2003 Veblen, T.T. Key issues in fire regime research for fuels management and ecological restoration. Pages 259-276 in: P. Omi and L. Joyce (technical eds). Fire, Fuel Treatments and Ecological Restoration: Conference proceeedings; 2002 16-18 April; Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 475 p.

AN INTRODUCTION TO KEY ISSUES IN FIRE REGIME RESEARCH FOR FUELS MANAGEMENT AND ECOLOGICAL RESTORATION

Thomas T. Veblen
Department of Geography
University of Colorado
Boulder, Colorado 80301

Email: veblen@spot.colorado.edu

Paper prepared for the Conference on Fire, Fuel Treatments and Ecological Restoration: Proper place, Appropriate Time, April 16-18, 2002, Fort Collins, Colorado

Abstract.

The basic premise behind many projects aimed at wildfire hazard reduction and ecological restoration in forests of the western United States is the idea that unnatural fuel buildup has resulted from suppression of formerly frequent fires. This premise and its implications need to be critically evaluated by conducting area-specific research in the forest ecosystems targeted for fuels or ecological restoration projects. Fire regime researchers need to acknowledge the limitations of fire history methodology and avoid over-reliance on summary fire statistics such as mean fire interval and rotation period. While fire regime research is vitally important for informing decision making in the areas of wildfire hazard mitigation and ecological restoration, there is much need for improving the way researchers communicate their results to managers and the way managers use this information.

INTRODUCTION

The two major management themes of this conference are: 1) fuel treatments for the purpose of reducing fire hazard, and 2) ecological restoration through a variety of management practices including prescribed fire. The title and content of the conference might lead to the impression that fire hazard reduction through fuel treatments and ecological restoration have convergent objectives in all forest ecosystems in the western United States. However, this implication needs to be explored on the basis of existing knowledge of historical fire regimes and forest conditions on a case by case basis for different forest cover types and different locations. In some forest ecosystems fire hazard reduction through fuels management may be achieved by restoring historic fire regimes of frequent surface fires. However, in other forest ecosystems, historic fire regimes included widespread stand-replacing fires at long intervals. In those systems, restoration of the historic fire regime will not reduce the hazard to property and humans. This essay introduces a series of papers on fire regimes by identifying some of the key issues and research challenges for fire regime research.

Political leaders and many resource management professionals often stress the the convergence of the goals and strategies of fire hazard reduction and ecological restoration in the forests of the western United States. For example, the official position of the Society of American Foresters in response to the 2000 fire season included the statement that:

> "The buildup of combustible materials (fuels) in the forests of the West is at an all-time high. Much of this can be attributed to the decades of fire suppression that allowed the fuels to build up so fires will now burn bigger and hotter than ever" -- Society of American Foresters, August 11, 2000 press release.

There is a widespread belief among resource managers, reflected by many of the papers presented in the current conference, that fuel accumulation during many years of fire suppression in western forests was the major cause of the widespread wildfires of the 2000 season. Likewise, there is a consensus that a perceived decline in "forest health" (tree diseases, mistletoe infection, and forest insect pests) is the result of fire exclusion. One of the leading experts on ecological restoration in western U.S. forests has written:

> "The dry forest ecosystems of the American West, especially those once dominated by open ponderosa pine forest, are in widespread collapse. We are now witnessing sudden leaps in aberrant ecosystem behaviour long predicted by ecologists and conservation professionals (see *Nature* 407, 5; 2000). Trends over the past half-century show that the frequency, intensity and size of wildfires

> will increase – by orders of magnitude – the loss of biological diversity, property and human lives for many generations to come." -- Covington 2000, p. 135.

The view that current fire hazard is largely attributable to fuel buildup under decades of fire exclusion is strongly reflected in the following passage from the National Fire Plan:

> "While the policy of aggressive fire suppression appeared to be successful, it set the stage for the intense fires that we see today. ...after many years of suppressing fires, thus disrupting normal ecological cycles, changes in the structure and make-up of forests began to occur. Species of trees that ordinarily would have been eliminated from forests by periodic, low-intensity fires began to become a dominant part of the forest canopy. Over time, these trees became susceptible to insects and disease. Standing dead and dying trees in conjunction with other brush and downed material began to fill the forest floor. The resulting accumulation of these materials, when dried by extended periods of drought, created the fuels that promote the type of wildfires that we have seen this year.
>
> In short, decades of aggressive fire suppression have drastically changed the look and fire behavior of Western forests and rangelands. Forests a century ago were less dense and had larger, more fire-resistant trees. For example, in northern Arizona, some lower elevation stands of ponderosa pine that once held 50 trees per acre, now contain 200 or more trees per acre. In addition, the composition of our forests have changed from more fire-resistant tree species to non-fire resistant species such as grand fir, Douglas-fir, and subalpine fir. As a result, studies show that today's wildfires typically burn hotter, faster, and higher than those of the past."-- National Fire Plan 2001.

While the National Fire Plan also recognizes the importance of other contributing factors to our current wildfire management crisis, including weather influences (i.e. the effects of La Niña) and the land use policies that have permitted uncontrolled growth at the wildland-urban interface, this quotation represents the dominant view of the current wildfire management problem among political leaders, resource managers, and the general public. For convenience, I will refer to this view as the "fire exclusion/fuel buildup" perspective on current fire hazard in western U.S. forests.

An important theme of this essay is that assessment of fire hazard, and especially ecological restoration, requires a sound understanding of historic fire regimes in the ecosystem of interest. "Fire regime" is used here to refer to the spatial and temporal variation of fires *and* *their effects* in a given area over a given time period. The parameters used for describing fire regimes are briefly discussed below under Methodological Issues. One major goal of fire regime research is to discover under what historic and present fire regimes and ecosystem conditions do the goals and methods of fuels reduction and ecological restoration converge.

