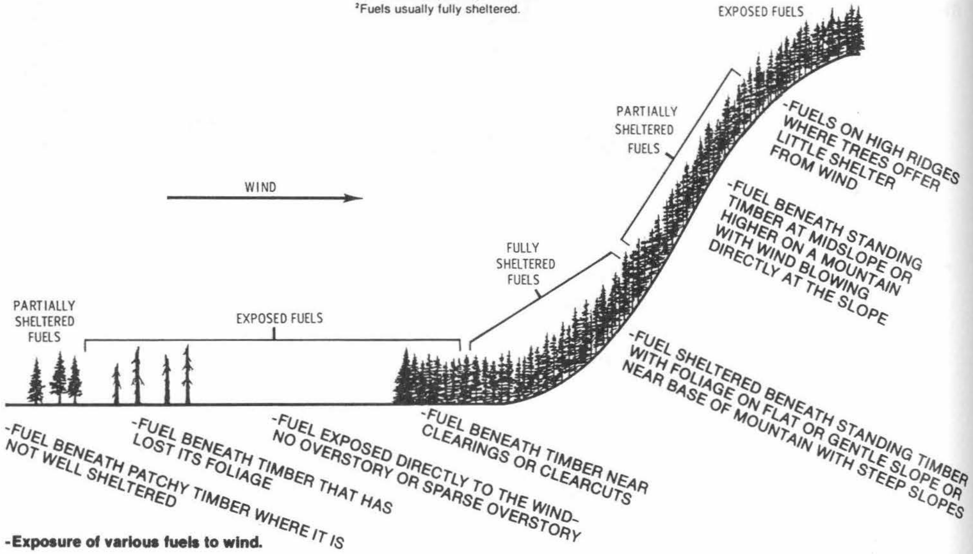
Water vapor is formed in the combustion process and from the moisture in the burning fuel. This vapor is carried aloft in the smoke or convection column



Wind adjustment table. Find the appropriate adjustment factor and multiply it by the 20-ft windspeed. Use the result as the midflame windspeed

Fuel exposure	Fuel model	Adjustment factor
EXPOSED FUELS		
Fuel exposed directly to the wind—no overstory or sparse overstory;	4	0.6
fuel beneath timber that has lost its foliage; fuel beneath timber near clearings or clearcuts; fuel on high ridges where trees offer little shelter from wind	13	0.5
	1,3,5,6,11,12 (2,7)[1] (8,9,10)[2]	0.4
PARTIALLY SHELTERED FUELS		
Fuel beneath patchy timber where it is not well sheltered; fuel beneath standing timber at midslope or higher on a mountain with wind blowing directly at the slop	All fuel models	0.3
FULLY SHELTERED FUELS		
Fuel sheltered beneath standing timber on flat or gentle slope or near base of mountain with steep slopes	All fuel models Open stands	0.2
	Dense stands	0.1

[1] Fuels usually partially sheltered.
[2] Fuels usually fully sheltered.

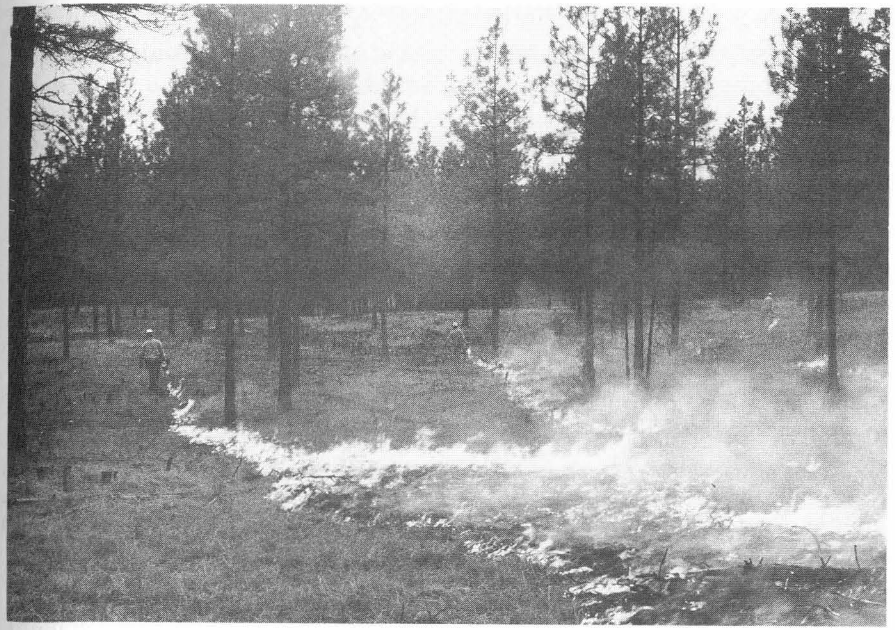


-Exposure of various fuels to wind.

Figure 2.6. *Windspeed must be adjusted from the 20-ft height to midflame level. Diagram shows the general wind profile near the surface. Table and diagram give adjustment factors based on fuel types, canopy cover, and topography.* From Rothermel (1983).

and can contribute to the formation of a white "cap." The heat released when the vapor condenses can add significant amounts of energy to the convection column, increasing its strength and adding to the fire activity. A fire is said to create its own wind when the column builds to the point where air rushes into the fire to replace air evacuated by the combustion column.

There is an interaction between fire and its environment when the ignition pattern is used by expert burners to modify the behavior of a prescribed fire (Figure 2.7). One strip or line of fire may be ignited, then additional parallel



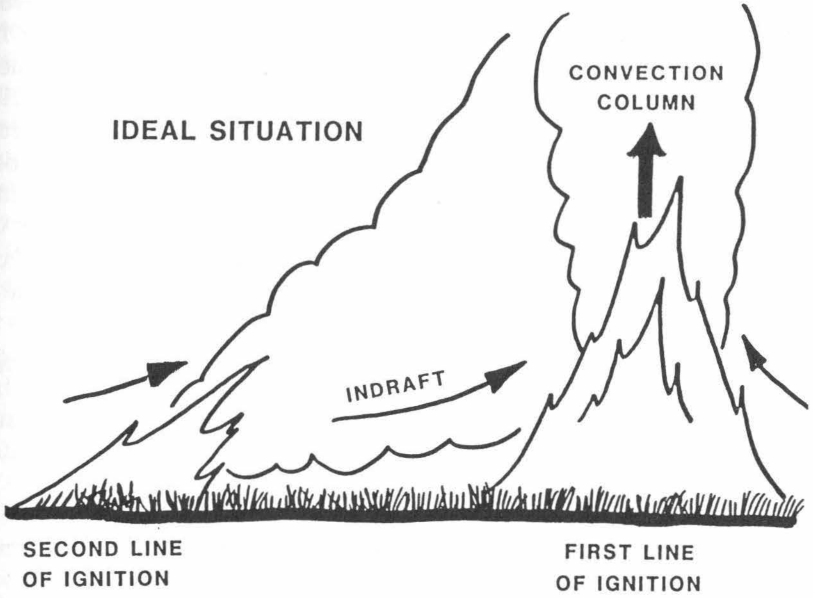


Figure 2.7. *The pattern of ignition can affect the behavior of the fire.* Strip fire photograph from Kilgore and Curtis (1987). Diagram from Rothermel (1985).

strips timed and spaced so that each portion of the fire generates enough heat to create an indraft and draw in the next. Similarily, ignition may begin with a substantial central area followed by ignitions around the premimeter that are drawn to the center.

These principles are also used as suppression techniques on a wildfire. A *backfire* lit in front of the main fire draws into the main fire, eliminating fuel for further fire spread. This differs from a *burnout* operation on a wildfire where a fire is lit for the purpose of eliminating fuel along prepared firelines or in an area the fire has not yet reached. The backfire directly affects the behavior of the main fire while a burnout affects the main fire when it reaches the barrier of an area of no fuel.

2.2 FIRE GROWTH

A wildland fire goes through several stages: ignition, transition to a spreading fire, acceleration or buildup of spread rate, and spread at a steady-state rate; sometimes a fire continues to increase in intensity, exhibiting elements of extreme fire behavior.

Ignition

Wildfires start from lightning strikes and from a variety of human causes including discarded cigarettes, sparks from equipment, and arched powerlines. Prescribed natural fires, by definition, start by lightning. Management ignited prescribed fires are started by techniques and equipment designed for that purpose. Ignition is determined by the relationship between the heat available from the ignition source and the heat required to bring the fuel to ignition, as described in Chapter 1. Schroeder (1969/unpublished, described by Bradshaw 1983) developed an estimate for probability of ignition based on the heat of preignition, the net amount of heat necessary to raise the temperature of a fuel particle from its initial temperature to its ignition temperature. The model is also based on the results of a study by Blackmarr (1972), who measured the influence of moisture content on the ignitability of slash pine litter by dropping lighted matches onto fuel beds conditioned to different levels of moisture content. Probability of ignition is the chance that an ignition will result if a firebrand lands on flammable material. Schroeder defined probability of ignition as a function of fuel moisture and of fuel temperature, which is estimated from ambient temperature and shading. Figure 2.8 shows example calculations of probability of ignition for a range of fine dead fuel moistures and ambient temperatures when fuel shading is 40%.

Lightning is an important source of ignition in some parts of the world. It is especially important when it occurs without rain. An extraordinary lightning episode on 30 August 1987 started 1600 fires in Southwest Oregon and Northwest California. Emissions from the Silver Fire, the largest of the fires that started that day, was discussed as an example in Chapter 1.

```
IGNITE
 1--DRY BULB TEMPERATURE, F    40.0  60.0  80.0 100.0 120.0
 2--1-HR FUEL MOISTURE, %       2.0   4.0   6.0   8.0  10.0  12.0  14.0
 3--FUEL SHADING, %            40.0


=======================================================================
PROBABILITY OF IGNITION, %                                       (V4.0)
=======================================================================
   DRY      I        1-HR FUEL MOISTURE, %
   BULB     I
   TEMP     I    2.      4.      6.      8.     10.     12.     14.
    (F)     I-----------------------------------------------------------
            I
  40.0      I   90.     70.     50.     40.     30.     20.     10.
            I
  60.0      I   90.     70.     50.     40.     30.     20.     20.
            I
  80.0      I  100.     80.     60.     40.     30.     20.     20.
            I
 100.0      I  100.     80.     60.     50.     40.     30.     20.
            I
 120.0      I  100.     90.     70.     50.     40.     30.     20.
```

Figure 2.8. *Example calculations for probability of ignition for a range of dead fuel moistures and ambient temperatures when fuel shading is 40%. Calculations from the BEHAVE fire behavior prediction system.* From Andrews (1986).

Lightning, or course, is a unique ignition source, supplying more energy to a fuel than most other sources, and the probability of ignition relationship described above does not apply. Latham and Schlieter (1989) developed equations for probability of ignition for lightning continuing currents. The relationships were based on laboratory experiments where the effect of several variables was examined. The most important of the variables associated with the discharge was its duration. They also found that moisture content (for moistures less than 40%) played a very small role in the ignition of duff from short-needled species; fuel depth was more influential. In the case of litter and duff from long-needled species, ignition probabilities depended mostly on the fuel moisture.

Point Source Fire

Wildfires generally start at a single point. In some cases there is a significant delay from ignition until the fire begins to spread. These fires are sometimes referred to as *holdover* fires. A lightning strike may cause the heart of a standing dead tree, or snag, to smolder for weeks before weather conditions change and fuels dry to the point where flaming spread is possible. An ignition may even smolder in ground fuels over the winter.

There is a period of time, referred to as *buildup* or *acceleration time*, from the time spread begins until the fire reaches an *equilibrium* or *quasi-steady-state* *spread rate.* The "quasi" is added because there is no actual steady-state in wildland fire. The relationship used in the Canadian Forest Fire Prediction System (Forestry Canada Fire Danger Group 1992) is shown in Figure 2.9. The relationship is based on experimental data from both laboratory and field for open canopy fuel types. The time required to reach equilibrium rate of spread from a point source ignition was found to be constant, regardless of weather conditions.

Fire spreads most rapidly in the direction of local wind and in the direction of upslope in uneven terrain. The fastest-spreading part of the perimeter is called the *front* or *head*; the slowest-spreading part is called the *back*. The lateral portions, or *flanks*, spread at intermediate rates. Growing from a point of ignition, a fire in uniform fuel on smooth terrain achieves an elongated shape under the influence of wind. As pointed out by Albini (1992), "it is a remarkable fact that the general shape is the same for a savanna fire, a shrub fire, or a timber crown fire."

An ellipse is often used to quantify the shape of a point source fire (Figure 2.10). The length-to-width ratio is greater with increasing windspeed. The more uniform the conditions, the closer to the elliptical shape. Given an estimate for the head fire rate of spread, the ellipse equation can be used to calculate the flanking and backing spread rates. Variation in fire shape is a result of fuel type changes, barriers, effect of slope and wind, and spotting.

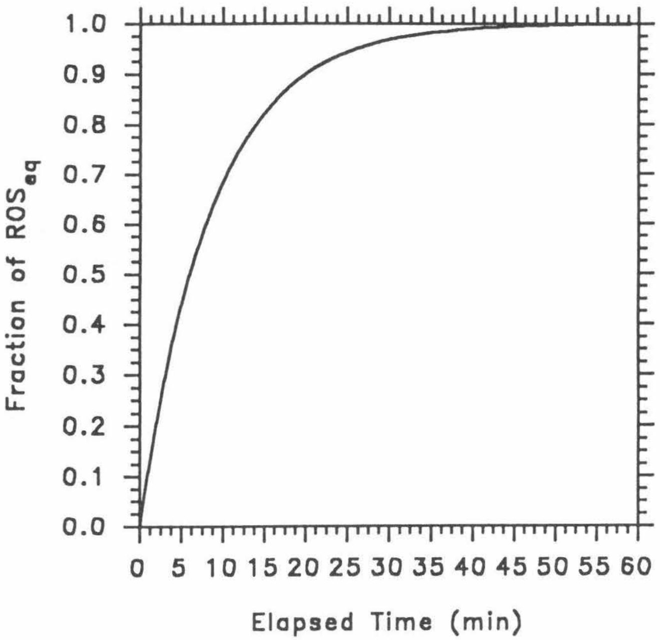


Figure 2.9. *Fire acceleration model for open canopy fuel types used in the Canadian Fire Behavior Prediction System.* From Forestry Canada Fire Danger Group (1992).

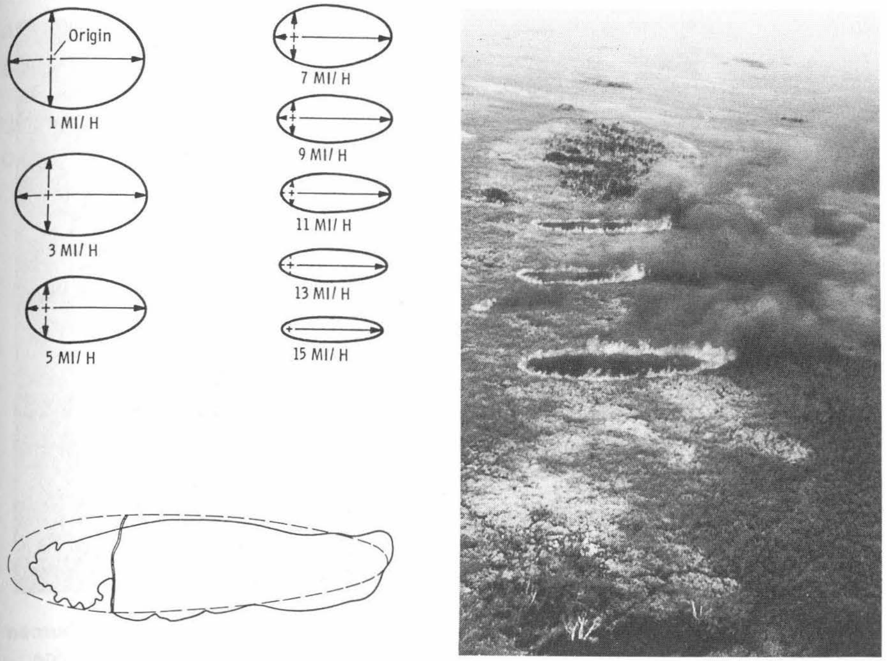


Figure 2.10. *Many fires have been shown to be approximately elliptically shaped. Length-to-width ratio of fire shape is a function of windspeed.* From Rothermel (1983). *Wandilo Fire in South Australia 1958.* From Anderson (1983). *Everglades NP photo courtesy of USDI National Park Service.*

Large Fires

A fire *spreads* by igniting new fuel along its outer perimeter. It may *grow* through ignition of fuel that is remote from its edge by producing burning embers or sparks that are transported by wind and the fire's convection column. All of the area inside the fire perimeter may not be burned. Figure 2.11 shows a burn mosaic resulting from a fast-moving fire in Yellowstone National Park in 1988.

Kerr and others (1971) characterized eight types of large fires, as summarized in Figure 2.12 and shown in Figure 2.13. The types are concerned with relationships between the convection column and the wind. They related the types to characteristics of spread, spotting potential, and smoke drift.

A Type I fire occurs with low surface windspeeds and low to moderate speeds aloft. Instability is usually present near the ground. A towering convection column, which may reach to 25,000 to 50,000 ft, remains vertical. The convection column may cause the fire to spread faster than would be predicted by surface wind observations. Virtually all combustion products are carried aloft in the rapidly rising convection column so smoke is negligible near the ground. For the same reason, spotting is minimal because potential firebrands

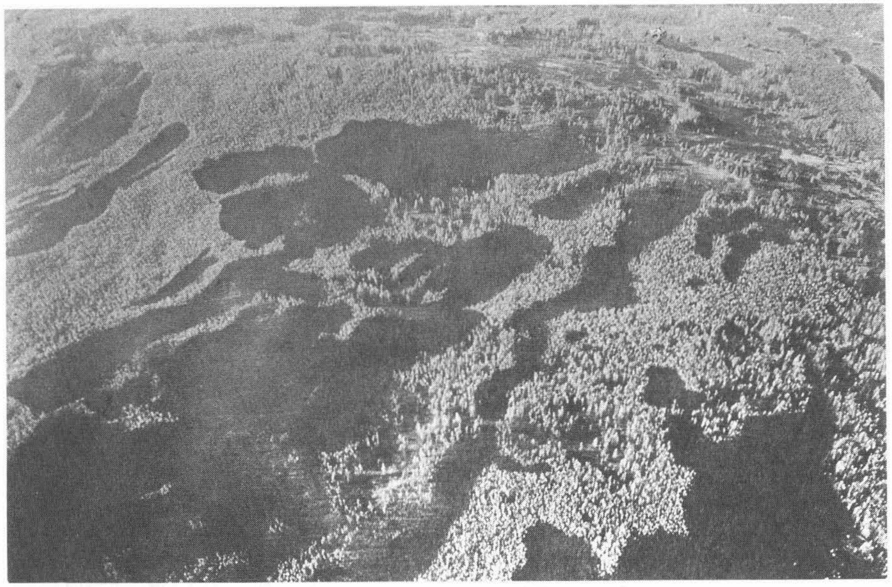


Figure 2.11. *Rapidly spreading crown fires generally leave a mosaic of burned and unburned fuel, Yellowstone National Park, 1988.* Photo by Robert A. Hartford, USDA Forest Service.

No	Type	Dominant Features
I	Towering convection column with light surface winds	Moderate to rapid fire spread persistent until changes in the atmosphere or fuel
II	Towering convection column over a slope	Rapid short-term spread with convection cutoff at ridge crests
III	Strong convection column with strong surface winds	Fast, shifting spread with short-range spotting
IV	Strong vertical convection cutoff by wind shear	Steady or shifting spread with occasional long-range spotting
V	Leaning convection column with moderate surface winds	Rapid, shifting spread with both short- and long-range spotting
VI	No rising convection column under strong surface winds	Very rapid spread driven by combined fire and wind energy; frequent close spotting
VII	Strong surface winds in mountainous topography	Rapid spread both up- and down-slope with frequent spotting and area ignition
VIII	Multiple head fires (mostly types I through V)	Broad fire front with two or more independent convection columns

Figure 2.12. *Summary of large fire types.* Based on Kerr and others (1971).

are carried so far aloft that they burn out before dropping back to the ground.

Type II fires burn in mountainous terrain under wind and stability conditions similar to those of Type I fires. The driving force for fire spread is not only the convection column but also the tilt of the slope, resulting in an

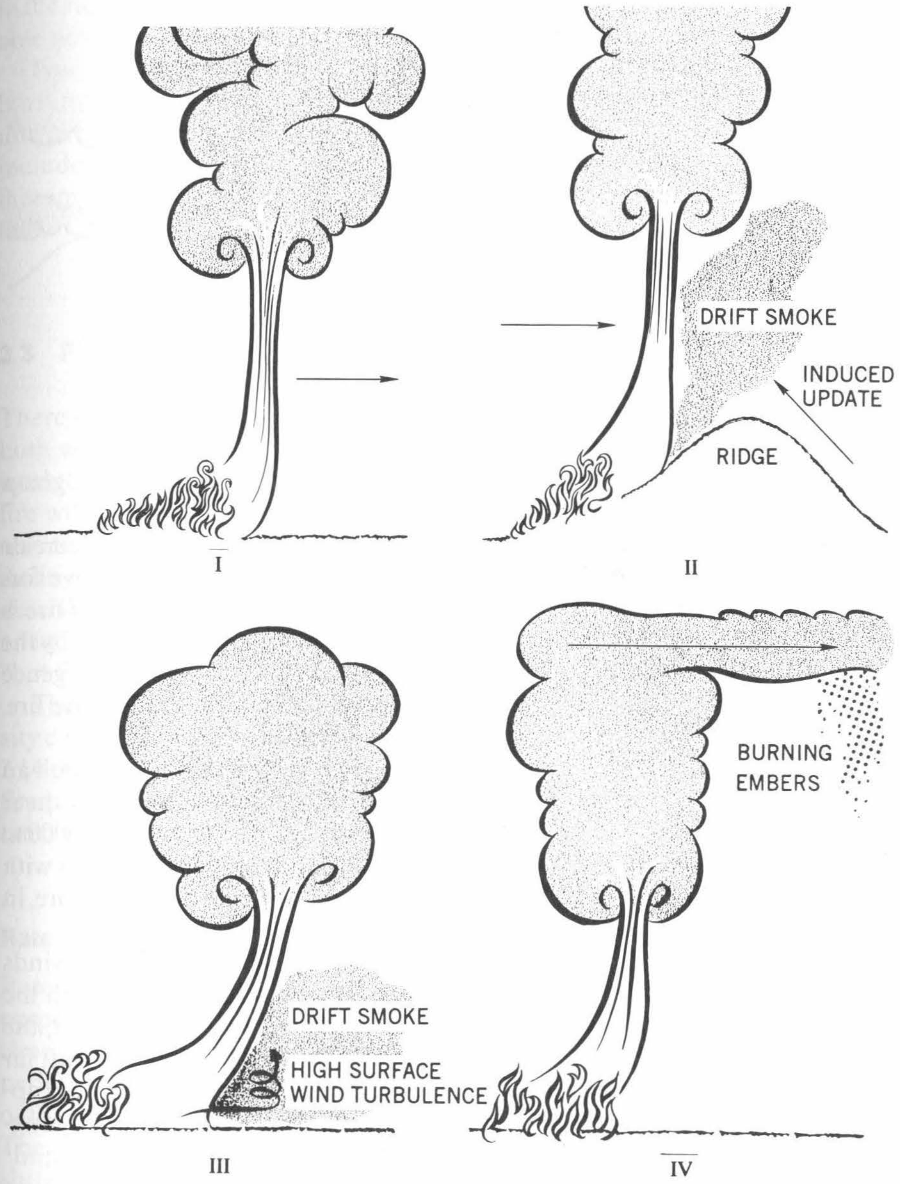


Figure 2.13. *Large fire types.* From Kerr and others (1971).

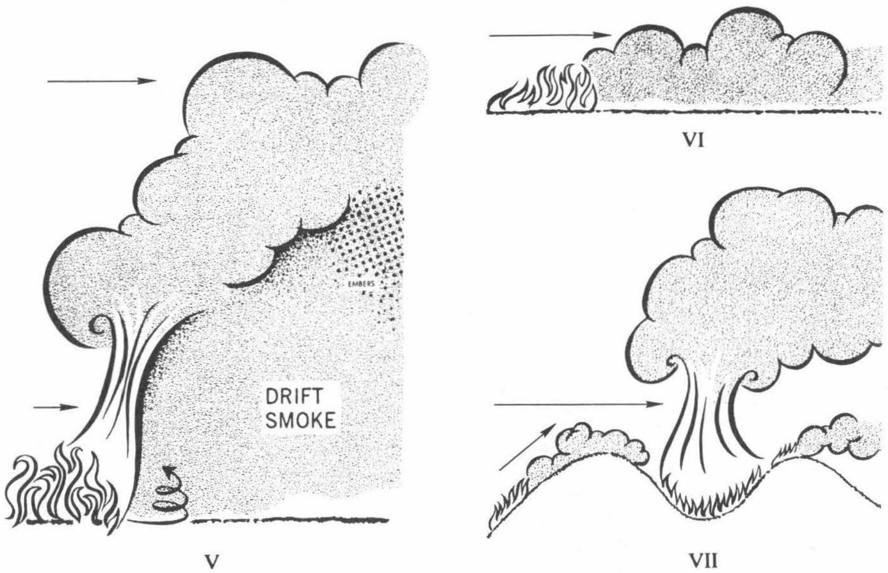


Figure 2.13. (Continued)

increased rate of spread. Smoke is plentiful along the slope to the ridgetop where it moves off into the upper air.

Type III fires burn under the influence of strong surface winds with decreasing winds aloft. They develop a towering convection column and move forward more rapidly than Type I fires. The driving energy for this type of fire is derived from the force of the convective activity strongly supplemented by the force generated by the strong surface winds. These winds form a convergence zone ahead of the fire with resulting strong vorticity at the head of the fire. There is usually considerable smoke for some distance downwind.

Large fires often occur under conditions typical of Types I or III, but with an otherwise towering convection column sharply cut off by a strong wind shear aloft, called a Type IV fire. This discontinuity in windspeed is common 5000 to 10,000 ft above the surface. This represents a highly dangerous situation with respect to long-distance spotting. Spot fires may occur 6 to 10 miles, or more, in advance of the fire front.

Type V fires occur when winds aloft increase with altitude. The strong winds aloft are usually accompanied by at least moderate surface winds. With the increased mixing of the convection column with the ambient air aloft, the column becomes quite disorganized or diffused with smoke carried aloft far downwind. Under these conditions there is also considerable smoke for appreciable distances in advance of the fire front. There is both short- and long-range spotting, becoming less frequent with increasing distance downwind.

Type VI fires are essentially wind-driven, occurring in neutrally stable to stable atmosphere. Strong surface winds prevent the convection column from rising more than a short distance above the surface. Smoke is often carried forward in a narrow ribbon for perhaps a hundred miles or more with slight dissipation. Spotting is confined to short distances ahead of the fire front.

Type VII fires burn under the conditions described for Type VI fires, but in mountainous topography they spread up the windward slopes with extreme rapidity, while showering great numbers of firebrands ahead of the fire. This area ignition, coupled with the highly turbulent winds in lee areas, can result in the rapid development of mass fire with extreme heat outputs and considerable convection activity causing very complex fire behavior patterns.

Type VIII fires, multiple-headed fires, are included because any intensely burning fire such as those described in Types I through VII tend to break up into two or more separate head fires when the fire front becomes long. Causes include variation in fuel and terrain, barriers, and separate convective cells in the atmosphere. These multiple heads may result in unburned islands of fuel.

2.3 FIRE SPREAD AND INTENSITY

There is a need to characterize rate of spread and intensity of wildland fire, both wildfire and prescribed fire. In the planning stages, this information is used to define the conditions under which a management ignited prescribed fire will be conducted, both to achieve the stated objectives of the burn and also to retain control of the fire. Predicted spread rate and intensity are used during a wildfire in determining suppression tactics. And it is important to describe the character of the fire for an evaluation of fire effects; it is less than adequate to do an analysis of vegetation response to "fire" versus "no fire" or to "hot fire" versus "cool fire."

The range of fire characteristics is tremendous, with spread rate and intensity covering ranges of values that can span three orders of magnitude. Figure 2.14 gives example values for rate of spread and total heat load related to nonfire physical phenomena. Flame length and fireline intensity values are related to fire suppression activities.

Rate of Spread

Rate of spread is measured from any point on the fire perimeter in a direction perpendicular to the perimeter. Rate of spread can vary considerably due to changing conditions, and is generally taken to be an average value over a period of time. The fastest rate of spread (ROS) is the forward ROS at the head of the fire. The backing ROS is much less, the flanking ROS is intermediate. The behavior of a backing or flanking fire can, however, change quickly with a shift in the wind. A 90° wind shift can change a long, slow-spreading flanking fire into a fast-spreading head fire.

RATE OF SPREAD

RATE OF SPREAD ft/min	TYPICAL FIRE SITUATION	EQUIVALENT TO
1	Litter fire, no wind, no slope	Line building rate for one person in heavy fuel
25	Aged medium slash, 100% slope	Backpacker going up 100% slope
250	Low sagebrush, Santa Ana wind	Brisk walk on level ground
800	Chaparral, Santa Ana wind	Good pace for a marathon run
1200	Dry, short grass high wind	4-minute mile

TOTAL HEAT LOAD

HEAT LOAD Btu/ft^2	FUEL CONSUMED tons/acre	ENERGY RELEASED ON 1 FT^2 WOULD
300	0.75 (grass)	Warm up 2 quarts of stew
1200	3 (tall grass)	Boil away 1 pint of water
4000	10 (1 in. pine duff)	Open car thermostat (5 gal. system)
12,000	30 (thinning slash)	Heat 10 Pulaski heads to full cherry red
48,000	120 (heavy logging debris)	Melt down an aluminum engine block (115 lb)

FLAME LENGTH AND FIRELINE INTENSITY

FLAME LENGTH feet	FIRELINE INTENSITY Btu/ft/sec	FIRE SUPPRESSION INTERPRETATION
< 4	<100	Fire can generally be attacked at the head or flanks by persons using handtools. Hand line should hold the fire.
4-8	100-500	Fires are too intense for direct attack on the head by persons using handtools. Handline cannot be relied on to hold fire. Equipment sucn as plows, dozers, pumpers, and retardant aircraft can be effective.
8-11	500-1,000	Fires may present serious control problems--torching, crowning, and spotting. Control efforts at the fire head will probably be ineffective.
>11	>1,000	Crowning, spotting, and major fire runs are probable. Control efforts at the head of the fire are ineffective.

Figure 2.14. *Examples of rate of spread and total heat load related to nonfire physical phenomena. Flame length and fireline intensity related to fire suppression activities.* Based on unpublished training notes, F. A. Albini.

Slope and wind affect the spread rate similarly because of the effect of tipping the flames toward or away from the fuels ahead of the fire. Interaction between wind and slope depends on magnitude and direction of influence of each (Figure 2.15). If wind is blowing upslope there is a cumulative effect and the head fire moves upslope, a common occurrence. It is also possible, however, for a fast-spreading fire to move downslope, as a chaparral fire under Santa Ana wind conditions.

The fuel element that has the greatest effect on the spread rate of a surface fire is the fine dead fuel—small twigs, grasses, and leaf and needle litter. Burnout of heavy fuels and duff continue after the flaming front has passed.

Intensity and Flame Length

Intensity is heat release per unit time. There are several ways of characterizing intensity. Reference is sometimes made to the intensity of the whole fire, but quantification of intensity for a specific area of the perimeter is appropriate for most applications. General principles of intensity and heat release were discussed in Chapter 1. Here we describe the intensity calculations as used in the United States fire behavior prediction system, BEHAVE. The equations are summarized in Figure 2.16. *Reaction intensity* is a heat release rate and is part of

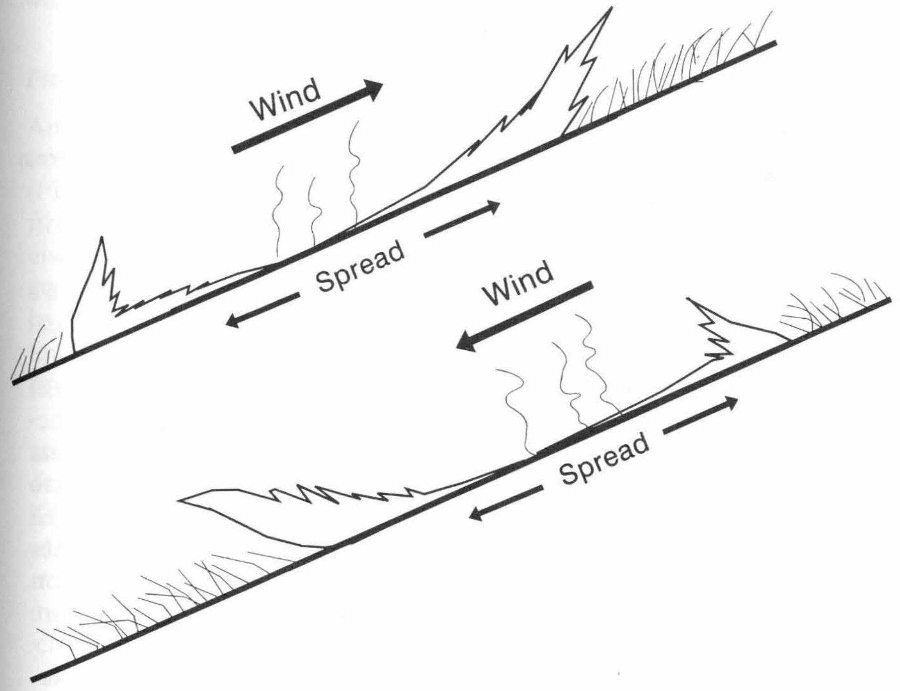


Figure 2.15. *The influence of wind and slope depends on the magnitude of each. The head fire may burn either up- or downslope.* Based on Rothermel and Rinehart (1983).

$$t_r = 384/\sigma$$

$$D = Rt_r$$

$$H_A = I_R t_r$$

$$I_B = I_R D/60 = I_R R t_r/60 = H_A R/60$$

$$F_L = 0.45 I_B^{0.46}$$

where

σ = characteristic surface-area-to-volume ratio of the fuel array, ft^2/ft^3
t_r = flame residence time, min
R = rate of spread, ft/min
D = flame depth, ft
I_R = reaction intensity, $\text{Btu/ft}^2\text{/min}$
H_A = heat per unit area, Btu/ft^2
I_B = Byram's fireline intensity, Btu/ft/s
F_L = flame length, ft

Figure 2.16. *Intensity equations used in the BEHAVE fire behavior prediction system.* From Andrews (1986).

Rothermel's fire spread model (1972). It is the heat released per minute from a square foot of fuel while in the flaming zone. *Heat per unit area* is the heat released from that square foot of fuel for the whole time the flaming zone is in that area. Heat per unit area is calculated from reaction intensity times *residence time.* Flame residence time was found by Anderson (1969) to be a function of the diameter of the fuel. *Byram's fireline intensity* (1959) is the heat released per second from a foot wide section of fuel extending from the front to the rear of the flaming zone, the *flame depth.* Fireline intensity is calculated from the reaction intensity times the flame depth, or heat per unit area times rate of spread. *Flame length* is a function of fireline intensity. Fire suppression interpretations of flame length and fireline intensity were given in Figure 2.14.

Example calculations of fire behavior from the BEHAVE fire behavior prediction system are given in Figure 2.17. This shows a comparison of calculated rate of spread, heat per unit area, and flame length for two sets of fuel moisture conditions for five fuel types. This illustrates the fire model's ability to reflect a wide range of behavior.

ENVIRONMENTAL CONDITIONS:						
Dead fuel moisture, %	4			10		
Live fuel moisture, %	70			200		
Midflame windspeed, mi/h	4			4		
Terrain slope, %	30			30		
FUEL MODEL	RATE OF SPREAD ch/h	HEAT PER UNIT AREA Btu/ft^2	FLAME LENGTH ft	RATE OF SPREAD ch/h	HEAT PER UNIT AREA Btu/ft^2	FLAME LENGTH ft
1--Short dead grass	87	96	4.5	43	59	2.6
4--Chaparral	95	2972	23	24	1570	9.1
5--Brush, 2 ft.	31	736	7.3	4	226	1.7
9--Hardwood litter	9	416	3.1	6	330	2.3
12--Heavy logging slash	19	3701	12.1	12	2933	8.9

Figure 2.17. *Calculations from the BEHAVE fire behavior prediction system for five fuel types and two sets of moisture conditions.* Based on Andrews (1986).

Fire Characteristics Chart

Andrews and Rothermel (1982) presented the concept of the fire characteristics chart as a way to display several fire behavior values as a single point (Figure 2.18). The fire characteristics chart for surface fires can display four fire characteristics simultaneously: rate of spread, heat per unit area or unit energy, fireline intensity, and flame length. The relationships are given in the equations in Figure 2.16. The chart lends itself well to classifying fire intensity by adjective ratings and color codes. Lines of equal fireline intensity and flame length on the fire characteristics chart correspond to the suppression interpretations in Figure 2.14.

The values for the low moisture conditions from Figure 2.17 are plotted on the fire characteristics chart in Figure 2.18. The range of behavior in different fuel types under the same moisture, wind, and slope conditions is evident. Grass fuels spread very fast, but with a low heat per unit area. Heavy logging slash spreads slower, but with a very high heat per unit area. Chaparral burns with both a high rate of spread and a high heat per unit area. It is possible for two fires to have the same calculated flame length, but to have very different character—high rate of spread and low heat per unit area, or low rate of spread and high heat per unit area.

