FORUM: ISSUES, MANAGEMENT, POLICY, AND OPINIONS

INTRODUCTION: STRENGTHENING THE FOUNDATION OF WILDLAND FIRE EFFECTS PREDICTION FOR RESEARCH AND MANAGEMENT

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ABSTRACT

As prescribed fire use increases and the options for responding to wildfires continue to expand beyond suppression, the need for improving fire effects prediction capabilities becomes increasingly apparent. The papers in this *Fire Ecology* special issue describe recent advances in fire effects prediction for key classes of direct (first-order) fire effects. Important gaps in predictive capabilities exist in pre-, active-, and post-fire measurement technology; in our ability to predict heat deposition to soil and plant surfaces from knowledge of fuels and models that simulate smoldering combustion, flame spread, and plume dynamics; in our ability to predict above and below ground plant heating and injury; in our understanding of the physiological causes of plant mortality; and in our knowledge of direct effects of fire on fauna and their habitats. Fire effects on shrub and grassland systems are particularly poorly studied. Recent advances in software systems, in which multiple models and databases are included in a single application tailored to address fire management questions, give impetus to foundational fire effects research that would improve fire effects prediction. In this introduction, we describe the range of approaches to predicting fire effects, from statistical to process; we define terminology used throughout the issue; and we highlight research and development needs. We offer the following goal as a challenge to the research community: the development of a comprehensive, first-order fire effects model employing a diversity of approaches (from statistical to process) and built to serve a range of applications (from research to land management).

Keywords: fauna, fire effects, fire metrology, fire modeling, fire monitoring, flora

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Effects of fires on soils, flora, fauna, watersheds, and ecosystems have received considerable attention in recent years as the size and impact of wildfires have increased and efforts to reduce hazardous fuels (Finney *et al.* 2007; Hessburg *et al.* 2007; Graham *et al.* 2009, 2010; Kim *et al.* 2009) and restore fire dependent ecosystems have accelerated (Fire Executive Council 2009, Keeley *et al.* 2009). Large and damaging wildfires have occurred in Australia (Bradstock 2008, Bradstock *et al.* 2009), Canada (Kasischke and Truetsky 2006, Stocks *et al.* 2008, Flannigan *et al.* 2009, Wang *et al.* 2010), China (Casanova *et al.* 2008), throughout the Mediterranean basin (Chuvieco *et al.* 2008, Pausas *et al*. 2008, Loene *et al.* 2009, San-Miguel-Ayanz *et al.* 2009), Siberia (Sukinin *et al*. 2004, Mollicone *et al*. 2006, Achard *et al.* 2008), southeast Asia (Khandekar *et al*. 2000), and the United States, particularly in Alaska, the southeast, and west (Westerling *et al.* 2006, Swetnam 2008, Littell *et al.* 2009).

The complexity of biomes of concern across the globe, the complexity of ecological processes of interest, and the complexity of science application issues that range from wildfire suppression to ecosystem restoration to landscape-scale ecosystem modeling (Bowman *et al.* 2009) all argue in favor of improving our understanding and ability to predict first-order fire effects. With managing wildfires emphasized in the new US wildland fire policy (wherein fire suppression is but one option; e. g., Fire Executive Council 2009), fire effects predictions would be particularly helpful in the incident management decision-making process wherein a decision to delay or forego suppression action may hinge on predictions of resource harm or benefit. Similarly, effective fuels treatment programs designed to treat hazardous fuels and protect communities and infrastructure rely on solid fire effects science to help assure that treatments are effective at mitigating the threat of fire while at the same time being based on ecological principles. It is widely recognized that fires are a critical element in the natural cycle of many ecosystems and are thereby critical to maintaining biodiversity (Bradstock 2008, Pausas and Keeley 2009). In the US, managers are encouraged through funding mechanisms to reintroduce fire into fire-dependent ecosystems where it has long been absent (NWCG 2001, HFRA 2003). This has led to an increased need to predict fire effects when designing and implementing restoration treatments (Graham *et al.* 2009, 2010; Keeley *et al.* 2009). Finally, with increasing awareness of global change issues and the role of fire in affecting global carbon cycles (Kasischke and Truetsky 2006, Flannigan *et al.* 2009), there is an increasing need for fire effects knowledge in ecosystem simulation models (Hessburg *et al.* 2007; Keane *et al.* 2007, 2008; Cary *et al.* 2009) that guide natural resource and carbon trading policies.

