Section 1—Overview and Integration

This report synthesizes scientific information to inform strategies that will promote resilience of socioecological systems and sustain values at risk in the Sierra Nevada and Southern Cascade Range. The chapters in this opening section integrate key findings and themes from the remaining chapters of the report. Chapter 1.1 is an introduction that explains the overall purpose and scope of the report, defines resilience and associated terms, and then considers how the concept of socioecological resilience can be applied to particular issues in this region. Chapter 1.2 is a comprehensive integration of the full report; it outlines a range of approaches to promote resilience in response to broad-scale management challenges. Chapter 1.3 provides a more focused synopsis of emerging strategies to promote ecological resilience, including restoring fire as an ecological process and reducing fire hazard through landscape-scale treatments designed to actively sustain wildlife habitat and restore riparian ecosystems. Chapter 1.4 is a summary of the role of climate change, and compiles findings from the other chapters of the report on projected impacts as well as strategies to promote resilience to these impacts. Finally, the last chapter of this section (1.5) reviews adaptive management initiatives from the study area, then highlights several cross-cutting research gaps where additional scientific information would help refine strategies to promote resilience.

Jonathan Long

Mortar holes at Harden Lake demonstrate the long history of interaction between humans and the forests and waters of the synthesis area.

Chapter 1.1—Introduction

Jonathan W. Long,[1] Carl Skinner,[2] Hugh Safford,[3] Susan Charnley,[4] and Patricia L. Winter[5]

Purpose

National forests in the Sierra Nevada and Southern Cascade bioregions have begun to review and revise their land and resource management plans (LRMPs). The three most southern national forests of the Sierra Nevada (Inyo, Sequoia, and Sierra) were selected to be the lead forests for the Forest Service Pacific Southwest Region (Region 5) and are among the first of the Nation's 155 national forests to update their plans. The new planning rule requires the forests to consider the best available science and encourages a more active role for research in plan development. To help meet this requirement, the Region 5 leadership asked the Pacific Southwest Research Station (PSW) to develop a synthesis of relevant science that has become available since the development of the existing LRMPs. Regional leadership and stakeholders suggested that *An Ecosystem Management Strategy for Sierran Mixed-Conifer Forests*, PSW-GTR-220 (North et al. 2009), served as a useful format, but that the content and scope of that report should be expanded to address additional biological, social, and economic challenges. In response to this request, a team of scientists from PSW and the Pacific Northwest Research Station (PNW) assembled to discuss the purpose of the effort and to engage with forest managers and stakeholders. Team members participated in the public Sierra-Cascades Dialog sessions and met with Forest Service leadership and managers, and external stakeholders, to learn about their concerns, interests, and management challenges.

Recognizing that a simple compilation or annotated bibliography of information would not meet management needs, the team discussed what format would make a synthesis more relevant and understandable. Most scientific research yields incremental steps forward, but those advances can be compiled to develop an understanding of broader issues and larger systems. Many of the major environmental challenges that are likely to significantly affect ecosystem resilience, such

[1] Research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

[2] Geographer (emeritus), U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002.

[3] Regional ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, 1323 Club Dr., Vallejo, CA 94592.

[4] Research social scientist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 620 SW Main St., Suite 400, Portland, OR 97205.

[5] Research social scientist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Dr., Riverside, CA 92507.

as climate change, wildfire hazard, and air pollution, are best understood at broad scales. To maintain and improve ecological integrity and associated ecosystem services (e.g., biodiversity, ecosystem health, water quality and quantity, recreation, economically viable communities) will require assessing and mitigating potential stressors in the near and long term across large landscapes. Therefore, the synthesis team sought to produce a synthesis of recent scientific information that would inform strategies to promote resilience of socioecological systems and sustain values at risk in the synthesis area over the short and long terms given expected stressors. This introductory chapter explains that objective in further detail.

Synthesis Area

This synthesis presents recent science that is relevant to forest planning in the synthesis area, which includes the forested mountains of the Sierra Nevada, the southern Cascade Range, and the Modoc Plateau (fig. 1). The synthesis primarily focuses on conifer-dominated forest ecosystems that constitute the vast majority of this area, although chapters in the "Water Resources and Aquatic Ecosystems" section discuss forested riparian areas (chapter 6.2), wet meadows (chapter 6.3), and lakes (chapter 6.4). The broader concepts considered in this document are likely to be useful beyond the area and ecosystems of focus. However, many of the specific examples may not necessarily be applicable to other areas, especially drier areas that are more representative of the Great Basin.

Scope and Approach

This synthesis emphasizes recent advances in scientific understanding that pertain to some of the most important issues facing managers across the synthesis area. These advances can help managers integrate ecological and social considerations across multiple spatial and temporal scales. The intent of this synthesis was not to create a comprehensive summary of the latest science, and chapters do not represent a complete review of all available literature. A number of management-oriented syntheses that focus on various topics and disciplines have recently become available. These are referenced within the synthesis chapters and are also listed in the appendix.

The science synthesis team selected topics they considered most highly relevant to management in the focal parts of the synthesis area, based on input from management, stakeholders, and reviewers, and to be consistent with priority topics highlighted in the planning rule:

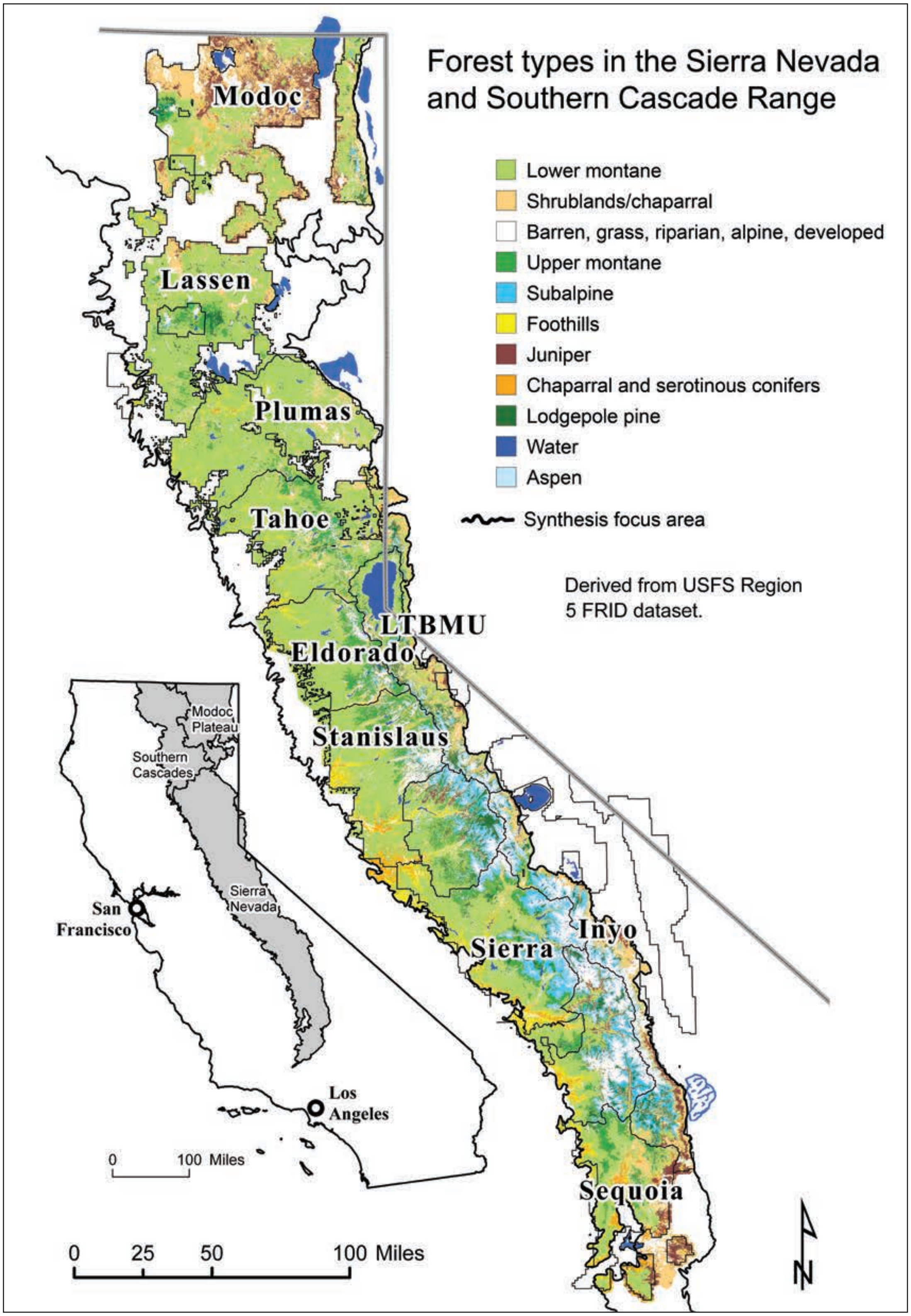

Figure 1—Focal areas of this synthesis are the conifer-dominated forests in the mountains of the Sierra Nevada, southern Cascade Range, and Modoc Plateau. LTBMU = Lake Tahoe Basin Management Unit. Map by Ross Gerrard.

> The planning rule is designed to ensure that plans provide for the sustainability of ecosystems and resources; meet the need for forest restoration and conservation, watershed protection, and species diversity and conservation; and assist the Agency in providing a sustainable flow of benefits, services, and uses of NFS lands that provide jobs and contribute to the economic and social sustainability of communities (USDA FS 2012).

This synthesis is modeled in part after two prior synthesis reports published by the Pacific Southwest Research Station, PSW-GTR-220 (North et al. 2009) and PSW-GTR-237 (North 2012), which focused on management strategies for Sierra Nevada mixed-conifer forests. These reports provided a foundation for many of the broader strategies emphasized in this synthesis, and similarly emphasized a few wildlife species that have been management priorities.[6] This synthesis expands beyond terrestrial forest and fire ecology to include watershed and aquatic values and social systems, given their importance in the planning rule. Central themes running through the synthesis are the importance of scaling up from short-term, site-scale understandings to address long-term, landscape-scale processes, and the importance of considering interactions within socioecological systems. In addition, the synthesis considers how changes in climate, air pollution, and other stressors are creating novel conditions that require broad adaptive approaches to management.

Like PSW-GTR-220 and PSW-GTR-237, this synthesis integrates findings from a range of scientific disciplines to inform the development of management strategies. The goal of this synthesis is to inform forest planning across the synthesis area rather than tactics at the project level. Strategic planning helps to define broad, integrative approaches that guide the goals, location, and timing of projects. Strategic goals are often more conceptual and qualitative than the quantitative nature of project planning (Wood and Dejeddour 1992). The scales of space and time considered in strategic planning are usually more expansive (across broad landscapes and decades) than scales considered in project-level planning, which focus on a more localized place over a few years (Partidário 2007). Therefore, the resolution and precision of useful information often differ between these levels of planning.

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[6] The two terrestrial wildlife chapters in this synthesis focus on three species that have been a priority for management and research: California spotted owl (*Strix occidentalis occidentalis*), fisher (*Pekania pennanti*), and Pacific marten (*Martes caurina*). These species have been designated as Forest Service Sensitive Species by the regional forester. They are likely to be a focus of fine-filter analysis and monitoring under the new planning rule. In addition, they have had special habitat designations and they range across large areas; these attributes pose special challenges for landscape-scale management.

Focus on Peer-Reviewed Literature

The science synthesis is not an exhaustive review of the literature, a task that would have been beyond the scope and resources of the synthesis team. This synthesis focuses on scientific findings from published, peer-reviewed literature, with the majority of references published since the last round of science synthesis in the region, which included the Sierra Nevada Ecosystem Project (Erman and SNEP Science Team 1997) and a follow-up report on livestock grazing (Allen-Diaz et al. 1999). Peer-reviewed literature is not the only valid source of information to inform management strategies, but a focus on that literature narrows the breadth to a more manageable level, highlights regional-scale strategic issues that have been considered by scientists (rather than narrower topics for which information may be very limited), and reduces the burden of having to add an additional layer of peer review. Several of the chapters also include gray text boxes that alert readers to recent or pending relevant studies that are not yet published in peer-reviewed literature. In addition, some chapters provide references to websites or reports on particular topics that illustrate important ideas, although particular findings from such sources are not presented nor endorsed.

This synthesis focuses on published peer-reviewed literature that was most relevant to the synthesis area, although chapters do include gray text boxes that alert readers to recent relevant studies that may not yet be published.

The emphasis on literature that has been clearly peer-reviewed is likely to leave out relevant scientific information that may be contained in reports by agencies, universities, and non-profit organizations, as well as in master's theses and dissertations. This restriction may pose particular concern for social, economic, and health issues. However, the plan revision process includes the parallel assessment phase, which is not limited to peer-reviewed literature.

In general, the team focused its scope to peer-reviewed research that occurred in the synthesis area or in forest ecosystems with relevant ecological or social conditions. Ecological and social research is always context specific, and there are few, if any, universal principles in either of these disciplines because place, time, and research scope all affect the data that are collected. Scientific studies are published with strict caveats about their spatial and temporal scales, making it difficult for managers and even other scientists to integrate and distill the information for particular management situations. The science synthesis tries to clarify the extent and limitations of available information, especially by highlighting various research gaps.

All chapters of the synthesis were reviewed by numerous individuals within Forest Service management and research, as well as by scientists from outside the Forest Service. This review process greatly helped to enhance both the content and readability of the synthesis.

Structure

The science synthesis has several formats that reflect the effort to distill and integrate relevant research at different levels. The majority of the synthesis is composed of chapters that summarize information or address key questions in specific topical areas (e.g., forest ecology, air quality, soils, and ecosystem services). These chapters address issues the authors considered highly relevant and ripe for synthesis, including topics suggested by managers, stakeholders, and reviewers.

The chapters in this first section have a different structure, which is designed to promote greater integration and generalization. Chapter 1.2, "Integrative Approaches," condenses much of the information from the different disciplines and summarizes themes that run through the topical chapters. Chapters 1.3, "Synopsis of Emergent Approaches," and 1.4, "Synopsis of Climate Change," are highly condensed chapters that succinctly integrate and summarize central themes relevant to management of Sierra Nevada forests. Those two subjects were selected to address emerging challenges faced by the national forests. The structure and tone of chapter 1.3 is intentionally different from other chapters; it outlines approaches to help promote socioecological resilience within the synthesis area that have emerged from science integration efforts, including several hypotheses to be tested in an adaptive management framework, perhaps within demonstration landscapes that have a special emphasis on monitoring, research, and modeling. A final chapter in the integration section (chapter 1.5) focuses on adaptive management efforts and research gaps that also cut across the topical sections. Readers are encouraged to explore these different levels to understand connections across the various disciplines and topics.

Definitions of Resilience and Related Concepts

> Our goal is to sustain and restore ecosystems that can deliver all the benefits that Americans want and need. Due to changing climate, we may not be able to restore them to their original condition, but we can move them toward ecological integrity and health. The Forest Service recognizes that increasing the pace and scale of restoration and active management of the National Forests is critically needed to address these threats to the resiliency of our forests and watersheds and the health and safety of America's forest-dependent communities (Tidwell 2012).

> Our goal for the Pacific Southwest Region is to retain and restore ecological resilience of the national forest lands to achieve sustainable ecosystems that provide a broad range of services to humans and other organisms (USDA FS 2011).

Current goals for Forest Service policies (stated above) emphasize the concepts of restoration, resilience, and integrity. These terms are related and they are often used together, although their specific definitions have different emphases.