Rothermel (1991c) expanded the surface fire characteristics chart to make it applicable for crown fires. That chart uses an alternate flame length model

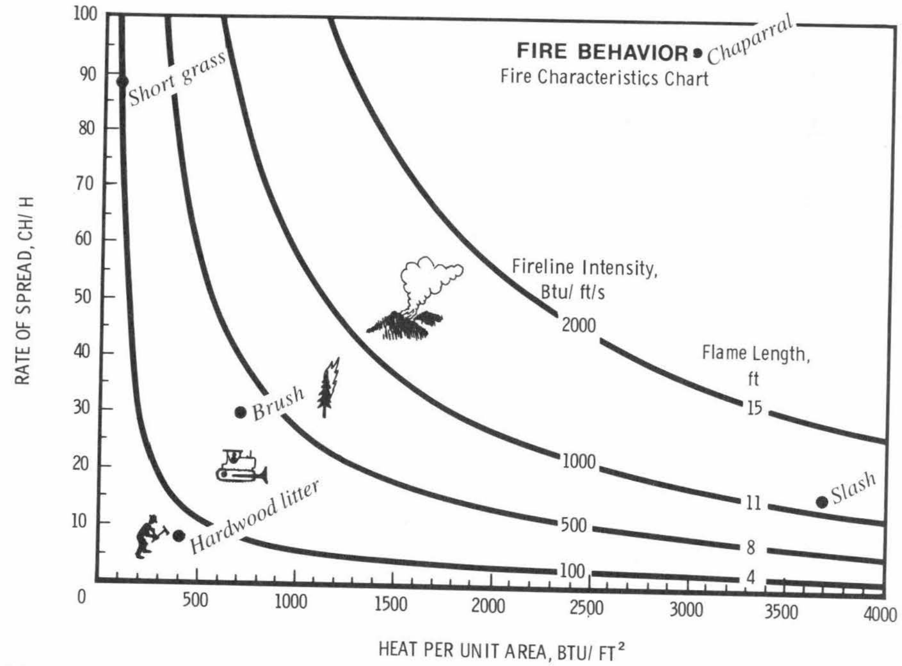


Figure 2.18. *Low moisture fire behavior values from Figure 2.17 plotted on a fire characteristics chart.* Based on Andrews and Rothermel (1982).

developed by Thomas (1962) and the large fuel burnout model developed by Albini (1976a). The crown fire characteristics chart includes methods for estimating the energy generated by the fire and a means of estimating whether crown fires will be wind-driven or dominated by the convection column (plume-dominated). Figure 2.19 is a plot of the fire behavior of two fires that are described as selected examples at the end of the chapter.

The crown fire characteristics chart shows the difference between surface fire and crown fire intensity, and the potential change in behavior as a fire moves from surface to crown. The chart also indicates the small range of behavior wherein control of fires can be expected to be successful (see Figure 2.14).

2.4 EXTREME FIRE BEHAVIOR

Several fire-dependent aspects of fire behavior are grouped for discussion here under the label "extreme fire behavior." They are characteristics that go beyond those exhibited by the majority of fires. Aspects of fire behavior that are included here as "extreme" include crowning, torching, horizontal roll vortices, spotting, and fire whirls. Although relatively few fires exhibit extreme fire behavior characteristics, the fires that do are very important. They can cause problems with safety, control, and suppression effectiveness.

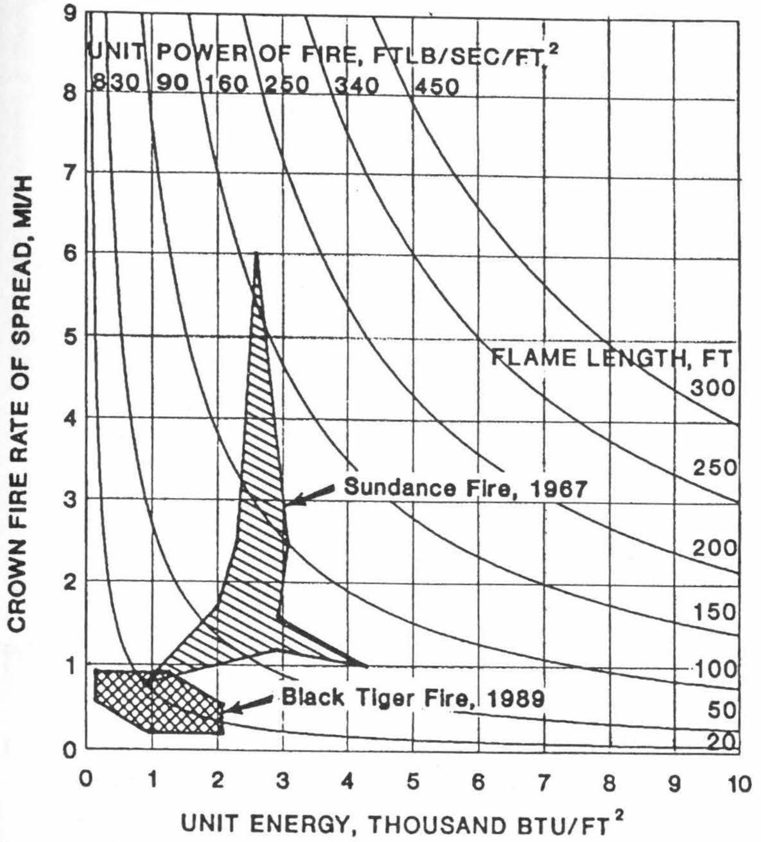


Figure 2.19. *Crown fire characteristics chart. Observed spread rate and intensity for the Sundance fire and Black Tiger fire, which are included as examples at the end of the chapter.* From Rothermel (1991c).

Crown Fire

A crown fire is one that spreads through the overstory. Crowning is one of the most spectacular fire behavior phenomenon that wildland fires exhibit. Crown fires are fast spreading and release a tremendous amount of heat energy in a relatively short period of time. Spread rates exceeding 7 mi/h and flame lengths over 150 ft have been recorded. When wind is strong and sustained, a running crown fire may continue and spread for several hours, burning out entire drainages and crossing mountain ridges that would normally be barriers. Rate of spread of running crown fires can vary widely as shown by the Sundance fire and the Mack Lake fire (Figure 2.20). Both of those fires are included with the examples at the end of this chapter.

Van Wagner (1977) describes three types of crown fires: dependent, active, and independent, according to whether fire in the tree crowns is dependent upon heat from the surface fire, spreading simultaneously with the surface

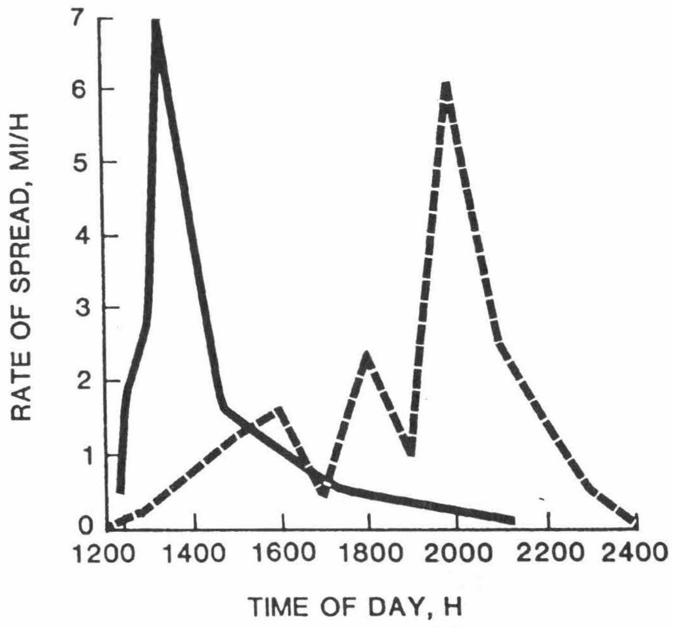


Figure 2.20. *Rate of spread for Sundance fire (dashed line) and Mack Lake fire (solid line).* From Rothermel (1991c).

fire, or spreading independently of fire in the surface fuels. Rothermel (1991c) further categorized fully developed crown fires as wind-driven fires or as fires dominated by their convection column, called plume-dominated fires. These two types of crown fire are based on Byram's (1959) analysis of the relationship between the power of the fire and the power of the wind.

The nature of the convection column is the most easily recognized feature for indicating the type of fire (Figure 2.21). If the power of the wind is greater than the power of the fire, a wind-driven fire will develop. Note that the wind velocity profile shows the wind velocity increasing with height. Consequently, the wind not only drives the fire, but bends the convection column sharply in the direction of the wind. A fire in which a strong convection column builds vertically above the fire is a characteristic of a plume-dominated fire. It is hypothesized that momentum feedback from the vertical velocity within the column causes turbulent indrafts which promote rapid combustion. The resulting increase in turbulence and fire intensity increases both convective and radiant heat transfer; accelerated fire spread is thus possible. This is a positive reinforcement process that can result in a towering convection column and spread rates that are unexpectedly fast for the wind conditions.

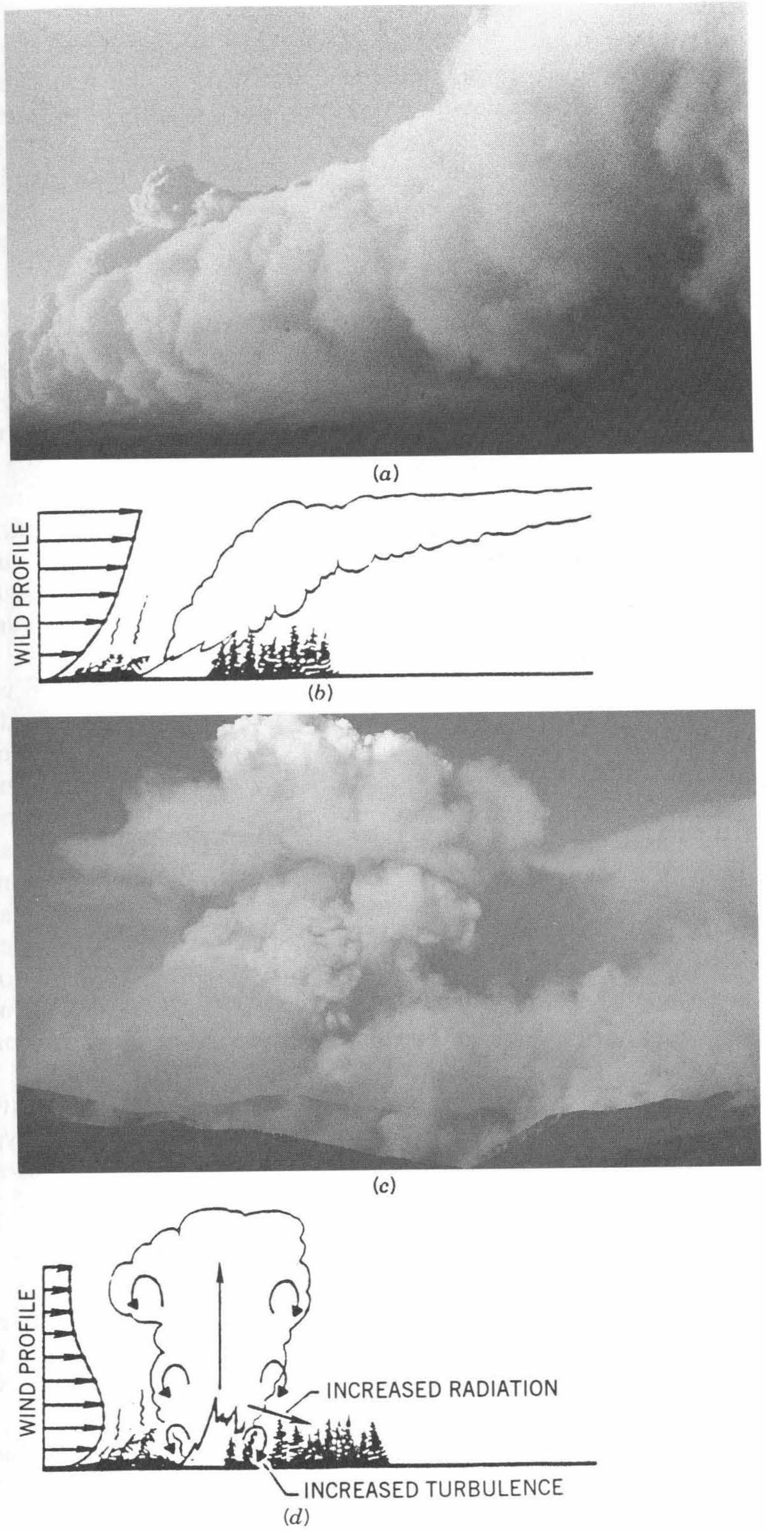


Figure 2.21. *Crown fires can be wind-driven or plume-dominated.* Diagrams from Rothermel (1991b). *Upper photo: Typical appearance of the convection plume above a wind-driven fire. Canyon Creek fire, 1988, Montana, grew from 57,000 to 247,000 acres in 16 hours. Lower photo: Typical appearance of the convection column above a plume-dominated fire (Silver fire in Southern Oregon, 1987).* From Rothermel (1991c).

A variation of plume-dominated fire behavior that can be extremely dangerous is one in which a downburst or microburst of wind blows outward near the ground from the bottom of the convection cell. For a short period, the fire is driven by wind. These winds can be very strong and can greatly accelerate a fire. Downburst conditions are initiated by evaporative cooling and precipitation that cools surrounding air, causing it to descend rapidly and spread horizontally at the ground level.

The transition from surface fire to crown fire marks a dramatic change in fire dynamics. Van Wagner (1977) proposed criteria for ignition and propagation of crown fires, depending on the fireline intensity of the surface fire and the distance between the base of the crown layer and the surface fuel layer. He defined the critical surface fire intensity for crowning in terms of the crown base height and the foliar moisture content.

Van Wagner also identified a condition to be satisfied if a crown fire is to propagate, relying on continuing ignition from below, afforded by the burning of surface fuels. This criteria comes from a parameter given by the product of spread rate and the global mass density of foliar fuel in the crown layer; it can be viewed as a lean flammability limit. In other words, the demise of a crown fire is predicted if it does not spread rapidly enough.

Beighley and Bishop (1990) list conditions favorable for a crown fire: dry fuels, low humidity and high temperatures, heavy accumulations of dead and downed litter, conifer reproduction and other ladder fuels, steep slope, strong winds, unstable atmosphere, continuous forest of conifer trees. Depending on the degree that these conditions are encountered, the intensity of a fire in surface fuels increases and flames reach into the crowns or climb ladder fuels into the crowns where the needle foliage will ignite and torching of one or more crowns occurs. Torching is the sudden involvement of the tree crown in flames from the base to the top in a few seconds. The flames may involve a single tree or a small group of trees. If conditions for sustained spread through the crowns are not favorable, the torching trees will quickly burn out, but in the process showers of firebrands can be produced that are lofted and can be spread by the wind.

A running crown fire can result when winds increase and the flames from torching trees are driven into adjacent trees. A running crown fire of any type is accompanied by showers of firebrands, fire whirls, smoke, and the rapid development of a strong convection column.

Horizontal Roll Vortices

Crown fires sometimes leave distinctive patterns of burned and unburned vegetation. For example, long strips, called streets, of conifer crowns with unburned (although usually scorched) needles are often seen in otherwise

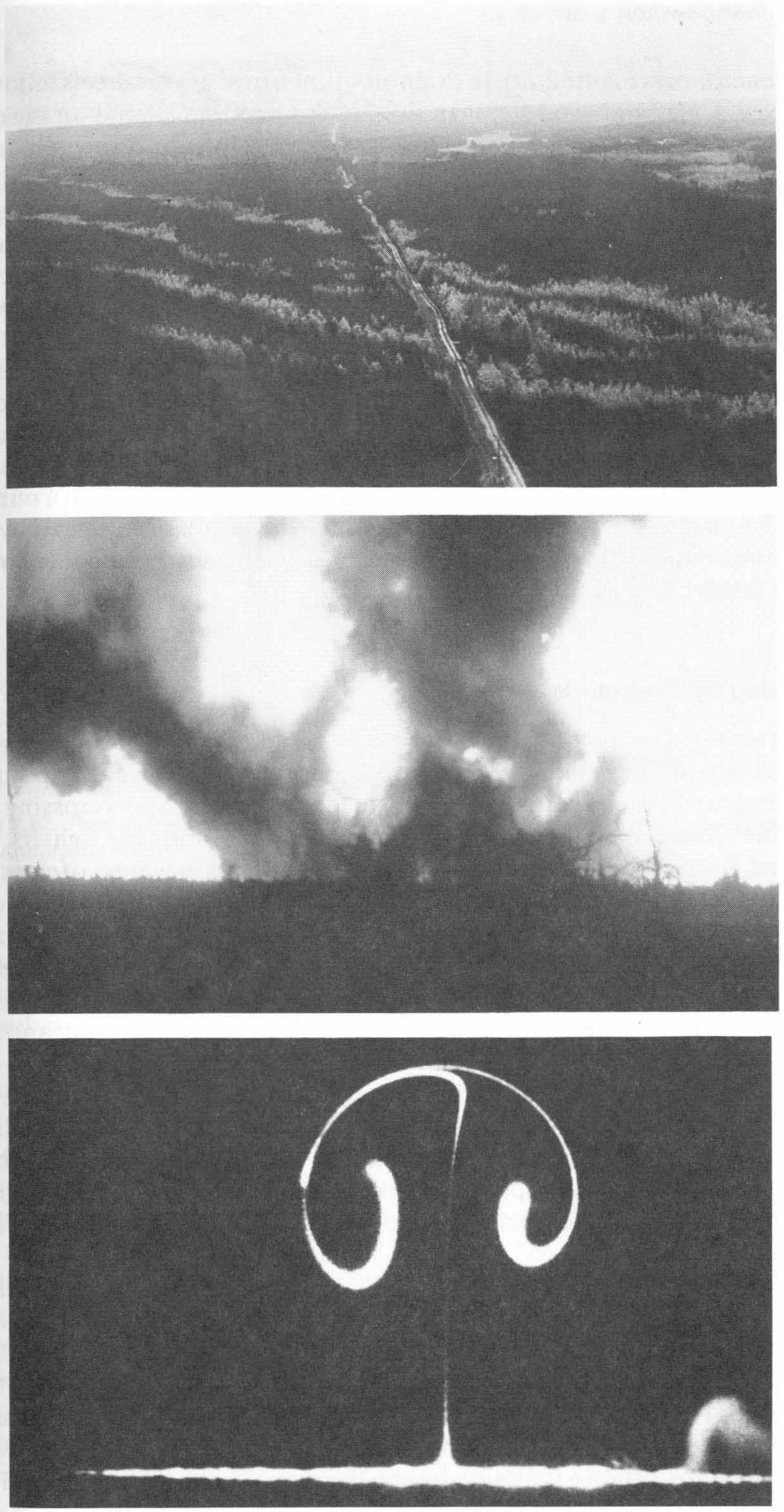


Figure 2.22. *Unburned tree crown streets on the Mack Lake fire. Smoke column split on the New Miner fire. Wind tunnel simulation.* From Haines (1987) and Haines and Smith (1983).

blackened areas (Figure 2.22). In examining unburned crown streets following one New Jersey and two Michigan fires, high scorch was found on the outer (opposite) sides of closely spaced tree trunks, with little or no scorch on the inner (facing) sides, indicating significant airflow outward from within all streets. Haines (1987) hypothesized that downward air movement caused by horizontal roll vortices formed these tree-crown streets and trunk-scorch patterns. He suggested that relatively cool air flowing downward from these vortices kept fire out of the crowns, and that as this air neared the ground, it spread out horizontally, in opposite directions from within the streets.

The hypothesis of the formation of tree-crown streets suggests that the action of a single vortex along the perimeter results in a single crown street. As the perimeter enlarges, that vortex dissipates and another vortex forms along the new perimeter, causing a second crown street. Continued formation and dissipation of vortices along the enlarging perimeter would result in a number of crown streets. Wind tunnel tests suggest chat downstream vortices may be a common boundary layer structure in wildfires where burning is concentrated along the fire's flanks.

Spotting by Firebrands

A fire is said to be spotting when firebrands, or pieces of burning material, are carried beyond the main perimeter and cause new starts, called spot fires. Spotting can be an important mechanism for fire growth. Spots crossing control lines hamper suppression efforts and sometimes trap fire fighters. Prescribed fires can escape their intended boundaries because of spotting. Spotting occurs over a wide range of distances. Under extreme conditions new fires can start miles in front of the main fire. On the other hand, short-range spotting may have little effect, because the main fire often overruns the spots before they can contribute to the spread. In black spruce in Alaska, spotting is a primary mechanism for fire growth and spread. Trees torch, spot, and start new surface fires which again cause the trees to torch and spot.

There are basically three aspects to the spotting issue: (1) the source of the firebrands—their type, size, and number; (2) the distance that firebrands are carried, the means of transport; (3) ignition of spot fires. There is a probabilistic question of how many spot fires there might be under certain conditions. This is difficult to predict because information on all three elements is needed but not available.

Many natural fuels make suitable firebrands: cone scales, grass clumps, bark flakes, parts of branchwood, and moss (Figure 2.23). One of the most effective firebrands is eucalyptus bark. The shaggy bark is easily lifted from the trees, and the curled shape gives it aerodynamic features that allow it to be carried for long distances. For a firebrand to be effective, it must continue to burn as it is transported and still be a viable heat source when it lands. Maximum spot fire distance is attained when the particle is nearly consumed just as it returns to the ground. Smaller particles would travel further but burn out before reaching the ground; larger ones could not travel so far.

Figure 2.23. *Possible firebrand material found on an airport runway near the Sundance fire.* From Anderson (1968).

Firebrands can be carried from surface fires, but they are more common from torching trees or from burning piles of debris. Spotting is an important factor in running crown fires. Firebrands are lifted by the convective buoyancy of the flaming zone. The convective updraft generated by the fire lofts particles upward where they become entrained in the ambient winds. They can also be lifted to the height where they are carried in the convection column. And firebrands can be carried by fire whirls, as described in the next section.

Albini (1979) developed a predictive model for the maximum distance between a source of firebrands—a burning tree or group of trees—and a potential spot fire (Figure 2.24). The model is an assemblage of six separate submodels, each for a distinct aspect of the overall process involved. The six submodels describe the following processes or phenomena: (1) the structure of a steady flame from the foliage of a tree or from a group of identical trees burning simultaneously that provides the initial lofting of a firebrand particle; (2)

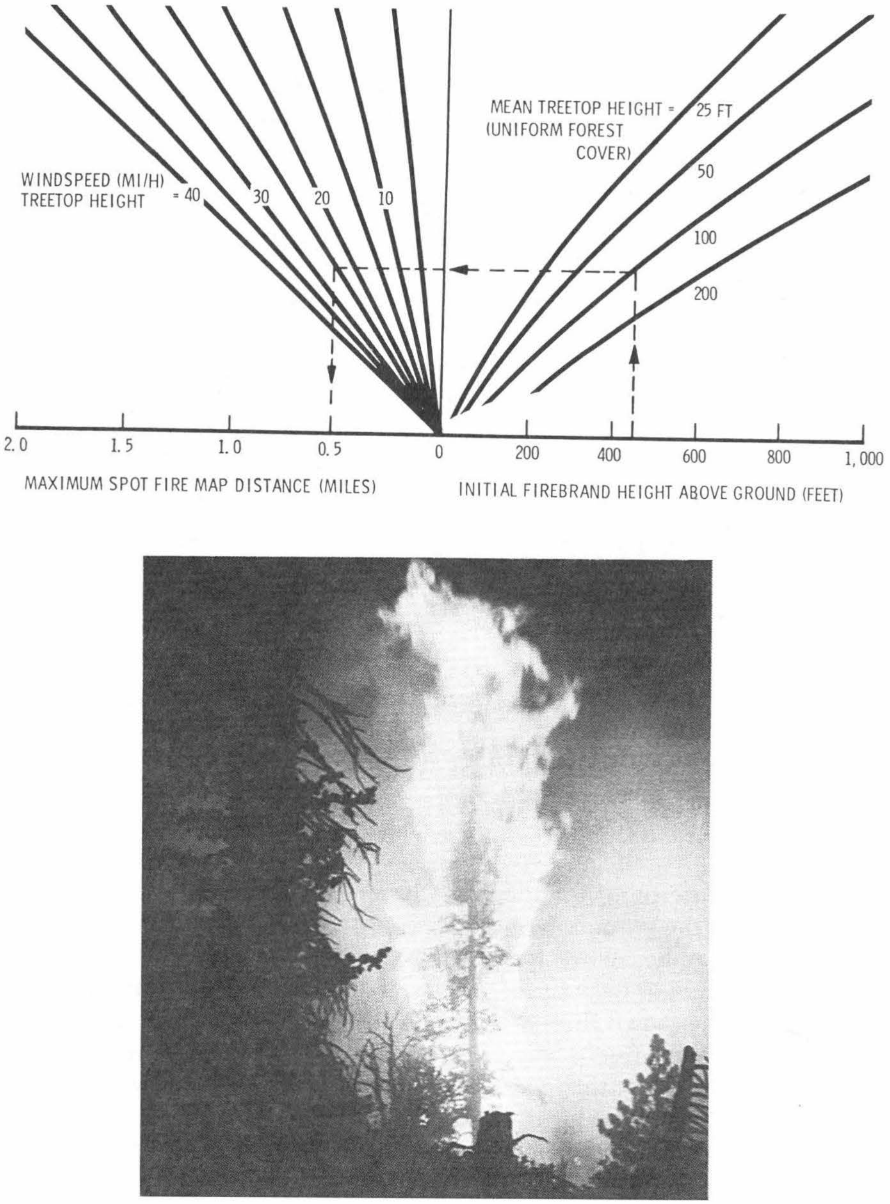


Figure 2.24. *Spotting distance nomogram and torching tree.* From Albini (1979). Photo courtesy of USDA Forest Service.

the structure of the steady, buoyant plume established by the flame that provides the lofting of the particle to its ultimate height; (3) the rate at which a woody particle burns as it moves through the atmosphere; (4) the trajectory of the firebrand in the steady flow field of the flame and the buoyant plume above it; height is predicted as a function of time; (5) the structure of the surface wind field over rough terrain—idealized as a sinusoidal elevation-versus-distance contour—that transports the firebrand from its maximum height above its burning tree origin to its downwind destination; and (6) the trajectory of a burning woody cylinder in a steady, but nonuniform, wind field.

Albini (1981) also extended the model to predict maximum spot fire distance from burning piles where there is a continuous steady flame from an isolated source such as burning piles of harvest debris or "jackpots" of heavy fuel. A further extension of the model (Albini 1983b) predicts maximum spot fire distance from wind-driven surface fires. A wind-driven fire in surface fuels without timber cover can give rise to significant spotting. Generally, the greater the intensity of the fire, the more severe the spotting problem it causes. Particles are lofted by strong thermals generated by the fire. Maximum viable firebrand height was shown to be proportional to the square root of the thermal strength, and the downwind drift distance during lofting proportional to the product of windspeed and the square root of the loft height. Once the maximum viable firebrand height is known, it can be used to predict the distance downwind that the particle will travel before it returns to the ground.

Fire Whirls

A fire whirl is technically a vortex, a gas mass with rotational motion (Figure 2.25). Fire whirls are an important element in safety and in wildfire and prescribed fire control considerations. They can be a major factor in causing spot fires beyond the fire area, by moving out of the area or by lifting and throwing firebands. Fire whirls vary greatly in size, strength, and duration. Most are small, but occasionally a large one of destructive size and force develops. They have been known to twist off trees more than 3 ft in diameter and to uproot and carry whole burning shrubs. Fire whirls can occur almost everywhere—on flat or mountainous terrain, in light or heavy fuel, and in stable or unstable atmosphere.

Fire whirls generally originate near the ground surface, like a dust devil; but they occasionally develop above the surface and then extend to the ground, like a tornado. Like a dust devil, fire whirl development depends on a supply of heated, buoyant air. Superheated air near the surface tends to rise in columns, which draw in more of the hot surface air. Some columns develop a strong rotational motion. The fact that some of the columns develop into fire whirls, whereas most do not, is probably due to mechanical action, such as friction with obstructions, starting the air rotation. Once started, the rotation is intensified by the upward-moving, buoyant air.

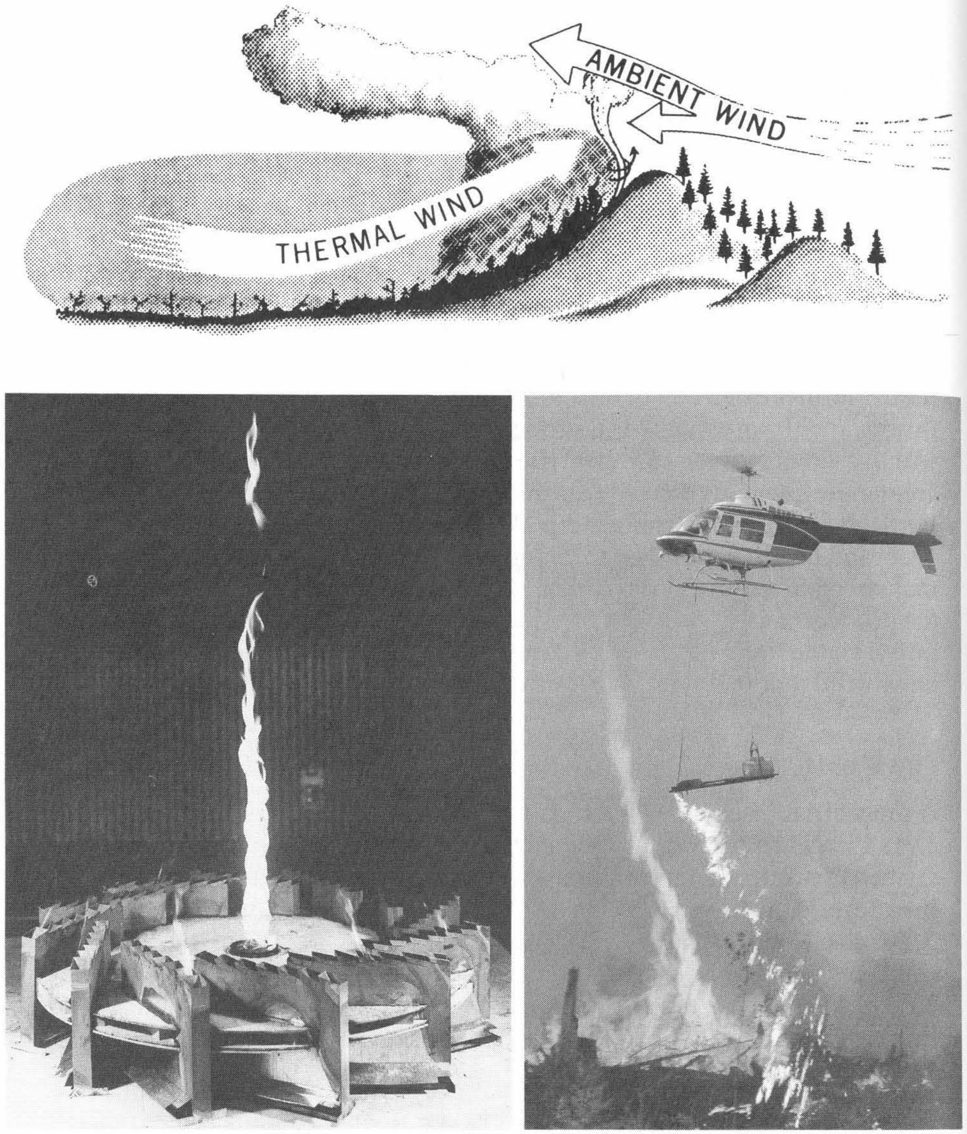


Figure 2.25. *Fire whirls. A common site for formation of firewhirls is on the leeward side of a ridge.* From Countryman (1971). Photographs courtesy of USDA Forest Service. Prescribed fire photograph by Colin C. Hardy.

The airflow pattern in and around a fire whirl can affect fire behavior. Moderately strong fire whirls about 50 ft in diameter have been observed to affect horizontal air flow up to 500 ft from the whirl itself. In the central core of a well-developed whirl, the air movement is likely to be downward. Adjacent to the core, however, is a strong updraft. Speed of the rotating air is greatest closest to the core, and decreases with the distance from the core. The rapidly moving air and effects of centrifugal force tend to prevent air from entering the vortex from the side. Most of the air must enter near the ground surface where the rotational flow is slowed by friction. Thus, a relatively thin layer of horizontally moving air flowing into the vortex from all sides is created.

The increase in combustion rate in a whirl is significant. In laboratory experiments with liquid fuels, the combustion rate increased to 5 to 6 times the rate in still air. The increased burning rate means increased fire intensity and more complete fuel consumption.

The high windspeeds in a whirl permit it to pick up burning debris, increasing the amount and extent of spotting. Because larger firebrands are picked up, they can burn longer and travel further before they burn out. Fire whirls can be stationary, but when they move out of the fire area they usually lose their active fire. They scatter their firebrands into unburned fuel a short distance ahead of the fire. The many resulting spot fires can create an intense fire front very quickly. A fire whirl can move at the speed of the prevailing wind speed. Ordinarily fire spread is much slower than the wind speed. Fast-moving fire whirls are more likely to occur on flat terrain, since they dissipate rather quickly on moving out of a fire in rough country.

Atmospheric instability is often favorable for development of fire whirls. In stable atmosphere, a parcel of air displaced vertically tends to return to its original level; in an unstable atmosphere it will tend to keep moving. Atmospheric instability encourages the strong updrafts that start fire whirls.

Fire whirls frequently appear where eddies in the airflow can be expected, either natural or generated by the fire. Thus, whirls can be expected on the lee side of obstructions, at sharp bends in canyons, and at the confluence of two or more canyons. They often develop on the lee side of a fire, particularly near the outside edges of the fire front. The most favorable situation for fire whirls is a fire burning on the lee side of a ridge. The heated air from the fire is sheltered from the general winds. Mechanical eddies that are produced as the wind blows across the ridge can serve as the triggering mechanism to initiate the whirl.

Fire whirls occur most frequently where heavy concentrations of fuels are burning and a large amount of heat is being generated in a small area. These are the conditions that can be present in prescribed fire where aerial ignition is used to ignite an area quickly.

2.5 PREDICTING FIRE BEHAVIOR

Fire behavior prediction is a combination of art and science. It is based on experience and on an understanding of the principles of fire behavior described in this chapter—the effect of topography, weather, and fuel, and recognition of conditions that lead to extreme fire behavior. Predictions can also be based on mathematical models that integrate important factors in a consistent way. Not all of the elements of fire behavior discussed in this chapter have been modeled, and it is not probable that that will ever be the case. Some aspects of fire behavior do, however, lend themselves to modeling.

Mathematical models are no substitute for experience, but they do provide a way to quantify fire behavior and to predict behavior based on analysis of the fire environment. An important feature of mathematical models is that they are repeatable—given the same input, they give the same answer. This is especially important in planning activities where alternative scenarios are examined. Model results can be compared to determine the effect of a change in wind, moisture, or fuel.

Fire behavior prediction is much more than use of a model to do the calculations. The process also includes determining the proper inputs for the calculations and interpreting the results for the application at hand. The spread and intensity models, for example, require windspeed as an input value. For an ongoing wildfire the value might be the wind measured on the fireline or it might come from a fire weather forecast. On the other hand, for prescribed fire planning, windspeeds for 0, 2, 4, and 6 mi/h might be used in determining the prescription; beyond a specific windspeed, the model might indicate that there would be control problems. After the fire behavior analyst on a wildfire does the calculations, the results are not communicated to decision-makers on the fire not in terms of numbers, but rather in general terms related to fire potential. Linking analytical calculations and experienced judgment is the key to fire behavior prediction.

Models and guidelines are often packaged into systems to aid decision-making. Systems take many forms (Figure 2.26), ranging from a simple cardboard meter designed for use by homeowners in assessing fire potential around their homes to a simulation model that uses sophisticated computers to simulate fire growth and behavior over uneven terrain, through variable fuel, under changing weather conditions. A system that has been widely used for prediction of fire behavior in the United States is called BEHAVE. It is a set of computer programs that includes models for spread, intensity, moisture, spotting, fire size, and so on (Figures 2.8 and 2.17 are examples taken from BEHAVE). The BEHAVE system also includes programs that help a person develop fire behavior fuel models for fuels that are not represented by one of the standard 13 fuel models.

As described by Rothermel (1991a), there are limitations to being able to predict fire behavior. Application of even expert talent and advanced prediction techniques was inadequate to the task of long-term fire growth prediction during the large fires of Yellowstone National Park in 1988. Limitations in long-range forecasting for local weather, significant precipitation, and especially wind, limit the prospects for success in predicting fire behavior more than a day or two into the future.

Fire behavior prediction is different from fire danger rating, which is reviewed in Chapter 4. The objective of fire behavior prediction is to estimate what a fire will do, while fire danger rating is a process for integrating and

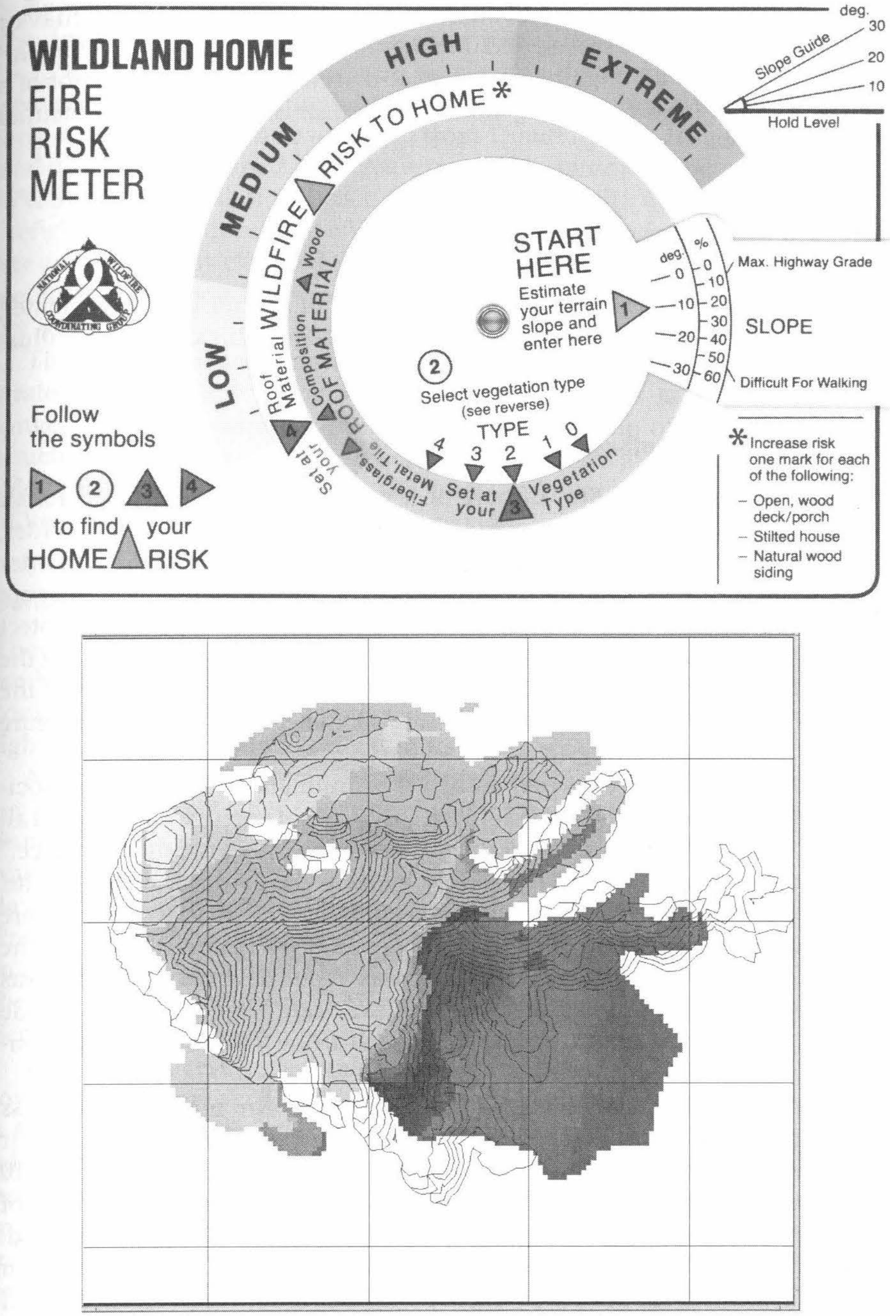


Figure 2.26. *Systems designed to aid decisionmaking take on many forms. Simple cardboard home risk meter (Simmerman and Fischer 1990). Fire spread patterns recorded for the Horizon prescribed natural fire at Yosemite National Park, California (shading), compared to daily perimeters predicted by the FARSITE simulation Finney and Andrews (1996).*

interpreting seasonal weather as an indicator of fire potential. Fire behavior prediction relates to the spread and intensity of a specific fire, whether for real-time prediction of an ongoing fire or what-if scenarios for the behavior of a hypothetical fire in the planning mode. Fire danger is a rating of fire potential for a large area.

