

Introduction to
**Wildland
Fire**



Second Edition

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Patricia L. Andrews

Richard D. Laven

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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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Contents

CONVERSION FACTORS	xix
ABBREVIATIONS USED IN TEXT	xxi
PREFACE	xxv
PART 1 FIRE ENVIRONMENT	
1. Wildland Fire Fundamentals	3
1.1 Combustion Process Overview / 4	
1.2 Intrinsic Fuel Properties / 7	
1.3 Heat and Heat Transfer / 11	
Heat Transfer: Conduction, Convection, Radiation / 12	
Heat Transfer Equations / 13	
1.4 Phases of Combustion / 14	
Preignition / 14	
Ignition / 18	
Combustion / 20	
Extinction / 23	

- 1.5 Fuel Consumption / 25
 - Duff / 27
 - Large Woody Fuel / 29
- 1.6 Products of Combustion / 29
- 1.7 Selected Examples / 34
 - Emissions From the Silver Fire, 1987 / 34
 - Rothermel's Fire Spread Model / 37

Further Reading / 45

2. Fire Behavior

46

- 2.1 The Fire Environment / 48
 - Topography / 49
 - Fuel / 51
 - Weather / 52
 - Fire Interaction With the Environment / 53
- 2.2 Fire Growth / 56
 - Ignition / 56
 - Point Source Fire / 57
 - Large Fires / 59
- 2.3 Fire Spread and Intensity / 63
 - Rate of Spread / 63
 - Intensity and Flame Length / 65
 - Fire Characteristics Chart / 67
- 2.4 Extreme Fire Behavior / 68
 - Crown Fire / 69
 - Horizontal Roll Vortices / 72
 - Spotting by Firebrands / 74
 - Fire Whirls / 77
- 2.5 Predicting Fire Behavior / 79
- 2.6 Selected Examples / 82
 - Black Tiger Fire, Colorado, 1989 / 82
 - Sundance Fire, Idaho, 1967 / 83
 - Air Force Bomb Range Fire, North Carolina, 1971 / 85
 - Mack Lake Fire, Michigan, 1980 / 85
 - Greater Yellowstone Area Fires, Wyoming and Montana, 1988 / 87

Further Reading / 89

3. Wildland Fuels

90

- 3.1 Fuel Change Over Time / 92
 - Abrupt Change / 95
 - Diurnal Change / 95
 - Seasonal Change / 95
 - Annual Change / 95
 - Successional Change / 96
- 3.2 Fuel Description / 96
 - Properties / 96
 - Components / 99
 - Complexes / 102
- 3.3 Fuel Classification / 102
 - Fuel Models / 102
 - Inventory / 104
 - Photo Guides / 105
 - Canadian Fuel Types / 106
- 3.4 Fuel Moisture / 106
 - Dead Fuel Moisture / 107
 - Live Fuel Moisture / 112
 - Drought / 117
 - Moisture Assessment / 118
- 3.5 Selected Examples / 121
 - Palmetto-Gallberry / 121
 - Aspen / 124

Further Reading / 127

4. Fire Weather

128

- 4.1 Basic Weather Processes / 129
 - The Atmosphere / 129
 - Earth's Heat Balance / 130
 - Atmospheric Pressure, Volume, and Temperature / 130
 - Temperature-Humidity Relationships / 132
- 4.2 Atmospheric Stability / 133
 - Lapse Rates / 133
 - Stability / 135
 - Inversions / 136
 - Lifting Processes and Thunderstorm Development / 137
 - Lightning / 139

- 4.3 Winds / 142
 - General Winds / 142
 - Local Winds / 144
 - Effect of Topography on Wind Speed and Direction / 147
 - Winds of Most Importance to Wildland Fire / 149
 - 4.4 Fire Climate and Fire Season / 154
 - Fire Danger Rating / 155
 - Drought Indexes / 161
 - 4.5 Selected Examples / 166
 - Interior Alaska and the Yukon / 166
 - South Pacific Coast / 166
 - Southern States / 167
- Further Reading / 168

PART 2 FIRE REGIME

5. Fire Ecology

171

- 5.1 Fire History and Fire Regimes / 171
- 5.2 Plant Adaptations to Fire / 180
 - Germination / 180
 - Rapid Growth and Development / 182
 - Fire-Resistant Foliage / 182
 - Fire-Resistant Bark / 183
 - Adventitious or Latent Axillary Buds / 183
 - Lignotubers / 184
 - Serotinous Cones / 186
- 5.3 Fire Effects / 187
 - Effects of Fire on Vegetation / 188
 - Effects of Fire on Wildlife / 190
 - Effects of Fire on Soil / 190
 - Effects of Fire on Water / 196
- 5.4 Fire and Ecosystems / 198
 - Classical View of Ecosystem Dynamics / 198
 - Contemporary Views of Ecosystem Dynamics / 200
 - Fire, Landscape Pattern, and Biological Diversity / 202
- 5.5 Selected Fire Regimes / 204
 - Tallgrass Prairie: The Great Plains / 204
 - Chaparral: Southern California / 205

- Ponderosa Pine: Southwest / 207
- Douglas-Fir: Pacific Northwest / 208
- Loblolly and Shortleaf Pine: The South / 209
- Lodgepole Pine: Rocky Mountains / 210

Further Reading / 212

6. Fire and Culture

213

- 6.1 Fire History / 215
 - Sources for Fire History / 217
 - Organizing Fire History / 228
 - Interpreting Fire History / 232
- 6.2 American Fire History / 233
 - Fire Practices by American Indigenes / 236
 - European Fire Practices / 241
 - American Fire Practices: Reclamation and Counterreclamation / 242
- 6.3 Creating a National System of Fire Management: The U.S. Forest Service / 246
 - Frontier Fire / 250
 - Backcountry Fire / 254
 - Mass Fire / 257
 - Wilderness Fire / 260
 - Intermix Fire / 266
- 6.4 Selected Fire Regimes: Historical Characteristics / 271
 - Eastern Great Plains / 271
 - Southern New England / 275
 - Southeast / 279
 - Lake States / 282
 - Pacific Northwest / 286
 - Northern Rockies / 289
 - Great Basin / 292
 - Southern California / 296
 - Southwest / 300

Further Reading / 305

7. Administration of Fire Regimes

309

- 7.1 Purposes of Fire Management / 309
 - Strategic Considerations / 309
 - Historical Considerations / 312
 - Political Considerations / 316
 - Administrative Considerations / 320

- Economic Considerations / 325
- Legal Considerations / 329
- Cultural Considerations / 335
- 7.2 Structure of Fire Management in the United States / 339
 - Federal Fire Management / 340
 - State Fire Management / 346
 - Local Jurisdiction Fire Agencies / 350
 - Private Institutions / 352
 - International Fire Relations / 354
- 7.3 Selected Fire Regimes: Administrative
 - Characteristics / 356
 - Tonto National Forest: The U.S. Forest Service / 357
 - Prineville District: Fire Management by the BLM / 360
 - Everglades National Park: Natural Area Fire Management / 363
 - North Carolina: A State Operation / 367
 - Boulder County: A Local Jurisdiction Manages Fire / 369
 - Southern California: An Interagency Ensemble / 372
 - The Alaska Fire Service: Managing a Subcontinent / 376
 - The Nature Conservancy: Fire Management on Private Preserves / 379
- Further Reading / 381

PART 3 FIRE MANAGEMENT

8. Programs for Fire Management

385

- 8.1 Fire Prevention / 386
 - Strategies of Fire Prevention / 387
 - Identification of Causes and Remedies / 388
 - Education / 389
 - Engineering / 392
 - Enforcement / 392
 - Lightning Fire Prevention / 394
- 8.2 Detection / 394
 - Objectives of Detection / 395
 - Detection Methods / 395
- 8.3 Fire Information Systems / 400
 - Communications / 400
 - Fire Intelligence Systems / 402