Restoration

Ecological restoration is commonly defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 1994: 132). The Forest Service has adopted the Society for Ecological Restoration (SER 1994) definition of ecological restoration while also incorporating the concepts of resilience and capacity to respond to future conditions by adding the following statement: "Ecological restoration focuses on reestablishing the composition, structure, pattern, and ecological processes necessary to facilitate terrestrial and aquatic ecosystems sustainability, resilience, and health under current and future conditions" (Office of the Federal Register 2012: 70).

Integrity

Originating from the field of water quality, ecological integrity has been defined as a combination of chemical, physical, and biological integrity, with integrity specifically defined as "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having species composition, diversity, and functional organization comparable to that of natural habitats of the region" (Karr and Dudley 1981: 56). Ecological integrity can be seen as a state that allows an ecosystem to withstand and recover from natural and human-caused perturbations (Karr and Dudley 1981). The definition of ecological integrity in the recent Forest Service Planning Rule reflects this concept of a resilient state: "The quality or condition of an ecosystem when its dominant ecological characteristics (for example, composition, structure, function, connectivity, species composition and diversity) occur within the natural range of variation and can withstand and recover from most perturbations imposed by natural environmental dynamics or human influence" (Office of the Federal Register 2012: 67).

Processes, Disturbances, and Stressors

Recent syntheses of ecological theory stress the importance of temporal and spatial scale of various changes in ecosystem structure, relative to the part of an ecosystem under consideration, when identifying ecological processes as “disturbances” and “stressors.” A disturbance is commonly defined as a relatively discrete event that disrupts ecosystem structure and alters resource availability (White and Pickett 1985), and which is caused by a factor external to the level of interest (Pickett et al. 1989, Rykiel 1985). A stressor refers to a more chronic influence that reduces the potential of ecosystems to be resilient to disturbances (Borics et al. 2013).[7] Others have applied the terms “pulse” to refer to short-term effects and “press” to describe long-term influences, with the time scale being relative to the lifespan of the affected organisms (Glasby and Underwood 1996).

Ecological Resilience

Resilience has been broadly defined as “the capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity” (Walker et al. 2006: 2), with “shock” being another term for a disturbance or pulse effect. This definition follows from an earlier concept of ecological resilience as the amount of disturbance a system can absorb without shifting into an alternate configuration or regime, where a different range of variation of ecological processes and structures reigns (Gunderson 2000). This definition does not require that a particular condition be desirable, as discussed further below, and it is possible for degraded systems to be resilient. However, applications of this definition do implicitly require consideration of temporal changes relative to a reference condition, either backward to a past condition (or range of conditions) or forward to a future condition. The ecological concepts of restoration, integrity, and resilience all depend on the definition of a reference state and our ability to measure departure from that state (Safford et al. 2012). Such a reference need not necessarily include human influence; however, the long presence of humans in California and their pervasive modern influence on ecosystems suggest that sustainable management will only be possible by explicitly acknowledging the roles that humans play and have played in affecting the status and trend of synthesis area ecosystems (Nowacki et al. 2012).

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[7] The Forest Service has defined stressors in relation to ecological integrity as “factors that may directly or indirectly degrade or impair ecosystem composition, structure or ecological process in a manner that may impair its ecological integrity, such as an invasive species, loss of connectivity, or the disruption of a natural disturbance regime” (Office of the Federal Register 2012: 70). This definition focuses more on the quality of outcome than the frequency of the event.

Integration of Social and Ecological Systems and Socioecological Resilience

A premise of this synthesis is that the success of attempts to restore the integrity of ecosystems or maintain or increase the resilience of ecosystems to global change will depend on the extent to which those efforts can integrate ecological and socioeconomic concerns (Folke et al. 2010). An interdependent socioecological system ("SES") has been defined by Redman et al. (2004) as:

1. A coherent system of biophysical and social factors that regularly interact in a resilient, sustained manner;
2. A system that is defined at several spatial, temporal, and organizational scales, which may be hierarchically linked;
3. A set of critical resources (natural, socioeconomic, and cultural) whose flow and use is regulated by a combination of ecological and social systems; and
4. A perpetually dynamic, complex system with continuous adaptation.

The success of attempts to restore the integrity of ecosystems or maintain or increase the resilience of ecosystems to global change will depend on the extent to which those efforts can integrate ecological and socioeconomic concerns.

Key areas of emphasis in the synthesis flow from the SES concept, including the importance of understanding linkages across spatial and temporal scales; the interaction of biophysical and social factors; the flow of critical resources or ecological goods and services that are natural, socioeconomic, and cultural; and the dynamic and adaptive nature of systems. This synthesis features discussion of the triple-bottom line concept (see chapter 9.1, "Broader Context for Social, Economic, and Cultural Components") as a framework for explicitly considering ecological, social, economic, and cultural values toward a more integrated understanding of benefits to society.

Socioecological Resilience and Adaptability

Scientists define socioecological resilience as the capacity of systems to cope with, adapt to, and influence change; to persist and develop in the face of change; and to innovate and transform into new, more desirable configurations in response to disturbance (Folke 2006). This definition emphasizes the dynamic and adaptive nature of socioecological systems and departs from narrower definitions of resilience that emphasize a return to an equilibrium condition following disturbance (Folke 2006). It also recognizes that ecological systems have potential to change in ways that are undesirable for human communities.

Adaptability refers to the capacity of humans to manage resilience, which determines whether people can respond intentionally to create a desirable configuration and to avoid undesirable ones (Walker et al. 2006). The idea of adaptation is emphasized in a definition of community resilience as "the existence, development,

Rather than trying to minimize or resist fires, floods, and other intrinsic ecological processes, resilience-based strategies emphasize facilitating more regular, lower severity events as a way to reduce the vulnerability of the socioecological system to unpredictable severe ones.

and engagement of community resources by community members to thrive in an environment characterized by change, uncertainty, unpredictability, and surprise" (Magis 2010: 402) (see chapter 9.4, "Strategies for Job Creation Through National Forest Management").

Systems that remain in a condition with essentially the same function, structure, identity, and feedbacks may demonstrate resilient change, whereas those that move to a new configuration may be described as undergoing transformation or "regime shift" (Berkes and Ross 2012). However, real world outcomes are unlikely to fall neatly into one category or the other, but rather are likely to fall along a continuum associated with changes in system function over time. Research within the synthesis area has been undertaken to try to determine where observed changes in high-elevation whitebark forests lie on such a continuum (see chapter 1.5, "Research Gaps: Adaptive Management to Cross-Cutting Issues").

Sugihara et al. (2006: 62) contended that fire was so regular and intrinsic in many California ecosystems that when viewed at the landscape scale and when operating within its natural range of variation, fire should be considered as an "incorporated ecological process" rather than as a disturbance (fig. 2). They compare fire to other processes, such as precipitation and flooding, which are essential to perpetuating ecosystems (Sugihara et al. 2006). Although both fires and floods can damage important values, they also have important roles in rejuvenating ecosystems by removing living and dead vegetation, resetting vegetation trajectories, redistributing nutrients, and exposing mineral soils. Especially in many forested ecosystems in California, human alteration of fire regimes through suppression has led to fires with behavior and effects that are outside the range of natural variation (Sugihara et al. 2006) (fig. 3). Accordingly, fire suppression acts as a stressor in such systems. Rather than trying to minimize or resist fires, floods, and other intrinsic ecological processes, resilience-based strategies emphasize facilitating more regular, lower severity events as a way to reduce the vulnerability of the socioecological system to unpredictable severe ones (de Bruijne et al. 2010, Liao 2012).

These definitions point to important concepts that can be incorporated in plans to promote ecological integrity and social well-being. The next chapter goes deeper into the concept of socioecological resilience by describing some of the potential threats to critical resources that could shift systems in the synthesis area to less desirable configurations.

Scott Stephens

Figure 2—Wildfires can be considered as an incorporated natural process in the Illilouette Basin within Yosemite National Park.

Zev Balsen

Figure 3—Crown fires can pose substantial threats to human communities, and the legacy of such events is an important consideration in promoting resilience of socioecological systems in the synthesis area. Shown here is a hotshot crew at the 2007 Antelope Complex Fire.

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Chapter 1.2—Integrative Approaches: Promoting Socioecological Resilience

Jonathan W. Long,[1] Carl Skinner,[2] Malcolm North,[3] Carolyn T. Hunsaker,[4] and Lenya Quinn-Davidson[5]

Introduction

This chapter begins by discussing current challenges for ecosystem management that emerged from multiple chapters of the full synthesis. It then considers integrative approaches to promote resilience, including general strategies that recognize the integrated nature of socioecological systems, the importance of promoting disturbance regimes upon which these systems have evolved, and opportunities to integrate social considerations into strategies (see chapter 1.1, "Introduction," for definitions of key terms). It continues by outlining an adaptive management approach to scale up current practices so that planning and implementation are more congruent with the scales at which processes affect ecosystems in the synthesis area. The following chapter 1.3, "Synopsis of Emergent Approaches," focuses on three important themes that are touched on in this chapter; these themes emerged largely from synthesizing findings from the forest ecology, fire, and wildlife chapters. Chapter 1.4, "Synopsis of Climate Change," summarizes how climate change relates to all the chapters in this synthesis and strategies to promote resilience to that stressor. Chapter 1.5, "Research Gaps: Adaptive Management to Cross-Cutting Issues," discusses a number of current adaptive management efforts and important topics that emerged as priorities for adaptive management and research. Altogether, the chapters in this section outline strategies to respond proactively to expected challenges in the synthesis area.

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[1] Research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

[2] Geographer (emeritus), U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002.

[3] Research plant ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

[4] Research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 2081 E. Sierra Avenue, Fresno, CA 93710.

[5] Staff research associate, University of California Cooperative Extension, 5630 South Broadway, Eureka, CA 95503.

The Challenge of Multiple Stressors

The challenges facing national forests in the synthesis area reflect long-standing natural processes including fire, decades of fire suppression and other practices that have altered ecosystems and increasingly, novel stressors associated with human activities within the region and even across the globe.

The challenges facing national forests in the synthesis area have grown much more complex as the forests themselves have changed and as external influences have evolved. These challenges reflect long-standing natural processes (including fire, drought, and insects), decades of fire suppression and other practices that have altered ecosystems (e.g., hydrologic modifications, habitat fragmentation, loss of biodiversity, etc.), and increasingly, novel stressors associated with human activities within the region and even across the globe (Folke 2006, Steffen et al. 2007). Incursions of nuisance plants and animals, diseases, and pollutants, combined with a legacy of human influences on climate, fire regimes, and species extinctions, are forming "novel ecosystems" (Hobbs et al. 2009), which do not have historical analogues upon which to base predictions or to serve as clear references for restoration. The remainder of this chapter focuses on several opportunities to promote system resilience to stressors.

There are many challenges to managing forests of the synthesis area in the 21st century, including an array of evolving, novel stressors:

- Dust from as far away as China may be causing snowpack to decline and polluting water bodies in alpine areas that have historically been regarded as relatively pristine wilderness (see chapter 8.1, "Air Quality").
- The barred owl (*Strix varia*) is invading forests at the expense of the California spotted owl, and there are no clear solutions to prevent this incursion (Gutierrez et al. 2007) (see chapter 7.2, "California Spotted Owl: Scientific Considerations for Forest Planning").
- The fisher is being poisoned by application of rodenticides by marijuana growers to protect their illicit crops (Gabriel et al. 2012) (see chapter 7.1, "The Forest Carnivores: Marten and Fisher").
- Populations of priority amphibians face combined effects of climate change, introduction of predatory fishes, disease, pesticides, disrupted flow regimes, and other habitat impacts (see chapter 6.4, "Lakes: Recent Research and Restoration Strategies").
- Climate change is projected to shift precipitation from snow to rain, which may reduce seasonal water availability in forest soils, and negatively affect aquatic systems and associated ecosystem services by altering channel stability and stream hydrographs, especially by reducing summer baseflows (see chapter 6.1, "Watershed and Stream Ecosystems").

- Climate-driven projections suggest that forests will become more susceptible to insect attack and disease caused by native and introduced pathogens (Evangelista et al. 2011, Sturrock et al. 2011). A complex interaction of climate change, altered fire regimes, and air pollution pose threats to forest resilience (see chapter 8.1). Research has already documented increased rates of insect attack, disease, and mortality in many Western forests that could portend vulnerability to substantial changes in forest structure, composition, and function (van Mantgem et al. 2009).
- Scientists report increasing frequency and extent of wildfires, along with the increasing occurrence of uncharacteristically severe wildfire in the synthesis area (Lenihan et al. 2003; Miller and Safford 2012; Miller et al. 2009, 2012; Westerling et al. 2011) (see chapter 4.1, "Fire and Fuels").

Land management agencies have a limited ability to prevent these impacts, but effective management actions can mitigate their effects. The new planning rule acknowledges the likelihood that some stressors may render it infeasible to maintain or restore ecological conditions to maintain a viable population of a species of conservation concern in a planning area. The existence of such stressors complicates management because it becomes harder to evaluate the effects of management actions without accounting for the stressor that cannot be controlled. Interactions between climate change, other stressors, and disturbances can induce positive feedbacks that threaten to push systems beyond key thresholds; these challenges should be considered as syndromes rather than as isolated problems (Rapport and Maffi 2011). Common indicators of such syndromes include losses of biodiversity, especially predators; simplifications of food webs; eutrophication of aquatic systems; and increasing prevalence of invasive species and diseases (Rapport and Singh 2006). Assessments, research studies, and management strategies that target these syndromes will be most effective if they consider multiple factors and their synergistic effects. Amphibians in lakes provide an example in the Sierra Nevada (see chapter 6.4) of how a response to a syndrome could include removing introduced fishes from lakes to help amphibians better withstand disease and climate change. Other strategies for assessing and responding to these syndrome impacts have been to develop highly integrated ecological indexes or state of the environment reports, which consider effects on both ecosystems and social systems, and emphasize opportunities for human actions to improve ecological health (Rapport and Singh 2006).

Conditions That May Reduce Socioecological Resilience

Periodic disturbance plays a fundamental role in the development of socioecological systems by facilitating reorganization and renewal (Cabell and Oelofse 2012, Folke 2006). However, people often regard such disturbances negatively because of their disruptive effects. Indeed, major shocks that push systems beyond critical thresholds can induce large and persistent loss in the flows of ecological services. Such shocks as well as more frequent stressors can reduce the ability of a system to recover from future disturbances.

Systems that remain in a condition with essentially the same function, structure, identity, and feedbacks may demonstrate resilient change, whereas those that move to a new configuration may be described as undergoing transformation or "regime shift" (Berkes and Ross 2012). However, real-world outcomes are unlikely to fall neatly into one category or the other, but rather are likely to fall along a continuum associated with changes in system function over time. For example, research within the synthesis area has been undertaken to try to determine where observed changes in high-elevation whitebark forests lie on such a continuum (see chapter 1.5).

Human actions have contributed to the potential for regime shifts that have negative impacts on livelihoods and societal development (Folke 2006). Stressors associated with anthropogenic activities, such as climate change, pollution, and species invasions, are critically important to consider from a socioecological perspective, although they are difficult to manage because they originate from outside local landscapes or do not recur frequently and predictably. Human alteration of fire regimes through suppression has promoted fires with behavior and effects that are outside the range of natural variation (Sugihara et al. 2006). The lasting legacy of fire suppression is an important stressor that can be directly addressed through management in the synthesis area, although reducing those accumulated fuels requires difficult tradeoffs among short- and long-term costs and risks to values held by different groups of people.

