Ecological Applications, 12(5), 2002, pp. 1418–1433

ECOLOGICAL RESTORATION OF SOUTHWESTERN PONDEROSA PINE ECOSYSTEMS: A BROAD PERSPECTIVE

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Abstract. The purpose of this paper is to promote a broad and flexible perspective on ecological restoration of Southwestern (U.S.) ponderosa pine forests. Ponderosa pine forests in the region have been radically altered by Euro-American land uses, including livestock grazing, fire suppression, and logging. Dense thickets of young trees now abound, old-growth and biodiversity have declined, and human and ecological communities are increasingly vulnerable to destructive crown fires. A consensus has emerged that it is urgent to restore more natural conditions to these forests. Efforts to restore Southwestern forests will require extensive projects employing varying combinations of young-tree thinning and reintroduction of low-intensity fires. Treatments must be flexible enough to recognize and accommodate: high levels of natural heterogeneity; dynamic ecosystems; wildlife and other biodiversity considerations; scientific uncertainty; and the challenges of on-the-ground implementation. Ecological restoration should reset ecosystem trends toward an envelope of ''natural variability,'' including the reestablishment of natural processes. Reconstructed historic reference conditions are best used as general guides rather than rigid restoration prescriptions. In the long term, the best way to align forest conditions to track ongoing climate changes is to restore fire, which naturally correlates with current climate. Some stands need substantial structural manipulation (thinning) before fire can safely be reintroduced. In other areas, such as large wilderness and roadless areas, fire alone may suffice as the main tool of ecological restoration, recreating the natural interaction of structure and process. Impatience, overreaction to crown fire risks, extractive economics, or hubris could lead to widespread application of highly intrusive treatments that may further damage forest ecosystems. Investments in research and monitoring of restoration treatments are essential to refine restoration methods. We support the development and implementation of a diverse range of scientifically viable restoration approaches in these forests, suggest principles for ecologically sound restoration that immediately reduce crown fire risk and incrementally return natural variability and resilience to Southwestern forests, and present ecological perspectives on several forest restoration approaches.

Key words: anthropogenic change; ecological restoration; ecosystem management; fire suppression effects; forest restoration programs; ponderosa pine forests; reference conditions; Southwestern United States, natural range of variation.

INTRODUCTION

The *Pinus ponderosa* (ponderosa pine) forests of the American Southwest (Arizona, New Mexico, and adjoining portions of Utah and Colorado) have experienced major changes in ecological structure, composition, and process because of recent human activities (Fig. 1). Over a century of livestock grazing, fire suppression, logging, road construction, predator control, and exotic-species introductions have altered most Southwestern ponderosa pine forests from conditions that had prevailed for thousands of years (Covington and Moore 1994, Swetnam et al. 1999). A critical change has been a dramatically increased vulnerability of these forests to large, destructive crown fires that threaten both human and ecological communities.

A general consensus has emerged that it is urgent to restore more natural conditions to these forests, but substantial debate persists about how to best achieve this goal (Nijhuis 1999, Covington 2000, Kloor 2000, Jenkins 2001). The purpose of this paper is to promote a broad and flexible perspective on ecological restoration of Southwestern ponderosa pine forests. We sup-

Manuscript received 15 June 2001; revised and accepted 29 October 2001; final version received 2 January 2002.
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FIG. 1. Ponderosa pine forests of the American Southwest. (Top) Open ponderosa pine forest representing ''typical'' pre-1900 conditions, with grassy understory and surface fire activity. (Bottom) Altered ponderosa pine stand in need of restoration, showing changes in both stand structure and species composition. The dense midstory of mixed conifer trees provides ladder fuels that favor crown fire development.

port the development and implementation of a diverse range of scientifically viable restoration approaches in these forests that address the critical issues of forest heterogeneity, scientific uncertainty, and effects on wildlife. In addition, we suggest principles for ecologically sound restoration approaches. It is not our intention to emphasize a critique of any particular model, but we do present ecological perspectives on several alternative forest restoration approaches.

BACKGROUND

Southwestern ponderosa pine ecosystems were shaped through time by stochastic and deterministic processes, including frequent surface fires, episodic regeneration, insect infestations, and regional climate events such as droughts (Dahm and Geils 1997, Allen and Breshears 1998, Kaufmann et al. 1998, Swetnam and Betancourt 1998). These processes contributed to heterogeneous forest spatial patterns at local and land-

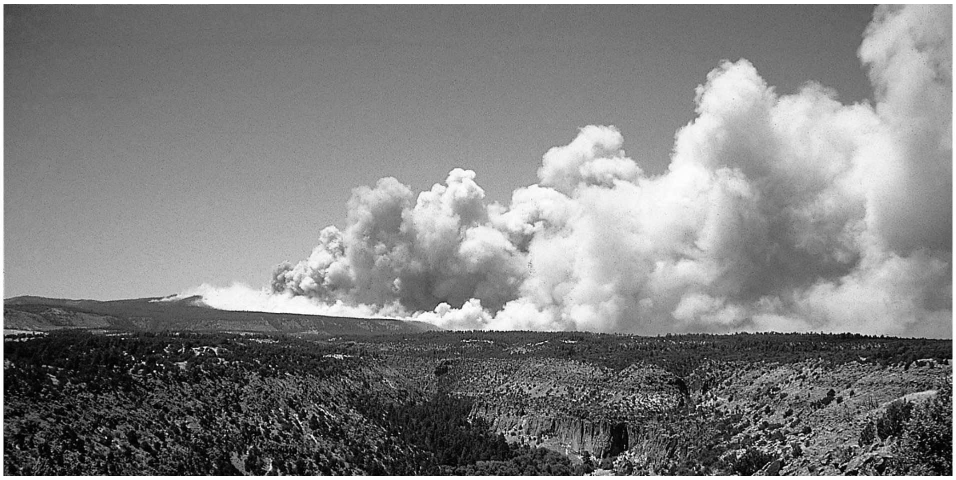

FIG. 2. View looking northwest at the Cerro Grande Fire on the afternoon of 10 May 2000 as it burned toward Los Alamos, New Mexico (USA). Similar large, stand-replacing fires are becoming increasingly common in Southwestern ponderosa pine forests.

scape scales (Cooper 1960, White 1985), with pattern shifts through time within a natural range of variability (Swetnam et al. 1999).

