Biological Conservation 145 (2012) 5–14

Contents lists available at SciVerse ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Review

Challenges and a checklist for biodiversity conservation in fire-prone forests: Perspectives from the Pacific Northwest of USA and Southeastern Australia

Thomas A. Spies [a,*], David B. Lindenmayer [b], A. Malcolm Gill [b], Scott L. Stephens [c], James K. Agee [d]

[a] US Department of Agriculture Forest Service, Pacific Northwest Research Station, 3200 Jefferson Way, Corvallis, OR 97331, USA
[b] Fenner School of Environment and Society, The Australian National University, Canberra, Australia
[c] Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720-3114, USA
[d] School of Forest Resources, University of Washington, Seattle, WA 98195, USA

ARTICLE INFO

Article history:
Received 15 March 2011
Received in revised form 26 July 2011
Accepted 17 September 2011
Available online 3 December 2011

Keywords:
Disturbance
Fire effects
Fire regimes
Human systems
Landscape management
Monitoring

ABSTRACT

Conserving biodiversity in fire-prone forest ecosystems is challenging for several reasons including differing and incomplete conceptual models of fire-related ecological processes, major gaps in ecological and management knowledge, high variability in fire behavior and ecological responses to fires, altered fire regimes as a result of land-use history and climate change, and the increasing encroachment into forest landscapes by humans. We briefly compare two ecologically distinct fire-prone forest regions, the Pacific Northwest, USA and southeastern Australia with the goal of finding ecological conservation generalities that transcend regional differences as well as differences in scientific concepts and management. We identify the major conceptual scientific and conservation challenges and then present a checklist of questions that need to be answered to implement place-based approaches to conserving biodiversity in fire-prone forest ecosystems. The two regions exhibit both similarities and differences in how biodiversity conservation is conceptualized and applied. Important research and management challenges include: understanding fire-prone systems as coupled natural-human systems, using the disturbance regime concept in multiple ways, dealing with large fire events, using language about the effects of fire with more precision, and researching and monitoring fire and biodiversity at multiple spatial scales. Despite the weaknesses of present conceptual models, it is possible to develop a checklist of principles or questions that can be used to guide management and conservation at local scales across systems. Our list includes: establishing the socio-economic context of fire management, identifying disturbance regimes that will meet conservation goals, moving beyond fuel treatments as a goal, basing management goals on vital attributes of species, and planning for large events including post-fire responses.

1. Introduction

Conserving biodiversity in fire-prone forest ecosystems is a major challenge to scientists and managers across the globe (Driscoll et al., 2011). The task is complicated by several factors including differing and incomplete conceptual models of key fire-related ecological processes, major gaps in ecological and management knowledge (especially at large spatial scales), high variability in fire behavior and ecological responses to fires, altered fire regimes as a result of land-use history and climate change, and the increasing encroachment into forest landscapes by humans. Given this complexity, it is difficult to develop and then apply general principles to guide and prioritize efforts and resources for conservation. Noss et al. (2006) state: "*Because forests are highly variable over space and time, few universal principles exist for integrating insights from ecology and conservation biology into fire management policies*". This problem is not unique to fire ecology. The search for generalities in ecology is often thwarted by contingency and ecological complexity that limit the development of predictive rules and create a pluralistic science (Mayr, 1997; Simberloff, 2004). Furthermore, application of simple rules in management can sometimes do more harm than good (Hobbs and Yates, 2003).

Despite problems of complexity and risks of perverse outcomes from simple but misleading rules, we believe that progress towards more effective approaches to biodiversity conservation in fire-prone environments can be made. The disciplines of fire ecology and conservation biology contain several useful conceptual models (e.g. fire regime, vital attributes) that can serve as the building blocks for a more general model. In addition, improvement in our scientific models and management practices will require more effort to integrate ecological and social aspects of fire (Pyne, 2007;

* Corresponding author. Tel.: +1 541 750 7354; fax: +1 541 750 7329.
E-mail addresses: tspies@fs.fed.us (T.A. Spies), david.lindenmayer@anu.edu.au (D.B. Lindenmayer), malcolm.gill@anu.edu.au (A.M. Gill), sstephens@berkeley.edu (S.L. Stephens), jagee@u.washington.edu (J.K. Agee).

0006-3207/$ - see front matter © 2011 Published by Elsevier Ltd.
doi:10.1016/j.biocon.2011.09.008

Bowman et al., 2009; Conedera et al., 2009). However, until recently, much current fire research, fire management and fire policy in places such as the US and Australia has been dominated by a focus on the physical phenomena of fire with an emphasis on fuel management and the mechanics of wildfire suppression (Noss et al., 2006). Fire ecology research is now increasing rapidly (e.g. Schwilk et al., 2009) and as our knowledge advances we will need updated conceptual frameworks to improve the effectiveness of conservation in fire-prone ecosystems.

Such approaches also must account for uncertainties associated with fire and climate change effects (Millar et al., 2007). Thus, the principles of risk management are important (Burgman, 2005), but understanding of risk management is often poor (Hummel et al., 2008). Development of robust and comprehensive conceptual frameworks that are also sensitive to complexity involves integration of ecological science with other domains, particularly the social sciences (e.g. McCaffrey, 2004). This is because, increasingly, progress in the science and application of conservation biology is dependent on a social and economic context (Redman et al., 2004) and better integration with management (Gill et al., 2002).

Given the lack of detailed empirical information, as opposed to conceptual predictive models about ecological effects of fire, it is difficult to provide planners and managers with decision support tools that are needed to deal with fire and biodiversity across a range of vegetation and landscape types. However, one way to make progress is through comparative studies of different ecosystems and management/policy environments to determine how well concepts, rules and approaches from one system apply to another (Knapp et al., 2004). This also can help: (1) generate new perspectives on existing theoretical frameworks, (2) unveil different or inconsistent applications of concepts and terminology which suggest alternative models or weakness in models and approaches, and (3) create new insights into how to restructure current conceptual frameworks to guide the management of fire-prone systems for ecological goals.

Our objectives in this paper were two-fold. The first was to identify major conceptual scientific and conservation challenges for conserving biodiversity in fire-prone forest ecosystems. The second was to outline a conceptual framework or checklist of questions and topics that need to be addressed in conserving biodiversity in these ecosystems. Given the complexity of fire regimes and biodiversity responses to fire, we assumed that rules that are simplistic and one-size-fits-all will be of limited value for making conservation decisions for particular places. Conversely, local efforts that deal with the ecological particulars of a place may become too narrowly focused and miss larger-scale phenomenon or concepts that could improve the broader or longer-term effectiveness of those efforts. We emphasize examples from fire ecology and conservation in the Pacific Northwest of the USA—where forests are dominated by conifer species and southeastern Australia—where forests are dominated by angiosperms, mostly species of *Eucalyptus*. We briefly characterize the ecological settings and biodiversity conservation issues in these two regions at the outset of this paper. We have chosen these areas because: (1) we have had many decades of collective experience in working in them, (2) they have been important areas for the development of forest conservation science, (3) they span a wide range of fire regimes, degrees of adaptation of the biota to fire regimes, and (4) are characterized by a suite of policy and management approaches to fire. Such variation should mean that our recommendations should be relevant to other regions and forest ecosystems. We acknowledge that our findings may not apply well in other regions with different forest types, (e.g. boreal or tropical), and land use patterns, (e.g. southern Europe), but we see no reason, why they should not apply to many situations. We then highlight some major conceptual challenges for developing general principles for biodiversity conservation in fire-prone forests which we discuss in the second section of this paper. Our review of challenges segues into our final section where we present a checklist of questions to guide more effective and robust integration of fire management and biodiversity conservation practices in forest landscapes.

2. Methods

Our paper is a combination of comparative review, synthesis, and expert opinion about management applications. We used several approaches to develop the paper. First, we developed a set of questions about fire and biodiversity concepts that apply to the two regions and then assembled and reviewed relevant literature from each of the regions. The literature was selected based on personal knowledge of existing literature (all of the authors have at least 20 years of experience in research and management problems in their respective regions and disciplines) and supplemented with Google-Scholar searches to fill in gaps and find recent papers. This initial search resulted in several hundred papers that were reviewed for relevance and significance before a final smaller set was selected for inclusion in the paper. We made a special effort to include papers that contradicted general paradigms or presented findings that were unique and illustrative of complex behaviors and relationships. We compared relative use of different combinations of the terms "fire regime", "fire history", "historical range of variability" and "severity" and "intensity" by conducting a Google Scholar keyword and phrase search that was limited to states in southeastern Australia and in the western US for the period 2002–2010. Percents of different combinations of term use in published papers were then calculated for each of the two regions. Finally, based on our literature review and expertise in application of fire ecology and biodiversity concepts in management we developed a checklist that we hypothesize will be useful in improving the scientific basis of management approaches to conserving forest biodiversity in fire-prone ecosystems.

