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12. Synthesis: Landscape Ecology and Changing Fire Regimes

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Fire is a ubiquitous ecosystem process, and one that is expected to respond rapidly and unpredictably in a changing climate. The effects of altered fire regimes will be felt in many if not most of Earth's ecosystems (Gillett et al. 2004; Millar et al. 2007; Bowman et al. 2009; Parisien and Moritz 2009). Consequently, fire managers will be challenged to envision and enable landscapes of the future in which ecological function is maintained, and adaptation strategies will have to be creative and dynamic (Peterson et al., Chap. 10). In this chapter we recap key lessons from the preceding contributions and comment on the state of the art in landscape fire theory, application, and management, with an eye toward specifying a research agenda for the landscape ecology of fire. Specifically, we explore the possibility that the energy-regulation-scale (ERS) framework (McKenzie et al., Chap. 1) could be applied to a wide variety of issues in fire ecology. We then present our (short list of) candidates for "key concepts" in the landscape ecology of fire.

12.1 What have we Learned about the Landscape Ecology of Fire?

In this book, we have mostly eschewed coverage of two mainstays of landscape ecology that have been covered extensively elsewhere: empirical analysis of spatial pattern based on remote sensing (Lillesand et al. 2003) and landscape fire simulation models (Mladenoff and Baker 1999; Turner et al. 2001; Keane et al. 2004). We have instead devoted a substantial section to theoretical considerations and questions of scale. Theoretical frameworks are an important complement to empirical data analysis and simulation modeling (O'Neill et al. 1986; Brown et al. 2002; Falk et al. 2007; West et al. 2009). Advances in theory must keep pace with progress in the creative application and extension of statistical methods in ecology and fire science (Diaz-Avalos et al. 2001; Moritz et al. 2005; Wu et al. 2006; Kellogg et al. 2008) and improvements in simulation modeling (Keane and Finney 2003). This momentum is driven not only by increased computing power, but also, and perhaps more importantly, by more judicious use of model evaluation (Scheller and Mladenoff 2007; Kennedy et al. 2008).

Section I (Concepts and Theory) suggests how new conceptual and theoretical models may enable us to think across scales and anticipate "no-analog" conditions for future fire regimes. For example, by defining landscape fire in terms of energy and regulation, McKenzie et al. (Chap. 1) offer a simple universal language for extrapolation into no-analog conditions. Indeed the energy in the Earth system (Pielou 2001), expressed through climate dynamics and evolving as global warming continues, propagates directly into landscape fire dynamics. McKenzie and Kennedy (Chap. 2) and Moritz et al. (Chap. 3) show that we can borrow tools liberally from other disciplines—physics, engineering, complex systems theory, and physiology—while increasing the robustness of core analyses within landscape ecology by quantifying relationships across scales. Landscape ecologists are known to claim that our field is "theory-challenged", or at the least limited to phenomenological observations and constrained by the complexity of "middle-number" systems (O'Neill et al. 1986; McKenzie et al., Chap. 1). Attention to scaling relations might overcome the seeming intractability of the middle-number domain and answer pressing questions about resilience and perhaps even sustainability of landscapes in a changing climate (Moritz et al. Chap. 3).

Section II (Climate Context) brings global and regional climatology into the landscape domain via cross-scale energy-water relations (Milne et al. 2002; Peters et al. 2004). Top-down controls on fire regimes (climate variability at multiple spatial and temporal scales—Gedalof, Chap. 4) are a direct manifestation of Earth's energy system. Both land-surface and ocean couplings with the atmosphere provide a coarse-scale manifestation of the energy-regulation polarity introduced by McKenzie et al. (Chap. 1). Littell and Gwozdz (Chap. 5) downscale this global polarity into the regional (ecosection) domain (Fig. 5.1). Water-balance deficit (DEF)(Stephenson 1990; Lutz et al. 2010), the outcome of the interaction among kinetic energy in radiation, potential energy in fuels, and the regulatory control of moisture, is the best predictor of fire extent at regional scales (see also Littell et al. 2009a). Although the role of DEF has yet to be quantified in the ERS framework of McKenzie et al. (Chap. 1), it shows promise for linking broad-scale fire climatology to the more complex and variable dynamics of landscape fire severity and spatial pattern and the ultimate consequences for landscape structure and composition (i.e., landscape memory— Peterson 2002).

