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Donald McKenzie, Carol Miller
and Donald A. Falk
Editors

The Landscape Ecology of Fire

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Cover illustration: Post-fire landscape pattern revealing the varying effects of forest management (clearcut logging) on wildfire severity in the Tripod Complex Fire (2006) in north-central Washington state, USA. Photo taken by and © Christina Lyons-Tinsley (University of Washington) and used with her permission.

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Dedication

In early 2007, Lara Kellogg and I (McKenzie) drafted an outline for what would become this book. Theretofore, she had completed a graduate degree with me and worked as a geospatial analyst. She had never done anything remotely akin to editing a technical book, but took the task with a balance of humility and confidence to which many of us aspire.

Lara was most at home in a vertical landscape of sky, rock, and ice whose remoteness and intensity most of us visit only in our dreams. Unlike many others of her persuasion, however, she was equally agile in the virtual landscape of points, pixels, and polygons. Having barely begun what surely would have been a creative and productive career as a landscape ecologist, her work on the spatial correlation structure of fire-history records set a standard for much future work in the field.

In April 2007 we lost Lara to the mountains she loved most, in the Alaska wilderness. She was orders of magnitude larger than life, and we thank her for the inspiration she provides us, in both our work and our daily lives, as we see this book to completion.

Foreword

In the mid 1980s I was asked to create a fire regime map of the Selway-Bitterroot Wilderness Area for the Bitterroot National Forest fire management staff. The well known fire historian Steve Barrett had already completed most of the work by synthesizing all available fire history results by forest habitat type, so I figured it would be easy to create a map of habitat types and then assign fire regimes to each habitat type. However, when the mapped fire regimes were compared to actual fire history field data, I found that the map's accuracy was disturbingly low, ranging from 40% to 60%. At first I thought that low accuracies were a result of inaccurate habitat type mapping, but subsequent revisions of the habitat type map that increased accuracies to over 80% did nothing to improve the accuracy of the fire regime map. I searched and searched for answers to this dilemma but in the end, I gave up and sent the map to the Bitterroot National Forest with a warning about its low accuracy. It wasn't until years later after reading Forman and Godron's Landscape Ecology book that I fully understood the profound influence of spatial and temporal context on fire regimes. It was clear that fire regimes are the manifestation of spatial factors, such as topography, wind, and patch characteristics, as they interact with antecedent climate, fuels, vegetation and humans across the landscape, and fire regimes would be difficult, if not impossible, to understand, let alone predict, without a spatiotemporal foundation.

Landscape ecology is the "glue" that holds ecosystem theory together and nowhere is that more evident than in the study of wildland fire ecology. Fire is one of those unique and complex processes that operates across multiple scales of space and time because its ignition and spread are dictated by diverse factors of climate, weather, fuels, and topography, which also operate at different scales. It wasn't until the field of landscape ecology burst onto the ecological scene in the early 1980s that the missing pieces of wildland fire dynamics fell easily into place. The concepts of scale, resolution, and extent fit perfectly into fire science and they helped explain new and exciting phenomena that would have never been discovered without a context of space. In my experience, it is only in the framework of landscape ecology that the many varied aspects of fire regimes can be explored and explained using the extensive body of fire history data collected by the many dedicated scientists. Moreover, as I learned in the Bitterroot project, it is difficult to map fire regimes across a landscape without a basic knowledge of landscape ecology fundamentals, and the identification of the appropriate scale, landscape extent, time frame, and spatial variability allows a more accurate depiction and prediction of fire regimes across large areas.

It would be difficult to overemphasize the impact that landscape ecology has had on wildland fire science, yet there have been few comprehensive summaries or syntheses of the integration of landscape ecology and wildland fire in the literature. It is the concepts of landscape ecology that make fire science much easier to understand, interpret, and apply. Particularly valuable is a physical or mechanistic approach to landscape fire ecology, where biophysical drivers such as climate, energy flux, and plant ecophysiology are used to build a more "unified theory of the ecology of fire." Fire processes and their interactions are dynamic and we should never assume that there is such a thing as an "equilibrium condition"; wildland fire ecology exhibits non-linear behavior that in turn produces non-equilibrium responses, which is important to consider when attempting to apply fire science to management issues.

