Restoring Natural Fire Regimes to the Sierra Nevada in an Era of Global Change

Jon E. Keeley
Nathan L. Stephenson

Abstract—A conceptual model of fire and forest restoration and maintenance is presented. The process must begin with clearly articulated goals and depends upon derivation of science-driven models that describe the natural or desired conditions. Evaluating the extent to which contemporary landscapes depart from the model is a prerequisite to determining the need for restoration. Model landscapes that include the historical range of variability are commonly used as target conditions in setting restoration objectives. Restoration is a corrective step that ultimately must be replaced by a maintenance process. In a world of changing climate, structural targets of historical conditions will become progressively less meaningful to ecosystem maintenance. Future fire management needs to focus more on fire as a process, in particular as it pertains to proper ecosystem functioning. One area in need of much further research is the critical role of gap formation in forest regeneration.

Forests of the Sierra Nevada in California, like other western coniferous forests, have had ecosystem processes greatly disturbed by fire management practices of the 20th century. This impact has been repeatedly documented through historical studies of fire frequencies revealed in the annual growth rings of fire-scarred trees. These dendrochronology studies show a high frequency of fire prior to Euroamerican settlement, with fires in many mid-elevation forest stands occurring at intervals of roughly every 5–25 years (fig. 1). The fact that these estimates are based upon trees that have persisted through repeated fires demonstrates that the pre-Euroamerican fire regime was one of low intensity/severity fires over a significant portion of the landscape. Beginning in the latter half of the 19th century, fire frequency declined and throughout the 20th century, fires have been largely excluded from these forests (fig. 1). This is in striking contrast to other Californian ecosystems such as lower elevation shrublands, where suppression has not diminished fire on the landscape (Keeley and others 1999).

Several factors contribute to highly successful fire exclusion in coniferous forests. Surface fuels are often separated from canopy fuels, reducing the tendency for crown fires (Kilgore and Sando 1975), and making fire suppression easier. Also, the fire season is moderately short, generally restricted to a period of three to four months plus humans contribute less to fire ignitions than lightning (Parsons 1981), which is confined to weather patterns often conducive to rapid fire suppression.

Fire exclusion has perturbed forest structure in several critical ways. It has allowed woody fuels and duff to accumulate to unnaturally high levels, it has greatly reduced the size and frequency of gaps necessary for regeneration of certain dominant trees, and it has apparently led to an alteration of forest age structure (GAO 1999; Stephenson 1999). These changes have created two potential problems: Fire hazard has been greatly increased, and forest ecosystem elements and processes have been altered in ways that may represent artifacts of human interference.

In response to these problems, over 30 years ago Sequoia and Kings Canyon national parks initiated a program aimed at restoring fire to these ecosystems, through prescribed burning (for example, the 1969 fire in fig. 1) and other fire management policies (Botti and Nichols 1979; Bancroft and others 1985; Graber 1985; Parsons 1990; Parsons and van Wagtendonk 1996). The purpose of this paper is to articulate the steps necessary to restoring fire to these ecosystems and to contrast this approach to the needs for sustainable management into the future.

Model of Forest Restoration and Maintenance

A conceptual model of fire restoration goals and objectives was presented by Parsons and others (1985) and more recently elaborated upon at a recent National Park Service workshop (fig. 2). This decision tree in figure 2 is an attempt to more clearly articulate the goals and methodology in restoration of Sierran forests. Each stage is elaborated upon below, but in brief; this process begins with precise goals and the derivation of science-driven models describing the structural and functional attributes of landscapes and ecosystems that meet those goals. Scientists and resource managers then work cooperatively to evaluate the extent to which contemporary conditions approximate the model. The conclusion for much of the Sierra Nevada landscape is that, due to nearly a century of fire exclusion, restoration is a necessary management response. An important part of having a model landscape is that it provides a clear target for restoration efforts, particularly in the setting of objectives. Afterwards, evaluation of restoration efforts is critical and requires careful monitoring, which may point out shortcomings in the restoration execution, or in the setting of target conditions or even in the formulation of the model landscape.

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Jon E. Keeley is Station Leader, U.S. Geological Survey, Biological Resources Division, Sequoia-Kings Canyon, Three Rivers, CA 93271-9651 U.S.A. Nathan L. Stephenson is Research Ecologist, U.S. Geological Survey, Biological Resources Division, Sequoia-Kings Canyon, Three Rivers, CA 93271-9651 U.S.A.