- 8.4 Fuel Management / 405
 - Fuel Reduction / 406
 - Fuel Conversion / 407
 - Fuel Isolation / 408
 - Fuel Management: Selected Examples / 410
- 8.5 Fire Research / 419
 - Fire Research: A Historical Synopsis / 421
 - Structure of Fire Research in the United States / 425
- 8.6 Fire Economics / 426
 - Concepts of Fire Economics / 428
 - The LCPL Theory / 433
 - Fire Financing / 435
 - Economic Modeling: Contemporary Status / 437
- 8.7 Planning for Fire Management
 - The Impact of Recent History / 439
 - Planning Principles and Guides / 440
- 8.8 Solving Fire Management Problems: Selected Examples / 441
 - Sequoia-Kings Canyon National Park: The Conundrum of Natural Fire / 442
 - Pacific Northwest: Slash and Burn / 443
 - Bandelier National Monument: Artifact and Landscape / 448

Further Reading / 451

9. Fire Suppression

456

- 9.1 Suppression Strategies / 457
 - Concepts of Control / 458
 - Methods of Control / 461
 - Model Suppression Evolution / 469
- 9.2 Suppression Resources / 472
 - Personnel / 474
 - Equipment / 476
 - Fire Retardants / 480
- 9.3 Organizing for Fire Suppression / 486
 - Incident Command System / 486
 - Complex Incidents / 492
- 9.4 Suppression Tactics: Sample Wildfires / 493
 - Initial Attack: A Pluralism of Practices / 494

- Extended Attack: Tactics by Logistics / 507
- Modified Attack: Limited Suppression / 508
- Monitored Attack: Control by Prescription / 509
- 9.5 Postfire Activities / 512
 - Reports: Restoring the Fire Organization / 512
 - Rehabilitation: Restoring the Land / 513
 - Relief: Restoring Society / 517
- 9.6 Fireline Safety / 518
 - Safety Considerations / 518
 - Fire Fatalities and Near Misses: Selected Case Studies / 526
- Further Reading / 536
- 10. Prescribed Fire** **538**
 - 10.1 Prescribed Fire Plans / 539
 - Objectives of Prescribed Fire / 540
 - Elements of a Prescribed Fire Plan / 540
 - Model Prescribed Fire Evolution / 545
 - 10.2 Prescribed Fire Operations / 546
 - Methods of Control / 546
 - Personnel / 549
 - Preburn Preparations / 549
 - Firing Operations / 550
 - Monitoring and Evaluating / 552
 - 10.3 Smoke Management / 554
 - Emissions / 555
 - Objectives of Smoke Management / 560
 - Strategies and Techniques / 562
 - 10.4 Prescribed Burning: Selected Examples / 566
 - Slash Burning: Northern Rockies / 567
 - Presuppression Burning: Southern California Chaparral / 569
 - Underburning: South Carolina Pine / 570
 - Underburning: Arizona Pine / 572
 - Ecosystem Maintenance: South Florida Wetlands / 574
 - Prescribed Natural Fire: Selway-Bitterroot Wilderness, Idaho / 577
 - Type Conversion: Western Rangelands / 579
 - Ecological Research: Konza Prairie, Kansas / 582
 - Habitat Burning: Albany Pine Bush, New York / 584

- 10.5 Prescribed Fire Breakdowns: Selected Case Studies / 586
 - Seney Fires, Michigan, 1976 / 587
 - Pocket Fire, Georgia, 1979 / 589
 - Mack Lake Fire, Michigan, 1980 / 590
 - The Greater Yellowstone Fires, 1988 / 592
 - The Unlit Fire: Blue Mountains, Oregon / 595
- Further Reading / 597

PART 4 GLOBAL FIRE

- 11. Global Fire** **601**
 - A New World Order on Fire / 601
 - 11.1 Global Fire History / 602
 - Paleofire / 603
 - Anthropogenic Fire / 604
 - Aboriginal Fire / 610
 - Agricultural Fire / 613
 - Imperial Fire / 616
 - Industrial Fire / 618
 - Fire as Future / 618
 - 11.2 Global Fire Ecology / 619
 - Biomass Burning: Atmospheric Integration / 620
 - The Carbon Cycle: Chemical Integration / 625
 - Biogeography of Fire: Geographic Integration / 629
 - 11.3 Global Fire Management / 640
 - Infrastructures / 641
 - America and the World / 644
 - Satellite Surveillance: Test Case for a Global System / 648
 - 11.4 National Fire Programs: Selected Examples / 649
 - Sweden / 650
 - Canada / 657
 - Australia / 667
 - South Africa / 676
 - Brazil / 683
 - Russia / 690
 - 11.5 Global Wildfire: Selected Examples / 700
 - Ash Wednesday (Australia, 1983) / 701
 - Burning Borneo (Indonesia, 1983) / 703

Black Dragon Fire (China, 1987) / 705
 Amazonia (Brazil, 1987-1988) / 708
 Greek Fire (Greece, 1988) / 710
 Conflagrating California (United States,
 1990-1993) / 713

Further Reading / 718

BIBLIOGRAPHY

725

CREDITS

750

INDEX

753

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 Renováveis
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
ILTER	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	Système 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 them-

selves 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 man-

agement 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 consensus 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 compet-

ing 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

We begin
of an ex-
wildland
between
the final
wildland
As the
fuel char-
the forest
landscape
subdivisi-
life habit.
From here
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sustainable
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to have
The an-
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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.

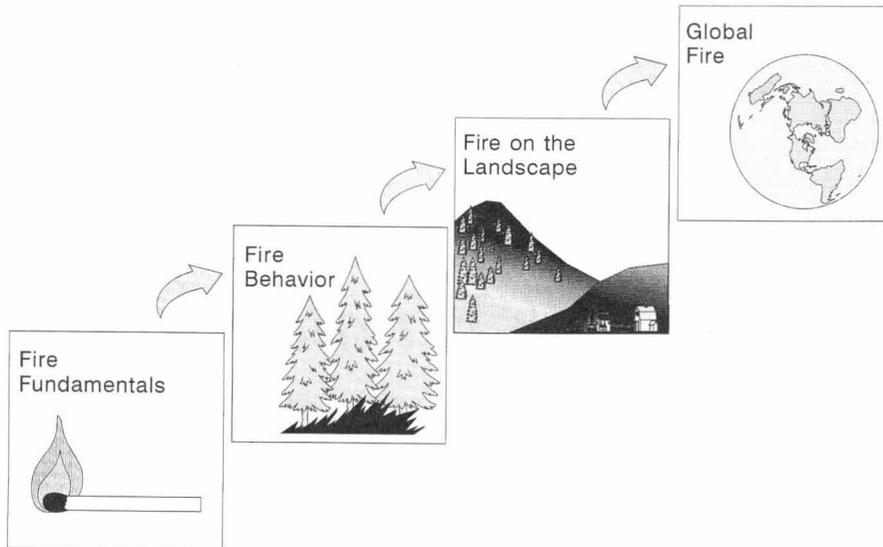


Figure 1.1. Expanding view of wildland fire. The dominating influence factors change with the scale.

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

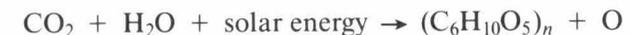


Figure 1.2. There is significant variability even in a controlled laboratory fire. Photo courtesy of USDA Forest Service.

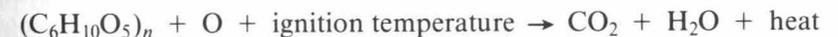
sun's energy are combined to produce cellulose, lignin, and other chemical components. Both decay and fire reverse that process. Decay is a slow process, with a barely noticeable release of heat over a long period of time. Fire, on the other hand, is a rapid release of the heat energy stored by photosynthesis.

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:



Combustion:



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 interchangeably.

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.

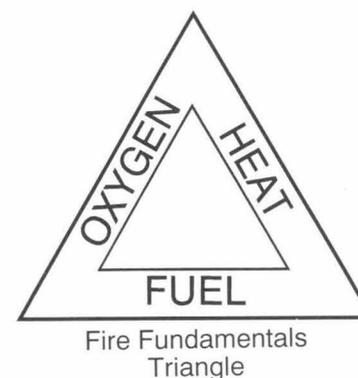


Figure 1.3. Fire fundamentals triangle. Oxygen, heat, and fuel must be present for fire to exist.