I believe that the next major advances in the field of wildland fire science will be in two areas: (1) the study of the variability of fire across spatiotemporal scales, and (2) the linkage of fire regimes with the biophysical processes that control them. Scaling laws, self-organized criticality, and power laws, along with semi-variance and geostatistical analyses, represent exciting new advances in understanding fire's spatial and temporal variability. But we must first understand the multi-scaled basic physical processes that influence fire dynamics if we are to understand wildland fire and manage its effects. This is more important than ever as we are faced with rapid and uncertain changes in climate, the coarsest and arguably most powerful driver of fire regimes.

In the end, the complexity of landscape fire dynamics must eventually be synthesized to a level where it can be understood and applied by natural resource management. Fire history and spatially explicit historical fire regimes are now being used by many managers to quantify the historical range and variability of landscape characteristics, and this envelope of variability is then used to prioritize, design, and implement management actions at multiple scales. This book presents essential information and some useful applications of landscape fire ecology for natural resource management. I only wish I had this book when I was spending long days and nights trying to improve that Selway-Bitterroot fire regime map.

March 19, 2010 Robert E. Keane

Preface

This is a book about fire on landscapes. We explore fire as a contagious spatial process from a number of perspectives, including fundamental theory, fire-climate interactions, interactions with other ecological processes, and ecosystem management. Along the way we visit traditional domains of landscape ecology such as scaling, pattern-process interactions, and the complex interplay of top-down and bottom-up controls on ecosystem dynamics. We devote considerable space to theoretical considerations, particularly cross-scale modeling and landscape energetics, which we believe are under-represented in the current literature on landscape ecology of fire and other disturbances. In the remainder of the book, we look at fire climatology in an explicitly spatial context, examine four case studies of fire dynamics, two topical and two geographic in focus, and discuss issues facing fire management under rapid global change.

Our geographic focus is western North America (Fig. 1). This not only reflects the expertise of the editors and authors, but also allows us to look at a single large and diverse bioregion from multiple perspectives. Moreover, fire regimes in western North America are relatively less modified by humans than many other fire-prone landscapes around the world. Western North America is endowed with expanses of uninhabited areas over which we have ample opportunity to observe fire at a variety of scales. This facilitates our examining the interactions of climate, vegetation, and fire; fire extent, severity, and spatial pattern; and fire's interactions with other disturbances such as insect outbreaks and with other ecological processes such as invasions of landscapes by non-native plants.

Fire regimes in western North America, and the western United States in particular, have evolved in a mostly temperate climate, ranging from maritime to continental, and from wet to arid. Topography is very diverse, ranging from flat to extremely rugged, with elevations from below sea level to greater than 4,000 m. Human-induced changes in the fire regime range from essentially none (subalpine and other systems with stand-replacing fire regimes) to significant (Native American burning, twentieth-century fire exclusion, human-facilitated spread of invasive non-native species). Major vegetation types include semi-arid grasslands, chaparral, semi-arid woodlands, and a wide range of conifer and mixed forests. Western North America therefore encompasses many (though not all) of the major

Fig. 1 Locations in the western USA of study sites analyzed or referred to in individual chapters of the book. Chapter numbers are in parentheses. Map color schemes here and elsewhere in the book draw substantially upon ideas at http://colorbrewer2.org/, developed by C.A. Brewer, Dept. of Geography, Pennsylvania State University

fire-regime types of Earth's fire-prone ecosystems, and we believe that the more general inferences from this book will have wide applicability around the world.

Section I focuses on the concepts of ecosystem energetics, scaling, and resilience. In Chap. 1, we outline a potential theoretical framework for landscape fire based on ecosystem energetics. This chapter provides a lens through which succeeding chapters may be viewed. We explore how the concepts of ecosystem energetics, top-down vs. bottom-up controls, and scaling laws might be integrated to provide both a theoretical framework that reduces the apparent complexity of landscape disturbance and a window into its underlying mechanisms.