The idea that current fuel levels are unnaturally high due to suppression of formerly frequent surface fires originated to a large extent from studies of ponderosa pine ecosystems. This viewpoint is best supported by multiple lines of research on Southwest ponderosa pine ecosystems showing that frequent-fire disturbance regimes were disrupted after Euro-American settlement throughout the Southwest resulting in major increases in stand densities and in larger and more intense wildfires (Moore et al. 1999). Supporting evidence comes from numerous retrospective studies of fire-scar reconstruction of fire regimes (Swetnam and Baisan 1996, Fulé et al. 1997), tree-ring based reconstructions of past stand structures (Covington and Moore 1994, Fulé et al. 1997, Mast et al. 1999), and historical evidence from photographs and early 20th century forest inventories (Moore et al. 1999). The frequent surface fires that had maintained open-canopy conditions declined dramatically in the late 19th century due to grass fuels reduction by introduced livestock and subsequently due to organized fire suppression activities (Swetnam and Baisan 1996, Moore et al. 1999). Detailed studies of past fire and forest conditions support a series of carefully planned and executed restoration projects in Southwest ponderosa pine ecosystems (Covington et al. 1997; Moore et al. 1999). This overall approach has become a model for a step-by-step process of conducting careful historical ecological research followed by experimentation and monitoring of restoration treatments. Similar approaches to ecological restoration are in earlier phases of development in ponderosa pine forests outside of Arizona (e.g. Brown et al. 1999, Kaufmann et al. 2000, 2001, Huckaby et al. 2001; Romme et al. this volume).

How applicable is the Southwest ponderosa pine model of fire exclusion and subsequent changes in forest conditions (e.g. Covington et al. 1997, Moore et al. 1999) to other forest ecosystem types and to ponderosa pine in other regions? For example, there is abundant documentation of pre-1900 stand-replacing fires occurring in apparently denser stands of ponderosa pine in the Colorado Rocky Mountains (Veblen and Lorenz 1986, 1991, Brown et al. 1999, Kaufmann et al. 2000, Mast et al. 1998, Ehle 2001). The occurrence of stand-replacing fires in some ponderosa pine forests prior to c. 1900 raises the issue of geographical variability in fire regimes for ponderosa pine-dominated forests. This theme will be explored further in the next section on ponderosa pine forests in the northern Front Range of Colorado. For other ecosystem types, such as California shrublands and boreal and subalpine forests in Canada the validity of the fire exclusion/fuel build up argument has been directly challenged (Keeley and Fotheringham 2001; Johnson et al. 2001). Thus, there is a need to conduct unique fire regime research for each particular area in order to evaluate the general applicability of the fire exclusion/fuel buildup viewpoint.

The goal of this essay is to show the need for conducting area-specific fire regime research to test the applicability of the fire exclusion/fuel build up viewpoint to particular ecosystems and potential management areas. My intent is not to evaluate the validity of the fire exclusion/fuel build up generalization for all the forests of the western U.S. Nor is it my intent to suggest that there is no need for fuels treatments over extensive surface areas or that we return to a Smokey Bear type of fire suppression policy. Instead, I propose that the broad generalizations of the fire exclusion/fuel buildup viewpoint be used to generate specific research questions and hypotheses that can be critically evaluated for particular cover types and locations. This essay will identify ways in which fire regime research can support resource planning and management decisions in both the contexts of fire hazard management and ecological restoration. I will first draw on several examples from northern Colorado. Then I will suggest ways in which fire regime research can better support resource planning and management decisions.

ASSESSING THE FIRE EXCLUSION/FUEL BUILDUP PERSPECTIVE IN SOME NORTHERN COLORADO FORESTS

The fire exclusion/fuel buildup perspective is based on several general premises that logically generate specific questions or hypotheses for particular forested landscapes (Table 1). Each question needs to be examined across a range of scales from individual stands (e.g. a few hectares to 100s of hectares) to landscape scales (e.g. 10s to 100s of square kilometers). Examples from northern Colorado illustrate major variations in fire regimes of different forest ecosystem types and allow comparison with similar ecosystem types in other regions.

Spruce-fir forests: long fire intervals

To evaluate the premise that fire exclusion has resulted in unnatural fuel buildup it is logical to ask: How different are modern fire regimes from historic fire regimes in spruce-fir forests in northern Colorado? Spruce-fir forests in northern Colorado have been shaped primarily by stand-replacing (crown) fires that recur to the same point or stand at relatively long intervals, usually much greater than a century in length (Veblen 2000, Sibold 2001, Kulakowski 2002). Surface fires occasionally occur but to date there is no documented occurrence of frequent (i.e. at repeated intervals of < 50 years) and widespread (i.e. affecting > 8 ha) surface fires. Although crown fires in the spruce-fir type typically kill most (>90%) of the canopy trees over large areas (100s to over 1000s of hectares), some fires have apparently been less intensive or less continuous resulting in younger post-fire cohorts intermixed with older trees that survived the most recent fire (Sibold 2001; Kulakowski 2002). Large percentages (i.e. > 25%) of spruce-fir forests mapped in areas of > 4000 hectares and at minimum map units of c. 8 hectares do not record any stand-replacing fires in the past c. 400 years.

Clearly, the fire regime of the spruce-fir cover type in northern Colorado is characterized by infrequent, crown fires that burn large areas. High severity fires resulting in spruce-fir stands of high tree densities are part of the natural fire regimes of this ecosystem type (Veblen 2000). Due to the long intervals between fires in the pre-1900 period, it is unlikely that fire exclusion has created forest conditions that are outside the historic range of variation. Fire history mapping in large areas (i.e. > 4000 ha) at multiple sites in northern Colorado, show that the post-1900 fire regime is not unique in comparison with time periods of similar length during the past c. 400 years (Sibold 2001, Kulakowski 2002). Periods of 80 to well over 100 years of no widespread (i.e. > 100 ha) fires in study areas of 4000 or more hectares are typical of the historic fire regimes of the spruce-fir cover type. Given these long intervals between widespread fires in these spruce-fir forests, the fire-free interval that began with fire suppression after c. 1910 is not outside the historic range of variability for this cover type.