2.6 SELECTED EXAMPLES

The following case studies offer brief synopses of several well-documented historical fires. Fire behavior principles discussed in this chapter are illustrated through examination of these fires.

Black Tiger Fire, Colorado, 1989

The Black Tiger fire is an example of a wildland/urban interface fire, an increasingly common occurrence. It started on 9 July 1989 near Boulder, Colorado. The final size was about 2100 acres. Within the first 5 to 6 hours after ignition, 44 homes and other structures were destroyed, and many others were damaged. More than 500 firefighters worked to contain the fire and protect homes. The distance from the point of origin to the northwest terminus of the fire at Sugerloaf Mountain is 2.5 miles. The spread rates and intensity of the Black Tiger fire were compared to those of the Sundance fire in Figure 2.19.

As stated in the case study prepared by the National Fire Protection Association (1989), "The conditions on Sunday, July 9 in that part of Colorado had all the elements in place for a dangerous fire, lacking only an ignition source." The fire was accidentally set, probably by a carelessly discarded cigarette. When first reported it was a small grass fire, about 40 × 10 ft. Residents were not successful in their attempts to extinguish it. Firefighters arrived on the scene 15 min after the first report; the fire was about 40 × 100 ft. The fire was crowning in another 4 min. The steep terrain and rate of spread upslope made a direct suppression attack on the fire's head from the point of origin impossible.

The principal vegetation across the Black Tiger fire area was tall grass under open ponderosa pine. Pockets of dense lodgepole pine and Douglas-fir were found on shaded slopes and along riparian zones. In the previous 10 years, the area had been ravaged by mountain pine beetles, leaving many of the pine trees dead and building up a thick carpet of needles on the ground. Dead and down fuels had been removed on some areas, but remained on others. The fire started in an area where ponderosa pine predominated. It then moved into an area of mixed conifers. Heavy forest litter buildup of dead trees, limbs, and brush in conjunction with low branches of live trees formed ladder fuels.

Rain had not fallen for at least 30 days during a period of high temperatures. The dry conditions were long term; snow pack the previous winter was only 25–75% of normal. Dry winds were blowing up the Black Tiger Gulch with greater force than usual. Firefighters estimated the upslope windspeeds in the early stages of the fire to have ranged from 15 and 25 mi/h. The slope over the total distance of the fire, 2.5 miles, averaged 23%, some parts being as much as 35%. Spotting ahead of the main fire front diluted the number of available firefighters and reduced the effectiveness of firelines, roads, and other fuel-free areas normally expected to help slow or stop a spreading wildfire. Aerial reconnaissance found burning roofs a quarter-mile or more ahead of the main fire front.

This fire, which soon outran the fire defenses in difficult terrain, demonstrated the predictable effects of a combination of factors: lack of rainfall, prolonged heat spell, wind, sloping topography, buildup of forest fuels, construction factors affecting the susceptibility of homes to fire, use of combustible construction materials, poor site access for emergency vehicles, and lack of home site maintenance for fire protection.

Sundance Fire, Idaho, 1967

The Sundance fire made a dramatic run of 16 miles and 50,000 acres on 1 September 1967. The fire occurred in Northern Idaho and spread through mixed conifer stands interspersed with logged areas. It took the lives of two firefighters (tractor operators) caught in its path.

As documented by Anderson (1968), the fire resulted from a lightning storm on 11 August. Four other fires from that storm were extinguished before the Sundance fire was discovered on 23 August. By the next day the Sundance fire was contained at 35 acres. Suppression activities continued for the next five days. Late in the evening of 29 August, it was reported to have jumped the line. Prevailing northeast winds and normal nighttime downslope winds resulted in a wind-driven fire moving downslope, with spotting up to $\frac{1}{2}$ mile ahead of the fire. By the morning of 30 August it was 2000 acres; it was 4000 acres on 1 September when it began its run.

The run was a result of a combination of dry fuels from a sustained drought, low humidities for over 72 h, increasing winds sustained for a period of 9 h, and a 4-mile active fire front existing on the morning of 1 September. The fire advanced 16 miles in 9 h (1400–2300) and created spot fires 10 to 12 miles northeast of the place of origin (Figure 2.27). Spotting activity increased during the day, reaching a maximum intensity during the period of highest winds in the late afternoon. Whereas spot fires early in the day contributed to the fire spread, late in the day a multitude of spot fires created fuel voids leading to the breakdown of the main front and contributing to the fire's termination. Other factors influencing the decreasing rate of spread were increasing humidity and decreasing wind after 2200, the downslope direction of burning, and to

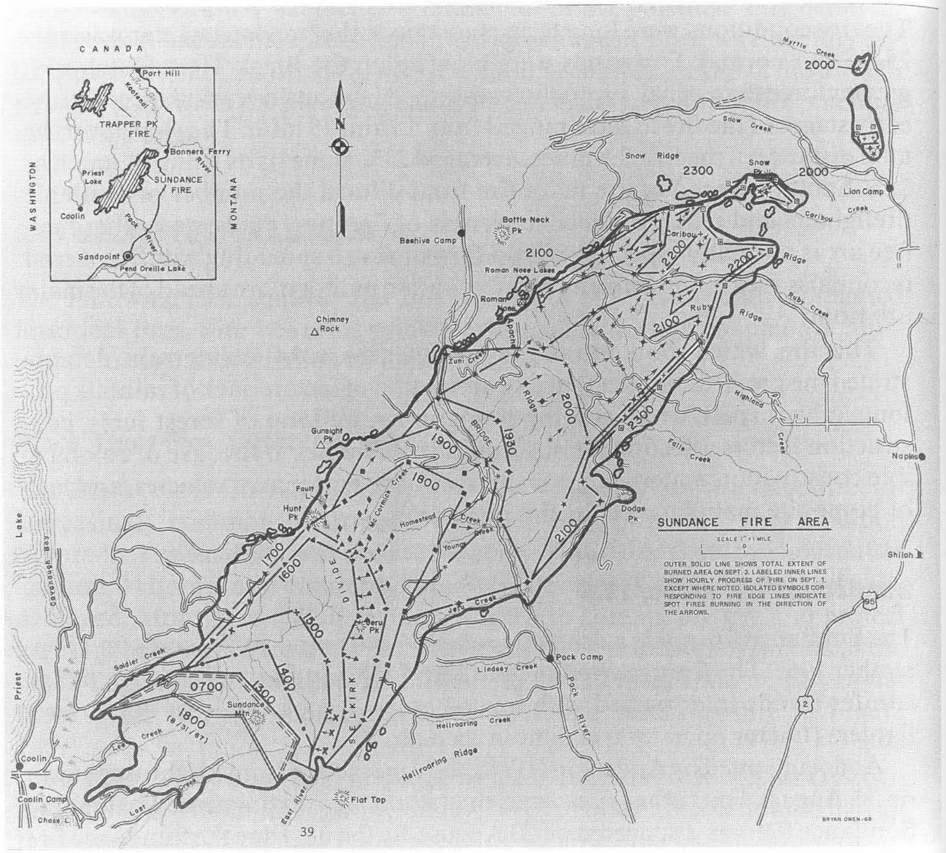


Figure 2.27. *Sundance fire area.* From Anderson (1968).

some degree the disruption of fuel continuity due to prior logging activities in the area.

The average rate of spread ranged from 1 to 6 mi/h, with brief periods having higher or lower values. The fire intensity built up to 22,500 Btu/ft·s and was releasing nearly 500 million Btu/s. A convection column rose to 35,000 ft. Extensive firebrand activity and debris were transported from the fire (see Figure 2.23). The brands were either lifted as high as 18,000 ft and transported by the wind or carried in vortices produced by the wind blowing around the convection column. Fire-induced winds that caused extensive blowdown could have been greater than 95 mi/h.

The spread rates and intensity of the Sundance Fire were compared to those of the Black Tiger fire in Figure 2.19. The rates of spread for the Sundance Fire were compared to those of the Mack Lake fire in Figure 2.20.

Air Force Bomb Range Fire, North Carolina, 1971

The Air Force Bomb Range fire burned in pocosins and marshlands along the coastal plain of eastern North Carolina and was documented by Wade and Ward (1973). The fire began on the morning of 22 March 1971, from a practice bomb on an Air Force range (an interesting example of ignition source). More than 23,000 acres of the 29,300 acre total burned during two major runs within the first 20 hours.

While topography was a major factor in both the Black Tiger fire and the Sundance fire, the Air Force Bomb Range fire occurred on virtually flat terrain. The fuel type was mainly evergreen pocosin shrubs, whose foliage and stems reach a minimum annual moisture content between 70 and 100% immediately prior to the initiation of new growth, usually in early April. Some of the area had been sprayed with herbicides two years before. A prescribed burn that followed was low intensity and did not cover much of the area. Thus, most of the desiccated shrubs on these quadrants were still standing. Grass on the area was also very flammable because it was still in the cured stage.

Because of the dry fuel and 20-mi/h winds, the fire was beyond control before the standby crew stationed on the range reached it. The fire crowned through more than 15,000 acres of pond pine during the next 20 h. The initial 14-mile run produced a narrow elongated shape pushed by high winds. Rates of spread averaged over 2 mi/h for 4 h and was near 5 mi/h during a 1-h period. Unburned tree crown streets can be seen in Figure 2.28. The fire eventually ran out of dry fuel after traveling 14 miles in about 7 hours.

The flanks remained active throughout the night of the 22nd until a cold front passed over the area before dawn on the 23rd. Passage of a dry cold front early the next morning resulted in a 6-mile run perpendicular to the first. This second run terminated because of wet fuel. A high water table prevented the consumption of large quantities of organic soils, but because the damp peat would not support the usual tractor-plow units, final control of the fire was not achieved until over an inch of rain and snow fell on the area.

Mack Lake Fire, Michigan 1980

The Mack Lake fire was an escaped prescribed fire. The prescribed fire was ignited in jack pane logging slash the morning of 5 May 1980 in the Huron National Forest. The purpose of the burn was to remove logging debris in preparation for replanting jack pine. The ultimate objective was habitat improvement. Within 2 hours the fire had spotted across the control line and was declared a wildfire. Within 10 more hours, and most of that confined to 6 peak hours of burning, the fire had burned 24,000 acres and released energy on the order of 3 trillion Btu's, as much as 90 thunderstorms or 9 times the energy released by the Hiroshima atomic bomb. In the process one firefighter (a tractor-plow operator) died and fire swept through the town of Mack Lake, destroying 44 residences. The fire was documented by Simard and others (1983).

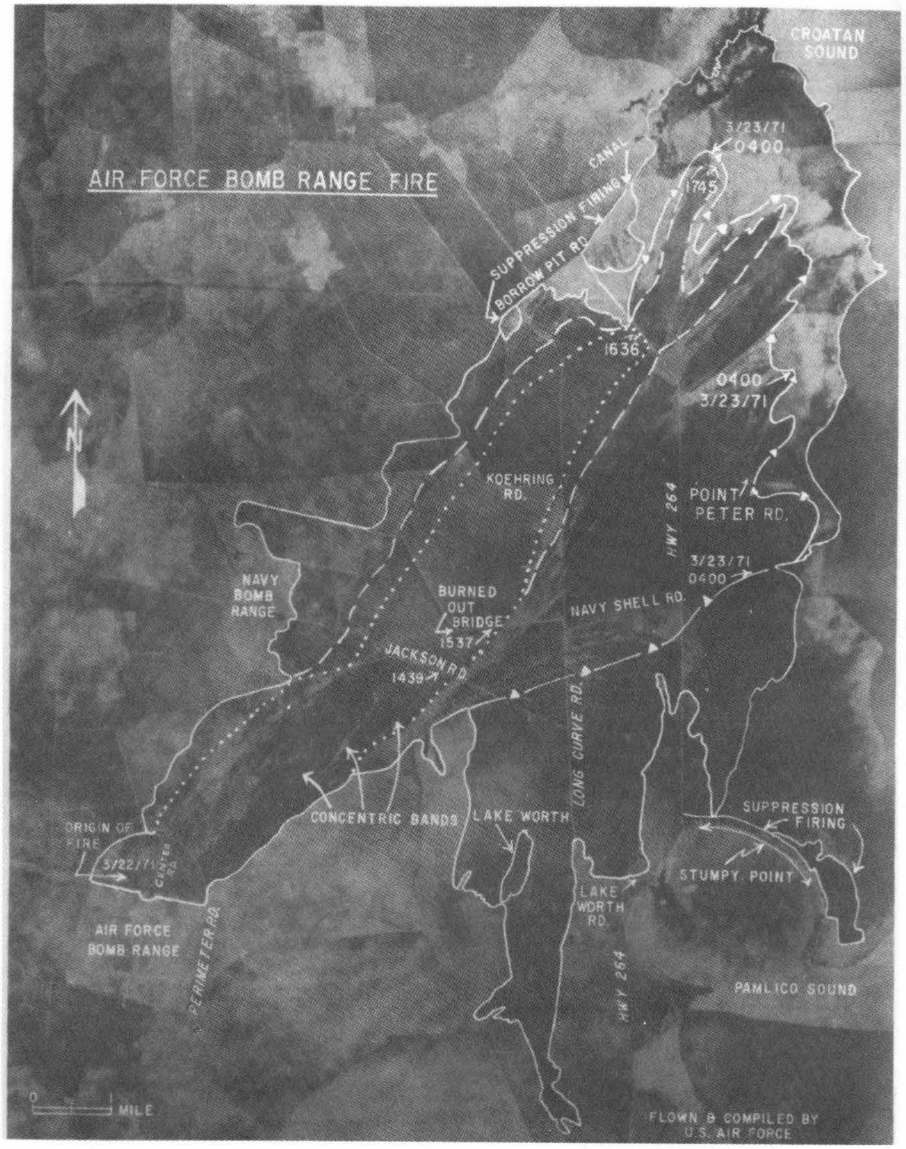


Figure 2.28. *Airforce Bomb Range fire area.* From Wade and Ward (1973).

No unusual fire activity was noted for the first 45 min. The piled slash burned vigorously, with flame lengths of 10 to 15 ft, but flame lengths between the piles were only 6 to 12 inches. Although some spot fires crossed the control line, they were easily contained and firing resumed. Then the fire spotted into standing jack pine timber adjacent to and upslope of the fire area. The area was more exposed to the wind and had heavier fuel loadings, resulting in a much higher rate of spread than experienced in the prescribed burn. Other spots occurred across the highway. An increase in windspeed was noted at this time. The fire began crowning 100 ft after it entered an extensive sapling-sized jack pine stand.

In the first 3.5 h, during which the fire advanced 7.5 miles, no amount of fireline or road width held or even slowed the fire. After the fire had advanced 4 miles, the passage of a dry cold front turned the southwest flank into a head fire. Aided by the change in fuels and ameliorating burning conditions, suppression crews contained the fire by constructing 35 miles of fireline just 30 h after it started.

Drought was not a factor in this fire. The fire occurred 6 days after 0.5 inch of rain fell, and only a slight precipitation deficit was recorded during the 4 months preceding the fire. Several conditions contributed to the escape of the prescribed fire: spotting from slash piles, irregular groups of uncut trees adjacent to the prescribed fire area, location of control lines near the top of a 25% slope, high windspeeds (15+ mi/h), low relative humidity (21%), and low fine fuel moisture (7%).

During its major run the fire traveled 7.5 miles in 3.5 h, with an average forward rate of spread of 2.1 mi/h. Surges occurred, with velocities of 6–8 mi/h. Fireline intensity for this period averaged 9300 Btu/ft · s. During the wind shift associated with frontal passage, the southern flank spread more vigorously, developing several small heads. With completion of the frontal passage, the onset of poorer evening burning conditions, and the exhaustion of jack pine fuels, the fire eventually expired. The increase in final size from the size attained during the major run was negligible.

Horizontal roll vortices may account for the residual burn pattern of unburned strips and burned bands in the crown fuels (see Figure 2.22).

Greater Yellowstone Area Fires, Wyoming and Montana, 1988

In the summer of 1988, Yellowstone National Park and adjoining areas within the National Forests, commonly referred to as the Greater Yellowstone Area (GYA), experienced the most extensive forest fires seen in the Western states since the great Northwest fires of 1910. Initially, some of the fires within Yellowstone Park were allowed to burn as prescribed natural fires, as provided in the Park's fire management plan. But when early summer rains did not materialize, the threat of drought necessitated that fire suppression measures be undertaken. By 24 July all the prescribed natural fires had been declared wildfires.

A total of 249 fires occurred in the GYA in 1988, about twice the average for the area. Thirty-one of those fires were initially classified as prescribed natural fires, 28 of these in Yellowstone National Park. Twelve of the 28 fires burned out at less than 1 acre; the remaining 16 later were declared wildfires and grew to large size despite intensive suppression efforts. Of the 249 fires in the GYA, 210 were suppressed at less than 10 acres. The North Fork fire was started on July 22 just outside the western boundary of the park by a woodcutter on the

Targee National Forest. It became the GYA's largest fire, burning 531,182 acres by the end of the burning season. During the 5-day period from 6 through 10 September, the total size of the GYA fires increased by 614,618 acres (Figure 2.29). The area encompassed by the final perimeter of the fires was about 1.7 million acres. Within the Park, the actual burn area was about 65% of the perimeter area after accounting for irregular fire perimeter and islands of unburned fuel (See Figure 2.11).

Despain (1990) had categorized the predominately lodgepole pine forest into five types based on age, growth, and decay of the forest. These ranged from recently burned stands containing seedlings and young trees to decadent stands of 300- to 500-year-old trees, many of which had fallen to the ground to produce extremely high concentrations of dead surface fuel interspersed with alpine fir regeneraton.

The size of the fires and length of exposed fireline contributed to the control problem. A young lodgepole pine forest does not have extensive litter on the ground; thus surface fire will usually not reach the tree crowns. But when the fire perimeter becomes large enough to include several fuel types, there is a high probability of a flare-up somewhere along the fire line, thereby initiating crowning. The dry conditions and presence of beetle-killed trees heightened the probability of fire moving into the crowns. There were several other reasons for the phenomenal fire growth of the Yellowstone fires. The continued drought was a major factor, not just because fires spread faster in dry fuels, but because it made fire suppression difficult, and on some fires, virtually impossible. Burning embers were lofted across fire control lines, highways, and rivers, descending on easily ignited fuels almost everywhere they fell.

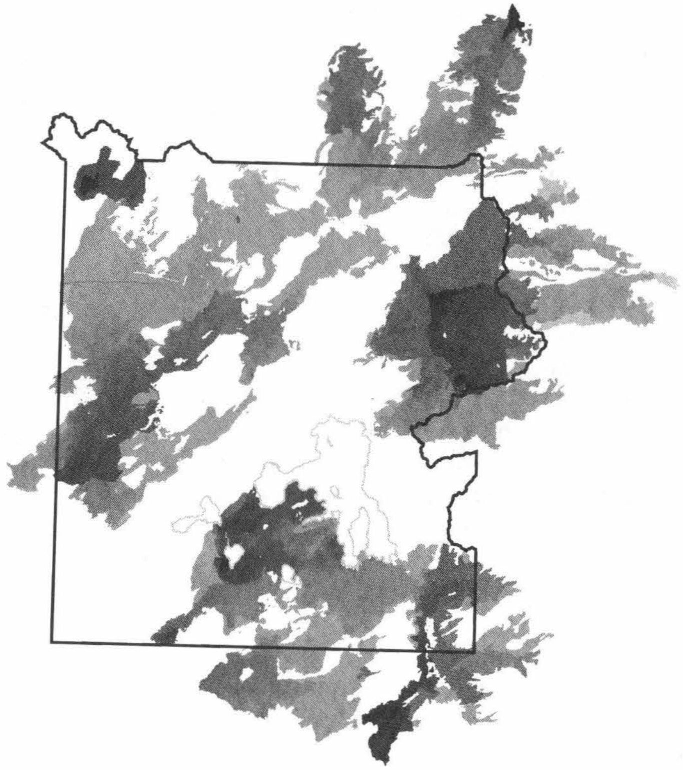


Figure 2.29. Greater Yellowstone Area fire map, 1988. Fire progression is shaded from black to light gray by date from 30 June to 1 October 1988. Based on Rothermel, Hartford, and Chase (1994).

As the season progressed, the increase in fire activity was dramatic. In early August the fires were averaging about 1 mile of spread per day, by late August about 3 miles a day, and in September strong winds caused runs of 7–14 miles a day. By the middle of August, daily burn times increased significantly as the fires burned into the night. On 10 September the weather changed and slowed the fires; humidity rose, rain began, and snow capped the higher peaks.

FURTHER READING

Rothermel describes methods and examples of fire behavior prediction in "How to Predict the Spread and Intensity of Forest and Range Fires" (1983) and "Predicting the Behavior and Size of Crown Fires in the Northern Rocky Mountains" (1991c). Andrews (1986) and Andrews and Chase (1989), in describing the BEHAVE fire behavior prediction system, give an overview of fire behavior and associated models, including assumptions and limitations of the models, example calculations, and technical references. The Forestry Canada Fire Danger Group (1992) describes the Canadian system in "Development and Structure of the Canadian Forest Fire Behavior Prediction System". Albini discusses fire behavior modeling in "Wildland Fires" (1984) and in "Dynamics and Modeling of Vegetation Fires: Observations" (1992). The U.S. National Wildfire Coordinating Group (NWCG) training courses (1993, 1994) developed by many people in the wildland fire community describe all aspects of fire behavior from an introduction to advanced calculations.

3

Wildland Fuels

Fuel is a critical leg in both of the fire triangles: fuel, oxygen, and heat of the fire fundamentals triangle (Figure 1.2) and fuel, topography, and weather of the fire environment triangle (Figure 2.2). Fuel doesn't cause fire, but it certainly changes the character of a fire, affecting the ease of ignition as well as fire size and intensity. Understanding fuel is important to all aspects of wildland fire, including fire suppression, fuel management, smoke management, wildland/urban interface, forest health and ecosystem management, and global climate change.

An examination of fuel depends on the scale under consideration: fire fundamentals, fire behavior, landscape, or global scale (Figure 1.1). When looking at fire on the fire fundamentals scale in Chapter 1, we examined the intrinsic fuel properties and their role in the combustion process. Intrinsic properties are the chemical and physical properties that define the fuel elements. As we move to the fire behavior scale, we look at the whole fuel complex—ground, surface, and crown fuels—and descriptors such as arrangement, size, and live-to-dead ratio. At the landscape level, we consider relationships among fuel complexes on the terrain and their size and location. This includes the wildland/urban interface, for example. The view of fuel for

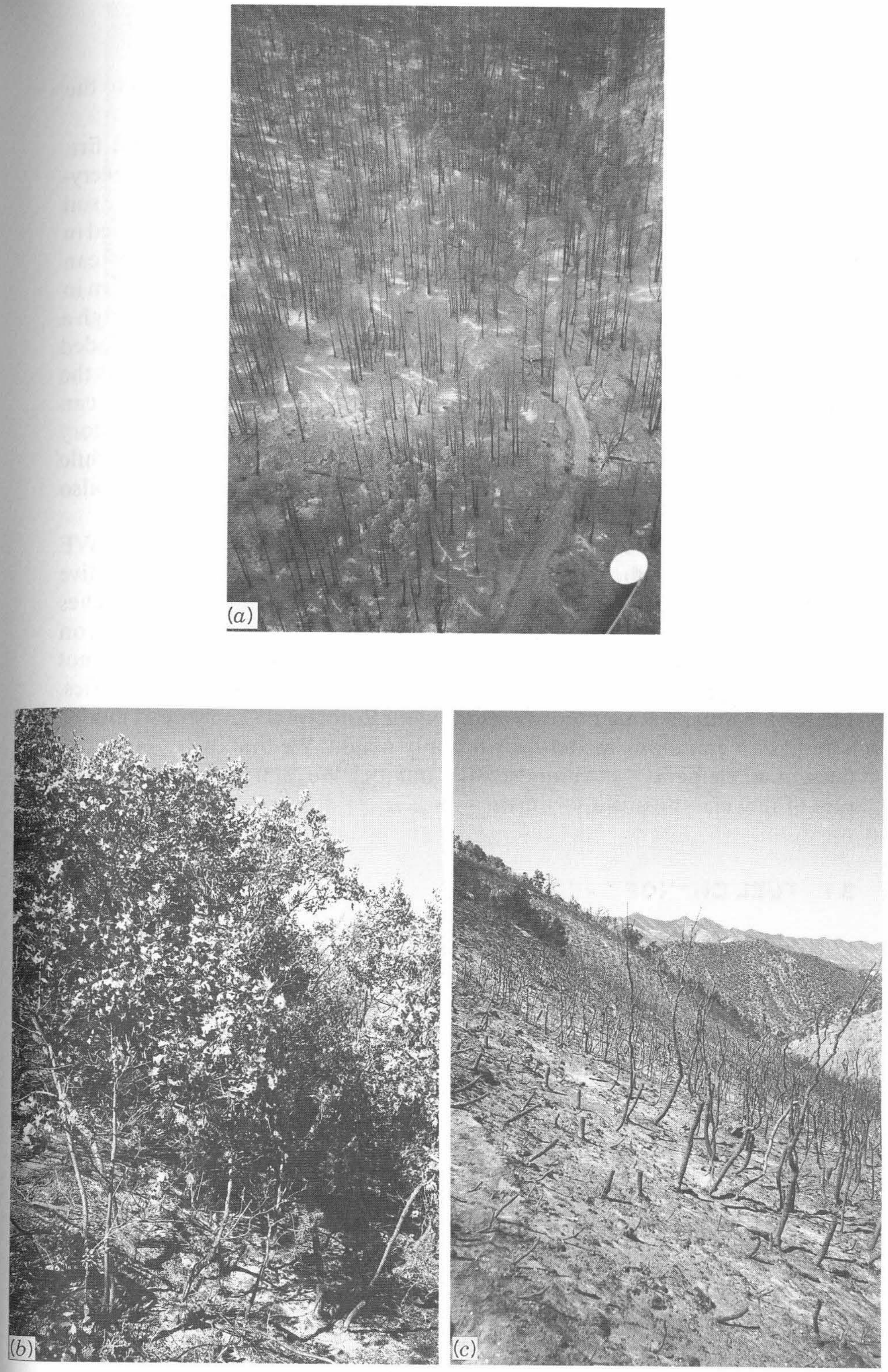


Figure 3.1. *Total fuel load is all of the vegetative material above mineral soil. Available fuel is a portion of that value depending on environmental conditions. (a) Under very dry conditions nearly all of the surface fuel is consumed. A line of ashes is all that remains of logs after the Dude fire in Arizona (26 June 1990).* Photo by Patricia L. Andrews, USDA Forest Service. *(b) An underburn through the litter dried the Gambles oak on the South Canyon fire.* From USDA/USDI (1994). *(c) Gambles oak remaining at the fatality site of the South Canyon fire, Colorado, 1994.* From USDA/USDI (1994).

this chapter is mostly at the fire behavior scale, with some references to the landscape level.

Wildland fuel is the vegetative material that burns in a wildland fire. Several more specific definitions must be considered. *Biomass* includes everything—all vegetative and animal material including the roots deep in the soil (although the term is sometimes used to describe the portion that is involved in wildland fire). *Phytobiomass* is the plant material above mineral soil, and can be considered *total fuel*. *Potential fuel* is the material on a site that might burn in a most intense fire, a value that is generally less than the total fuel. Although a fire doesn't consume the entire bole of living trees, that component is included as part of the total fuel; it is not included as potential fuel. *Available fuel* is the fuel that is available for combustion in a given fire (Figure 3.1). The value can vary widely for a site, depending on environmental conditions. An understory burn might consume only part of the grass, litter, and shrubs on one day, while on another day with more favorable burning conditions the fire might also involve the overstory and the duff.

The meaning of the term "fuel" varies with the application. The BEHAVE fire behavior prediction system, for example, refers to fuel as surface fuel, live components less than $\frac{1}{4}$ inch in diameter and dead components up to 3 inches in diameter (not ground or crown fuel; not logs). Logging slash inventories, on the other hand, are concerned with dead woody surface fuel (not live fuel; not herbaceous plants, shrubs, or leaf litter). Quantification of fuel also varies. Fuel depth and packing ratio are required for Rothermel's fire spread model, whereas an emissions model requires only weight. We first discuss descriptions of all elements that compose wildland fuel. We then give several examples of fuel classification schemes.

3.1 FUEL CHANGE OVER TIME

Fuel can be described in terms of fuel type and fuel state. *Fuel type* is a description of the fuel itself, while *fuel state* is dependent on changing environmental conditions. Fuel state is related to moisture content.

Fuel, like everything in nature, is not static. It changes over time—from hourly change in the moisture content of dead twigs to successional changes that occur over decades. A discussion of the way that fuel changes over time provides a framework for discussion of both fuel type and fuel state. Fuel

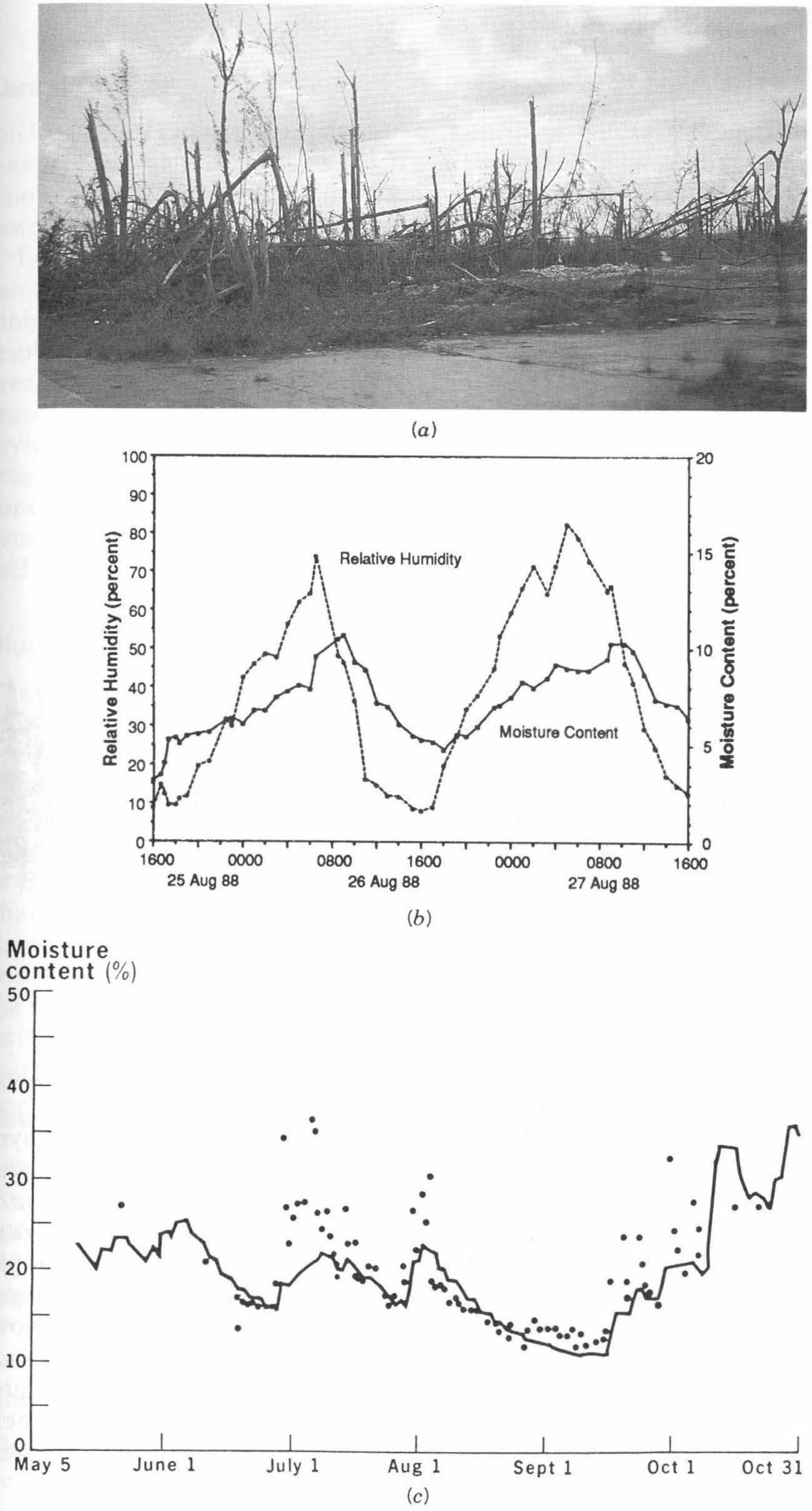


Figure 3.2. *Fuel changes occur at various time scales: abrupt, diurnal, seasonal, annual, and successional. (a)* Abrupt *changes in fuel arrangement caused by Hurricane Hugo, North Carolina, 1989.* Photo by Ron Coats, USDA Forest Service. *(b)* Diurnal *variations of fine dead fuel moisture and relative humidity during the fires in Yellowstone National Park, 1988.* From Hartford and Rothermel (1991). *(c)* Seasonal *variation in the moisture of large logs at Priest River Experimental Forest.* From Fosberg and others (1981). *(d)* Annual *change of small fuel loadings versus thinning slash age and basal area cut as a function of slash age.* From Carlton and Pickford (1982). *(e)* Successional *change after fire.* Carol Evans, USDA Forest Service.

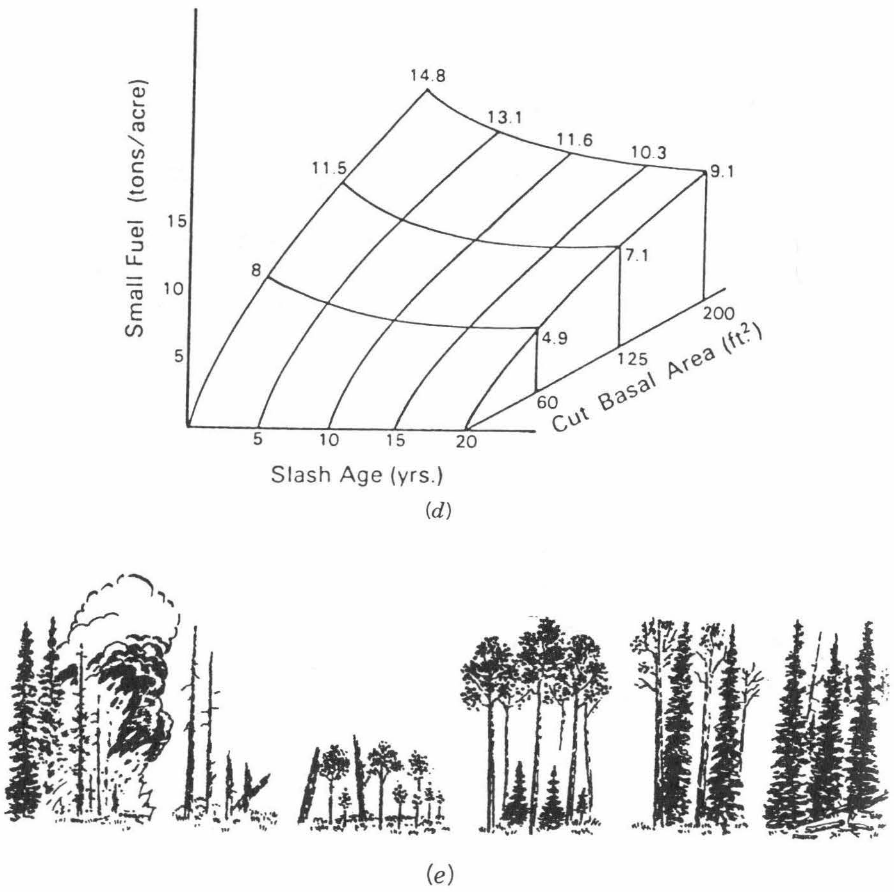


Figure 3.2. (Continued)

change can be caused by (1) *disturbance*, both human and natural, such as logging, construction of roads and structures, hurricanes, fire, insect, and disease; (2) *weather*, including diurnal changes in air temperature and humidity, synoptic weather changes, and seasonal change; and (3) *biological/physiological cycles*, such as greenup and curing, leaf drop, decay, and plant succession.

We consider fuel change over five time scales (Figure 3.2): (1) *Abrupt* changes due to a disturbance result in changes in fuel type. Frost is an example of an abrupt change that results in a change in fuel state. (2) *Diurnal* changes occur on an hourly timeframe. As temperature and humidity vary throughout the 24-h cycle, so does fine dead fuel moisture (state change). (3) *Seasonal* changes occur on a monthly scale and can be changes in both type and state. (4) *Annual* changes in fuel are changes in fuel type from one year to another. (5) *Successional* changes occur over very long time periods, decades or even hundreds of years.

Abrupt Change

Fuel type can change abruptly due to human or natural causes. Human management actions such as logging or chaining cause a change in the amount and arrangement of the fuel. Similarly, natural forces such as fire or wind cause abrupt change in fuel type (Figure 3.2a).