McKenzie and Kennedy (Chap. 2) review quantitative scaling relationships in fire regimes and describe how they can be used to discern controls operating at different scales. They review the basis for scaling laws in fire-size distributions, fire frequency, and fire hazard. These authors also use scaling laws to illuminate the spatial autocorrelation structure in fire-history data, which in turn reveals the dominant drivers of historical fire occurrence and extent.

In Chap. 3, Moritz, Hessburg, and Povak focus on scaling laws that describe fire size distributions and show how the spatial domain over which these scaling laws obtain is linked to dominant scales of regulation. They further present ideas about how self-organized ecosystem dynamics play out at these characteristic "landscape scales", possibly building or enhancing landscape resilience.

Section II attends to one of the most important drivers of landscape fire dynamics: climate. Fire climatology references spatial scales broader than the usual domain of landscape ecology and is the subject of these two chapters. Gedalof (Chap. 4) reviews fire climatology with an emphasis on broad spatial patterns of climate drivers of fire and how they interact with biome-scale vegetation across North America. He invokes the idea of top-down vs. bottom-up controls on landscape fire, introduced in Chaps. 1–3, as they apply at regional to continental scales.

In Chap. 5, Littell and Gwozdz develop statistical fire-climate models at a finer spatial scale in the Pacific Northwest, USA. They introduce the idea of seasonal water-balance deficit as an overarching control of fire extent at regional scales and present ideas for scaling climate-fire models down to landscapes while maintaining the water-balance mechanism as a control.

Section III focuses on the ecological consequences of landscape fire dynamics. In Chap. 6, Smithwick reviews the interactions of fire with the biogeochemistry of ecosystems, using the well studied Greater Yellowstone Ecosystem as an example of the lessons learned about biogeochemical resilience. Whereas most fire-effects research looks at species, populations, and communities, Smithwick discusses the relatively unexplored idea that ecosystem functions such as decomposition and nutrient cycling are important contributors to resilience in the face of disturbance.

Swetnam, Falk, Hessl, and Farris (Chap. 7) provide an overview of methods for reconstructing historical fire perimeters from fire-scar records (which are essentially point data) as a tool for understanding the landscape spatial patterns of unmanaged fire. They review methods of interpolation, comparing both accuracy and assumptions implicit in a variety of methods. They then give a prospectus of the application of spatial reconstruction to both contemporary and future fire management.

In Chap. 8, Keeley, Franklin, and D'Antonio use the large and biologically rich state of California, USA, as a geographic template for examining the interplay of fire, climate, invasive species, and human populations. California's forests, shrublands, and grasslands, along with other Mediterranean ecosystems, are some of the world's most diverse with respect to species composition, landforms, and land use. Ecosystem dynamics in this region are analogously complex and provide a challenging arena for understand landscape fire dynamics in the face of extensive invasion by persistent non-native species.

Cushman, Wasserman, and McGarigal (Chap. 9) examine potential consequences of landscape fire dynamics for wildlife habitat in a Rocky Mountain landscape in northern Idaho, USA. They report a simulation experiment on the relative effects of climate change vs. management alternatives on habitat for two wildlife species with contrasting life-history traits. Their work poses the very relevant question of whether even fairly aggressive management can be effective given expected future changes in climate.

Our focus on the relatively uninhabited lands of western North America in no way obviates the need to consider the human dimension of the landscape ecology of fire in a contemporary context. Section IV provides two perspectives on fire management in the future. In Chap. 10, Peterson, Halofsky, and Johnson discuss fire management opportunities on landscapes that are moderately to intensively managed. They present both a technical overview of fire and fuels management, with implications for ecosystem function in future climate, and a review of adaptation strategies from a consensus of land managers.

By contrast, Miller, Abatzoglou, Syphard, and Brown (Chap. 11) look at fire management in areas protected as wilderness across the western United States. Acknowledging that fire regimes and their management do not exist in isolation from exogeneous forces of change, they explore how the future context of wilderness fire management might change with two future trends: increasing temperatures leading to more episodes of extreme fire weather, and increasing housing densities leading to greater risk and greater incidence of human-caused fires in wilderness areas. Using two contrasting examples, they discuss how the challenge to meet fire-management objectives could intensify in many wilderness areas.