This conclusion is specific to the c. 4000 hectare scale at which these studies were conducted and to the spruce-fir cover type. Future research at broader spatial scales potentially may alter these research findings, but the current state of knowledge indicates that fire occurrence in spruce-fir forests is not outside the historic range of variability of the past c. 400 years. Thus, the premise that fire exclusion has created unnatural fuel buildup in these spruce-fir forests is not supported. Likewise, apparent forest health problems should not be attributed to unnaturally long fire intervals resulting from fire exclusion in the spruce-fir cover type. Indeed, widespread outbreaks of the major lethal forest insect in this cover type, the spruce beetle (*Dendroctonus rufipennis*) caused massive mortality of spruce during a well documented 19th century outbreak in northwestern Colorado long before any significant influences of EuroAmericans on these forests (Baker and Veblen 1990, Veblen et al. 1991).

Ponderosa pine-dominated montane forests: spatial variability

The long fire intervals typical of spruce-fir forests make it a relatively clear example of where the fire exclusion/fuel buildup viewpoint is not valid, but the situation is more complex at lower elevations in the montane zone of ponderosa pine and Douglas-fir forests. In the northern Front Range there are areas primarily at lower elevations and near ecotones with grasslands where fire-scars indicate relatively frequent occurrence of non-lethal surface fires in ponderosa pine stands prior to the early 1900s (i.e. many fire intervals < 20 years at a spatial scale of c. 100 ha; Veblen et al. 2000). Historical photographs and tree ages indicate that since the early 1900s there has been a substantial increase in tree densities in these ponderosa pine ecosystems (Veblen and Lorenz 1986, 1991, Mast et al. 1998). Thus, at lower elevations (and at mid-montane sites adjacent to grasslands) there are sites in the northern Front Range where conversion of formerly open woodlands to relatively dense stands of ponderosa pine are qualitatively similar to the pattern widely documented in Arizona (Moore et al. 1999). Likewise, this pattern of increased tree density under reduced fire frequency is well documented for some sites in the southern Front Range (Brown et al. 1999, Kaufmann et al. 2000). In such areas the fire exclusion/fuel build up viewpoint is supported.

The challenge is to determine the spatial limits of this pattern of substantial increase in tree density following exclusion of formerly frequent surface fires. Towards higher elevation and at more mesic sites in the northern Front Range, there is a variety of evidence indicating that the historic fire regime was a mixed-severity regime including both stand-replacing and surface fires. In the northern Front Range in ponderosa pine forests, the pre-1900 frequency of fire events inferred from fire scars declines dramatically at increasing elevation (Veblen et al. 2000). At the spatial scale of c. 50 to 200 ha at elevations above c. 2100 m most fire intervals are well over 50 years in length, and there is no evidence of frequent (i.e. repeated intervals < 20 years), widespread surface fires. In these stands with relatively long fire intervals and in the surrounding areas, the predominant age structure type is even-aged with most stands originating between the mid-1800s and early 1900s, but with remnants of older cohorts as well (Veblen and Lorenz 1986; Sherriff and Veblen unpublished data).

Historical photographs of the upper montane zone taken in the late 1800s to early 1900s show that large areas of ponderosa pine-dominated forests (typically with some component of Douglas-fir and other species) had burned in stand-replacing crown fires in the mid- to late-1800s prior to any significant fire exclusion or unnatural fuel buildup (Veblen and Lorenz 1991). Research is currently underway to spatially define habitats according to the relative importance of past stand-replacing versus surface fires in shaping the current structure of ponderosa pine-dominated stands across their full elevational range in Boulder County (Sherriff and Veblen in progress). Our preliminary evidence indicates that except for a small area at lower elevations, on drier aspects, and near grassland ecotones, the structure of existing ponderosa pine forests was shaped primarily by stand-replacing fires. Over most of the surface area of the ponderosa pine cover type in the areas where we have collected data or done reconnaissance, the pattern of dense stands due to recovery following 19th century burning is much more common than the pattern of dense stands resulting from tree encroachment following cessation of frequent surface fires.

Although current understanding of changes of fire regimes and forest conditions in the low elevation ponderosa pine forests is consistent with restoration of more frequent surface fires (e.g. on City of Boulder Open Space lands; City of Boulder 1999), it does not support that prescription for the larger part of the distribution of the ponderosa pine cover type. For much of the montane zone in Boulder County restoration of the historic fire regime would require a significant (probably dominant) component of stand-replacing fires. Due to the high density of residences in this area, it is unlikely that restoration of the historic fire regime is feasible or socially desirable. Prior land use decisions have severely limited the current opportunities for ecological restoration. For purposes of fire hazard reduction in the upper montane zone, stand thinning and prescribed burning may be appropriate prescriptions, but in this case the goals of fire hazard reduction and ecological restoration do not converge.

An important caveat to the above discussion is that it is based on observations and interpretations largely at the scale of individual stands of a few ha to 200 ha in extent. Although cessation of frequent surface fires does not appear to account for currently dense stands over most of the range of this cover type in Boulder County, it may be that the post-1900 reduction in fire occurrence has created an unnatural forest age structure with few young post-fire stands at the scale of all the upper montane zone of Boulder County. This may be the case, but it seems more likely that the widespread burning of the late 19th century has contributed more to the homogeneous age structure of the montane zone. Thus, if fuel continuity is contributing to increased fire hazard the effects of past increases in fire occurrence play at least as great a role as does fire exclusion.