Fuel state can change abruptly as a result of frost. The foliage may look the same, remaining green immediately after a frost, but there can be a dramatic moisture change, greatly affecting fire behavior. A similar dangerous situation results from an abrupt change in moisture when a fire has burned through an area, drying fuels that are not involved in the fire. The fire burns through the grass and litter, drying the brush (see Figure 3.1c) or through the surface fuels drying the overstory. A change in wind direction can result in a reburn of the area, this time through another fuel layer. This is a dramatic example of the concept of "available fuel." Part of the fuel was available the first time, but because of a change in wind and in the moisture of the dried fuel, more of the fuel complex becomes available, sometimes with disastrous results.

Diurnal Change

The moisture content of fine dead fuel changes throughout the day in response to weather changes, such as temperature, relative humidity, and solar radiation. Figure 3.2b shows the diurnal cycle of fine dead fuel moisture and relative humidity for two days during the fires in Yellowstone National Park in 1988. The fuel moisture remained low at night, allowing the fires to burn vigorously.

Because fine dead fuels have such an influence on fire spread, hourly changes in that fuel component are important. It is possible to estimate the times of day when fire will be most active—generally increasing midafternoon and decreasing at night. If fine dead moisture remains low (dry) at night the fire may continue active burning. This information is also used in timing prescribed fire ignition.

Seasonal Change

Fuels change throughout the year due to cumulative effects of weather and to normal biophysiological cycles. The greenup and curing of live vegetation, deciduous leaf drop, and changes in moisture of logs and duff occur on a monthly scale. Some seasonal changes are in fuel type, others in fuel state. Leaf drop changes the fuel type; changes in moisture of logs and duff and greenup and curing are changes in state (Figure 3.2c).

Annual Change

The fuel complex changes from year to year due to vegetation growth and decay as well as buildup and decay of dead vegetation. Yearly changes in the southeastern United States in the palmetto-galberry type are discussed in a selected example at the end of the chapter. Changes in ponderosa pine fuel beds after thinning from one drainage on the eastern side of the Cascade Range in Washington State have been described mathematically by Carlton and Pickford (1982) as a function of slash age (time since logging) and basal area of trees removed (Figure 3.2d). The functional relationship can be used to estimate fuel change over time as an assessment of potential fire hazard after logging.

Successional Change

Fuel also changes on a much longer time frame, by tens and hundreds of years. Vegetation changes type over long periods of time through successional changes, from grass to brush to timber. Patterns are changed as a result of human intervention, such as fire suppression (Figure 3.2e).

3.2 FUEL DESCRIPTION

To describe fuel type, we start by examining those physical *properties* that affect the way the material burns. Properties include quantity, size, compactness, and arrangement. We then look at fuel *components*, which are related to the way that vegetation grows. Components may be specified as ground, surface, and crown fuel as well as grass, litter, brush, or overstory. We then move to fuel *complexes*, which are associations of components. Examples are sagebrush/grass and timber with grass and litter understory.

Properties

Intrinsic fuel properties (heat content, chemical content, etc.) were discussed in Chapter 1. Here we discuss extrinsic properties. The intrinsic properties of standing dead grass do not change when the grass is mowed. But the behavior of a fire through that fuel is different due to the arrangement of the fuel particles, an extrinsic property. Similarly, the intrinsic properties of a log don't change when it is split into kindling, but the wood burns quite differently due to a change in the surface-area-to-volume ratio.

Quantity Fuel loading is the ovendry weight of fuels in a given area, often expressed in tons/acre or lb/ft^2. Expressing loading on an ovendry basis

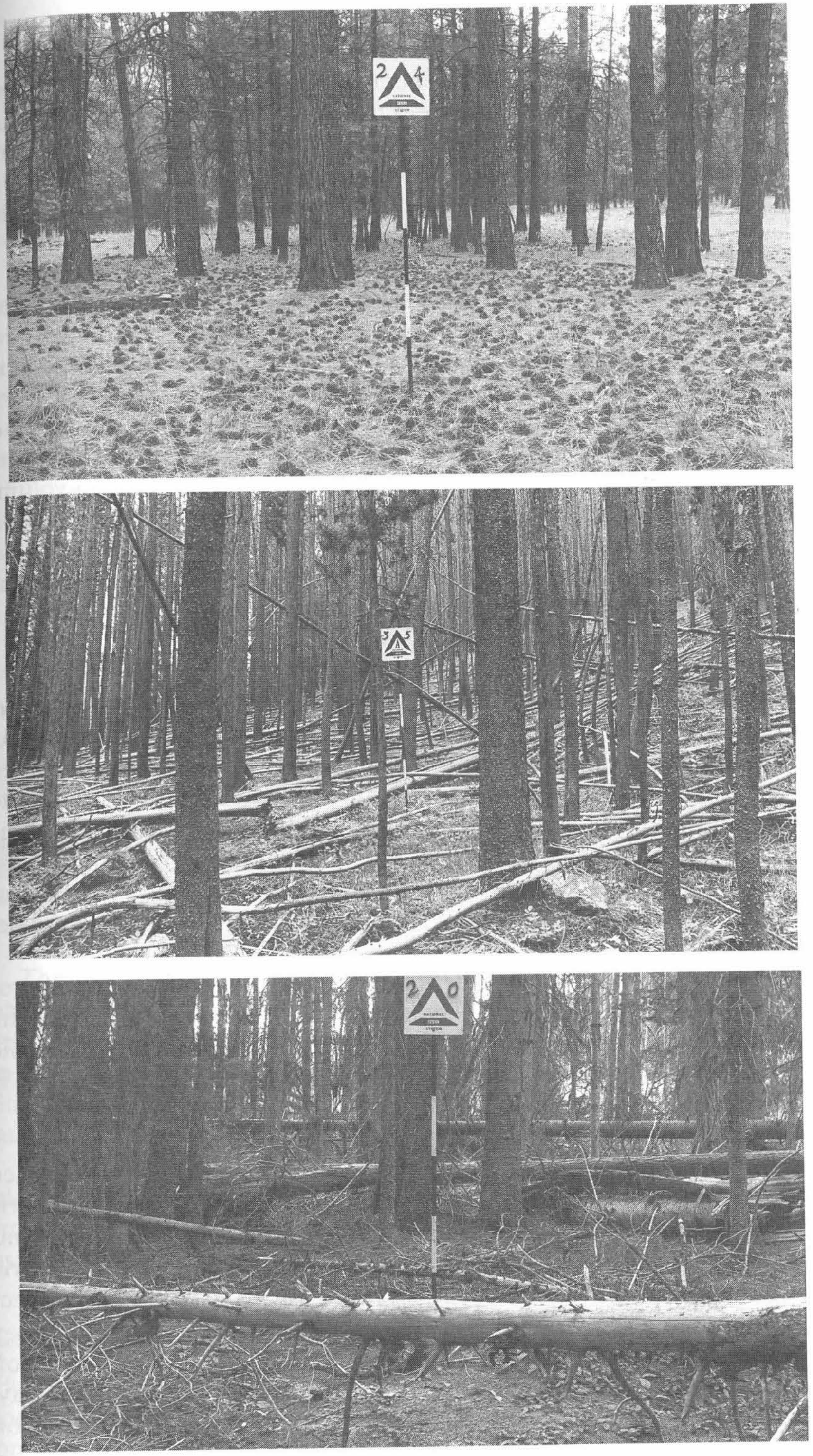


Figure 3.3. *Loadings of downed woody material vary widely as illustrated: 1 ton/acre in a ponderosa pine stand (top); 12 tons/acre in a lodgepole pine stand (middle); and 40 tons/acre in a spruce-fir stand (bottom).* From Brown and See (1981).

allows fuel state (moisture content) to be considered separately from fuel type. Fuel loading varies greatly for different fuel complexes (Figure 3.3). A grass type may be 1 to 5 tons/acre, while logging slash may be 30 to 200 tons/acre. The quantity of ground fuel is often specified in terms of duff depth. Ovestory fuel quantity is sometimes specified as trees per acre or as the weight of the needles.

Size and Shape It is clear from the experience of starting a campfire that small fuels ignite and sustain combustion easier than large pieces of fuel. Less heat is required to remove fuel moisture and raise a small fuel particle to ignition temperature. Thus it is the fine dead fuels that carry the flaming fire front. The size of a fuel particle is often given as the ratio of the surface area of a fuel to its volume (ft^2/ft^3). For fuels that are long with respect to their thickness it's 4/d ft^{-1}; the higher the ratio, the finer the particle. The surface-area-to-volume ratio of a $\frac{1}{4}$-inch-diameter twig is 200 ft^{-1}, while that of a 6-inch-diameter log is 8 ft^{-1}. This is a meaningful measure of fuel particle size because of its relationship to rates of change in fuel temperature and in moisture content. There are also relationships between surface-area-to-volume ratio and ignition time and spread rate.

Compactness Compactness can be thought of as the spacing between fuel particles. The closeness and physical arrangement of the fuel particles affect both ignition and combustion. In most cases, slower spread rates occur when fuels are compacted. Loosely compacted fuels will normally react faster to moisture changes and have more oxygen available for combustion. Packing ratio is a function of depth and load as well as particle size. Compactness relates to the spacing of fuel particles and affects ignition time and combustion through its influence on oxygen supply and radiant energy transfer between particles.

Bulk density, the weight per unit volume of a fuel complex, is an appropriate measure of porosity of a fuel complex. It fails to precisely express the amount of fuel complex occupied by actual fuel volume because the specific gravity of fuel is disregarded. Thus, only weight, and not volume of fuel, is incorporated in an expression of bulk density.

Arrangement The way that fuel particles are arranged has a great influence on fire behavior. Arrangement includes the orientation of fuel particles (horizontal or vertical) and the spatial relationship between particles. Grass and brush are vertically oriented fuel types, while timber litter and logging debris are horizontally oriented. Relationships between load and depth with respect to arrangement are shown in Figure 3.4.

In the case of large dead logs, arrangement can make the difference of whether the fuel burns or not (Figure 3.5). Arrangement also refers to the way that the fuel particles are mixed, the live-to-dead ratio, and the relationship of fine dead fuels to the rest of the fuel complex.

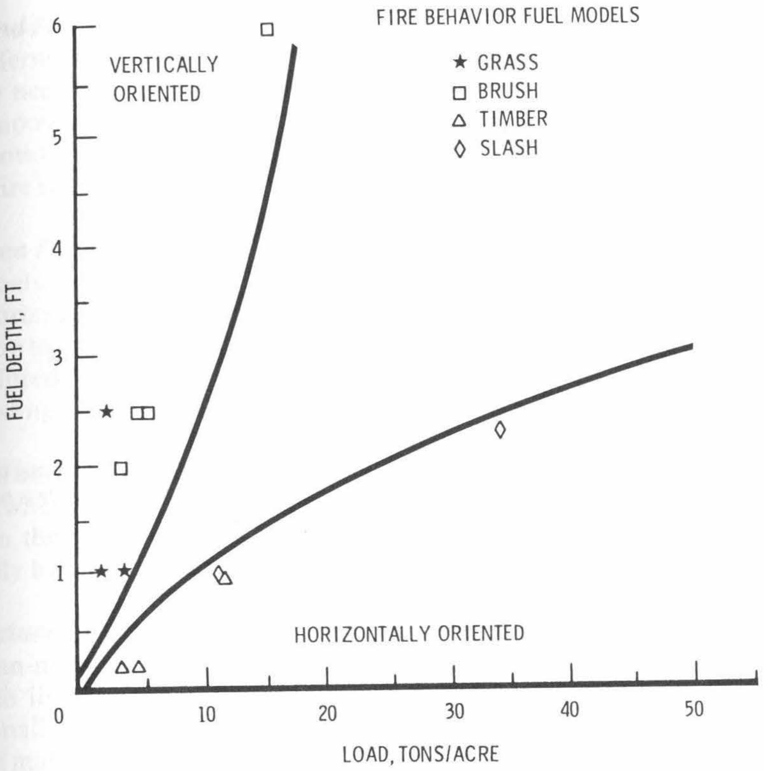


Figure 3.4. *Fuel depth vs. load for the standard fire behavior fuel models (see Figure 3.8). Grasses and shrubs are oriented vertically while timber, litter, and slash are oriented horizontally.* From Anderson (1982).

The arrangement of fuels in the horizontal plane can influence fire behavior and can be a determining factor in whether the fire will burn or spread at all. If the open areas are barren and void of fuels, it will be difficult for a fire to travel from one fuel island to another without strong winds and spotting. Similarity, the horizontal continuity of crown fuel can determine whether a sustained crown fire is possible.

The vertical arrangement of fuels influences which parts of the fuel complex are included in the fire. A fuel ladder (Figure 3.6) can transport the fire from the surface fuel to the crowns, with a significant change in fire behavior as described in Chapter 2.

Components

Fuel components can be categorized according to vertical layer—ground, surface, and aerial or crown fuel (as shown in Figure 3.6). This grouping is based on significant differences in the behavior of fire through each layer.

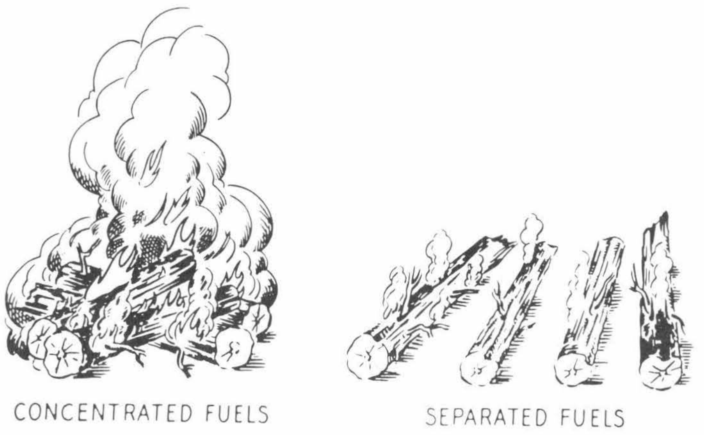


Figure 3.5. *Fuel arrangement determines how a group of large logs will burn. A pile of logs creates a hot fire because the burning logs radiate heat to each other. When the pile is broken up, radiant heat transfer is greatly reduced.* From Barrows (1951).

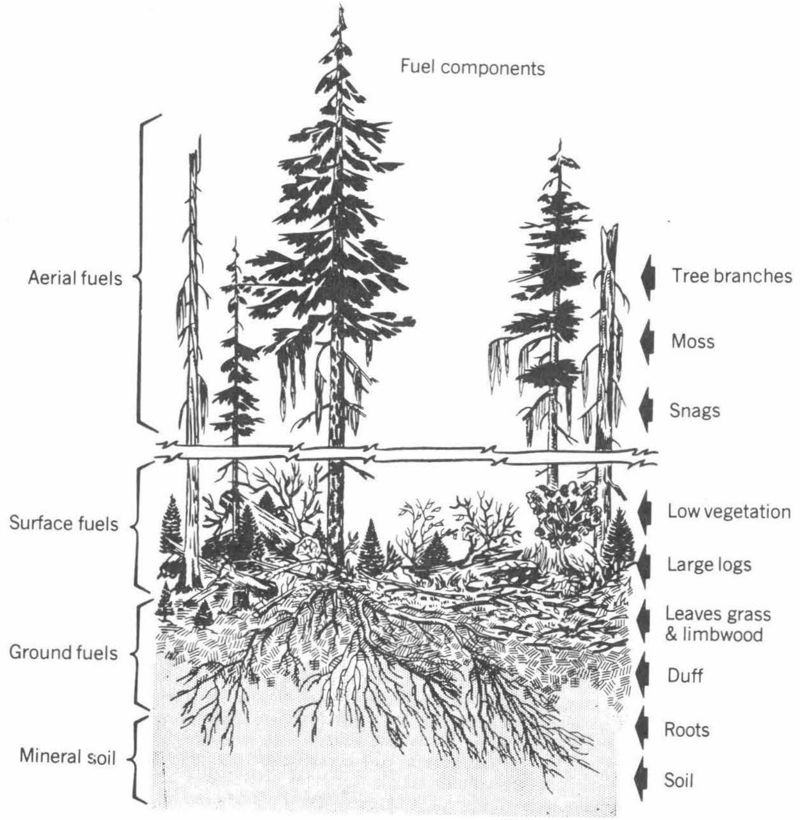


Figure 3.6. *Fuel components are categorized according to ground, surface, and aerial or crown fuel.* From Barrows (1951).

Ground Fuel Ground fuels include duff, roots, and rotten buried logs. *Duff* is the fermentation and humus layers of the forest floor. The top of the duff is where needles, leaves, and other castoff vegetation material have begun to decompose. Individual particles usually will be bound by fungal mycelium. The bottom of the duff is mineral soil. Because of the compactness of ground fuel, fire spread will be slow, typically burning by smoldering combustion.

Surface Fuel Since most wildland fires ignite in and are carried by the surface fuels, this fuel level has received the most emphasis. Surface fuels can be categorized according to physical characteristics of the vegetation: standing trees up to about 6 ft, shrubs, herbaceous vegetation (grasses and forbs), forest floor litter, and downed woody material (Figure 3.7). *Litter* is the surface layer consisting of freshly fallen leaves, needles, twigs, stems, and bark.

Aerial or Crown Fuel Crown fuel includes overstory trees and large shrubs. Even when the canopy is not included in the fire, it affects the behavior of the fire in the surface fuel. Timber stands with open canopies, for example, usually have a faster spreading surface fire than closed stands.

Structures Wildland fuel technically includes vegetative material, but human-made structures might also be considered a fuel component. People like to live in homes surrounded by natural vegetation. Thus homes occasionally become part of the fuel involved in a wildland fire. Use of natural forest materials in construction makes the structure more of a "wildland fuel," susceptible to becoming involved in and even contributing to a wildfire.

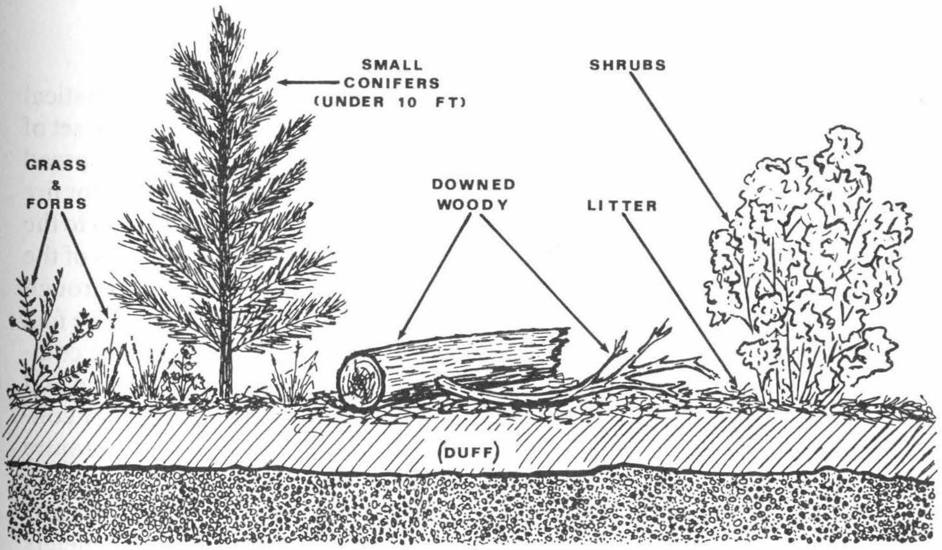


Figure 3.7. *Vegetative components included in surface fuel.* From Brown and others (1982).

Complexes

A fuel complex is an association of fuel components based on vegetation communities. These biological systems are described in various ways such as cover type or habitat type. It is difficult to relate these directly to fuel. Fuel generally occurs as mosaics, rarely unbroken and continuous over large areas. Vegetation types in the United States range from black spruce and feather moss in Alaska to sawgrass in Florida and Hawaii, and from wetland vegetation in the southeast to desert plants in the southwest. A description of these vegetation communities as a fuel complex depends on fuel properties and components that have an effect on wildland fire.

A rangeland fuel complex, for example, may consist of only grass or of a combination of grass and brush. A conifer timber fuel complex consists of overstory trees and an understory that can be just litter and grass or might include heavy dead and down fuel and brush. Two fuel complexes, aspen and palmetto–gallberry, are discussed as selected examples at the end of the chapter.

3.3 FUEL CLASSIFICATION

There is essentially infinite variability in fuel, in kind, amount, size, shape, position, and arrangement. The need to organize fuel description information has resulted in various methods of fuel classification. Classification schemes have traditionally depended on the aspect of fire that is under consideration. The fuel classification schemes described here are fuel models, inventory, photo guides, and Canadian fuel types.

Fuel Models

A fuel model is a stylized and simplified description of fuel for a mathematical fire behavior model. A fire model is a set of equations; a fuel model is a set of numbers that describe the fuel for the fire model. Rothermel's fire spread model was described at the end of Chapter 1; application of that model for fire behavior prediction was given in Chapter 2. Providing fuel information to the fire model in terms of a fuel model makes the complex set of equations of the fire model easy to use. Because the fire model calculates rate of spread through surface fuels, that is the aspect of the fuel complex that is included in the fuel model. The set of 13 standard fuel models shown in Figure 3.8 is most commonly used. Two of the programs in the BEHAVE fire behavior prediction and fuel modeling system allow a person to develop custom fuel models for conditions that are not covered by the 13. Those procedures do not require detailed field inventory.

The differences in fire behavior are basically related to the fuel load and its distribution among the fuel particle size classes. Fuel model parameters include load and surface-area-to-volume ratio for each class (live and dead),

Fuel model	Typical fuel complex	Surface-area-to-volume ratio(ft^{-1})[1]/ fuel loading (tons/acre) 1-h	10-h	100-h	Live	Fuel bed depth	Moisture of extinction dead fuels	Characteristic surface area-to-volume ratio	Packing ratio
						Ft	*Percent*	*Ft^{-1}*	
	Grass and grass-dominated								
1	Short grass (1 ft)	3,500/0.74	—	—	—	1.0	12	3,500	0.00106
2	Timber (grass and understory)	3,000/2.00	109/1.00	30/0.50	1,500/0.50	1.0	15	2,784	.00575
3	Tall grass (2.5 ft)	1,500/3.01	—	—	—	2.5	25	1,500	.00172
	Chaparral and shrub fields								
4	Chaparral (6 ft)	2,000/5.01	109/4.01	30/2.00	1,500/5.01	6.0	20	1,739	.00383
5	Brush (2 ft)	2,000/1.00	109/0.50	—	1,500/2.00	2.0	20	1,683	.00252
6	Dormant brush, hardwood slash	1,750/1.50	109/2.50	30/2.00	—	2.5	25	1,564	.00345
7	Southern rough	1,750/1.13	109/1.87	30/1.50	1,500/0.37	2.5	40	1,562	.00280
	Timber litter								
8	Closed timber litter	2,000/1.50	109/1.00	30/2.50	—	.2	30	1,889	.03594
9	Hardwood litter	2,500/2.92	109/0.41	30/0.15	—	.2	25	2,484	.02500
10	Timber (litter and understory)	2,000/3.01	109/2.00	30/5.01	1,500/2.00	1.0	25	1,764	.01725
	Slash								
11	Light logging slash	1,500/1.50	109/4.51	30/5.51	—	1.0	15	1,182	.01653
12	Medium logging slash	1,500/4.01	109/14.03	30/16.53	—	2.3	20	1,145	.02156
13	Heavy logging slash	1,500/7.01	109/23.04	30/28.05	—	3.0	25	1,159	.02778

[1] Heat content = 8,000 Btu/lb for all fuel models.

Figure 3.8. *Fuel model parameters and calculated fuel bed descriptors for the standard 13 fire behavior fuel models.* From Andrews (1986).

fuel bed depth, and moisture of extinction. Moisture of extinction is the moisture at which the fire will not spread. Other parameters required by the fire model are generally held constant: density, heat content, and mineral content. Characteristic surface-area-to-volume ratio and packing ratio are calculated from the other parameters.

Fuel models are described in terms of fire behavior first and vegetation type second. The choice of fuel model is made through photographs and description provided by Anderson (1982) or by a dichotomous key. Following is a description of fuel model 6, often called "dormant brush:"

> Fires carry through the shrub layer where the foliage is more flammable than fuel model 5, but this requires moderate winds, greater than 8 mi/h (13 km/h) at midflame height. Fire will drop to the ground at low wind speeds or at openings in the stand. The shrubs are older, but not as tall as shrub types of model 4. A broad range of shrub conditions is covered by this model. Fuel situations to be considered include intermediate stands of chamise, chaparral, oak brush, low pocosin, Alaska spruce taiga, and shrub tundra. Even hardwood slash that has cured can be considered. Pinyon–juniper shrublands may be represented but may overpredict rate of spread except at high winds, like 20 mi/h (32 km/h) at the 20-foot level.

In addition to static fire behavior fuel models, dynamic fuels models have been developed for some fuel types, accounting for a change in fuel type over time. An example of a dynamic fuel model for palmetto–gallberry is given at the end of the chapter. Eleven of the 13 fire behavior fuel models were first developed for the 1972 National Fire Danger Rating System (NFDRS). The 1978 revision of NFDRS included equations to reflect the influence of heavy dead fuels; thus a new set of 20 fuel models was developed, some including up to 8-in.-diameter logs. The original 13 fuel models continue to be used for fire behavior prediction.

Inventory

Brown and others (1982) have developed comprehensive procedures for inventorying living and dead surface vegetation for fuel appraisal. They describe how to conduct field work and estimate loading of downed woody material, forest floor litter and duff, herbaceous vegetation, shrubs, and small conifers. Weights by species are determined for shrubs and small conifers. Coverage of shrubs and herbaceous vegetation is estimated. The several sampling methods involve counting and measuring the diameters of downed woody pieces along a transect, comparing quantities of litter and herbaceous vegetation against standard plots that are sampled and weighed, tallying shrub stems by basal diameter classes, tallying conifers by height classes, and measuring duff depth.

Photo Guides

Photo guides for appraising fuels have been developed for specific fuel types including recent logging slash, aged slash, and natural dead and downed fuel (see Figure 3.24). Many of the guides are for appraising downed woody fuel, to rate the potential fire behavior in the fuel shown in each photo, giving loading and size class distribution of downed woody fuel. Information accompanying each photo includes information such as forest cover type, habitat type, age of overstory, elevation, aspect, and information from a dead-and-down fuel inventory. In addition, fire behavior for an "average bad" fire weather situation is often included. The elements rated include rate of spread, intensity, torching, crowning, resistance to control, and an overall fire potential rating. Various methods have been used to predict potential fire behavior for the various photo guides, including a resistance to control rating, Rothermel's fire model, and the experienced judgment of fuel and fire behavior experts.

Group / Identifier	Descriptive name
Coniferous	
C-1	Spruce–lichen woodland
C-2	Boreal spruce
C-3	Mature jack or lodgepole pine
C-4	Immature jack or lodgepole pine
C-5	Red and white pine
C-6	Conifer plantation
C-7	Ponderosa pine–Douglas-fir
Deciduous	
D-1	Leafless aspen
Mixedwood	
M-1	Boreal mixedwood–leafless
M-2	Boreal mixedwood–green
M-3	Dead balsam fir mixedwood–leafless
M-4	Dead balsam fir mixedwood–green
Slash	
S-1	Jack or lodgepole pine slash
S-2	White spruce–balsam slash
S-3	Coastal cedar–hemlock–Douglas-fir slash
Open	
O-1	Grass

Figure 3.9. *Canadian Fire Behavior Prediction system fuel types.* From Forestry Canada Fire Danger Group (1992).

Canadian Fuel Type

Fuel type for the Canadian Fire Behavior Prediction (FBP) system has been defined as "an identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behavior under defined burning conditions." More specifically, a fuel type is a fuel complex of sufficient homogeneity and extending over an area of sufficient size that equilibrium fire behavior can be maintained over a considerable time period. The FBP system organizes fuel types into five major groups, with a total of 16 discrete fuel types. Fuel types in the FBP system are described qualitatively, rather than quantitatively, using terms describing stand structure and composition, surface and ladder fuels, and the forest floor cover and organic (duff) layer. FBP system fuel type descriptions do not rigorously or quantitatively follow forest inventory patterns; however, knowledgeable fire managers can develop methods to classify their land base and vegetation data for fire planning. A list of FBP system fuel types is given in Figure 3.9. Following is a description of Fuel Type C-3 (Mature Jack or Lodgepole Pine):

> This fuel type is characterized by pure, fully stocked (1000–2000 stems/ha) jack pine stands that have matured at least to the stage that crown closure is complete and the base of live crown is substantially separated from the ground. Dead surface fuels are light and scattered. Ground cover is basically feather moss over a moderately deep (10 cm) compact organic layer. A sparse conifer understory may be present.

3.4 FUEL MOISTURE

The preceding sections on fuel description and classification relate to fuel type. We now discuss the state of the fuel—fuel moisture. Potential fuel was defined as the fuel that could burn under extreme conditions. The amount of fuel that is available for combustion in a given fire (available fuel) is determined largely by the amount of water in the fuel (fuel moisture).

The process by which fuel moisture affects combustion was covered in Chapter 1. Water is a heat sink; it must be boiled away before the fuel can be heated to ignition temperature. If the required heat is more than is available, then there is no fire. When moisture content is high, fires are difficult to ignite, and burn poorly if at all. With little moisture in the fuel, fires start easily, and wind and other driving forces, may cause rapid spread at high intensities.

Fuel moisture affects all aspects of fire behavior and fire effects: spread rate, intensity, smoke production, fuel consumption, and plant mortality. In addition, moisture is such a critical factor in assessing fire potential that moisture calculations are the foundation of fire danger rating systems (discussed in Chapter 4).

Fuel moisture is a product of the cumulative effects of past and present weather events. In addition, moisture content of live vegetation is affected by biological processes. Fuel moisture can change in minutes in the case of lichen, or weeks as in large logs, or over the season for greenup and curing of live vegetation. Fuel moisture, in fact, changes in all time scales: abrupt, diurnal, seasonal, annual, and even at the successional scale, if we consider the effect of changing fuel and weather (global climate change) on moisture.

Moisture varies in space as well as in time. The complex arrangement of fine fuel particles on the forest floor can produce wide variations in the moisture content throughout the fuel layer because of varying degrees of exposure of individual fuel particles to wetting and drying forces. Variation within a live plant at a point in time results from factors such as exposure to the sun and foliage age. There can even be significant variability within a single fuel element. The moisture content of a large log is never uniform. Figure 3.10 shows the variation in moisture content within a log. The reality of this variability must be recognized when a measured or calculated fuel moisture value is cited.

Moisture content is generally expressed as a percentage on an ovendry weight basis. The fraction of moisture content is the weight of the water (initial fuel weight minus dry weight) divided by the weight of the ovendry material. Dead fuel moisture can be a low as 1 or 2% in deserts. Fiber saturation is 30 to 35%. Sound wood at higher moistures has water in cracks, in pores, or in spaces between cells. Decayed wood has many open spaces between woody fibers and so can hold water like a sponge up to 300% or more. Live fuel moisture generally ranges from about 50 to 300%, but can be over 1000%. Duff moisture content is highly variable, up to several hundred percent. In some situations, seemingly wet ground fuel can burn.

Dead Fuel Moisture

Process The amount of water in a fuel particle is always changing, depending on how wet or dry the environment is. Fuel can gain moisture either through liquid water or through water vapor. The process of fuel drying is accomplished by evaporation to the environment.

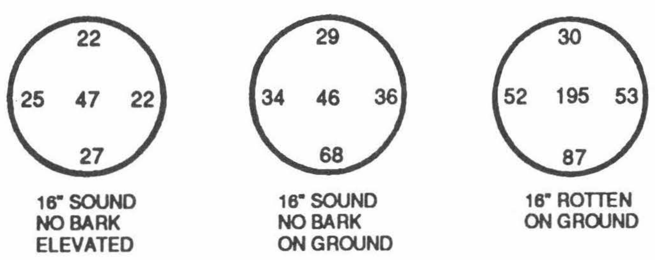


Figure 3.10. *Moisture content varies within a log. Percentage moisture content at top, bottom, center, and sides of three selected logs. The moisture contents are averages of measurements taken at 1-, 2-, 3-, 5-, and 7-ft intervals.* From Reinhardt and others (1991).

The hygroscopic nature of the materials making up the dead cell walls makes it possible for them to adsorb water vapor from the air. The water molecules that penetrate and are held to the cell walls and the few molecular layers that adhere to the cell walls are called bound water. The amount of bound water at the fiber saturation point for most plant fuels is in the range of 30 to 35% of dry fuel weight. Adsorption and desorption processes are due to diffusion at locations in the fuel that contain bound water but no free liquid water.

Many processes occur at the fuel surface; these events largely determine transfer within the fuel. Heat loss is due to conduction away from the surface and to radiative cooling. Heat gains are due to solar radiation and convective heating by the ambient air. The amount of liquid water on the fuel surface is affected by rainfall and by condensation and evaporation. These processes control surface gain or loss of moisture above the fiber saturation point.

Influences Dead fuel moisture is a result of the environment; it is affected by all three legs of the fire environment triangle: fuel, weather, and topography. The primary influence is weather. The way that fuels react to weather changes depends on the composition and size of the fuel as well as location. Topography affects the microclimate and determines the amount of sun that the fuel receives.

Characteristics of fuel that affect its moisture include the composition of the material (needles, leaves, grass, duff, sound wood or rotten wood) and the size of the fuel (diameter of wood, depth of duff). In addition, the presence of surface layer, such as bark or wax, on the fuel affects the way it gains and loses moisture.

The location of the fuel is also a factor—whether it is on or above the ground and whether it is under a canopy or in the open. In an open area, exposure to direct solar radiation results in a lower average daytime moisture content and a greater amplitude to the moisture content cycle than under an adjacent canopy. Following rain, material on the ground is subject to a more humid environment, resulting from evaporation of moisture from the duff layer. When dry, however, absorption of solar radiation raises the duff surface temperature, thereby lowering surface relative humidity, which, in turn, reduces the moisture content of fuels on the ground. Dead fuels attached to the plants are exposed to different conditions than those on the ground (e.g., frosted leaves on brush vs. leaf litter on the ground).

In deep and compact fuel beds, air circulation in the lower layers may be nearly nonexistent. Precipitation soaking down through the fuel into the soil may then produce relative humidities near 100% at the lower levels, and this can persist for appreciable times. Subsequent drying starts at the top and works downward. In deep fuels, it is not uncommon for the surface layer to become quite flammable while lower layers are still wet. Reverse conditions also occur after prolonged drying, resulting in the topsoil and lower duff becoming powder dry. Then morning dew on the surface, high relative humidity, or a light shower may cause moisture conditions that are higher at the surface than lower in the duff.

The weather elements that affect dead fuel moisture content are rain, wind, solar radiation, and the temperature and humidity of the air. When the temperature reaches the dew point, water condenses on the fuel. Past rain and snow affect the moisture of soil and ground fuels, which thereby affect the moisture of fuels laying on them. Wind can have both a drying and a wetting effect. For fuels in the sun the wind's cooling action can offset its drying action.

Solar radiation has long been recognized as an important influence on fuel moisture due to increase in fuel temperature. The intensity of sunlight varies with time of day, time of year, slope, aspect, latitude, and haziness of the atmosphere.

Equilibrium Moisture Content The equilibrium moisture content (EMC) may be defined as the value that the actual moisture content approaches if the fuel is exposed to constant atmospheric conditions of temperature and humidity for an infinite length of time. A dry fuel in a moist environment reaches equilibrium at a lower value than a moist fuel approaching the same equilibrium point from above (Figure 3.11). EMC is a condition wherein a fuel is very close to being in equilibrium with the moisture of the air immediately surrounding it. At this stage, no further significant net exchange of moisture will take place. Actually, in nature this is a transitory situation, since the atmospheric conditions surrounding the fuel seldom remain stable for long.

Figure 3.11 illustrates how the moisture content of fine forest fuels is influenced by relative humidity, and that different fuels react differently to environmental changes. Air temperature also affects EMC: EMC decreases as air temperature increases.

Timelag Dead fuels can be classified according to the time it takes the fuel to adjust to changes in the environment (Figure 3.12). When a change occurs, the moisture moves toward a new equilibrium. How quickly these fuels gain or lose moisture in response to wetting or drying cycles establishes their response time. Timelag is an expression of the rate at which a given fuel approaches its equilibrium moisture content. Timelag interval, or response time, is defined as the time required for dead fuel to lose approximately 63% $(1 - 1/e)$ of the difference between its initial moisture content and equilibrium moisture content in an atmosphere of constant temperature and humidity. The duration of these time periods is a property of the fuel. Timelag can be expressed in minutes or hours or days. For clarity, hours are generally used.

The average timelag period varies with the size and other factors of the fuels. For extremely fine fuels the average period may be a matter of minutes, while for logs it ranges upward to a month or more. Dead branchwood 2 inches in diameter, for example, has an average timelag period of about 4 days. Logs 6 inches in diameter have an average timelag of about 36 days. A 2-inch

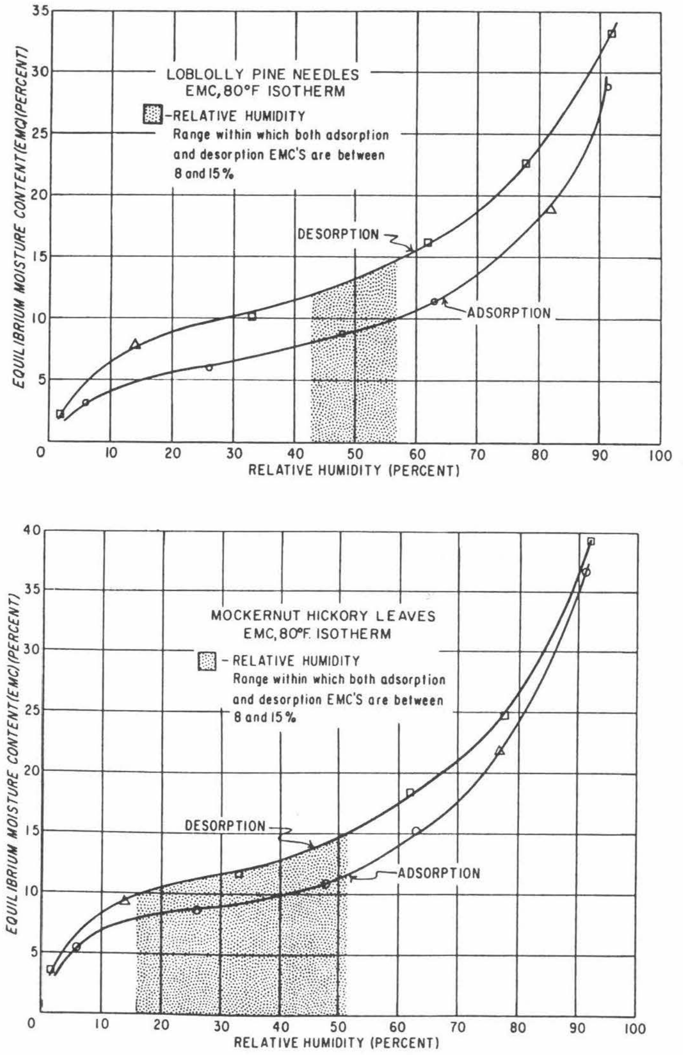


Figure 3.11. *Equilibrium moisture content (EMC) during desorption and adsorption cycles of fine fuel materials found in forests of the southeastern United States. The range of relative humidity that gives fuel moistures from 8 to 15% are shaded.* From Blackmarr (1972).

litter bed with an average timelag period of 2 days can be considered the equivalent, in moisture response characteristics, of dead branchwood ($\frac{1}{4}$ inch diameter) having a similar timelag period if there is no significant moisture exchange between the litter and the soil.