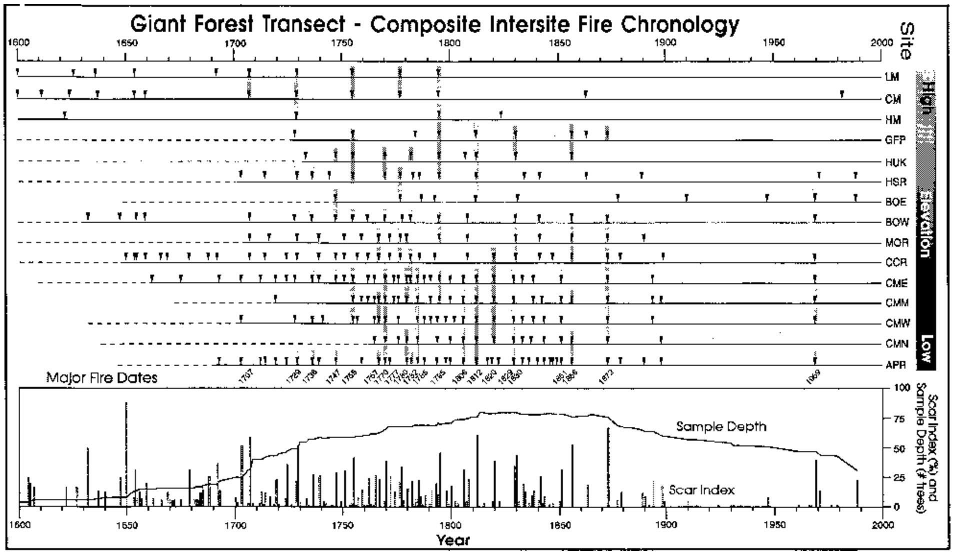

Figure 1—Example of fire scar dendrochronology data used to calculate fire return intervals—composite site fire chronology for 15 sites and 91 samples (76 logs/snags and 15 trees) in the Kaweah Drainage, Sequoia National Park (from Caprio and Swetnam 1995). Triangles indicate fire scars and each horizonatal line is a composite of all fires recorded by two or more trees at a site (0.5-2 ha). Dashed lines reflect the interval prior to first fire scar.

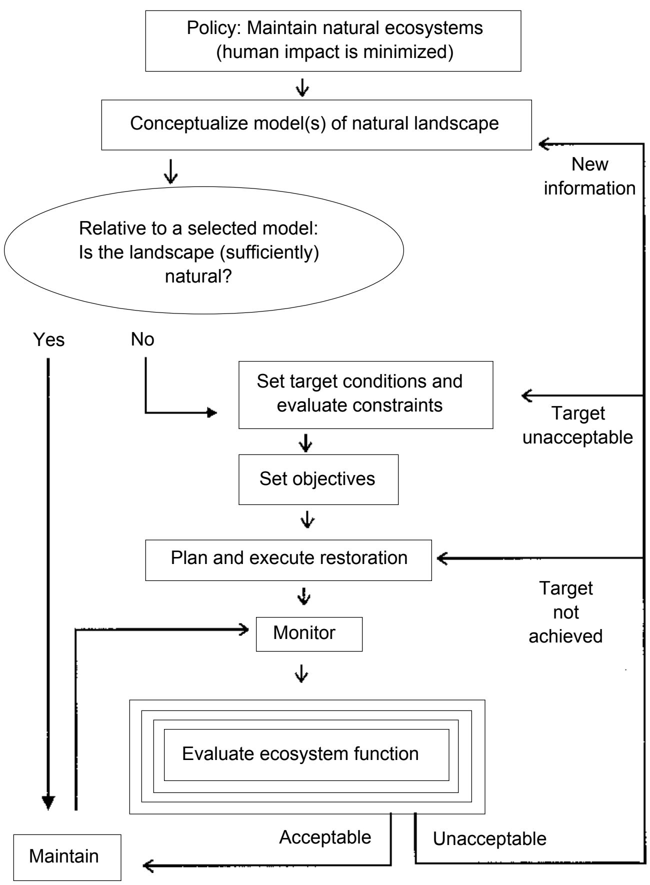

Figure 2—Decision tree diagram for implementing restoration and maintenance of fire in National Park ecosystems, based on collective efforts of the "Fire Management Objectives Workshop," Rancho Cordova, CA; 3-6 November 1998.

Ultimately, it is expected that restoration is an interim process, one that leads to maintenance of the desired condition.

Step 1: Goals

An important National Park Service goal (fig. 2) is to restore and maintain natural ecosystems (NPS 1988; Wagner and Kay 1993). This is complicated by differences of opinion on defining "natural" (for example, Kilgore 1985) and, even within agencies such as the National Park Service there is a lack of consistency in how the term is defined (Bancroft and others 1985). We maintain that the underlying feature connecting most definitions of natural is a lack of human influence, for example, areas that allow "the unimpeded [by humans] interaction of native ecosystem processes and structural elements" (Parsons and others 1985). Some argue that no part of the landscape is truly natural because humans have at least indirectly affected all parts of the biosphere (for example, Shrader-Frechette and McCoy 1995). We do not dispute this, but in a relative sense there are regions that are less affected than others are. Therefore, ***natural is defined here as environments where human impacts are minimized***. This is, of course, relative to one's frame of reference, and thus a natural environment to an urbanite may be far too heavily affected by humans to be considered natural to a person steeped in the wilderness experience. One advantage of replacing a qualitative notion of naturalness with such a quantitative concept is that a level of naturalness can be empirically determined. One caveat relevant to the goal of minimizing human impact is the realization that *achieving this goal* often requires human intervention, particularly when restoration of perturbed ecosystems is necessary (Hunter 1996).

Step 2: Models of Natural Landscapes

A necessary first step to forest restoration is to conceptualize models of what we believe a natural landscape should look like and how it should function (fig. 2). This is the step that is most dependent on input from scientific research. In the case of Sierra Nevada ecosystems, we have a substantial body of information to draw upon (SNEP 1996). The results from numerous studies show that mid-elevation Sierra Nevada forests are currently experiencing fire-free periods many times longer than at anytime in the past 2000 years (Swetnam 1993).