A single book cannot cover the entire field of landscape fire ecology. Consequently, we have eschewed coverage of some topics that might be central to a broad survey of the field but have been well covered in other recent publications. For example, we do not review landscape fire simulation models or remote sensing of fire characteristics. Similarly, we do not provide surveys of the use of landscape metrics in the description of fire pattern and dynamics, or of spatial considerations in sampling designs in fire ecology. Instead, we focus on new and emerging ideas about the landscape ecology of fire that are not well covered in the existing literature. We hope that the chapters in this book stretch familiar concepts, touch upon new ideas and directions, and present a range of perspectives for the study of landscape fire ecology. We encourage the reader to use this volume as a complement to existing published work.

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Part I
Concepts and Theory

Chapter 1
Toward a Theory of Landscape Fire

Donald McKenzie, Carol Miller, and Donald A. Falk

1.1 Introduction

Landscape ecology is the study of relationships between spatial pattern and ecological process (Turner 1989; Turner et al. 2001). It is the subfield of ecology that requires an explicit spatial context, in contrast to ecosystem, community, or population ecology (Allen and Hoekstra 1992). One major theme in landscape ecology is how natural disturbances both create and respond to landscape pattern (Watt 1947; Pickett and White 1985; Turner and Romme 1994). Landscape disturbance has been defined *ad nauseum*, but here we focus on its punctuated nature, in that the rates of disturbance propagation are not always coupled with those of other ecological processes that operate more continuously in space and time. Disturbance can therefore change landscape pattern abruptly, and large severe disturbances can be a dominant structuring force on landscapes (Romme et al. 1998).

Fire is a natural disturbance that is nearly ubiquitous in terrestrial ecosystems (Fig. 1.1). Because fire is fundamentally oxidation of biomass, the capacity to burn exists virtually wherever vegetation grows. Occurring naturally in almost every terrestrial biome, fire and its interactions with ecosystems enable the study of landscape pattern and process under a wide range of climates and geophysical templates (Bowman et al. 2009).

Fire represents one of the closest couplings in nature of abiotic and biotic forces (Chap. 6). Fires are frequent, severe, and widespread enough in multiple regions and ecosystems to have served as a selective evolutionary force, engendering adaptive responses across a variety of plant and animal taxa (Bond and Midgley 1995; Hutto 1995; Bond and van Wilgen 1996; Schwilk 2003). Conveniently, the combustion process itself does not undergo evolutionary change. In that way it is unlike insects

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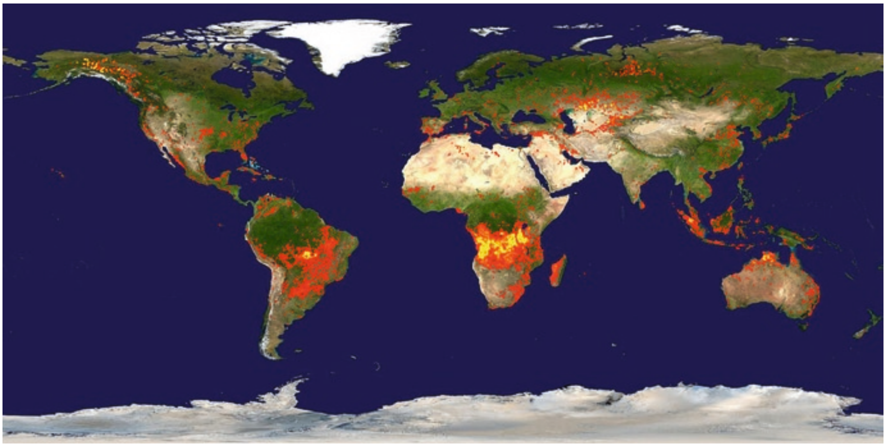

Fig. 1.1 Global compilation of MODIS fire detections between 19 and 28 June 2004 (Image courtesy of MODIS Rapid Response System http://rapidfire.sci.gsfc.nasa.gov/firemaps/)

responsible for outbreaks, which evolve (and co-evolve) with host species over millennia (Royama 1984; Logan and Powell 2001). Fire as a physical and chemical process is fundamentally the same today that it was millions of years ago, and arguably will be the same a million years from now, although its behavior and effects on landscapes change with the development of ecosystems and vegetation.