The concept of timelag was developed by Byram in 1963 (unpublished) and expanded by Fosberg (1970). The resolution was appropriate for fire danger rating needs at that time. Fuels were grouped into four timelag classes: up to 2 h, 2 to 20 h, 20 to 200 h, and greater than 200 h. Class midpoints then were taken as the title for each timelag class: 1 h, 10 h, 100 h, 1000 h. Although this is an oversimplification, the terminology continues to be used. A direct equivalence is made to diameter and timelag: 1 h = 0–$\frac{1}{4}$ inches; 10 h = $\frac{1}{4}$–1 inch; 100 h = 1–3 inches; 1000 h = >3 inches diameter.

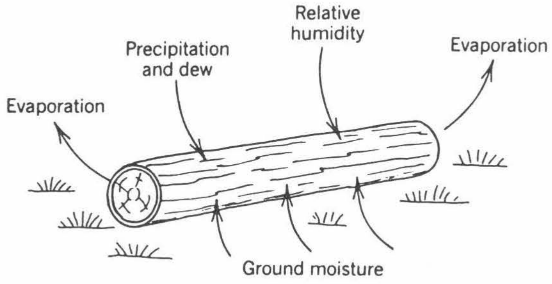


Figure 3.12. *Factors influencing moisture exchange in wildland fuels.*

Applying the strict timelag classification to fire behavior prediction can cause errors. Anderson (1990b) found a great variation in response times for fine forest fuels (Figure 3.13). Timelags for grasses, mosses, and lichens were on the order of 2 to 4 h, weathered conifer needle litter was 2 to 14 h, and recently cast conifer needles had response times of 5 to 34 h. Calling these 0- to $\frac{1}{4}$-inch-diameter fuels "1-h timelag fuels" is obviously misleading.

Anderson (1985) showed the effect of timelag (Figure 3.14). A repeating diurnal cycle was established from August weather data for O'Neill, Nebraska. This diurnal cycle was used to establish the forcing EMCs experienced during each 30-min period in the 24 hours from 2 P.M. to 2 P.M. The significant feature is not how much lag there is in moisture behind the weather condition, but the reduction in sensitivity to change. This results in a misrepresentation of afternoon fuel moisture. Although the EMC forcing function ranges from 14.8 to 6.1%, the range for grasses drops to 6.3%, and for the slowest responding needles the range is only 0.9%. Fine fuels with long timelags will take long periods of dry weather to reach the low moisture contents that can be reached in 1 day by fuels with true 1-h timelags.

Fine dead fuel moisture is an important factor in determining fire behavior, particularly the rate of spread of a spreading surface fire. An example is the hourly variation for two days during the Yellowstone National Park fires of 1988. Low fuel moisture at night allowed active burning through the night (see Figure 3.2b).

Reindeer lichen is among the fastest drying of forest fuels. Péch (1989) showed that when submerged in water it can increase in moisture to 400%, and when drying in shade it can lose 63% of its free moisture in less than 2 h. Reindeer lichen is a major surface fuel in vast regions of the boreal and subartic forests.

The moisture of larger dead fuel affects the behavior of the fire behind the flaming front. The moisture content affects the burnout rate and the amount of

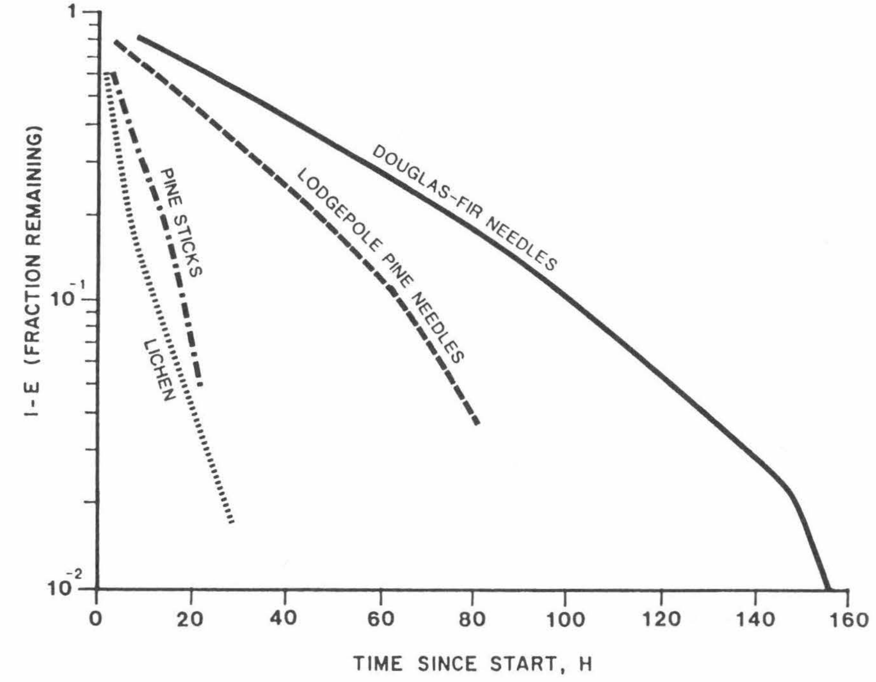


Figure 3.13. *Response time for moisture change for witch's hair lichen, $\frac{1}{2}$-inch ponderosa pine sticks, lodgepole pine needles, and Douglas-fir needles.* From Anderson (1990b).

fuel that is consumed. When fuels are very dry there can be 100% consumption where all that is left of logs is a tell-tale line of ashes (see Figure 3.1b).

The limiting rate at which water diffuses into wood is less than most rainfall rates; excess rain is shed by solid wood. The moisture content of large roundwood is thus related to rainfall duration. In contrast, ground fuel retains much of the excess water in the fuel bed structure; duff moisture content is related to rainfall amount.

Live Fuel Moisture

Wildland fires are often influenced by living vegetation. Grasses, ferns, shrubs, mosses, herbaceous plants, and trees may either contribute actively to the energy of a fire, or they may serve as a heat sink and retard fire propagation and intensity.

While dead fuel moisture is a function of weather conditions, live fuels exhibit seasonal changes in moisture in accordance with physiological processes such as spring flushing and fall curing. There is significant variability in plant phenology, morphology, and physiology. In a study on summer moisture contents of understory vegetation in northeastern Minnesota, for example, Loomis and others (1979) found averages of seasonal moisture content percentage ranging from 138% for Labrador tea to 1027% for bluebead lily.

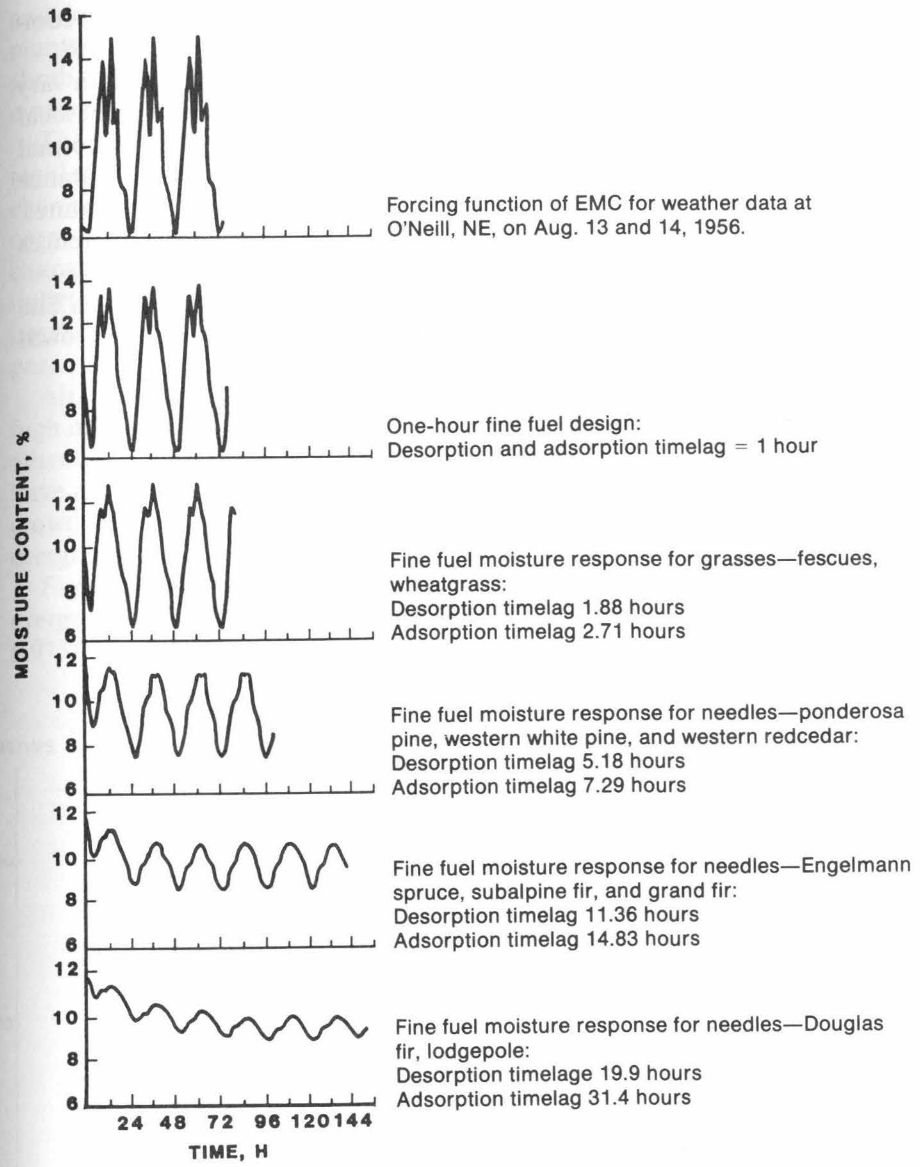


Figure 3.14. *Not all fine forest fuels respond to moisture changes with 1-h timelags. As the timelag increases, the response becomes slower and less sensitive.* From Anderson (1985).

Water movement in a forest is a function of both physical and physiological factors. Physical factors such as precipitation and soil storage provide the water supply, while atmospheric evaporative force supplies the demand. The tree is the transport system from the soil to the atmosphere; however, this transport is controlled by physiological responses by the tree to the physical environment. Running (1978) described a general perspective of the components of a process-oriented model for live fuel moisture (Figure 3.15).

The moisture content of living plant foliage of wildland species can vary markedly with seasonal changes. The patterns are usually typical for the local species and climate, but are tempered in timing by deviations from normal weather, such as amount and spacing of precipitation, date of disappearance of snowpack, or the occurrence of unseasonably warm or cool temperatures. Elevation and aspect affect local microclimate and produce local differences in seasonal development of many plant species.

Moisture content of new foliage is highest at the time of emergence. The moisture normally declines from the peak quite rapidly during leaf growth and development, then somewhat more slowly to a terminal value. In annual plants, the end result is the death of the plant. In perennials and deciduous shrub and tree species, the end result is the death of the foliage, while in evergreens some leaves live and others die and fall.

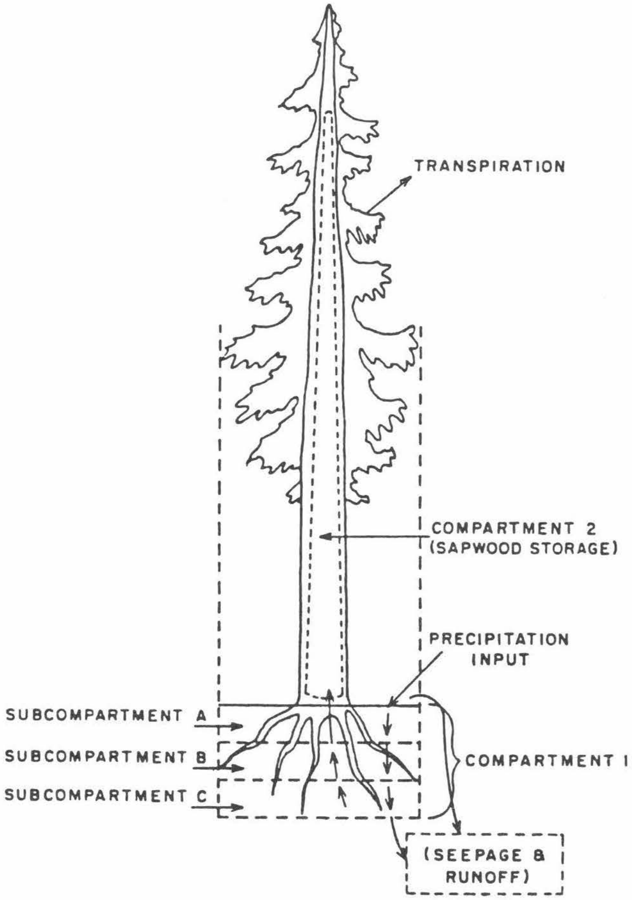


Figure 3.15. *General perspective of the components of a process oriented model for live fuel moisture. Compartment 1 is defined as water available to the tree from soil within its rooting zone. Compartment 2 is defined as water available from transpiration stored within the sapwood of the tree.* From Running (1978).

The decrease in plant foliage moisture is usually not smooth, but an irregular succession of ups and downs. Foliage moisture content may even change during the course of the day. These irregularities may result from one or more causes, including periodic changes in food-manufacturing demands, changes in weather, and variations in available soil moisture. Within the individual leaf, however, moisture is maintained within tolerable limits during the growing season through the ability of the leaf to open or close the leaf pores and thus regulate the rate of transpiration to the atmosphere.

All deciduous foliage is the current year's growth and maintains relatively high moisture content during most of the growing season. Evergreens, on the other hand, particularly those that retain their foliage for a number of years, have much lower average foliage moisture during the growing season. Old growth foliage with its lower moisture may constitute 80% or more of the total evergreen foliage volume.

Figure 3.16 shows the seasonal variation in the moisture content of both evergreen and deciduous shrubs in North Carolina. Blackmarr and Flanner (1975) observed moisture content cycles in new foliage, old foliage (for ever-

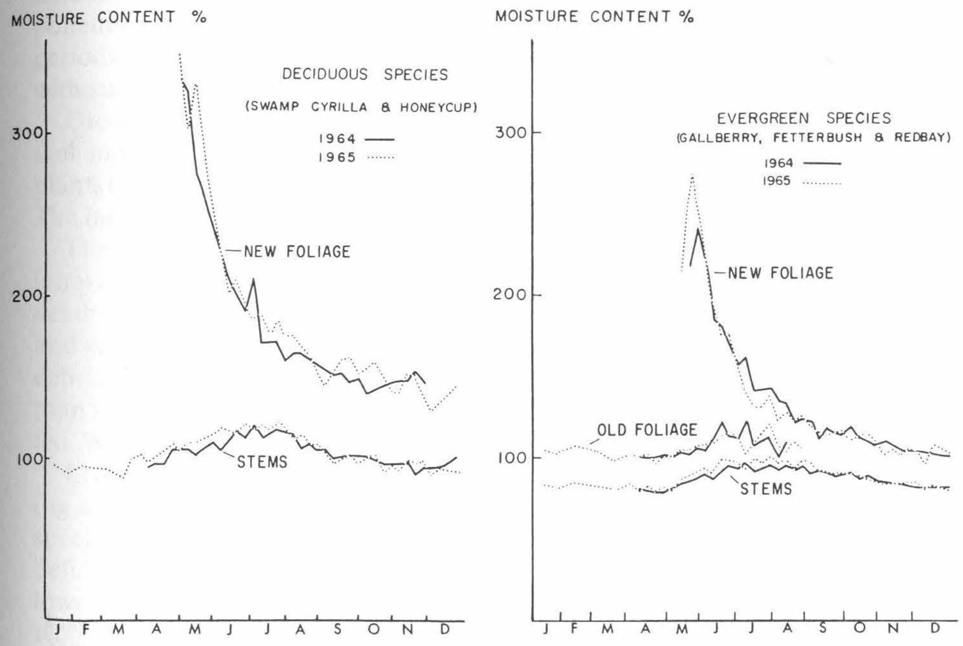


Figure 3.16. *Annual moisture content cycles in selected deciduous and evergreen pocosin shrubs during two years showing differences in stems and new and old foliage.* From Blackmarr and Flanner (1975).

green species), and stems. Most species exhibited a rapid buildup of moisture content as new growth resumed in the spring. Moisture contents declined rapidly during the first few weeks of growth, then tapered off gradually toward the end of the growing season. Each species had a characteristic pattern of moisture content variation that was relatively constant over two growing seasons. Evergreen shrubs usually had lower moisture contents than deciduous shrubs at any given time of the year.

The moisture content of old conifer foliage decreases and reaches a minimum in spring and then gradually increases to a maximum later in the summer. The timing of both the flushing of new conifer foliage and the minimum moisture content of the old foliage varies with altitude, occurring earlier at lower elevations and later at higher elevations. Otherwise, the general trends in foliar moisture appear to be similar from year to year. Figure 3.17 shows the mean seasonal moisture variations in old foliage for jack pine and black spruce in central Alberta, Canada.

The low preflushing moisture content of conifer foliage in the spring is associated primarily with the increase in dry matter, which subsequently declines as the moisture percentage increases. This latter decline in dry matter coincides closely with the initiation of new growth and appears to be similar quantitatively to the dry matter increase in new foliage. Seasonal variations in foliar moisture, however, appear to be affected more by changes in the actual water content than by the changes in ovendry weight.

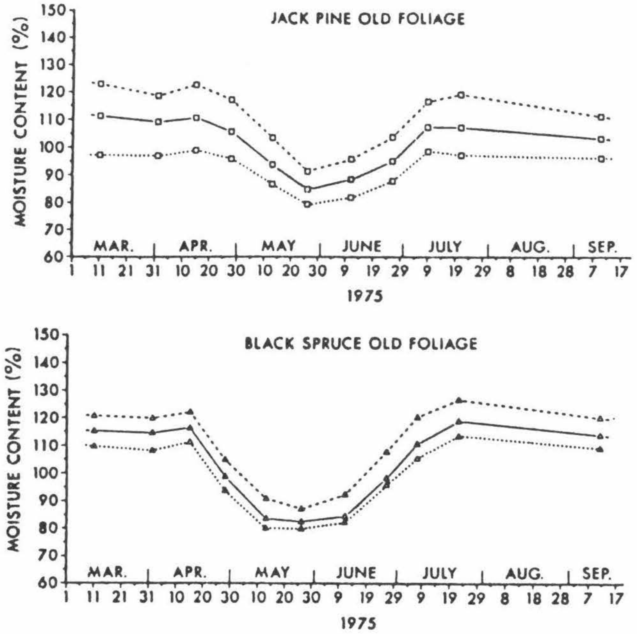


Figure 3.17. *Mean seasonal moisture variations in old foliage for Jack pine and black spruce for foliage ages 1 year old (dashed line), 2 years old (solid line), and 3+ years old (dotted line). Each of the mean values plotted is based on ovendry weights of five samples.* From Chrosciewicz (1986).

Annual grasses are much more sensitive to seasonal and short-term weather variations than are most other live wildland fuels. Shallow-rooted grasses depend primarily on adequate surface soil moisture for full top development. Annuals mature, produce seed, and begin to cure and dry. Deficient surface moisture at the beginning of the season, or its depletion by hot, dry weather may shorten the growth period. Similarly, because of the weather, the curing time may vary from 3 weeks to 2 months after noticeable yellowing. Annual grasses may die and reach a highly flammable stage while broadleaf foliage is still in prime growth.

Perennial grasses have deeper, stronger root systems than annuals and are somewhat less sensitive to short-term surface soil moisture and temperature changes. The principal differences in moisture content result from a later maturing date and a slower rate and longer period of curing (see Figure 3.27).

Drought

From the viewpoint of wildland fire, drought is important in that it affects the amount of available fuel. Because of their low moisture content, fuel components that might not otherwise burn become available fuel during during periods of drought. The result is more intense fires and increased difficulty with suppression efforts.

Drought effects go beyond the normal seasonal trends in both live and dead fuel moisture described above. Prolonged moisture deficiency can cause plants to die, large logs to lose moisture to their center, and deep duff to dry out. The lack of soil moisture can cause stress in live plants.

The moisture of the fine fuels that control fire spread through surface fuels is not affected by drought. But additional fine dead fuels might be added due to death of live plants and foliage. The moisture content of large fuel components and ground fuel are dependent on long-term drying processes. Large woody debris can actually sublime moisture in cold winter when snow cover is less than normal, causing early spring moisture contents much lower than expected. When dry, these fuels can add significantly to the intensity of a fire.

Live vegetation responds to drought in a variety of ways. Particularly striking are the variations found in the drought-resistant brush and chaparral species in the semiarid West. It is not uncommon for midseason soil-moisture deficiency to cause cessation of growth in these species, with foliage moisture lowering to between 40 and 50%. Usually, these plants retain the ability to recover after the next rain. Prolonged severe drought, however, can prove fatal to major branches or even to whole shrubs. Conflagration potential is then at its peak.

Moisture Assessment

There are several ways to assess fuel moisture content. Fuel moisture values can be obtained through direct measurement, through inference from some other variable, or through calculation based on observable weather elements.

Direct Measurement Fuel moisture can be obtained from a sample of the material. The sample is weighed, dried, then weighed again (Figure 3.18). The ovendry moisture content is calculated. Sampling might be used when there is no good method of calculation or inference. It is important to use sound sampling techniques. A few pieces of live grass in a dead grass sample can greatly bias the results. There is always a lot of variability at a site. A good sampling scheme must be determined so that a good estimate of moisture might be obtained. The moisture of live leaves and needles can change during a day and can vary within a plant (Figure 3.19).

There are instruments that read moisture content directly. Fuel moisture probes, which use electric resistance to measure moisture content were developed for lumber and are sometimes used for wildland fuel. The probe is activated by pressing its two electrodes firmly into a sample. Probes can give quick estimate in the field when time doesn't allow for sampling. Again, the issue of variability on a site and within a fuel element must be considered. In addition, because the probes were developed for use with lumber, they can measure only a limited range of moisture contents.

Figure 3.18. *Fuel samples are clipped into a can, weighed, dried, and weighed again to determine moisture content.* Photo by Melanie Miller. From Norum and Miller (1984).

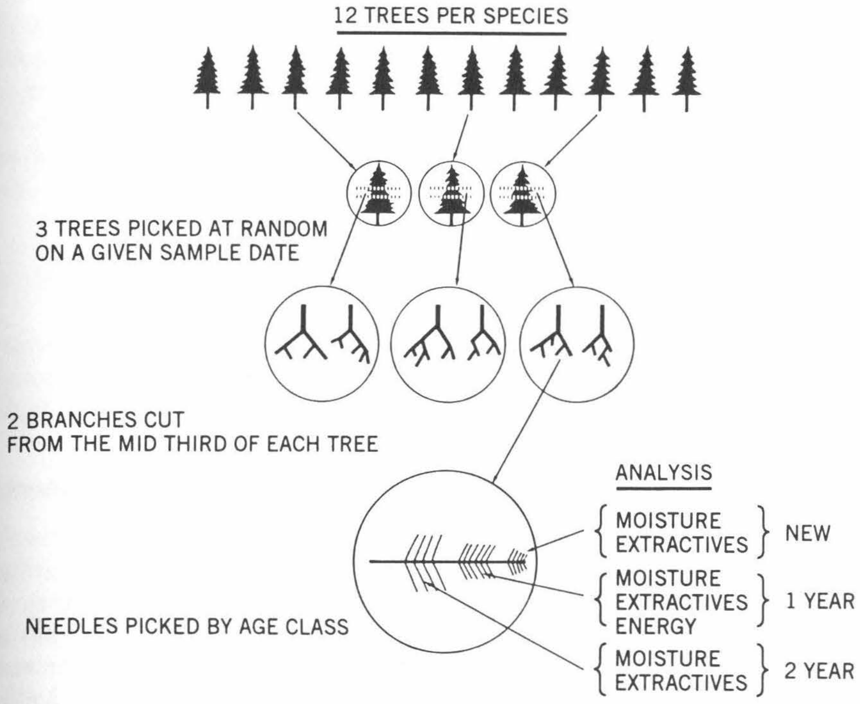


Figure 3.19. *A foliage sampling scheme used for ponderosa pine and Douglas fir.* From Philpot and Mutch (1971).

A method of estimating dead fuel moisture for a site is based on fuel-moisture indicator sticks, consisting of four $\frac{1}{2}$-inch ponderosa pine sapwood dowels spaced $\frac{1}{4}$ inch apart on two $\frac{3}{16}$-inch dowels. The $\frac{1}{2}$-inch dowels are approximately 20 inches long. Each set is carefully adjusted to weigh 100 g when ovendry. The sticks are exposed 10 inches above a litter bed in the open on wire brackets (Figure 3.20). Forest and rangeland fuel, of course, does not consist of dowels. Thus this method is somewhere between direct measurement and inference. The moisture of the stick is determined from its weight and an inference is made about the moisture of the fuels in the area. The value of this method is in its ease of use and consistency. The indicated moisture represents the cumulative effects of past changing weather factors on these standardized fuel sticks over a period of time preceding the observation.

Inference Fuel moisture can be inferred from other information, such as the color of the vegetation. Mutch (1967) related the color of cheatgrass to moisture content. When cheatgrass is dead, it responds readily to changes in atmospheric moisture because of its fine structure. The characteristic color changes while it is curing (from green to purple to straw color) indicate impending flammability because these colors are generally correlated with

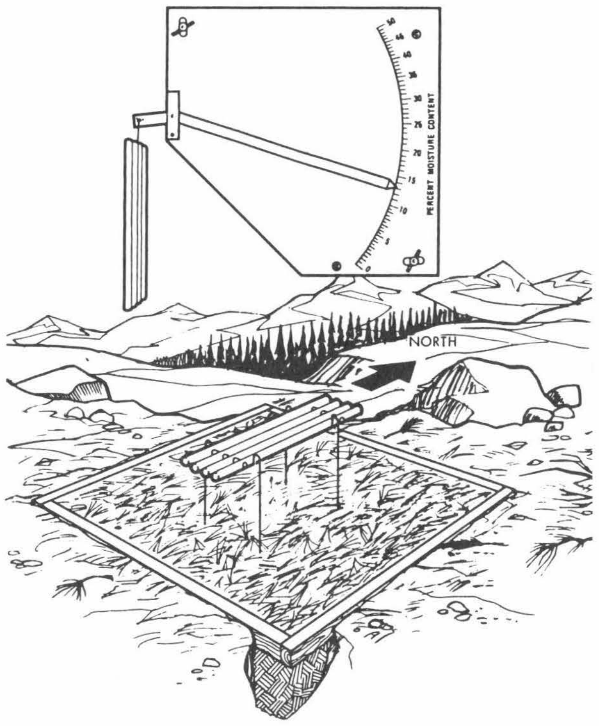


Figure 3.20. *Fuel moisture indicator sticks of the $\frac{1}{2}$-inch size are used to estimate the moisture content of dead fuels of comparable timelag. They are exposed on a wire rack 10 inches above a bed of litter. By weighing them, their moisture content can be obtained.* From Schroeder and Buck (1970).

progressive drying of plants. An experiment at several sites came up with the following relationship: green is >100%, purple is 30–100%, and straw is <30%.

Fuel moisture inference can also be applied at a very different scale. Burgan and Hartford (1993) discuss the use of satellite imagery to assess the state of live vegetation for wildland fire potential in the United States. (Similar methods have been applied elsewhere.) The Normalized Difference Vegetation Index (NDVI) is calculated from reflectance of red and near infrared light from earth's surface. The NDVI value is related to the amount of actively growing biomass, increasing with greenup and decreasing as vegetation cures.

Calculation For some types of fuel, mathematical models have been developed for calculating fuel moisture as a function of observable weather variables. Because the response of dead fuels is physical rather than biological, more work has been put into those models. A fine dead fuel moisture model can be based on recent conditions, while a larger fuel must be calculated from a longer record of weather data. Calculations are especially valuable in using forecasted weather to assess future moisture values, in planning applications, and in comparing one day to the next or one site to another. Models provide consistency. All of the influencing variables are not included in the models, nor will site variability be reflected. Models won't give the moisture for individual fuel particles, but rather a representative value for an area.

3.5 SELECTED EXAMPLES

Following is a discussion of two fuel complexes, palmetto–gallberry in the southeastern United States and aspen in the western United States. Concepts of fuel type, fuel state, and change over time are illustrated.

Palmetto-Gallberry

Palmetto and gallberry are two of the most common plants occurring in forest understories on the Lower Coastal Plain of the southeastern United States. In this area, live and dead fuels accumulate so rapidly that a wildfire in a 5-year accumulation can seriously damage or kill the pine overstory, even though the pines are fire resistant. To preclude destructive wildfires, burning is often prescribed for hazard reduction (Figure 3.21). The fuel type, called palmetto–

Figure 3.21. *The palmetto-gallberry fuel type in the southeastern United States is burned periodically to reduce fire hazard in pine plantations.* Photo from USDA Forest Service.

gallberry, is the complex association of saw palmetto and common gallberry with many other plants beneath slash pines or mixtures of slash and longleaf pine. Openings frequently contain small shrubs and wiregrass.

The mathematical model developed by Rothermel (1972) predicts fire spread and intensity best if the fuel is relatively homogeneous. It is difficult to adequately characterize a heterogeneous fuel complex like the palmetto-gallberry type where fuel height and fuel loading vary widely. Fuel height may range from 1 to 6 or more feet, while loading may vary widely from 1 to 25 tons/acre. This variation makes it impossible to construct a single fuel model that is typical of the type.

Hough and Albini (1978) characterized the palmetto-gallberry fuel complex and then adjusted several variables, such as fuel depth and moisture content of extinction, so that the output of Rothermel's model was representative of measured fire behavior. They developed a dynamic fuel model that accounts for site conditions, fuel-accumulation time, and species composition. The model permits reasonably precise prediction of fire behavior, as well as systematic analysis of the consequences of fuel treatments.

A palmetto-gallberry fuel complex can be completely described by specifying age of rough (years since last burn), height of understory (visual height), percentage of coverage by palmetto, basal area of overstory stand, and moisture content of dead and live fuels. The first three variables define the standing understory fuel loadings by size class. The overstory stand density (basal area) is an indicator of tree biomass and hence of foliar litter production rate. This variable, in conjunction with the age of the rough, permits the computation of litter accumulation (pine needles) on the site. The equations used to estimate fuel loading are given in Figure 3.22. Physical and chemical characteristics of fuel components are given in Figure 3.23.

Fuel component dry weight	Regression equation
Live foliage	$-0.0036 + 0.00253(AR) + 0.00049\ (PPal) + 0.00282(HT^2)$
Live 0–$\frac{1}{4}$ inch	$+0.00546 + 0.00092(AR) + 0.00212(HT^2)$
Live $\frac{1}{4}$–1 inch	$-0.02128 + 0.0014(AR^2) + 0.00314(HT^2)$
Dead foliage	$+0.00221(AR^{0.51263})\ \exp\ (0.02482\ (PPal))$
Dead 0–$\frac{1}{4}$ inch	$-0.00121 + 0.00378(\ln AR) + 0.00118(HT^2)$
Dead $\frac{1}{4}$–1 inch	$-0.00775 + 0.0021\ (PPal) + 0.00007(AR^2)$
L layer	$(0.03632 + 0.0005336(BA))\ (1 - (0.25)^{AR})$

Note: AR, age of rough (years); PPal, coverage of area by palmetto (%); HT, height of understory (ft); BA, basal area of overstory (ft^2/acre).

Figure 3.22. *Equations used to estimate fuel loading (lb/ft^2 on dry-weight basis) of palmetto-gallberry fuel components used as input to Rothermel's 1972 fire model.* From Hough and Albini (1978).

Fuel condition and size class	Low heat value (Btu/lb)	Particle density (lb/ft^3)	Total ash (lb/lb)	Silica-free ash (lb/lb)	Surface area/volume (ft^2/ft^3)
Aerial fuels					
Live foliage	8175 ± 92	45.5 ± 3.4	0.041 ± 0.007	0.015 ± 0.007	2322 ± 211
Live 0–$\frac{1}{4}$ inch	8302 ± 66	49.6 ± 1.5	0.032 ± 0.005	0.017 ± 0.006	467 ± 98
Live $\frac{1}{4}$–1 inch	8166 ± 179	47.4 ± 3.2	0.016 ± 0.002	0.012 ± 0.001	166 ± 35
Dead foliage	8299 ± 256	30.7 ± 1.0	0.038 ± 0.001	0.009 ± 0.002	1999 ± 359
Dead 0–$\frac{1}{4}$ inch	8229 ± 184	31.9 ± 2.7	0.031 ± 0.006	0.010 ± 0.006	322 ± 60
Dead $\frac{1}{4}$–1 inch	8167 ± 335	27.4 ± 4.3	0.013 ± 0.002	0.006 ± 0.002	151 ± 37
Surface fuels					
Dead L layer	8592 ± 138	30.4 ± 3.2	0.036 ± 0.016	0.012 ± 0.016	1806 ± 230
Dead 0–$\frac{1}{4}$ inch	8229	31.9	0.031	0.010	325 ± 52
Dead $\frac{1}{4}$–1 inch	8393 ± 119	27.0 ± 4.2	0.018 ± 0.008	0.011 ± 0.004	107 ± 23

Note: Values are means ± standard deviations.

Figure 3.23. *Physical and chemical characteristics averaged over all plots by major fuel conditions and size classes representing the palmetto-gallberry fuel complex.* From Hough and Albini (1978).

Aspen

Aspen is widely distributed throughout North America. It occupies approximately 7 million acres in the western United States. Fire has played an integral part in the development of aspen forests (see Figure 3.2e). Aspen exists as both a climax and seral species but is seral on the majority of sites, eventually to be replaced by conifers. On stable aspen sites, frequent fires can maintain a grass-forb community, with aspen suckers confined to the shrub layer. Infrequent fires produce varying effects on stand structure. Low-intensity fires cause thinning and encourage an all-aged condition. High-intensity fires result in new even-aged stands. Seral aspen is gradually replaced by conifers. This may take 200 to 400 years or more, depending on the potential for establishment and growth of conifers. If succession continues without fire, aspen will eventually be crowded out.

Brown and Simmerman (1986) provide methods for appraising fuels and flammability in aspen forests as a means for choosing good opportunities for prescribed burning and for determining the environmental conditions favorable for a successful burn. Fuels were classified into five types that differed substantially in vegetation and potential fire behavior. The classification of understories was keyed to amount of shrubs and productivity of herbaceous vegetation. Photographs of each plot were rated in terms of potential fire behavior for an "average bad" fire weather situation. Five expressions of fire behavior were rated: rate of spread, fire intensity, torching, resistance to control, and overall fire potential. An example from the photo series is shown in Figure 3.24. Figure 3.25 is a summary of fuel data from the sampled stands. Predicted fireline intensities for typical late summer conditions (Figure 3.26) reflect the differences among fuel types due to fine fuel loadings, particularly the high herbaceous component.

Determining when fuels are ready to burn is more complicated in aspen forests than in most other vegetation types. Curing is probably the most important variable to monitor. Finding the proper time for ignition requires waiting until live fuels are adequately cured and selecting the time when windspeed and dead fuel moistures are in prescription. Adequate curing is particularly important where herbaceous vegetation is the primary fine fuel. Curing increases flammability considerably in these types. The trade-off, however, between waiting for further curing to increase flammability and autumn rains that end the burning season means that aspen stands should be burned as soon as possible. Delays in burning will result in fewer accomplishments because the time in prescription is usually short.

Figure 3.27 shows curing trends and moisture content of live fuels in aspen stands for two seasons. The grasses had substantially lower moisture contents and cured at faster rates during early summer than forbs. Differences in moisture contents of the green and transition stages was relatively small, especially for forbs. Thus moisture contents of the green and transition stages can be considered the same for purposes of estimating curing and judging flammability. The transition stage typically is characterized by yellowing of plant parts.

Fuel class: Aspen/tall forb — Stand No. 21

Community type: *Populus tremuloides/Ligusticum filicinum*

FUEL LOADINGS	*Lb/acre*	*kg/m²*
a. Herbaceous	1,060	0.119
b. Shrub	40	.004
c. Litter	1,130	.127
Downed woody		
d. 0 to ¼	180	.020
e. ¼ to 3	16,030	1.797
f. 3+	59,510	6.670
Subtotals		
Fines	2,400	.270
D. woody 0-3	16,210	1.816

VEGETATION CHARACTERISTICS	
Shrub cover, %	3
Basal area, ft²/acre	
Aspen	203
Conifer	0

FIRE RATING	
Intensity	Low-Med
Rate of spread	Low
Torching	Low
Resistance to control	Medium
Overall	Low-Med
Probability of a successful burn	Moderate

STAND LOCATION	
National Forest	Bridger-Teton
Ranger District	Jackson
Drainage	Little Dry Cottonwood Creek
Photo date	September 1983

Figure 3.24. *Example from the photo series for aspen fuels.* From Brown and Simmerman (1986).

Fuel	Aspen/ shrub	Aspen/ tall forb	Aspen/ low forb	Mixed/ shrub	Mixed/ forb
			Lb/acre		
Herbaceous	670 (230 to 1,000)	1,330 (1,030 to 2,020)	300 (180 to 460)	90 (80 to 90)	290 (10 to 550)
Shrubs[1]	3,170 (980 to 6,150)	110 (0 to 440)	260 (0 to 630)	3,040 (2,480 to 3,610)	630 (100 to 1,350)
Litter	1,810 (420 to 2,810)	1,600 (790 to 2,240)	1,350 (170 to 2,740)	1,980 (1,920 to 2,040)	1,680 (740 to 2,560)
Fines[2]	6,140 (4,030 to 9,390)	3,170 (1,970 to 3,990)	2,430 (1,640 to 3,330)	6,050 (5,850 to 6,250)	3,070 (2,150 to 3,560)
Downed woody 0 to 1 inch	2,440 (710 to 4,220)	1,080 (620 to 1,440)	2,600 (1,460 to 3,690)	4,240 (3,400 to 5,080)	2,710 (1,440 to 3,900)
Downed woody 0 to 3 inch	7,020 (3,580 to 12,510)	7,340 (1,510 to 16,210)	5,720 (3,290 to 7,600)	6,970 (5,550 to 8,390)	7,810 (4,090 to 12,250)
			Percent		
Shrub cover	40 (30 - 60)	10 (0 - 20)	10 (0 - 30)	60 (60 - 70)	20 (10 - 30)

[1] Shrubs include foliage and stemwood.