Wildland fire is a rapid oxidation process, commonly called combustion, which consumes living and dead vegetation (fuels) and releases materials and energy. Materials released include nutrients, charcoal, and inert ash left within the burned area (Neary *et al.* 2005) and the particulates and gasses released as smoke (Sandberg *et al*. 2002). The energy released during combustion has the potential to injure organisms or damage property. First-order fire effects (Reinhardt *et al.* 1997, 2001; Reinhardt and Crookston 2003; Crookston and Dixon 2005; Lentile *et al.* 2006) are those social and ecological effects that are directly attributable to a fire; that is, they are in close proximity to the fire in both space and time (Figure 1). In contrast, second-order fire effects arise from more contingent webs of causality in which first-order effects are an integral part. For example, a fire may consume vegetation and leave a site exposed and predisposed to massive erosion, but it is the specific nature of post-fire precipitation that determines the actual erosion (Robichaud *et al.* 2007, Cerdà and Robichaud 2009). In this example, post-fire erosion, e.g., mudslides, is a second-order fire effect mediated by the magnitude of the first-order effects. In a social context, fire directly affects people, property, and infrastructure, thereby directly affecting the health and livelihood of individuals and communities. In an ecological context, fire directly affects the state and transformations of all ecosystem variables, including floral and faunal populations, carbon stocks, nutrient cycling, and wa-