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Fire is a fundamental ecological process that often repeats in relatively predictable ways across a landscape. Native Americans in the synthesis area historically lived with fire and used it to promote ecological outcomes that supported their communities (fig. 1). Changes in forest fuel and habitat conditions over time can leave systems vulnerable to regime shifts (Agee 2002). If forests that have uncharacteristically large accumulations of living and dead fuels are not managed, when they inevitably burn there will be a loss of ecosystem services, including biodiversity and other social values (Franklin and Agee 2003). Consequently, various topical sections of this synthesis describe negative

Jonathan Long

Figure 1—California black oaks demonstrate the importance of viewing social and ecological systems in an interconnected manner. Because these trees have been cultivated and used by Native Americans and other people, they have important roles in providing wildlife habitat, and their condition is fundamentally connected to fire regimes in the synthesis area.

consequences of large and severe fires on many socioecological values in the modern era. These impacts include the following:

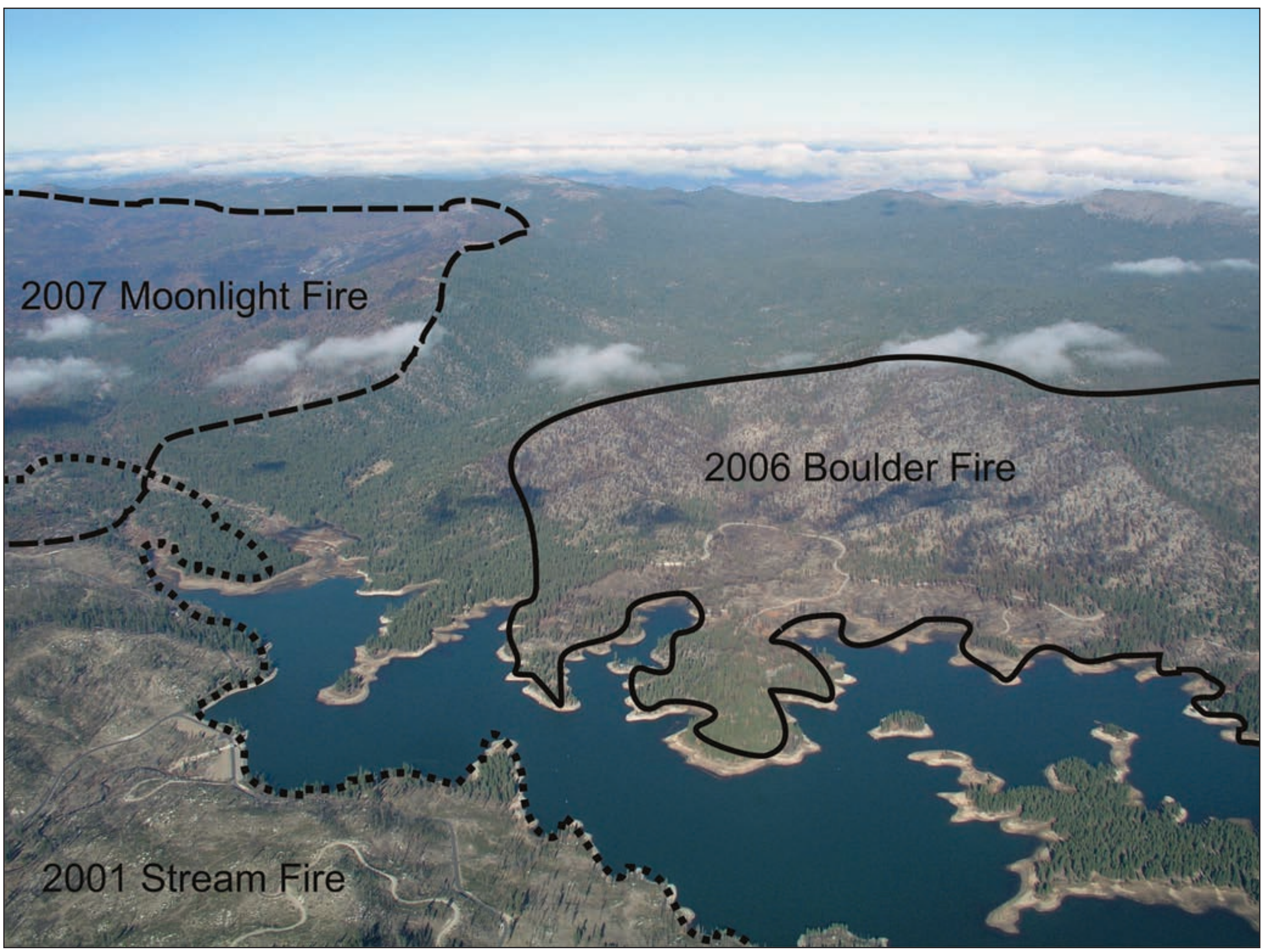
1. High levels of tree mortality over large areas can forestall recovery of forested conditions and associated ecosystem services for long periods (decades to centuries) and may be a catalyst for regime shifts as climate change progresses. Even if these systems begin to regrow trees, they may be more vulnerable to effects of future fires (chapter 4.3, "Post-Wildfire Management")
2. Widespread tree mortality and persistent loss of trees may be associated with significant emissions of carbon, as forests are converted from carbon sinks into source areas for extended period (Dore et al. 2012) (chapter 2.1, "Forest Ecology").

3. Large patches of tree mortality may represent a loss of breeding habitat for species such as California spotted owl, fisher, and Pacific marten (chapters 7.1 and 7.2).
4. Intense, large, and long-lasting wildfires are likely to cause exceedances of air quality standards instituted to protect human health (Cisneros et al. 2010). It is much more difficult to control air quality and other impacts from those wildfires than from prescribed fires (chapter 8.1).
5. Although aquatic systems often demonstrate relatively high levels of resilience and important rejuvenating effects following wildfire, very large and severe wildfires may induce significant channel erosion and reorganization that can extirpate vulnerable aquatic populations, degrade downstream water quality, reduce storage capacity of downstream reservoirs, and elevate flood risks (chapters 4.3 and 6.1).

It is difficult to identify critical thresholds beyond which the resilience of social systems substantially erodes (see chapter 9.4, "Strategies for Job Creation Through National Forest Management"). However, fires can cause a range of impacts to social values, and much greater impacts are expected to result from fires that burn intensely, over large areas, and for long periods. It is also important to recognize that residential fire disasters can be avoided through treatments in the narrow "home ignition zone" surrounding dwellings (Cohen 2000, Reinhardt et al. 2008). However, large, intense and unmanageable wildland fires pose significant and costly challenges to agencies responsible for addressing short-term health and safety hazards, including smoke, flooding, and erosion. Such fires can induce the acute stresses of evacuation, as well as longer term impacts to individual health and community well-being (Hodgson 2007). Severe wildfires that cause widespread tree mortality affect socioeconomic values, including timber flows that contribute to local economies and maintain their infrastructure and markets for forest products. The nonmarket value of wildfire impacts are potentially very large but also challenging to assess owing to the size and diversity of resources that may be affected; the variability of responses across space and time (including the possibility that social preferences are likely to vary over time), and the infeasibility of valuing the cultural heritage of indigenous peoples (Venn and Calkin 2009). Furthermore, large fires threaten values held by people well beyond California, as residents of New England expressed willingness to pay substantial sums to treat and protect old-growth forests associated with spotted owls from high-intensity wildfire (Loomis and Gonzalez-Caban 1998).

Large and severe fires (fig. 2) may constitute a threat to resilience for some components of a socioecological system but not others. Recent syntheses have focused on the problem of "megafires," which some authors have described as having catastrophic damages in terms of human casualties and economic losses (San-Miguel-Ayanz et al. 2013). Adams (2013), writing from a perspective in Australia, suggested a size threshold for such megafires at 100 000 ha. Until the Rim Fire of 2013, none of the fires within the synthesis area had exceeded that size threshold. Although fire size alone can increase risks and challenges during an event, it is important to consider consequences rather than size alone (Reinhardt et al. 2008).

Because the concept of resiliency is scale-dependent and requires viewing outcomes along a continuum (see chapter 1.1), it is important to evaluate whether outcomes are "characteristic" by considering the spatial and temporal arrangement of a series of events in relation to the expected distribution of outcomes. Not all fires that result in widespread tree mortality should be viewed as causing a loss



Scott Stephens

Figure 2—Multiple fires have burned large patches with high severity in the watershed of Antelope Lake; such processes have potential for both short-term and long-lasting impacts to a wide range of social and ecological values. Fire boundaries illustrated by Brandon Collins.

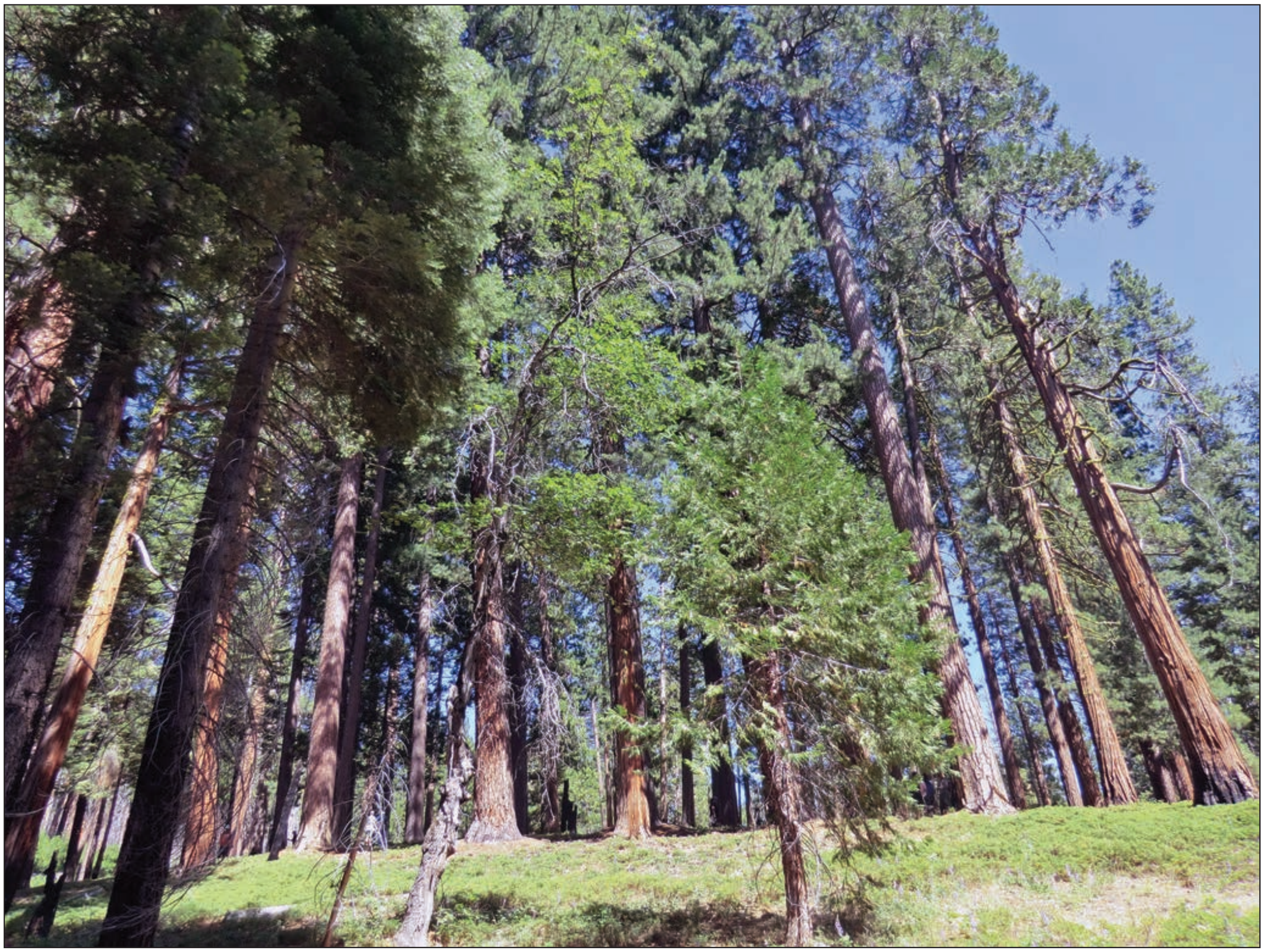
of ecological resilience; in some cases, trees may have invaded areas that were much more open or even dominated by nonforest vegetation under a fire regime that existed prior to fire suppression (see chapter 4.3). From a long-term landscape perspective, such fires may be seen as corrective. Yet, the cumulative landscape impact of large areas of high-severity burns followed by reburns may also lead to transformations of ecosystems, including extended periods with reduced availability of mature forest (see chapter 4.3). Consequently, long-term impacts to important ecological services are likely to be linked to the size of the high-severity patches, which influences recovery of both terrestrial and aquatic systems (Dunham et al. 2007, Lentile et al. 2007). Another concern associated with large patches of high-severity burn is the potential loss of genetic diversity, especially of trees that may have special resistance to nonfire disturbances such as insects and diseases.

The cumulative landscape impact of large areas of high-severity burns followed by reburns may also lead to transformations of ecosystems, including extended periods with reduced availability of mature forest. Long-term impacts to important ecological services are likely to be linked to the size of the high-severity patches, which influences recovery of both terrestrial and aquatic systems.

The ultimate measure of resilience is how systems respond to major shocks, so it can be a difficult property to evaluate except in hindsight. However, there may be useful surrogates or indicators that point to vulnerabilities. Chapter 1.5 considers the need to evaluate impacts of fires of different severities, and concludes with further consideration of indicators of resilience. There will be important resources that decline in the absence of recurring fire. Some of these components may include yellow pines, sugar pine, and California black oak in frequent fire mixed-conifer forests (fig. 3 and chapter 4.2) and wildlife species that depend on habitat created and maintained by fire of different severities. In addition, valuable components such as large trees can become increasingly vulnerable to fire as duff accumulates in the absence of frequent fire (Hood 2010). A general approach for evaluating impacts of wildfire on social and ecological values is to measure ecological departure from historical range of variability (HRV) (Venn and Calkin 2009). Such an emphasis is consistent with the idea that both the curtailment of fire and uncharacteristically severe wildfires are undesirable. Moritz et al. (2013) discuss a conceptual approach to guide ecosystem management using boundaries associated with too much or too little fire based upon HRV and social preferences and cite examples of applications, including an analysis of risks of fire in chaparral communities to viability of steelhead populations in southern California.

Risks of Insufficient Treatment

North et al. (2012) pointed out that large areas of the Sierra Nevada are unlikely to receive needed forest treatments. Forgoing treatments can result in lasting impacts to ecosystems, human communities, and myriad ecosystem services. For example, deferring tree harvest for extended periods can not only impose social and economic impacts, but can also result in losses of key infrastructure needed to



Jonathan Long

Figure 3—Large "legacy" pine trees loom over a California black oak and incense cedars in an area that has burned twice in the past 30 years within Yosemite National Park.

maintain capacity to conduct restoration treatments and preserve options for future forest management (see chapter 9.5, "Managing Forest Products for Community Benefit"). Furthermore, the global dimensions of economic and environmental issues mean that reducing harvests in local forests can have an unintended consequence of increasing environmental impacts much farther away (Berlik et al. 2002). For yellow pine and mixed-conifer forests, the likelihood of major disruptions in the long term may increase if effective treatments are not implemented, with effectiveness often being marked by the combination of targeted mechanical or hand removal of trees followed by treatment to reduce surface fuels, typically by fire (Agee and Skinner 2005, Safford et al. 2012c). For instance, computer modeling by Scheller et al. (2011) indicated that the threat of large, severe wildfires to habitat of fisher over large areas likely outweighs the expected short-term negative effects

Lack of treatment may exact a higher cost than first imagined, and the desire to avoid short-term risk from an institutional perspective must be weighed against the larger social risks that may be compounded through insufficient action.

of fuels treatments on fisher population size. Moreover, the analysis noted that the benefits of treatment would be even greater if climate change makes wildfires larger and more severe (see chapter 1.4). In a similar vein, Roloff et al. (2012) completed a risk analysis of fuels treatments for northern spotted owls in southwest Oregon, which suggested that active management posed fewer risks than no management in fire-prone landscapes, although they cautioned that this strategy requires testing through field evaluation under an adaptive management framework. For these reasons, lack of treatment may exact a higher cost than first imagined, and the desire to avoid short-term risk from an institutional perspective must be weighed against the larger social risks that may be compounded through insufficient action.