Since European settlement in the middle to late 1800s, pervasive changes have tended to homogenize ponderosa pine forest patterns in the Southwest. Large trees have decreased in number due to logging. Historic livestock grazing and fire suppression have promoted the development of unnaturally dense stands of suppressed young trees. This condition now threatens the remaining large trees through competition and by fueling increasingly extensive crown fires (Covington and Moore 1994, Covington et al. 1994) as in ponderosa pine forests of other regions (Agee 1993, Everett et al. 1997, Smith and Arno 1999). In some stands species compositions have shifted toward less fire-resistant trees such as *Abies concolor* (white fir), *Pseudotsuga menziesii* (Douglas-fir), and *Juniperus* (juniper) species. These changed conditions now affect millions of hectares of ponderosa pine in the Southwest (U.S. General Accounting Office 1999).

Alteration of stand structures and species compositions has in turn altered natural processes in Southwestern forests. Understory grasses and forbs have decreased in abundance and diversity (Covington and Moore 1994, Bogan et al. 1998), replaced by deep mats of slowly decomposing pine needles. As a result, nutrient cycling dynamics have been disrupted (White 1994) and overall biodiversity levels decreased (Allen 1998). Old-growth ponderosa pine forests have become rare (Harrington and Sackett 1992, Noss et al. 1995) and meadows have shrunk due to tree encroachment (Swetnam et al. 1999). Some vertebrate animal species, such as the Northern Goshawk (Reynolds et al. 1992, U.S. Fish and Wildlife Service 1998; but see Kennedy 1997), are thought to have declined in abundance due to habitat alterations. Hydrologic cycles have been modified in more densely forested watersheds, likely decreasing total streamflows, peak flows, and base flows (Ffolliott et al. 1989). An increase in number, size, and severity of stand-replacing fires (Dahm and Geils 1997, Swetnam and Betancourt 1998, Hardy et al. 1999) threatens both human and ecological communities (Moir and Dieterich 1988, U.S. General Accounting Office 1999). The aftermath of such fires includes short-term amplification of erosion and flooding (Agee 1993, White 1996, Robichaud et al. 2000).

Landscape scars created by total canopy destruction may persist as grasslands or shrublands for decades to centuries because ponderosa pine seed production and recruitment is erratic, and the relatively heavy, wingless seeds cannot disperse far from surviving, mature trees. For example, large portions of the 1950 A1 fire near Flagstaff, Arizona, USA, remain as grassland, and the 1953 Circle Cross Fire in the Sacramento Mountains, New Mexico, USA, contains much persistent shrubland (M. Savage, *unpublished data*). If the current trajectories of anthropogenically driven change continue, serious ecological damage to ponderosa pine ecosystems will accumulate (Covington et al. 1994, Noss et al. 1995).

These worrisome trends have long been evident to some forest scientists and ecologists (Weaver 1951, Cooper 1960). Only recently, however, has a broad scientific, social, and political consensus emerged that restoration of ecological sustainability in Southwestern ponderosa pine forests is necessary and urgent (Covington and Moore 1994, Covington et al. 1994, 1997, Suckling 1996, Nijhuis 1999). This social and political consensus has developed rapidly in response to recent major wildfire seasons, such as 2000, when 3×10^6 ha burned nationwide (Fig. 2). Although much of this burned area was in non-forested landscapes, or in high-elevation forest types that are adapted to high-intensity fires (Morrison et al. 2000), ecologically worrisome crown fires in ponderosa pine and mixed-conifer forests were common, and are a chief focus of concern. Much of this concern also stems from the fact that urban encroachment into these pine-dominant forests is extensive and increasing.

Ecological restoration efforts in the United States have recently been proposed for millions of hectares of public lands by federal, state, and local government agencies (e.g., USDA Forest Service 2000, USDA and USDI 2000*a*, *b*, USDI 2000, Western Governors' Association et al. 2001, Marston et al. 2001, Matthews 2001). These restoration proposals generally seek to thin forests with combinations of tree harvesting and prescribed burning to increase resilience to natural disturbance events such as fires, insects, and regional drought, and thereby reduce the risk of catastrophic fire events.

Vigorous public and scientific debates have developed over the relative risks and trade-offs of different approaches to restore forests in the Southwest (Suckling 1996, Nijhuis 1999, Covington 2000, Kloor 2000, MacNeil 2000, Jenkins 2001), as in other regions (Brown 2000, Marston et al. 2001). Silvicultural approaches focused on tree harvest have been criticized based on concerns that short-term economics rather than ecological sustainability or decreasing fire hazard are the real underlying justifications of treatments. Although prescribed fire programs have been underway for several decades, the scale and intensity of these restoration efforts have been inadequate to reverse the overall trends of degradation in Southwestern pine forests. Concerns about excessive smoke and the risks of prescribed burning (highlighted by the Cerro Grande Fire of 2000) have also constrained public support for the use of fire alone as a restoration treatment.

A Broad Restoration Perspective

In this paper we offer a broad perspective on ecological restoration of Southwestern United States ponderosa pine forests. We propose not so much a contrast from current models as an expanded view that encompasses and supports a diverse range of scientifically viable restoration approaches. This includes the current, most widely debated and applied Southwestern ponderosa pine model, which involves a relatively precise restoration of presettlement stand structures (Moore et al. 1999). There is a clear need for reference-based approaches that integrate structure, composition, and ecosystem processes. Such restoration models need to be adequately flexible to address the diverse ecological and social conditions in Southwestern forests. We believe that the practice of ponderosa pine restoration will be best served by a variety of approaches across a broad range of forest settings.

Ecological restoration aims to enhance the resilience and sustainability of forests through treatments that incrementally return the ecosystem to a state that is within an historic range of conditions, known as the "natural range of variability" (Landres et al. 1999). The Society for Ecological Restoration (Tucson, Arizona, USA) offers the following definition of "*ecologial restoration*: 'the process of assisting the recovery and management of ecological integrity. Ecological integrity includes a critical range of variability in biodiversity, ecological processes and structures, regional and historic context, and sustainable cultural practices.' "[11] Several key issues suggest a need for a broad perspective on ecological restoration of Southwestern forests: high levels of natural heterogeneity across forest landscapes; current and future conditions that may fall outside the natural range of variability; wildlife habitat and other biodiversity considerations; and our imperfect understanding of these complex systems. We focus here on ecological considerations in ponderosa pine forest restoration, acknowledging that the success of restoration programs also requires political, financial, and social support. Our intent is not to exclude such dimensions, but to clarify the scientific basis for forest restoration programs.