Fire regime research in the upper montane zone of ponderosa pine-dominated forests in Boulder County indicates that prior to 1900, infrequent years of exceptionally favorable fire weather are associated with evidence of extremely widespread fire, probably including a major component of stand-replacing fires (Veblen et al. 2000). That retrospective perspective, in combination with current fuels conditions and dense residential development, suggests that fire hazard reduction is likely to take precedence over ecological restoration in this area. Tree-ring evidence indicating that large areas of the montane zone burned during extreme droughts in the past supports management that gives priority to fire hazard mitigation. Yet, at the same time the scale and severity of pre-1900 fires in this ecosystem type raises questions about the long-term effectiveness of fire hazard mitigation activities.

MAJOR RESEARCH CHALLENGES FOR ECOLOGICAL RESTORATION

In the context of restoration of fire to western forest ecosystems, the first objective is to have a sound understanding of the historic fire regime and the potential effects of EuroAmericans on the fire regime and forest conditions. This requires area-specific research for the ecosystem of interest. Once the general nature of trends in the fire regime and especially the possible effects of fire exclusion are known, there remain a number of research challenges applicable to many ecosystems targeted for restoration. The following are examples of the most common of these research challenges.

1. What was the temporal variability of the fire regime over multi-century reference periods?

Reference conditions should not be defined by a snapshot in time, such as the conditions for a few years or decades at the time of extensive EuroAmerican settlement which for most of the west is between c.1850 and 1880. Use of reference conditions should not stress a reconstruction of static conditions at a particular point in time. Instead, the goal should be to understand the recent evolutionary environment of an ecosystem, which, at a minimum requires knowledge of temporal variability over periods of several centuries. Most importantly, the historical context should be as complete as possible to identify temporal trends that may be related to climatic variation for one or two centuries just prior to and during intensive EuroAmerican settlement. For example, for the Southwest and Colorado there is abundant tree-ring evidence showing that the second half of the 19th century was climatically more conducive to fire occurrence than the period from c. 1790 to 1830 (Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000, Veblen et al. 2000, Donnegan et al. 2001). The 1790 to 1830 period of reduced fire occurrence in this large region has been linked to variation in the El Niño-Southern Oscillation which has significant teleconnections to the weather of the Southwest and the southern Rocky Mountains (Swetnam and Betancourt 1998, Kitzberger et al. 2001, Veblen and Kitzberger in press). These decadal to centennial scale variations in climatic influences on fire regimes during the reference periods need to be recognized and considered in our understanding of current and future ecosystem fluxes.

2. How was the fire regime influenced by Native Americans?

There are strong and contrasting opinions about the influence of Native Americans on historic fire regimes in the western United States (e.g. see the regional reviews of this theme in Vale 2002). Broad generalizations about the pervasive influence of Native Americans (e.g. Denevan 1992) are not testable and lead to sterile debates unlikely to resolve the issue. Instead, the question of Native American influence needs to be re-framed into tractable research questions. These research questions should be directed at particular ecosystem types and locations. For example, in northern Colorado in spruce-fir forests the dependence of years of widespread fire on exceptionally dry conditions that may only occur a few times per century reduces the likelihood that fires set by Native Americans could have had a major influence on the structure of this landscape. In contrast, at the ecotone of ponderosa pine forests and the Plains-grasslands, fuel dessication is sufficient in most summers so that anthropogenic ignitions are more likely to have spread and to have burned significant areas. Potentially, comparative studies of areas with and without archeological evidence of human occupation can detect past effects of Native Americans on fire frequency and seasonality through fire-scar studies (e.g. Kaye and Swetnam 1999). However, determination of a detectable human influence on fire frequency does not directly address the larger question of how significantly landscapes were modified by burning by Native Americans. Multiple lines of evidence, including reconstructions of vegetation from fossil pollen and historical observations of early explorers, may improve our understanding of this issue, but it is likely to remain highly controversial.

3. How did native and introduced herbivores affect fuels and fire regimes?

It is widely recognized that in some ecosystems, such as in Southwest ponderosa pine ecosystems, fire occurrence declined with the introduction of sheep and cattle, which must have reduced grass fuels (Swetnam and Baisan 1996). However, variations in the populations of native herbivores such as bison, deer and elk due to Native American hunting or natural causes potentially had significant impacts on quantity and type of fuels in some ecosystem types. Browsing and grazing by large herbivores can either increase or decrease the success of tree establishment, depending on the tree species and competing shrub and herbaceous species. Early predator control efforts in some areas may have resulted in irruptions of populations of large herbivores that changed vegetation composition and structure early in the 20th century. These potential influences of fluctuating populations of large herbivores on fine fuels and stand structures have received relatively little research attention (but see Fulé et al. 2002).

4. How have invasive plant species altered fire regimes?

Exotic plant species potentially can change the fire regime by changing fuel continuity. Cheatgrass (*Bromus tectorum*) is an introduced grass which has increased the fire hazard over millions of acres in the western United States (Menakis et al. this volume). Thus, restoration of fire to some ecosystem types needs to take into account that the potential for fire spread and intensity has been significantly altered by such fuel changes.

5. What was the spatial variability of the fire regime within a particular ecosystem type?

As stated previously, different locations of the same forest ecosystem type have had different historic fire regimes for a variety of reasons ranging from subtle differences in climatic seasonality, lightning patterns, understory characterisitics, site productivity (related to geology, soils, and/or climate), and potentially use by Native Americans. Such factors constitute the geographic context for particular ecosystems of a given cover type, such as the ponderosa pine cover type. Geographical context is likely to account for some of the differences reported for fire parameters like frequency and severity within the ponderosa pine cover type. Forest cover types determined solely by the physiognomic dominant (i.e. ponderosa pine) are too broadly defined to expect them to have uniform fire regimes. Forest cover types with broad geographical distributions are likely to exhibit a significant range of historic fire regimes due primarily to regional scale climatic variation. At a local scale spatial variability is also important within the same cover type as previously illustrated by the spatial variability within the ponderosa pine cover of the northern Front Range (Veblen et al. 2000). Spatial variation at both local and broad scales needs to be better understood to avoid over generalizations about fire regimes at the level of forest cover types.