It appears that fire exclusion has altered the structure and composition of mid-elevation forests (Stephenson 1999), and knowledge of these changes will be valuable in creating a conceptual model of natural Sierran forests. Ideally, a model of such forests would be derived from empirical studies of forest structure under natural fire regimes. Isolated examples of forests that have been allowed over the past three decades to return to some semblance of a natural fire regime exist in the Sierra Nevada (such as Sugarloaf Valley in Kings Canyon National Park or Illilouette Basin in Yosemite National Park [NPS fire records]). Study of these forests could provide a valuable model of natural forest structure and function. One limitation to this approach is the possibility that decades of fire exclusion have so altered forest structure that when the natural process of fire is allowed to return, it will not restore the natural forest structure and composition (Bonnicksen and Stone 1985). In other words, fire regimes are a deterministic process, solely controlled by fuel load distribution—once this has been altered, the system cannot return to its natural state unless the natural fuel structure is first recreated. Alternatively, the fire regime is driven by a combination of factors, including fuels, weather and topography that vary spatially and temporally, producing multiple possible stable points (Christensen 1991a), and making it more likely that returning the process of fire is sufficient to recreate a semblance of natural forest conditions (Stephenson 1999). If this latter view is more or less correct, studies of areas subjected to quasi-natural fire regimes will ultimately provide far more information on the multitude of ecosystem components needed for true ecosystem restoration than will any alternative method of reconstructing past forests.

Other approaches have focused on reconstructions of forest dominants by comparative studies of historical photographs and written descriptions, as well as inferences drawn from contemporary forest demographics (Skinner 1997; Stephenson 1999; Swetnam and others 1999). These reconstructions provide a view of late 19th century forests that are termed the "pre-Euroamerican" condition and are commonly used as targets for restoration. One rationale for embracing this typological approach to forest restoration is that such conditions "portray to the extent feasible, either the same scene that was observed by the first Euroamerican visitor to the area or the scene that would have existed today, or at some time in the future, if Euroamerican settlers had not interfered with natural processes" (Bonnicksen and Stone 1985). This of course is debatable.

A variety of observations suggest that past forests had lower tree density, and very different demographic distribution of age classes, with limited accumulation of forest floor fuels and greater landscape diversity of forest patches than 20th century forests (Vankat and Major 1978; Parsons and DeBenedetti 1979; Bonnicksen and Stone 1982; Vale 1987; Roy and Vankat 1999; Ansley and Battles 1998; Stephenson 1999). In order to be empirically useful, pre-Euroamerican models need to be made explicit for specific landscapes, and specifying, at least in a probabilistic sense, the proportion of landscape dominated by different forest types and forest structures (Christensen 1991a; Taylor and Skinner 1998). For much of the Sierra Nevada we lack sufficient knowledge for anything other than rather general projections. Lastly, it is a reasonable inference that, concomitant with structural changes in forests, there have been changes in important ecosystem functions but we have little direct information on processes other than fire.

In summary, fire regimes are the best understood component of the pre-Euroamerican landscape (for example, fig. 1) (Swetnam 1993; Caprio and Swetnam 1995; Swetnam and others 1998), although it is unknown to what extent Native Americans contributed to this fire regime and the debate still continues as to whether we should consider their fires as natural. Far less is known about the forest structure and landscape patterns present at the time of Euroamerican settlement, and the reconstructions that have been made deal only with a few dominant tree species. While such reconstructions are the closest we have to a forest model of natural conditions, most are based on late 19th century landscapes and the influence of Euroamerican settlers present in significant numbers since the mid 1800s has not been adequately considered (Barrett 1935; Cermak and Lague 1993). In the Sierra Nevada, fire frequencies generally declined during the settlement period (for example, fig. 1), prior to the era of organized fire suppression. This decline has been attributed to either diminished ignition sources following the demise of Native American populations (Keeley 1981) or to the reduction in fuels attributable to the rise in livestock grazing (Swetnam and others 1998). Further declines in fire frequency have occurred in the 20th century (for example, fig. 1) and this, as well as apparent changes in forest structure and function are thought to be primarily due to fire suppression, however, it remains to be seen how much of this change might be attributable to warmer, moister conditions of the 20th century (Graumlich 1993; Scuderi 1993).

Of course limitations such as these should not prevent us from applying this model, but they do caution against unequivocal acceptance of pre-Euroamerican models as definitive statements on the natural range of conditions.

Step 3: Evaluating Contemporary Landscapes

Considering the ecosystem process of fire, the contemporary landscape clearly exhibits substantial deviation from that expected of natural landscapes (for example, fig. 1). Also, there is widespread agreement that contemporary forest structure (for example, Table 1) deviates from natural conditions. In evaluating contemporary landscapes it is necessary to evaluate the situation from the perspective of whether these landscapes are "sufficiently natural" for resource management purposes. In many people's minds this

Table 1—Aspects of forest structure and fire regime considered in evaluating contemporary landscapes restoration needs.

Structure	Fire regime
Composition	Return interval
Density	Season
Age distribution	Size
Patch size	Intensity/severity
Patch frequency	Gap size
Potential fuels	Gap distribution

means within the range of historical variability (for example, Morgan and others 1994; Millar 1997; Stephenson 1999). However, constraints such as our ability to restore natural processes, need to be considered. In addition, the range of "natural variability" may not include all ecosystem components considered important by stakeholders.