Recognizing and Resolving Scale Mismatches

Research to understand socioeconomic and ecological processes is often restricted to a narrow range of influences, effects, localities, and timeframes that facilitate study (see table 1 for common spatial scales of ecological studies), but these constraints may not sufficiently reflect important processes that operate at larger scales. These types of scale mismatches have exacerbated debates over how best to manage national forests. In the Sierra Nevada, research has rarely been conducted in an interdisciplinary, cross-scale fashion that could enable better understanding of the dynamics and interactions of patterns over multiple scales of both space and time (Bissonette 1997). Many of the areas that have been designated for experimental approaches are relatively small (see table 1 in chapter 1.5). Likewise, there have been few attempts to craft a cohesive, interdisciplinary management strategy aimed at achieving multiple but seemingly disparate objectives. Forest management practices are often regulated by standards set for localized conditions at a single point in time, despite the fact that forest conditions continuously change in both space and time via stand development and disturbance processes. The integrated approach suggested in PSW-GTR-220 by North et al. (2009) took important steps forward in promoting a landscape strategy and collaboration across the disciplines of forest ecology, wildlife biology, and silviculture. The follow-up report, PSW-GTR-237, also edited by North (2012), extended those recommended considerations to include bark beetles, climate change, and various wildlife communities, and featured examples of collaboration and adaptive management experiments.

Integrated management strategies that consider effects at scales of 50 years or more, across local to large spatial scales, and across ecological and social dimensions, could help enhance socioecological resilience. Management approaches that seem suboptimal from a stand-level perspective may be favored when seen from a

Table 1—Minimum scales needed to evaluate ecological data that can be collected at various spatial scales to answer research and management questions

Typical minimum scale of data	Ecological attributes or processes
Plot (<1 to 4 ha) (<1 to 10 acres) to stand scale (40 ha or 100 acres)	• Vegetation structure, composition, and regeneration • Fire effects on plants, soils, insects, wildlife with small home ranges, etc. • Effects of some mechanical and prescribed fire treatments and wildfires • Soil structure and chemistry • Soil erosion • Wildlife with small home ranges, such as small mammals, birds, and amphibians • Use of habitat patches by species with large home ranges (i.e., nest patch and foraging patch) • Meadows • Air pollution effects • Tree genetics
Small landscape scale (40 to 400 ha or 100 to 1,000 acres), including headwater watersheds	• Linkages between terrestrial watersheds and aquatic systems • Stream water quantity and quality • Benthic macroinvertebrates • Sediment loads • Fire effects on stands to small watersheds • Fire history and stand structure reconstruction
Intermediate landscape scale (400 to 40 000 ha or 1,000 to 100,000 acres)	• Terrestrial wildlife with large home range dynamics (e.g., raptors, forest carnivores, and other large mammals) and fishes • Fire history and stand structure reconstruction • Fire severity patterns • Fuel treatment effectiveness to reduce large, high-intensity wildfires • Climatic influences on fire regimes and subbasin hydrology
Large landscape scale (40 000 ha or 100,000 acres and larger)	• Population dynamics of wildlife with large home ranges • Landscape genomics • Climatic influences on regional fire activity

Note: For non-ecological data, see the scale discussion in chapter 9.1, "Broader Context for Social, Economic, and Cultural Components."

landscape perspective (or vice versa), because the effects of treating a stand may influence how the landscape as a whole responds to fire. For this reason, strategies that opportunistically target areas suggested by high fuel loads, low treatment costs, and reduced obstacles (such as regulations, additional planning requirements, or avoidance of potential litigation) can leave large parts of the landscape vulnerable to uncharacteristically severe wildfire under a management regime dominated by fire suppression. In a similar fashion, aquatic scientists have reinforced the importance of moving beyond reach-scale evaluations of conditions and projects to assessing how management shifts the cumulative distribution of stream conditions within a watershed over decades (Benda et al. 2003). The importance of a landscape perspective to promote forest resilience is detailed in the following chapter (1.3).

Strategies to Promote Socioecological Resilience

The introduction to this synthesis (chapter 1.1) defines socioecological resilience as “the capacity of systems to cope with, adapt to, and shape change; to persist and develop in the face of change; and to innovate and transform into new, more desirable configurations in response to disturbance.” **This synthesis focuses in particular on the long-term challenges posed by wildfire and climate change because of their potential to affect the resilience of socioecological systems throughout the region.** This section considers several general strategies to address these kinds of challenges, beginning with several principles that emerge from a broad-scale perspective on ecological resilience.

Box 1.1-1

General Strategies for Addressing Challenges

- Recognize and address scale mismatches—the temporal and spatial scales of management systems may not be well matched to the scales of environmental variation (Cumming et al. 2006).
- Consider long-term (more than 50 years) risks in addition to short-term (fewer than 10 years) expected outcomes. Management focused on avoiding short-term risks is unlikely to sufficiently account for infrequent disturbances such as severe wildfires, nor for the progressive effects of climate change.
- Set adaptable objectives and revisit them, because there may be a lack of clear solutions, certain options may prove unrealistic, and new opportunities may become apparent as conditions change (Hobbs et al. 2010). In particular, the occurrence of large fires is likely to affect plans.
- Rely more on process-based indicators than static indicators of structure and composition, while recognizing that restoration of structure and process must be integrated.
- Integrate valuation tools, decisionmaking tools, modeling, monitoring, and, where appropriate, research to evaluate responses and better account for the risks and tradeoffs involved in management strategies. Although applications of such tools entail many caveats, technologies have advanced to facilitate concurrent analysis of many tradeoffs, such as effects on air quality, fire risk, wildlife habitat, water quality, water quantity, and cultural and economic values.

Promoting Heterogeneity, Emulating Natural Disturbances, and Restoring Processes

Actively promoting forest heterogeneity through silviculture and managed fire is an important restoration strategy, especially given the threat of climate change (see chapter 2.1). Current forest conditions are often relatively homogenous owing to past management practices and the absence of fire. Forests that developed under the influence of frequent, mostly low- and moderate-intensity fires exhibited very heterogeneous conditions that were likely produced by interacting effects of site productivity, topography, and fire history. These forests were common historically, but are now very limited because of fire suppression. Researchers have suggested actively promoting greater diversity in stand structure, age, species composition, and genetic backgrounds within those species as a hedging strategy to address uncertainty associated with climate change (Notaro et al. 2012). Treatments to reduce and promote variation in stem density and fuel loads should promote forest resilience to large disturbances associated with climate change, including droughts and insect and disease outbreaks (Fettig 2012, Littell et al. 2012, Safford et al. 2012b, Sturrock et al. 2011). To promote desired wildlife habitat and other forest restoration objectives, traditional uniform treatments could be modified to yield more variable density structure and canopy closure consistent with reference conditions (Knapp et al. 2012, North and Sherlock 2012, North and Stine 2012).

Treatments to reduce and promote variation in stem density and fuel loads should promote forest resilience to large disturbances associated with climate change, including droughts and insect and disease outbreaks.

North et al. (2012) suggested that the most practical strategy for treating large areas is to significantly expand managed fire, while recognizing the importance of structural treatments to facilitate such a strategy. This approach builds on the principle of natural disturbance-based management (North and Keeton 2008), and it is consistent with recent research concerning the importance of fire in riparian and aquatic ecosystems (see chapters 6.1, 6.2, and 6.3). A recent review of the Fire and Fire Surrogate study concluded that fire should be maintained whenever possible, because mechanical treatments did not serve as surrogates for fire for most variables (McIver et al. 2013). Arkle and Pilliod (2010) similarly concluded that using early-season prescribed fire in upland forests was unlikely to serve as a surrogate for the reference fire regime in maintaining integrity of riparian and stream systems. However, as Knapp et al. (2009) explained, in systems that have departed significantly from the reference fire regime, it may take a series of treatments (including out-of-season prescribed burns) to reduce fuel loads sufficiently before in-season fires will more predictably yield desired outcomes. Successful adaptive management strategies will anticipate wildfire disturbances and seek to direct them to achieve desired conditions. For areas with frequent fire regimes, Hirsch et al. (2001) called for “fire-smart” management strategies that acknowledge the inevitability of wildfire. This approach prompts consideration of how immediate risks associated with use of prescribed fire may be offset by potential to reduce future wildfire risks.

There are many areas where treatments to modify stand structures would help to facilitate returning fire as a primary disturbance mechanism (Miller and Urban 2000). Varying forest conditions with micro- and macro-topography can help increase heterogeneity and provide managers with a template for how and where to vary treatments. Recent studies provide information on how forest conditions and fire regimes varied according to topography when active fire regimes were operating historically (Beaty and Taylor 2001; Scholl and Taylor 2010; Taylor 2000; Taylor and Skinner 1998, 2003) and in landscapes where fire regimes have been partially restored (Lydersen and North 2012). Treatment strategies that build on the concept of emulating natural disturbance regimes would alter treatment type and intensity according to topographic position; for some landscapes in this synthesis area, such an approach might include reducing fuels preferentially on drier southern and western slopes, as compared to north slopes and canyon bottoms, and initially managing ridgetops for fuelbreaks (Weatherspoon and Skinner 1996).

Emphasizing process-based restoration and indicators—
Because a resilience-based restoration strategy places so much emphasis on the dynamism of systems, it demands greater attention to functional processes. Conditions and processes are so interconnected that restoration has to address both; however, restoration ecology has placed increasing emphasis on restoration of dynamic ecological processes versus static targets for structure and composition (Harris et al. 2006). For example, scientists in the field of stream restoration have called for less emphasis on in-stream structural approaches in favor of reestablishing disturbance regimes (fires and floods), vegetation dynamics, coarse woody debris recruitment, and lateral and longitudinal stream connectivity that build in-stream habitat (see Palmer et al. 2005 and chapter 6.1). In terrestrial forests that experience frequent fires, researchers contend that ecologically based restoration depends on successfully restoring mostly low- to moderate-intensity fire as a keystone process, while recognizing that fire regimes and stand structures must be restored in an integrated way (see chapter 4.1 and Allen et al. 2002). Therefore, structural indicators remain essential, but they have to be considered in light of dynamic processes, and there is a need for indicators and metrics that focus on process. It will be necessary to rely on modeling and monitoring to evaluate whether important habitat elements are likely to be sustained over time.

In addition to abiotic processes like fires and floods, it is also important to consider biotic processes as indicators of ecological resilience. For example, predation is an important process given the potential for trophic cascades when predators are lost (see chapter 7.1). Using an example from Lake Tahoe, Vander Zanden et al. (2003) demonstrated how consideration of long-term changes in food webs can guide restoration efforts, in particular by targeting systems where such changes have been less extensive.

Researchers studying aquatic systems have asserted that management systems have tended to rely too much on indicators of acceptable habitat conditions and water quality standards rather than embracing system dynamics and disturbance regimes (Rieman et al. 2003). Some decisionmaking systems may provide incentives to treat priority species and water quality as constraints, with an emphasis on avoiding short-term potentially negative impacts. However, approaches based upon promoting resilience need to sustain ecological values over the long run. Foundational components include the physical-chemical aspects of soil and water, which in turn support vegetation and habitat for terrestrial and aquatic organisms. Because foundational ecological processes, such as soil water storage, may not have explicit targets, there may be a tendency to undervalue, or even ignore them in decisionmaking. Yet, as noted in chapter 6.1, forest treatments have the potential to enhance system resilience to multiple stresses by increasing soil water availability. Such treatments, along with meadow restoration (see chapter 6.3), also have potential to enhance the yield, quality, and timing of downstream water flows and resulting ecosystem services. Another approach emphasized in promoting resilience of fluvial systems is to reestablish reference hydrologic regimes, including overbank flows in wet meadows (see chapter 6.3) and natural hydrograph patterns in regulated rivers (see chapter 6.1). The strategic orientation of PSW-GTR-220 (North et al. 2009) and PSW-GTR-237 (North 2012), which focus on restoring heterogeneity and landscape-scale ecological processes, can address aquatic resources by incorporating key hydrologic processes as treatment objectives rather than primarily as constraints.

Using fire regime metrics to evaluate performance—
By addressing system dynamics, process-based indicators avoid some of the shortcomings that may be posed by structural indicators, but they still pose a risk of oversimplification. Carefully selected fire regime metrics can be useful for setting priorities and evaluating performance, because they focus on a key disturbance process. Sugihara et al. (2006) identify seven important attributes for characterizing fire regimes, including fire return interval, seasonality, size, spatial complexity, fireline intensity, severity, and type. The total amount of area burned in any given

year does not necessarily indicate failure or success, because there has been such a deficit of fire on the landscape since the onset of fire suppression. The proportion of area burned at low, moderate, and high severity and how the fires threaten human life and property are more important indicators. Area burned at low to moderate severity could be an important indicator of progress, whereas the extent of high-severity fire could be a useful indicator of a problem (Weatherspoon and Skinner 1996). In terms of achieving restoration goals, expectations for particular areas would need to be based on historical variation and/or contemporary reference sites, current conditions, and projections of climate change and future disturbance (Safford et al. 2012a). Fire return interval departure (FRID) analyses can help evaluate departures from reference conditions at a large scale. However, FRID analyses may not provide sufficient detail to apply these metrics at the project scale, and fire recurrence intervals alone are insufficient to drive treatment priorities (see chapter 4.1). For example, depending on values at risk and socioecological context, it may be more important to maintain a restored or minimally departed condition in one area than it would be to correct a significantly departed condition in another.

It is also important to consider the various dimensions of the fire regime other than simple averages of fire frequency, since the variation in fire regime characteristics within and among fires is a more important influence on landscape heterogeneity and biodiversity (Agee 2002). Individual low-severity burns are generally insufficient to restore reference structure and process after long fire-free periods (Collins et al. 2011, Miller and Urban 2000, Skinner 2005). Consequently, a metric like time since last fire may be useful as an initial look or as a short-term indicator of management performance, but it should not necessarily be construed as an indicator of a restored fire regime (see chapter 4.1). Unqualified measures of area burned or area treated would not be particularly useful indicators of restoration of ecological process. More multidimensional metrics are needed to evaluate effectiveness in reducing hazard or in restoring ecosystems.

Large areas affected by uncharacteristically severe fire may shift ecosystems into less desirable states that may persist for long periods, especially because climate change is also influencing those trajectories.