METHODOLOGICAL ISSUES

Most methodological discussions of fire history techniques have focused on the description of fire regimes from the basic descriptors of fire frequency and area burned or their analytical derivatives such as mean fire interval or fire rotation (e.g. Arno and Peterson 1983, Johnson and Gutsell 1994, Baker and Ehle 2001). However, ecological understanding of the effects of past fires requires a much more comprehensive description of a fire regime including spatial pattern, severity, effects on tree demography, and interactions with other disturbances (Table 2). For modern fires a wide variety of techniques and data sources (e.g. maps of the pre-burn vegetation, field sampling, remote sensing and monitoring) can be used to obtain comprehensive descriptions of the basic descriptors of fire events and their ecological effects. In retrospective studies of fire regimes, quantification of the descriptors is unlikely to be completely accurate.

Fire history in forested areas can be described quantitatively on the basis of two principal types of tree-ring evidence: dates of fire scars (fire-interval approach) or age of stands that presumably regenerated following stand-replacing fires (stand-origin approach). The fire-scar based approach usually provides annual (or even seasonal) resolution of the dating of past fire events but is limited in its ability to determine the spatial extent of past fires. . Two important limitations of the fire-scar based method that have long been recognized are the lack of scar evidence of some fires and the disappearance of fire-scar evidence due to death of trees such as in the case of more recent stand-replacing fires that destroy the evidence of fires (Arno and Sneck 1977, McBride 1983, Agee 1993). Because not all fires leave scars, fire-scar evidence should be regarded as an index of past fire occurrence rather than as the equivalent of past fire. Absence of the evidence (the fire scar) is not necessarily evidence of absence of the event (the fire). Furthermore, the locations of fire-scarred trees may not be representative of the unsampled landscape, and subjective (targeted) selection of sample trees may be a source of bias. Opinions vary widely about the importance of these limitations and how to best sample the landscape for fire-scarred trees (Johnson and Gutsell 1994, Swetnam and Baisan 1996, Lertzman et al. 1998, Baker and Ehle 2001).

In more mesic forests where crown fires are common and major episodes of tree establishment typically follow fire, fire history studies are based on the dating and mapping of stand origins (Johnson and Gutsell 1995). There are numerous potential sources of error in this approach as well. These include the difficulty of identifying the oldest trees in post-fire cohorts and of precisely determining tree germination dates (Kipfmueller and Baker 1998). The occurrence of time lags of variable duration between the fire event and tree establishment may be a major source of error in dating fires, particularly if fire scars do not clearly narrow done the range of possible dates. Recognition of post-fire cohorts is sometimes difficult when multiple less severe burns have affected the same patch. In some cases it may be difficult to distinguish between post-fire cohorts and tree establishment following other disturbances (blowdown, insect outbreaks) or the influences of climatic variation on tree demography. One of the most intractable problems is the “overburn problem”. The stand-origin method is based on the observation that fires are stand-replacing which means that part or all of the evidence of previous fires may be destroyed by more recent burns. The determination of areas burned by previous fires is imprecise because decisions must be made about how to draw the perimeters of earlier fires based on often extremely fragmentary evidence or subjective estimates of past fire spread. The difficulty of determining past fire perimeters varies widely from event to event. The most common summary statistic used in stand-origin studies is fire rotation, which is the time required to burn the entire study area (Romme 1980). Since fire rotation requires accurate measurement of past fire areas, the rotation statistic may be seriously inaccurate.

Fire regime researchers take many measures to assure that they properly recognize the field evidence of past fires, sample them effectively, and interpret them appropriately. Nevertheless, in most fire regime studies there is uncertainty about the accuracy and completeness of the fire regime reconstruction. Furthermore, there is substantial difference of opinion about the appropriateness and utility of different summary statistics of fire regimes (Johnson and Gutsell 1994, Swetnam and Baisan 1996 Huggard and Arsenault 1999, Minnich et al. 2000, Baker and Ehle 2001). In the current volume, Falk and Swetnam (2002) explore the spatial scaling dependency of fire frequency distributions with the aim of developing scaling rules for high frequency fire regimes. Baker and Ehle (2002) examine some of the uncertainties of estimating mean fire intervals in ponderosa pine ecosystems, and conclude that past studies have over-estimated fire occurrence in these systems. MacLean and Cleland (2002) demonstrate the application of geostatistical procedures to historical land survey data to better estimate the spatial extent of fires from surveyors' notes.

Given the limitations of both fire-scar and stand-origin methods of describing fire regimes, and the uncertainty that either improved sampling procedures or analytical techniques can remedy these problems, I propose some recommendations to fire regime researchers:

1. *Clarify objectives and assess reliability of methods.* For example, a fire history study based solely on fire-scar data can produce valid and useful analyses of temporal trends of fire occurrence in relation to land use or climatic variation, but will usually not yield a comprehensive description of the fire regime. If the goal is to assess past fire severity and effects on tree demography, then evidence of tree age population structures, tree mortality, and/or tree growth releases are also necessary.

2. *Use multiple lines of evidence to interpret past fire regimes*. Evidence of past fires should be collected from as many different sources as possible. Whenever feasible tree-ring evidence should be complemented by written sources (e.g. General Land Office surveys and other landscape descriptions) and historical photographs.

3. *Researchers should present their reconstructions of past fire regimes and stand conditions as estimates.* Particularly due to the problem of disappearing evidence it is unlikely that all fires will be recorded over time periods of many centuries. This is less of a problem in fire regimes of exclusively non-lethal surface fires, but is a major problem in mixed-severity and crown fire systems due to destruction of evidence by the more recent stand-replacing fires.