Starting from simple triggers (lightning, striking a match), fire on landscapes develops into a complex spatio-temporal process both driven and regulated by abiotic and biotic factors (Johnson 1992; Johnson and Miyanishi 2001; van Wagtendonk 2006). Fire behavior and fire effects reflect the relative strengths of multiple drivers, interacting at variable scales of space and time (Table 1.1). At fine scales (10^{-1}–10^{1} m^2), fire spread and intensity are conditioned by properties of fuel (mass, availability, spatial arrangement, and moisture), ignition (type, intensity, frequency, and spatial distribution), and ambient weather (air temperature, wind speed, and humidity). As a fire spreads over larger spatial scales (10^{1}–10^{3} m^2) other factors gain in importance, particularly topographic variation (aspect, slope, and slope position). As a result of these interactions, a fire can cover 5,000 ha or more in a day, or smolder and creep through ground fuels for months.

The spatial and temporal scales of fire are intuitively observable and comprehensible by humans, although reconciling them quantitatively with the spatiotemporal domain of “normal” ecosystem processes introduces profound challenges, chiefly because of the different rates and scales at which processes occur. Fire can reset landscape processes and their spatial pattern, often across community and watershed boundaries, thereby forcing managers to take a landscape perspective. Planning at scales that are too fine will fail to account for disturbances that arise outside small management units; planning at scales that are too coarse, such as regional scales, will not account for local patterns of spatial and temporal variability

Table 1.1 Spatiotemporal properties of fire regimes and drivers of fire behavior and effects. Drivers act on means, variances, and extremes of properties (Adapted from Falk et al. (2007))

	Climate, weather	Vegetation, fuels	Topography, landform
Temporal distribution			
Frequency or fire interval	Ignition availability and flammability; wind, humidity, and temperature patterns; fuel moisture	Vegetation productivity, postfire recovery and fuel buildup	Interaction of fire size with fuel availability; topographic barriers to fire spread
Duration	Drought or days without rain; frontal and synoptic climatic dynamics	Fuel biomass, condition, size distribution, connectivity; consumption rates	Topographic controls on rate of spread; fire spread barriers; rain shadows
Seasonality	Seasonal progression and length of fire season; effects on fuel phenology	Fuels phenology: green up, curing, and leaf fall	Topographic effects on fuel types, moisture, and phenology
Spatial distribution			
Extent	Local and synoptic weather control of ignition and fire spread	Vegetation (fuels) abundance and connectivity	Topographic influences on fire spread; fire compartments
Pattern (patch size, aggregation, contagion)	Orographic and frontal atmospheric instability, wind vectors, spatial distribution of ignitions	Spatial pattern of landscape fuel types (fuel mosaic)	Topographic influences on fire spread and spatial distribution of fuel types and condition
Intensity and severity	Microclimate and weather influences on spatial patterns of fuel moisture and abundance	Vegetation (fuel) mass, density, life-history traits, configuration; vertical and horizontal connectivity of surface and canopy layers	Slope and aspect interactions with local microclimate and weather

and are in danger of applying one-size-fits-all solutions (Chap. 10). Likewise, although fires occur as “events” over time spans of days to months, the postfire ecosystem response can unfold over decades to centuries. Landscape ecology provides a template for the analysis of both fire behavior and fire effects, and as a discipline offers the concepts and tools for understanding fire across scales (Turner et al. 2001; Falk et al. 2007).