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

1.2 INTRINSIC FUEL PROPERTIES

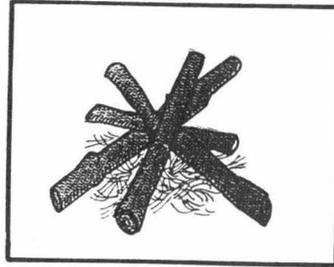
We examine wildland fuel by separating the discussion according to those properties that are intrinsic to the fuel and those that are extrinsic. Intrinsic fuel properties are those that delineate the plant parts, including fuel chemistry, density, and heat content. Extrinsic fuel properties include relative 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.

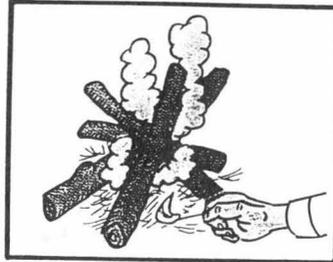
Wildland fuel consists of the cell wall polysaccharides, i.e., cellulose and hemicelluloses, which are readily pyrolyzed; lignin, which mainly forms char; extractives, particularly the terpenoid hydrocarbons, and lipids, which provide a ready source of combustible volatiles; and ash content, which exerts 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.

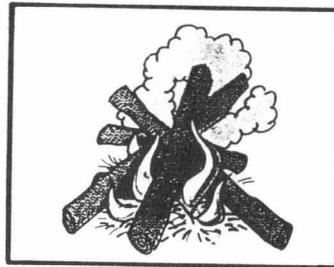
1. Campfire fuel is a mixture of dry fine and heavy fuel. It is placed on mineral soil to eliminate the possibility of smoldering ground fire.



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.



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)

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 (micro-

fibrils), 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.

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 carbonaceous 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, par-

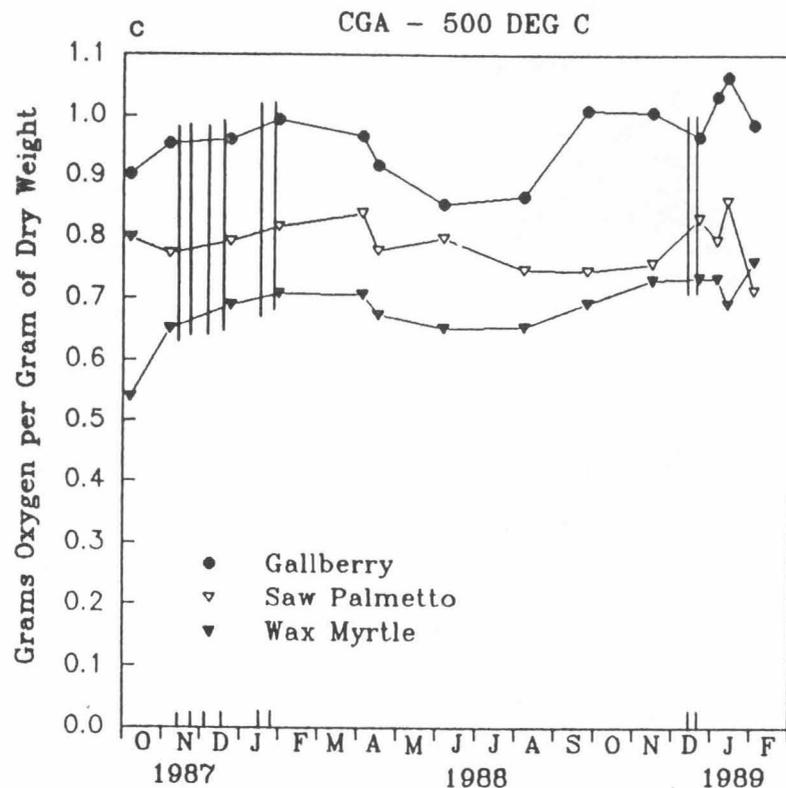


Figure 1.5. Combustible gas analysis (CGA) for freeze-dried samples of gallberry, saw palmetto, and wax myrtle at 500°C (932°F). Vertical lines indicate those dates when minimum temperatures were less than 0°C (32°F). From Burgan and Susott (1991).

ticularly 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.

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 black-body.

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 $W/m \cdot K$, where \dot{q}'' is in W/m^2 , T is in $^{\circ}C$ (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

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

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

$$E = \epsilon\sigma T^4 \quad W/m^2$$

where σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} W/m^2 K^{-4}$), 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:

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

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

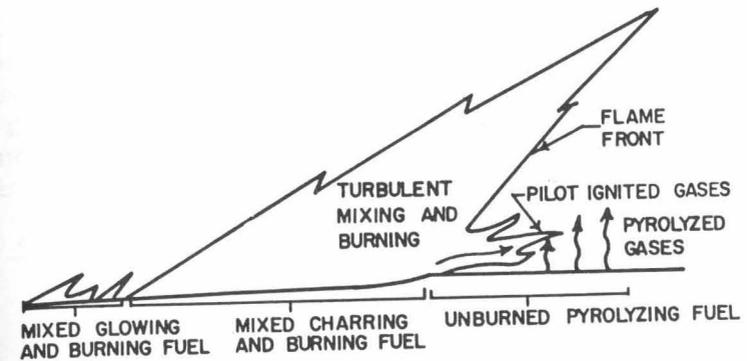


Figure 1.6. Flaming zone combustion characteristics in the presence of wind. From Rothermel and Anderson (1966).

products of pyrolysis and by volatilization of waxes, oils, and other compounds in the vegetation.

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 $100^{\circ}C$ ($212^{\circ}F$). 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 $250^{\circ}C$ ($480^{\circ}F$) are reached. At $325^{\circ}C$ ($620^{\circ}F$) it breaks down rapidly, evolving large quantities of

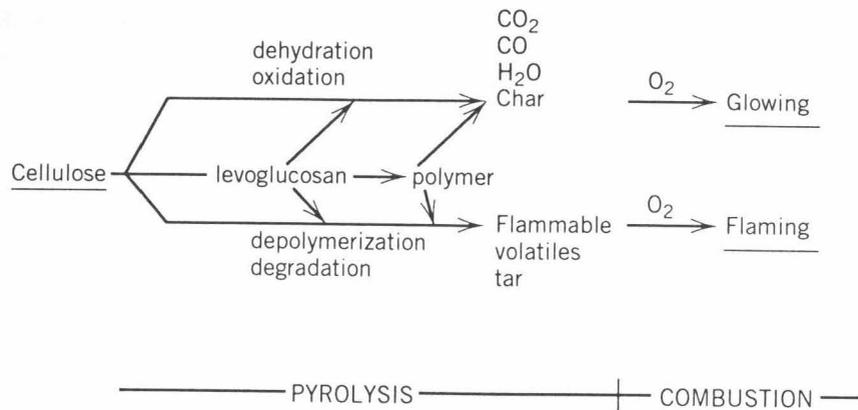


Figure 1.7. Pathways for the pyrolysis of cellulose. From Philpot (1971).

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

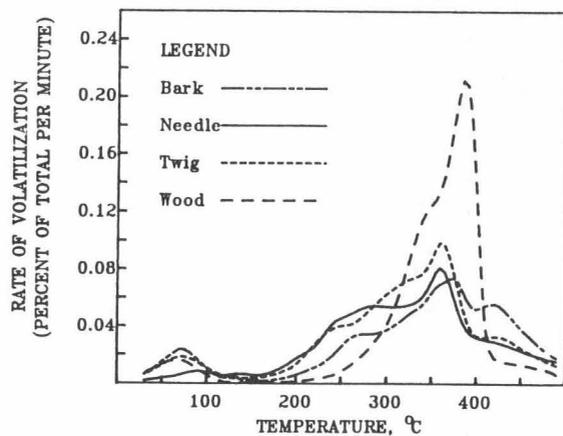


Figure 1.8. Examples of different rates of fuel volatilization as a function of temperature. From Ward (1990).

there are a great number of complex pyrolytic reactions involved in volatile production.