[2] Fines include live and dead herbaceous plants and shrubs, litter, and 0- to ¼-inch downed woody fuel.

Figure 3.25. *Average fuel loadings and shrub cover from sampled stands representing the aspen fuel types. Ranges in values are in parentheses.* From Brown and Simmerman (1986).

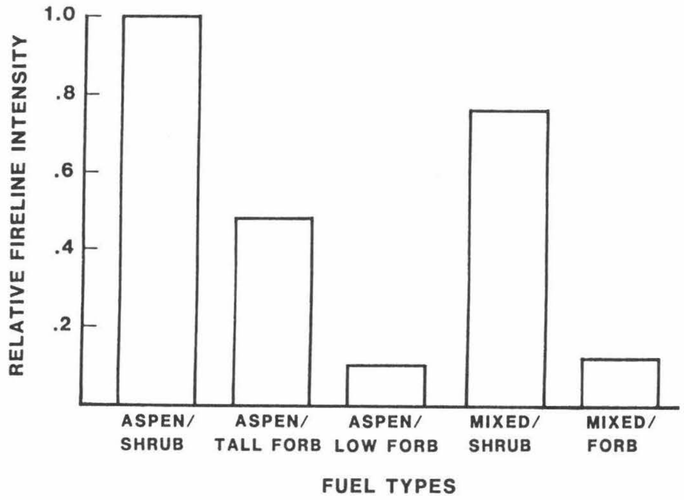


Figure 3.26. *Fireline intensity calculated under the assumption that 50% of the herbaceous vegetation is cured, fine fuel moisture content is 8%, slope is 0%, and midflame windspeed is 4 mi/h. The intensities are relative, being expressed as a fraction of the intensity for aspen/shrub.* From Brown and Simmerman (1986).

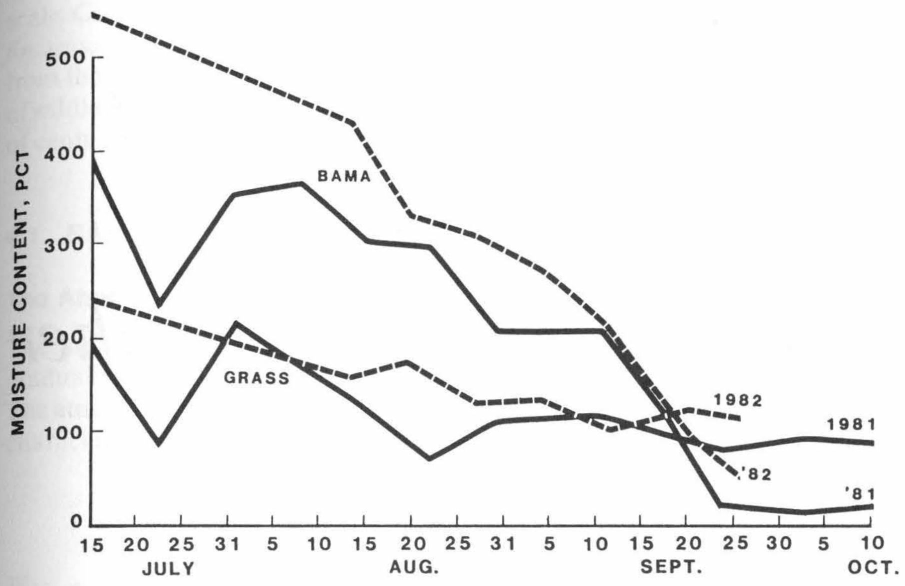


Figure 3.27. *Moisture content of herbaceous vegetation from an aspen stand in Wyoming. Precipitation during August and September was 1.56 inches in 1981 and 4.66 inches in 1982.* From Brown and Simmerman (1986).

Cured leaf tissue shows brown coloration rather than yellow. Cured grass stocks remain straw colored, but the yellow is largely washed out.

Under aspen canopies, frost damage occurs later than in open areas or than in low-lying areas where cold air collects. A hard freeze, however, can cure live vegetation quickly. Temperatures less than 15 to 20°F can cure forbs and shrub foliage in just a few days. If the freeze occurs before abscission layers form, the shrub leaves will remain attached to the stems, adding to the flammability of surface fuels.

FURTHER READING

Fuel models for the U.S. Fire Behavior Prediction System are described by Anderson (1982) in "Aids to Determining Fuel Models for Estimating Fire Behavior," by Burgan and Rothermel (1984) in "BEHAVE: Fire Behavior Prediction and Fuel Modeling System—FUEL Subsystem" and by Burgan (1987) in "Concepts and Interpreted Examples in Advanced Fuel Modeling."

Canadian fuel types are described by the Forestry Canada Fire Danger Group (1992) "Development and Structure of the Canadian Forest Fire Behavior Prediction System." Canadian fuel types are also illustrated in posters such as Alexander and Lanoville's (1989) "Predicting Fire Behavior in the Black Spruce-Lichen Woodland Fuel Type."

Schroeder and Buck (1970) include a good chapter on fuel moisture in their book *Fire Weather.*

4

Fire Weather

Weather is an important leg of the fire environment triangle (see Figure 2.2). At times it can totally dominate the fire environment, overshadowing the influence of fuel and topography. Running crown fires can spread through mountainous terrain essentially without regard to topography. The influence of fuel moisture and fuel distribution can be neutralized when a fire is being driven by strong winds. On the other hand, the influence of weather can be more subtle. The diurnal variation in temperature and humidity, for example, has a significant influence on fuel moisture and therefore on fire behavior.

Weather is the state of the atmosphere and the changing nature of the atmosphere surrounding the earth. Fire weather includes those elements that influence wildland fire, both on the surface and up to 10 miles above the land.

Methods of fire behavior prediction were discussed in Chapter 2. The success of predicting fire behavior is in a large part dependent on the ability to forecast the weather, a difficult task even for a fire weather forecaster. Success in fire behavior prediction also depends on observation and interpretation, the ability to recognize patterns and interactions. Anyone involved with wildland fire should have a basic understanding of fire weather. Its interpretation is an art.

The question of scale in both time and space is important. Meteorology may be considered on a macro scale, the circulation of air around the globe; on a meso scale, the movement of particular air masses and large scale eddies and on a micro scale, where local heating and cooling differentials, site-specific winds, surface inversions, and microclimates are the objects of interest.

Weather changes and effects can be abrupt, as in the case of lightning strikes and microbursts. Fire weather is often viewed at an hourly or daily scale. Changes throughout the year, in both weather and fuel, determine the *fire season*. A look at weather for many years determines the *fire climate*. And from the very long view, discussions of *global climate change* examine the role of wildland fire as both a cause and an effect of change that occurs on the order of centuries.

4.1 BASIC WEATHER PROCESSES

The Atmosphere

The atmosphere extends hundreds of miles above the earth, but thins so gradually that it is impossible to say exactly where it ends and space begins. The atmosphere is divided into several layers, based primarily on temperature characteristics (Figure 4.1).

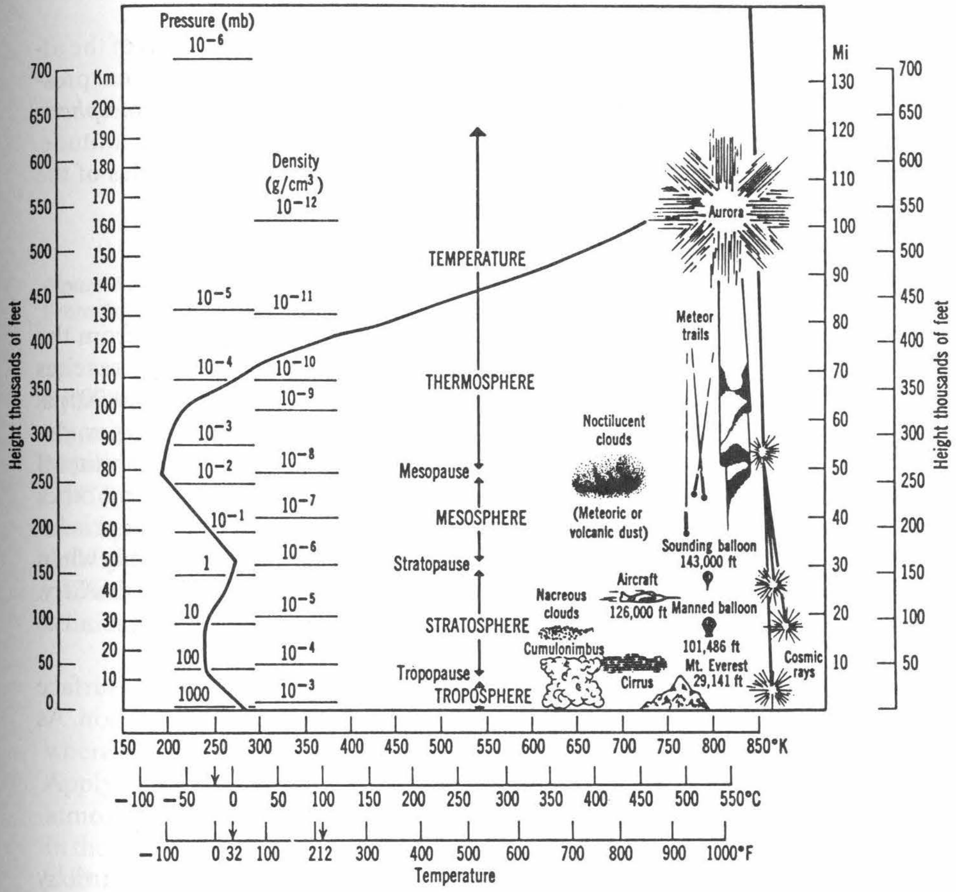


Figure 4.1. *Structure of the atmosphere.* From Cole (1975).

The troposphere is the lowest layer of the atmosphere. Temperature generally decreases with altitude, except for occasional shallow layers. Its depth varies from 5 miles over the North and South poles to about 10 miles over the equator. The transition between the troposphere and the stratosphere is the tropopause, the approximate top of thunderstorm activity.

The troposphere is the region of changeable weather and contains three-quarters of the earth's atmosphere by weight. We will concentrate our attention on this layer. Air in the troposphere is composed of primarily two gases. Dry air contains about 78% nitrogen by volume and 21% oxygen. Of the remainder, argon makes up about 0.93% and carbon dioxide between 0.03 and 0.04%. In addition to these gases, the troposphere contains a small, though significant, amount of water vapor, from near zero in desert and polar regions up to 4 or 5% in jungle regions. Water vapor has a very important effect on weather; without it, there would be no clouds or rain. The troposphere also contains salt and dust particles, smoke, and other industrial pollutants. These impurities affect the visibility through the atmosphere and also serve as nuclei for the condensation of water vapor and cloud formation.

The total weight of a 1-inch square of air from sea level to the top of the atmosphere averages 14.7 lb or 29.32 inches of mercury. This is the normal pressure exerted by the atmosphere at sea level and is called the *standard atmospheric pressure.* Atmospheric pressure rapidly decreases with increasing altitude. Nearly half of the weight of the atmosphere is within about 3.5 miles of the surface.

Earth's Heat Balance

Nearly all heating of the earth's surface and its atmosphere comes from the sun through solar radiation. On the average, 50% of the sun's energy reaches the earth's surface, 30% of the heat energy is reflected into space, and 20% is absorbed by the atmosphere. The distribution of solar radiation varies, depending on location and atmospheric conditions (Figure 4.2). The ability of the atmosphere to retain heat through absorption by water vapor and other gases is called the *greenhouse effect.* Thus, the drop in surface temperature is far less on cloudy nights than on clear nights. This effect is quite noticeable when comparing the rapid temperature fall at night in the desert, where the air is dry, with the slower decrease in temperature in coastal regions, where the air is moist.

The earth also loses heat by processes other than radiation. Some surface heat is transferred to the surrounding air by conduction and convection. As the ground cools, the air in contact with it also cools.

Atmospheric Pressure, Volume, and Temperature

The earth's weather circulation results from differential heating of the earth by the sun and by the process the atmosphere goes through in trying to come to equilibrium. Winds, storms, and clouds are the result of the relationships among atmospheric pressure, volume, temperature, and water vapor content. Many weather processes can be attributed to one or both of these two concepts: (1) Compression of the atmosphere results in warming and expansion of the atmosphere in cooling, and (2) colder air is denser and will sink when surrounded by warmer air.

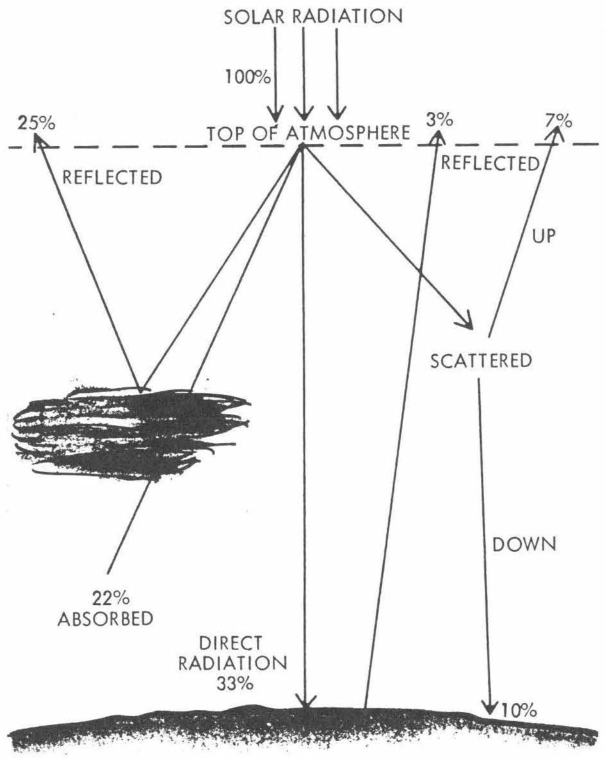


Figure 4.2. *Approximate distribution of incoming solar radiation during average cloudiness.* From Schroeder and Buck (1970).

The temperature of air changes as pressure and volume change. This relationship can be described by the Ideal Gas Equation:

$$pv = mRt$$

where p is pressure, v is volume, m is mass, t is temperature, and R is a constant. Applying this equation to air, we find that temperature and volume change as atmospheric pressure changes. For example, if a parcel of air is lifted vertically in the atmosphere, its volume will increase and its temperature will cool due to a decrease in atmospheric pressure. Conversely, a descending parcel of air will warm and decrease in volume because of increasing atmospheric pressure.

Thus, air expands and cools as it is lifted to higher elevations and warms and compresses as it descends to lower elevations.

The Ideal Gas Equation also shows another important relationship, this time in the horizontal. Since volume is related to density (mass per unit volume or *m/v*), we can say that warming is accompanied by a decrease in density, and cooling by an increase in density. Thus, colder air is denser and will sink when surrounded by warmer air.

Temperature-Humidity Relationships

When discussing atmospheric moisture, the amount present at any one time or place is commonly quantified as dew point temperature, relative humidity, and wet bulb temperature. *Dew point* is the temperature to which air must be cooled to reach its saturation point at constant pressure. It is a measure of the air's absolute humidity, or how much water vapor is in the air. If air cools to its dew point, condensation occurs and dew, fog, or clouds will form.

To determine exactly how dry or moist the air is at any given time or place, we use a unit of measure called relative humidity. *Relative humidity* is the ratio of the amount of moisture in the air to the amount that the air could hold at the same temperature if it were saturated. Relative humidity is always expressed as a percentage.

The amount of moisture in the air can also be determined by the *wet bulb temperature*, the lowest temperature to which the air can be cooled by evaporating water into it at constant pressure. The greater the difference between the wet and dry bulb temperatures, the drier the air.

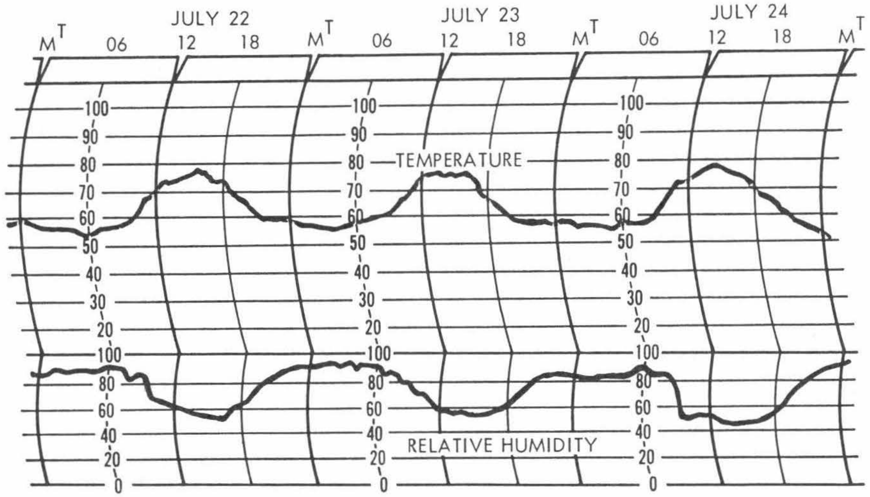


Figure 4.3. *Typical temperature and relative humidity traces for a low-level station are nearly mirror images of each other. They are less closely related at mountain stations.* From Schroeder and Buck (1970).

As temperature goes up at constant pressure, relative humidity goes down and vice versa. Maximum relative humidity generally occurs about sunrise, at the time of minimum temperature. After sunrise, humidity drops rapidly and reaches a minimum at about the time of maximum temperature. It rises more gradually from the late afternoon through the night. This is called the *diurnal variation* of temperature and humidity (Figure 4.3).

Changes in terrain, vegetation, clouds, and wind can create wide ranges in temperature and relative humidity over a small area. The controlling factor is how these parameters affect the amount of incoming and outgoing radiation that impacts the ground. Wind mixes the air near the ground, and vegetation intercepts incoming solar radiation during the day and outgoing radiation at night (Figure 4.4).

Daytime temperatures normally decrease with altitude with a corresponding rise in relative humidity. When nighttime cooling begins under clear skies, the temperature change with height is usually reversed. Cold air flows downslope and collects in the valley, resulting in colder air and higher relative humidity at lower elevations than at higher elevations.

4.2 ATMOSPHERIC STABILITY

Atmospheric stability is the resistance of the atmosphere to vertical motion. The earth's atmosphere is constantly moving and mixing. Air moves horizontally or vertically in response to the earth's rotation and to large and small changes in temperature and pressure. Wind is the horizontal movement of air. The vertical movement of air is related to stability. Depending on the temperature distribution in the atmosphere, air can rise, sink, or remain at the same level. Stable air resists vertical motion. Unstable air encourages vertical motion.

Lapse Rates

Lapse rate is the change in temperature with altitude. Normally, temperature decreases with altitude, but this can change as daytime solar heating and nighttime cooling change the temperature distribution of the lower atmosphere. The temperature lapse rate can range from a +15°F/1000 ft to a −15°F/1000 ft. The lapse rate continually changes as air circulates within the atmosphere and is warmed by compression or cooled by expansion. If this movement occurs without a transfer of heat or mass into the system, it is called an *adiabatic process.* When discussing atmospheric stability we are concerned with three lapse rates: dry lapse rate, moist lapse rate, and average lapse rate.

The *dry adiabatic lapse rate* is 5.5°F/1000 ft. A bubble or layer of dry (unsaturated) air will always have a temperature decrease of 5.5°F/1000 ft when lifted due to decreasing pressure and expansion. On the other hand, it will have a temperature increase of 5.5°F/1000 ft if it is forced downward and is compressed.

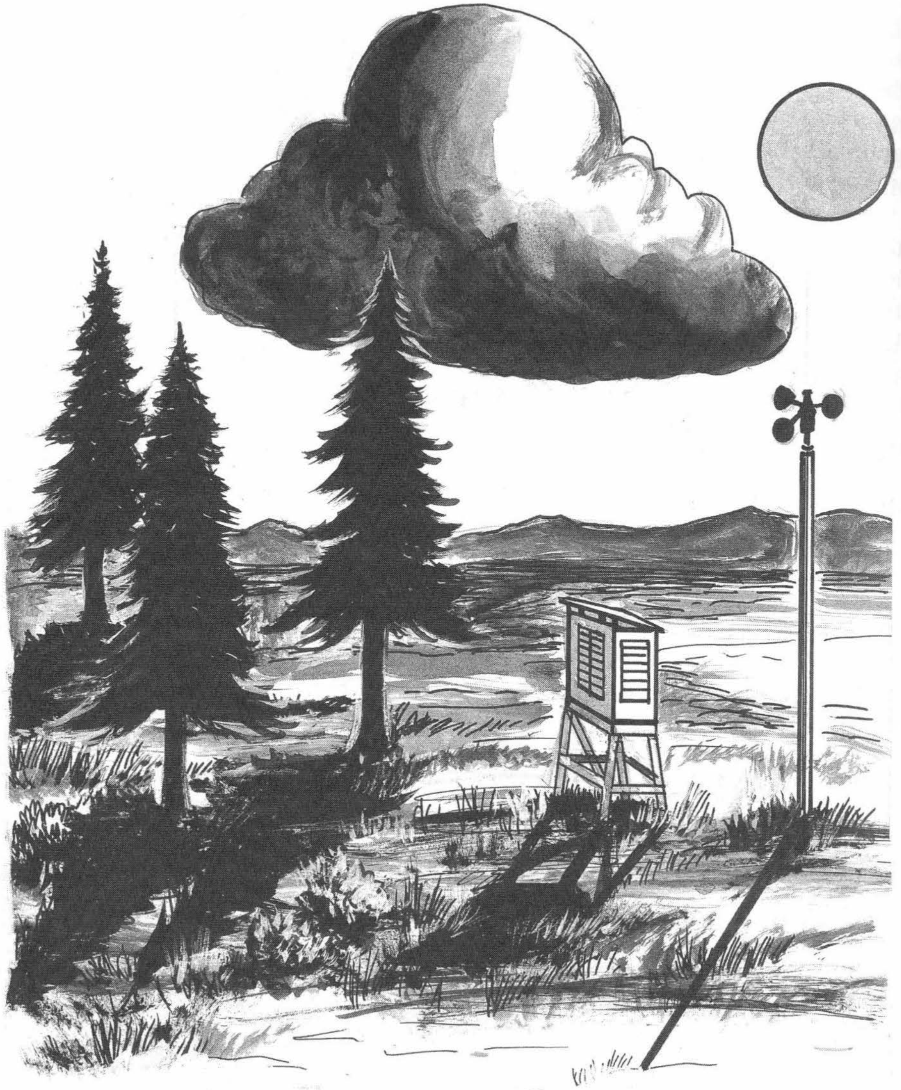


Figure 4.4. *Incoming solar radiation is affected by vegetation cover and clouds.* From Rothermel and others (1986).

The *moist adiabatic lapse rate* is 3°F/1000 ft. When air cools, its relative humidity increases. When a bubble or layer of air rises in the atmosphere, it cools with a corresponding rise in relative humidity. Air rises and cools at the dry adiabatic lapse rate until it reaches its saturation point. If it continues to rise, it will cool at the moist adiabatic lapse rate (Figure 4.5). If the relative humidity reaches 100%, the air becomes saturated and clouds form. This saturated air now cools at a lesser rate due to latent heat of condensation.

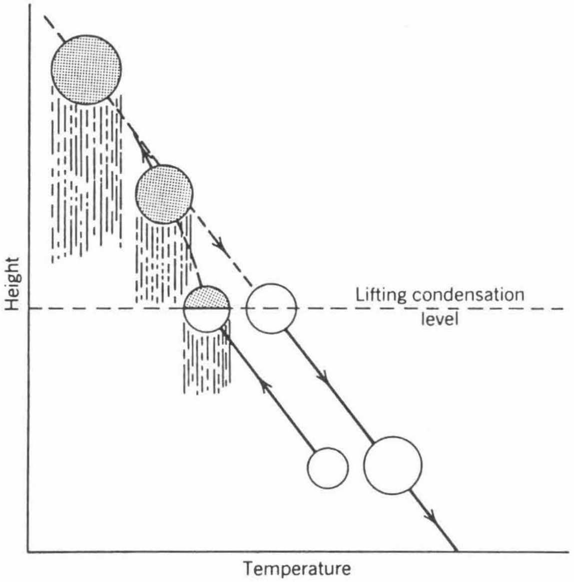


Figure 4.5. *A parcel of air is lifted according to the dry adiabatic rate until it reaches saturation, from which point it rises according to the wet adiabatic rate. Precipitation means that energy and mass have been lost from the system, so the descent process does not simply reverse the ascent. The parcel returns warmer and drier than it began.* From Cole (1975).

The atmosphere may or may not have a temperature distribution that fits the dry or moist lapse rates. Usually it does not. The average temperature change throughout the lower atmosphere over time and space is about 3.5°F/1000 ft.

Stability

Air may be stable or unstable, depending on its temperature lapse rate. If the temperature decrease in the air mass is greater than 5.5°F/1000 ft, the air is *unstable* (Figure 4.6). Unstable air encourages the vertical movement of air and tends to increase fire activity. If the temperature decrease in the air mass is less than 5.5°F/1000 ft, the air is *stable*. Stable air discourages the vertical movement of air and usually decreases or holds down fire activity.

Unstable air can contribute to increased fire behavior by increasing the chances of firewhirls, by increasing the potential for gusty surface winds, by increasing the heights and strengths of convection columns, and by increasing the chance of firebrands being lifted by the column. With unstable air, stronger winds aloft can be brought down to the lower atmosphere and produce stronger and gusty surface winds. There is better ventilation so air quality problems are usually minimized. Smoke convection columns rise much higher in unstable air. Chimneys, of a sort, develop, with indrafts feeding the

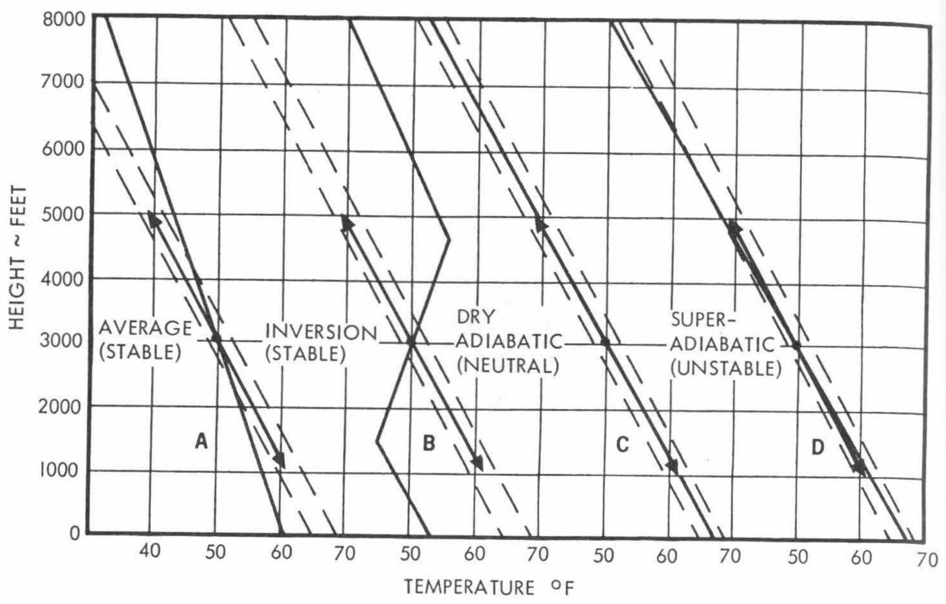


Figure 4.6. *In unsaturated air, the stability can be determined by comparing the measured lapse rate (solid lines) to the dry-adiabatic rate (dashed lines). The reaction of a parcel to lifting or lowering may be examined be comparing its temperature (arrows for parcel initially at 3000 feet and 50°F) to the temperature of its environment.* From Schroeder and Buck (1970).

fire at the base of the column and strong convective currents rising through the column. The greater the instability and fire intensity, the stronger the indrafts and convection column updrafts.

The *Haines Index* (1988) is a stability index designed for fire weather use. It is used to indicate the potential for wildfire growth by measuring the stability and dryness of the air over a fire. It is calculated by combining the stability and moisture content of the lower atmosphere into a number that correlates well with large fire growth. The stability term is determined by the temperature difference between two atmospheric layers; the moisture term is determined by the temperature and dew point difference. The Haines Index can range between 2 and 6. The drier and more unstable the lower atmosphere is, the higher is the Haines Index.

Dry air affects fire behavior by lowering fuel moisture. Instability can enhance the vertical size of the smoke column, increasing chances of a plume-driven crown fire (see Figure 2.21).

Inversions

An *inversion* is a layer of very stable air where the temperature increases with increase in altitude. Temperatures in an inversion may increase as much as 15°F/1000 ft in altitude. Inversions act as a lid and severely limit vertical motion in the atmosphere. Smoke will generally rise to the inversion, then flatten out and spread horizontally. There are three types of inversions, categorized by how they are formed and whether they are located at the earth's surface or aloft: radiation or nighttime inversion, marine inversion, and subsidence inversion.

Radiation or *nighttime inversions* are the most common type of inversion. They are formed when air is cooled at night, primarily by contact with the earth's surface, creating a condition of cool, heavier air below warmer air. The layer of cool air near the surface deepens as the night progresses. This produces a very stable condition, warm air above cool air. Conditions usually begin to reverse after sunrise. Inversions usually disappear sometime before noon as unstable conditions continue to develop. When the inversion dissipates and unstable conditions develop, fire activity can increase, sometimes rapidly. Winds may increase suddenly, temperatures increase, and relative humidity decrease.

The *marine inversion* is a common type of inversion found along the coast, particularly along the west coast of the United States. In this case, cool, moist air from the ocean spreads over low-lying land. The marine layer is topped by much warmer, drier, and relatively unstable air.

Subsidence inversions are associated with high-pressure systems in the upper atmosphere. Sinking air in a high-pressure system warms and dries as it descends to lower altitudes. This results in a layer of warm, dry air that becomes progressively warmer and drier as it drops closer to the surface. Subsidence is a slow process that occurs over a period of several days.

Normal daily changes in stability are related to temperature changes. For a typical summer day with clear skies and light winds, the lowest layers of the atmosphere are stable at night, with the greatest stability just before sunrise, and unstable during the late morning and afternoon, with the greatest instability during late afternoon, the hottest part of the day.

Normal seasonal variations in stability are related to the seasonal variations in temperature. Winter has more stable conditions than the other seasons due to colder temperatures and longer nights. Conversely, summer is the most unstable season due to warmer temperatures and longer hours of sunlight. Spring and fall are harder to define.

Stability affects the shape, growth, and size of smoke columns. If we hold factors such as fuel, topography, and other weather elements constant, unstable air will enhance the vertical development (shape), rapid expansion (growth), and increased proportions (size) of smoke columns as compared to stable conditions.

Lifting Processes and Thunderstorm Development

There are four lifting processes that can cause thunderstorm development: convection or thermal, orographic, frontal, and convergence (Figure 4.7).

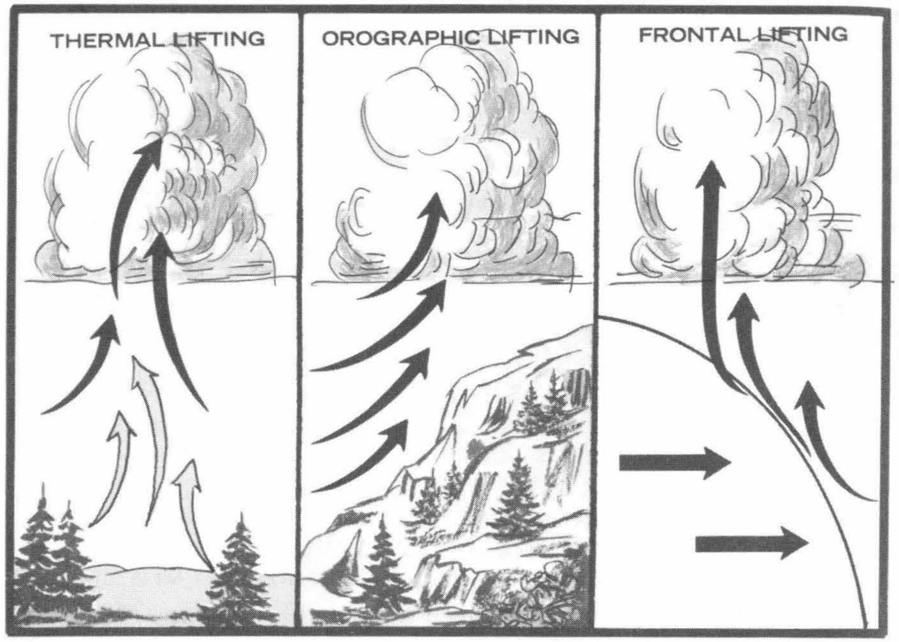


Figure 4.7. *Lifting processes that can cause thunderstorm development.* From Schroeder and Buck (1970).

Strong heating of air near the ground results in *thermal lifting*. As the air warms, it becomes buoyant and cools as it is forced aloft. If the heated air contains enough moisture and rises high enough in the atmosphere, condensation will occur and cumulus clouds will form.

Orographic lifting occurs in mountainous terrain when a mass of moving air is forced to rise because of the presence of a slope. Air that is forced upward cools at the dry lapse rate. If this air cools to its dew point temperature, clouds develop.

With the *frontal lifting* process a moving, cooler air mass pushes its way under and lifts a warmer air mass. Again, this lifting action can produce cumulus clouds if saturation occurs. Cumulus cloud development is usually associated with cold front passages, while stratus clouds generally accompany a warm front.

Convergence is present during all of the three preceding lifting processes, but it can also be an independent mechanism. Convergence occurs when more air moves horizontally into an area than moves out. The excess air is forced upward. Lifting by convergence always occurs around low-pressure systems or in areas of opposing wind directions. With more air flowing toward the center of the low, air piles up and is forced upward.

Thunderstorms have many variations in growth and behavior, but typically go through three stages of development and decay: cumulus, mature, and dissipating stages (Figure 4.8). The *cumulus stage* starts with a rising column of moist air that develops a cumulus cloud that grows vertically. The towering cumulus cloud takes on a cauliflower-like appearance, with clear-cut tops. These clouds have strong indrafts into the base of the cloud that may increase surface winds. Updrafts in the cumulus or towering cumulus stage can cause wind directions to change as the air begins to move toward the developing cumulus cloud.

The *mature stage*, the most active portion of the thunderstorm cycle, begins when rain or virga starts falling out of the base of the cloud. The frictional drag exerted by the rain initiates a downdraft. There is now a downdraft in part of the cloud and an updraft in the remainder. The updraft is warmer and the downdraft is colder than the surrounding air in the cloud. An anvil-shaped layer, composed of ice crystals, forms at the top of the cloud and lightning occurs. It is now a thunderstorm and the cloud is called a cumulonimbus cloud. Downdrafts that reach the ground result in cool, gusty surface winds that can be experienced within about 10 miles or so of the thunderstorm.

During the *dissipating stage*, the entire thunderstorm becomes an area of downdrafts. As the updrafts end, the source of moisture and energy for continued growth and activity is cut off. Rain falls from the cloud, but becomes lighter and eventually ends. Gradually the downdraft weakens, the rain ends, and the cloud begins to dissipate.

Lightning

In fair weather, the atmosphere has a positive charge with respect to the earth. When a cumulus cloud grows into a cumulonimbus, the electrical fields in and near the cloud are altered and intensified. The charges are held on water drops and ice particles. The upper portion of the cloud becomes predominately positively charged and the lower portion becomes negatively charged. The negative charge near the cloud base induces a positive charge on the ground, a reversal of the fair-weather pattern (Figure 4.9).

Most cloud-to-ground discharges originate in the cloud and progress to the ground. They take place in two stages. First, a leader stroke begins with a negative discharge from the cloud and works its way downward to the ground in a series of probing steps. The negative core is surrounded by positive charges. When the core gets within 30 ft or so of the ground, a breakdown event occurs. The negative core and positive surrounding charges combine, making a very hot, rapid discharge that is seen by the eye as lightning.

Lightning sometimes occurs in the cumulus stage, but reaches its greatest frequency at the time the cell reaches maturity and its greatest height. The start of rain beneath the cloud base at the beginning of the mature stage marks the onset of the greatest lightning danger. Once lightning has started, it may continue well into the dissipating stage of the cell.