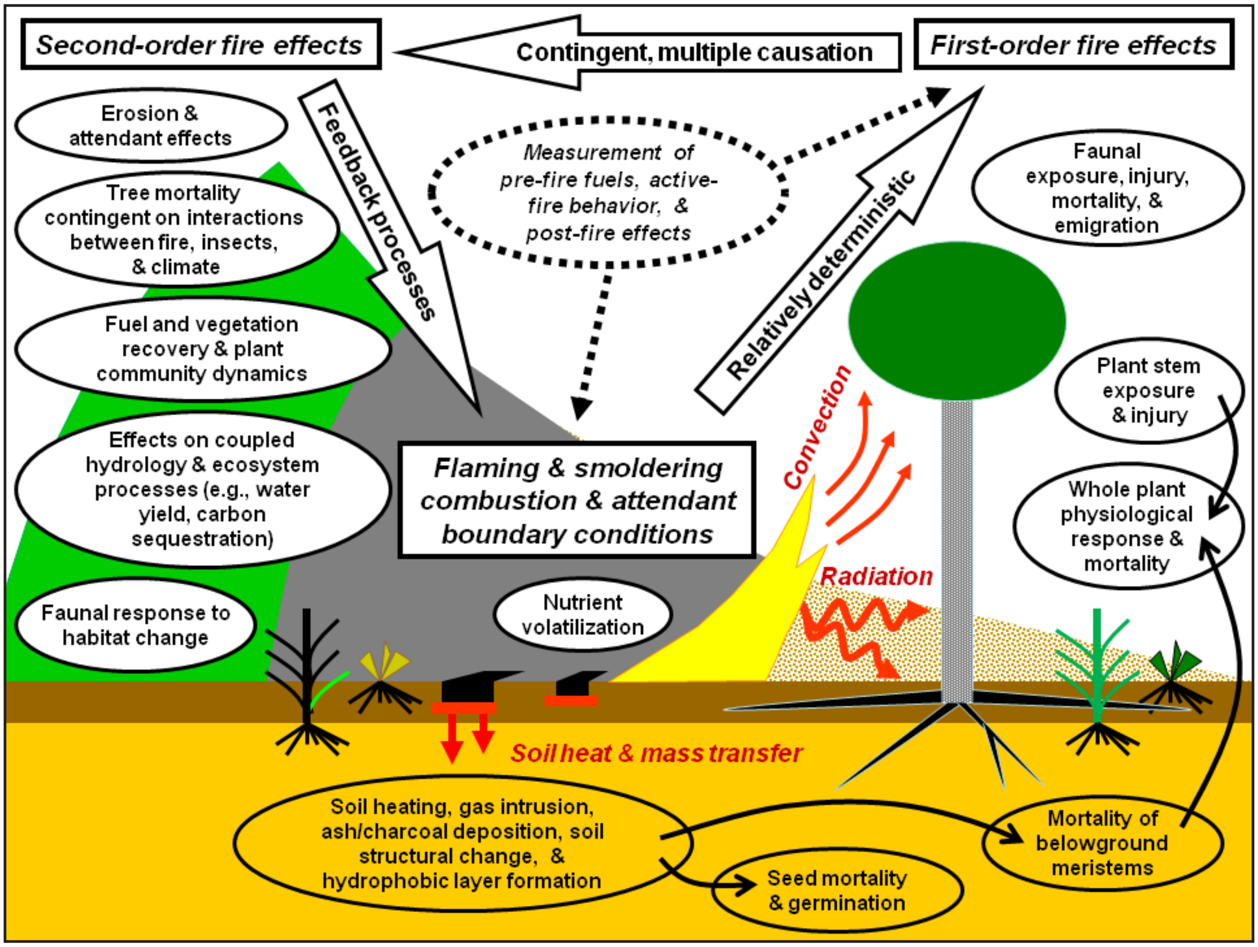

Figure 1. The focus of this *Fire Ecology* special issue is the relatively direct ecological effects of combustion processes and the heat and mass transfer that result. We explore knowledge gaps and process modeling of first-order fire effects on soils, trees, herbs, shrubs, and fauna. The webs of causation resulting in second-order (indirect) effects that play out on landscapes over the years following fires are often anchored in effects of the first order.

ter and energy budgets. Collectively, the magnitude of these changes define the ecological impact of the fire (Ryan 2002), often referred to (rather ambiguously) as severity (Keeley 2009).

In practice most managers, policy makers, and the public do not care about the distinction between first- and second-order fire effects. They care about outcomes that affect them. The distinction between first- and second-order fire effects is, however, important to those conducting fire effects research. It is important for organizing concepts, designing experiments, understanding causal relationships, assigning attribution, and communicating results. In practice, it can be difficult to isolate first-order fire effects from second-order fire effects. For example, it can be difficult to determine if tree mortality is caused by direct injury from the fire or secondary infestation by insects, as an injured tree can be destined to die regardless of insect attack.

An important question for researchers, research organizations, and funding agencies is how we might best advance fire effects prediction. Understanding of first-order fire effects is founded on an understanding of a range of biophysical processes that occur at the time of the fire. This is not to suggest that ecologists need to become combustion engineers or physical scientists to do their work, but it does suggest that it is highly desirable to have a conceptual understanding of how fire effects arise from biophysical processes, and it speaks to the need for interdisciplinary studies that couple fire behavior with observable effects. The process-response approach (Johnson 1985) has demonstrated promise for producing predictive models that are applicable across taxa and ecosystems and are adaptable to novel situations. We argue that process models and theory should guide the design of empirical field studies, and that such field studies should aid in model parameterization and theoretical advance. The alternative is to continue with an anecdotal, haphazard, and piecemeal program of fire effects discovery that confuses more than it clarifies.

Application of process models to wildland fire ecology has progressed steadily since the 1950s and 1960s when the first models were proposed (e.g., Spalt and Reifsnyder 1962, Martin 1963, Fahnestock and Hare 1964). First-order fire effects arise from a chain of causation beginning with flaming and smoldering combustion followed by heat and mass transport, which, in turn, drive soil heating and physical and chemical transformations as well as vegetative and faunal (microbes, insects, mammals, etc.) exposures to heat, combustion products, and altered environmental conditions. A cascade of additional related effects occur, including faunal injury, mortality, and behavioral response and injury to herb, shrub, and tree tissues. Certain types of plant injury lead deterministically to the death of whole plants or their parts (Michaletz and Johnson 2008). A mechanistic understanding of relatively direct fire effects, and an ability to predict them, typically requires the application of approaches from disciplines including combustion, heat and mass transfer, fluid dynamics, and physiology (Johnson and Miyanishi 2001).