Managing long-term post-wildfire outcomes—
Uncharacteristically severe wildfires will continue to affect large areas of the synthesis area in coming decades. The Burned Area Emergency Response (BAER) program addresses short-term postfire impacts to life, property, and ecosystems, but a longer term strategy is important for promoting resilience of ecosystems within severely burned landscapes (see chapter 4.3). The Forest Service in California has recently developed a template to help guide national forests in planning for restoration and long-term management of post-wildfire landscapes. Postfire conditions offer opportunity to realign ecosystem structure, function, or composition with expected future climate. Large areas affected by uncharacteristically severe fire

may shift ecosystems into less desirable states that may persist for long periods, especially because climate change is also influencing those trajectories. Additional research and extensive monitoring are needed to ensure that treatments of those areas do not rely on untested approaches applied in a piecemeal fashion without consideration of landscape context and changing climate.

Social and Ecological Integration

The "triple bottom line" concept, which emphasizes social, economic, and ecological dimensions of sustainability (see chapter 9.1, "Broader Context for Social, Economic, and Cultural Components"), underscores the understanding that human and natural ecosystems are interdependent (see also chapter 4.2, "Fire and Tribal Cultural Resources"). Chapter 9.2, "Ecosystem Services," in particular notes the importance of understanding natural ecosystems as a foundation that generates finite streams of ecological services that benefit human societies and have limited substitutability. Findings from research (see section 9 in particular) suggest that an important part of a strategy to promote socioecological resilience is to explicitly consider social effects of forest management strategies on near and more distant human communities, as well as how community capacity can facilitate management to promote resilience. Researchers studying socioecological systems note that

Box 1.1-2

Summary of Approaches for Integrating Social Considerations Into Strategies

- Consider the integrated nature of socioecological systems; approaches that address issues from a narrow perspective are less likely to succeed in the long run than strategies that consider ecological, social, economic, and cultural components. Recognizing and measuring ecosystem services and other sociocultural values can help to consider impacts to communities and ecosystems as part of this approach.
- Use participatory and collaborative approaches to facilitate adaptive responses and social learning. Many of the topical sections of this synthesis note how scientists have moved toward such approaches as a way of promoting resilience, especially where management systems may be geographically and culturally distant from people who use the forests and their local knowledge systems (examples in chapter 9.6, "Collaboration in National Forest Management," include grazing management and incorporation of traditional ecological knowledge).

no single approach to governance, including broader and more active participation by local communities, will solve problems in managing socioecological systems (Ostrom 2007), because human-environment relationships are so complex and differ from one place to another. However, there is growing recognition that engagement, capacity building, and participation are often necessary components of strategies that promote resilience through social learning (Fernandez-Gimenez et al. 2008).

Recognizing ecosystem services and other sociocultural values—
The shift to thinking about integrated socioecological systems has spurred efforts to value ecosystem services (see chapter 9.2), because an ecosystem's capacity to generate such services is the foundation for social and economic development (Folke 2006b). Understanding changing demand for many ecosystem services at different scales is crucial for developing appropriate ecosystem management strategies (Grêt-Regamey et al. 2012). An important component of a resilience strategy may be to moderate societal expectations for ecological services rather than trying to provide a constant or ever-increasing supply. The Sierra Nevada encompasses watersheds that support millions of people and a large part of the global economy; therefore, potential impacts to water quality and quantity are of great importance locally, regionally, and even globally. Impacts of treatments and wildfires on these services are an important research topic (see chapter 6.1 as well as chapter 1.5).

The sociocultural value of ecosystems is not limited to direct uses by people, as it also extends beyond the Sierra Nevada and southern Cascade Range. Research has shown that people living far from the Sierra Nevada hold substantial values for the region's ecosystems and especially for their charismatic fish and wildlife (Loomis and Gonzalez-Caban 1998, Richardson and Loomis 2009). Ecosystems also support community identity and sense of place (see chapter 9.1). These values resist quantification and commodification but may be critical to maintaining the sustainability of socioecological systems (Berkes et al. 2006, Ostrom 2007).

Emphasizing values sustained by the forests may help facilitate communications with diverse members of the general public, local residents, landowners, and other groups. Studies have shown that science-based planning and communication are important for improving acceptability of proposed actions, such as wildfire risk reduction treatments, biomass utilization, and salvage logging (see chapter 9.5). Because local communities often play a role in management practices related to biodiversity enhancement, soil and water protection, and improving other ecosystem services, managing forest products on national forest lands to benefit those communities can in turn provide environmental benefits for forest and rangeland ecosystems across ownerships (see chapter 9.5).

Considering impacts to communities and ecosystems—
An integrated landscape-scale strategy can promote restoration in ways that benefit both local communities and ecosystems using specific approaches that are discussed within chapter 9.4. However, potential solutions may entail various tradeoffs between ecological and social impacts at multiple scales. For example, tools like stewardship contracts afford certain benefits and flexibility to promote ecological restoration, but under current policies, they can also incur potential impacts to communities by reducing payments to local governments. Redressing public policies that create disincentives for ecological restoration may be important in developing a successful long-term strategy.

Encouraging a shift from burning debris from harvest or fire hazard reductions in piles to burning in biomass facilities could yield significant environmental and economic benefits.

An important issue raised in different topical sections of this synthesis concerns the potential to generate energy and fuel from forest biomass. This approach holds promise for simultaneously reducing greenhouse gas and smoke emissions, promoting renewable energy and U.S. energy security, and facilitating larger scale forest treatments in support of reduced fire hazard and ecological restoration. There has been considerable debate concerning whether forest biomass should be regarded as carbon-neutral, and assessments of the overall impact of emissions hinge on assumptions about fire regimes (Winford and Gaither 2012). However, there is consensus that the utilization of "waste" biomass debris that would otherwise release carbon quickly into the atmosphere (through decay or pile burning) is likely to be carbon friendly (Johnson 2009). Therefore, encouraging a shift from burning debris from harvest or fire hazard reductions in piles to burning in biomass facilities could yield significant environmental and economic benefits. Researchers have sought to estimate a sustainable supply of biomass that represents a byproduct of other management objectives, such as precommercial thinning and wildfire hazard reduction (Parker et al. 2010). However, development of biomass utilization in the Sierra Nevada requires consideration of an array of ecological, economic, and social factors, and the overall impact and acceptability of biomass initiatives depends heavily on local conditions (see chapter 9.5).

Promoting collaboration and partnerships—
Consistent with an all-lands approach, working at the landscape scale will require greater coordination and partnerships with private landowners, nongovernmental organizations, and state and local governments. In addition, collaboration demands consideration of views and interests of stakeholders at broad scales, including people who may be farther away than those who have traditionally been included in planning. Although collaboration entails costs and complications, stakeholder input and participation from early stages can be crucial in outlining shared goals and objectives, facilitating shared learning and problem solving, and building

trust (Bartlett 2012). Although reaching consensus may not necessarily be a goal of planning, research from other areas, such as the yellow pine forests of northern Arizona, suggests that diverse stakeholder groups are able to reach consensus about managing very large landscapes (Hampton et al. 2011, Sisk et al. 2006), particularly because treatments need to initially target only a portion of the landscape to effectively reduce the risk of large, intense wildfires (Ager et al. 2007, Loehle 2004, Schmidt et al. 2008, Syphard et al. 2011). Achieving such agreement may be easier in high-relief areas where topography has a strong influence on effective treatment options and more difficult in areas with high-profile values (e.g., sequoia groves and habitat for wildlife species of concern). However, there are no guaranteed outcomes from adopting a collaborative process, and, as outlined in chapter 9.6, "Collaboration in National Forest Management," cross-boundary collaboration may be particularly challenging in some communities. That chapter also suggests that fire could be a rallying point, given that creating strategies to reduce fire risk across boundaries may enhance cooperation.

Science-based monitoring and feedback mechanisms that enable adaptive management practices are valuable for correcting course and building trust and cooperation (Cox et al. 2010, Fernandez-Gimenez et al. 2008). Such adaptive systems are important because there are significant gaps in scientific knowledge of the behaviors of these complex systems, as outlined in chapter 1.5. Furthermore, these approaches embed capacity to identify and benefit from new information discovered as a result of monitoring, shifts in social systems or values, shifts in ecological systems or dynamics, or a change in their interactions. A wide range of collaborative approaches to adaptive management, including participatory research and monitoring, and collaborations with tribal groups to investigate effects of reintroducing traditional burning practices, is discussed in chapter 9.6.

Institutionalized science-management partnerships are an approach to collaborative adaptive management that has been developed in the synthesis area. These partnerships have attempted to facilitate the dissemination of scientific information directly to resource managers, while providing researchers with a better understanding of contexts and constraints, including the challenges associated with climate change (Littell et al. 2012). Robust science-management partnerships may also provide the added benefit of building stakeholder trust and encouraging creative approaches to adaptive management. Regional examples of these science-management partnerships include the Tahoe Science Consortium, Southern Sierra Conservation Cooperative, Northern California Prescribed Fire Council, and California Fire Science Consortium.

Employing Adaptive Management Strategies

Phased Strategies for Long-Term Resilience

Considering management strategies in terms of phases may help reconcile short- and long-term priorities, reduce both short- and long-term risks, and facilitate adaptation to changing conditions. Attempts to restore a more natural disturbance regime of fire as an ecological process without first securing vulnerable communities and resources could have undesirable outcomes. Accordingly, a starting point for many landscapes has been to emphasize fire hazard reduction in areas of high value, such as the wildland-urban interface (WUI), as well as other areas where human-caused ignitions are likely to cause problems. Though such treatments can be effective, conditions on adjacent private lands in the WUI and the susceptibility of structures also determine effectiveness of wildfire defenses. As a result, involvement and cooperation of local communities is important in implementing treatments in a coordinated way across property boundaries (Weatherspoon and Skinner 1996).

Although WUI-focused approaches may do little to restore resilience to the larger landscape (Schmidt et al. 2008), they may expand windows of confidence in allowing fire to return. A major challenge is to go beyond localized fire hazard reduction and pursue a goal of restoring conditions where fire can be returned safely as a key process in the landscape. This goal is an integral part of a larger landscape resilience strategy. A near-term emphasis on reducing fire hazard in strategic areas can secure a margin of safety for pursuing longer term objectives. However, treatments driven by near- and long-term objectives do not necessarily need to be applied in a distinct sequence, but rather could be adapted to the needs, constraints, and opportunities of particular contexts. Accordingly, a strategic approach would likely blend more short-term defensive fire risk reduction as well as more restorative treatments for the long term. For example, resource managers may be able to take advantage of wildland fire opportunities without necessarily completing near-term strategic defensive treatments. In addition, strategically located treatments intended to reduce the potential for uncharacteristically severe wildfire would not necessarily need to be limited solely to achieving that objective. Rather, they could incorporate elements designed to promote future wildlife habitat, increase stand resilience to insects, diseases, and drought, and achieve other facets of the long-term goal (Weatherspoon and Skinner 1996). There are opportunities to enhance habitat for wildlife and other resources when seeking to reduce wildfire risk in developed areas (Eitzel et al. 2012); such an approach can be important because those areas may also harbor important biodiversity (Manley et al. 2006) and provide wildlife-related ecological services, including recreational opportunities.

A major challenge is to go beyond localized fire hazard reduction and pursue a goal of restoring conditions where fire can be returned safely as a key process in the landscape.

The hallmark of a strategic approach is the spatial and temporal arrangement of treatments to promote landscape resilience, rather than targeting the least costly locations or those that exhibit the worst fuels conditions. Although these strategies may be guided by local knowledge, geospatial decision support software, such as the Landscape Treatment Designer (Ager et al. 2012b), can be valuable in designing and evaluating such strategies.

Near-term phase: strategic treatments in a fraction of landscape to reduce fire hazard and promote resilience—
A near-term strategy would select areas for treatment to inhibit the potential for high-intensity wildfire to burn in uncharacteristically large patches. This approach sets up the landscape to achieve long-term goals. Treatments in this phase would represent a mix of approaches to promote conditions where wildfire can occur without unacceptably severe outcomes. Topography, vegetation, expected fire behavior, and resource concerns can guide development of treatment strategies (Skinner et al. 2006). Multiple landscape modeling studies suggest that if treatments are strategically placed, an initial target of treating 10 to 25 percent of the landscape within a period of 5 to 10 years can effectively reduce the likelihood of unacceptably large, high-intensity fires (Ager et al. 2007, 2010; Finney et al. 2007; Schmidt et al. 2008; Syphard et al. 2011). A strategy based on within-stand and across-landscape heterogeneity appears suited to deter the spread of high-intensity fire across the landscape while providing for a wide range of habitat conditions (Knapp et al. 2012, Weatherspoon and Skinner 1996). This phase may require a number of years to be completed, as some areas may require sequential treatments before they would achieve the desired condition (Skinner 2005). In some areas, strategic fuels treatment has been examined through the Fireshed planning effort (Bahro et al. 2007). This near-term strategic approach may reflect various strategies designed to impede wildfire spread similar to that modeled by Ager et al. (2013), including broad landscape protection as well as the restoration of dispersed fire barriers.

Managed fire will likely become increasingly important for promoting resilience in forest ecosystems particularly important in the many areas that are inaccessible to mechanical treatments to remove smaller trees.

Long-term phase: landscape-scale restoration of resilience and heterogeneity—
Objectives for this long-term phase would focus on expanding restoration work while sustaining a desired mosaic of ecological conditions through time. Integrating predictive habitat models with silvicultural and fire models would help to evaluate these spatial and temporal dynamics. A combination of corrective treatments to bring areas back into a desired condition and maintenance treatments would need to be applied. Tradeoffs between treating new areas and maintaining existing areas would need to be considered using models to account for costs of treatment, changing fire conditions, and other factors (Finney et al. 2007).

Corrective treatments and maintenance treatments may be distinguished more by their objectives than by their means of treatment. However, managed fire will likely become increasingly important for promoting resilience in forest ecosystems (North et al. 2012). As outlined in chapter 1.3, this approach would be particularly important in the many areas that are inaccessible to mechanical treatments to remove smaller trees.

As wildfires occur, they may alter the priorities for treatment across the landscape, and create new opportunities to influence ecological trajectories (fig. 2). As a consequence, greater integration with post-wildfire treatment plans, both before and after such fires occur, is another important facet of a resilience-based landscape strategy (see chapter 4.3). To be successful, adaptive strategies may require integration of land management plans and fire management plans to address short-term responses to wildfire as well as long-term objectives for large-scale fire restoration. Post-wildfire plans are important not only because fires are likely to be widespread agents of change, but also because wildfires can open windows of opportunity to learn and to take actions to promote future resilience (Littell et al. 2012).

Incentives for landscape-scale restoration—
Although strategic defense treatments can facilitate a larger restoration approach, they do not necessarily constitute restoration, because their intent is primarily to alter fire behavior to aid suppression activities and ameliorate wildfire impacts while working to produce conditions that reestablish fire as an ecological process. Hence, this approach relies strongly upon a resistance strategy (Millar et al. 2007).

Treatments would have to include some fire component to be considered fully restorative, even though mechanical treatments will in many cases be needed before fire can be safely applied. To encourage restoration, it would be appropriate to recognize and accord greater weight to treatments that come closer to facilitating reference fire regimes based upon frequency, seasonality, severity, and spatial pattern. Performance metrics based heavily on area treated will incentivize treating the easiest parts of the landscape in a concentrated fashion; therefore, they may hinder a strategic approach to promote resilience. Consequently, selection of appropriate performance metrics is a particularly important topic for management and science to consider (see chapter 1.5). Promoting more integrated accounting of ecological outcomes may help to facilitate actions that may generate significant gains over the long-term but involve shorter term risks and costs. As an example, one approach to integrate consideration of land management and air quality objectives has been to make decisions about prescribed burning through a more unified or joint institutional structure, as reported from a successful program in western Australia (Adams 2013).