The importance of heterogeneity in time and space

Ecological restoration requires an understanding of, and respect for, the variability of ponderosa pine ecosystems across the Southwest. These forests are created by dynamic interactions among natural processes (such as fire) and forest structure (such as tree density and canopy openings), across variable landscapes. Regeneration and disturbance patterns interact with long- and short-term climate fluctuations and human activities to influence fire frequency, intensity, size, seasonality, and severity (Baisan and Swetnam 1997, Swetnam and Betancourt 1998, Kaye and Swetnam 1999, Grissino-Mayer and Swetnam 2000). Forest patterns and processes often exhibit lagged interactions with climate fluctuations, along with substantial inertia in the face of climate change. Consequently, forests often exist in disequilibrium with current climate.

Variability in structure and process means that patterns of stand density, species composition, and disturbance regimes differ significantly across landscapes and throughout the region. Ponderosa pine grows across a 1500-m elevational gradient in many mountain ranges (e.g., Allen and Breshears 1998), with at least 21 different ponderosa pine "habitat types" recognized across diverse landscape conditions in the Southwest (Alexander and Ronco 1987). Documented pre-1900 mean fire-return intervals varied from about 4 to 36 yr in Southwestern ponderosa pine forests (Swetnam and Baisan 1996). Post-suppression species compositions have been markedly affected by increased recruitment of fire-sensitive *Pinus edulis* (piñon) and juniper species at low elevations and mixed-conifer species at higher elevation (Fig. 1). Mature tree densities (>30

[11] URL: ⟨http://www.ser.org⟩

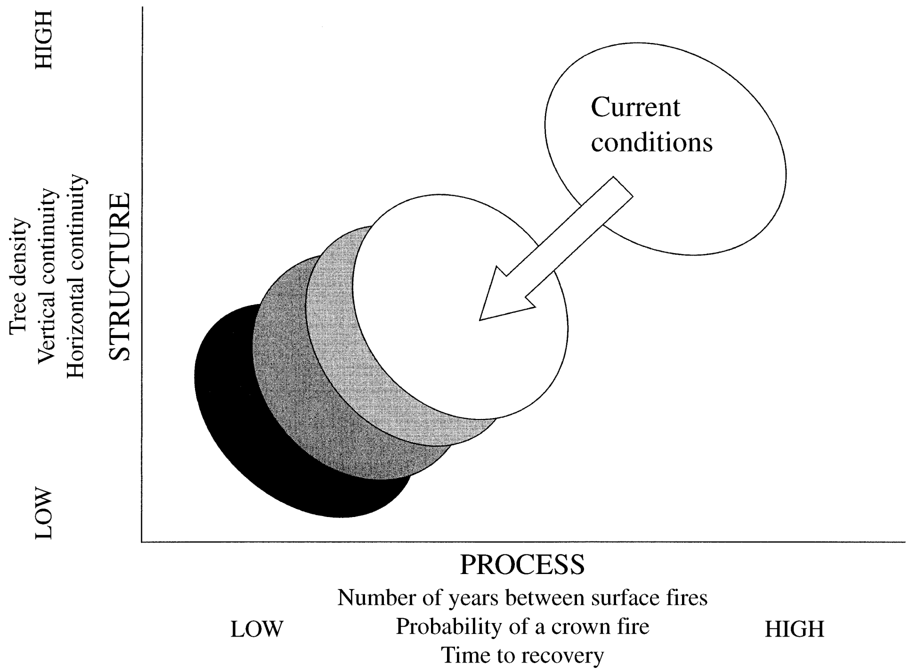

FIG. 3. Schematic representation of the restoration concept. If the natural range of variability is seen as a multidimensional "envelope" of ecological conditions, then the goal of restoration is to move an altered ecosystem back toward its pre-disruption envelope (the darkest region), and to allow natural processes over time to dynamically reestablish a range of natural structural conditions.

cm [12 inches] in diameter at breast height) measured ca. 1900 AD in Southwestern pine ecosystems ranged between 19 and 126 trees/ha (8–51 trees/acre) (Woolsey 1911), whereas today densities of all live stems often exceed 2470 trees/ha (1000 trees/acre) (Allen 1998; D. Falk, *unpublished data*).

This variability in ponderosa pine forests affects management approaches, as recognized by Pearson (1950:13): "Foresters are constantly reminded that since conditions change from one place to another, management cannot be uniform." Ecological restoration should recognize and retain the natural heterogeneity characteristic of presettlement forests (White and Walker 1997). Given the heterogeneity of Southwestern ponderosa pine forests, identifying general ecological reference conditions for restoration goals can be difficult, if not arbitrary.

Use of the natural-range-of-variability concept for restoration

The concept of "natural range of variability" has some theoretical flaws and practical limitations (Landres et al. 1999, Millar and Wolfenden 1999, Swetnam et al. 1999), but nevertheless has proven useful as a framework for evaluating the current status of ecosystems relative to past conditions, and for identifying ecologically justifiable restoration goals (Kaufmann et al. 1994, Morgan et al. 1994, White and Walker 1997, Landres et al. 1999). Southwestern forests experienced some level of human influence for thousands of years, but human-caused changes in ponderosa pine after 1850 far exceeded the influence of indigenous people (Covington et al. 1994, Kaye and Swetnam 1999, Allen 2002). In particular, the cessation of the historical regime of frequent, low-intensity fires has pushed structural characteristics of many forests well outside the natural range of variability that existed over the past millennium (Swetnam et al. 1999).

Ponderosa pine restoration treatments should be designed to reestablish trends in forest processes, particularly fire, leading to natural ranges of variation in composition and structure (Landres et al. 1999, Moore et al. 1999, Stephenson 1999). If the natural range of variability is seen as an envelope of conditions, then the goal of restoration is to move an altered ecosystem toward its pre-disruption envelope, and to allow, or use, natural processes over time to dynamically reestablish diverse natural structures (Fig. 3).

In the long term, the best way to align forest conditions to track ongoing climate changes is to restore fire, which naturally correlates with current climate. Some stands need substantial structural manipulation before fire can safely be reintroduced, but in many cases fire can then do the preponderance of the work of ecological restoration, recreating the natural interaction of structure and process.