3. Ecological settings

The Pacific Northwest of the USA and south-eastern Australia are characterized by a diversity of vegetation types and fire regimes that range from frequent surface fires (<10 years) to infrequent high-severity fires (intervals if >200 years) (Agee, 1993; Gill and Catling, 2002). Conifers in the family *Pinaceae* dominate forests in the Pacific Northwest while trees of the genus *Eucalyptus* dominate the forests of southeastern Australia. Post-fire succession is also variable in both regions with successional seres ranging from a few years between short-interval fires to many centuries in Douglas-fir (*Pseudotsuga menziesii*) and tall mountain ash (*Eucalyptus regnans*) forests (Agee, 1993; Gill and Catling, 2002). Although there are many differences between the two regions, some of the stand development processes and structures are similar. For example, the dominant trees with Douglas-fir/western hemlock (*Tsuga heterophylla*) and tall mountain ash forests are characterized by: lack of a soil seed bank, tree canopy closure within 10–40 years, and development of massive trees and multi-storied vegetation layers canopies that requires several centuries to develop (Franklin et al., 2002; Lindenmayer and Franklin, 2002). Vegetative reproduction (i.e. sprouting) after fire appears to be much more common in *Eucalyptus* forests compared to forests in the Pacific Northwest. Exceptions to regeneration from seed occur in mixed evergreen forests of southwest Oregon and northern California, where evergreen hardwood trees, some shrubs, and coast redwood (*Sequoia sempervirens*) sprout readily after damage to or death of stems (Skinner et al., 2006).

Humans have had long and strong influences on fire regimes and forest structure in both regions: about 10,000 years in the

Pacific Northwest (Hessburg and Agee, 2003), and over 40,000 years in Australia (Bowman, 2003). Settlement of landscapes in the late 19th and early 20th centuries in both regions by cultures of European origin has altered fire regimes with variable effects including increasing density of forests as a result of fire exclusion.

4. Biodiversity conservation threats

Forest and fire-related biodiversity concerns have been significant and widespread in both regions. Logging of old-growth and clearing of native forests have historically been the most prominent drivers of biodiversity change and loss in both regions. However, as policies have been enacted to reduce logging and protect habitat for threatened species, management and conservation efforts have shifted to focus on other issues and threats including effects of altering fire regimes and occurrence of large high intensity fires in reserves intended for species sensitive to particular fire regimes (Noss et al., 2006; Healey et al., 2009). The impact and uncertainties associated with increasing fire frequency driven by climate change (Cary, 2002; Westerling et al., 2006) further adds to the challenges faced by managers.

5. Major conceptual challenges

A wide range of studies in the Pacific Northwest and southeastern Australia reveal major conceptual challenges to developing general principles and guidelines for biodiversity conservation in fire-prone environments, not only in these regions, but in many places around the world. We outline some of these challenges in the following section. This provides a prelude to the final section of this paper, where we outline a checklist of topics to consider in developing place-based management plans.

5.1. Fire and biodiversity are imbedded in a socio-ecological system

Fire management and the conservation of biodiversity are deeply embedded socio-ecological or coupled natural and human systems (Liu et al., 2007) in which fire, biodiversity, and people interact, often in complex ways. Efforts to plan or manage these components in isolation will miss important drivers and constraints and ultimately fail. Such systems are characterized by feedbacks and unintended consequences that can thwart plans based on inadequate thinking or narrow objectives. The degree of coupling between natural and human systems is increasing for several reasons. First, humans are increasingly settling in fire-prone environments where more and more homes and lives are lost to fire (Stephens et al., 2009a). There are also significant biodiversity conservation issues at the interface of urban, rural and wildlands (Gill and Stephens, 2009). For example, in Australia, a significant minority of threatened species occurs at the fringes of urban environments (Lindenmayer and Burgman, 2005), where there are also substantial fire risks (Carey et al., 2003). Second, the area of high intensity fire may be increasing as a result of anthropogenic-driven climate change (Pittock, 2005; Miller et al., 2009; Steffen et al., 2009). Third, biodiversity in many areas has been already been degraded and is threatened by continuing non-fire losses of habitat from land cover conversion, unsustainable logging and urbanization (Hansen et al., 2005).

The reality that biodiversity goals are typically secondary to concerns about property and human safety set fundamental constraints on options to maintain or restore fire-related biodiversity. Failure to acknowledge coupled human-fire-biodiversity systems is further compounded by a lack of clear objectives for biodiversity across many ownerships and in many resource management policies. Clearly articulated goals and quantifiable objectives are crucial to managing landscapes for biodiversity (Spies et al., 2007; Lindenmayer et al., 2008). These cannot be specified for a landscape or ecosystem *a priori*—they must be developed based on local conditions and level of knowledge.

5.2. Fire regime is a foundational concept in conservation but we need to understand how to use it

Fire regimes form the basis of planning and management in fire-prone ecosystems. The concept of a disturbance regime is well established in disturbance ecology (Gill, 1975; Pickett and White, 1985; Conedera et al., 2009). Characterizing sites within a region or vegetation type in terms of the type, frequency, intensity and timing of disturbances is the only way to understand biophysical processes that vary across spatial and temporal scales. The approach is valuable not only for making sense out of highly variable systems but for evaluating ecological effects on species, communities, and processes which maybe more influenced by the cumulative effects of fires than by individual events.

The disturbance regime concept is applied in different ways, which are illustrated by comparing applications in the Pacific Northwest and in southeastern Australia. First, fire regimes (in terms of frequency and severity) have been mapped across the USA at national and regional scales (Morgan et al., 2001; Malamud et al., 2005) and are used for various reasons including prioritizing fuel treatment activities (Morgan et al., 2001) (Fig. 1). Published fire regime maps are rare in Australia, although there is recognition of the need for them (Gill and Bradstock, 2003). The limited number of fire regime maps in Australia usually comprise spatial information on between-fire intervals and seasonality (e.g. Russell-Smith et al., 2007); agency maps based on time since fire are sometimes used in management planning for parks and other government land.

A second way in which the disturbance regime concept is applied differently between the Pacific Northwest and in southeastern Australia relates to perspectives about historical conditions. For example, in a recent Google Scholar search, we found that the phrase "historical range of variability" was associated with the "fire regime" in about 6.6% out of 2050 papers that mentioned the western states of the western US, while only one paper out of 318 associated the two phrases when the search was restricted to states in eastern Australia. In addition, the term "fire history" is more commonly associated with "fire regime" in the western US studies than in Australia (46% versus 40% of papers). The use of historical regimes as a guide for management assumes that the native species of a region will be adapted to historical disturbance regimes and thus efforts to retain or restore whole community assemblages and ecosystem processes should be based on providing as many of the elements of the historical disturbance regime as possible (Hunter, 2007). This approach is most suitable where the historical disturbance regime is relatively well known and where a systems (e.g. communities, ecosystems) strategy to conserving biodiversity is applied. However, this approach will not be very useful if the disturbance regime is poorly known or has been altered as a result of climate change or human influences on landscape structure and dynamics (Millar et al., 2007). Furthermore, biodiversity plans and actions are often driven by concerns for the conservation of a particular species or ecological process and therefore a community or systems approach will not be optimal for all components of a system (Cushman et al., 2008).