Christensen (1991b) cautions that "successful policies will have three common characteristics: (1) clearly stated operational goals, (2) identification of potential constraints, and (3) recognition of the variability and complexity of the successional process." While resource managers may have clearly stated operational goals, scientists are some way from fully understanding the complexity of forest structure and function and how past management activities may constrain future successional responses.

Steps 4, 5, and 6: Targets and Objectives in Restoration

For much of the Sierra Nevada, forests do not meet our criteria of pre-Euroamerican conditions in terms of both structure and process (Table 1), and thus are candidates for restoration (SNEP 1996). There is widespread agreement that restoring fire to Sierran forests should focus on the "pre-Euroamerican condition" as the appropriate restoration target, a perspective consistent with the 1963 "Leopold Report" (Leopold and others 1963) guideline for reducing contemporary human impacts and restoring pre-Euroamerican conditions. The pre-Euroamerican condition model is not without criticism, as is often the case with such typological restoration targets (Noss 1985; Pickett and Parker 1994). While selecting the pre-Euroamerican time period as the appropriate target can be debated, it at least provides conditions for which we have some hope of emulating. In general, there is much more agreement on the use of this target condition than on techniques of restoring this target condition. Disagreement centers largely over whether restoring the process of fire is sufficient when forest structure may have been altered by decades of fire exclusion (Stephenson 1999). Currently these matters are being addressed in the USDA/USDI Joint Fire Science Program (http://ffs.psw.fs.fed.us/), which will study the ecological impacts of forest fuel reduction alone and in combination with structural manipulation.

In addition to a clear articulation of target conditions, successful restoration requires a careful evaluation of constraints, and development of a proposal with obtainable objectives.

Steps 7 and 8: Monitoring and Evaluating Ecosystem Function

Monitoring is a critically important part of the restoration process and provides the input necessary to evaluate ecosystem functioning (Keifer and Stanzler 1995; Keifer 1998; Keifer and others 2000a; Mutch and Parsons 1998; Haase and Sackett 1998). Many ecological, sociological, and political considerations will influence the decision regarding the acceptability of ecosystem function. If ecosystem functioning is unacceptable there are several potential reasons. The restoration process may have been in error, either in the planning or execution. Correcting such problems often requires more technical expertise in restoration techniques. Another reason may be that the selection of target conditions was flawed, or constraints not adequately evaluated, such as the need to retain or restore certain target species. Even if programs are successful in restoring naturally functioning ecosystems, the results may not meet goals of some stakeholders. Solving these problems might require a reevaluation of goals, perhaps even placing naturalness at a lower level of priority (for example, Graber 1995). Lastly, new research may provide information that alters the model of natural landscapes (Step 2).

Step 9: Maintaining Natural Ecosystems

Restoration is a corrective step that, if successful, should be replaced by a maintenance process (fig. 2). Maintenance also requires constant monitoring and evaluation, but potentially involves different approaches than restoration.

Fire Management and Future Global Change

Vitousek and others (2000) have reviewed the evidence for anticipated changes in climate. Rapid increases in greenhouse gases are projected to alter both temperature and precipitation patterns. Coupled with anticipated increases in lightning (Price and Rind 1994) there is reason to expect future fire regimes will differ significantly from past fire regimes (Parsons 1991; Ryan 1991; Torn and Fried 1992) and changes will occur faster than ever observed in the past (Vitousek and others 2000). In light of anthropogenically induced climate changes, focusing upon model conditions of the 19th century may be like trying to hit a moving target. Or, as Peter Vitousek noted, "in a changing world we need to distrust baselines."

One could argue that anticipated climate changes are anthropogenic and therefore if the objective is to minimize human influence, then resource management goals should be directed at circumventing these climate changes. Not only would such an approach present intractable problems but it ignores the reality that even without human influences, there is no reason to assume environments of the 19th and 21st centuries would remain the same (for example, Anderson and Smith 1990; Swetnam 1993; Scuderi 1993; Graumlich 1993; Millar and Woolfenden 1999).

When anticipated climate changes are viewed in the context of other global changes, such as increasing population pressure and ecosystem fragmentation, 19th century typological models of the structural conditions expected from natural fire regimes will need to be replaced by models focused more on fire as a natural ecosystem process. This requires mathematical models that capture the dynamic interaction between ignition patterns, weather and fuels. Presently we lack models sufficient to make precise predictions of future fire regimes. Perhaps more important, however, is the observation that such models are commonly limited by the validity of their underlying assumptions (Loehle and LeBlanc 1996). In other words, before we can develop such models, we need a clearer mechanistic understanding of how these parameters have and will affect fire regimes, past, present, and future.

Role of Ignition Patterns in Determining Fire Regimes

Lightning is the sole natural source of ignition in these and in most other ecosystems (Show and Kotok 1924; van Wagtendonk 1986). There is debate in the literature as to whether or not Native American ignitions should be part of our model of a natural landscape and the debate illustrates the multitude of different considerations resource managers and scientists must consider (Table 2). Resolution of this argument is needed for more than merely satisfying academic curiosity as it affects both policy and science. If we agree that natural ecosystems have minimal human impacts, then there would be little reason for including Native American burning in our model of a natural landscape, but it may justifiably be included in models of cultural landscapes. Also, our perception of pre-Euroamerican forest structure and function is heavily influenced by fire scar records and these records are used in the setting of restoration targets. If Native American burning is not adequately ascertained, then we may be targeting cultural rather than natural landscapes. In cases where cultural landscapes are the desired condition, then teasing out the contribution of Native American burning from the fire scar record will provide information on the extent to which past burning patterns might be recreated by lightning alone, and thus the extent to which prescription burning subsidies will be needed.