The successful reintroduction of frequent surface fire in the Gila Wilderness, New Mexico, USA, exemplifies how incremental fire treatments can achieve substantial restoration of ponderosa pine forests. Detailed quantitative studies of before-and-after forest densities are lacking, but qualitative observations (including repeat photographs) by knowledgeable fire managers (Webb and Henderson 1985; P. Boucher and R. D. Moody, *unpublished report* [1996] to the Gila National Forest [Silver City, New Mexico, USA]) and fire scientists (Rollins 2000; T. W. Swetnam, *personal observations*) suggest that repeated natural fire use (as many as four events since 1975 in some areas) have successfully opened up ponderosa pine stands, and helped to reestablish grassy understories. A key to the Gila's success was a sufficiently large area where smoke and threats of occasional flare-ups during the burning season (sometimes months) do not threaten urban areas. Another key to this success was that managers were patient and incremental in implementing the burning program; most of the large fires were initially allowed to burn only during the relatively cool and wet season after the start of the Southwest monsoons in July or August. Although such large, roadless areas are uncommon, the Gila's example shows that mechnical thinning is not always a prerequisite for forest restoration treatments with fire.

Restoration aims to eventually move forests back to within the natural range of variability. However, this need not necessarily be accomplished in the first treatment or tied to a particular moment in time or past forest structure. Initial treatments can be designed to markedly decrease crown fire risks at stand and landscape scales by decreasing the continuity of hazardous fuel conditions. Conservative initial treatments would be the minimum necessary to reduce vulnerability to stand-replacement fire to an acceptable level. We propose that conservative, incremental treatments involving both mechanical thinning and fire over time periods of years to decades are ecologically appropriate and advisable for many Southwestern forests.

There is a clear need to begin widespread restoration treatments now to reduce the threat of catastrophic fire. Such treatments should use a variety of prescriptions and treatments to address trade-offs and produce diverse restoration outcomes. For example, restoration back to presettlement tree densities through intensive thinnings greatly reduces risk of crown fire spread in areas of concentrated treatment (Fulé et al. 2001), but may generate more slash surface fuels initially than lighter thinnings. Large slash loads can exacerbate the short-term fire hazard unless mitigated (Graham et al. 1999), which can be expensive and/or have substantial environmental effects (e.g., machine crushing slash into the ground surface). Less intensive treatments, sufficient to reduce crown fire risk and strategically placed to interrupt continuous fuels, may be able to more quickly address a larger proportion of the regional forest. While practical and economic considerations, such as direct risk to human communities, may drive treatment strategies in some situations, long-term ecological goals should also guide treatment actions if ecological restoration is desired. Incrementally thinning ponderosa forests over a period of years using varied combinations and intensities of chainsaws and fire may effectively reduce fire risks while maintaining ecological integrity.

Biodiversity considerations

Southwestern ponderosa pine forests provide habitat for at least 250 species of vertebrate animals (Patton and Severson 1989, New Mexico Department of Game and Fish 2000), as well as many plants. When restoration treatments modify the physical and biotic environment, plants and animals are affected in various ways (Rieman and Clayton 1997, Oliver et al. 1998; W. W. Covington, A. Waltz, P. Fulé and G. Verkamp, *unpublished report* to U.S. Bureau of Land Management, Arizona Strip District). Of particular concern is the potential for restoration actions to reduce the viability of metapopulations of sensitive species through habitat alteration and fragmentation (Stacey et al. 1996, U.S. Fish and Wildlife Service 1998, Holthausen et al. 1999). This includes invertebrates and soil organisms that are critical to ecosystem function.

An incremental approach to restoration provides opportunities for the adjustment of future treatments based on wildlife responses, so as not to foreclose future options. Restoration projects should strive to minimize or spatially constrain adverse impacts to rare, sensitive, and declining species. Care should be taken to ensure that adequate habitat is maintained for sensitive species during the phase between initial treatment and final restoration.

Not all wildlife habitat elements are equally vulnerable or irreplaceable. For example, large oak trees grow slowly and are especially valuable habitat for a wide array of wildlife (Rosenstock 1998). Some areas should be left untreated to serve as habitat refuges during the stress of treatments, until new landscape conditions are known to provide adequate habitat.

Native plants and animals are adapted to the naturally high levels of heterogeneity in Southwestern ponderosa pine ecosystems, and some species are dependent upon diverse habitats for their survival (e.g., Reynolds et al. 1992, U.S. Fish and Wildlife Service 1995, Dodd et al. 1998). Thus, biodiversity considerations reinforce the need to avoid creating uniform stand and landscape conditions. A diverse landscape with patches of variable tree densities, including some areas of relatively high density, should be developed to accommodate species with different habitat adaptations. Retaining some dead, deformed, and diseased trees, and some clumps of large trees with interlocking crowns, will maintain structural complexity and important food and nesting habitat (Bennetts et al. 1996, Bull et al. 1997). Such trees are important elements of genetic diversity in their own right as well (Millar and Libby 1989, Rehfeldt 1991, Ledig 1992).

Restoration activities often involve biodiversity trade-offs, particularly in the short term and at the local scale. For example, snags and downed logs provide essential habitat for many birds and mammals (Bull et al. 1997), but these woody structures are susceptible to destruction in restoration treatments, especially from fire (Tiedemann et al. 2000). However, restoration treatments also provide opportunities to increase habitat heterogeneity and biodiversity. For example, where large snags are scarce because of past management activities, new ones will be created through fire mortality and other disturbances as forests are restored (Pearson 1950). The restoration of more diverse habitat structures and of natural processes such as surface fire and associated nutrient cycling should help many native species (cf. Johnson and Wauer 1996; W. W. Covington, A. Waltz, P. Fulé, and G. Verkamp, *unpublished report* to U.S. Bureau of Land Management, Arizona Strip District). The increased vigor and diversity of native understory plant species after restoration will provide important habitat conditions for many kinds of animals (e.g., Waltz and Covington 1999) and hopefully increase resistance to ongoing and future invasions by exotic plants (Crawford et al. 2001).

Scientific uncertainty and the limitations of historical reference conditions

Ecological restoration must recognize the limits of scientific knowledge. While a large body of research exists on ponderosa pine forests, we are still limited in our understanding of ecosystem function. Historical fire frequency is often the most reliable element of our reconstructions, although it too has limitations (Swetnam et al. 1999). We know less about past distributions of fire size, severity, and spatial pattern than we do about frequency (Morgan et al. 2001). Swetnam and Baisan (1996) and Baker and Ehle (2001) discuss uncertainties and biases associated with the sampling design and data analyses of fire-scar studies.