A third difference in the application of the disturbance regime concept focuses on what type of regime (regardless of a usually unknown pre-settlement history) is needed to provide for a particular species, ecological processes, or land management objective (Gill, 1981). This type of application appears to be more common in Australia, where human culture has affected fire regimes for more

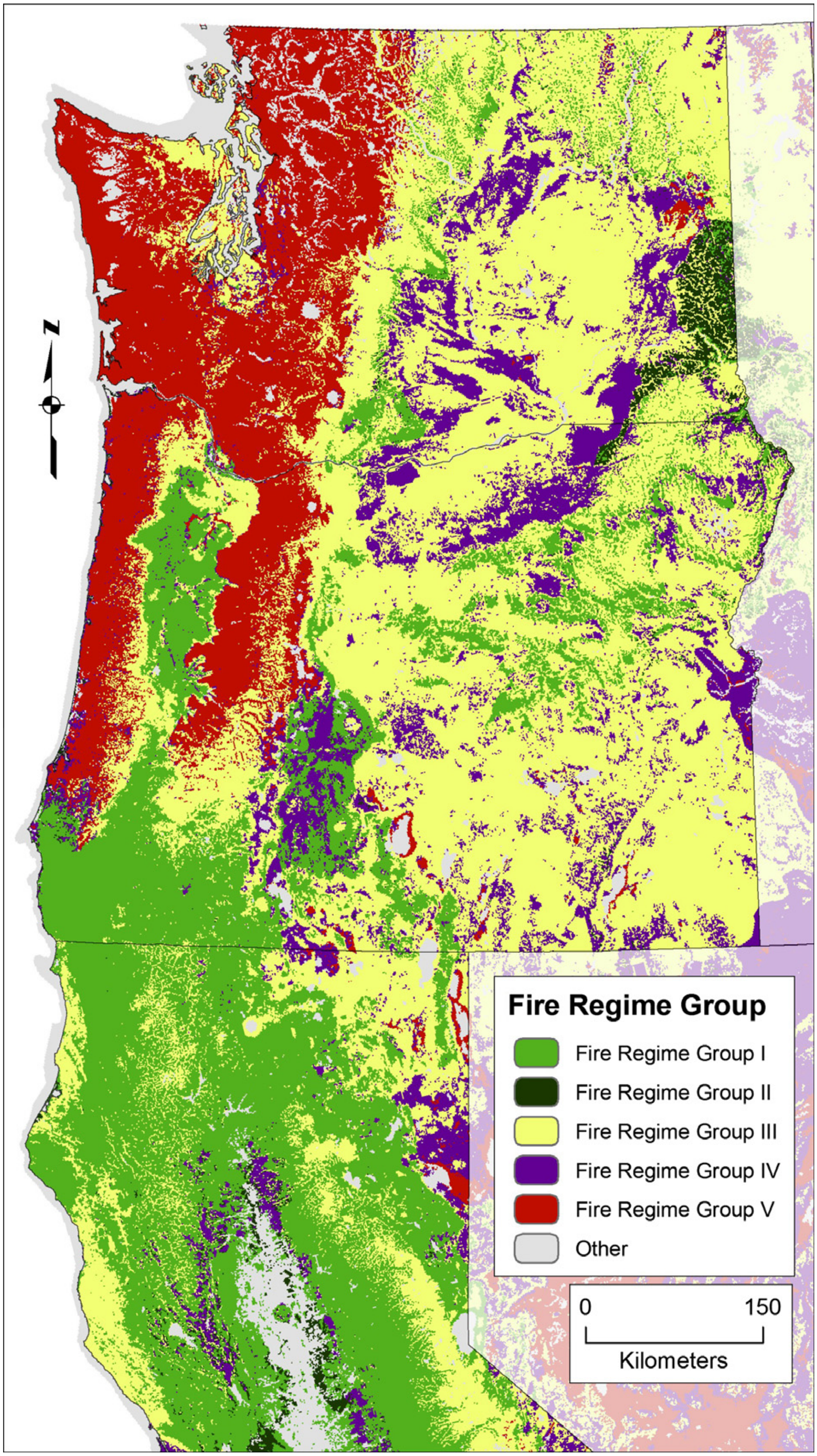

Fig. 1. Fire regimes of the Pacific Northwest and Northern California. Fire Regime Groups: I – Fire Return Interval (FRI) ⩽35 yrs, Low and Mixed Severity; II–FRI ⩽35 yrs, Replacement Severity; III – FRI 35-200 yrs, Low and Mixed Severity; IV –FRI 35-200 Years Replacement Severity; V – FRI >200 Year Fire Return Interval, Any Severity; Other, Water, Snow/Ice, Barren, Sparsely Vegetated, Indeterminate Fire Regime. *Source*: http://www.landfire.gov/NationalProductDescriptions12/php.

than 40,000 years (Bowman, 2003). In short, under this approach, the persistence or extinction of a species is a function of the cumulative effects of managed fire events characterized by factors such as type, intensity, season and interval. This application has some advantages over the first in that: (1) it does not need to assume a constant climate, detailed knowledge of disturbance history, and an unchanging human cultural influence on landscapes, species and disturbances, and (2) it can be focused more on the particular elements of biodiversity that are of greatest concern to managers. The disadvantages of this approach are that it requires an intimate knowledge of the autecology of the most vulnerable species and it assumes that a species-by-species approach is a feasible approach to management. This assumption may not be valid if there are multiple species of concern or the species and ecological processes of an area are poorly known. The use of species functional groups can make it more feasible to deal with the diversity of ways that plant and animals respond to fire (e.g. Rowe, 1983; Noble and Slatyer, 1980). However, grouping of species will reduce effectiveness of the strategy for individual species in a group (Pausas et al., 2004) and the relationships between fire regimes and groups of species can be highly variable (Whelan, 2002), including variation arising from different scales of observation. Use of life history markers (Noble and Slatyer, 1980) assists in the search for the most critical species in terms of fire regimes. Nevertheless, the use of ecologically-based disturbance regimes in biodiversity management appears more realistic than using historically-based regimes given the reality of climate change.

5.3. Dealing with individual major fire events

Although the fire regime concept is the foundation of fire ecology, it is also true that individual fire events, especially large, intense fires can have a major impact on ecosystem function (Pyne, 2004; Foster et al., 1998; Williams and Bradstock, 2008) and exert profound long-term effects on the biota (Ford, 1979; Gill, 1999; Lindenmayer, 2009) and landscape structure (Weisberg and Swanson, 2003). From a conservation perspective, large events can be viewed as an opportunity to restore ecological diversity and processes and/or a threat to the viability of populations of rare or endangered species whose distributions may be restricted to small habitat patches as a result of the cumulative effects of habitat losses or other factors (McCarthy and Lindenmayer, 2000). For example, the 2002 Biscuit Fire in southwestern Oregon created a diversity of open habitat types (Thompson and Spies, 2009) in what had become relatively dense forest landscape during the 20th century. But it also adversely affected 17% (28,000 ha) of the habitat of the threatened northern spotted owl (*Strix occidentalis caurina*) on the Rogue-Siskiyou National Forest (USDA-USDI, 2004). Similarly, the February 2009 fires in southeastern Australia have had major impacts on over 30% of the entire known distribution of the nationally endangered Leadbeater's Possum (*Gymnobelideus leadbeateri*). In another example from southeastern Australia, wildfire (bushfire) appears to have contributed to the loss of the last populations of the Kangaroo Island Emu (*Dromaius novaehollandiae*) (Ford, 1979). However, many species are adapted to and require periodic, intense and large fires that create new habitats; this ecological reality poses a challenge for conservation and management.

5.4. Ecological effects of fire are variable and we need more precise language and better models of hierarchical ecological effects

Wildfires, especially large ones, are often portrayed as "catastrophic" events in the media and by some ecologists and managers (see Keane et al., 2008). However, this is usually not true from a biodiversity conservation perspective (Franklin and Agee, 2003) because the habitats of many species and many ecological processes are dependent on wildfire (Stephens and Ruth, 2005), and single events rarely eliminate species. Indeed, the effects of wildfires on biodiversity may only be understood from studies of multiple organisms across a range of spatial and temporal scales and over long temporal periods (Whelan, 1995; Parr and Andersen, 2006; Wittkuhn et al., 2011). One problem impeding the development of a better understanding of fire effects at ecologically-relevant spatio-temporal scales is that terminology associated with the fire behavior and impacts are often used inconsistently or incorrectly (Keeley, 2009). Disturbance regimes are more likely to be characterized in terms of severity in the western USA whereas intensity is the common lexicon in Australia. For example, a key word search in Google Scholar for 2002–2010 found that "severity" was used alone with "fire regime" more than seven times as frequently (11.8%) in papers from the western states of the US than the eastern states of Australia (1.6%). "Intensity" was used alone with fire regime in 27% of the papers in the US and 55% of the papers in Australia. These terms are different and this difference matters for both ecological and management responses (Keeley, 2009) and complicates cross-system learning. Fire intensity is a measure of the energy release rate of a fire edge (Agee, 2003). Fire severity is a measure of damage to plants, or the loss or change of organic matter (Keeley, 2009). A crown fire can be both high intensity and high severity but in other cases a surface fire may have low intensity but potentially a high severity (e.g. where it smolders in organic soils and litters and kills plants rooted there).