4. *Researchers should not overemphasize summary statistics such as mean fire intervals or fire rotation.* Mean fire intervals (both composite and individual tree intervals) have an uncertain ecological meaning. To place too much emphasis on the statistical significance of differences in mean fire intervals is dangerous because of the probable inaccuracy of recording all fire events. Likewise, fire rotation is unlikely to be measured accurately because of the difficulty of measuring the perimeters of past fires from either fire scars or from the fragments of post-fire cohorts that may have survived more recent fires.

5. *Researchers need to report full descriptive data and ranges of estimated parameters to the*

resource management community. Restrictions on publication space in peer-reviewed journals often allow presentation of only concise summary statistics to describe fire regimes. Researchers should make available to managers full descriptions of the unreduced data sets. For example, reports should include full fire history charts including all sample trees rather than composite lines that summarize the data from numerous trees. Likewise, reports should include complete stand-origin maps and detailed accounts of the procedures used for reconstructing the perimeters of past fires. Ranges of parameters should be given based on alternative interpretations of the accuracy and precision of the data.

For managers concerned with ecological restoration I make the following recommendations about using the results of fire regime studies:

1. *Do not adopt summary statistics such as the mean fire interval as management goals.* These are rarely accurate enough to justify mimicking them, and in addition, changes in other variables (e.g. climate, herbivores, invasive plant species) may make them inappropriate as management prescriptions. Instead of attempting to mimic a potentially inaccurate summary statistic of a fire regime, managers should consider multiple lines of evidence that indicate clear trends or trajectories in fire occurrence and ecosystem conditions.

2. *Define goals in terms of ranges of desired vegetation conditions*. Precise and accurate descriptors of the vegetation conditions are unlikely to be obtained, and managing for a broader range of conditions builds some buffering into the management plan. In most cases, greater heterogeneity resulting from a range of management prescriptions is likely to contribute to management success.

3. *Require area-specific data and analyses to support management decisions.* Studies conducted elsewhere rarely yield results or a model of fire regime and past stand conditions that can be uncritically applied to an unstudied situation. This is true even for the same forest cover type. Thus, the findings from studies done off site may at best be used as insights into the formulation of hypotheses to be tested by data collection and analysis in new study areas or management units.

4. *Use adaptive management and monitoring to assess management success.* Current knowledge of ecosystem dynamics is incomplete and may change in ways that are important for the goals of ecological restoration. Management goals and strategies should be regarded as hypotheses to be tested by future research and monitoring (Christensen et al. 1996). This requires continued communication between managers and researchers. Managers need to be able to adapt to inevitable surprises and trends, such as unpredicted diseases and forest pest

outbreaks as well as climatic variation. Adaptability and accountability require that a high funding priority be given to monitoring programs that compare expected outcomes with objective measures of results.

CONCLUSIONS

This essay was written to introduce some of the key limitations and issues in fire regime research in the context of wildfire hazard management and ecological restoration. One of the principal messages is that broad generalizations and premises need to be carefully examined for particular ecosystems and management objectives. The goal of the essay has not been to challenge the widespread consensus that fire exclusion has had undesirable consequences in many western forest ecosystems. Rather, it is hoped that critical evaluation of the premises of the fire exclusion/fuel buildup viewpoint for particular ecosystem types and areas will help to avoid inappropriate or ineffective management strategies. Forest ecosystem types with demonstrated historic fire regimes of frequent surface fires and fuel buildup during the fire exclusion period should be targeted for ecological restoration, which may also converge with reduction of fire hazard to property and humans. In contrast, in forest ecosystems characterized by historic fire regimes with long intervals between stand-replacing fires, attempts to create new fire regimes of frequent surface fires are inconsistent with ecological restoration.

As implied by the subtitle of the Conference, fuels management and ecological restoration need to be attentive to “proper place” and “appropriate time.” Fire regime research can inform management decisions about the proper place and time for fuels management and restoration of fire to ecosystems. Fire regime research has and continues to inform management decisions in useful and important ways, but the quantity and quality of this research needs to be improved. Clearly there is a need for greater involvement of fire regime researchers in the early phases of project planning and continued communication between researchers and managers in the monitoring phases of restoration and fire mitigation projects.

ACKNOWLEGMENTS

For discussion and comments on a draft of the manuscript I thank Karen Eisenhart, Dominik Kulakowski, Rosemary Sherriff, and Jason Sibold.

LITERATURE CITED

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C.

Arno, S.F., and K.M. Sneck. 1977. A method for determining fire history in coniferous forests of the mountain west. U.S. Department of Agriculture Forest Service General Technical Report **INT-42**.

Arno, S.F. and T.D. Peterson. 1983. Variation in estimates of fire intervals: a closer look at fire history on the Bitterroot National Forest. USDA Forest Service Research Paper INT-301.

Baker, W.L. and D. Ehle. 2001. Uncertainty in surface-fire history: The case of ponderosa pine forests in the Western United States. Canadian Journal of Forest Research 31: 1205-1226.

Baker, W.L. and D. Ehle. 2002. Uncertainty in surface-fire history and restoration of ponderosa pine forests in the western United States. This volume.

Baker, W.L. and T.T. Veblen 1990. Spruce beetles and fires in the nineteenth century subalpine forests of western Colorado. Arctic and Alpine Research **22**:65-80.

Brown, P.M., M.R. Kaufmann, and W.D. Shepperd. 1999. Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. Landscape Ecology **14**:513-532.

Christensen, N.L., A.M. Bartuska, J.H. Brown, S. Carpenter, C. D'Antonio, R. Francis, J.F. Franklin, J.A. MacMahon, R.F. Noss, D.J. Parsons, C.H. Peterson, M.G. Turner, and R.G. Woodmansee. 1996. The report of the Ecological Society of America committee on the scientific basis for ecosystem management. Ecological Applications **6**:665-691.