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

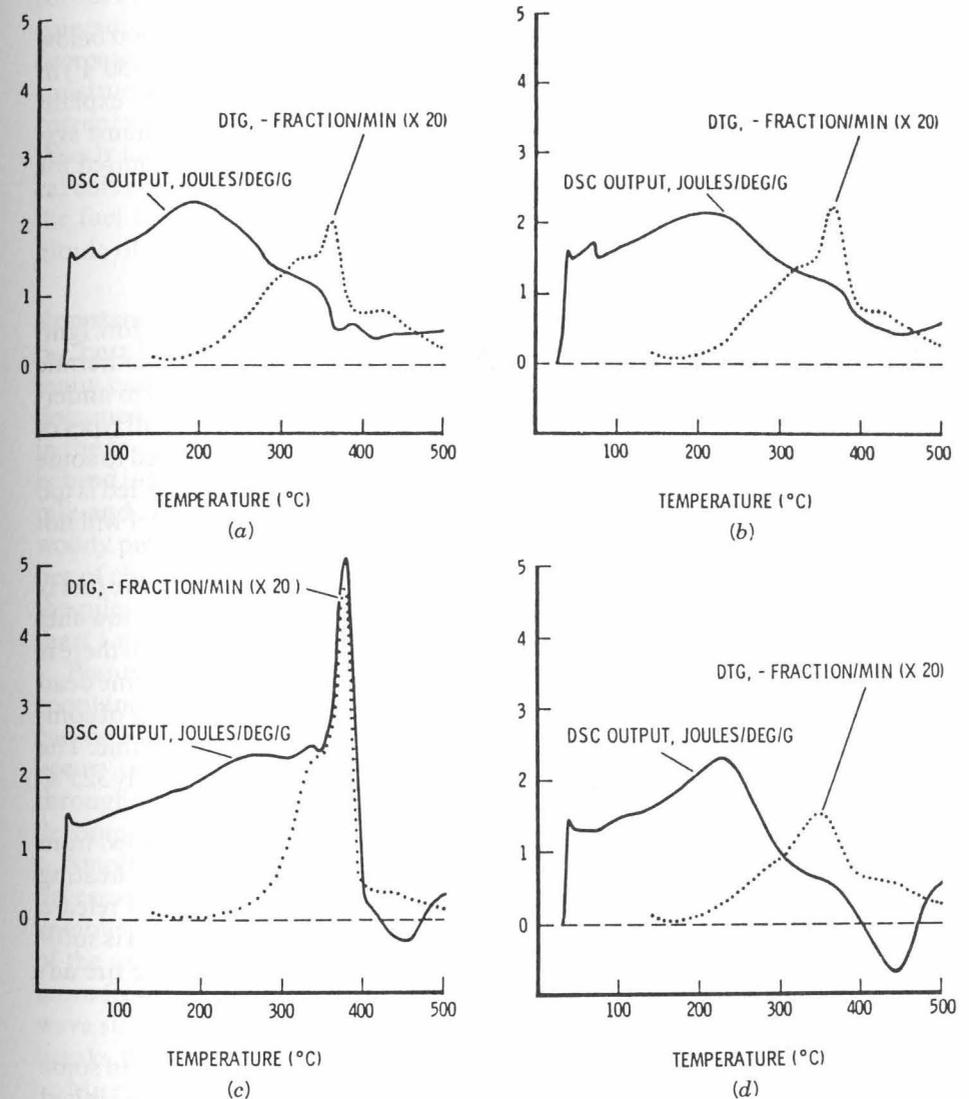


Figure 1.9. Differential scanning calorimetry (DSC) and derivatives of thermogravimetry (DTG) plots for (a) green ponderosa pine needles, (b) cured ponderosa pine needles, (c) sound Douglas fir wood, and (d) rotten Douglas fir wood. From Susott (1982b).

and DTG curves 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 volatilized 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 look-

ing 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 pyrolyzate 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.

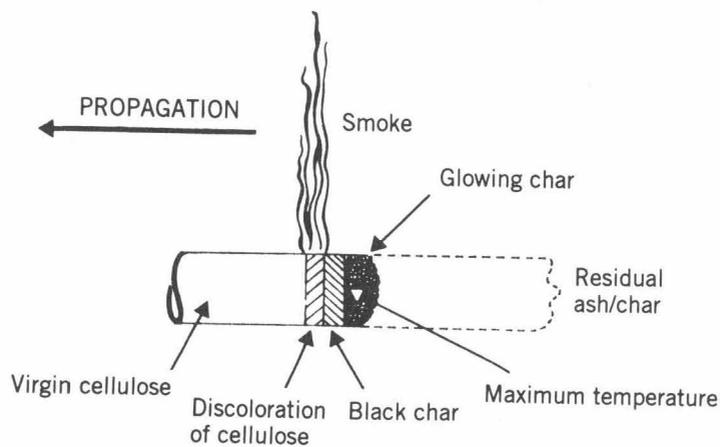


Figure 1.10. Representation of steady smoldering along a horizontal cellulose rod. From Moussa and others (1977).

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.

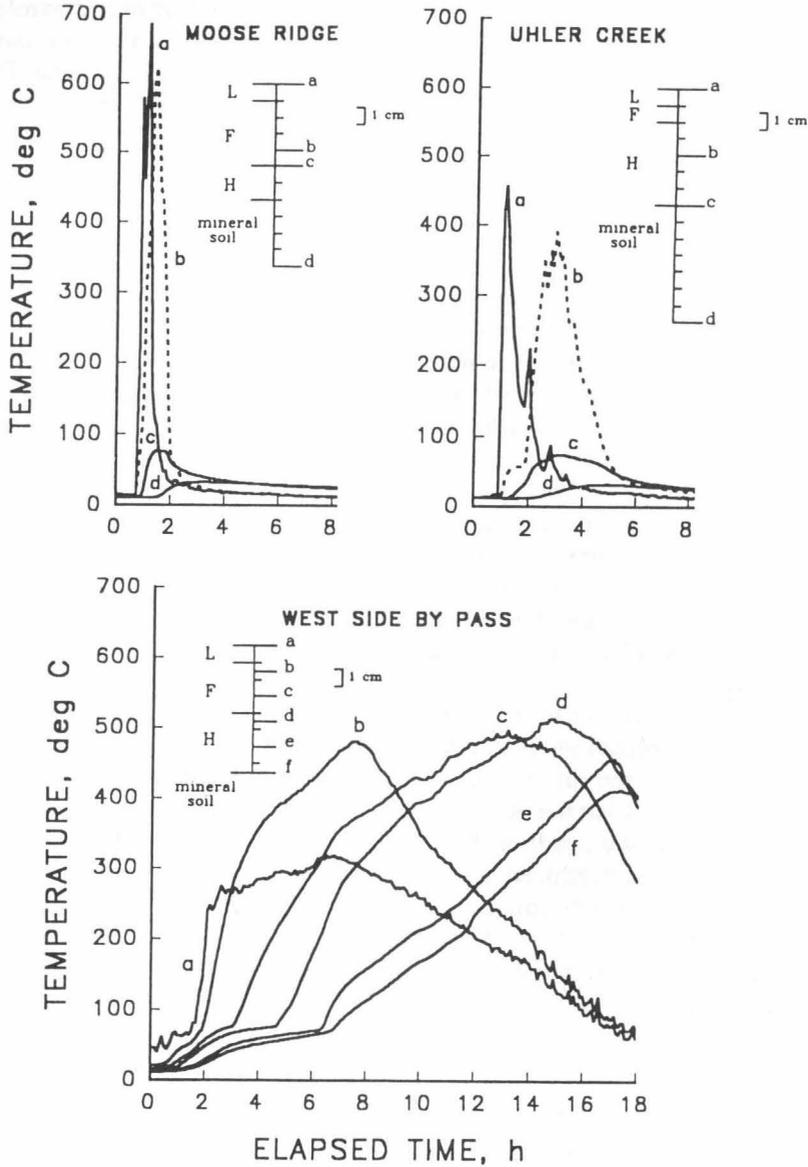


Figure 1.11. Temperature histories in the litter (L), fermentation (F), humus (H), and mineral soil. Insets show vertical placement of temperature sensors relative to the forest floor profile. The fires were in northern Idaho and western Montana. The Moose Ridge and Uhler Creek were in slash; the West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