The use of the term fire severity has been inconsistent and ineffective for characterizing the ecological effects of fire (Jain, 2004; Keeley, 2009). This is because the term is too general for specific applications and comparison across fires. While remote-sensing based fire severity indices (e.g. dNBR, Collins et al., 2009) facilitate comparison of aggregate ecological effects across fires, such indices do not necessarily predict particular fire effects or ecosystem responses (Keeley, 2009). For example, fire severity differs between the forest floor and the canopy (Jain and Graham, 2007) and fire effects will differ among species (e.g. impacts on resisting species and enduring species; Rowe, 1983). If the immediate effects of fire on vegetation, severity, are to be predicted, then fire intensity is a suitable variable to use.

Like White and Jentsch (2001), we consider that progress toward improved biodiversity conservation in fire-prone forests will depend on relating fundamental variables of disturbance regimes with ecological effects and responses. Consequently, knowledge of the trajectories of post-fire ecological recovery is crucial, including stand development and vegetation succession (Krebs, 2008). In many forest ecosystems, species composition after forest fires is related to initial pre-fire conditions (i.e. the original composition) (Egler, 1954) with perhaps some transitory composition change (Franklin and Agee, 2003). Thus, while changes in forest structure and ecosystem processes may occur, species composition often remains broadly similar (Frelich and Reich, 1998; Gill, 1999; Brown and Smith, 2000; Stephens et al., 2008; Wittkuhn et al., 2011). Exceptions do occur, however, such as where alternative vegetation types can arise that persist for long periods.

Confusion about the effects of a fire on habitat development often arises when differences in vegetation dynamics are not taken into account. Post-fire vegetation dynamics varies by life history characteristics of the species, especially the dominants, site productivity, and fire severity. For example, on dry, relatively unproductive sites in the Pacific Northwest region, a wildfire reduced the severity of a subsequent wildfire for more than 20 years (Mazza, 2007), while a wildfire on more productive sites lead to dense young sclerophyll vegetation in southwestern Oregon and northern California with increased probability of high severity fire in the first 10–20 years (Thompson et al., 2007; Odion et al., 2010). In central Sierra Nevada, upper-elevation mixed conifer forests, multiple lightning –ignited fires without suppression resulted in no change in fire severity over the period 1974–2005 (Collins et al., 2009), and forests dominated by Jeffrey pine (*Pinus jeffreyi*) and lodgepole pine (*Pinus contorta*) had smaller high severity patch size (Collins and Stephens, 2010). Conversely, in other forest regions, the prolonged absence of fire can allow accumulation of fuels in older forests which makes them more susceptible to the next fire (Schoennagel et al., 2004), particularly in forests that once experienced frequent (<30 years), low-moderate intensity fires.

Invasive plant species are major global threat to the existence of native species and have altered evolutionary processes (Mooney and Cleland, 2001) and they can add further variability to fire effects (Driscoll, 2007). Fire has been recommended as a way of managing invasive species, and there are examples of successes (DiTomaso et al., 1999), but fire often increases their abundance and cover (Klinger et al., 2006; Driscoll, 2007) and can alter fire regimes (Brooks et al., 2004). There is no *a priori* reason why alien species should behave any differently to indigenous species. In the forests of the western US, fire exclusion, while increasing the risk of high-intensity, high-severity fire, has also excluded alien plant species in some areas that typically require high light levels and disturbed mineral soil (Keeley, 2005). Consequently, fuel reduction activities to protect homes or late successional habitat in some places pose a risk of increasing the occurrence of invasive species especially if they are associated with mechanical treatments (Rose and Fairweather, 1997; Schwilk et al., 2009). Invasive species can also influence fire regimes either by increasing flammability or reducing it (Driscoll, 2007).

5.5. We have many options for how to deal with fire

Given the complexities and uncertainties associated with the human-fire-biodiversity complex, deciding which management approach is best requires careful consideration. But, the choices are not simply to manage or not, since a "no action" decision regarding vegetation and fire will have consequences for humans, wildlife, and ecosystem services, such as carbon sequestration. The absence of information and knowledge should not be an excuse for doing nothing or a misapplication of the precautionary principle (Cooney, 2004). In fact, in the absence of knowledge, doing something using management or research experiments is even more important (Walters, 1986). There are many options for dealing with fire (Pyne, 2004; Stephens et al., 2009a) including:

1. managing wildfires (including allowing them to burn) to produce ecological benefits while protecting lives and structures,
2. full suppression of wildfires,
3. a combination of the two above; since 2009 in the USA, some fires are simultaneously managed for suppression and ecological objectives,
4. prescribed fire, and
5. other fuel manipulations.

Depending on the goals and the particulars of how these practices are implemented, the outcomes for biodiversity can be either positive or negative or neutral. In many areas of the western US, where the goal is to reduce the probability of large high intensity fires, fuel reduction treatments can be a strategy to meet both human and biodiversity goals. These treatments attempt to achieve the following objectives: reduce surface fuels, reduce ladder fuels, and reduce canopy density (canopy density is a relatively small component of fire hazards in forests that once burned frequently (Stephens and Ruth, 2005)). The effectiveness and necessity of these treatments will vary across forest types. In fire regimes that are fuel limited (as opposed to climate or ignition limited), these treatments can actually have the desired effect of reducing fire intensity and subsequent severity. However, if treatments are not fully carried out or not effective in reducing surface fuels, they can actually increase the risk of high severity fire (Stephens, 1998; Agee and Skinner, 2005).

It is possible to reintroduce a regime of frequent, low to moderate severity fire. However, in some cases in the Pacific Northwest, understory thinning and mechanical fuel reduction can be used to reduce the risk of undesirable fire effects and the combination of the two is most effective to produce forests more resistant to wildfire (i.e. lowering the intensity of fire) and possible drought from climate change (Schwilk et al., 2009; Stephens et al., 2009b; Agee and Skinner, 2005). However, these efforts must be undertaken at landscape levels to be truly effective (Finney et al., 2007; Moghaddas et al., 2010; Collins et al., 2011). Restoration and fuel reduction efforts can have divergent ecological effects and result in tradeoffs among different types of biological diversity. For example, manipulations of stand structure to reduce risk of loss of older forest to high severity fire and restore large pines in dry forests of the Pacific Northwest can also reduce habitat quality for the threatened Northern Spotted Owl in the margins of its range where it uses dry mixed-conifer forests that have become dense as a result of lack of fire (Spies et al., 2006). This situation has lead to controversy about how to meet ecosystem and species objectives in these areas (Spies et al., 2009).

The emphasis in eastern Australia, by contrast, has been focused more on using prescribed fire to not only reduce the risk of high-severity wildfires, but also to maintain certain plant and animal species that might be extirpated from sites if fires are either too frequent or too infrequent. In addition, there are major discussions about both the spatial extent of prescribed fire as well as the frequency and regularity of between-fire intervals for prescribed fire (Gill, 2008). Varying prescribed fire intervals within a specified range is considered more likely to sustain species than using a constant interval between fires. The challenge with this approach is to apply this method with often limited knowledge of species life-history attributes (Whelan, 2002). Associated with prescribed burning and suppression actions is the establishment of fuel breaks at landscape-levels. Gill (2008) points out how road networks established for fire suppression and prescribing burning could have adverse affects on biodiversity because they can be sources of unwanted human-caused fires. Roads are also major conduits for the dispersal of invasive species (Wace, 1977). In both southeastern Australia and the Pacific Northwest, a landscape approach is needed because there are vegetation types and landscape settings where fuel management through prescribed burning is not only ineffective but inappropriate for biodiversity conservation. For example, in southeastern Australia prescribed fire may not be possible in rainforests and mountain ash (*E. regnans*) forests and in PNW prescribed fire is not appropriate in western hemlock/Douglas-fir forests or higher elevation Pacific silver fir (*Abies amabilis*) forests.

The five fire management options we outlined above encompass only a subset of the actions that can be taken within the human-fire-biodiversity system. From a biodiversity conservation perspective, species can be added or removed through various approaches and substitutes for fire (e.g. mechanical or chemical management interventions). These can modify vegetation structure and composition in ways that approximate some of the effects that fire would have had on the biota. As an example, to promote the conservation of the highly endangered Eastern Bristlebird (*Dasyornis brachypterus*) in eastern Australia (which has limited movement ability and potentially sensitive to the effects of prescribed burning), Baker (1997) recommended strategic slashing of vegetation.