Designing a landscape strategy requires carefully considering opportunities to promote wildlife, riparian, and aquatic habitat values rather than avoiding such priority areas. Applying the principle of emulating natural disturbance regimes would likely benefit riparian areas and habitat for species of concern over the long term, but this approach would benefit from testing within an adaptive management framework.

Economic considerations are particularly important in planning a landscape scale strategy because treatments of areas that have not been harvested for many decades may provide resources to restore parts of the landscape where harvest costs are likely to exceed biomass revenues (Hartsough 2003, North 2012). Although corrective treatments will remove merchantable trees, returns from maintenance treatments are likely to be much smaller. Consequently, opportunities to receive greater returns for smaller tree biomass will be important in accelerating the pace and extent of restoration treatments.

Demonstration landscapes—
Designing a landscape strategy requires carefully considering opportunities to promote wildlife, riparian, and aquatic habitat values rather than avoiding such priority areas. Applying the principle of emulating natural disturbance regimes would likely benefit riparian areas and habitat for species of concern over the long term, but this approach would benefit from testing within an adaptive management framework, including experimentation, modeling, intensive monitoring, and research on particular issues. Experimental approaches to landscape management, focusing on fire-related treatments in particular, have been tested on relatively small scales within experimental forests and other adaptive management areas in the synthesis area (see chapter 1.5). Larger demonstration areas could facilitate evaluation of treatment impacts on wildfire at the landscape scale and on a wide range of species with large home ranges, such as California spotted owls and fishers. The Dinkey Collaborative Forest Landscape Restoration Project has enabled observations of the effects of prescribed fire on fishers, but larger areas would be needed to address questions of connectivity for forest carnivores. The Northwest Forest Plan set up 10 adaptive management areas (AMAs), which ranged in size from around 37 000 ha (92,000 ac) to almost 200 000 ha (500,000 ac), to afford managers an opportunity to test new approaches at large scales and adjust standards and guides to local conditions. Scientists have noted that the plan's potential to facilitate large-scale experimentation has not been fulfilled owing to disagreements over what constitutes adaptive management and a perceived or real lack of sufficient flexibility to test different strategies (Rapp 2008, Stankey et al. 2003). Nevertheless, the Goosenest Adaptive Management Area (GAMA), located within this synthesis area, has demonstrated some on-the-ground progress (Rapp 2008). Whereas managers used the larger area to explore strategies pertaining to raptors, goshawks, and spotted owls, the GAMA Ecological Research study was undertaken to specifically test a variety of treatments designed to achieve the AMA's goal of accelerating late-successional conditions in young-growth forests. Explicitly designated demonstration areas, as described in chapter 1.3, could play an important role in facilitating the landscape-

scale adaptive management needed to reconcile short-term risks with long-term gains. This type of active adaptive management approach would benefit from a robust partnership involving management, research, and stakeholder groups.

Riparian areas—

Landscape strategies that consider fire regime and topography interactions in designing treatments should be able to accommodate riparian area concerns (North 2012, Skinner et al. 2006). Management to promote resilience of small to medium stream reaches that historically burned frequently like adjacent uplands would facilitate similarly frequent, low- to moderate-intensity fire (see chapter 6.2, "Forested Riparian Areas"), rather than being set aside as unmanaged buffer zones that are more susceptible to high fire intensity. However, in riparian areas that function differently than uplands, other tactics are warranted because of higher soil moisture and stronger connectivity to aquatic systems. Experimental, scientifically informed harvesting and burning techniques could illuminate new ways to improve riparian conditions and improve understanding of treatment effects on water flow, water quality, soils, riparian and aquatic biota, and impacts from wildfire. This approach would require consideration of large woody debris loading, shading, stream channel stability, and nutrient inputs, among other factors (Burton 2005). As part of a long-term adaptive management strategy, experiments in riparian areas would help to address a significant research gap.

Special wildlife management areas—

Areas of special management have been designated for several wildlife species, for example, protected activity centers (PACs) for California spotted owl and den buffer areas for fisher. In these areas, restrictions on vegetation management have been linked to site location and hazard levels (wildland-urban interface versus wildlands), but they have generally made treatments more challenging to implement. In wildland settings, mechanical treatments have often been restricted or not allowed, and approved treatments (e.g., prescribed fire and hand removal of fuels) have often been limited to specific timeframes or prescriptions (see sidebar on limited operating periods in chapter 1.5). PACs were originally designated as an interim measure, but they have become long-term zones with little to no active management (Berigan et al. 2012). In some cases, their boundaries have been revised based on changes in conditions and long-term monitoring data (Berigan et al. 2012), but in other cases, unoccupied areas have remained set apart from the general forest matrix.

Because areas within primary habitat for species of concern may be at relatively high risk for uncharacteristically severe wildfire (Ager et al. 2012), treatments within such areas could aid their long-term conservation despite short-term risks of impacts (Scheller et al. 2011). It would be valuable to evaluate the effects of including or excluding core wildlife areas from treatment within landscape-scale plans. Extensive monitoring within demonstration landscapes could help to test tradeoffs between short-term risks and long-term gains for species conservation projected through modeling (see chapter 1.3). Another approach would be to use abandoned areas and margins of core areas as a surrogate to evaluate treatment effects on occupied habitats. Use of robust modeling tools as part of an adaptive management framework may highlight the ways in which landscape-scale strategies can promote long-term improvements in habitat. The focus needs to move beyond effects easily seen at the stand scale to effects that are not as easily seen at the landscape scale, but that can still be modeled and validated through monitoring. This approach may aid conservation and recovery of additional species of concern as research is better able to evaluate the quality and connectivity of their habitats.

Promoting future habitat and appropriate habitat connectivity—
Where landscapes appear to have deficits of priority species habitat compared to the likely HRV, plans could be developed to guide management activities to restore high-quality habitat (North 2012) following conservation approaches suggested by Thompson et al. (2011) and Spencer et al. (2011). Landscape-level restoration strategies could be developed to promote desired habitat conditions where they currently do not exist, using concepts and tools like the HRV, climate adaptation strategies, and scenario planning (Nydick and Sydoriak 2011, Peterson et al. 2011). Landscape strategies would include treatment designs that consider and promote habitat connectivity appropriate to the landscape, keeping in mind the potential undesirable effects of connectivity, such as unwanted spread of severe fire or invasive species. The maintenance of habitat connectivity would be an important consideration as treatments progress through the landscape and as forest conditions change with stand development. Landscape analysis tools that can evaluate multiple objectives are well suited to help resource managers evaluate these tradeoffs (see chapter 7.1 for examples).

Applying landscape-scale modeling—
Because experimentation is so costly, difficult, and slow, modeling will be an important component of developing and adjusting an adaptive management strategy. The "fireshed" modeling approach demonstrated the potential for spatial analyses to evaluate complex tradeoffs across large areas over many decades (Bahro et al. 2007). Although the term "fireshed" may imply an emphasis on fuels reduction, the intent of the approach is to focus thinking at the broader landscape scale at which fire operates rather than at a more limited project scale. In this sense,

fireshed is analogous to watershed except it is based on the scale at which fire operates informed by fire history, fire regimes, topography, vegetation, expected fire behavior, and the risk of problem fires (Bahro et al 2007). The objective of fireshed assessment would be to develop plans that limit the risk of large, high-intensity fires while considering a broad array of values—including watersheds, viewsheds, smokesheds, wildlife habitat quality and connectivity, ecosystem services, and other social and economic values—in an integrated approach at an appropriate landscape scale. Landscape-scale simulations suggest that these broad treatment strategies may benefit wildlife species (Scheller et al. 2011). Combining multiple tools may be necessary to assess treatment effects on the distribution of seral stages/structural types, associated habitat values, and connectivity through time at multiple scales. An example of an integrated approach applied the Forest Vegetation Simulator (FVS) tool to model effects at the smaller scale of fisher home ranges (Thompson et al. 2011), while designing fuels treatments based on landscape analyses (e.g., Fireshed, Flammap), local knowledge of prevailing winds, and the general direction of historical large wildfires. Modeling habitat for priority species at the landscape scale would allow projections of the future arrangement of dense patches, matrix, and openings based on treatments and wildfires under different management strategies. The complementary use of modeling and monitoring can examine potential air quality benefits of prescribed burning, managed wildfires, and other treatments to mitigate hazardous conditions during wildfires (see chapter 8.1). Chapter 9.6, "Collaboration in National Forest Management,") notes that participatory approaches to modeling and data visualization may be a useful way to engage stakeholders in sharing knowledge of the environment and considering management alternatives in relation to the particular geography of a landscape.

Monitoring effects on species of concern—
Although habitat modeling will be important to evaluate potential outcomes at large scales, species monitoring will also remain a significant part of an overall resilience strategy. Effects of treatments on current habitat conditions would need to be monitored to estimate how species of concern are likely to respond. Although many species appear to either benefit from or be indifferent to fuels reduction treatments (Stephens et al. 2012), other species associated with high canopy closure and high structural complexity may be negatively affected by conventional treatments. However, even these species persisted within landscapes that historically had considerable amounts of open forest conditions and early seral habitat created and maintained by frequent, low- and mixed-severity fires (Perry et al. 2011). Chapters 1.3 and 7.1 focus more on this issue. In particular, chapter 7.1 notes that tension

Although many species appear to either benefit from or be indifferent to fuels reduction treatments, other species associated with high canopy closure and high structural complexity may be negatively affected by conventional treatments. However, even these species persisted within landscapes that historically had considerable amounts of open forest conditions and early seral habitat created and maintained by frequent, low- and mixed-severity fires.

between achieving fire-related objectives and promoting habitat for fisher may be more significant when addressing the forest understory rather than the large trees in the overstory. Again, landscape management strategies that emphasize heterogeneity, in addition to robust monitoring in treated areas, may be able to account for and address the needs of different priority species.

Monitoring plans are expected to include both a coarse-filter approach to evaluate landscape-scale habitat patterns and ecological processes, and a fine-filter approach to ensure that at-risk species are being conserved. Integrating modeling with monitoring of field conditions can help to evaluate how ecosystems are changing at broad scales where experimentation may be impractical. Noon et al. (2012) recommended targeting a small number of species based on management objectives and the species' ecological roles, sensitivity to change, and conservation importance; however, they recognized that multiple species approaches, as described by Manley et al. (2004), are appropriate for species that can be detected using the same protocols (for example, breeding birds, small rodents, and mesocarnivores).

Management Implications

- Strategic placement and phasing across the landscape using a combination of prescribed fire, managed wildfire, and mechanical treatments can accomplish the following:
    - Shift disturbance regimes toward patterns that are more consistent with how ecosystems evolved and promote resilience to stressors such as climate change.
    - Reduce undesirable losses from the terrestrial, aquatic, and socioeconomic components of socioecological systems that can result from large, severe, and dangerous wildfires.
    - Promote important values for the long term, including habitat needs for species of concern, favorable water flows, traditional cultural resources, forest products and associated livelihoods and infrastructure, and other ecosystem services and social benefits.
- Measures of ecological departure from the HRV can be useful for evaluating effects of wildfire on socioecological values and to design and evaluate strategies to promote resilience.
- Approaches for reestablishing historical processes within aquatic ecosystems, in addition to terrestrial treatments, can include restoring incised channels in wet meadows, removing introduced fishes from lakes, and promoting more natural stream hydrographs below dams.

- Development and implementation of these approaches through collaborative, placed-based efforts can strengthen existing community capacities and reduce vulnerabilities to major disruptions.

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Chapter 1.3—Synopsis of Emergent Approaches

Malcolm North,[1] Brandon Collins,[2] John Keane,[3] Jonathan W. Long,[4] Carl Skinner,[5] and Bill Zielinski[6]

This synopsis presents three integrated themes that emerged from synthesizing information about biological resources. These themes become particularly important when managing forests to promote resilience at large landscape scales and long timeframes. This synopsis summarizes ideas in the longer chapter 1.2, "Integrative Approaches: Promoting Socioecological Resilience," by using a concise style in which definitions, citations, and elaboration of some key points are included in endnotes.

The emergent theme for promoting resilience is working with and adapting to dynamic ecological processes at broader scales. From this broad perspective, two integral concepts emerge: (1) restoring fire as an ecological process, and (2) reducing fire hazard while sustaining wildlife habitat and restoring riparian ecosystems. Implementing and testing these concepts may require establishing the proposed demonstration landscapes.

Management practices based upon these concepts would also be improved by considering potential effects on economic, social, and cultural components. Questions that are particularly important for integrating socioecological components include how to select appropriate scales for planning in particular areas (see Cheng and Daniels [2003] and chapter 9.1, "Broader Context for Social, Economic, and Cultural Components"); how to design forest treatments in ways that benefit local communities (see chapter 9.4, "Strategies for Job Creation Through Forest Management," and 9.5, "Managing Forest Products for Community Benefit"); and how to consider local and traditional ecological knowledge and promote participation in monitoring programs (see chapter 9.6, "Collaboration in National Forest Management").

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[1] Research plant ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

[2] Research fire ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

[3] Research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

[4] Research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr. Davis, CA 95618.

[5] Geographer (emeritus), U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002.

[6] Research wildlife biologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1700 Bayview Dr., Arcata, CA 95521.

Managing Forests for Resilience

Increasing forest resilience[7] in the Sierra Nevada will require management strategies that work with and adapt to dynamic ecological processes at broader scales. Current practices often concentrate on containing fire, sustaining large trees, and preserving wildlife habitat, in an attempt to maintain stasis with stand-level management. This approach is fundamentally at odds with dynamics in fire-dependent forests and will constrain rather than facilitate an adaptive response to climate change. Management actions might be better guided by evaluating how well they restore heterogeneous forest conditions that are congruent with how site productivity and historical fire intensity affected local growth and mortality.[8]

Many ecosystems processes[9] are complex and difficult to measure, compelling resource managers and scientists to use surrogate assessments, such as structural condition or indicator species presence. Forest management in the Sierra Nevada has often applied indicators derived from other forest ecosystems, particularly the Pacific Northwest, such as old-growth forest characteristics and spotted owl viability.[10]

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[7] Definitions of resilience have evolved as the concept has been adopted and more widely employed in ecology (e.g., Folke et al. 2004; Holling 1973, 2010; Walker et al. 2004; see chapter 1.0, "Introduction," for this synthesis).

[8] Recent research (Falk et al. 2006a) has stressed that restoration efforts should first assess whether structure, composition, or process measurements may provide the most efficient, albeit indirect, measure of ecosystem condition. A pattern in ecosystems with frequent disturbance regimes (e.g., fluvial plains, fire-dependent forests) is that measurements of disturbance processes are often the most effective metrics of restoration (Falk et al. 2006b).

[9] Ecological processes can be both biotic (e.g., competition, growth, nutrient cycling, etc.) and abiotic (e.g., fire, erosion, flooding, etc.). A general definition is "the physical, chemical and biological actions or events that link organisms and their environment." In many Sierra Nevada forests, the processes that appear to most strongly influence forest structure and composition are fire and site productivity (Lydersen and North 2012). Managing forests so that the conditions produced are congruent with these two processes is likely to maintain and restore other ecosystem processes that are much more difficult to assess.