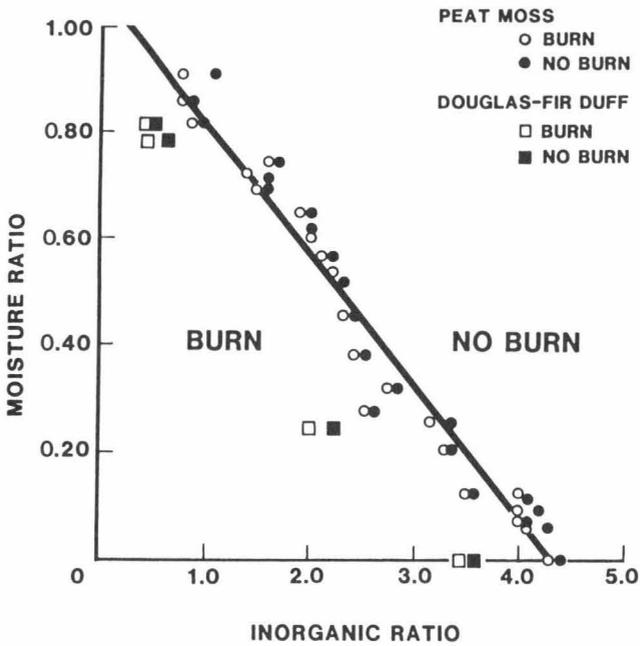


Figure 1.12. Linear estimate of smoldering limits of smoldering forest duff. From Frandsen (1987).

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,

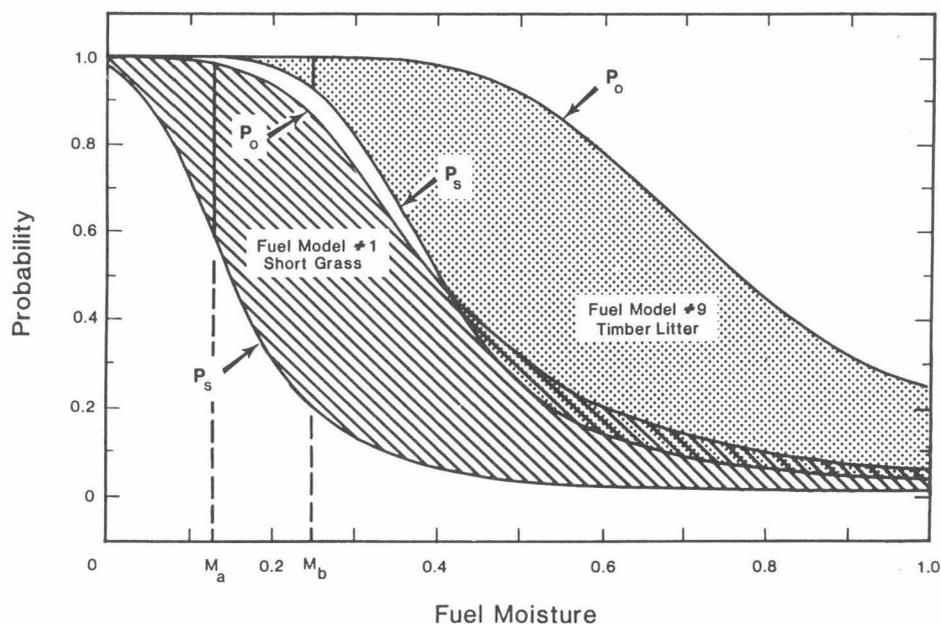


Figure 1.13. Comparison of marginal burning zones for two stylized fuel models. P_o is the probability that the fire will go out; P_s is the probability of a "steady-state" fire with 100% continuous flame front. $M_a = 0.12$ is the often used moisture of extinction for short grass; $M_b = 0.25$ is used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

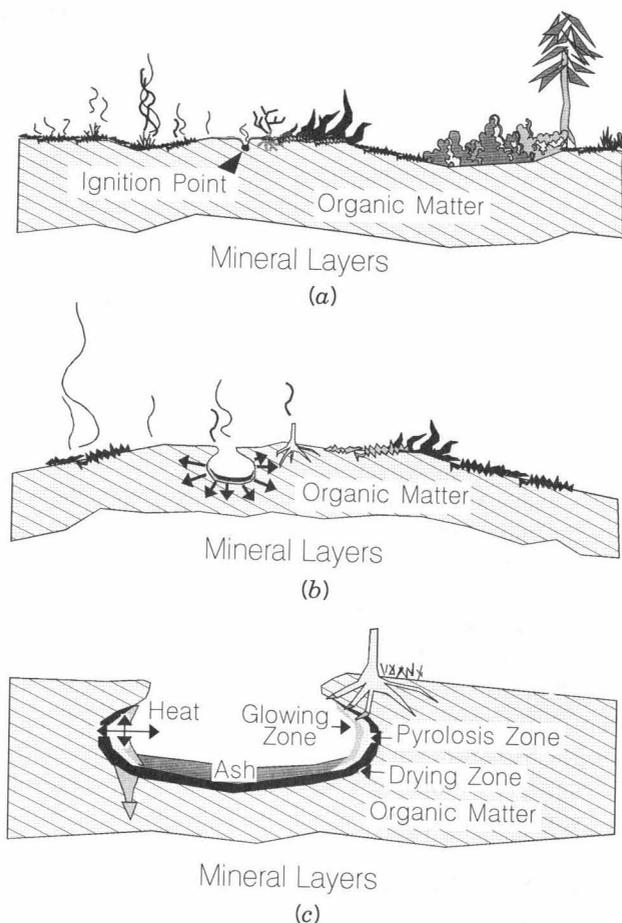


Figure 1.14. Schematic diagram of the smoldering process. (a) initial ignition point of smoldering initiated by a passing surface fire. (b) Concentric spread of the burn hole from the initial point. (c) Pyrolysis zone and drying zone ahead of the glowing zone in a fully developed burn hole. Heat generated 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