Reserves are a long-standing approach to protection of biodiversity from natural resource extraction and human activity. However, in fire-prone forest ecosystems, "hands-off" approaches, often applied in reserves in wetter environments, may not be appropriate (Spies et al., 2006; Gill, 2008). This is especially true if reserves have had a history of fire exclusion or past management that has eliminated key components of diversity (e.g. large old trees) or leaves them vulnerable to undesirable high-severity wildfire. In such cases, mechanical treatments and prescribed fire may be needed to reach a more desired condition for biodiversity, although, such actions in reserves can be controversial (Spies et al., 2009). However, given the ecological variability that is present in most reserves (from microsite to landscape), especially large ones, it may not be feasible or desirable to conduct prescribed burning or other fuel manipulations across the entire reserve or even the majority of it for either ecological or socio-economic reasons. Increased use of managed wildfire in remote forests should be considered (Collins and Stephens, 2007). Carefully designed, landscape strategies that explicitly treat areas to reduce high intensity crown fires also may be needed (Finney et al., 2007). In most landscapes, fire refugia—places that typically do not burn or burn with lower frequency and/or intensity—could be critical to maintaining biodiversity (Mackey et al., 2002). Where fire refugia are important, landscape-level fuel reduction strategies will be needed to reduce the risk that fuel continuity will facilitate the spread of high intensity fire into areas that support fire sensitive populations and ecosystem functions. It is not easy to assess tradeoffs in risk to biodiversity from fuel management activities themselves against risk possessed by wildfires that could burn refugia. Nevertheless, this conundrum suggests that managers should avoid applying the same policies and practices everywhere.

5.6. Multi-scale monitoring and research is critical for dealing with variability and uncertainty

Despite the extensive work completed to date, it is remarkable how little is known about the impacts of fire and hence the lack of predictive ability of biotic responses to fire (Whelan, 2002). Much of our current focus concerns the physical behavior of fire and ecological studies at the stand scale (Schwilk et al., 2009; Boerner et al., 2009). Models and empirical studies of the ecological responses to fire are far less well developed, especially at landscape scales (Whelan, 2002; Wittkuhn et al., 2011).

Lack of knowledge should be a strong motivator for taking actions that are accompanied by monitoring of management actions and more focused experiments—both natural and planned. Federal land management agencies in the Pacific Northwest have developed biodiversity monitoring programs and then implemented them for over 10 years (Spies and Martin, 2006). The emphasis has been on the Northern Spotted Owl, but other species and landscape indicators have also been used to evaluate the effectiveness of the Northwest Forest Plan. This monitoring effort has proven quite valuable in assessing environmental trends for species and landscapes. For example, monitoring has revealed that populations of the Northern Spotted Owl have declined, despite reduced timber harvesting and an increasing area of older forest (Lint, 2005). Monitoring also has indicated that losses of older forest habitat to wildfire across the region are in line with expectations, but in dry forest provinces, some large fires have converted thousands of hectares of older forest to early successional stages (Spies et al., 2006; Healey et al., 2009) in landscapes where old forest has been depleted by past logging. Interactions of climate change, fire and insect and disease outbreaks pose a risk to the long-term viability of species

Table 1
Major elements of a fire-biodiversity-management checklist and key questions.

1. Socio-economic context—Overall management goals and constraints
- a. What is the relative importance of property versus biodiversity goals?
- b. What are the socio-economic limits of meeting biodiversity goals?

2. Disturbance regimes
- a. To what level of spatial and temporal detail can historical and contemporary regimes be determined? How can regimes be best described in relation to biodiversity conservation?
- b. Is the historical, indigenous, regime still possible/desirable given landscape change, socio-economic constraints and climate change?
- c. What regime (historical or novel) is needed to meet biodiversity goals which consider all animal and plant species?
- d. What lessons from historical regimes can be used to guide development of new regimes?
- e. How might regimes change in the future in response to atmospheric, climatic, demographic, and land-use changes and invasive species?

3. Biodiversity management plans and practices
- a. What are landscape-level goals, objectives and measures for biodiversity?
- b. What are landscape-level priorities for fire-management actions to maintain or restore biodiversity?
- c. What site-level options exist for using mechanical and/or fire methods to reach goals described in terms of structure, composition and dynamics of vegetation?
- d. What are the current risks to biodiversity associated with fire management (both action and lack of action)? How are they distributed - over multiple spatial and temporal scales?

4. Responses to wildfire events
- a. When and where are there key habitats/species' populations that need to be protected from wildfire and management actions during suppression activities?
- b. When and where, and of what type, is ecological restoration work needed where legacies of past management (e.g. roads, logging) affect the recovery potential of post-fire vegetation (e.g. Monsanto and Agee, 2008; Stephens and Moghaddas, 2005)?
- c. Where goals are primarily economic (e.g. recovery of wood) or safety (falling trees near roads or trails), where are key places in landscape where some dead trees can be left to retain some habitat diversity? Where goals are primarily ecological there is typically little reason to salvage dead trees (Lindenmayer et al., 2009) except as noted in 4b above.
- d. Are public engagement strategies in place to communicate the risks and benefits of particular fire regimes, and different recovery strategies (including minimal intervention that allows natural processes to drive recovery of the ecosystem)?

5. Ecological effects at multiple scales
- a. Can the ecological effects of fires and regimes (both wild and prescribed) be articulated and tradeoffs identified?
- b. What are the expected short-term versus long-term post-fire trends in species and ecosystems?
- c. What terminology is most appropriate to characterize variable fire effects?
- d. How can these effects be communicated to managers and the public in terms of different ecosystem goods and services systems (e.g. wildlife habitat, clean water, carbon emissions?

6. Life history characteristics of desired species and range of variability of communities and ecosystems
- a. What are the critical, most vulnerable, species with respect to particular fire-regimes (not just intervals between fires)? Are the autecologies of such key species known well enough to use as a basis for management?
- b. If the autecologies are not well known, can systems (regimes, landscape patterns and dynamics) be used as a substitute or in tandem?
- c. Can tradeoffs among species or between species and ecosystem (e.g. community, landscape, processes) goals be articulated ? (see Section 5.5)

7. Monitoring and adaptive management
- a. Can multi-scale management experiments help resolve uncertainties?
- b. What monitoring programs are needed at site, landscape and regional scales?
- c. What kind of social learning networks are most effective in fostering communication among scientists, managers, and various publics so as to minimize the chances of species' extinction or other undesirable changes in biological diversity?

associated with older forests in some landscapes. Despite the success of this monitoring effort, its short comings also have become apparent. For example, such programs are unable to readily quantify relationships between cause and effect (i.e. why have populations of the Northern Spotted Owl declined?). Nevertheless, ongoing monitoring and adaptive management are critical for ecological and monitoring learning, particularly in relation to understanding the effects of wildfires on biodiversity.

6. A checklist of considerations for conserving biodiversity in fire-prone landscapes

The preceding section has emphasized that the conservation of biodiversity in fire-prone forests is a major challenge to scientists, managers and policy makers across the globe. Our brief review of fire-related conservation issues in the Pacific Northwest and southeastern Australia further emphasizes the array of challenges to the development of more robust and useful theories or conceptual frameworks. For example, the concept of disturbance regimes, which is central to both fire ecology and coarse filter approaches to species conservation, is applied differently in the two regions and each approach (historical regime versus new regime) has advantages and disadvantages. With the increasing influence of climate change and the cumulative effects of land use change, "new" regime approaches may be more tractable but this further adds to the complexity challenge (see next section).

Despite the differences between the two regions, we believe it is possible to develop a general, scientifically-defensible checklist of topics or questions that should be addressed in developing and stimulating thinking about fire management plans for particular landscapes (Table 1). We argue that the checklist is valuable not only for Pacific Northwest, USA and southeastern Australia, but also many other fire-prone ecosystems around the world. In some regions of the world, such as the southeastern US there is progress on integrating socio-ecological concerns about biodiversity and fire in management. For example, some agencies such as the US Park Service have considerable experience in managing wildland fire for multiple objectives (USDI-NPS, 2008). However, we are not aware of other peer-reviewed publications that review scientific concepts and provide guidance for management in the form of a checklist.

We present this checklist below as questions for consideration by fire and biodiversity researchers and managers. The checklist identifies a combination of management perspectives (e.g. what are management priorities) and scientific perspectives (e.g. ecological effects at multiple scales). We present both perspectives because progress in conservation of fire-prone ecosystems can only be made if managers better understand ecological processes and researchers better understand management constraints.

Providing guidelines or checklists for ecosystems characterized by fire, ecological interactions, and the demands of human society is extremely challenging – no two fires are the same and there are a myriad of possible ecological and socially-based approaches to fire. Yet, we are not starting from scratch. Conservation biologists and fire ecologists have a large body of theory and empirical knowledge on which to base the development of new management frameworks and scientifically-based learning. Our checklist provides a framework for planning and decision making that could lessen the risk that managers become overwhelmed by a blizzard of ecological details (*sensu* Bowman, 2003) and make poor decisions or miss important considerations. The list also mixes management and scientific considerations because progress on conservation in fire-prone systems requires that managers and researcher work together. Our checklist is not comprehensive nor is it the only way to structure the issues, but we believe that it provides a foundation to meeting the challenges of conserving biodiversity in fire-prone socio-ecological systems.