Role of Weather and Fuels in Determining Fire Regimes

There is debate in the literature as to the relative importance of fuels and weather in driving fire regimes. On the one hand, fuels are considered to be of overriding importance in determining fire regimes. On the other hand prehistoric changes in fire regimes have been tied to climate (Edlund and Byrne 1991; Swetnam 1993) and contemporary fire regimes show a strong climatic signal in the southern Sierra Nevada (Chang 1999) as well as in other regions (Schroeder 1964). Future changes in weather are not known with any certainty but projections for Sierra Nevada forests suggest an increase in the annual window of opportunity for fire and potential for altered fire intensities (Parsons 1991). It is questionable to what extent resource managers will allow such changes to be expressed in future fire regimes. Indeed, presently fire managers allow fires to burn only under a subset of potential weather conditions, which probably do not capture the full range of natural variability.

Further complicating matters is the level of landscape development (such as roads and buildings) within otherwise largely natural landscapes. Such habitat fragmentation greatly affects fuel continuity and the capacity for lightning ignitions to burn landscapes in patterns that would be observed in the absence of such human interference. In addition, policies of total fire suppression on lands adjacent to natural areas will further limit the ability of lightning alone to recreate natural fire regimes in wilderness areas. These factors argue that “natural” fire regimes

Table 2—There is substantial evidence of Native American burning in the Sierra Nevada (Wickstrom 1987), but that information alone can not answer the question of whether or not Native American burning patterns should be included in restoration and maintenance of natural fire regimes.

Arguments for inclusion	Arguments for exclusion
(1) These ignitions were part of the pre-Euroamerican environment and therefore they fit the Leopold Report goals.	(1) Sustainable forest management can not focus indefinitely on Pre-Euroamerican forest conditions and the 1963 Leopold Report should be viewed only as an historically important stage in the evolution of park policy.
(2) Native Americans were “in tune” with their environment and managed landscapes in a responsible manner, unlike contemporary humans (Kilgore 1985), i.e., “open and parklike forests” are aesthetically more pleasing than “dog-hair thickets of white fir” (Graber 1995).	(2) Early Americans exploited their environment in a manner that was not qualitatively different from contemporary humans and given sufficient time they were capable of causing unwanted changes in their environments (e.g., Betancourt and van Devender 1981; Diamond 1986, 1996).
(3) Native Americans were a “natural” part of the landscape (Kilgore 1985).	(3) This Euro-centric perspective presumes the existence of unknown qualities that separate Native Americans from the rest of humanity (e.g., Callicott 2000). Restoring Native American burning is not ecological restoration but rather **cultural restoration**.
(4) These ignitions were not sufficient to alter burning caused by lightning alone and therefore inclusion is largely irrelevant (Swetnam et al. 1998; Stephenson 1999).	(4) Lightning ignitions alone were insufficient to account for fire scar records (Kilgore and Taylor 1979) or natural landscape patterns (Reynolds 1959) and therefore inclusion is highly relevant to how we interpret the past and manage the future.

will increasingly require human subsidy in the form of prescription burning (this justification for burning subsidy falls outside the criticism posed by Parsons and others (1985) against trying to emulate Native American burning). It is not logically inconsistent to use fire as a manipulative tool (for example, Johnson and Miyanishi 1995) for the purpose of restoring natural conditions, when the intent is to counterbalance other human impacts.

Recreating and Maintaining Natural Landscape Patterns

The natural range of variation in Sierran landscapes is a product of temporal and spatial changes in fire regime. Describing differences in fire regimes is often difficult because regimes are sometimes classified by the characteristics of the fire and sometimes by the effects produced by the fire (Brown 1995). Natural fire regimes in Sierran forests are often described as consisting of *understory* or *low intensity surface* fires, which contrasts with fires in other ecosystems, such as boreal forests or chaparral, that are typically *high intensity* or *stand-replacing* fires (fig. 3). Strictly speaking, low intensity surface fire regimes are more typical of savannas or open forests where fuels are largely herbaceous and such a regime does not adequately describe fire in mid-elevation Sierran forests (Keeley and Zedler 1998). Woody fuels, and their heterogeneous distribution in these forests, generate a mixture of low and high intensity burning. Commonly high intensity burning is restricted to individual trees or small clusters, but as Show and Kotok (1924) noted, "local crown fires may extend over a few hundred acres." Such high intensity fires in the past are suggested by dramatic growth releases in annual rings (Stephenson and others 1991; Mutch and Swetnam 1995). In addition to mortality from high intensity hot spots, surface fires also create gaps by causing mortality in younger age classes and vulnerable species such as *Abies concolor* (Kilgore 1973).