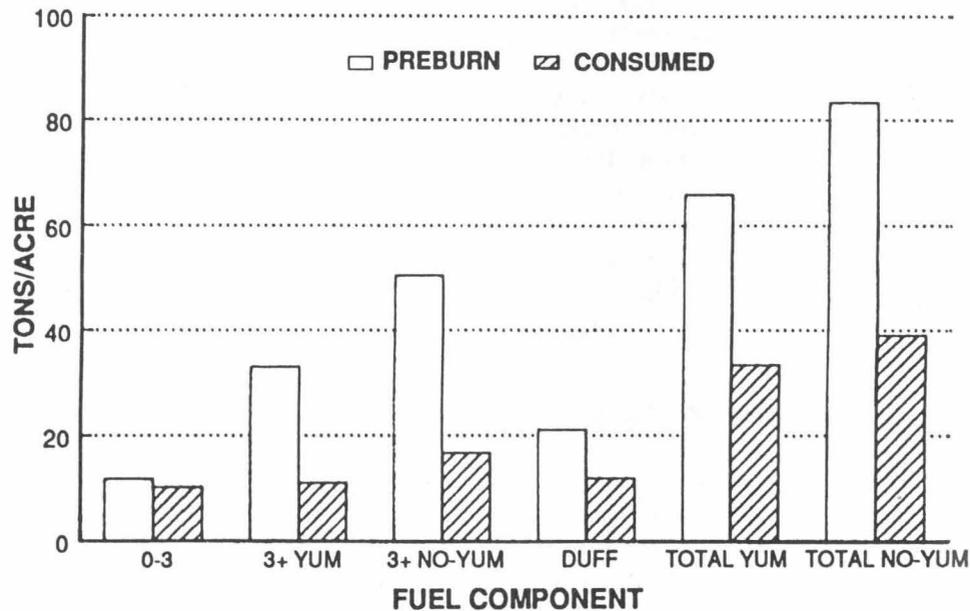
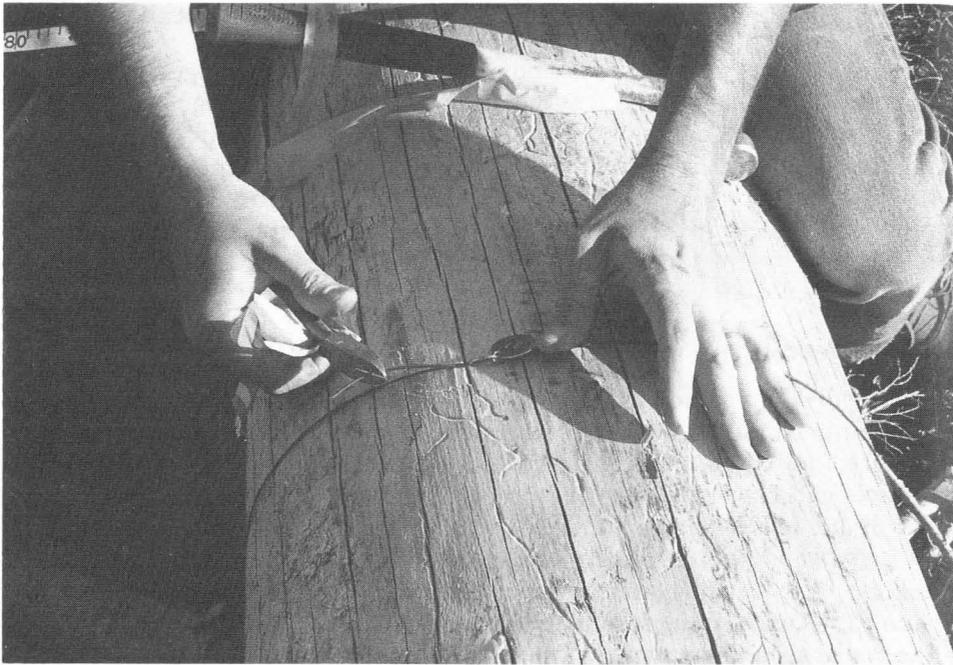


Figure 1.15. Log being wired for diameter-reduction sampling. Average preburn fuel loadings and fuel consumption for sampled logging units in Northern Idaho. In 12 of the clearcut units a YUM (yarding of unmerchantable material) treatment was applied: Unmerchantable material greater than 6 inches in 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 ($>800^\circ\text{C}$ ($<1500^\circ\text{F}$)), rapid formation of particles and accretion of carbonaceous organic particles will occur. Consumption of the particles requires prolonged exposure at high

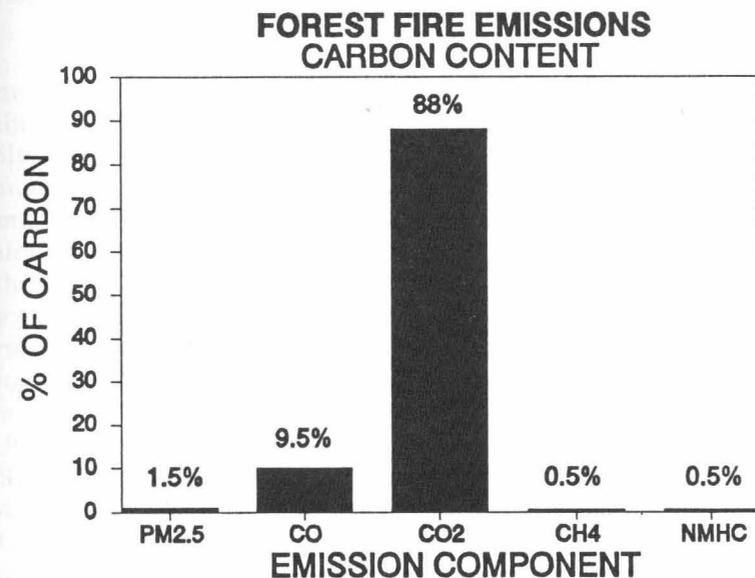


Figure 1.16. The average percentage of total carbon released by biomass burning in the United States in the form of CO , CO_2 , and hydrocarbons. PM2.5 is particulate matter less than $2.5 \mu\text{m}$ diameter. From Ward (1990).

temperatures ($>800^{\circ}\text{C}$ ($>1500^{\circ}\text{F}$)) 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 $2.5\ \mu\text{m}$ 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 $0.15\ \mu\text{m}$. The volume distribution, which for a first approximation represents the mass distribution, shows a bimodal distribution with peaks at $0.5\ \mu\text{m}$ and greater than $43\ \mu\text{m}$ (Figure 1.17). The mass of particulate matter between 1 and $10\ \mu\text{m}$ makes up less than 10% of the total mass.

The trace elements for samples of particles less than $2.5\ \mu\text{m}$ in diameter (PM_{2.5}) are shown in Figure 1.18 as a percentage of the PM_{2.5} 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 PM_{2.5} 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

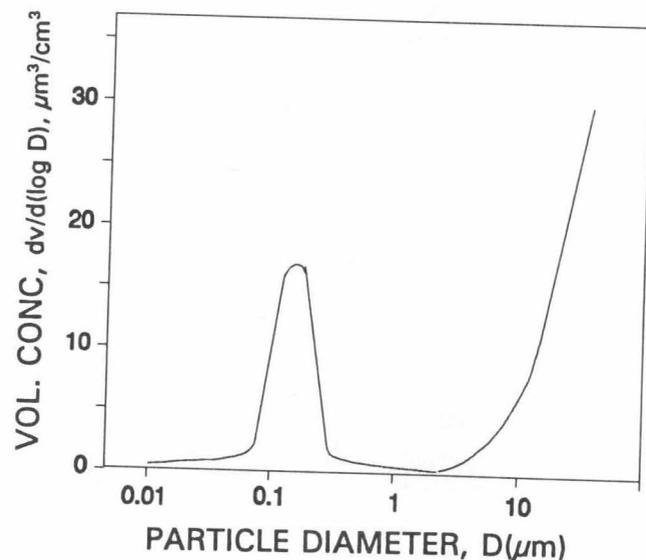


Figure 1.17. Volume by particle size fractions measured for prescribed fires of logging slash in the Western United States from an airborne sampling platform. From Radke and others (1990).

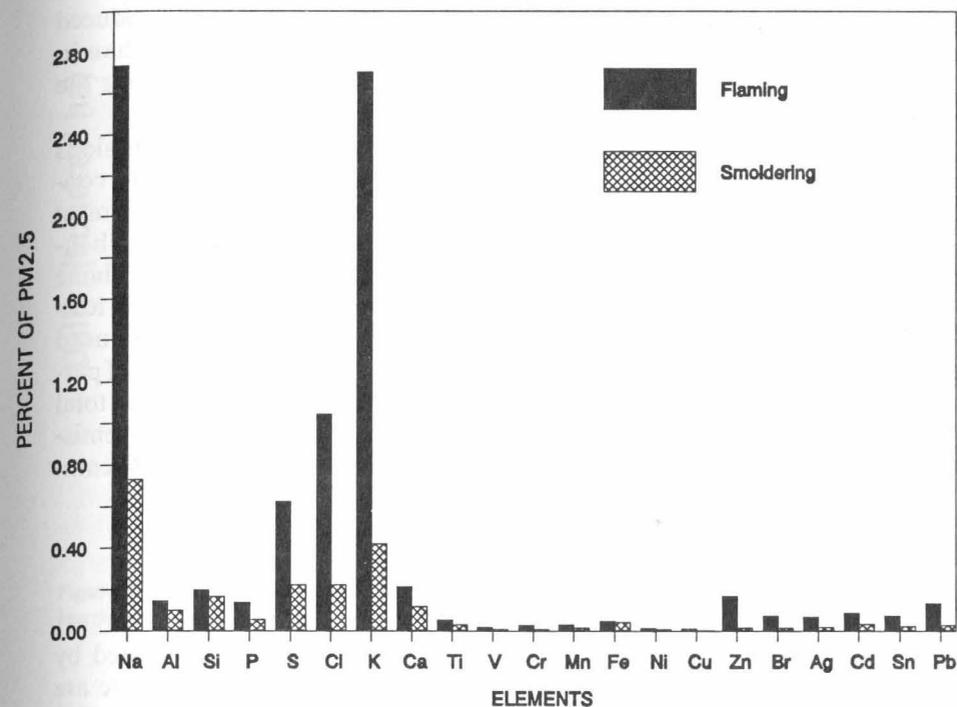


Figure 1.18. Percentage composition of particulate matter less than $2.5\ \mu\text{m}$ diameter in smoke from logging slash fires in Western United States. From Ward (1990).