Section III (Landscape Dynamics and Interactions) maps the multiple influences of spatial processes and climate onto real ecosystems, while highlighting the importance of fire's interactions with other physical and ecological processes. These studies illustrate multiple processes interacting with changing landscape fire regimes, including ways that these interactions may be transformed, possibly abruptly and in unexpected ways, in a rapidly changing climate. Smithwick (Chap. 6) presents a model of biogeochemical resilience based on the interactions of fire with the often unseen elements on a landscape, e.g., nutrient pools. These biogeochemical processes and pools may be just as important in determining future ecosystem trajectories (and with them resilience to abrupt change) as more obvious features such as vegetation structure and composition. Swetnam et al. (Chap. 7), on the other hand, exploit the information contained in vegetation pattern and show how the deep temporal record in fire-scarred trees can be mapped into the spatial domain of landscape ecology. By combining traditional dendroecological methods of identifying local fire years with the tools of geospatial modeling, fires and fire regimes can be reconstructed spatially, and their landscape properties analyzed. For example, interpolation of point records into landscape surfaces offers a window into the configuration of past landscapes. Such reconstructions open the door to understanding landscape dynamics, such as the influence of post-fire mosaics that create “landscape memory” and affect subsequent disturbances (Fig. 12.1). Keeley et al. (Chap. 8) focus on the effects of invasive species on fire regimes in a uniquely complex and variable landscape (California, USA). They highlight the dependencies and interactions that make future projections at landscape scales uncertain at best. Invasive species are “game changers” in many ecosystems, particularly in the many cases of pyrophilic species that can alter fuel complexes and thus the extent, severity, and seasonality of landscape fire. Cushman et al. (Chap. 9) also highlight an uncertain future as they address the effects of landscape fire regimes on wildlife habitat in the central Rocky Mountains (USA), where fire regimes may change significantly in the future (Keane et al. 2004). Two lessons emerge from their simulations. First, the influences of warming temperatures are likely to dominate habitat changes in this forested landscape, overriding the effects of even the most aggressive attempts by management to resist change. Second, ensemble projections provide much better estimates of future ranges of variation than single scenarios, whether the modeling tools be at global (GCMs) or landscape (fire and vegetation) scales.

Section IV (Landscape fire management, policy, and research in an era of global change) applies these ideas about fire as a landscape process to pressing issues in ecosystem management. This is the human dimension, where the central challenge is to develop new options for guiding landscape fire regimes in an era of rapidly changing land use and climate, such that both ecosystems and human populations can adapt. The urgency of understanding the dynamics of fire-human interactions and identifying paths for adaptation is in large measure a result of the rapid changes in regional and global climate projected for the 21st century. Outcomes of the workshops reported by Peterson et al. (Chap. 10) on adapting to climate change suggest that although there is a bewildering array of problems facing land and natural resource managers, there is also a wealth of experience and creativity in this human resource, which has observed and documented fire on diverse landscapes over many years. These authors also highlight the need for thinking “out of the box” about options for active management of fire regimes, not to replicate some historical or desired condition *per se* but to anticipate landscape structures that will be resilient to fires in a warming world. Miller et al. (Chap. 11) call our attention (gently) to the elephant in the room of futuring: human population growth. The need to reintroduce wildfire in many wilderness landscapes is well documented, but as the interface between human dwellings and wilderness becomes more extensive and complex, encouraging wilderness fire becomes more delicate, contentious, and constrained. Out-of-the-box thinking may be necessary to find solutions that work across boundaries. In combination with global climate change, with the promise of longer fire seasons and larger more intense fires, human population and land use exacerbate all problems of fire management.

12.2 Research Needs

Where do we go from here? What follows is conceptual synthesis of major research directions, rather than a list of specific projects. For a recent example of a detailed research agenda for landscape fire, see Cushman et al. (2007).