A central concern in landscape ecology is the feedback that can exist between landscape pattern and ecological processes (White 1987; Turner 1989). In the case of fire, the mechanisms for this pattern-process dynamic are reasonably well understood at the fine scales for which fire behavior models were built

(Johnson and Miyanishi 2001; Linn et al. 2006), albeit not always quantified accurately enough for reliable landscape predictions (Keane and Finney 2003; Cushman et al. 2007). As fire opens canopies, causes differential mortality, consumes standing biomass, affects watershed hydrology and soils, and prepares seedbeds, it acts as a powerful agent of landscape pattern formation. At the same time, however, the spread and behavior of fire depend explicitly on some of those very same landscape attributes, such as the distribution, type, age, and condition of vegetation. The spatial and temporal distributions of biomass and moisture influence the spread of fire, inhibiting the spread of fire where biomass is too scarce or too wet, and allowing fire to spread only where conditions are favorable to combustion. Fire is therefore a *contagious* disturbance (Peterson 2002), in that its intensity depends explicitly on interactions with the landscape.

The feedback between fire and landscape pattern is strong and ecosystem-specific, and provides a perfect illustration in nature of the interaction of pattern and process. Over time this pattern-process interaction creates *landscape memory*, a legacy of past disturbance events and intervening processes (Peterson 2002). This memory can be spatially sparse, but temporally rich, as with a spatial pattern of fire-scarred trees (Kellogg et al. 2008), or the converse, as with a landscape pattern of age classes and structural types (Hessburg and Agee 2005). Landscape memory extends to the less visible but no less important functional properties of ecosystems, such as biogeochemical processes (Chap. 6).

Fire effects illustrate this interaction of pattern and process. Fire consumes biomass as it spreads, producing a patch mosaic of burned areas on the landscape, whose heterogeneity reflects the combined effects of the spatial patterns of fuels, topographic variation, and microscale variation in fire weather. Burned areas produce characteristic patterns of spatial variability in severity and patch sizes. This tendency is the basis for the widespread use of remote sensing and geographic information systems (GIS) to quantify and evaluate fire as a patch-generating landscape process.

Remotely derived imagery has revolutionized the field of burn severity mapping, especially by greatly improving the precision and accuracy of characterizations of postfire environments (MTBS 2009). Both qualitative and quantitative metrics of burn severity can be derived from satellite imagery based on reflected and emitted electromagnetic radiation (Miller and Yool 2002; Holden et al. 2005; Key and Benson 2006). Although most burn severity work to date has used just two spectral bands from LANDSAT images at 30-m resolution, multi-spectral and panchromatic data are increasingly available at multiple resolutions as fine as 1 m. Hyperspectral imaging (Merton 1999) and LiDAR (Lentile et al. 2006) also hold promise for more refined analysis of the three-dimensional structure of postfire landscapes.

A recently burned landscape is striking to look at. Spatial patterns of burn severity are often very heterogeneous, even within fires assumed to be stand-replacing (Fig. 1.2). Indices abound to quantify and interpret landscape spatial pattern (McGarigal et al. 2002; Peterson 2002), and have been used widely to understand spatial patterns specifically with respect to fire (Romme 1982; Turner et al. 1994). Our interest here, however, lies specifically in the processes that both generate and are controlled by that spatial pattern. For example, patterns of burn severity and the spatiotemporal structure of fire-scar records emerge from the cumulative effects of individual events and their interactions, but how these dynamic interactions play out over larger spatial and temporal scales is less well understood. A framework is needed for connecting these events and interactions that is conceptually and computationally feasible at the scales of landscapes. In this chapter we propose a theoretical framework that reduces the apparent complexity of ecosystem processes associated with fire. A full development of this theory would entail a formal structure for landscape fire dynamics and quantitative models for individual transformations of its elements (*sensu* West et al. 2009). Here we are content with suggesting a way of thinking about landscape fire that "streamlines" its complexity to a level that is tractable for both research and management.

1.2 An Energetic Framework for Understanding Landscape Fire

Earth system processes reflect the distribution of energy across scales of space and time (Pielou 2001). The climate system, for example, is a direct manifestation of the flows of energy near the Earth's surface, including the uplift of equatorial air masses and major convection processes such as Hadley cells and atmospheric circulation, all of which redistribute incoming solar energy. Ocean circulation is likewise driven by system energetics, which are evident in three dimensions between deep and surface waters across thermohaline gradients and major quasi-periodic ocean-atmosphere couplings (El Niño Southern Oscillation, Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, North Atlantic Oscillation). Earth's fluxes of energy drive biogeochemical cycles that connect flows of materials and energy within and among ecosystems. Biogeochemical cycles, such as those of carbon and nitrogen, link the biotic and abiotic domains and reflect feedbacks between biological and non-biological components of the Earth system. Ecosystem ecologist H. T. Odum (1983) observed that biogeochemical cycles can be considered a form of energy flow at all scales, and that other ecological processes such as succession and productivity can be viewed as expressions of organized energetics.