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.

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 pro-

duction of carbon monoxide relative to carbon dioxide. Methane is produced in much larger quantities during the smoldering combustion phase than in the flaming phase. Emission 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 PM_{2.5} 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 PM_{2.5} emissions from prescribed burning.

Digital data ("map layers") were used in a raster-based GIS to derive daily PM_{2.5} 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,

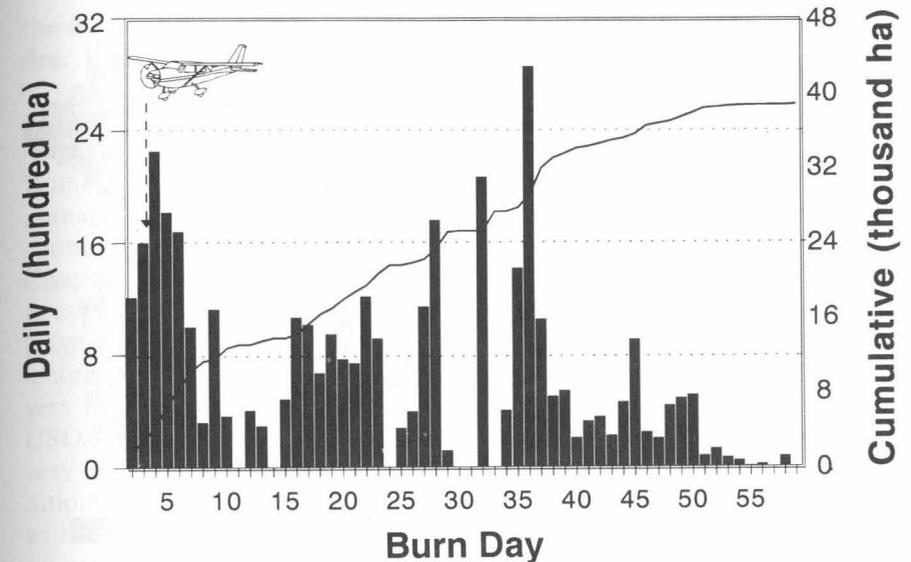


Figure 1.19. Daily burned area for 58 days of the 1987 Silver fire in southwest Oregon. From Hardy and others (1993).

low, medium, and high) derived from photogrammetric interpretation of images acquired after the fire; and (4) elevation zone.

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 PM_{2.5} (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 PM_{2.5} 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

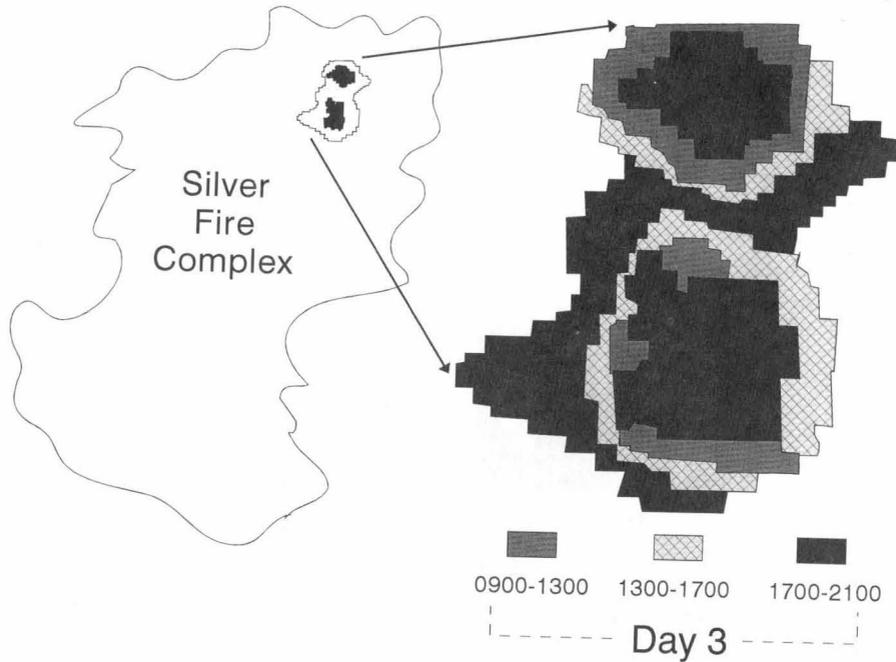


Figure 1.20. Day 3 of the fire broken into three 4-h burning periods. From Hardy and others (1993).

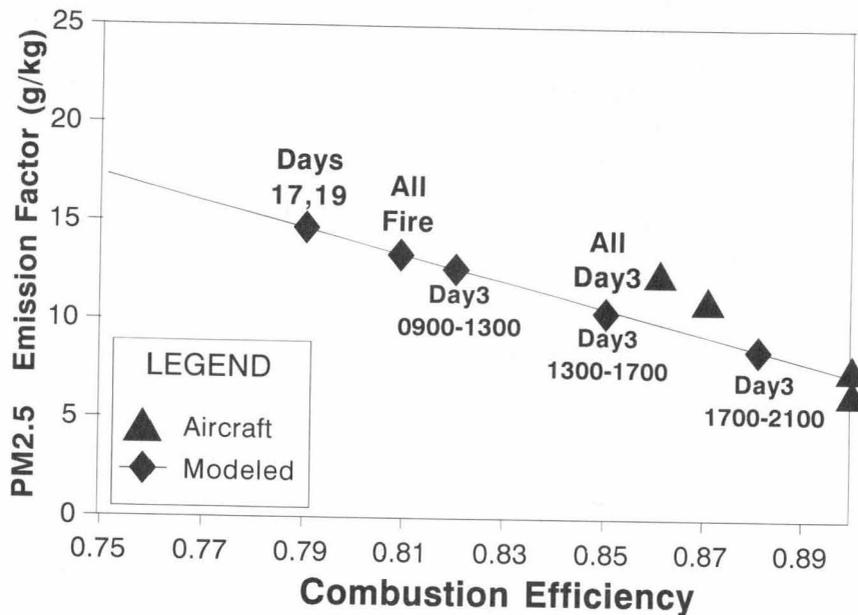


Figure 1.21. Modeled and observed data for EF_{PM2.5} and combustion efficiency. From Hardy and others (1993).