Most lightning discharges are within a cloud or cloud-to-cloud. Cloud-to-ground lightning is usually a discharge between the negative lower portion of

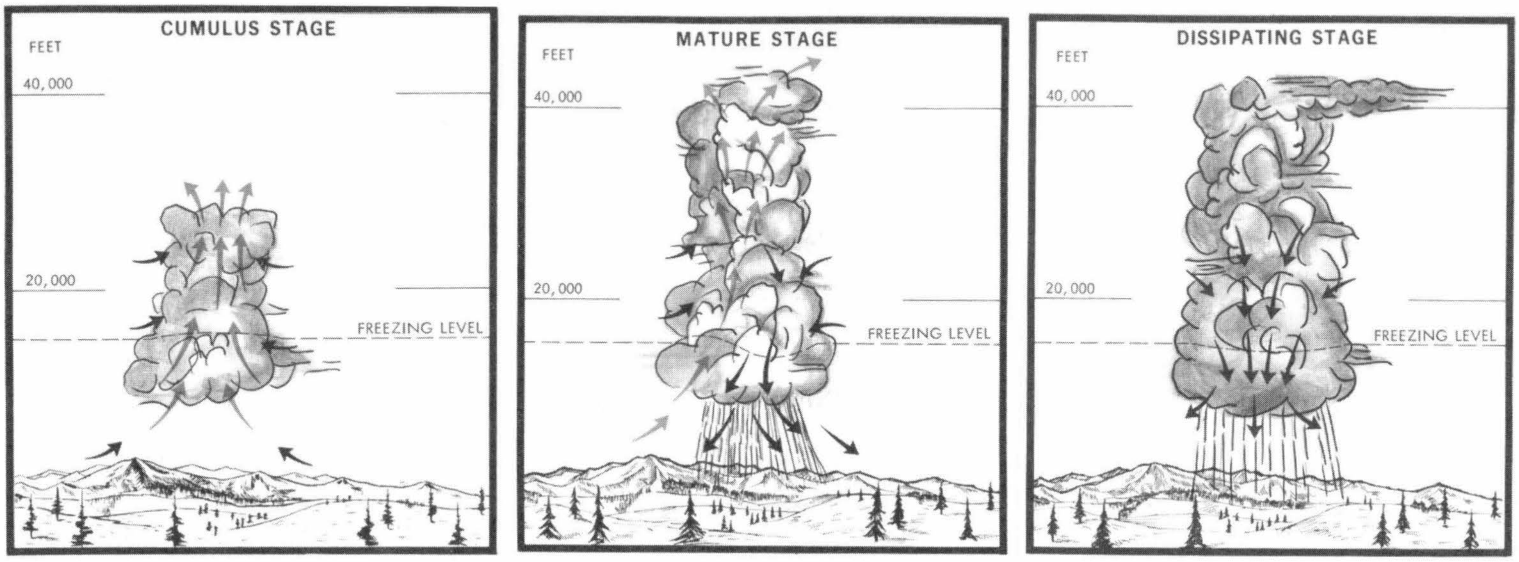


Figure 4.8. *Stages of thunderstorm development: cumulus, mature, and dissipating stages. From Schroeder and Buck (1970).*

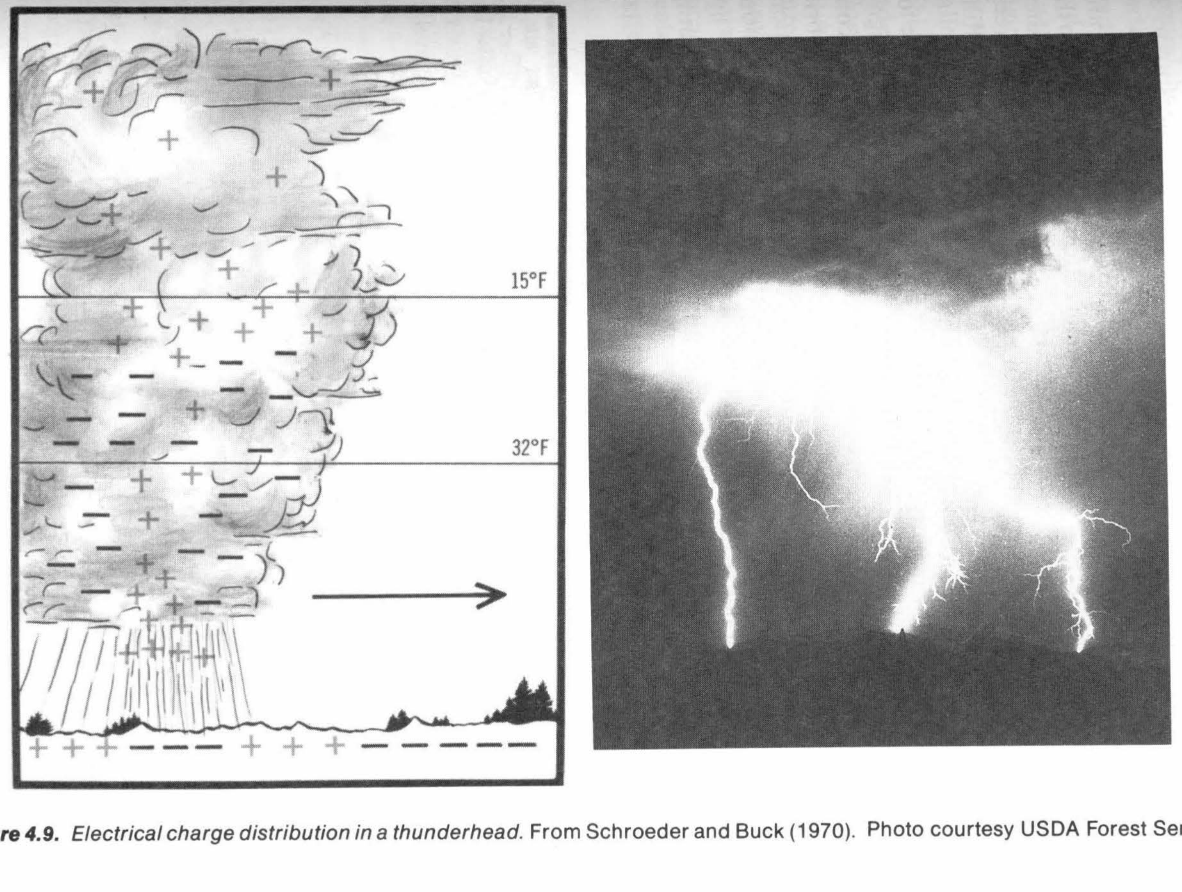


Figure 4.9. *Electrical charge distribution in a thunderhead.* From Schroeder and Buck (1970). Photo courtesy USDA Forest Service.

the cloud and the induced positive charge on the ground. There are, however, discharges that originate in the positive charge center near the top of the cloud or in anvils. In normal thunderstorms, about 5% of the discharges to ground are positive discharges. Positive discharges can occur at distances up to 30 miles from the cloud.

Discharges to ground have been separated into two types, positive and negative, according to the sign of the charge that is effectively moved from the cloud to the ground. These events are called positive and negative flashes. Each flash to the ground, whether positive or negative, is composed of several discrete events called strokes. Each stroke is a charge-moving event, starting with a leader and ending with a return discharge.

Few of the positive or negative lightning strokes to ground are suitable for fire ignitions. Fuquay and others (1972) showed that strokes that cause ignition must have a special component called a continuing current (or long continuing current). Flashes that have continuing currents are called hybrid flashes. The characteristic that is important for fire ignition is its duration. Continuing currents can last up to about 0.5 s; the median value is about 0.125 s. About 20% of negative flashes and 95% of positive discharges are hybrid flashes. Of all flashes to ground, then, about 25% have a continuing current.

4.3 WIND

By simple definition, *wind* is the horizontal movement of air relative to the earth's surface. In the study of wildland fire we are concerned with winds of two scales in the atmosphere: the larger scale general wind and the smaller scale local wind.

General Winds

All winds blow in response to pressure differences. In the very broad synoptic scale, the winds that are produced are called *general winds. Winds aloft* are the winds that blow in the upper atmosphere, unaffected by friction from terrain or other surface characteristics.

The surface of the earth is characteristically rough and will disrupt the winds due to frictional effects. This creates a turbulent zone next to the earth's surface that varies in thickness with the roughness of the surface and the speed of the wind. The *free air* or *gradient winds* are those winds that occur at the top of the frictional disturbance layer. The average depth or thickness of this layer may be quite shallow over uniform, flat terrain; or it can be as deep as 2000 to 3000 ft in complex, mountainous terrain. The frictional layer also varies in depth from day to day.

Temperature differences lead to pressure differences, called *pressure gradients*. Whenever horizontal pressure gradients exist, the air will be subject to a force pushing it from higher toward lower pressure. This can be on a very large scale of hundreds of miles or on a very small scale of a few feet.

Several natural forces interact to produce continual movement of the air around the earth, thus producing widely varied weather patterns. Because the earth is not heated uniformly by the sun, resulting temperature differences lead to large-scale pressure differences. Warm air near the equator tends to rise and spread poleward in both hemispheres. Meanwhile, cold air at the poles sinks and flows toward the equator. As the air moves from the equatorial regions, it is affected by the earth's rotation. In the northern hemisphere, the air is deflected to the right as the earth rotates on its axis. This deflection is called the *Coriolis force*. The uneven heating and cooling of the earth is responsible for producing a series of *wind belts* that circle the earth at various latitudes. One of these wind belts is called the prevailing westerlies. Closer to the North Pole, high pressure is maintained and easterly winds occur.

At some latitudes, the air tends to pile up to cause belts of high surface pressure. These belts are never uniform, but instead consist of a series of rather large pressure cells. Some of the pressure cells are relatively fixed, such as the polar high, while others are migratory. Weather is closely dependent on the location and movement of these primary pressure cells and other smaller-scale pressure patterns. Surface pressure maps show cells of high pressure and cells of low pressure (Figure 4.10). Isobars are the lines of equal air pressure,

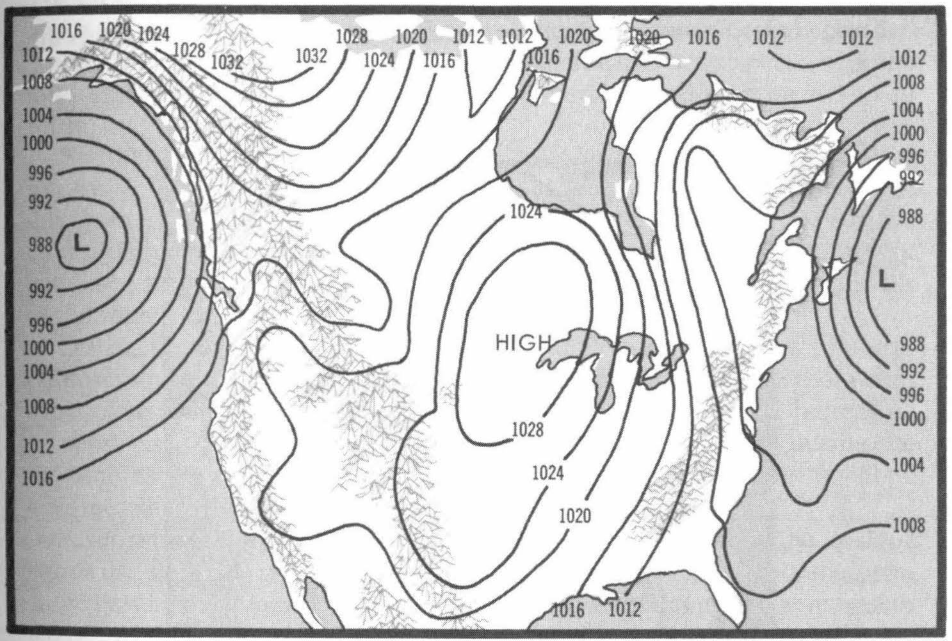


Figure 4.10. *A surface weather map is a graphical picture of the pressure distribution obtained by drawing lines, called isobars, through points of equal sea-level pressure. Isobars outline areas of high and low pressure.* From Schroeder and Buck (1970).

with their patterns outlining the areas of high and low pressure. The distance between isobars shows the pressure gradient. Windspeed is proportional to the gradient; where the gradient is tighter, the general winds are stronger, and where gradient is relaxed, the winds are lighter.

Typically, pressure cells move from west to east across the United States, being guided by the upper level westerlies. However, at times they can move in other directions, which further complicates weather patterns. Air in a high-pressure cell moves clockwise and outward from the cell; air in a low-pressure cell moves counterclockwise and toward the center of the cell. The boundary between two air masses of different temperatures and other characteristics is called a *weather front* (Figure 4.11). Typically, air masses are stable ahead of a front, unstable near the front, and stable behind the front.

Local Winds

Local or *convective winds* are smaller-scale winds caused by local temperature differences. Terrain has a very strong influence on local winds, and the more varied the terrain, the greater the influence. In many areas, the general winds are blocked by high terrain, and local winds are the predominant daily winds. Common local winds include sea and land breezes, slope winds, and valley winds.

As a result of local-scale temperature and pressure difference, a *sea breeze* begins to flow inland from over the water, forcing the warm air over the land to rise and cool adiabatically. In the absence of strong general winds, this air flows seaward aloft to replace air that has settled and moved toward shore, and thus completes a circulation cell.

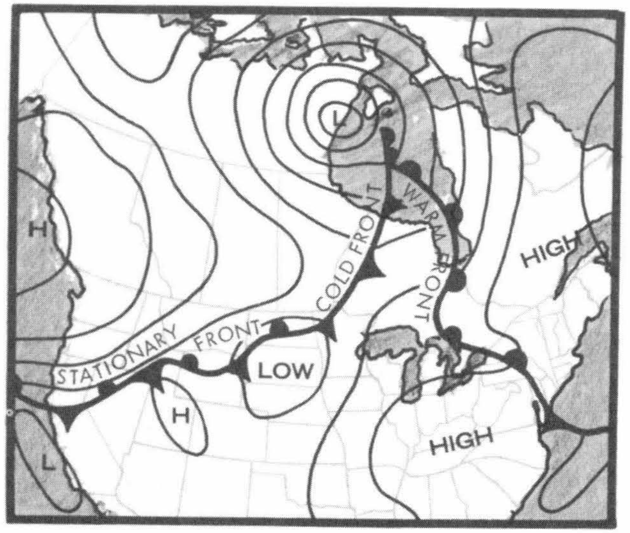


Figure 4.11. *Fronts are classified by the way they move relative to the air masses involved. At a cold front, cold air is replacing warm air. At a warm front, warm air is replacing cold air.*

The sea breeze begins between midmorning and early afternoon, depending on time of year and location. It strengthens during the afternoon and then ends shortly after sunset. The sea breeze begins at the coast, then gradually pushes farther inland during the day, reaching its maximum penetration about the time of maximum heating. Cooler temperatures and higher relative humidities accompany the sea breeze as it moves inland. Typical speed of the sea breeze is 10 to 20 mi/h. However, it can locally attain 20 to 30 mi/h along the California, Oregon, and Washington coasts.

Along the Pacific coast, fog or low clouds, very cool temperatures, and high humidity accompany the sea breeze as it moves inland, usually resulting in diminished fire activity. In the southeastern United States, lines of thunderstorms frequently develop along the sea breeze as it moves inland from the coast. This results in strong shifting winds, cooler temperatures, higher relative humidities, and possible thundershowers—weather very similar to cold fronts. Strong shifting winds associated with these "sea breeze fronts" have caused control and safety problems for many fires in the Southeast.

The *land breeze* at night is the reverse of the daytime sea breeze circulation. At night, land surfaces cool more quickly than water surfaces. Air in contact with land then becomes cooler than air over adjacent water. Again, a difference in air pressure develops between air over the land and over the water. The air must be replaced, but return flow aloft is likely to be weak and diffuse and is diminished in the prevailing general winds. The land breeze begins 2 to 3 h after sunset and usually ends shortly after sunrise. Windspeeds with the land breeze are lighter than with the sea breeze, typically between 3 to 10 mi/h.

Another type of convective wind is the *slope wind*. Slope winds are local diurnal winds present on all sloping surfaces. They flow upslope during the day as the result of surface heating, and downslope at night due to surface cooling (Figure 4.12). Slope winds are produced by the local pressure gradient caused by the difference in temperature between the air near the slope and air at the same elevation away from the slope.

During the day, the warm air sheath next to the slope serves as a natural chimney and provides a path of least resistance for the upward flow of warm air, *upslope winds*. The layer of warm air is turbulent and buoyant, increasing in depth as it progresses up the slope. This process continues during the daytime as long as the slope is receiving solar radiation. When the slope becomes shaded or night comes, the process is reversed.

A short transition period occurs as a slope goes into shadow; the upslope winds die, there is a period of relative calm, and then a gentle, smooth downslope flow begins. *Downslope winds* are very shallow and may not be represented by an adjustment to the 20-ft windspeed (see Figure 2.6). The cooled dense air is stable, and the downslope flow tends to be quite smooth and slower than upslope winds. The principal force here is gravity. Downslope winds usually continue throughout the night until morning, when slopes are again warmed

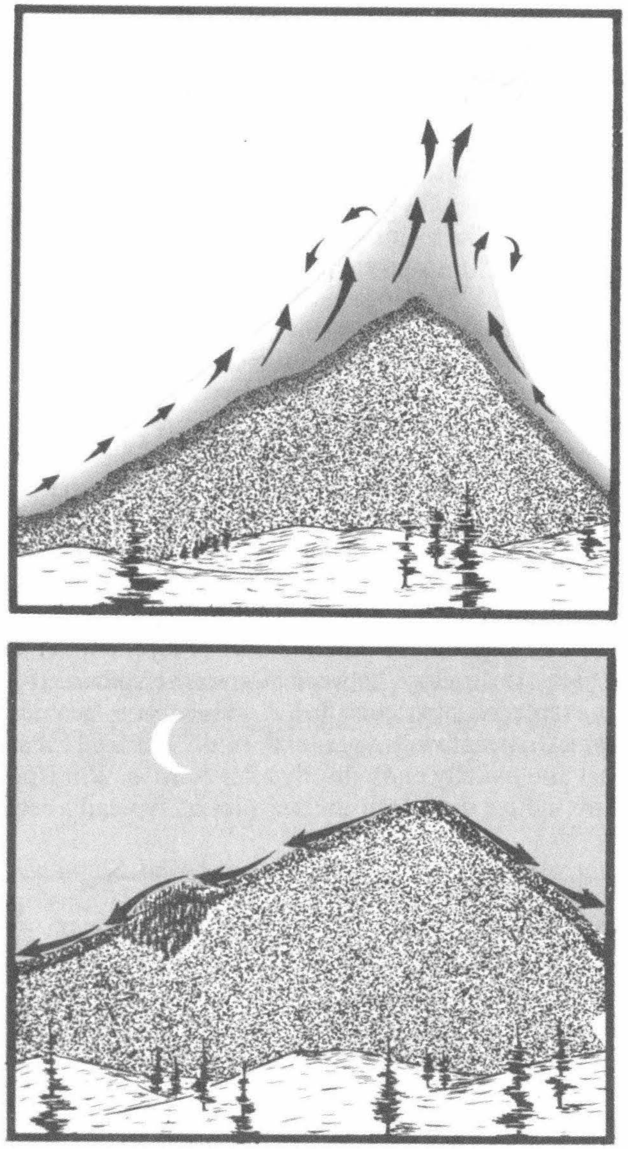


Figure 4.12. *Upslope winds are shallow near the base of slopes but increase in depth and speed as more heated air is funneled along the slope. Warm air bubbles forced upward cause turbulence which increases the depth of the warmed layer. Downslope winds are shallow, and the flow tends to be laminar. The cold air may be dammed by obstructions such as dense brush or timber.* From Schroeder and Buck (1970).

by solar radiation. The times during which winds change from downslope to upslope and vice versa depend on aspect, time of year, slope steepness, current weather conditions, and other lesser factors.

During the day, air in mountain valleys and canyons ends to become warmer than air at the same elevation over adjacent plains or larger valleys, thus creating a pressure gradient that results in *upvalley winds*. The main difference between upslope winds and upvalley winds is that the upvalley winds do not start until most of the air in the valley has warmed. Usually, this is late morning or early afternoon, depending largely on the size of the valley. These winds reach their maximum speeds by mid- or late afternoon and continue into the evening.

The transition from upvalley to *downvalley winds* takes place in the early night. The transition is gradual: first the downslope winds, then a pooling of cool, heavy air in the valley bottoms. The cool air in the higher valley bottoms will flow to lower elevations and increase in velocity as the pool of cool air deepens. This continues through the night and diminishes after sunrise.

The velocities of the slope and valley winds vary considerably with the terrain and current weather conditions. For example, slope and valley winds develop better under clear skies when the heating and cooling processes are more pronounced. Slope and valley winds are less pronounced and may not even develop under cloudy skies. Other factors to consider would be the length and steepness of the slope. Aspect is also important; north slopes typically have the lightest upslope winds due to their reduced insolation.

Effect of Topography on Windspeed and Direction

The several ways that topography can affect wind can be put into three categories: mechanical, turbulent, and frictional. There is some overlap.

Mechanical Effects The earth is solid, and the atmosphere is a fluid. When moving air collides with a topographic feature, such as a mountain range or peak, the air's motion is modified. Directional channeling, Venturi effect, and wave actions are all variations of mechanical and/or diverting effects of topography. *Directional channeling* is the case where a large drainage in a plateau region or any area allowing a general wind flow diverts some of the wind flow and sends it in a direction parallel to the drainage. Air pouring through a pass, saddle, or gorge will be speeded up due to the so-called *Venturi effect*. Air flows from higher toward lower pressure. At the surface, the higher pressure air is the cooler air mass, that is, it contains the heavier, denser air.

When strong winds move across a prominent mountain range in a direction perpendicular to the range, a wave form can be imparted to the general wind flow at and above the ridge crest. This is most likely when the air mass is stable aloft. These so-called *mountain waves* can extend many miles downstream as they gradually dampen out (Figure 4.13).

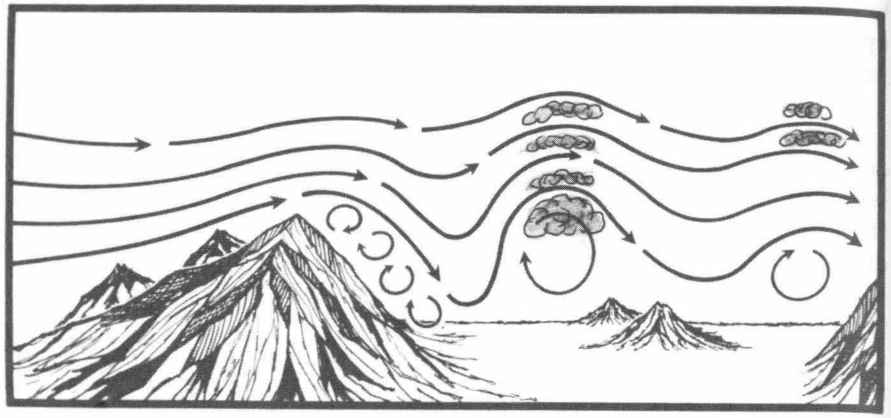


Figure 4.13. *Mountain waves form when strong winds blow perpendicular to mountain ranges. Considerable turbulence and strong updrafts and downdrafts are found on the lee side. Crests of waves may be marked by lens-shaped wave clouds, but at times there may be insufficient moisture to form clouds.* From Schroeder and Buck (1970).

Below the ridge line on the lee side, the air motions may be quite turbulent. The danger with mountain waves is that as daily heating in the lee-side basins progresses, the air there become increasingly unstable. Quite often, the mixed layer will become deep enough to link up to the level of the mountain waves, and then pull the strong winds down to the surface. Another atmospheric factor that contributes is the presence of strong high pressure and associated subsidence on the windward side of the range.

Turbulent Effects Whenever airflow is diverted over or around a prominent obstruction, it is unlikely to make a smooth transition back into a smooth, unified wind. Zones of turbulence known as *eddies* will usually form on the lee side of a significant obstruction to the wind. These eddies may be in the vertical plane or the horizontal plane. Eddies often form at the confluence of tributaries during strong canyon or valley winds. Another turbulent place is to the lee of spur ridges extending down into the main canyon. This effect would be most pronounced during late afternoon, when local upcanyon winds are at their peak.

Thermal turbulence is caused by differential surface heating, and it can have a great deal of effect on the low-level wind. Different land surfaces absorb, reflect, and radiate varying amounts of heat. Warm air rises and mixes with other air moving across the terrain. This mixing action has differing effects on surface winds, but often makes them gusty and erratic.

Frictional Drag All types of winds are slowed down by the drag caused by friction as they approach the earth's surface. Varying surface roughness causes varying amounts of frictional drag.

Winds of Most Importance to Wildland Fire

The winds discussed in this section can produce severe fire weather conditions. Cold front winds, foehn winds, thunderstorm downdrafts, microbursts, and low-level jets can totally dominate the fire environment.

Cold Front Winds A weather front is the boundary zone between two adjacent air masses. With a cold front, the colder denser air mass behind the front actively displaces the warmer, less dense air ahead of the front (Figure 4.14). A typical United States cold front moves at 20 to 30 mi/h, but speeds can be considerably faster or slower. Winds ahead of an approaching cold front usually shift gradually from southeast to south, and on to southwest. As the cold front passes, winds shift rapidly to west, then northwest (Figure 4.15). Windspeeds increase in strength as a front approaches, and usually become quite strong and gusty when the front passes an area. This is because pressure gradients are tight, and strong upper winds are more easily mixed down to the surface in very unstable air. Typical cold front windspeeds range between 15 and 25 mi/h, but can be much higher with strong cold fronts.

Cold fronts may bring thunderstorm activity, with possible precipitation. However, during the summer months in the western United States, cold fronts are often dry. They have moderate to strong winds and cooler air, but not enough moisture for precipitation. Warm fronts are relatively weak compared to cold fronts, and have little significance during fire season.

Foehn Winds Foehn winds are a special case of general winds, associated with mountain range systems. They occur as heavy, stable air pushes across a mountain range and then descends the slopes on the leeward side, becoming warmer and drier due to compression. Foehn winds tend to be stronger at night because they combine with local downcanyon winds.

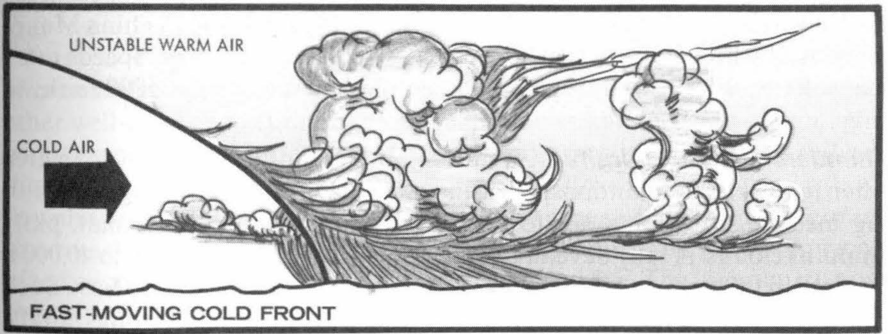


Figure 4.14. *With rapidly moving cold fronts, the weather is more severe than with slow-moving cold fronts. If the warm air is moist and conditionally stable, as in this case, then scattered showers and thunderstorms form just ahead of the cold front.* From Schroeder and Buck (1970).

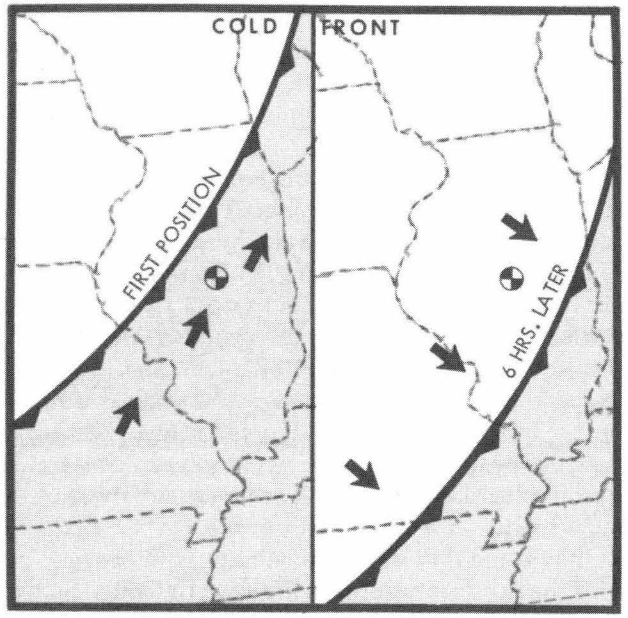


Figure 4.15. *Winds increase ahead of a cold front, become gusty and shift abruptly, usually from a southwesterly to a northwesterly direction, as the front passes.* From Schroeder and Buck (1970).

The Santa Ana wind creates critical fire weather situations in areas of southern California during fall and winter. The chinook wind occurs on the east slopes of several large mountain ranges in the western United States. Chinook winds are most prevalent on the east side of the Rocky Mountains during fall and winter. Among other well-known foehn winds in the western United States are East winds, North winds, and Mono winds (Figure 4.16). Foehn winds can also occur on the eastern slopes of the Appalachian Mountains. All foehn winds can cause serious fire control problems. Speeds often reach 40 to 60 mi/h, and some have been measured in excess of 90 mi/h.

Thunderstorm Downdrafts Cumulonimbus clouds can build over an area when there is adequate atmospheric moisture and instability, along with a lifting mechanism to force air to rise. Thunderstorms begin as small, puffy cumulus clouds. A fully developed thunderstorm can reach 30,000 to 40,000 ft or more in the western United States, and 60,000 to 70,000 ft in the East. Such clouds have vast amounts of stored energy. Not only are there strong indrafts into the base of the cloud, but strong downdrafts occur with the release of its energy.

The bases of mature thunderstorms are ragged from downdrafts and virga. Air moving down out of the thunderstorm base is cooled by evaporation, becoming much heavier than surrounding air. It also accelerates due to gravity. Downdrafts that reach the ground usually spread radially in all directions. This results in cool, gusty surface winds (often referred to as a *gust front*) that can be experienced within about 5 to 10 miles of the thunderstorm. In mountainous terrain, this distance can be considerably farther due to channeling by ridges and/or canyons. Surface wind velocities will often be 25 to 35 mi/h. Thunderstorm downdrafts will be cooler and somewhat more moist than surrounding air.

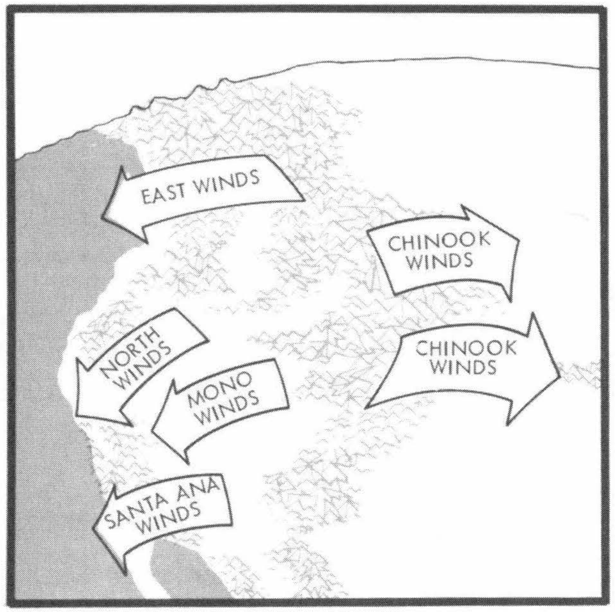


Figure 4.16. *Foehn winds are known by different names in different parts of the mountainous West. In each case, air is blowing from a high-pressure area on the windward side of the mountains to the low-pressusre or trough area on the leeward side.* From Schroeder and Buck (1970).

Microbursts A *downburst* is a downdraft associated with a thunderstorm or other well-developed cumulus clouds that induces an outburst of damaging winds on or near the ground. When the downburst is small (0.25–2.5 miles in diameter), it is a *microburst*, larger ones are *macrobursts*. Not all downdrafts are downbursts. Horizontal windspeeds generally exceed 40 mi/h on the ground in a true downburst. Downdrafts from thunderstorms have long been recognized as contributing to the dynamics of wildland fire. The microburst, however, was first identified in 1974.

A great variety of conditions can produce microbursts, but two extreme situations seem to create them in large numbers—wet and dry. It is believed that both types require raindrops as an initial condition because evaporation of these drops cools the air, which then falls as it gets heavier (Figure 4.17). Humid areas, like the southeastern United States, usually experience wet mic-

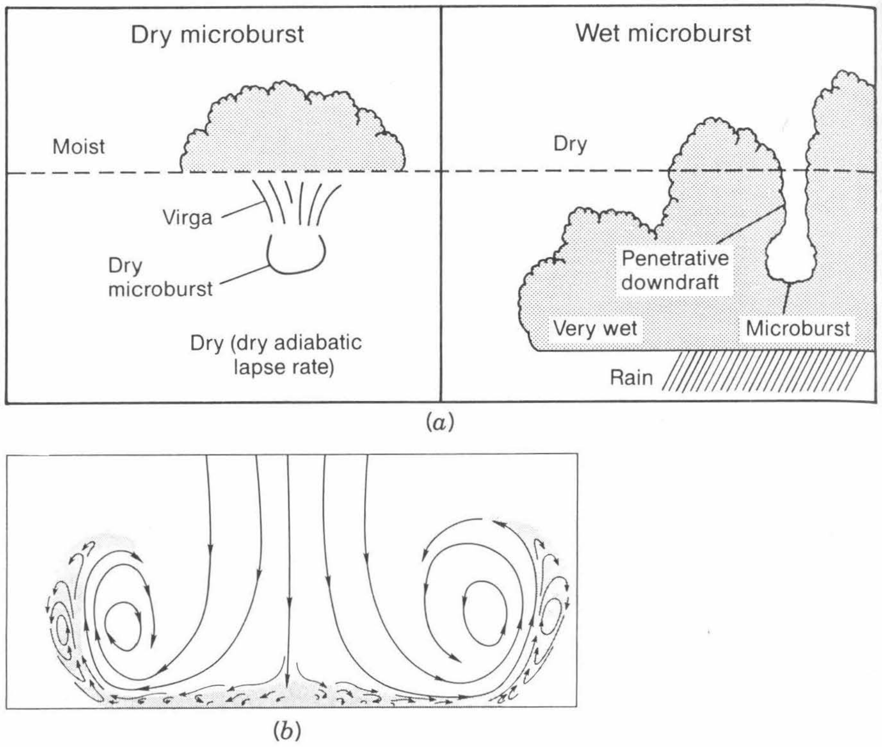


Figure 4.17. *(a) Conceptual models of wet and dry microbursts. (b) Cross section of a conceptual vortex ring model of a microburst.* From Caracena and others (1990).

roburststs, associated with moderate to heavy rain. Haines (1988a) described a 1981 Florida wildland fire that killed two firefighters. Following the microburst, a heavy rainstorm, lasting for 15 to 20 min, nearly extinguished the wildfire.

Dry microbursts occur in a very dry environment, as is common over the semiarid western Great Plains and intermountain region, where cloud bases are often higher and precipitation may evaporate before it reaches the ground. The evaporative cooling of the air intensifies the downdraft, producing a microburst. Near the cloud base, winds and rain converge around the descending air, feeding into it.

Microbursts can be generated by a convection column over a fire as well as by a cumulus cloud. The resulting strong winds can instantly change the character of a fire from a low intensity surface fire to an uncontrollable crown fire. The occurrence of precipitation or virga may indicate the development of a microburst from a plume-dominated fire.

Low-Level Jet Streams These are currents of relatively fast moving air near the earth's surface. They are similar to the well-known jet stream in the upper

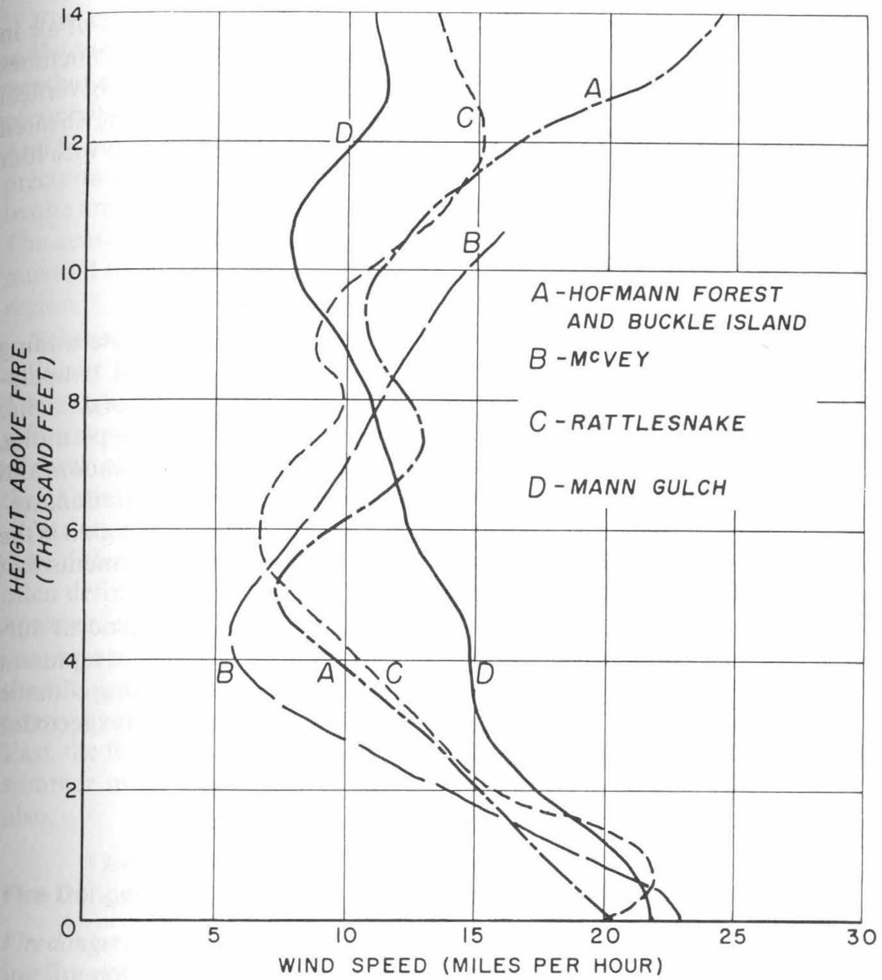


Figure 4.18. *Wind profiles associated with four fires that exhibited extreme fire behavior. The wind profile was taken from the station nearest the fire area: (A) Charleston, South Carolina, 17 April 1950; (B) Rapid City, South Dakota, 10 July 1939; (C) Red Bluff, California, 10 July 1953; (D) Great Falls, Montana, 5 August 1949.* From Byram (1954).

atmosphere. However, the maximum windspeed is considerably less, typically ranging from 25 to 35 mi/h. The maximum speed comes at an altitude from 100 ft to several thousand feet above ground level. They are most often observed in the central plains of the United States ahead of cold fronts. Low-level jet streams can cause rapid fire spread when they drop to the earth's surface. And they can increase surface wind speeds and gustiness through the downward transport of momentum. Of the 64 large fires examined by Haines (1988a), 47% of the eastern fires and 27% of the western fires were associated with low-level jets.

Because windspeed normally increases with altitude, a stratum of air in which the lower layers are moving faster than the upper layers is sometimes called a "reverse wind profile." A reverse wind profile allows a strong vertical convection column to develop directly over the fire without being sheared away by winds aloft. Figure 4.18 shows the wind profiles associated with four fires that exhibited extreme behavior.

4.4 FIRE CLIMATE AND FIRE SEASON

Fire weather occurring on a particular day is a dominant factor in determining the fire potential on that day. Fire weather elements include wind, temperature, humidity, precipitation, and so on. *Fire climate* is a synthesis of daily fire weather over a long period of time, an important concept for fire planning, preparedness, and prescribed fire. Climate largely determines the amount and kind of vegetation in an area; and climate sets the pattern of variation, seasonally and between one year and another. The fire climate of a region is the composite or integration over a period of time of the weather elements that affect fire behavior.