This mixture of surface burning and localized high intensity fires leads to a landscape mosaic of canopy gaps (fig. 3). Oftentimes this process is described as a "moderate" intensity burn, but that terminology fails to capture the action as much as describing a person who has fallen off a roof as having been, on average, midway between the roof and the ground. Agee (1995) describes such a fire regime as one "ranging from underburns, to significantly thinned stands, to stand-replacement [gaps]." The term *stand-thinning* fire regime perhaps best captures the pattern, and places appropriate emphasis on the importance of gap generation rather than fire intensity. This landscape gap pattern is critical to long term forest maintenance as many dominant trees depend upon such gaps for regeneration, which leads to quasi-even age forest patches (Show and Kotok 1924; Bonnicksen and Stone 1982, Stephenson and others 1991). The landscape mosaic of gap generated patches also likely has profound impacts on the distribution of wildlife.

Gap size varies spatially and temporally. Under a natural stand-thinning fire regime an individual fire may generate a significant number of small (single tree) gaps and a much smaller percentage of larger gaps. In order to scale up our models of natural conditions from forest stands to landscapes we need to make predictions about the expected distribution of gaps. For a natural Sierran landscape we hypothesize, with very limited data, a distribution of gap sizes distributed as depicted in figure 4. This may adequately describe past landscape patterns but following nearly a century of fire exclusion, we have altered the landscape by reducing the frequency and size of gaps (Skinner 1995). However, in the future gaps are likely to be larger due to unnatural fuel accumulation that is predicted to produce more high intensity stand-replacing fires (fig. 4). In short, heavy fuel accumulation and high intensity fires are not unnatural in Sierra Nevada forests but rather the spatial extent of high intensity fires was limited in the past, but now the potential size has increased. In more general terms, fire exclusion is moving the system from a fine scale to a coarse scale landscape.

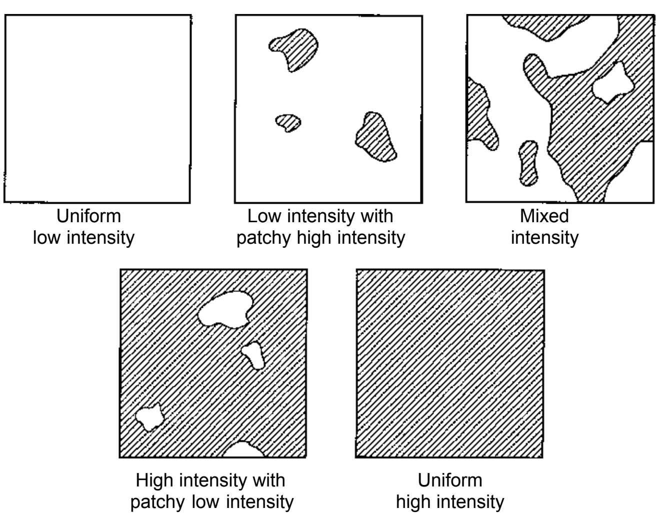

Figure 3—Range of variation of fire intensity patterns (from Stephenson and others 1991).

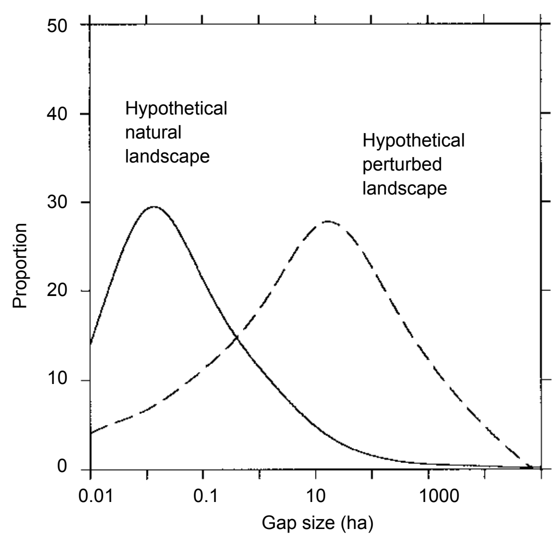

Figure 4—Hypothetical distribution of fire generated gaps (and subsequent forest patches) expected for natural Sierran landscapes and those perturbed by fire suppression.

Future Research Needs

In an era of many types of global change, sustainable wilderness management requires a clearer understanding of the natural range of variation in fire regimes and subsequent landscape mosaics (Morgan and others 1994; Millar 1997), plus an understanding of the resilience of these ecosystems to deviation from that range. In the southern Sierra Nevada, and elsewhere, fire scar dendrochronology has been extraordinarily valuable in recreating past landscapes (Swetnam 1993; Caprio and Swetnam 1995; Skinner and Chang 1996; Swetnam and others 1998). Much remains to be gleaned from this work, particularly in the determination of bounds on the natural range of variation in fire regime at both the landscape and community scales.

Making statistically valid inferences about landscape patterns of burning with fire scar dendrochronology data has limitations that need further exploration. These fire histories are not based upon random samples of the landscape, rather they, by necessity, focus on sites with fire scarred trees and possibly in densities higher than the landscape as a whole. The southern Sierra Nevada is an extraordinarily rugged mountain range and accessibility is certainly a factor in selection of sites, both for dendrochronoligists as well as Native Americans. Barrett and Arno (1982) have shown (in the Rocky Mountains) that study sites proximal to Native American settlements had a much higher incidence of burning than more distal sites. In the Sierra Nevada, one approach to validating inferences beyond local study sites might be a simple comparison of fire scarred tree density at sample sites with the density from random landscape samples.