7. Unresolved and emerging issues

While we do have a solid scientific basis for using the above list to guide biodiversity conservation in fire-prone systems, there are several especially large gaps in our knowledge that require special emphasis:

7.1. Spatial heterogeneity

Managing to create fire mosaics and spatial heterogeneity is increasingly a goal but there are many expressions of heterogeneity and it is difficult to generalize about the ecological effects of one type of heterogeneity from another (Gill, 2008).

7.2. Early successional environments

After decades of focus on conserving late successional habitats, we are now realizing the importance of early successional environments (Franklin and Agee, 2003; Hutto, 1995; Swanson et al., 2011) – but they are currently very poorly studied.

7.3. Climate change adaptation strategies

Many strategies for enhanced biodiversity conservation in response to rapid climate change are underpinned by efforts to promote adaptation and habitat connectivity (Opdam et al., 2006) but we lack basic studies of the ecological effects of these actions (Steffen et al., 2009).

7.4. Fire and carbon budgets

As mitigation strategies for climate change focus on increasing carbon sequestration (Danielsen et al., 2009), we need better information on how fire management strategies influence carbon dynamics (Hurteau and North, 2009; Mitchell et al., 2009; Stephens et al., 2009c; Bradstock and Williams, 2009).

Acknowledgements

We thank the Focused Science Delivery Program of the PNW Research Station for the funding which supported this work.

References

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, DC.
Agee, J.K., 2003. Historical range of variability in eastern Cascade forests, Washington, USA. Landscape Ecology 18, 725–740.
Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211, 83–96.
Baker, J., 1997. The decline, response to fire, status and management of the eastern bristlelbird. Pacific Conservation Biology 3, 235–243.
Boerner, R.E., Huang, J.H., Hart, S.C., 2009. Impacts of fire and fire surrogate treatments on forest soil properties: a meta-analytical approach. Ecological Applications 19, 338–358.
Bowman, D.M., 2003. Bushfires: a Darwinian perspective. In: Cary, G., Lindenmayer, D., Dovers, S. (Eds.), Australia Burning: Fire Ecology, Policy and Management Issues. CSIRO Publishing, Collingwood, Victoria., pp. 3–14.
Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., Defries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., Swetnam, T.W., van der Werf, G.R., Pyne, S.J., 2009. Fire in the earth systems. Science 324, 481–484.
Bradstock, R.A., Williams, R.J., 2009. Can Australian fire regimes be managed for carbon benefits? New Phytologist 183, 931–934.
Brooks, M.L., D'Antonio, C.M., Richardson, D.M., Grace, J.B., Keeley, J.E., DiTomaso, J.M., Hobbs, J.R., Pellant, M., Pyke, D., 2004. Effects of invasive alien plants on fire regimes. BioScience 54, 677–688.

Brown, J.K., Smith, J.K. (Eds.), 2000. Wildfire in Ecosystems: Effects of Fire on Flora. General Technical Report, RMRS-GTR-42, USDA Forest Service Rocky Mountain Research Station, Ogden, UT.

Burgman, M.A., 2005. Risks and Decisions for Conservation and Environmental Management. Cambridge University Press, New York, 488p.

Carey, A., Evans, M., Hann, P., Lintermans, M., MacDonald, T., Ormay, P., Sharp, S., Shorthouse, D., Webb, N., 2003. Wildfires in the ACT 2003: Report on Initial Impacts on Natural Ecosystems. Technical Report 17. Environment ACT, Canberra.

Cary, G.J., 2002. Importance of a changing climate for fire regimes in Australia. In: Bradstock, R.A., Williams, J.E., Gill, A.M. (Eds.), Flammable Australia: the Fire Regimes and Biodiversity of a Continent. Cambridge University Press, pp. 26–46.

Collins, B.M., Stephens, S.L., 2007. Managing natural fires in Sierra Nevada wilderness areas. Frontiers in Ecology and the Environment 5, 523–552.

Collins, B.M., Stephens, S.L., 2010. Stand-replacing patches within a mixed severity fire regimes: quantitative characterization using recent fires in a long-established natural fire area. Landscape Ecology 25, 927–939.

Collins, B.M., Miller, J.D., Thode, A.E., Kelly, M., van Wagtendonk, J.W., Stephens, S.L., 2009. Interactions among wildland fires in a long-established Sierra Nevada natural fire area. Ecosystems 12, 114–128.

Collins, B.M., Stephens, S.L., Roller, G.B., Battles, J.J., 2011. Simulating fire and forest dynamics for a landscape fuel treatment project in the Sierra Nevada. Forest Science 57, 77–88.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A.F., Krebs, P., 2009. Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. Quaternary Science Reviews 28 (5–6), 555–576.

Cooney, R., 2004. The Precautionary Principle in Biodiversity Conservation and Natural Resource Management: an Issues Paper for Policy-makers, Researchers and Practitioners. IUCN, Gland, Switzerland and Cambridge, UK, 51p.

Cushman, S.A., McKelvey, K.S., Flather, C.H., McGarigal, K., 2008. Do forest community types provide a sufficient basis to evaluate biodiversity? Frontiers in Ecology and Environment 6, 13–17.

Danielsen, F., Beukema, H., Burgess, N.D., Parish, F., Bruhl, C.A., Donald, P.F., Murdiyarso, D., Phelna, B., Reijnders, L., Struebig, M., Fitzherbert, E.B., 2009. Biofuel plantations on forested lands: double jeopardy for biodiversity and climate. Conservation Biology 23, 348–358.

DiTomaso, J.M., Kyser, G.B., Hastings, M.S., 1999. Prescribed burning for control of yellow starthistle (*Centaurea solstitialis*) and enhanced native plant diversity. Weed Science 47, 233–242.

Driscoll, D.A., 2007. The diverse impacts of grazing, fire and weeds: how ecological theory can inform conservation management. In: Lindenmayer, D.B., Hobbs, R.J. (Eds.), Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles. Blackwell Publishing, Malden.

Driscoll, D.A., Lindenmayer, D.B., Bennett, A.F., Bode, M., Bradstock, R.A., Cary, G.J., Clarke, M.F., Dexter, N., Fensham, R., Friend, G., Gill, M., James, S., Kay, G., Keith, D.A., MacGregor, C., Russell-Smith, J., Salt, D., Watson, J.E.M., Williams, R.J., York, A., 2011. Fire management for biodiversity conservation: key research questions and our capacity to answer them. Biological Conservation 143, 1928–1939.

Egler, F.E., 1954. Vegetation science concepts. I. Initial floristic composition a factor in old field development. Vegetatio 4, 412–417.

Finney, M.A., Seli, R.C., McHugh, C.W., Ager, A.A., Bahro, B., Agee, J.K., 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. International Journal of Wildland Fire 16, 712–727.

Ford, H.A., 1979. Birds. In: Tyler, M.J., Twidale, C.R., Ling, J.K. (Eds.), Natural History of Kangaroo Island. Royal Society of South Australia, Adelaide, pp. 103–114.

Foster, D.R., Knight, D.H., Franklin, J.F., 1998. Landscape patterns and legacies resulting from large, infrequent forest disturbances. Ecosystems 1, 497–510.

Franklin, J.F., Agee, J.K., 2003. Forging a science-based national forest fire policy. Issues in Science and Technology 20, 59–66.

Franklin, J.F., Spies, T.A., Van Pelt, R., Carey, A., Thornburgh, D., Berg, D.R., Lindenmayer, D., Harmon, M., Keeton, W., Shaw, D.C., 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management 155, 309–423.

Frelich, L.E., Reich, P.B., 1998. Disturbance severity and threshold responses in the boreal forest. Conservation Ecology 2, 7. <http://www.consecol.org/vol2/iss2/art7>.

Gill, A.M., 1975. Fire and the Australian flora: a review. Australian Forestry 38, 4–25.

Gill, A.M., 1981. Adaptive responses of Australian vascular plant species to fires. In: Gill, A.M., Groves, R.H., Noble, I.R. (Eds.), Fire and the Australian Biota. Australian Academy of Science, Canberra, pp. 243–272.