Uncertainties in the reconstruction of forest stand composition and spatial structure result from missing evidence, such as logs and stumps removed by fire, logging, and decay (M. M. Moore, D. W. Huffman, W. W. Covington, J. E. Crouse, P. Z. Fulé, and W. H. Moir, *unpublished report* to USDA Forest Service, Rocky Mountain Station, Flagstaff, Arizona). Reconstruction of the density and location of large trees is far more reliable than of small-diameter stems and seedlings that decompose rapidly or burn even in surface fires (Stephenson 1987). Reconstructed overstory-tree densities are thus best used conservatively as minimum values for establishing quantitative restoration targets for stand density, rather than as maxima. Knowledge of other ecological conditions in the past, such as wildlife population dynamics, may be highly uncertain because available methods preclude precise reconstructions. Uncertainty will also exist because society is unlikely to invest in the development of detailed reconstructions of past stand structures and fire histories for every restoration site, suggesting the need for site-specific flexibility to develop restoration targets based upon an inferred natural range of variability in stand conditions.

A sense of urgency in reducing the threat of destructive fires should be balanced with patience in accomplishing restoration, along with major commitments to thoughtful experimentation and monitoring to ensure we learn as rapidly as possible. Restoration science is young, and it is difficult to predict the results of our actions. Application of a broad restoration perspective, implemented through a variety of alternative treatments, will be more effective than any single restoration treatment.

Principles for Ecological Restoration of Southwestern Ponderosa Pine Forests

Here we outline 16 broad principles for restoration of Southwestern United States ponderosa pine forest ecosystems. Application of these principles will foster implementation of a diverse range of ecologically justifiable restoration projects. While focused on ponderosa pine forests, these principles also apply more generally to other forest types in the Southwest, such as some piñon–juniper and mixed-conifer forests.

1) *Reduce the threat of crown fire*.—A key restoration priority must be the rapid reduction of the widespread risk of unnatural crown fires, both within stands and across landscapes. The initial treatment on any site should be substantial enough to decrease forest vulnerability to stand-replacing fire.

2) *Prioritize and strategically target treatment areas*.—Key considerations for prioritizing restoration treatment areas are degree of crown fire risk, proximity to human developments and important watersheds, protection of old-growth forests and habitats of sensitive species, and strategic positioning to break up landscape-scale continuity of hazardous fuels (Weatherspoon and Skinner 1996, Agee et al. 2000, Finney 2001). For example, a landscape of alternating north- and south-facing ridges could have restoration treatments focused on the south-aspect sites to reduce the continuity of hazardous fuels at the landscape scale, and thereby restore more natural conditions at both site and landscape scales.

3) *Develop site-specific reference conditions*.—Site-specific historical ecological data can provide information on the natural range of variability for key forest attributes, such as tree age structure and fire regimes, that furnish *local* ''reference conditions'' for restoration design. A variety of constraints, however, prevent the development of historical information on every hectare of land needing restoration. General goals should be to restore ecological integrity and functioning, rather than precise stand structural conditions as they existed at a particular point of time in the past.

4) *Implement multiple conservative interventions*.—Incremental restoration through multiple treatments is a conservative approach to achieving desired changes.

Restoration treatments should strive to use the least disruptive techniques, and balance intensity and extensiveness of treatments. In many areas, conservative initial treatments would be the minimum necessary to adequately reduce the threat of unnatural crown fire. For example, a conservative strategy would be the placement of treatment areas to interrupt fuel continuities and thereby reduce overall landscape risk of extensive crown fires, despite treating only a small fraction of the landscape (Agee et al. 2000). Fires ignited by lightning or by people under carefully prescribed conditions may be sufficient to reestablish natural conditions in many locations (e.g., in the Gila Wilderness of New Mexico [USA]). In the extensive areas where fire alone cannot safely reduce tree densities and hazardous ladder fuels, mechanical thinning of trees will be needed before the introduction of prescribed fire. Patient, effective treatments will provide more options for the future than aggressive attempts to restore 120 yr of change at once. In certain areas, however, such as some urban–wildland interfaces, trade-offs with imminent crown fire risks require consideration of rapid, heavy thinning of most small-diameter trees.

5) *Utilize existing forest structure*.—Restoration efforts should incorporate and build upon valuable existing forest structures such as large trees and groups of trees of any size with interlocking crowns. These features are important for some wildlife species, such as Abert's squirrels and goshawks, and should not be removed completely just to recreate specific historical tree locations. Since evidence of long-term stability of precise tree locations is lacking, the selection of ''leave'' trees and tree clusters in restoration treatments can be based on the *contemporary* spatial distribution of trees, rather than pre-1900 tree positions. Historical forest structure conditions can be restored more quickly by maximizing use of existing forest structure. Leaving some relatively dense within-stand patches of trees need not compromise efforts to reduce landscape-scale crown fire risk.

Gus Pearson, the patriarch of ponderosa pine silviculture in the Southwest, recognized the need to be flexible and use existing stand structures. Pearson (1950:29) stated that the use of theoretical tree-density distributions as guides for silvicultural treatments ''are for application in principle rather than in letter, because the stands must be taken as found and remedies must be sought in modification rather than reconstruction.'' This is also true for ecological restoration.

6) *Restore ecosystem composition*.—Where fire suppression has allowed fire-sensitive tree species like junipers or white fir to become abundant in historical ponderosa pine forests, treatments should set a trend toward restoring dominance of the more fire-resistant ponderosa pines. However, mechanical removal of all fire-sensitive invaders is inappropriate, given the heterogeneous and dynamic nature of these forests. Restoration of fire may eventually restore locally appropriate forest tree composition and structure (Miller and Urban 2000).

Missing compositional elements, such as herbaceous understories or extirpated vertebrates and invertebrates, also require restoration attention. The forest understory, including shrubs, grasses, and forbs, is an important ecosystem component that directly affects tree regeneration patterns, fire behavior, watershed functioning, wildlife habitat, and overall patterns of biodiversity. Similarly, soil organisms are vital elements that can influence community composition and dynamics (Hole 1981). A robust understory provides a restraint on tree regeneration and is essential for carrying surface fires. The establishment and maintenance of more natural patterns of understory vegetation diversity and abundance are integral to ecological restoration. Understories should be protected from overgrazing during restoration to allow full recovery of herbaceous biodiversity and biomass, and of associated ecosystem components and processes such as pollinators and surface fires.

The implementation of restoration treatments requires special care to protect soils and watersheds (Jurgensen et al. 1997, Rieman and Clayton 1997). Minimizing mechanical disturbance of soils and avoiding the construction of new roads will minimize sedimentation, disruption of surface runoff, and other detrimental ecosystem effects (Trombulak and Frissell 2000). Minimizing ground disturbance also will reduce impacts to the numerous archeological sites found in many Southwestern forests.