- **What would a fully developed theory of landscape fire look like?** We proposed an initial framework in Chap. 1 that could take advantage of scaling relations in key variables such as heat flux from combustion, potential energy in fuels, and topographic variance. A fully developed theory would not be expected to predict the behavior of individual fires (joining most fire behavior models under some conditions), but rather would provide estimates of aggregate properties of fire-affected landscapes such as patch-size distributions or spatial variability in fuel loadings.
- **Bring our understanding of the energy-water (or energy-regulation) dynamic in fire climatology down to landscape scales**. Climate-model downscaling *per se* currently reaches a limit at about 4–12 km resolution (Salathé et al. 2007); downscaling from weather station records has been successful to about 0.5 km (Daly et al. 2008). If water relations are the key to fire-climate modeling, however, as Littell and Gwozdz (Chap. 5) suggest, then it is theoretically possible to estimate landscape variability in fuel moisture at scales relevant to landscape fire (30–100 m). We also should be careful about inferring that water-balance deficit will have similar effects on fire in ecosystems of widely different aridity (McKenzie and Littell n.d.).
- **Improve our ability to predict and quantify high-energy fire events** (Romme et al. 1998; Peters et al. 2004; Gedalof et al. 2005; Scheffer et al. 2009). Transient high-energy fire events, which are most difficult to predict, have the most long-lasting effects on landscape pattern and process (Romme et al. 1998). Predicting individual events, is especially challenging because of their largely stochastic nature on the landscape. Likely progress will be in predicting their propensity or frequency, which should be more a function of mean-field conditions than of a fortuitous alignment of necessary and sufficient conditions.
- **Improve our understanding of how the spatio-temporal structures in fire history reflect landscape fire dynamics** (Moritz 2003; McKenzie et al. 2006; Falk et al. 2007; Scholl and Taylor 2010). Fire-scar data can reveal both landscape pattern of fires and the nature of controls (e.g., top-down vs. bottom-up) on historical fire regimes, in the absence of a record of either the weather or the fuel abundance and condition associated with any particular fire (McKenzie and Kennedy, Chap. 2; Swetnam et al., Chap. 7). If we can infer controls on historical fire regimes, we can better predict how fire-prone landscapes may change as the controls change, and where management intervention is more likely to succeed. Fire scar evidence can be better integrated with other sources

of information about unmanaged fire regimes, such as age structure reconstructions and charcoal analysis.

- **Fill major geographic gaps in our understanding of fire regimes**. This book was limited in scope to western North America, where fire regimes are particularly well documented. Would the same questions as asked in this book be appropriate for very different systems such as the Eurasian boreal forest (Gustafson et al., n.d.; Conard and Ivanova 1997; Stocks et al. 1998) or the Australian Jarrah forest (Bell and Koch 2006) (e.g., see Figure 1.4), which are clearly shaped by fire?
- **Find fire-induced tipping points for the reorganization of ecosystems, particular those that might be reached as a result of climate change**. Keeley et al. (Chap. 8) and others before them (Zedler et al. 1983) point to the sensitivity of California chaparral to increasing fire frequency; there is a tipping point beyond which the dominant vegetation changes irreversibly. Are there similar tipping points elsewhere, perhaps associated with fire severity, fire extent, fire-insect interactions, biogeochemistry (Smithwick, Chap. 6), or multiple stresses associated with fire (McKenzie et al. 2009)? For example, high elevation mountainous landscapes could see much more area become flammable earlier in the fire season (Miller et al., Chap. 11), thereby altering fire regimes with unknown consequences for vegetation.
- **Are there truly "landscape" scales in fire ecology?** Despite being common parlance, the landscape scale remains ill-defined. There may be ways to quantify the inherent scales of fire regimes, however. For example, Moritz et al. (Chap. 3) identify a "meso-domain" within which scaling laws in fire-size distributions follow power laws (see also Reed and McKelvey 2002). Analogously, McKenzie et al. (Chap. 1) posit domains of maximum ecological complexity associated, albeit loosely, with spatial scales (Fig. 1.5).

12.3 Concluding Thoughts

Fire is an integral part of landscape process, memory, and resilience, as opposed to an external perturbation (despite our liberal use of the term "disturbance" throughout). We see fire as something that ecosystems generate, not something exogenous that happens to them. As a contagious process, it "bleeds" across scales and requires a specification of ecosystem dynamics that is robust across scales. We hope that our readers come away, at a minimum, with new perspectives (and research ideas) in three areas.