Gill, A.M., 1999. Biodiversity and bushfires: an Australia-wide perspective on plant-species changes after a fire event. In: Gill, A.M., Woinarski, J., York, A. (Eds.), Australia's Biodiversity: Responses to Fire. Plants, Birds and Invertebrates. Environment Australia, Canberra, pp. 9–53.

Gill, A.M., 2008. Underpinnings of Fire Management for Biodiversity Conservation in Reserves Report 73. State of Victoria Department of Sustainability and Environment. <http://www.dse.vic.gov.au/DSE/nrenfoe.nsf/LinkView/D605713F058416B3CA2575460081998982345 96C0DA9C1ADCA256EF60010E43F>.

Gill, A.M., Bradstock, R., 2003. Fire regimes and biodiversity: a set of postulates. In: Cary, G., Lindenmayer, D., Dovers, S. (Eds.), Australia Burning: Fire Ecology, Policy and Management Issues. CSIRO Publishing, Collingwood, Victoria, pp. 15–25.

Gill, A.M., Catling, P.C., 2002. Fire regimes and biodiversity of forested landscapes of southern Australia. In: Bradstock, R.A., Williams, J.E., Gill, A.M. (Eds.), Flammable Australia: Fire Regimes and Biodiversity of a Continent. Cambridge University Press, pp. 351–369.

Gill, A.M., Stephens, S.L., 2009. Scientific and social challenges for the management of fire-prone wildland–urban interfaces. Environmental Research Letters 4, 034014.

Gill, A.M., Bradstock, R.A., Williams, J.E., 2002. Fire regimes and biodiversity: legacy and vision. In: Bradstock, R.A., Williams, J.E., Gill, A.M. (Eds.), Flammable Australia: Fire Regimes and Biodiversity of a Continent. Cambridge University Press, pp. 429–446.

Hansen, A.J., Knight, R.L., Marzluff, J.M., Powell, S., Brown, K., Gude, P.H., Jones, K., 2005. Effects of exurban development on biodiversity: patterns, mechanisms, and research needs. Ecological Applications 15, 1893–1905.

Healey, S., Cohen, W., Spies, T.A., Mouer, M., Pflugmacher, D., Whitley, M., Lefsky, M., 2009. The relative impact of harvest and fire upon landscape-level dynamics of older forests: lessons from the northwest forest plan. Ecosystems 11, 1106–1119.

Hessburg, P.F., Agee, J.K., 2003. An environmental narrative of Inland Northwest United States forests, 1800–2000. Forest Ecology and Management 178, 23–59.

Hobbs, R.J., Yates, C.J., 2003. Impacts of ecosystem fragmentation on plant populations: generalising the idiosyncratic. Australian Journal of Botany 51 (55), 471–488.

Hummel, S., Donovan, G.H., Spies, T.A., Hemstrom, M.A., 2008. Conserving biodiversity using risk management: hoax or hope? Frontiers in Ecology and the Environment 7, 103–109.

Hunter, M.L., 2007. Core principles for using natural disturbance regimes to inform landscape management. In: Lindenmayer, D.B., Hobbs, R.J. (Eds.), Managing and Designing Landscapes for Conservation. Blackwell Science, Oxford, pp. 408–422.

Hurteau, M., North, M., 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. Frontiers in Ecology and Environment 7, 2–7.

Hutto, R.L., 1995. Composition of bird communities following stand-replacement fires in northern Rocky Mountain (USA) coniferous forests. Conservation Biology 9, 1041–1058.

Jain, T.B., 2004. Tongue-tied. Wildfire 22 (July/August), 26.

Jain, T.B., Graham, R.T., 2007. The Relation Between Tree Burn Severity and Forest Structure in the Rocky Mountains. USDA Forest Service General Technical Report, PSW-GTR-203.

Keane, R.E., Agee, J.K., Fule, P., Keeley, J.E., Key, C., Kitchen, S.G., Miller, R., Schulte, L.A., 2008. Ecological effects of large fires on US landscapes: benefit or catastrophe? International Journal of Wildland Fire 17, 696–712.

Keeley, J.E., 2005. Fire management impacts on invasive plants in the western United States. Conservation Biology 20, 375–384.

Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. International Journal of Wildland Fire 18, 116–126.

Klinger, R.C., Brooks, M.L., Randall, J.M., 2006. Fire and invasive plant species. In: Sugihara, N.G., van Wagtendonk, J.W., Fites-Kaufman, J., Shaffer, K.E., Thode, A.E. (Eds.), Fire in California Ecosystems. University of California Press, Berkeley.

Knapp, A.K., Smith, M.D., Collins, S.L., Zambatis, N., Peel, M., Emery, S., Wojdak, J., Horner-Devine, M.C., Biggs, H., Kruger, J., Andelman, S.J., 2004. Generality in ecology: testing North American grassland rules in South African savannas. Frontiers in Ecology and Environment 2, 483–491.

Krebs, C., 2008. The Ecological World View. CSIRO Publishing, Melbourne.

Lindenmayer, D.B., 2009. Forest Pattern and Ecological Process: a 25 year Study in the Wet Forests of Victoria, South-Eastern Australia. CSIRO Publishing, Melbourne.

Lindenmayer, D.B., Burgman, M.A., 2005. Practical Conservation Biology. CSIRO Publishing, Melbourne.

Lindenmayer, D.B., Franklin, J.F., 2002. Conserving Forest Biodiversity: a Comprehensive Multiscaled Approach. Island Press, Washington.

Lindenmayer, D.B., MacGregor, C., Wood, J.T., Cunningham, R.B., Crane, M., Michael, D., Montague-Drake, R., Brown, D., Munz, R., Gill, A.M., 2008. Testing hypotheses associated with bird recovery after wildfire. Ecological Applications 18, 1967–1983.

Lindenmayer, D.B., Burton, P.J., Franklin, J.F., 2009. Salvage Logging and its Ecological Consequences. Island Press, Washington DC.

Lint, J., 2005. Northwest Forest Plan-the First 10 years (1994–2003): Status and Trends of Northern Spotted Owl Populations and Habitat. USDA Forest Service General Technical Report, PNW-GTR-648.

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., Taylor, W.W., 2007. Complexity of coupled human and natural systems. Science 317, 1513–1516.

Mackey, B., Lindenmayer, D.B., Gill, A.M., McCarthy, M.A., Lindesay, J.A., 2002. Wildlife, Fire and Future Climate: a Forest Ecosystem Analysis. CSIRO Publishing, Melbourne.

Malamud, B.D., Millington, J.D.A., Perry, G.L.W., 2005. Characterizing wildfire regimes in the United States. Proceedings of the National Academy of Sciences 102, 4694–4699.

Mayr, E., 1997. This is Biology. Belknap Press of Harvard University Press, Cambridge, MA.

Mazza, R., 2007. Managing Forests after Fire. Science Update 15. USDA Forest Service, Pacific Northwest Research Station.

McCaffrey, S., 2004. Thinking of wildfire as a natural hazard. Society and Natural Resources 17, 509–516.