City of Boulder. 1999. Forest ecosystem management plan, Open Space and Mountain Parks. City of Boulder, Colorado.

Covington, W.W. 2000. Helping western forests heal: the prognosis is poor for US forest ecosystems. Nature 408:135-136.

Covington, W.W., and M.M. Moore. 1994. Southwestern ponderosa forest structure: changes since Euro-American settlement. Journal of Forestry **92**:39-47.

Denevan, W.M. 1992. The native population of the Americas in 1492. 2nd edition. University of Wisconsin Press, Madison, Wisconsin.

Donnegan, J. and A.J. Rebertus. 1999. Rates of succession and mechanisms of subalpine forest succession along an environmental gradient. Ecology **80**: 1370-1384.

Donnegan, J., T.T. Veblen, and J.S. Sibold. 2001. Climatic and human influences on fire history in Pike National Forest, central Colorado. Canadian Journal of Forest Research 31: 1526-1539.

Ehle, D.S. 2001. Spatial and temporal patterns of disturbance and ponderosa pine forest structure in Rocky Mountain National Park. Masters Thesis, University of Wyoming, Laramie, Wyoming.

Fulé, P.Z., W.W. Covington and M.M. Moore. 1997. Determining reference conditions for ecosystem management of Southwestern pondersosa pine forests. Ecological Applications **7**:895-908.

Fulé, P.Z., W.W. Covington, M.M. Moore, T.A. Heinlein, and A.E.M. Waltz. 2002. Natural variability in forests of the Grand Canyon, USA. Journal of Biogeography 29:31-47.

Goldblum, D. and T.T. Veblen. 1992. Fire history of a ponderosa pine/Douglas-fir forest in the Colorado Front Range. Physical Geography **13**:133-148.

Grissino-Mayer, H.D. and T.W. Swetnam. 2000. Century-scale climae forcing of fire regimes in the American Southwest. Holocene 10: 213-220.

Hadley, K.S. and T.T. Veblen. 1993. Stand response to western spruce budworm and Douglas-fir bark beetle outbreaks, Colorado Front Range. Canadian Journal of Forest Research **23**:479-491.

Huckaby, L.S., M.R. Kaufmann, J.M. Stoker, P.J. Fornwalt. 2001. Landscape patterns of montane forest age structure relative to fire history at Cheesman Lake in the Colorado Front Range. Pages 19-27 in: R.K. Vance, W.W. Covington, C.B. Edminster, and J.A. Blake (technical coordinators). Ponderosa pine ecosystems restoration and conservation: steps toward stewardship, 2000 April 25-27, Flagstaff, AZ. Proceedings RMRS-P-22. Fort Collins, CO: USDA Forest Service.

Huggard, D.J. and A. Arsenault. 1999. Comment—Reverse cumulative standing age distributions in fire-frequency analysis. Canadian Journal for Forest Research 2:1449-1456.

Johnson, E. A. and S. L. Gutsell. 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research **25**:239-287.

Johnson, E.A., K. Miyanishi, and S.R.J. Bridge. 2001. Wildfire regime in the boreal forest and the idea of suppression and fuel buildup. Conservation Biology 15: 1554-1557.

Kaufmann, M.R., C.M. Regan, and P.M. Brown. 2000. Heterogeneity in ponderosa pine/Douglas-fir forests: Age and size structure in unlogged and logged landscapes of central Colorado. Canadian Journal of Forest Research. 30:698-711.

Kaufmann, M.R., P.J. Fornwalt, L.S. Huckaby, and J.M. Stoker. 2001. Cheesman Lake– A historical ponderosa pine landscape guiding restoration in the South Platte watershed of the Colorado Front Range. Pages xxxx in: R.K. Vance, W.W. Covington, C.B. Edminster, and J.A. Blake (technical coordinators). Ponderosa pine ecosystems restoration and conservation: steps toward stewardship, 2000 April 25-27, Flagstaff, AZ. Proceedings RMRS-P-22. Fort Collins, CO: USDA Forest Service.

Kaye, M. and T.W. Swetnam. 1999. An assessment of fire, climate and Apache history in the Sacramento Mountains, New Mexico. Physical Geography 20:305-330.

Keeley, J.E. and C.J. Fotheringham. 2001. Historic fire regime in southern California shrublands. Conservation Biology 15: 1536-1548.

Kipfmueller, K.F. and W.L. Baker. 1998. A comparison of three techniques to date stand-replacing fires in lodgepole pine forests. Forest Ecology and Management **104**: 171-177.

Kitzberger, T., T.W. Swetnam, and T.T. Veblen. 2001. Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation. Global Ecology and Biogeography 10: 315-326.

Kulakowski, D. 2002. Interactions among natural disturbances in subalpine forests in northwestern Colorado. Ph.D. dissertation. University of Colorado, Boulder.

Lertzman, K., J. Fall and B. Dorner. 1998. Three kinds of heterogeneity in fire regimes: At the crossroads of fire history and landscape ecology. Northwest Science **72**:4-23.

Maclean, A.L., and D.T. Cleland. 2002. The use of geostatistics to determine the spatial extent of historical fires as an aid in understanding fire regimes for northern lower Michigan. This volume.

Mast, J.N., T.T. Veblen and Y.B. Linhart. 1998. Disturbance and climatic influences on age structure of ponderosa pine at the pine/grassland ecotone, Colorado Front Range. Journal of Biogeography **25**:743-767.

McBride, J.R. 1983. Analysis of tree rings and fire scars to establish fire history. Tree Ring Bulletin **43**:51-67.

Menakis, J.P., D. Osborne, and M. Miller. 2002. Mapping departure from historic natural fire regimes caused by cheatgrass in the Great Basin. This volume.