First, landscape memory is the cumulative outcome of landscape fire dynamics (Peterson 2002; Moritz et al. Chap. 3). Fire's legacy on the landscape is clear in some locations while subtle in others, long-lasting in some while transient in others (Fig. 12.1). Deconstructing landscape memory illuminates fire history and its interactions with ecosystem processes over time and space. This deconstruction should be engineered in a way that enables projections of alternate futures by tuning parameters estimated therein.

Second, the interactions of top-down and bottom-up regulation of fire regimes provides a coherent framework for problems across scales, and thus a potential foundation for a theory of landscape fire. The ERS framework, or some analogue, provides a deep mechanism in ecosystem energetics, and thus physics, for the tangible expression of top-down and bottom-up regulation in real ecosystems. There is much more room for empirical, modeling, and theoretical work to create a mature model of what regulates fire regimes.

Third, scaling laws in fire regimes provide an expression of complex dynamics. Scale is featured in every landscape ecology book, and indeed landscape fire research is closing in on Levin's (1992) oft-quoted goal of understanding how ecological processes change across scales. Quantitative scaling laws can at least complement, and in some cases replace, hierarchical models (McKenzie et al., Chap. 1). This is likely to be especially true when contagious disturbance (fire) is a significant element of landscape dynamics.

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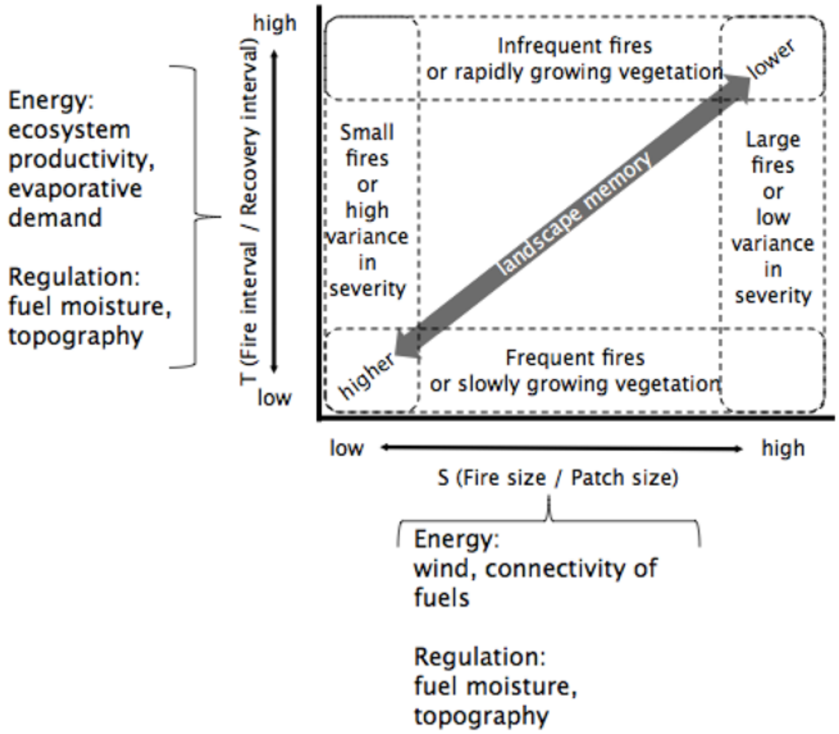
Fig. 12.1. The spatio-temporal domain of landscape memory in ecosystems affected by fire. The ratio of fire interval to vegetative recovery interval, T, and the ratio of fire size to the grain of the landscape, S, manifest from the system energy and regulatory controls (McKenzie et al. Chap 1). Calibration of the S and T axes depends on the spatial and temporal extent in question and so is subject to scaling laws. Fire size is related to the slope of the interval-area relation and point fire interval to its Y-intercept (Falk et al. 2007). “Higher” landscape memory is associated with more persistent and self-organized patterns, whereas “lower” landscape memory entails more transient and unstable patterns.

Figure 12.1



high
low
T (Fire interval / Recovery interval)
Energy:
ecosystem
productivity,
evaporative
demand
Regulation:
fuel moisture,
topography
Infrequent fires
or rapidly growing vegetation
lower
Small
fires
or
high
variance
in
severity
landscape memory
Large
fires
or
low
variance
in
severity
higher
Frequent fires
or slowly growing vegetation
low
high
S (Fire size / Patch size)
Energy:
wind, connectivity of
fuels
Regulation:
fuel moisture,
topography