Weather refers to the shorter-term atmospheric conditions that occur during individual days or months in individual years. Climatic statistics represent a synthesis of this weather over a period of many years. The resulting climatic description thus serves to indicate the range of weather that may be expected at future time (Figure 4.19).

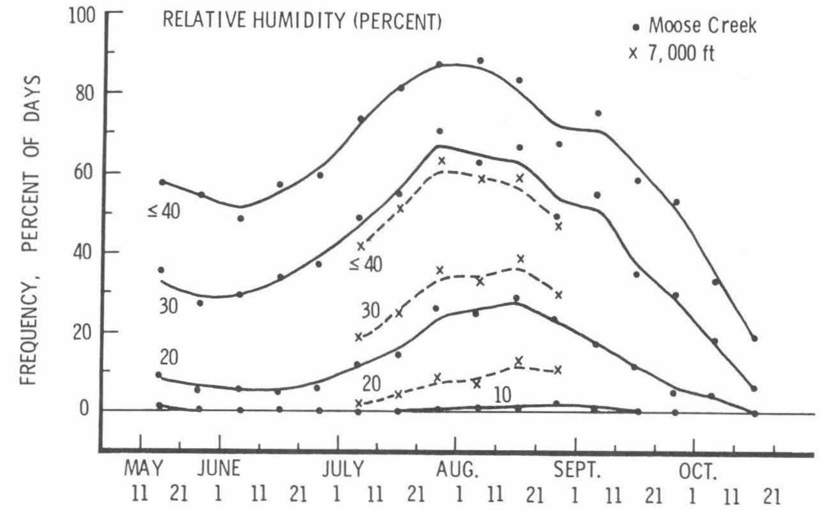


Figure 4.19. *Fire season frequencies of specified 10-day average relative humidity at 1500 PST, 1951–1970; Moose Creek Ranger Station (elevation 2460 ft) and 7000 ft ridgetop. Selway-Bitterroot Wilderness, Idaho.* From Finklin (1983).

Fire climate cannot be described by considering the weather elements individually. Fire potential responds to the combined effects of all of the fire-weather elements. For example, a region may have strong winds, but if they occur with precipitation, they are of much less importance to the fire climate. And fire climate is more than averages. Two areas may have the same annual precipitation; but the amount may be evenly distributed throughout the year in one area and concentrated during one portion of the year in another area. The seasonal distribution, the extremes, the frequency, and the duration must all be considered in describing precipitation in the fire climate of a region.

Schroeder and Buck (1970) considered geographic and climate factors to delineate 15 broad regions over the North American continent (Figure 4.20). These regions differ in one or more aspects, giving each a distinctive character affecting wildland fire. There is, of course, much local variation. A description of three of the regions is included in the selected examples at the end of the chapter.

Variations in climate, along with variations in vegetative conditions, produce differences in the *fire seasons* from one region to the next. Fire season is often defined in terms of wildfire occurrence. The use of prescribed fire can, however, effectively extend the fire season. In general, the fire season in the western and northern regions of the continent occurs in the summertime. But the fire season becomes longer as one goes from north to south, becoming nearly a year-round season in the Southwest and southern California. In the East, the fire season peaks in the spring and fall. Some fires occur during the summer months, and in the southeastern states they can occur in winter also.

Fire Danger Rating

Fire danger rating is an integration of weather elements and other factors affecting fire potential. In many fire danger rating systems, only the weather elements are considered. The other legs of the fire environment triangle (Figure 2.2), fuel and topography, are assumed constant. Fire danger rating systems produce numeric indexes of fire potential that are used as guides in a variety of fire management activities, including staffing for fire control, scheduling prescribed fire, and fire prevention.

Analysis of day-to-day fire weather, i.e., fire danger rating, offers a way to track the fire season and to compare one season to another. Seasonal plots of a fire danger index are useful in visualizing how the season is progressing and in comparing one year with another, or to seasonal average or extreme values (Figure 4.21).

Site-specific weather is needed to project the behavior of a specific fire. Fire danger rating, on the other hand, uses weather observations at a fixed site to give a broad area assessment of fire potential. The difference between fire behavior and fire danger is essentially a matter of scale.

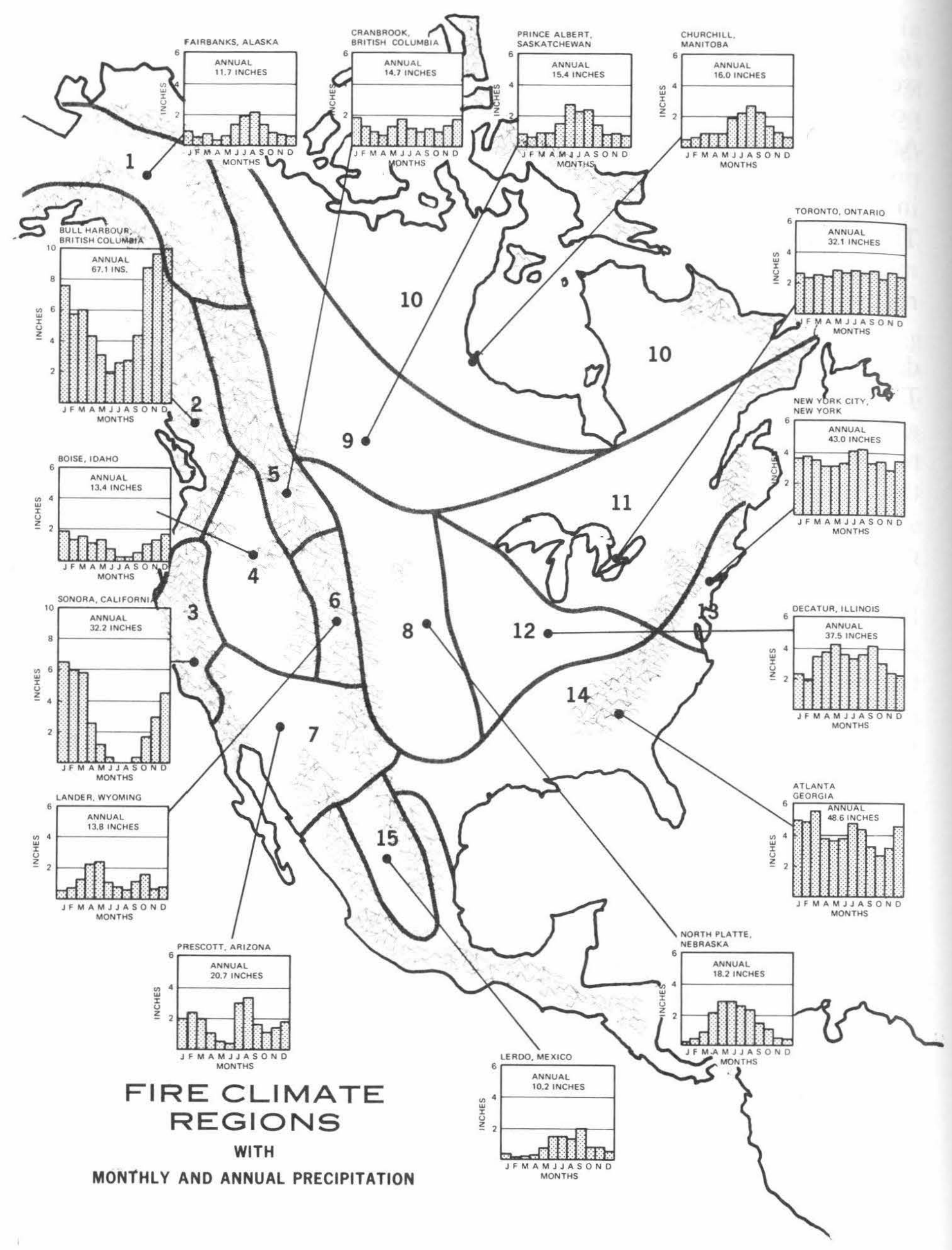


Figure 4.20. *Fire climate regions of North America. The associated bargraphs give the monthly and annual precipitation for a representative station.* From Schroeder and Buck (1970).

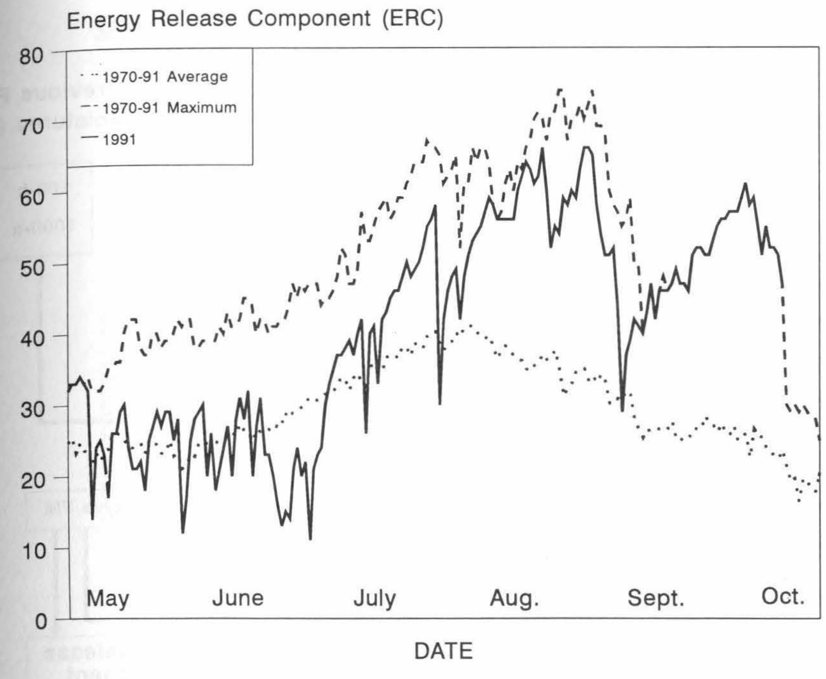


Figure 4.21. *Seasonal plot of Energy Release Component (ERC) for the Missoula, Montana area showing the 1991 fire season compared to the average and maximum for 1970–1991.* From Andrews and Bradshaw (1992).

Several successful fire danger rating systems are in use around the world. We discuss here only two North American systems, the United States National Fire Danger Rating System and the Canadian Fire Weather Index System.

U.S. National Fire Danger Rating System (NFDRS) The main indexes produced by NFDRS are Spread Component (SC), Energy Release Component (ERC), and Burning Index (BI) (Figure 4.22). Other indexes, such as lightning and human occurrence indexes and a fire load index, were part of the original formulation of NFDRS; they are rarely used and are therefore not discussed here. The Keetch–Byram Drought Index (KBDI) is now part of NFDRS and is discussed in the next section. The calculation of SC is related to spread rate, ERC to energy release, and BI to flame length or fireline intensity.

Because NFDRS provides an indication of fire potential over large administrative areas, a general description of the area is appropriate. Fuel and topography are assumed constant over the area. Site description includes slope class (choice of 5), fuel model (choice of 20), and a designation of the herbaceous fuel type as either annual or perennial.

Each afternoon at 1400 local standard time (LST), the following weather elements are measured: relative humidity, air temperature, state of weather

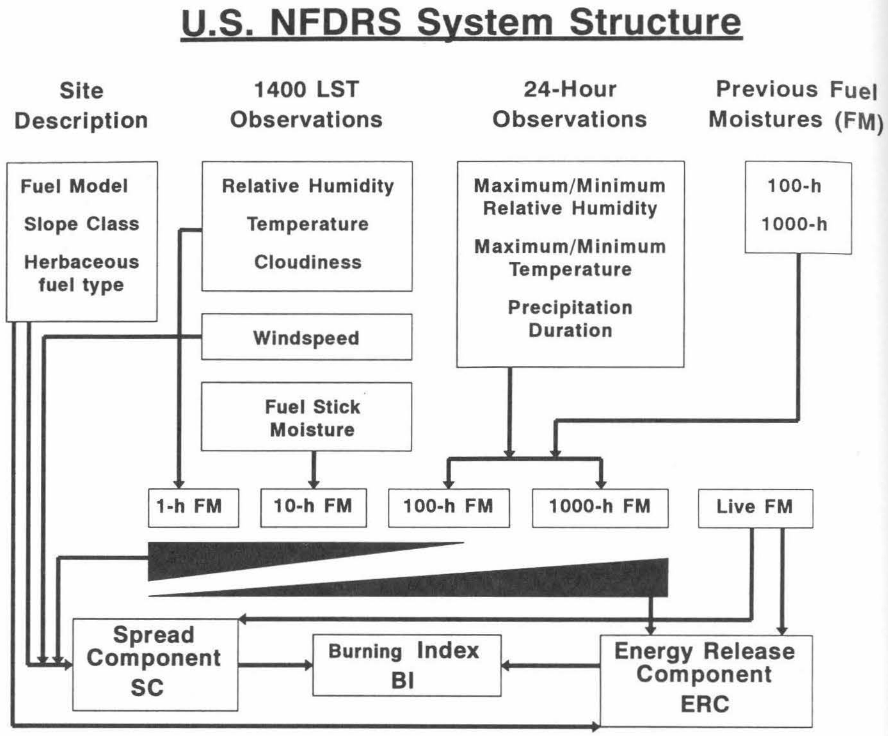


Figure 4.22. Structure of the U.S. National Fire Danger Rating System (NFDRS) showing the relationship among site description, weather observations, intermediate fuel moisture calculations, and final indexes. From Andrews and Bradshaw (1992).

(cloud cover and type of precipitation if any), and windspeed (10-min average). The weather observation also includes a number of elements for the 24-h period: maximum and minimum relative humidity and temperature, and precipitation duration and amount.

The moisture content of live fuel and four size classes of dead fuel are calculated from the weather observations and previous moisture values. Dead fuel is categorized by diameter or timelag as described in Chapter 3. The moisture content of the 10-h fuel is sometimes based on stick weight (see Figure 3.15). Calculation of live fuel moisture is based on the 1000-h moisture content. An option offered by the 1988 revision of NFDRS is entry of a greenness factor based on direct observation of state of live fuel.

All the indexes are affected by dead fuel moisture but to different extents. The wedge below the dead moisture boxes in Figure 4.22 indicates a mathematical weighting that emphasizes the large 100-h and 1000-h fuel for ERC, while smaller 1-h and 10-h fuels are emphasized for SC. (1000-h fuel has no influence on SC). Note that windspeed influences SC but not ERC. The relationship among SC, ERC, and BI is shown in Figure 4.23.

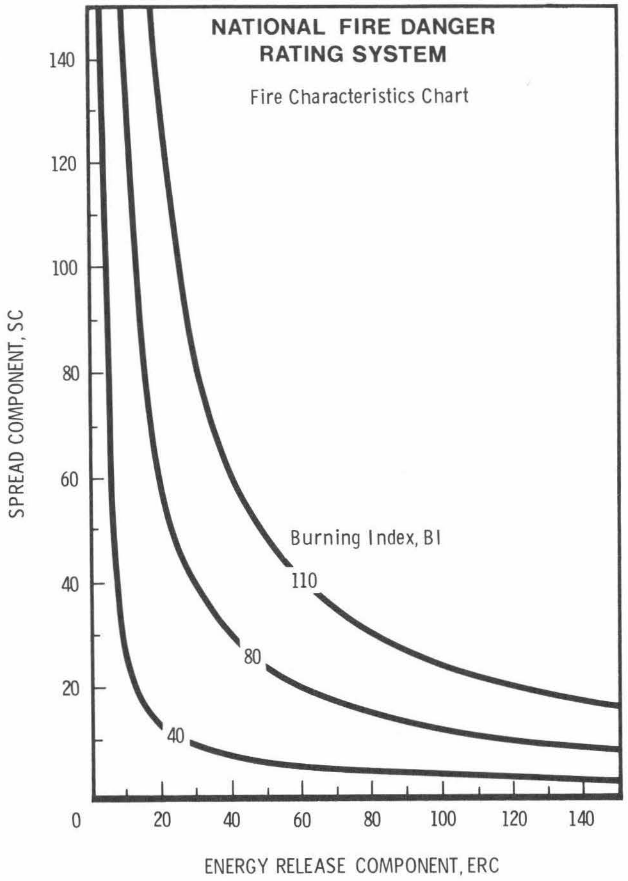


Figure 4.23. Fire characteristics chart showing the relationship among Energy Release Component, Spread Component, and Burning Index. From Andrews and Rothermel (1982).

Canadian Fire Weather Index (FWI) System The Fire Weather Index (FWI) System consists of six components (Figure 4.24). The three fuel moisture codes, the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), and the Drought Code (DC), are numerical ratings of the fuel moisture content of fuel moisture content of fine surface litter, loosely compacted duff of moderate depth, and deep compacted organic matter, respectively. The three fire danger indexes, the Initial Spread Index (ISI), the Buildup Index (BUI), and the Fire Weather Index (FWI) component itself, are intended to represent rate of fire spread, fuel available for combustion, and frontal fire intensity.

The FWI System components depend solely on daily measurements of dry-bulb temperature, relative humidity, a 10-m open wind speed, and 24-h cumulated precipitation recorded at noon local standard time. The three moisture

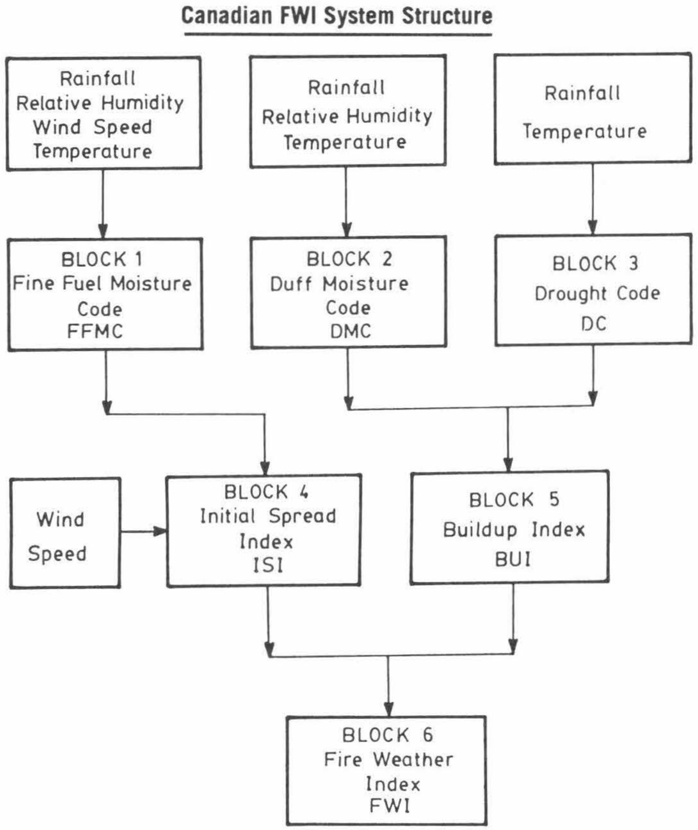


Figure 4.24. *Block diagram of the Canadian Fire Weather Index (FWI) System showing the relationship among weather observations, moisture calculations, and indexes.* From Van Wagner (1987).

codes are in fact bookkeeping systems that add moisture after rain and subtract some for each day's drying. The codes are expressed on scales related to actual fuel moisture.

The three fuel moisture codes plus wind are linked in pairs to form two intermediate indexes and one final index. The ISI, which combines the effects of wind and the fine fuel moisture content represented by the FFMC, represents a numerical rating of fire spread rate without the influence of variable fuel quantity. Because the ISI is dependent solely on weather, actual rate of spread (ROS) can be expected to vary from one fuel type to another over the range of the ISI because of differences in fuel complex characteristics and wind exposure. The BUI, which combines the DMC and DC, represents a numerical rating of the total fuel available for combustion. The BUI was constructed so that when the DMC is near zero the DC would not affect daily fire danger (except for smoldering potential) no matter what the level of DC. The FWI, which combines the ISI and BUI, represents a relative measure of the potential intensity of a single spreading fire in a standard fuel complex (i.e., a mature pine stand) on level terrain. Jack pine and lodgepole pine forest types form a more or less continuous band across Canada, thus the concept of a standardized fuel type.

FWI System components and their values have different interpretations in different fuel types, because the System was developed to represent fire behavior in a generalized, standard fuel type.

Comparison of NFDRS and FWI From the above discussion of NFDRS and FWI, it is clear that there are many similarities. There are also significant differences. Both systems use daily weather observations or forecasts to calculate fuel moisture of several fuel elements and then combine them into indexes of fire danger, related to spread (SC and ISI), heat release or available fuel (ERC and BUI), and frontal fire intensity (BI and FWI). The relationship among SC, ERC, and BI is similar to that among ISI, BUI, and FWI (see Figure 4.23). Although there are differences in the weather elements required for each system, they are basically the same—temperature, humidity, wind, and precipitation. NFDRS requires more weather input than does FWI.

NFDRS attempts to evaluate the "worst" conditions on a rating area by measuring the weather for fire danger in the open on extreme (southwesterly or westerly) exposures. The FWI, in contrast, represents fire danger under a closed forest stand. NFDRS offers a choice of 20 fuel models that describe a range of grass, brush, forest, and logging debris. FWI represents conditions in a generalized pine forest, most nearly the jack pine and lodgepole pine type. NFDRS represents the moisture content of roundwood off the ground, without bark, in the open, whereas the FWI assesses the moisture of surface litter and duff under a canopy.

The type of model used to calculate moisture and fire danger indexes differ, to some extent because of differences in the training and approach taken by researchers in the two countries (engineers vs. foresters). The models in NFDRS are analytical, being based on the physics of moisture exchange, heat transfer, and other known aspects of the problem. Rothermel's fire spread model was described at the end of Chapter 1. It is the formulation of that model that allows a description of the fuel as an input. The Canadian models are primarily founded on a mass of field data of three kinds: weather, fuel moisture, and test-fire behavior, all collected over several decades. Canadian models are best applied to the fuel type in which the data were collected.

Drought Indexes

Palmer (1965) begins his discussion of drought by putting the term in perspective: "Drought means various things to various people, depending on their specific interest. To the farmer drought means a shortage of moisture in the root zone of his crops. To the hydrologist it suggests below average water levels in streams, lakes, reservoirs, and the like. To the economist it means a water shortage which adversely affects the established economy. Each has a concern which depends on the *effects* of a fairly prolonged weather anomaly." He suggested that drought be considered as a strictly meteorological phenomenon and evaluated as a meteorological anomaly characterized by a prolonged and abnormal moisture deficiency. But this approach wasn't entirely satisfactory. Because of misinterpretation of his drought index strictly as a measure of the current status of agricultural drought, he constructed a crop moisture index that takes into account only those moisture aspects that affect vegetation and field operations.

A drought period may be defined as an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply. Further, the severity of drought may be considered as being a function of both the duration and magnitude of the moisture deficiency. The term drought is reserved for dry periods that are relatively extensive in both time and space. A moisture shortage that is termed drought in one region may not be considered so elsewhere, and a shortage may be less serious in one season than it would be in another.

To a land manager concerned with wildland fire, drought may mean a situation in which fuels are drier and fires are more intense than normally expected. Under drought conditions, more fuel is available. Ground and crown fuels may burn, whereas under normal conditions, only the surface fuels would burn. A drought index for wildland fire should be chosen based on its reflection of the effects of the drought on wildland fuel. Different indexes represent moisture deficiency in different fuel elements—large, surface fuels (logs), litter and duff layers, soil profiles, and living foliage.

Drought can set the stage for severe wildfires. The supply of moisture to tree and plant roots decreases, and the loss of water by transpiration from leaves increases. Dried plant matter on the ground adds to the supply of combustibles. And the low moisture content of logs and duff makes those fuel components available to burn.

Long-term moisture deficiency in itself, however, cannot be used to forecast critical fire situations. If the smaller fuels are wet or green and winds are calm, serious fires usually will not occur at any time of year. Most critical fires are caused from a combination of factors that occur in conjunction with drought conditions.

Several indexes are available to track drought for wildland fire applications, including Palmer's drought index (1965) and crop moisture index (1968). Keetch and Byram (1968) developed a drought index (KBDI) specifically for wildland fire applications. The Energy Release Component and 1000-h moisture content from the U.S. NFDRS and the Drought Code and Duff Moisture Code from the Canadian FWI System are also used to indicate drought conditions.

Keetch-Byram Drought Index Keetch and Byram (1968) designed a drought index specifically for fire potential assessment. It is a number representing the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff and upper soil layers. It is a continuous index, relating to the flammability of organic material in the ground.

The KBDI attempts to measure the amount of precipitation necessary to return the soil to full field capacity. It is a closed system ranging from 0 to 800 units and represents a moisture regime from 0 to 8 inches of water through the soil layer. At 8 inches of water, the KBDI assumes saturation. Zero is the point of no moisture deficiency and 800 is the maximum drought that is possible. At any point along the scale, the index number indicates the amount of net rainfall (in hundredths) that is required to reduce the index to zero, or saturation.

The KBDI is easy to compute and provides a continuous record because it is updated daily. It is now included as an NFDRS index. The inputs are weather station latitude, mean annual precipitation, maximum dry bulb temperature, and the last 24 h of rainfall. Reduction in drought occurs only when rainfall exceeds 0.20 inch (called net rainfall). The computational steps involve reducing the drought index by the net rain amount and increasing the drought index by a drought factor.

Figure 4.25 shows the ERC and KBDI for 1987 and 1988 for the Mammoth weather station in Yellowstone National Park. Those two fire seasons were quite different. In 1987 there were 34 fires, together covering 973 acres; only 1 fire was over 10 acres. The year 1988 set new standards for "worst case" with 60 fires covering 861,531 acres. The difference between the seasons is reflected by both the ERC and KBDI plots. The ERC dropped off in the fall of 1988 due to high nighttime humidity and precipitation less than 0.20 inch. This decrease in the ERC corresponded to a decrease in fire activity.

Canadian Drought Code The Drought Code (DC) component of the Canadian Fire Weather Index System is an indicator of the moisture content of deep organic layers, large downed wood, and the availability of water in small streams and swamps. As shown in Figure 4.24, rainfall and temperature are used to calculate the DC.

The DC shows definite seasonal trends influenced by the climate of a region. The seasonal trend in DC values precludes setting fire danger classes based on the DC. A single value early in the spring, while being very high for that time of the year, may only fall into a midrange of the whole season. Graphs produced by McAlpine (1990) can be used to determine how observed DC values compare with historical DC values for the station (Figure 4.26). Unusually dry (or wet) years show up as being above (or below) the one standard deviation line.

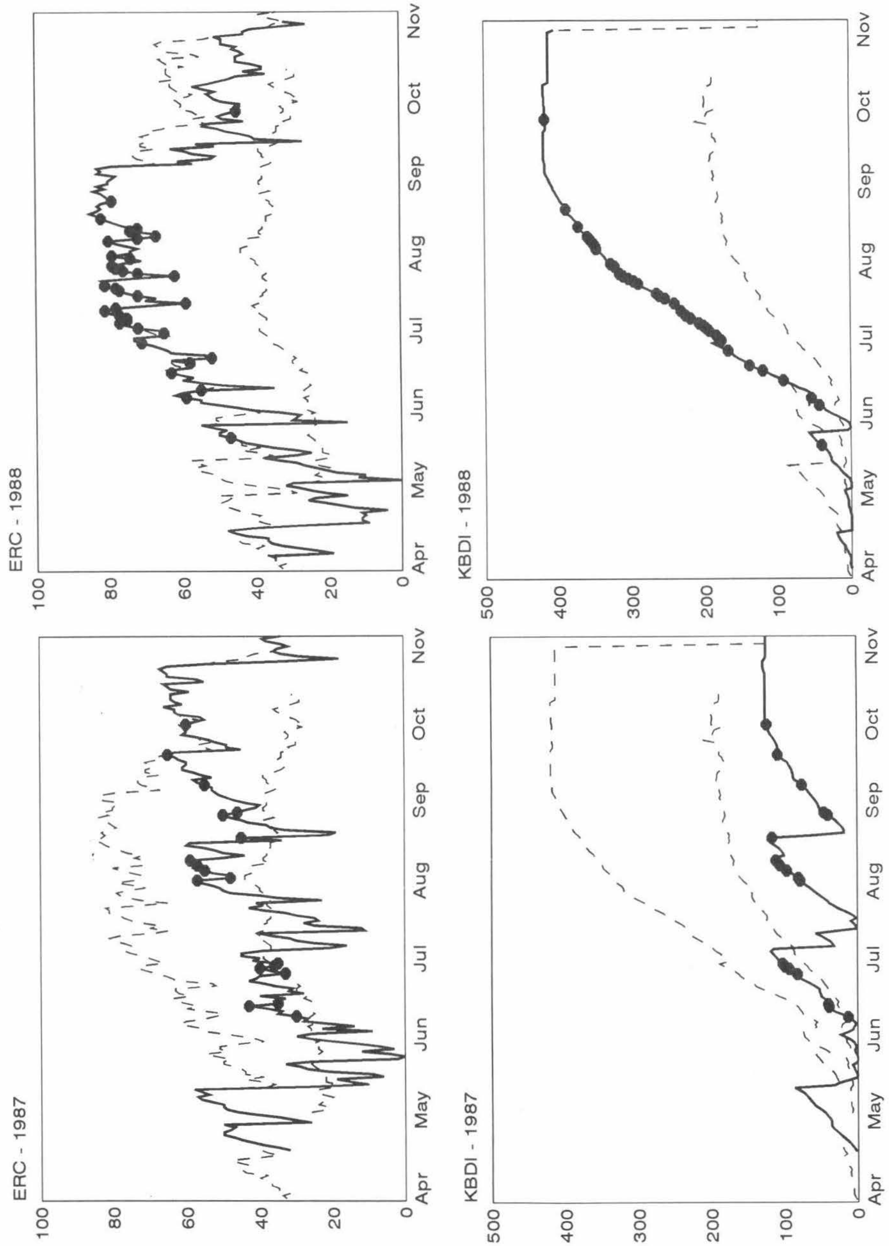


Figure 4.25. *Plots of Energy Release Component (ERC) and Keetch-Byram Drought Index (KBDI) for 1987 and 1988 in Yellowstone National Park (Mammoth weather station). Maximum and average for 1965–1992 are shown as dashed lines. Days on which fires were discovered are indicated with dots.* From Andrews and Bradshaw (1995).

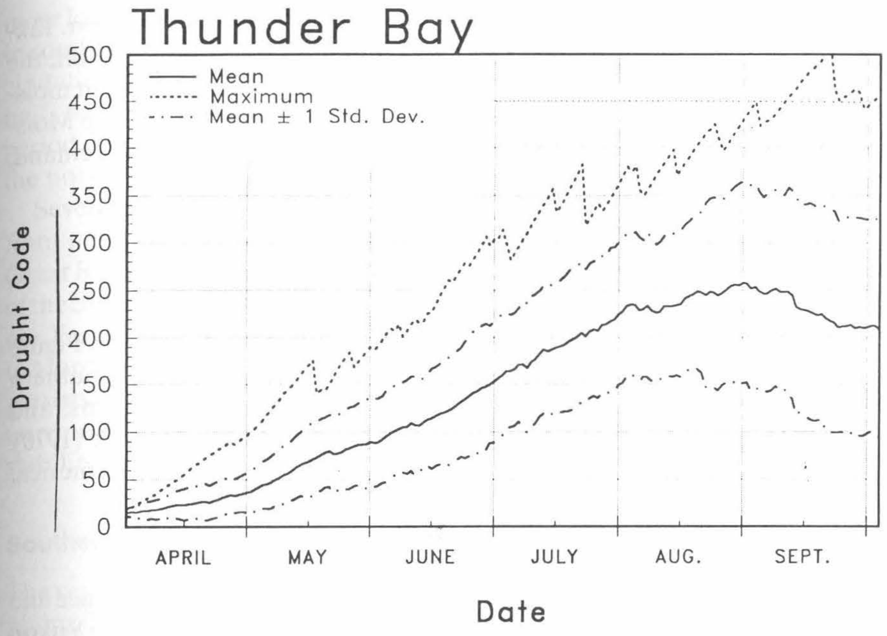


Figure 4.26. *Canadian Drought Code (DC) maximum, average, and ±1 standard deviation for Thunder Bay based on 35 years of weather data.* From McAlpine (1990).

Palmer Drought Index A sophisticated index of meteorological drought was developed in the 1950s by Wayne Palmer (1965) It is based on the concept of supply and demand: Supply is represented by precipitation and stored soil moisture; demand is figured by a formula that combines moisture loss through evapotranspiration (evaporation from land and water surfaces and transpiration from vegetation) with both the amount of moisture needed to recharge the soil moisture and the amount of runoff required to keep rivers, lakes, and reservoirs at normal levels.

The results of this water-balance accounting produce either a positive or a negative figure, which is weighted by a climatic factor. The final figure is an index that expresses the degree of abnormality over a period of several months in a particular place. An index of +2 to −2 indicates normal conditions; −2 to −3 indicates a moderate drought, −3 to −4 a severe drought, and below −4 an extreme drought.

The Palmer index is normalized. Similar values should mean similar drought level at any location. It is a slow response system. Given a wet spring followed by a dry summer, the index can still indicate a moderate drought by late summer.

Crop Moisture Index Palmer's Crop Moisture Index (1968) is a more short-term index that measures the degree to which growing crops have received adequate moisture during the preceding week. The Crop Moisture Index is computed from average weekly values of temperature and precipitation. Taking into account the previous moisture conditions and current rainfall, the index determines the actual moisture loss and hence the crop's current moisture demand. If moisture demand exceeds available supplies, the Crop Moisture Index has a negative value; if current moisture meets or exceeds demand, the value is positive.

4.5 SELECTED EXAMPLES

Following is a description of three of the 15 climate regions shown in Figure 4.20: Interior Alaska and the Yukon (1), South Pacific Coast (3), and Southern States (14). Vegetation, meteorological conditions, weather patterns, and typical fire season are described according to Schroeder and Buck (1970). These examples illustrate the wide range of fire climates in North America.

Interior Alaska and the Yukon

The vegetation in Interior Alaska and the Yukon is predominantly spruce and aspen, with some tundra and other lesser vegetation to the north. The Yukon Basin has a warm, short summer. Continental heating has produced summertime temperatures of 100°F; however, temperatures as low as 29°F have occurred in July. Winters are extremely cold. The high coastal mountains generally prevent the invasion of maritime polar air masses at low levels. The Brooks and other mountain ranges block the inflow of even colder continental polar air from the north.

Annual precipitation is only about 10 to 15 inches, the maximum occurring during the summer in convective showers and with weak fronts. Precipitation is highest in the southern portion, which includes the northern extension of the Cordilleran Highlands and their parallel chains of lesser mountains. Although precipitation is maximum in summer, it is so scant that wildland fuels dry out considerably during the long, clear, dry summer days. Dry thunderstorms are not infrequent. The usual fire season starts in May after melting of the winter snows and lasts until September.

South Pacific Coast

The vegetation in the south Pacific coast region consists of grass in the lowlands, brush at intermediate levels, and extensive coniferous stands in the higher mountains. Temperatures along the immediate coast are moderated both winter and summer by the ocean influence. But only short distances inland, winter temperatures are somewhat lower and summer temperatures average considerably higher.

The annual precipitation is generally light, around 10 to 20 inches at lower elevations. Precipitation in the mountain areas reaches up to 60 inches or more locally. Summers are usually rainless, with persistent droughts common in southernmost sections. Widespread summer thunderstorms, with little precipitation reaching the ground, particularly in the mountains of the northern half, occasionally result in several hundred local fires within a 2- or 3-day period. The fire season usually starts in June and lasts through September in the north, but in the south critical fire weather can occur year round.

Several synoptic weather types produce high fire danger. One is the cold-front passage followed by winds from the northeast quadrant. Another is a Great Basin High that produces foehn-type Mono winds along the west slopes of the Sierras and Coast ranges, and the Santa Ana winds of southern California. Peak Santa Ana occurrence is in November, and there is a secondary peak in March. A third high fire danger type occurs when a ridge or closed high aloft persists over the western portion of the United States. At the surface, this pattern produces very high temperatures, low humidities, and air-mass instability.

Southern States

The vegetation in the southern states consists mainly of pines along the coastal plains, hardwoods in bays and bottomlands along stream courses, and mixed conifers and hardwoods in the uplands. Flash fuels, flammable even very shortly after rain, predominate in this region. The topography along the Gulf and Atlantic is low and flat. Inland from the Atlantic Coast it merges with an intermediate Piedmont area. The southern Appalachians are included in this region, and the central portion includes the lower Mississippi Valley.

Summers are warm and generally humid, because the region is almost continuously under the influence of a maritime tropical air mass. Winters have fluctuating temperatures. When maritime tropical air moves over the region, high temperatures prevail. Following the passage of a cold front, continental polar air may bring very cold temperatures—well below freezing—throughout the southern states.

Annual precipitation varies from 40 to 60 inches over most of the region, except for about 70 inches in the southern Appalachians and over 60 inches in the Mississippi Delta area, and falls mostly as rain. The influence of the moist maritime tropical air from the Gulf of Mexico causes abundant rainfall in all seasons, with slightly higher amounts in August and September due to the presence of hurricanes in some years. Spring and fall have less precipitation than summer or winter, with spring being wetter than fall. Winter precipitation is usually associated with frontal lifting or with lows that develop over the southern states or the Gulf of Mexico and move through the region. Summertime precipitation is mostly in the form of showers and thunderstorms. During the colder months, much fog and low stratus are formed by the cooling of the maritime tropical air as it moves northward.

The fire season in the Southern States is mainly spring and fall, although fires may occur during any month. Lightning accounts for only a minor number of fires. Very often the most critical fire danger weather occurs with the passage of a dry cold front. The strong, gusty, shifting winds with the cold front and dry unstable air to the rear set the stage for extreme fire behavior.

FURTHER READING

Schroeder and Buck (1970) prepared a thorough, well illustrated presentation of *Fire Weather*. That publication and weather lessons in the U.S. National Wildfire Coordinating Group (NWCG) fire behavior courses S-290 and S-490 (1994, 1993), prepared in large part by the fire weather meteorologists at the National Interagency Fire Center, were used extensively in writing this chapter. Baughman (1981a) compiled "An Annotated Bibliography of Wind Velocity Literature Relating to Fire Behavior Studies."

The U.S. National Fire Danger Rating System is described by Deeming, Burgan, and Cohen (1978) in "The National Fire Danger-Rating System—1978," by Bradshaw and others (1983) in "The 1978 National Fire-Danger Rating System: Technical Documentation," and by Burgan (1988) in "1988 Revisions to the 1978 National Fire-Danger Rating System." The Canadian system is described by Van Wagner (1987) in "Development and Structure of the Canadian Forest Fire Weather Index System" and by Stocks and others (1989) in "The Canadian Forest Fire Danger Rating System: An Overview."

Part Two

Fire Regime