A gradient in approaches, ranging from statistical to process-based, has been used to predict first-order fire effects (Dickinson and Johnson 2001; Michaletz and Johnson 2007, 2008). On one end are statistical relationships that involve collection of information on the effect of interest and the development of statistical equations (often called models) that relate the effect of interest to a set of independent variables (e.g., Ryan and Reinhardt 1988, Ryan and Amman 1994, McHugh *et al.* 2003, Hood and Bentz 2007, Hood *et al.* 2007). On a parallel path, one considers the processes that cause the effect of interest and builds mathematical models that are solved (analytically or numerically) to predict the effect from fire behavior (e.g., Mercer *et al.* 1994, Michaletz and Johnson 2008). These process models range from highly detailed to approximate, yet always include inputs and parameters that must be estimated from data. In the middle of the range in predictive approaches lies the development of groups of variables, often through dimensional analysis, that capture the salient features of the processes by which an effect is caused and whose parameters are estimated from data (e.g., Van Wagner 1973).

The process approach provides one with the potential to produce relatively general models, given, of course, that the models are sufficiently complete and parameter estimates and inputs can be obtained. Process models serve as hypotheses to be tested and, consequently, can form a strong basis for advance in understanding. Statistical models are strictly valid only under the conditions under which the models were developed, and are often accurate within those conditions, but are often used outside their range of validity (Hood *et al.* 2007). Arguably, statistical models could be made more general if the form of the statistical equations and the variables they contained were determined through a consideration of the processes involved, perhaps through dimensional analysis, rather than by automatic selection of variables (e.g., Johnson and Miyanishi 2001, Bova and Dickinson 2005). Process modeling is facilitated in the current day by the continuous improvement in computer software and hardware; researchers are no longer restricted to analytical solutions of process models that, from the need to simplify, may require that one ignore key processes. A risk of increased complexity is that models may become difficult to understand, less stable, or their parameters may become too numerous or difficult to estimate.

In the following seven papers in this *Fire Ecology* special issue (Table 1), we consider the latest work in process modeling in fire ecology and consider how to advance both the science and its application for the benefit of

Table 1. Papers in this *Fire Ecology* special issue and the main deficiencies they identify in measurement and process modeling capabilities and in model application to land management.

Author(s)	Title	Key research and development needs
Kremens *et al.*	Fire metrology: current and future directions in physics-based measurements	Development of ground-based LiDAR fuel sampling techniques, application of airborne fire radiation mapping to a range of ecosystems, critical examination of satellite-based fire severity measurements.
Massman *et al.*	Advancing investigation and physical modeling of first-order fire effects on soils	Models for predicting soil-surface boundary conditions from smoldering and flaming combustion and the inclusion of pressure-driven advective flows as well as heating-related dynamic feedbacks in soil heating models.
Butler & Dickinson	Tree injury and mortality in fires – developing process-based models	The ability to predict the boundary conditions that drive soil and tree heating, greater knowledge of tree thermal and physical characteristics, a merging of statistical and process approaches for predicting tree mortality.
Kavanagh *et al.*	A way forward for fire-caused tree mortality prediction: modeling a physiological consequence of fire	High vapor pressure deficits in the plume may cause unappreciated impairment to trees' water conducting systems which may cause either outright mortality or loss in productivity. A better understanding is needed of the physiological responses of trees to fire exposures and their role in both causing tree death directly and increasing tree vulnerability to other stressors (e.g., drought, insect attack).
Stephan *et al.*	First-order fire effects on herbs and shrubs: present knowledge and process modeling needs	The belowground distribution and responses of bud and seed populations to fire are poorly known. Predictions of subsurface mortality are uncertain because of a limited ability to predict soil surface boundary conditions that drive soil heating, a problem arising from both a poor knowledge of the spatial arrangement of fuels and inadequacies in flaming and smoldering combustion models.
Engstrom	First-order fire effects on animals: review and recommendations	Effects of fire on faunal habitats are generally seen to be more important than direct effects on individuals, though data are lacking. Species-Centered Environmental Analysis is presented as a means of defining key effects on habitats that can serve as targets for first-order fire effects modeling.
Reinhardt & Dickinson	First-order fire effects models for land management: overview and issues	Software systems under development for use by land managers are built on a foundation of predictive fire effects models that suffer from the weaknesses discussed in this special issue.

both research and land management. The series of papers is not comprehensive in its coverage, either in the range of topics considered or in the depth of literature review, but highlights key gaps in our understanding and modeling capabilities relative to first-order fire effects (Table 1). Other sources of information intended to aid managers in meeting diverse fire objectives include numerous syntheses and reviews such as the Fire Effects Information System (http://www.fs.fed.us/database/feis/) and "The Rainbow Series," which synthesizes information on effects of fire on flora (Brown and Smith 2000), fauna (Smith 2000), air (Sandberg *et al.* 2002), soils and water (Neary *et al.* 2005), and exotic and invasive species (Zouhar *et al.* 2008).