7) *Retain trees of significant size or age*.—Large and old trees, especially those established before ecosystem disruption by Euro-American settlement, are rare, important, and difficult to replace. Their size and structural complexity provide critical wildlife habitat by contributing crown cover, influencing understory vegetation patterns, and providing future snags. Ecological restoration should protect the largest and oldest trees from cutting and crown fires, focusing treatments on excess numbers of small young trees. Given widespread agreement on this point, it is generally advisable to retain ponderosa trees larger than 41 cm (16 inches) dbh and all trees with old-growth morphology regardless of size (i.e., yellow bark, large drooping limbs, twisted trunks, flattened tops). Despite the heterogeneity of forest site and stand conditions in the Southwest, cutting of larger trees will seldom be ecologically warranted as ''restoration'' treatments at this time due to their relative scarcity. Following this guideline would significantly reduce hazards of stand-replacing fires in most cases and also favor the development of future old-growth forest conditions (Moir and Dieterich 1988, Harrington and Sackett 1992). Public concern about forest manipulation would also be reduced by ensuring that ''large'' trees are not being targeted.

Some ponderosa pine forests contain extremely old trees and dead wood remnants that may be small but are important because they contain unique and rare scientific information in their growth rings (Grissino-Mayer et al. 1997). Such trees have become increasingly scarce in the late 20th century, and the initial reintroduction of fire often consumes these tree-ring resources. Restoration programs should identify, inventory, sample, and preserve them where possible.

8) *Consider demographic processes*.—The underlying processes of natural tree regeneration and mortality should be incorporated in restoration design. Southwestern conifer regeneration occurs in episodic, often region-wide pulses, linked to wet–warm climate conditions and reduced fire occurrence (Savage et al. 1996, Swetnam and Betancourt 1998, Mast et al. 1999). Periods with major regeneration pulses in the Southwest during the 20th century include the 1910s–1920s and 1978–1998 (Savage et al. 1996, Swetnam and Betancourt 1998). Some of this regeneration would have survived under natural conditions. Restoration efforts should retain a proportion of these cohorts, toward the goal of maximizing options for ecosystem resiliency.

9) *Integrate process and structure*.—Ecological sustainability requires the restoration of process as well as structure (Stephenson 1999). Natural disturbance processes, including fire, insect outbreaks, and droughts, are irreplaceable shapers of the forest. In particular, fire regimes and stand structures interact and must be restored in an integrated way; mechanical thinning alone will not reestablish necessary natural disturbance regimes. At the same time, fire alone may be too imprecise or unsafe in many settings, so a combination of treatments may often be the safest and most certain restoration approach.

Perhaps the single best indicator of whether a proposed approach should be considered as ''ecological restoration'' of a ponderosa pine forest is to evaluate whether the treatment will successfully restore surface fire as a keystone process. Approaches that do not include an explicit and long-term commitment to restore frequent surface fire fail to merit the adjective ''ecological.''

10) *Control and avoid using exotic species*.—Seeding of exotic grasses and forbs should be prohibited as ecologically incompatible with good restoration. Once established, exotic species can be extremely difficult or impossible to remove. Even seeding with native species from commercial sources risks the near certainty of exotic weed contaminants and the establishment of non-local genotypes at the expense of locally evolved and adapted genotypes. The common use of annual cereal crops such as rye and barley that typically decline to low levels within a matter of years still leaves persistently altered ecosystems through ''the ghost of competition past,'' as their initial flush of growth tends to monopolize the soil resources, reduce the success of native plants (Barclay 2000), and alter long-term successional outcomes.

If enhancement of herbaceous vegetation is needed, using locally hand-collected wild seeds or transplanting individuals from nearby areas into treatments to serve as seed sources is slower and more expensive, but ecologically safer. In general, it is ecologically desirable to avoid seeding, and to instead allow native herbaceous vegetation to recover incrementally through natural processes of dispersal and establishment after restoration treatments.

The widespread practice of seeding exotic grasses to ''rehabilitate'' watersheds after severe fires could be largely eliminated by preemptive restoration treatments that reduce fire severity and foster recovery of native herbaceous ground cover before crown fires occur. Restoration treatments should also routinely incorporate early actions to control the establishment and spread of aggressive exotics that can be expected from restoration-related site disturbance (Crawford et al. 2001). Control actions should include active detection efforts to identify infestations at an early phase, and treatments ranging from hand-pulling to the careful spot application of biodegradable herbicides.

11) *Foster regional heterogeneity*.—The Southwest is a region of complex topography, hydrology, and soils. As a result, biological communities vary at local, landscape, and regional scales, and so should restoration efforts. Ecological restoration should also incorporate the natural variability of disturbance regimes across heterogeneous landscapes. Heterogeneity should be fostered in planning and implementing ecological restoration at all spatial scales, including within and between stands, and across landscape and regional scales.

12) *Protect sensitive communities*.—Certain ecological communities embedded within ponderosa pine forests, such as some riparian areas, could be adversely affected by on-site prescribed burning or mechanical thinning. Restoration efforts should protect these and other rare or sensitive habitats, which are often hotspots of biological diversity, particularly those that are declining in abundance and quality in the region.

13) *Assess cumulative effects*.—It is important to consider and plan for the cumulative effects of restoration work, since these efforts will take place synchronously throughout large areas in the Southwest. Restoration projects will also occur within a regional context of other human actions such as timber sales, private land developments, roads, and livestock grazing. These land uses have varied impacts at all scales, and often uncertain interactions with restoration efforts must be considered cumulatively.

14) *Protect from overgrazing*.—Grass, forb, and shrub understories are essential to plant and animal diversity and soil stability. Robust understories are also necessary to restore natural fire regimes and to limit excessive pine seedling establishment (Rummell 1951, Madany and West 1983). Where possible, defer livestock grazing after initial surface fire treatment until the herbaceous layer has fully recovered (Belsky and

TABLE 1. Variables that should be considered in the development of an ecological restoration plan. Each restoration project will have a unique plan, based on locally appropriate choices for each variable, reflecting local priorities and the diversity of ponderosa pine forests in the region.