[10] Management practices in the Pacific Northwest such as clearcutting have truncated forest seral stages, largely eliminating the long disturbance-free period of old forest conditions. This reduced the amount of forest containing large structures and deep, multilayered canopies, putting those conditions and the species associated with them at risk. Management practices in the Sierra Nevada also reduced the number of large trees in many areas, raising concerns for sensitive species associated with these stand attributes. Practices in the Sierra Nevada, however, often did not remove all large, old structures or completely reset forest seral stage. Perhaps a more pervasive management impact has been largely eliminating low-intensity fire, putting frequent change and the forest heterogeneity it produced at risk. The seral stage most imperiled in Sierra Nevada forests is that created by frequent, low-intensity fire.

Managers and scientists still have much to learn about frequent-fire forests in the Sierra Nevada by looking to active-fire regime landscapes within its borders (e.g., Illilouette Basin in Yosemite National Park, Sugarloaf Basin of Sequoia and Kings Canyon National Parks, Beaver Creek Pinery in the Ishi Wilderness) (Collins et al. 2007, 2008; Collins and Stephens 2010; Taylor 2010) and to the south (i.e., Sierra San Pedro Mártir in Mexico) (Stephens 2004, Stephens and Fry 2005, Stephens and Gill 2005, Stephens et al. 2007). The research that has come from these areas is probably more directly applicable to Sierra Nevada forest dynamics than is some of the information from the infrequent disturbance and relatively mesic conditions of Pacific Northwest forests west of the Cascade Range.

Indicators from other regions, such as old forests in the Pacific Northwest, which have profoundly different disturbance regimes and climate, are unlikely to be congruent with the reference heterogeneity and dynamism of Sierra Nevada forests. Because current old growth and spotted owl nesting habitat will change, proactive management can plan for creating these conditions in future forest landscapes.

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An emphasis on these indicators has often focused management at the stand scale, which can then get bogged down in identifying optimal forest structure on an acre-by-acre basis. Terrestrial treatments at fine scales may also be insufficient for addressing watershed and aquatic ecosystem processes on a scale effective for restoration. When desired habitat is managed at the scale of individual parcels, it can lose sight of the major ecological processes (e.g., growth, mortality, disturbance) that will continue to shape the larger landscape. These dynamics can render forest plans with static structural and habitat goals obsolete by the time they complete public and administrative review.[11] The new planning rule directs national forests to embrace and accommodate ecosystem change.[12]

Research suggests that a prudent approach may be to increase forest landscape heterogeneity at multiple scales with management practices that promote the structure and composition that might have been produced by historical, frequent fire disturbance.[13] Sierra Nevada managers have been experimenting with principles from PSW-GTR-220 (North et al. 2009), such as using existing stand conditions and topography as a template to vary treatments while meeting fire hazard reduction, wildlife habitat, and forest restoration objectives. This approach is consistent with recent research showing that topography, site productivity, and fire history interact to influence burn intensity and forest heterogeneity.[14] Many modern forests are relatively homogenous, with much higher stem density and canopy cover than

[11] Wildfire, beetle mortality, and drought stress often change forest condition, but change in wildlife habitat designations do not always follow suit. For example, managers cannot decommission or retire PACs once they are established if there has not been “significant” change to the habitat, even if the PAC becomes unoccupied by owls. There is currently no threshold that defines “significant” change, leaving it unclear whether the designation should remain after moderate changes to habitat conditions that are common in dynamic ecosystems.

[12] Final Planning Rule, Section 219.8 (Sustainability): “The plan must provide for social, economic, and ecological sustainability within Forest Service authority and consistent with the inherent capability of the plan area, as follows… iv) System drivers, including dominant ecological processes, disturbance regimes, and stressors, such as natural succession, wildland fire, invasive species, and climate change; and the ability of terrestrial and aquatic ecosystems on the plan area to adapt to change.”

[13] See North et al. (2009) and North (2012).

[14] See Lydersen and North (2012).

existed under an active fire regime.[15] Unless treated, these conditions will limit forest resilience to drought and climate change. Management activities that reduce stem density and move forests toward the range of conditions that would result from natural interactions between frequent fire and varying site productivity are likely to improve landscape resilience to both acute (e.g., high-severity wildfire, drought, etc.) and chronic disturbances (e.g., understory burning, climate change, bark beetles, air pollution, etc.).[16]

Management Implications

- Forests managed to be congruent with what potential fire behavior and site productivity would produce will be more in sync with the two dominant processes—growth and mortality—that fundamentally shape Sierra Nevada forests.[17]
- Practices suggested in PSW-GTR-220 and discussed in PSW-GTR-237 may help create these conditions and increase the landscape heterogeneity needed for resilient terrestrial and aquatic ecosystems.

Restoring Fire as an Ecological Process

Restoration of fire as an ecological process is the most efficient means of promoting forest resilience and rejuvenating aquatic habitat in much of the Sierra Nevada.

Wildfire is a major catalyst through which the effects of a changing climate will be expressed (fig. 1). Managing fire in contemporary forests riddled with human development has significant risks. Notwithstanding these concerns, restoration of fire as an ecological process is the most efficient means of promoting forest resilience and rejuvenating aquatic habitat in much of the Sierra Nevada. In addition, there are large portions of wildland landscapes (e.g., steep slopes, wilderness, roadless areas, etc.) where mechanical treatment is infeasible. Thinning will be a substantial component of forest treatments; however, it is important to consider how fire might be used

[15] An example: by one estimate (Forest Service Westcore data), tree density on Forest Service land averages 280 stems/ac. In contrast, Lydersen and North (2012) found stem densities ranging from 45 to 134 stems/ac on ridge and lower slope stands, respectively, in old-growth mixed conifer with restored fire regimes. They also found canopy cover ranged from 19 to 49 percent on ridges and midslope stands, respectively. We are not aware of any estimate of average canopy cover for the Sierra Nevada, but observation suggests current conditions are usually much higher and lack spatial variability.

[16] Betancourt (2012) suggested that landscape heterogeneity decreases the probability of synchronous high-intensity disturbance over large scales. In frequent-fire forests, some processes (e.g., seed dispersal and microclimate amelioration) and forest conditions (plant and animals that require undisturbed refugia) may not be resilient to large increases in the patch size of high-severity fire.

[17] There is not a single structural condition that would always be produced by a set fire behavior. Rather, variation in weather and fuel conditions at the time of burn is likely to produce a range of outcomes that would give management general bounds within which to define a desired condition.

Malcolm North

Figure 1—2008 wildfire in the Marble Mountain Wilderness that had a range of fire severities creating postburn heterogeneity.

rather than preemptively dismissing it as impractical. To increase the pace and scale of fuels reduction and forest restoration, management may need to enlarge project areas and incorporate fire at broad scales. This effort will involve expanding burn windows, and in some instances, targets for allowable fire-caused tree mortality.

Fire must be controlled in areas near homes, but in much of the forested wildlands, there are opportunities for wider use of fire for fuels reduction and forest restoration. Current rates of fuels reduction, even when wildfire is included regardless of severity, treat less than 20 percent of the area that may have burned historically each year in the Sierra Nevada.[18] Research suggests that outside of the wildland urban interface[19] (WUI) a more practical objective is to reduce adverse

[18] See North et al. (2012).

[19] In the Healthy Forests Restoration Action of 2003, the WUI is defined as up to 1.5 mi from communities at risk or as defined in individual community fire protection plans.

The pace, scale, and restoration benefits of fire would be significantly increased if national forests identified large, contiguous blocks of forest to be treated, and then moved these blocks out of fire suppression to be maintained with prescribed and managed wildfire.

fire effects and intensity rather than occurrence and size.[20] A recent comparison of fire severity and size between Forest Service and Yosemite National Park lands found that the park's policy of allowing most lightning fires to burn relatively unimpeded under a range of fire weather conditions had achieved fire patterns that were closer to desired historical conditions.[21] The pace, scale, and restoration benefits of fire would be significantly increased if national forests identified large, contiguous blocks of forest to be treated, and then moved these blocks out of fire suppression to be maintained with prescribed and managed wildfire (fig. 2).[22] Outside of the WUI, forests could be zoned for a range of wildfire responses consistent with desired effects and made a priority for managed fire use.[23] More creative and flexible ways of working with fire could help achieve restoration objectives. Greater use of wildland fire will require continued interagency coordination (especially between land management and air quality regulatory agencies), strategic monitoring, robust science-management partnerships, and increased support of fire management programs from agency leadership and the general public. Approaches that focus primarily on containing fire through suppression, regardless of burning conditions, sacrifice opportunities for using fire for ecological benefits and promise more dangerous and more destructive fires in the future.

[20] See Reinhardt et al. (2008).

[21] See Miller et al. (2012).

[22] Recent research (Ager et al. 2012b, 2013) has developed models for optimizing fuels treatment locations across a landscape to facilitate managed wildfire and prescribed fire use, rather than the traditional allocation designed to aid suppression.

[23] Dellasala et al. (2004) suggested a comparable three-zone approach.

Marc Meyers

Figure 2—Variable forest structure produced by a restored fire regime in Sugarloaf Valley, Sequoia-Kings Canyon National Park.

Management Implications

- In mid-elevation forests, use of frequent, low- and moderate-intensity fire is the most effective management practice for restoring forest resilience in the advent of climate change. Treatment prescriptions could often be guided by what is needed to restore fire to the area.
- Outside of the WUI, each national forest could zone areas for different fire responses (e.g., let burn and monitor, containment but not suppression, allow surface but not crown fire, etc.) under specified weather percentile conditions.
- More remote firesheds could be identified, fuels treated in strategic locations, and desired conditions maintained by prescribed fire and managed wildfire.

Demonstration Landscapes for Reconciling Fuels Treatment, Wildlife Habitat, and Riparian Restoration

Current practices and regulations make it difficult to manage forested landscapes for broad-scale processes. Forest planning often involves a patchwork of designations; for example, the Sierra Nevada Forest Plan Amendment includes protected activity centers, habitat conservation areas, and riparian conservation areas) within which forest practices are limited. Management decisions under these constraints often becomes triage, with treatments opportunistically targeting forests with the highest fuel loads that do not face operational or stakeholder barriers. Proactive, integrated landscape management will be needed to effectively reduce fire hazard while providing immediate and long-term wildlife habitat and restoring riparian ecosystems. Exploring this may require relaxing some of the constraints, on an experimental basis, in demonstration areas. The intent is to test how habitat for sensitive species can be maintained and improved across a landscape without using spatially explicit protection or buffer areas. To date, management and research have not collaborated and experimented on the scale needed to examine how treatments that promote forest resilience can be reconciled with the provision of sensitive species habitat and riparian restoration. Without taking that step, it may be impossible to effectively manage Sierra Nevada forests at a scale that is consistent with some species habitat use patterns or the ecological processes inherent in these forests. The body of research, much of it recent, supports this approach and provides a solid foundation for moving forward. Demonstration landscapes might be identified where a collaborative team would define a desired condition, and management would be planned and implemented at a broad scale while relaxing constraints on current forest practice designations.

Recent success with several collaborative projects in the Sierra Nevada suggests some institutional structures that may facilitate success. First, effective broad-scale management efforts could be based on a collaborative process.[24] A key to successful collaboration is that participants define a desired condition and identify immediate and long-term objectives.[25] Second, science-based monitoring and its active incorporation in adjusting management practices are essential both for course correction and as a means of building trust and cooperation. A third guideline is the inclusion of rural community concerns and economic factors in decisionmaking. Landscape management requires public support, and for long-term viability, a self-sustaining economic base. Projects that cultivate stakeholder and community involvement, and plan for generating sufficient revenue to support long-term management objectives, could weather shrinking budgets and steadily fund monitoring that better accomplishes broad-scale restoration.

Management actions aimed at restoration of dynamic, broad-scale processes that produce a range of vegetation conditions similar to those under which Sierra Nevada ecosystems evolved should help to conserve coarse-scale terrestrial and aquatic biodiversity.

Although principles in PSW-GTR-220 suggest a general approach (North et al. 2009), optimal management of a landscape for all wildlife species while reducing fire hazards is still in a developmental stage. Current policy focuses on sensitive species and is weighted toward maintaining and creating high canopy cover, old-forest conditions. This fine-filter approach does not adequately consider the habitat needs of a broader range of species and the shifting dynamics in frequent-fire forests. Management actions aimed at restoration of dynamic, broad-scale processes that produce a range of vegetation conditions similar to those under which Sierra Nevada ecosystems evolved should help to conserve coarse-scale terrestrial and aquatic biodiversity. For terrestrial wildlife, this approach would include developing variable habitat conditions for species associated with different seral stages, from primary disturbance conditions (i.e., black-backed woodpecker and postfire habitat-associated species), to early succession (fox sparrow, deer, etc.), through old-forest conditions, and the diversity of prey species upon which top trophic predators depend. For riparian ecosystems, reductions in forest density and judicious fire

[24] Collaborative teams by definition strive for consensus. However, it is not always possible to get 100-percent agreement. Effective and efficient collaboration may hinge on eventually voting on some issues and then moving forward following the majority's intent (Bartlett 2012).

[25] There are several collaborative groups that have made significant progress and can provide practical lessons, including all three collaborative forest landscape restoration programs, the Dinkey Landscape Restoration, the Amador-Calaveras Consensus Group Cornerstone, and the Burney-Hat Creek Basin. Sagehen Experimental Forest has also had tremendous success with its collaborative efforts, including the implementation of demonstration plots to help visualize treatment options.

Box 1.3-1

An Adaptive Management Proposal to Evaluate Tolerance by Fishers for Disturbance

A reasonable hypothesis to be tested in an adaptive management framework is whether fishers can tolerate fuels treatments up to the levels that may be needed to reduce risk of uncharacteristically severe wildfire at the landscape scale. Fishers have evolved with the effects of fire on their habitat, yet it is uncertain how much disturbance via fire and fuels treatment they may tolerate. Researchers on the Sierra National Forest,[26] however, have surveyed multiple study areas equivalent to the average size of a female fisher home range (approximately 13 km^2 [5 mi^2]) and evaluated the percentage of those areas that were covered by treatments, including a combination of prescribed fire, thinning, salvage logging, and other forms of timber harvest, over 3-year periods (a reasonable estimate of fisher generation time). Evaluation of these data could suggest levels of treatment per year that might be tolerated by fisher, and those levels could be compared to the areas that modeling results suggest need to be treated to reduce the likelihood of unacceptably large, high-intensity fires (10 to 25 percent of a landscape over a 5- to 10-year period) (Ager et al. 2007, 2010; Finney et al. 2007; Schmidt et al. 2008; Syphard et al. 2011). To be cautious, the area treated should account for the relative suitability of habitat patches as well as their contribution to fisher habitat conditions within the local area. For example, impacts to fishers may be too great if treatments target important patch types in a poor quality home-range area; this is in contrast to treatments that target less important habitat patches in a higher quality home-range area. This approach remains a hypothesis to be tested, but the proposed rate and extent of disturbance in fisher habitat may permit the coexistence of fishers with a rate of application of fuels treatments that will also protect their habitat from loss from high-intensity fire. Fishers may tolerate such a rate, especially because the fraction of the landscape needed to reduce wildfire risk may only partially coincide with occupied fisher areas. It is important to caution, however, that this proposal represents the desire to create a starting point for collecting new information that can evaluate its merit. This proposed guideline needs to be tested in an adaptive management framework and to be integrated with other emergent approaches.

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[26] Thompson, C.M.; Purcell, K.L. 2013. Unpublished data from fisher study. On file with: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Forestry Sciences Laboratory, 2081 E. Sierra Avenue, Fresno, CA 93710-4639.

use[27] could enhance soil water balance and help restore stream microclimate, nutrient, and sediment processes that support aquatic diversity. The heterogeneity of conditions within Sierra Nevada riparian areas suggests delineating riparian management zones using scalable widths based upon soil moisture, geomorphic settings, and other local landscape characteristics.