In addition to the question of Native American burning, are questions related to the extrapolation of point data (individual fire scarred trees) to the spatial pattern of burning generated by composite samples (all fire scarred trees in a stand). Fire return intervals estimated from composite samples are usually much shorter than intervals recorded by individual trees. It is important to recognize that estimates drawn from composite samples carry with them certain assumptions about fire behavior. These need to be closely examined because composite estimates play a significant role in determining burning prescriptions in forest restoration plans (Keifer and others 2000b).

Some have suggested that point data should not be used to infer a spatial pattern to a fire because of the localized nature of many lightning ignited fires (Minnich and others, in press). However, dendrochronologists often restrict inferences about spatial patterns of burning to instances where widely scattered trees reveal scars from both the same year and season, thus strengthening the assumption that they constitute different points of a single widespread fire (Caprio and Swetnam 1995; Swetnam and others 1998). The failure of an individual fire scarred tree to record a fire, when it occurs within a circumscribed burned area, is generally attributed to the vagaries of scar formation— such trees are considered uninformative about that particular fire. It would be prudent, however, to consider the possibility that such trees may reflect intra-stand variation in burning. That is, fires may not burn uniformly through a stand and individuals may not scar because the fire skipped their particular patch (Dieterich 1980; Brown and others 1995). If so, this may alter the fire manager's perspective on the acceptable standards for evaluating prescription-burning patterns.

Knowledge of intra-stand variation in natural fire regimes will add to our ability to manage forests with the appropriate level of gap structure. Gaps are critical to the regeneration of certain species in Sierran forests, for example, *Pinus ponderosa* and *Sequoiadendron giganteum* (Kilgore and Biswell 1971; Mutch and Swetnam 1995; Keifer 1998; Stephens and others 1999). Gaps play two critical roles in the regeneration of these species – they provide a suitable site for seedling recruitment and, because of the absence of mature trees, fuels accumulate more slowly (fig. 5A). This increases the likelihood that fires burning in adjacent forests will skip—or burn incompletely—these regeneration sites for some period of time following patch initiation, thus promoting sapling survivorship (fig. 5B). Such a scenario is required for successful recruitment, since fires at a young age are commonly lethal to coniferous seedlings and young saplings (Swezy and Agee 1991; Regelbrugge and Conard 1993), and is predicted from simulation models of natural fire regimes (van Wagtendonk 1986).

Fire scar dendrochronology may provide some evidence of such intra-site variation in burning. It is a widespread custom in fire scar dendrochronology studies to ignore the first interval from the pith (~germination) to first scar

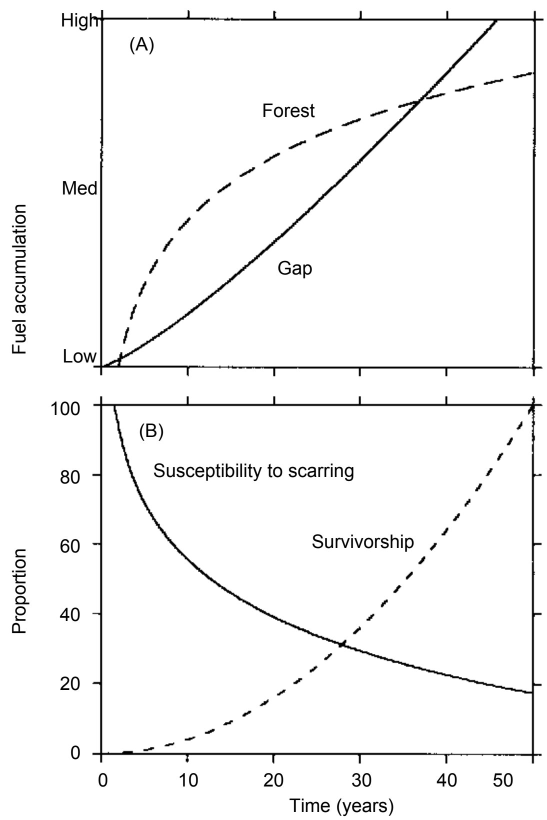

Figure 5—Expected postfire changes in (A) fuel accumulation in forests burned by low intensity underburns vs gaps generated by high intensity fire, and (B) susceptibility of saplings to formation of first scar and the expected seedling/sapling survivorship of a repeat fire.