In Kremens *et al*., the development of fire measurement technologies (fire metrology) is explored, including methods used to quantify both fire behaviors that are important for predicting fire effects and direct fire effects themselves. The paper discusses the need for more research on both ground-based measurements (e.g., light detection and ranging- [LiDAR-] based techniques for fuel mapping, in-fire sensors for measuring convective and radiative heat fluxes) and remote measurements (e.g., airborne LiDAR for canopy fuel characterization, airborne fire radiation mapping, satellite-based reflectance measurements used to estimate fire effects). In all cases, calibration steps are required to provide quantitative and repeatable data. The paper lays down the measurement grand challenge wherein pre-, active, and post-fire measurements at a range of scales are combined with biophysical process models in order to describe and understand fire behavior and direct effects in a quantitative, validated, and comprehensive way.

Massman *et al.* consider coupled mass and heat transfer in soils during fires and the transformation of soil physical and chemical properties, some irreversible, that occur as a result of intense heating. Results from an experimental, high-intensity pile burn are presented. Substantial soil gas fluxes were observed and are thought to be caused by advective flows driven by pressure differentials arising from fire dynamics that may also occur in free-spreading fires. Pressure-driven flows are currently not included in models of soil effects, a situation that may explain inaccuracies in soil heating predictions. Results illustrate a lack of basic understanding about soil heating and the need for fundamental measurements and model revision.

Butler and Dickinson describe the development of process models of tree heating, injury, and mortality. A key limitation in our ability to model tree injury is a lack of measurements and models linking fire behavior with heat deposition at soil and vegetative surfaces (e.g., tree stems, branches, buds). The time courses of heat deposition at these surfaces from flames, smoldering fires, and plumes are called boundary conditions, an important requirement for simulating heat transfer within soil and vegetation and are obtainable from measurements or models (boundary conditions can also refer to the time courses of gas concentrations, plume velocities, etc., around objects during fires). Much work needs to be done on soil heating and the boundary conditions that drive soil heating. A major limitation is that there is no operational smoldering combustion model of duff. The lack of a smoldering combustion model poses severe limitations for predicting basal cambium and root necrosis. Further development of duff moisture models is also needed. The paper also finds that there is scope for merging statistical tree mortality models and process approaches to predicting tree injury—two endeavors that have previously proceeded on near parallel paths. Development of datasets of species- and region-specific tree properties (e.g., tissue moisture contents, allometric relationships, thermophysical properties) is required for application of process models.

Kavanagh *et al*. build on the tree injury and mortality theme, demonstrating how little we actually know about tree physiological responses to fires. As an example, a novel hypothesis is developed about fire effects from exceedingly high vapor pressure deficits in plumes that cause unseen impairment to a tree's water conducting systems. Clearly, basic measurements of tree functional impairment and physiological response following fires are needed to meet the goal of developing relationships and models that can be used to predict tree mortality after fires. At present, unless certain threshold levels of injury occur (e.g., stem girdling, complete mortality of canopy meristems), only statistical approaches can be used to predict stem and tree mortality.

Current understanding of fire effects on herbs and shrubs is explored in Stephan *et al*. and many gaps in our knowledge are identified. A priority for research is the prediction of fire effects on below ground regenerative structures (buds and seeds). To support this effort, apart from descriptions of vertical and horizontal distributions of plant components below ground and their response to heating, there is also a need for an improved ability to model soil heating from flaming and smoldering combustion at a spatial resolution appropriate for the variation in surface fuels and distribution of plants. In the context of tree roots and basal cambium, improved predictions of soil heating require definition of boundary conditions during fires that are a function of local fuel characteristics and how those fuels combust. Also of interest are further developments in capabilities for modeling the heating of basal bunchgrass meristems from smoldering fire, above ground seeds in protective capsules, and shielded above ground meristems. The characteristics of a comprehensive model of first-order fire effects on herbs and shrubs are outlined.