The ecosystem energy perspective offers a general framework for understanding landscape fire as a biophysical process. Fire redistributes energy, and in doing so, can dramatically transform landscape pattern. Here we outline a framework for understanding the landscape ecology of fire from an energetic perspective. In this energy—regulation—scale (ERS) framework we view fire as an ecosystem process that can be understood by examining how energy is transformed and redistributed, subject to regulation, across scales. We seek metrics associated with both energy and regulation that will be building blocks for a fully quantitative theory. The term *regulation* is intended in a broad heuristic sense, and is not intended to imply or be parallel to any genetic or molecular mechanism.

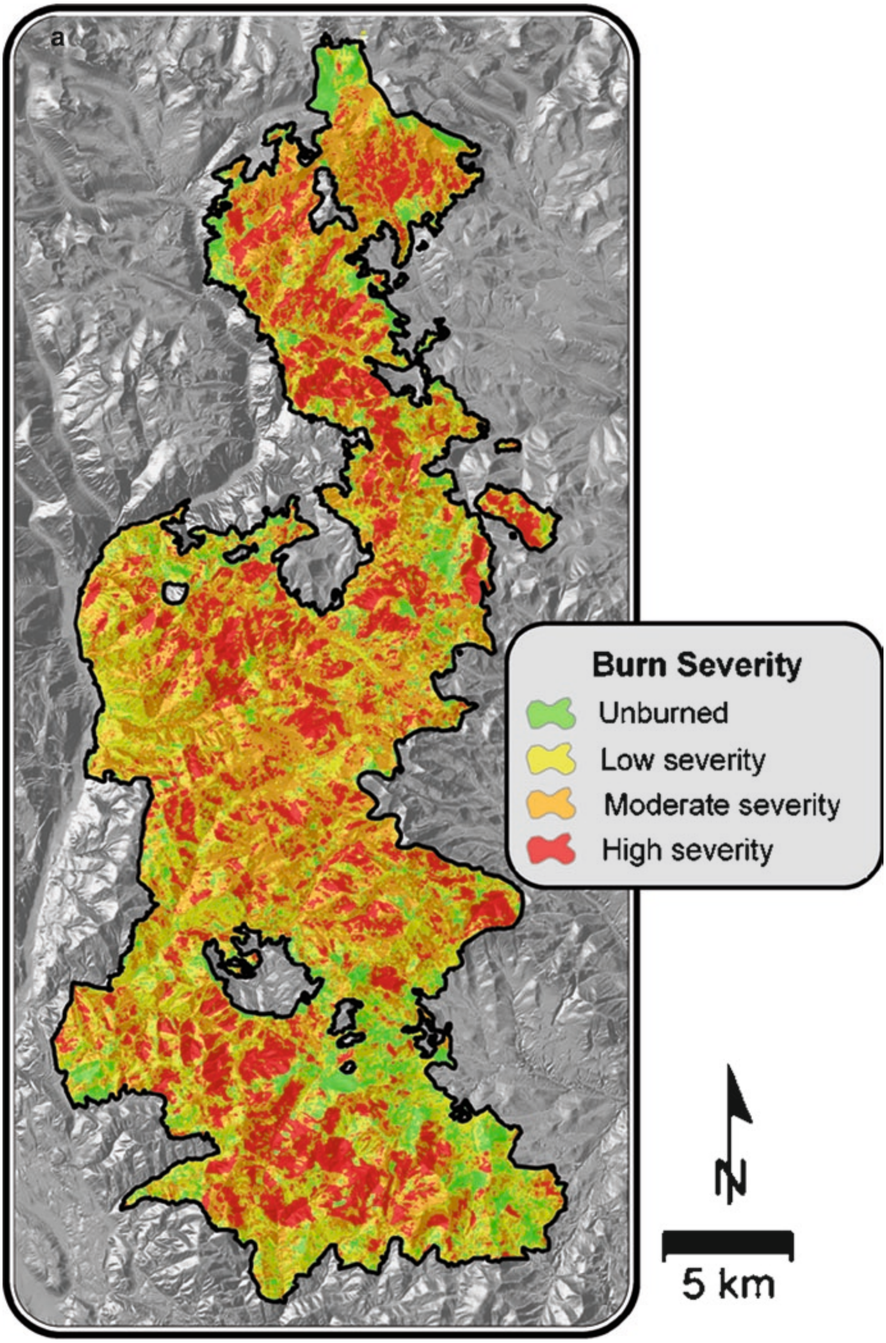
a
Burn Severity
Unburned
Low severity
Moderate severity
High severity
N
5 km