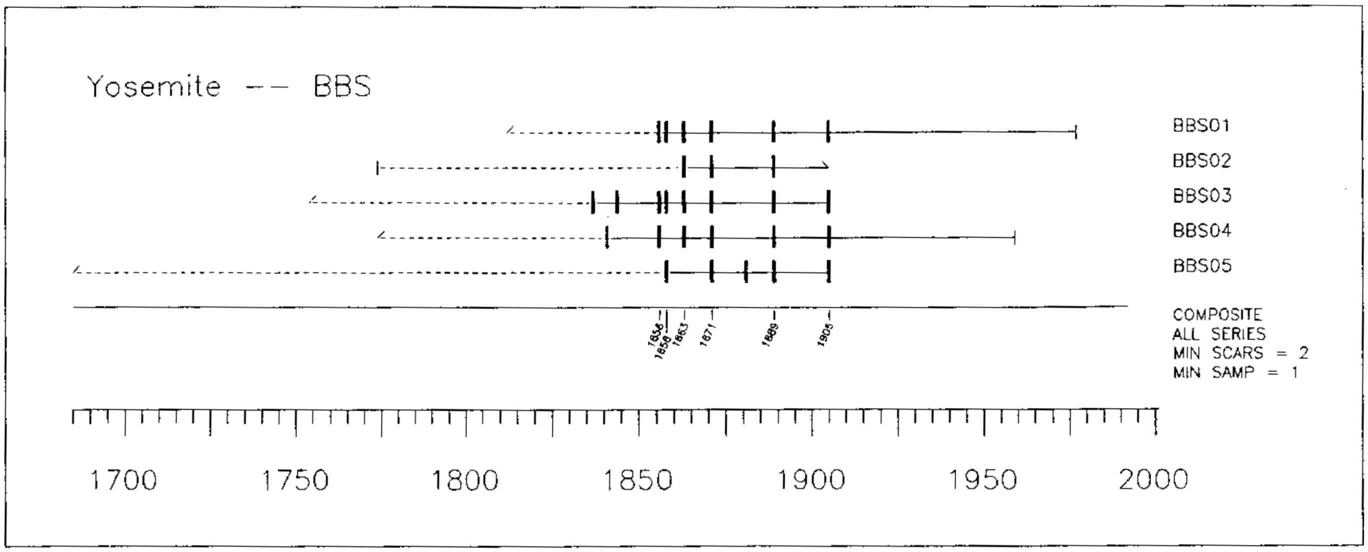

Figure 6—Fire scar dendrochronology record for individual trees at a mid-elevation site in Yosemite National Park (from Swetnam and others 1998). Bold vertical marks indicate fires and dashed horizontal lines reflect the period from the pith to the first scar.

formation (fig. 6). Omitting this fire interval has been justified because (1) it is not known if it is a fire interval and (2) the interval would not include that period of time from the last fire to germination and would thus give shorter fire intervals than was really the case (Baker 1989). At present there is insufficient information available to make either of these arguments very compelling. Justification #1 applies to all fire intervals and in fact is the basis for using composite fire histories. The second is logically justifiable, however, in the vast majority of cases the time from the pith to first scar is longer than the average fire interval for that tree and including it usually increases the estimated fire return interval. Others have suggested that prior to the first scar, saplings are less susceptible to scarring, however there is no empirical evidence of such a phenomenon (Tom Swetnam, personal communication, September 1999).

However, rather than including this interval from germination to the first fire in a composite fire history it might be worth considering the extent to which this reflects events occurring in gaps. Because bark thickness increases with age, it is reasonable to expect that the propensity for initial scar formation should be high in young saplings and decrease with time (fig. 5B). Thus, the failure to find scars in young trees is due either to fire-caused mortality eliminating young trees (Gutsell and Johnson 1996) or failure of fire to burn the patch or microsite where the seedling has established. This initial interval between establishment and first fire scar could provide a means of getting at estimates of intra-stand variation in burning and the period of time patches need to be released from fire in order to achieve successful recruitment. This is reflected in a comparison of fire return intervals calculated for the first interval compared to the average calculated by all other intervals (Table 3). This example suggests that patches may require a significant fire-free period for successful recruitment, a conclusion that has relevance to the evaluation of post-fire monitoring of prescribed burns and future prescription plans.

Table 3—Comparison of reported fire-return interval (excluding first interval) with calculated fire return-intervals for period from pith to first scar—period from germination to first scar would be longer due to the sampling of fire scars at various heights above ground level (data from Swetnam and others 1998).

Site	Reported fire return interval		Fire interval from germination to first scar	
	$\bar{X}$	S.E.	$\bar{X}$	S.E.
Mariposa grove (Yosemite NP)	5.0	0.8	38.3	5.2
Giant forest (Sequoia NP)	10.2	2.0	45.1	7.9

Conclusions

After nearly a century of highly successful fire suppression there is an urgent need for restoring fire to many Sierran forests, both because the current situation jeopardizes ecosystem stability and because it represents a dangerous fire hazard (GAO 1999). Pre-Euroamerican models of forest structure may be an appropriate target for contemporary restoration efforts, but future forest maintenance will need to shift emphasis from structure to process. The ideal of allowing just natural lightning ignited fires to eventually return fire to its natural role (Parsons and others 1985) is appropriate. However, the reality of the situation is that lightning ignited fires alone are incapable of recreating natural landscapes. There are several reasons for this. Habitat fragmentation by roads creates barriers to natural fire spread. Additionally, lightning fires that threaten developments, commercial timber or watershed processes will always be suppressed, both within natural areas, such as national parks, as well as on adjacent private and public lands. It is our belief that the goal of restoring and maintaining ecosystems with minimal human impact is not incompatible with the reality that this will require fire subsidies in the form of prescription burning.

Future management requires a better understanding of the natural range of variation in fire regimes. Due to a century of wildfire exclusion, most of our direct knowledge of fire in the Sierra Nevada is based on observations of prescribed fires—either intentional prescribed burns or unintentional natural fires, both of which are allowed to burn only under "acceptable" weather/fuel/geographic conditions. In the absence of human interference there is reason to believe that the landscape has historically burned under a greater mixture of fire intensities and severities. Future progress in our understanding of natural fire regimes is most likely to progress through modeling of both fire and forest processes, for example by coupling weather/fuel-driven fire spread models (Weise and Biging 1997) with climate-driven forest dynamics models (Urban and Miller 1996; Miller and Urban 1999). The extent to which this approach alters management of Sierran forests will depend upon other ecological and political constraints.

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