As described in Engstrom, direct effects of heat and smoke on fauna include injury, mortality, and emigration; effects that have generally been considered to be of secondary importance to habitat effects unless an endangered population or species has a limited, local distribution. To better quantify direct effects, a call is made for more studies of marked individuals. Clearly important are indirect effects on faunal populations through fire effects on their habitat. Knowledge of key habitat requirements for a species can provide targets for fire effects modeling, both from first-order fire effects models (e.g., downed woody material combustion, shrub cover reduction, canopy opening, snag creation) and second-order effects models (e.g., microclimate alterations, food resource availability, vegetation change). To aid in elucidating gaps in understanding of fire effects on fauna, Engstrom illustrates the use of Species-Centered Environmental Analysis (James *et al.* 1997) for describing the webs of causality through which fires cause their effects on a given species.

The papers discussed above all show how we can improve predictions of fire effects through improved understanding, measurement, and modeling of the processes involved. Next, the question becomes how we might best make those advances accessible to land managers. Reinhardt and Dickinson, in the final paper, discuss existing and emerging software systems for use by researchers and land managers to conduct risk assessments, develop prescriptions for fuel treatments or prescribed fire, and support long-term planning. A current trend is to collect multiple fire effects models and databases within a single software system, the one-stop-shopping long demanded by land managers (e.g., the Integrated Fuels Treatment Decision Support System, IFT-DSS; Wells 2009). First-order fire effects models have a foundational role in these software systems and the means by which to improve that foundation are explored (e.g., use of the community model paradigm, construction of required databases).

Commonalities in research needs emerge from this special issue, needs that cut across the range in first-order fire effects on soils, trees, herbs, shrubs, and fauna (Figure 1). First, many fire effects predictions rely on predictions of fire (flaming combustion) models (e.g., soil heating from intense flaming, effects on tree stems and crowns, faunal smoke exposures). Thus, development of fire models (e.g., landscape fire spread models, coupled fire-atmosphere models) and the databases they require (e.g., landscape fuel characteristics at sufficient resolution, topographically determined weather) can only help with efforts to predict fire effects. Second, further development of smoldering combustion models and the databases on which they rely will, among other benefits, improve our ability to provide the boundary conditions required by soil and basal stem heating models and for predicting the mortality of tree, shrub, and herb components that occur within the duff and soil (e.g., roots, below ground buds, seeds). Improved prediction of smoldering combustion will also benefit efforts to predict post-fire erosion (e.g., Robichaud *et al.* 2007). Third, improvements are needed in soil heating models themselves because of their incomplete portrayal of the soil heating process (e.g., lack of advection-driven mass transport). Finally, continued development of measurement techniques for quantifying pre-fire fuels, active-fire heat release, heat deposition and other boundary conditions, and post-fire effects are needed to develop a fundamental understanding of fire effects and support fire effects modeling efforts. Clearly, advancing first-order fire effects prediction will require collaboration among researchers from a range of backgrounds including engineering, physics, and ecology.

As a way to challenge and focus the research community, we offer the following goal: the development of a comprehensive, first-order fire effects model employing a diversity of approaches and built to serve a range of applications. A comprehensive model should be modular (i.e., consisting of many sub-models) and accessible so that it facilitates both research and the development of land management software systems. Competition among alternative approaches (i.e., sub-models) based on validation against common datasets would serve to stimulate creativity and, after validation, would open the door to ensemble fire effects forecasts that provide a means of assessing uncertainty. Accessibility and continual improvement could be fostered by following the community model paradigm (see Reinhardt and Dickinson, this issue). Successful community models (e.g., the Fire Dynamics Simulator led by the National Institute of Standards and Technology and the Weather Research and Forecasting model led by the National Center for Atmospheric Research) often are characterized by long-term institutional and financial support and the dedicated efforts of champions. In embarking on a journey to produce a process-based, comprehensive fire effects model, some problems will be solved quickly while others, because of their difficulty, will require long-term focus.

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