Fig. 1.2 **(a)** Fire-severity classes on the 2006 Tripod Complex Fire in northcentral Washington, USA. Fire severity classes are identified from LANDSAT imagery using the algorithm of Key and Benson (2006). **(b)** Photos demonstrate low-mixed severity as crown scorch (*above*), and mixed severity as juxtaposed high- and low-severity patches (*below*). Fire-severity data are from the Monitoring Trends in Burn Severity (MTBS) project. http://www.mtbs.gov. Accessed 1 November, 2009 (Photos courtesy of C. Lyons-Tinsley)

1. Energy. Incoming solar energy is the ultimate basis for plant growth and thus the fuels involved in combustion. Solar energy is also the basis for atmospheric circulation and the weather that influences moisture conditions of fuels and fire behavior. Vertical energy transfer in the atmosphere generates lightning, the primary non-human source of ignitions. The preconditions for fire are thus related inextricably to energy sources and fluxes.
2. Regulation. Ecosystems are subject to controls that affect the energy flux rates important to landscape fire. Forests store energy (fuel) as living and dead biomass aboveground and in soils, and the time it takes to accumulate a storehouse of biomass that will burn is subject to biotic and abiotic controls on growth and decomposition that vary across ecosystems (Aber and Melillo 1991). The energy fluxes associated with the combustion process itself are facilitated or constrained by atmospheric humidity, temperature, and air-mass movement (weather). Topography works in a similar fashion with landscapes having regions of low resistance to fire spread (e.g., steep slope gradients in the direction of wind) or high resistance (cliffs, lakes, persistent fuel breaks). Indeed all three elements of the traditional "fire triangle"—fuels, weather, and topography—can be interpreted as ecosystem components involved in regulating the flow of energy across a landscape (Table 1.2).
3. Scale. Flows of energy and mass (stored energy) are concentrated at characteristic scales of space and time (Holling 1992). For example, the main regulators of combustion at the space and time scales of millimeters and seconds (combustible fuel mass and moisture, a heat input source, and sufficient oxygen to sustain combustion) are different from those that regulate fire occurrence at subcontinental and decadal scales (interannual to decadal variation in winter precipitation, spring and summer temperature and humidity, prior fire history and regrowth of flammable biomass). Between these two ends of the scaling "gradient", fire dynamics play out across landscapes, in ways that are more complex and heterogeneous, and less tractable to analyze.

Within this "ERS" framework, we can recast the standard pattern-process polarity in landscape ecology (Turner et al. 2001) by examining energy in landscape fire. Following basic physics, we partition energy into potential and kinetic energy. Potential energy (PE) is stored mostly in biomass, in the form of molecular bond energy. Increases in biomass (productivity) are affected by kinetic energy (KE) in the form of photosynthetically active radiation (PAR), and regulated by levels of soil and foliar moisture. The potential energy in biomass is transformed rapidly into kinetic energy during a fire. Heat flux (radiative, convective, conductive) is basic to the physics of fire spread. The spatial interplay of heat flux with the connectivity of potential energy in fuels manifests as contagion on the landscape. Rates and directions of fire spread are determined by the interaction of heat flux, generated by the transformation of potential energy in fuels and driven by fire weather, with landscape pattern (*regulation*), producing the observed complex spatial patterns of landscape fire.