Minnich, R.A., M.G. Barbour, J.H. Bruk, and J. Sosa-Ramírez. 2000. Californian mixed-conifer forests under unmanaged fire regimes in the Sierra San Pedro Mártir, Baja California, Mexico. Journal of Biogeography 27:105-129.

Moore, M.M., W.W. Covington, and P.Z. Fulé. 1999. Reference conditions and ecological restoration: a southwestern ponderosa pine perspective. Ecological Applications 9: 1266-1277.

Romme, W.H. 1980. Fire history terminology: report of the Ad Hoc Committee. Pages 135-37 *in* M.A. Stokes and J.H. Dieterich, editors. Proceedings of the fire history workshop, Oct. 20-24, 1980. Tucson, Arizona. U.S. Department of Agriculture Forest Service, General Technical Report **RM-81**.

Romme, W.H., M.L. Floyd-Hanna, D.D. Hanna, and P. Kemp. 2002. Experimental thinning and burning of ponderosa pine forests in southwestern Colorado: effects on canopy structure, understory composition, and fuels. This volume.

Sherriff, R., T.T. Veblen, and J.S. Sibold. 2001. Fire history in high elevation subalpine forests in the Colorado Front Range. Ecoscience. 8:369-380.

Shinneman, D.J. and W.L. Baker. 1997. Nonequilibrium dynamics between catastrophic disturbances and old-growth forests in ponderosa pine landscapes of the the Black Hills. Conservation Biology **11**:1276-1288.

Sibold, J. 2001. The forest fire regime of an upper montane and subalpine forest, Wild Basin, Rocky Mountain National Park. Masters Thesis, University of Colorado, Boulder, CO.

Swetnam, T.W. and J.L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal variability in the American Southwest. Journal of Climate **11**:3128-3147.

Swetnam, T.W., C.D. Allen, and J.L. Betancourt. 1999. Applied historical ecology: Using the past to manage for the future. Ecological Applications **9**:1189-1206.

Vale, T.R. 2002. Fire, native peoples, and the natural landscape. Island Press, Washington, D.C.

Veblen, T.T. 2000. Disturbance patterns in southern Rocky Mountain forests. Pages 31-54 *in* R.L. Knight, F.W. Smith, S.W. Buskirk, W.H. Romme and W.L. Baker, editors, Forest fragmentation in the Southern Rocky Mountains. Colorado University Press, Boulder, Colorado.

Veblen, T.T., K.S. Hadley, M.S. Reid, and A.J. Rebertus. 1991. Stand response to spruce beetle outbreak in Colorado subalpine forests. Ecology **72**: 213-231.

Veblen, T.T. and T. Kitzberger. In press. Inter-hemispheric comparison of fire history: The Colorado Front Range, U.S.A. and the Northern Patagonian Andes, Argentina. Plant Ecology.

Veblen, T.T., T. Kitzberger and J. Donnegan. 1996. Fire ecology in the wildland/urban interface of Boulder County. Unpublished report to the City of Boulder Open Space Department, Boulder, Colorado.

Veblen, T.T., T. Kitzberger and J. Donnegan. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. Ecological Applications 10:1178-1195.

Veblen, T.T. and D.C. Lorenz. 1986. Anthropogenic disturbance and recovery patterns in montane forests, Colorado Front Range. Physical Geography **7**:1-24.

Veblen, T.T. and D.C. Lorenz. 1991. The Colorado Front Range: a century of ecological change. University of Utah Press, Salt Lake City, Utah.

Table 1. Examples of some of the premises of the fire exclusion/fuel build up viewpoint and possible area-specific research questions.

Major Premises	**Possible research questions to be examined for particular areas**
Fire exclusion has created unnatural fuel buildup.	Do modern fire regimes differ greatly from historic fire regimes? Is there clear evidence of disruption of formerly frequent fires following EuroAmerican settlement?
Severe, widespread fires are due to unnatural fuel buildup after decades of fire exclusion.	Did large, crown fire events occur prior to any effects of fire exclusion?
Elimination of formerly frequent surface fires has created dense stands in the modern landscape.	What was the historic range of tree densities prior to effects of fire exclusion? What other explanations might account for dense stands today, such as stand responses to logging or abundant burning in the late 19th century?
Recent years of widespread, severe fires (e.g. the 2000 fire season) are due primarily to the effects of fire exclusion rather than climatic variation.	Did historic fire regimes include fire events similar to those of the 2000 fire season? Has recent climatic variation contributed to any recent increases in fire frequency or severity? Has climatic variation in the past resulted in fires of similar extent and severity to recent fires?
Current levels of pathogen and insect outbreaks are unnatural and are the consequence of fire exclusion.	What was the range of pathogen and insect outbreaks prior to fire exclusion?

Table 2. Some basic descriptors of fire regimes of potential use in historic fire regime studies.

Descriptor	Definition and comments
Fire frequency	This is the number of fires per unit time in some designated area (Romme 1980).
Fire area	The surface area burned by each fire. Spatial variability of severity within the burn perimeter is often difficult to determine in retrospective studies, especially those based primarily on fire scars. Often perimeters are assigned to fire areas even though it is known that some unknown amount of the area within the perimeter did not burn.
Fire spatial pattern	This is a description of the spatial pattern of the area burned in relation to the spatial heterogeneity of the abiotic (slope, aspect, elevation) and biotic environment (species composition, stand structure, stand age).
Severity	Severity is usually measured as the amount of damage done by the fire (e.g. tree basal area killed, height of scorching) but in some situations responses to the post-fire environment may indicate severity (e.g. tree-growth releases, amount of post-fire tree establishment, sedimentary records of hydrological and depositional changes).
Fire effects on tree demography	This includes changes in tree establishment or mortality rates that can be linked to the fire.
Interactions with other disturbances	This includes the timing and severity of other disturbance events such as insect outbreaks, pathogen attacks, and wind throw that may either influence or be influenced by the fire event.