McCarthy, M.A., Lindenmayer, D.B., 2000. Spatially-correlated extinction in a metapopulation model of Leadbeater's Possum. Biodiversity and Conservation 9, 47–63.
Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications 17, 2145–2151.
Miller, J.D., Safford, H.D., Crimmins, M., Thode, A.E., 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12, 16–32. doi:10.1007/S10021-008-9201-9.
Mitchell, S.R., Harmon, M.E., O'Connell, K.E.B., 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecological Applications 19, 643–655.
Moghaddas, J.J., Collins, B.M., Menning, K., Moghaddas, E.E.Y., Stephens, S.L., 2010. Fuel treatment effects on modeled landscape level fire behavior in the northern Sierra Nevada. Canadian Journal of Forest Research 40, 1751–1765.
Monsanto, P.G., Agee, J.K., 2008. Long-term post-wildfire dynamics of coarse woody debris after salvage logging and implications for soil heating in dry forests of the eastern Cascades, Washington. Forest Ecology and Management 255, 3952–3961.
Mooney, H.A., Cleland, E.E., 2001. The evolutionary impact of invasive species. Proceedings of the National Academy of Sciences 98, 5446–5451.
Morgan, P., Hardy, C., Swetnam, T.W., Rollins, M.G., Long, D.G., 2001. Mapping fire regimes across time and space: understanding coarse and fine-scale patterns. International Journal of Wildland Fire 10, 329–342.
Noble, I.R., Slatyer, R.O., 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. Plant Ecology 43, 5–21.
Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T., Moyle, P.B., 2006. Managing fire-prone forests in the western United States. Frontiers in Ecology and the Environment 4, 481–487.
Odion, D.C., Moritz, M.A., DellaSala, D.A., 2010. Alternative community states maintained by fire in the Klamath Mountains, USA. Journal of Ecology 98, 96–105.
Opdam, P., Stengrover, E., van Rooij, S., 2006. Ecological networks: a spatial concept for multi-actor planning of sustainable landscapes. Landscape and Urban Planning 75, 322–332.
Parr, C.L., Andersen, A.N., 2006. Patch mosaic burning for biodiversity conservation: a critique of the pyrodiversity paradigm. Conservation Biology 29, 1610–1619.
Pausas, J.G., Bradstock, R.A., Keith, D.A., Keeley, J.E., 2004. Plant functional traits in relation to fire in crown-fire ecosystems. Ecology 85, 1085–1100.
Pickett, S.T.A., White, P.S., 1985. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Orlando.
Pittock, A.B., 2005. Climate Change: Turning up the Heat. CSIRO Publishing, Melbourne.
Pyne, S.J., 2004. Tending Fire: Coping with Americas Wildland Fires. Island Press, Washington, DC.
Pyne, S.J., 2007. Problems, paradoxes, paradigms: triangulating fire research. International Journal of Wildland Fire 16, 271–276.
Redman, C.L., Grove, J.M., Kuby, L.H., 2004. Integrating social science into the long-term ecological research (LTER) network: social dimensions of ecological change and ecological dimensions of social change. Ecosystems 7, 161–171.
Rose, S., Fairweather, P.G., 1997. Changes in floristic composition of urban bushland invaded by *Pittosprum undulatum* by Northern Sydney, Australia. Australian Journal of Botany 45, 123–149.
Rowe, J.S., 1983. Concepts of fire effects on plant individuals and species. In: Wein, R.W., Maclean, D.A. (Eds.), The Role of Fire in Northern Circumpolar Ecosystems. Wiley and Sons, New York, pp. 135–154.
Russell-Smith, J., Yates, C.P., Whitehead, P.J., Smith, R., Craig, R., Allan, G.E., Thackway, R., Frakes, I., Cridland, S., Meyer, M.C.P., Gill, A.M., 2007. Bushfires 'down under': patterns and implications of contemporary Australian landscape burning. International Journal of Wildland Fire 16, 361–377.
Schoennagel, T., Veblen, T.T., Romme, W.H., 2004. The interaction of fire, fuels, and climate across Rocky Mountain Forests. Bioscience 54, 661–676.
Schwilk, D.W., Keeley, J.E., Knapp, E.E., McIver, J., Bailey, J.D., Fettig, C.J., Fiedler, C.E., Harrod, R.J., Moghaddas, J.J., Outcalt, K.W., Skinner, C.N., Stephens, S.L., Waldrop, T.A., Yaussy, D.A., Youngblood, A., 2009. The national Fire and Fire Surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecological Applications 19, 285–304.
Simberloff, D., 2004. Community ecology: is it time to move on? The American Naturalist 163, 787–799.
Skinner, C.N., Taylor, A.H., Agee, J.K., 2006. Klamath mountains bioregion. In: Sugihara, N.G., Van Wagtendonk, J.W., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, California, pp. 170–194.
Spies, T.A., Martin, J.R., 2006. Monitoring late-successional forest biodiversity in the Pacific Northwest, USA. The Forestry Chronicle 82, 364–367.
Spies, T.A., Hemstrom, M.A., Youngblood, A., Hummel, S., 2006. Conserving old-growth forest diversity in disturbance-prone landscapes. Conservation Biology 20, 351–362.
Spies, T.A., Johnson, K.N., Burnett, K.M., Ohmann, J.L., McComb, B.C., Reeves, G.H., Bettinger, P., Kline, J.D., Garber-Yonts, B., 2007. Cumulative ecological and socio-economic effects of forest policies in coastal Oregon. Ecological Applications 17, 5–17.
Spies, T.A., Miller, J.D., Buchanan, J.B., Lehmkuhl, J.F., Franklin, J.F., Healy, S.P., Hessburg, P.F., Safford, H.D., Cohen, W.D., Kennedy, R.S.H., Knapp, E.K., Agee, J.K., Moeur, M., 2009. Underestimating risks to the Northern Spotted Owl in fire-prone forests: response to Hanson et al. Conservation Biology 24 (1), 330–333.
Steffen, W., Burbidge, A., Hughes, L., Lindenmayer, D.B., Musgrave, W., Stafford-Smith, M., Werner, P., 2009. Climate Change and Biodiversity: an Adaptation Response for Australia. CSIRO Publishing, Melbourne.
Stephens, S.L., 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. Forest Ecology and Management 105, 21–34.
Stephens, S.L., Moghaddas, J.J., 2005. Silvicultural and reserve impacts on potential fire behavior and forest conservation: 25 years of experience from Sierra Nevada mixed conifer forests. Biological Conservation 25, 369–379.
Stephens, S.L., Ruth, L.W., 2005. Federal forest-fire policy in the United States. Ecological Applications 15, 532–542.
Stephens, S.L, Fry, D., Franco-Vizcano, E., 2008. Wildfire and forests in Northwestern Mexico: the United States wishes it had similar fire problems. Ecology and Society 13, 10. <http://www.ecologyandsociety.org/vol13/iss2/art10/>.
Stephens, S.L., Adams, M.A., Handmer, J., Kearns, F.R., Leicester, B., Leonard, J., Moritz, M.A., 2009a. Urban-wildland fires: how California and other regions of the US can learn from Australia. Environmental Research Letters 4, doi:1088/1748-9326/4/1/014010.
Stephens, S.L., Moghaddas, J.J., Ediminster, C., Fiedler, C.E., Hasse, S., Harrington, M., Keeley, J.E., McIver, J.D., Metlen, K., Skinner, C.N., Youngblood, A., 2009b. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. Ecological Applications 19, 305–320.
Stephens, S.L., Moghaddas, J., Hartsough, B., Moghaddas, E., Clinton, N.E., 2009c. Fuel treatment effects on stand level carbon pools, treatment related emissions, and fire risk in a Sierran mixed conifer forest. Canadian Journal of Forest Research 39, 1538–1547.
Swanson, M.E., Franklin, J.F., Beschta, R.L., Crisafulli, C.M., DellaSala, D.A., Hutto, R.L., Lindenmayer, D.B., Swanson, F.J., 2011. The forgotten stage of forest succession: early-successional ecosystems on forest sites. Frontiers in Ecology and the Environment 9, 117–125.
Thompson, J.R., Spies, T.A., 2009. Vegetation and weather explain variation in crown damage within a large mixed severity-wildfire. Forest Ecology and Management 258, 1684–1694.
Thompson, J.R., Spies, T.A., Ganio, L.M., 2007. Reburn severity in managed and unmanaged vegetation in a large wildfire. Proceedings of the National Academy of Science 104, 10743–10748.
USDA-USDI, 2004. Biscuit Fire Recovery Project Final Environmental Impact Statement. <http://www.fs.fed.us/r6/rogue-siskiyou/biscuit-fire/feis/> (accessed 28.08.08).
USDI-NPS, 2008. Wildland Fire Management, Reference Manual 18, Branch of Wildland Fire, Division of Fire and Aviation. <http://www.nps.gov/fire/download/fir_wil_rm18.pdf> (accessed 16.07.11).
Wace, N., 1977. Assessment of dispersal of plant species – the car borne flora of Canberra. Proceedings of the Ecological Society of Australia 10, 166–186.
Walters, C., 1986. Adaptive Management of Renewable Resources. Macmillian Publishing, New York.
Weisberg, P.J., Swanson, F.J., 2003. Regional synchroneity in fire regimes of western Oregon and Washington, USA. Forest Ecology and Management 172, 17–28.
Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313, 940–943.
Whelan, R.J., 1995. The Ecology of Fire. Cambridge University Press, Cambridge.
Whelan, R.J., 2002. Managing fire regimes for conservation and property protection: an Australian response. Conservation Biology 16, 1659–1661.
White, P.S., Jentsch, A., 2001. The search for generality in studies of disturbance and ecosystem dynamics. Progress in Botany 62, 399–450.
Williams, R.J., Bradstock, R.A., 2008. Large fires and their ecological consequences. International Journal of Wildland Fire 17, 685–687.
Wittkuhn, R.S., McCaw, L., Will, A.J., Robinson, R., Andersen, A.N., Van Heurck, P., Farr, J., Liddelowe, G., Cranfield, R., 2011. Variation in fire interval sequences has no detectable effects on species richness or community composition in fire-prone landscapes of south-west Western Australia. Forest Ecology and Management 216, 965–978.