Post-treatment structure: age, size, density
Stem density, by size class
Basal area (m^2/ha), by size class
Crown cover (%)
Snags and down logs (no./ha, mass/ha), by size class
Thinning size cap (i.e., maximum-diameter tree removed)
Old tree protection measures (e.g., removal of basal fine fuels and ladder fuels; removal of competing understory stems)
Composition
Retention of fire-sensitive or shade-tolerant native tree species
Existing canopy trees (%)
Understory recruitment (%)
Control or elimination of non-native understory species
Spatial configuration
Distribution of mature trees, random to clustered
Reliance on presettlement cluster locations for post-treatment configuration
Use of existing tree clusters in post-treatment configuration
Retention of heterogeneous (spatially variable) structure and density at stand and landscape scales
Ecosystem processes and disturbances
Restoration of natural or prescribed fire regime
Projected post-treatment distribution of fire intervals (e.g., mean and range)
Post-treatment livestock grazing regime
Overall restoration plan
Site-specificity of treatment prescription
Time span over which thinning treatments are implemented
Number of restoration-treatment entries
Long-term monitoring commitment
Monitoring components (e.g., plants, animals, soil, water)
Level of detail of measurements
Frequency of measurements
Duration of measurements
Adaptive management loop in decision process

Blumenthal 1997). Prevention of overgrazing must be an integral part of ponderosa pine forest restoration.

15) *Establish monitoring and research programs*.—Given the uncertainties about effects of restoration treatments, well-designed monitoring, research, and documentation programs are essential if we are to learn from, and evaluate the success or failure of, ongoing restoration efforts. Wildlife and understory plant populations can be monitored as indicators of ecological change and restoration outcomes. Monitoring programs must be put in place before treatments begin, and must evaluate responses of key ecosystem components and processes at multiple scales (Covington and Moore 1994, Covington et al. 1997). Even better, when possible, restoration projects should be set up as experiments with replicates and controls to test alternative hypotheses (Covington et al. 1997). One benefit of the perspective proposed here is that it will test the ecological effects of restoration efforts across a wide range of treatments and prior forest conditions. The locations and prescriptions for all restoration treatments should be archived in a geographic information system (GIS), so that land managers and researchers now and into the future have access to site-specific records of restoration treatments.

16) *Implement adaptive management*.—Ecological restoration is an incremental process that may take a century or two to fully achieve. It requires a long-term management commitment, especially to maintain natural fire regimes and to protect and develop old-growth stands. Restoration will be most successful where land managers learn from treatment experiences and adaptively adjust their approaches through time (Holling 1978). Extended social and fiscal support will be needed to sustain such long-term restoration programs.

Conceptually, each of the restoration principles outlined above can be thought of as describing one or more axes of variation. For example, intensity of thinning treatment, heterogeneity within the treatment area, post-treatment species composition, experimental unit size, fidelity to location of existing tree clusters, and post-thinning fire frequency constitute design variables for restoration (Table 1). Thus, the principles describe a set of key dimensions in the design of restoration treatments, and any particular project will choose a unique set of values for the variables. These principles support implementation of a diverse range of ecological restoration projects.

Ecological Perspectives on Several Forest Restoration Approaches

As debate over restoration of Southwestern United States forests has intensified (Njjhuis 1999, Jenkins 2001), a variety of philosophies and approaches are being presented that differ in their core perspectives and probable on-the-ground outcomes. These approaches include emphases on: (a) fire-risk reduction, (b) economics, (c) natural regulation, and (d) structure-oriented restoration. Here we provide some reflections from an ecological perspective on these varying restoration approaches.

Fire risk reduction

Concerns over catastrophic crown fire impacts to human communities and ecosystems, along with the current availability of substantial funding to reduce hazardous forest fuel conditions (see the National Fire Plan [USDA and USDI 2000*a*]), have the potential to drive ecologically insensitive projects, which are not really restorations. If the primary objective of a project is solely to reduce crown fire risk (which may be an appropriate societal goal in some areas), even ''successful'' treatments may further damage forests rather than restoring them. When ecological principles are applied, however, fire risk reduction can be an essential part of ''ecological restoration'' of ponderosa pine forests (Fulé et al. 2001).

Economics

Concerns exist that legitimate and desirable economic goals, such as sustaining rural economies and minimizing subsidy costs, could also lead to ecologically insensitive thinning or logging projects masquerading as forest ''restoration'' (Hanson, 2000, Jenkins 2001, National Forest Protection Alliance 2001). Projects focused on economic outcomes do not qualify as ''ecological restoration'' unless the treatments are based on ecological principles.

However, if ecological principles are used then economic utilization of forest products may enhance forest restoration. For example, restoration treatments will occur sooner and over larger areas if some costs can be recovered through the sale of wood from small-diameter stems. Restoration can be an opportunity for the re-engagement of local communities in the creation of more sustainable forest-based economies (e.g., see the Community Forest Restoration Act of 2000).

Natural regulation

One perspective on Western forests believes that: (1) stand-replacing fires do not cause severe ecological damage because crown fires are natural; and (2) the forests will heal themselves best if we take a hands-off approach and allow natural processes to function with minimum interference (Wuerthner 1999).

Extensive stand-replacing fires naturally occurred in many western forest types (Agee 1993), but not in Southwestern ponderosa pine forests (Swetnam and Baisan 1996). Recent fire history studies in the Black Hills of South Dakota (USA) (Shinneman and Baker 1997) and in the Front Range of Colorado (USA) (Brown et al. 1999) suggest that ponderosa pine forests in those regions may have sustained crown fires of unknown size in the presettlement era. Although no such evidence has been reported for Southwestern ponderosa pine forests, it is possible that localized crown fires were not unknown in this forest type before 1900. Certainly, fire effects are always variable, and even modern crown fires do not have uniformly devastating effects across all burned landscapes. However, the increasingly large crown fires of recent years in ponderosa pine forests are clearly resulting in extreme hydrological, geomorphic, and ecological responses, including amplified flooding (Veenhuis 2002), accelerated soil erosion and stream channel changes (White 1996, Robichaud et al. 2000), loss of old-growth forest (e.g., the Cerro Grande Fire affected much old-growth forest, including large portions of a ∼15 mile^2 contiguous patch where essentially all trees were killed [C. Allen, *personal observations*]), increasing abundance of invasive exotics (Crawford et al. 2001), and conversion of forests to different vegetation types (M. Savage, *unpublished data*). The current state of ecological and historical knowledge of Southwestern ponderosa pine forests provides compelling justifications to actively manage to restore more resilient and sustainable conditions (Covington and Moore 1994, Swetnam et al. 1999).

Presettlement structure restoration

The most substantial scientific work to address the need for restoration of Southwestern ponderosa pine forests and to determine the ecosystem effects of treatments has been made by Covington and co-workers at the Ecological Restoration Institute of Northern Arizona University (Kaye and Hart 1998; W. W. Covington, A. Waltz, P. Fulé, and G. Verkamp, *unpublished report* to U.S. Bureau of Land Management, Arizona Strip District). Their efforts have focused on attempts to reconstruct and reestablish specific stand reference conditions that existed just prior to the date of cessation of the natural fire regime (Moore et al. 1999). The goal has been to replicate tree densities and spatial patterns as accurately as possible for sites where presettlement stand structures have been reconstructed. Conceptually, this approach takes a broad view of ''reference conditions,'' and incorporates the restoration of surface fire as a key process. However, there are some ecological issues concerning on-the-ground implementation of this approach.