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

$$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \epsilon Q_{ig}}$$

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/ft²·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

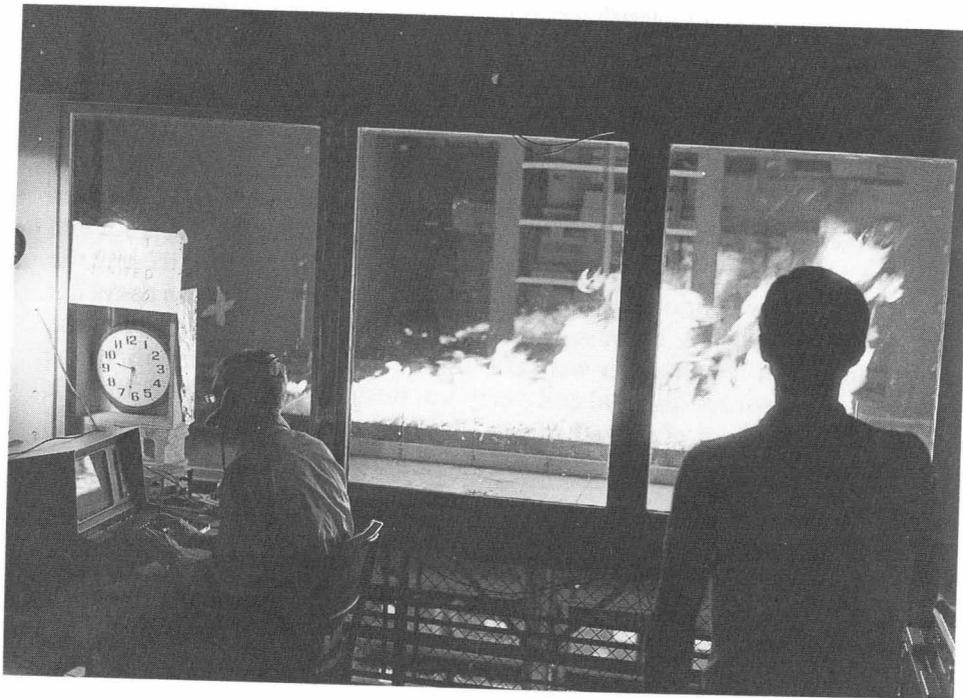
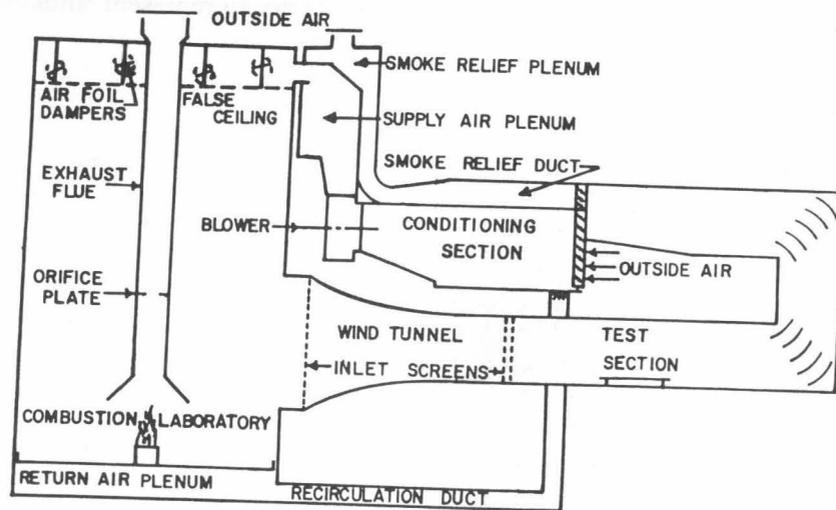


Figure 1.22. Laboratory conditions can be used for controlled experiments. Diagram from Rothermel and Anderson (1966). Photograph courtesy of USDA Forest Service.

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 oven-dry 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.

Symbol	Parameter	Units	
		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. oven-dry wood	fraction	fraction
S_T	total mineral content, wt. minerals/wt. oven-dry wood	fraction	fraction
S_E	effective mineral content, wt. silica-free minerals/wt. oven-dry 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. oven-dry wood	fraction	fraction

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

Element	English		Metric	
	Equation	Units	Equation	Units
Rate of spread	$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \epsilon Q_{ig}}$	ft/min	$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \epsilon Q_{ig}}$	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	$\beta_{op} = 3.348 \sigma^{-0.8189}$ $A = 133 \sigma^{-0.7913}$		$\beta_{op} = 0.20395 \sigma^{-0.8189}$ $A = 8.9033 \sigma^{-0.7913}$	
Moisture damping coefficient	$\eta_M = 1 - 2.59 \frac{M_f}{M_x} + 5.11 \left(\frac{M_f}{M_x}\right)^2 - 3.52 \left(\frac{M_f}{M_x}\right)^3$		$\eta_M = 1 - 2.59 \frac{M_f}{M_x} + 5.11 \left(\frac{M_f}{M_x}\right)^2 - 3.52 \left(\frac{M_f}{M_x}\right)^3$	
Mineral damping coefficient	$\eta_s = 0.174 S_e^{-0.19} (\max = 1.0)$		$\eta_s = 0.174 s_e^{-0.19}$	
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	$\phi_w = CU^B \left(\frac{\beta}{\beta_{op}}\right)^{-E}$ $C = 7.47 \exp(-0.133 \sigma^{0.55})$ $B = 0.02526 \sigma^{0.54}$ $E = 0.715 \exp(-3.59 \times 10^{-4} \sigma)$		$\phi_w = C(3.281U)^B \left(\frac{\beta}{\beta_{op}}\right)^{-E}$ $C = 7.47 \exp(-0.8711 \sigma^{0.55})$ $B = 0.15988 \sigma^{0.54}$ $E = 0.715 \exp(-0.01094 \sigma)$	
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	$\epsilon = \exp(-138/\sigma)$		$\epsilon = \exp(-4.528/\sigma)$	
Heat of preignition	$Q_{ig} = 250 + 1116 M_f$	Btu/lb	$Q_{ig} = 581 + 2594 M_f$	kJ/kg
Packing ratio	$\beta = \frac{\rho_b}{\rho_p}$		$\beta = \frac{\rho_b}{\rho_p}$	

Figure 1.24. Fire spread equations. English units from Rothermel (1972) and Albin (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

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

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

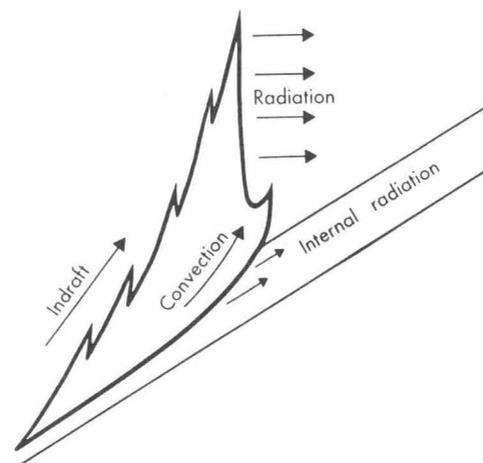
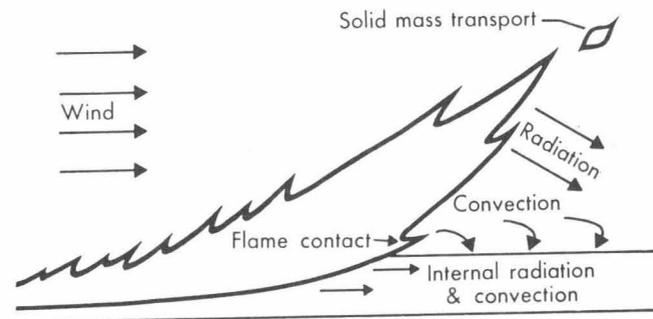
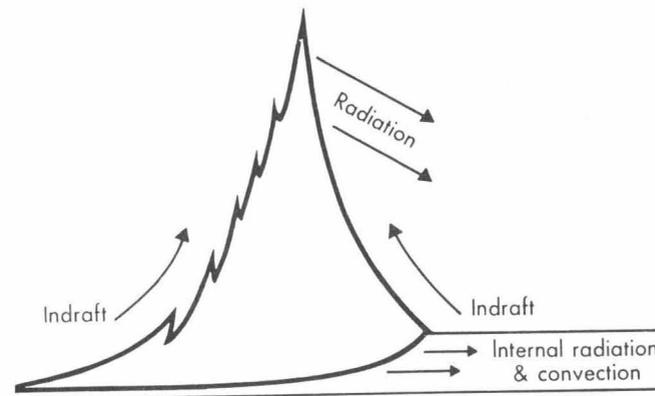


Figure 1.26. Schematic of no-wind, wind-driven, and upslope fires. From Rothermel (1972).

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 $\rho_b \epsilon$ and the heat of preignition Q_{ig} :

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

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):

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

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 $\rho_b \epsilon$. 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 Consumption by Prescribed Fire in Northern Idaho Mixed Conifer 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."