The choice of a specific moment in time as the initial restoration target—for example the date of the last widespread fire in the late 1800s (Moore et al. 1999)—is potentially problematic. Any particular moment is unique in the long-term history of an ecosystem, and forests often exist in disequilibrium with current climate to some degree (Millar and Woolfenden 1999). Moreover, an increasing body of evidence indicates that late 20th century and current climate is unprecedented on a time scale of at least 1000 yr (Mann et al. 1998, Crowley 2000).

Restoration of structural characteristics of a forest back to the date of the last widespread fire in the late 19th century implies that tree recruitment processes of the 20th century were entirely unnatural. In fact, post-settlement tree regeneration pulses would have contributed important structural elements to contemporary forests, even if tree-thinning surface fires had continued. It is difficult to estimate what proportion of these cohorts, much less which individual trees, would have survived to maturity (Mast et al. 1999). It may be unwise to automatically choose a century-old date as a regional target condition for current forests, as the replication of plant densities and spatial arrangements that existed at any particular date in the past may compromise ecosystem resilience in future decades and centuries. For example, this structure-oriented approach can result in the aggressive removal of too many trees during the initial entry, which may seriously constrain ecosystem response and management options. Given their relatively slow growth rates, existing trees represent a form of biological capital that should be conserved. Multiple, incremental treatments, using combinations of fire and thinning, may be more conservative and ecologically justifiable than the immediate restoration of a particular structural element, such as the ca. 1880 spatial distribution of overstory tree stems.

Given the great heterogeneity of Southwestern ponderosa pine forests, local data on fire history and presettlement stand structures are required to implement this precise structural restoration approach. Collecting such data is expensive and requires the persistence of presettlement forest ''evidences'' (Fulé et al. 1997), which have been lost in some locations due to logging, harvesting of fuelwood, fire, or decay. As a result, it is not practical, cost effective, or in some cases even possible to reconstruct detailed structural reference conditions for every restoration project area. Moreover, some important data (such as density and spatial distribution of small trees) cannot be reconstructed from remnant historical evidence.

A structure-oriented approach to forest restoration is being proposed for wide implementation in the Southwest because of its methodological clarity, grounding in quantifiable conditions, and scientific and political support (Covington et al. 1997, Moore et al. 1999, Jenkins 2001). We consider historic structure to be one ecologically valid reference criterion for forest restoration. There are, however, theoretical and practical concerns over regional application of a structure-oriented approach (see Morgan et al. [1994], Kaufmann et al. [1994], Landres et al. [1999], Wagner et al. [2000], and Southwest Forest Alliance [2001] for reviews and discussions). We contend that a broader conceptual basis, as outlined in this paper, provides a more comprehensive framework, and one that reflects the diverse ecological conditions that exist in Southwestern forests. We agree with Covington (2000:136) that there is no '''one size fits all' approach to restoring the ecological integrity of ponderosa pine forests.'' A diversity of restoration approaches should be applied in the Southwest.

Conclusions

A primary goal of ecological restoration should be to enhance resilience and sustainability of ecosystems. Incremental adjustment of ecosystems back within an envelope of natural range of variability should achieve this goal (Covington and Moore 1994, Holling and Meffe 1996, Stephenson 1999). A successful restoration is one that sets ecological trends in the right direction. In Southwestern ponderosa pine ecosystems this means reducing tree density and ladder fuels along with associated crown fire risk, protecting large trees, restoring surface fires, and increasing herbaceous ground cover and overall biodiversity levels. A conservative restoration program would incorporate natural variability by avoiding uniform treatments across extensive areas. Spatial heterogeneity is critical to forest biodiversity. Existing forest structures, such as tree groups and large trees, should not be removed simply to recreate historical tree spatial patterns. While historical reference conditions are useful for identifying the types, magnitudes, and causes of ecosystem change, such reconstructions are best used as general guides rather than as precise and rigid prescriptions (Landres et al. 1999).

Theories of restoration ecology and the practice of ecological restoration are evolving rapidly. We propose not so much a departure from current models as a broader framework that encompasses a diversity of approaches. Restoration science cannot proceed without empirical tests and experimentation across a broad range of conditions, and restoration practice needs to incorporate new insights derived from the scientific and practical creativity of many individuals and institutions. We need steady progress in restoration science in order to sustain the social, political, and financial support required for an effective regional restoration program. Some restoration experiences, however, will probably prove humbling, as our knowledge and methods will always be imperfect.

Risks and trade-offs are inherent in wildland management. For example, a controversial trade-off involves consideration of merchantable timber harvest as part of restoration. Commercial activities can help fund restoration of less hazardous forest fuel conditions more quickly, but raise the risk of extractive economic imperatives dominating decision making about ''restoration'' activities.

We need to begin large-scale restoration of ponderosa pine ecosystems now. The present vulnerability of these forest ecosystems requires that we temper our need for more complete information with an urgency created by the current risk of crown fires. Even restoration failures at this point can provide information useful in refining future work, as long as we simultaneously invest in research and monitoring. At the same time, we must be cautious in our application of restoration treatments. We must manage for surprise, whether from climate variability, human influences, or the synergies among known and unknown factors. It would be prudent to incorporate buffers for uncertainty in restoration work. Impatience, extractive economics, or hubris could lead to widespread application of unduly intrusive treatments that could further damage forest ecosystems. The broad perspective outlined here supports vigorous but conservative approaches for immediately reducing crown fire risk and restoring natural variability and long-term resilience to ponderosa pine forest ecosystems in the American Southwest.

Acknowledgments

We appreciate the efforts of colleagues at the Grand Canyon Forest Partnership and the Ecological Restoration Institute of Northern Arizona University to share their restoration experiences and perspectives, especially Pete Fulé, Wally Covington, and Brad Ack. Carl Edminster, Bill Block, Jon Keeley, Peter Landres, Dave Parsons, Phil Weatherspoon, and an anonymous reviewer provided helpful comments on earlier versions of this paper. This material is based upon work supported by the USDA Forest Service, U.S. Geological Survey, Wilburforce Foundation, Laird Norton Foundation, New Mexico Community Foundation, and the National Science Foundation under Grant number SBR-969410.

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