As forest management strategies place more emphasis on a coarse-filter approach to biodiversity, sensitive species populations presently at risk still need to be maintained or increased. Monitoring of sensitive species while treatments are implemented would help to evaluate impacts and provide for course corrections (see box 1.3-1 for a suggested approach in fisher habitat). Recently developed fisher and spotted owl habitat models[28] can be used to evaluate different management alternatives and their expected influence on current and future habitat conditions. These analyses would include designing and maintaining habitat connectivity[29] across a dynamically changing landscape.

Practices in demonstration landscapes would be considered experimental and subject to initial evaluation against the best available sensitive species habitat and fire behavior models, and longer term evaluation from monitoring results.

Management Implications: Demonstration Landscapes

- Establish demonstration landscapes with an objective of restoring ecological processes and resilience while maintaining safeguards to minimize the loss of ecosystem services and habitat in the short term.
- When necessary, constraints on management practices from land use designations could be relaxed to achieve landscape resilience objectives. These practices would be considered experimental and subject to initial evaluation against the best available sensitive species habitat and fire behavior models, and longer term evaluation from monitoring results.

[27] Recent research suggests that riparian forests on many first- and second-order streams in the Sierra Nevada may have had fire regimes comparable to adjacent uplands (van de Water and North 2010, 2011). This reinforces the idea that riparian areas should not be set aside when designing landscape-level treatments.

[28] See Ager et al. (2012a), Gaines et al. (2010), Thompson et al. (2011), and Zielinski et al. (2010).

[29] Forest conditions that facilitate landscape connectivity vary between species, making it difficult to plan and manage "corridors" for an array of wildlife. Riparian areas have an important function as corridors, as research suggests that even under an active fire regime, historical riparian forests had higher stem density and canopy cover than upland forests (van de Water and North 2011). To maintain this high-cover corridor and avoid wildfire wicking, riparian forests could become a priority for light fuels treatment (i.e., surface and small ladder fuels). A more sophisticated approach, albeit focused on forest carnivores, is the multiple species habitat connectivity modeling that is nearing completion (collectively for Pacific fisher, marten, wolverine, and Sierra Nevada red fox) (Spencer and Rustigian-Romsos 2012). This effort received input, over several years, from species and connectivity modeling experts. Another more explicit modeling approach of note is the California Essential Habitat Connectivity Project (Spencer et al. 2010), which produced a coarse level of wildlife connectivity statewide.

- Demonstration landscape boundaries could be identified based on fireshed concepts (i.e., 100,000 to 200,000 ac in size) to be consistent with the scale of the dominant process, fire.[30]
- These landscapes might be established in areas with extensive ongoing monitoring or research (e.g., spotted owl demographic study areas, southern Sierra fisher occupancy monitoring area, instrumented watersheds, etc. [see fig. 1 in chapter 1.5]). This strategic placement would significantly reduce costs and "startup" time because long-term baseline data are available at these sites.
- Desirable locations could include places without large WUIs or checkerboard ownership; places near wilderness or National Park Service lands to provide a buffer for species and a comparison landscape with less intensive active management. Once located, strong commitment and innovation would be needed from local Forest Service leadership.
- Create a collaborative team among managers (including the Regional Ecology program), stakeholders, and research scientists to develop a desired condition for the demonstration landscape and a science-based, question-driven monitoring program[31] to inform and modify management with updated information.

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[30] The primary intent is to manage the entire landscape to a condition where it is resilient to ecosystem stress, particularly fire, drought, and large bark beetle infestations. Widespread reintroduction of fire is the best means to build this resilience. All areas in the landscape could be managed collectively to achieve landscape-level resilience, although some areas may not need active treatment. For example, an area that is too steep for mechanical treatment and has low or moderate fuel loads may not currently be a priority for treatment, but it could be included within plans for managed wildfire or an adjacent prescribed fire. Similarly, some areas that are naturally more resilient owing to their moist conditions or shaded aspects (i.e., north- and east-facing slopes and some riparian areas) may also not be priorities for treatment.

[31] The science-based, question-driven monitoring program in Appendix E of the Sierra Nevada Framework could be updated to more fully address the social dimensions of socioecological resilience. Monitoring that evaluates the effects of management decisions on socioecological resilience might (1) reflect relevant ecological, social, and economic processes in a "triple bottom line" framework; (2) use metrics that are quantifiable, reasonably available to managers, and within the scope of management influence; (3) incorporate concerns of scientists, managers, and local experts; and (4) be linked to potential changes in management based upon the results of monitoring.

Monitoring plans could be centered on a coarse-filter approach to evaluate landscape-scale habitat patterns and ecological processes, but could include some fine-filter monitoring to ensure that at-risk species are being conserved. Integrating modeling with monitoring of field conditions could help evaluate how ecosystems are changing at broad scales where experimentation may be impractical. Modeling would be an important component of developing and adjusting an adaptive management strategy. Predictive habitat models could be integrated with silvicultural and fire models. Tradeoffs between treating new areas and maintaining existing areas would need to be considered using models to account for costs of treatment, changing fire conditions, and other factors.

- Planning for desired conditions accounts for long-term, large-scale context. Objectives for smaller areas, such as stands or stream reaches, are identified in the context of the entire landscape and over a long timeframe (e.g., see sidebar in chapter 2.1, "Forest Ecology").
- As a general treatment implementation guide, models in fire (FARSITE/FlamMap), wildlife (fisher and owl habitat trajectory), and forest restoration (PSW-GTR-237 ArcGIS LMU macro) could be used to project and plan future conditions.
- Use prescribed fire and managed wildfire wherever possible to most effectively achieve or maintain ecosystem resilience.
- For long-term sustainability, many projects would need to generate their own revenue and support local economies. Without compromising ecological integrity, economic and social factors need to be explicitly included in planning, monitoring, and management to ensure long-term viability.

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Chapter 1.4—Synopsis of Climate Change

Angela Jardine[1] and Jonathan Long[2]

Introduction

Changes in climate can interact with other stressors to transform ecosystems and alter the services those ecosystems provide. This synopsis presents themes that run through the synthesis report regarding the impacts of a changing climate on the forests and waters of the synthesis area as well as long-term, broad-scale, science-based strategies to promote system resilience to those impacts. Scientific observations of climate variations in air temperatures and precipitation (type and quantity) and their interactions have been directly linked to changes in stream flows (amount and timing), fires (frequency and severity), and ecosystem structure and function over the past several decades. Future climate scenarios suggest a strong likelihood for increased exposure of socioecological systems in the synthesis area to wildfire, droughts, intense storms, and other natural disturbances. Many of the social, economic, and cultural impacts of climate change are expected to be disproportionately greater on rural communities, natural resource-based communities, Native American communities, and groups with less financial resources to facilitate adaptation (see chapter 9.3, "Sociocultural Perspectives on Threats, Risks, and Health," and Wear and Joyce [2012]). Well-synthesized information about strategic responses to climate change is available in the chapter on climate change in PSW-GTR-237 (Safford et al. 2012) and the recent report *Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector* (Vose et al. 2012).

Many of the social, economic, and cultural impacts of climate change are expected to be disproportionately greater on rural communities, natural resource-based communities, Native American communities, and groups with less financial resources to facilitate adaptation.

Observed and Predicted Climate Change in the Synthesis Area

Climate refers to the long-term weather patterns (i.e., precipitation, temperature, humidity, sunshine, wind velocity, fog, frost, and hail storms) for a given region. Climate dynamics are the products of a complex system that entails large natural variability on different temporal and spatial scales (Lucarini 2002). There is important climatic variation from north to south within the synthesis area, as well as east-west variation. Despite this complexity, there are several recent trends and projections that appear to be relatively consistent across climate change scenarios

[1] Field research engineer and Ph.D. candidate, Programa Clima e Ambiente, Instituto Nacional de Pesquisas da Amazônia e Universidade do Estado do Amazonas, Manaus, Amazonas, Brazil.

[2] Research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

and most parts of the synthesis area, including increased average annual and seasonal temperatures, increased length of freeze-free season and fire season, increased droughts, and increased storm severity (Das et al. 2011, Overpeck et al. 2013, Safford et al. 2012).

Across the Southwestern United States (California, Nevada, Utah, Arizona, Colorado, and New Mexico), temperatures since 1950 are reported to be the warmest in the past 600 years, with average daily temperatures in the most recent decade (2001–2010) being higher than any other decade since 1901 (the period of record used for a standardized comparison of the first decade of the 21st century to the entire record of the 20th century using the PRISM monthly gridded analysis dataset) (Hoerling 2013). Likewise, the spatial extent of drought from 2001 through 2010 covered the second largest area observed for any decade since 1901, and total streamflows in the four major drainages of the Southwest (Sacramento/San Joaquin, Upper Colorado, Rio Grande, and Great Basin) fell 5 percent to 37 percent below the 20th-century averages during the 2001–2010 decade (Overpeck et al. 2013).

In the Sierra Nevada, warming temperatures since the 1980s are generally attributed to increasing nighttime minimum temperatures across the region; however, different elevations have experienced a range of temperature changes (Safford et al. 2012). For example, the annual number of days with below-freezing temperatures in higher elevations is decreasing, whereas the number of extreme heat days at lower elevations is increasing (Safford et al. 2012). Changing temperatures combined with elevation differences influence the type of precipitation received in the Sierra Nevada, which in turn greatly impacts regional hydrology and fire vulnerability.

Observations show an increase in the proportion of precipitation falling as rain instead of snow since the 1980s (Harpold et al. 2012, Safford et al. 2012). This change has manifested in spring snowpack decreases of at least 70 percent across the lower elevations of the northern Sierra Nevada, a trend that has not yet been observed in the higher elevation southern Sierra Nevada. By 2002, spring thaw and peak streamflows were occurring 1 to 4 weeks earlier than they had 50 years earlier in the central Sierra Nevada (Stewart et al. 2005). Such changes have extended the fire season in the Sierra Nevada, particularly in low- to mid-elevation conifer forests (Safford et al. 2012). A longer fire season, associated with earlier drying and more cured fuels, has been linked to increases in the size or intensity of wildfires across the Western United States in general and the Sierra Nevada and southern Cascade Range specifically (Miller and Safford 2012, Miller et al. 2012, Safford et al. 2012, Westerling et al. 2006). These changes are a primary concern for forest and water resource managers across the synthesis region.

One of the most significant projected changes in climate for the synthesis area over the next century is an increase in average temperature by 2 to 4 °F (1.1 to 2.2 °C) in the winter and double that amount in the summer (Safford et al. 2012). Changes in precipitation are less clear and may differ within the synthesis area (Safford et al. 2012). In the Sierra Nevada, models project a decrease in mountain snowpack of at least 20 percent and up to 90 percent over the next century (Safford et al. 2012). This prediction is a major concern for water resource managers, who are already trying to balance various demands for water during periods of low flows. These changes are associated with projected reductions in streamflow, especially during the spring, on the western slopes of the Sierra Nevada, with greater impacts expected in the south (San Joaquin basin) than in the north (Sacramento basin) (VanRheenen et al. 2004). Flood potential is predicted to increase for high-elevation, snow-fed streams owing to shifts toward earlier peak daily flows (driven by increasing temperatures), increases in the frequency and magnitude of storms, and an increased proportion of precipitation falling as rain instead of snow (Das et al. 2011, Overpeck et al. 2013, Safford et al. 2012). For the western slopes of the Sierra Nevada, wintertime "wet" floods are expected to become more frequent and intense, while spring and summer snowmelt floods are expected to become smaller (Das et al. 2011, Overpeck et al. 2013).

Despite uncertainty about changes in annual precipitation, many models suggest increases in area burned in the Sierra Nevada, particularly on the drier eastern side, even in scenarios when precipitation increases (Hayhoe et al. 2004, Krawchuk et al. 2009, Lenihan et al. 2008). Simulations also point to widespread conversion of conifer-dominated forest to mixed evergreen forest as broadleaved trees, especially oaks, and shrubs increase at lower elevations, extensive expansion of grassland vegetation (primarily via fire-driven conversion of woody vegetation), and to loss of alpine and subalpine vegetation at high elevations (Lenihan et al. 2008). Crimmins et al. (2011) noted that water balance, rather than temperature, drives changes in plant distributions, and that increases in precipitation in recent decades may be resulting in downhill as well as uphill expansion of some plant species. Their findings have resulted in some scientific debate (Dobrowski et al. 2011, Stephenson and Das 2011).

Although many of the datasets discussed above focus on measurements of climate over the past 100 years or so, it is important to consider longer term perspectives when considering potential impacts to ecosystems. Taking a long-term view allows distributions of plants and animals to be seen as constantly shifting along complex and variable gradients (Stine 2004). The ranges of species will tend to contract into refugia during unfavorable periods and expand outward under more favorable conditions. In response, scientists have proposed using soft boundaries and corridors for long-term management plans (Stine 2004). This approach was a driving force behind setting guidelines for conservation of the California spotted owl rather than adoption of reserves (Verner 1997). As an alternative to a reserve approach for conserving biodiversity in the face of environmental change, Davis et al. (1996) considered establishment of biodiversity management areas that would have multiple uses but maintain an emphasis on species conservation. Another finding from studies with long-term perspective is that aquatic ecosystems may be particularly affected by climate change, with the indigenous fauna being survivors from past droughts that strained those habitats (Stine 2004). However, key challenges facing the broader socioecological systems are how well those species, as well as human systems, can tolerate the impacts of climate change in combination with other stressors that have been introduced within the past two centuries.

Marc Meyer

Figure 1—This red fir stand in the Illilouette Valley of Yosemite National Park has experienced multiple fires in recent decades.

Approaches to Promote Resilience to Climate Change

Chapter 1.2 summarizes strategic approaches to meet the challenges of promoting socioecological resilience. Current climate change impacts and those predicted to occur in the near and distant future challenge the ability to manage natural resources now and especially in the long term. The following points highlight concerns, strategic approaches, and research needs from various chapters of this science synthesis that focus on climate change. Readers are encouraged to review the chapters listed at the end of each example (and the references therein) for greater detail.

- **Recognize and address scale mismatches—**The temporal, spatial, and functional scales of management systems may not be well matched to the scales of environmental variation.

Forest ecology research has concentrated on narrow spatial and temporal scales; however, effective planning for climate change should consider long temporal periods and large spatial scales to account for widespread changes in disturbance regimes. Designing treatments at larger scales allows strategies to better account for landscape-scale processes, such as wildfires and insect outbreaks, as well as species that have large ranges. (See chapter 1.2.)

- **Consider long-term (>50 years) risks** in addition to short-term (<10 years) expected outcomes.

Large old-forest structures, which provide vital habitat for a variety of fauna in the synthesis area, take decades or centuries to develop; landscape plans should promote recruitment of these habitat features and promote forest resilience by increasing growing space and reducing the risk of uncharacteristic high-intensity fire. (See chapters 2.1, "Forest Ecology;" 7.1, "The Forest Carnivores: Marten and Fisher;" and 7.2, "California Spotted Owl: Scientific Considerations for Forest Planning.")

Many of the ecological services afforded by mountain meadows are threatened by a warming climate, and these vulnerabilities appear to be particularly high in several central Sierra Nevada watersheds, including the American, Mokelumne, Tuolumne, and Merced. Restoration efforts in these systems may help to delay runoff and increase summertime low flows. (See chapter 6.3, "Wet Meadows.")

Post-wildfire flooding and debris flows can have significant downstream impacts, including accelerated filling of reservoirs and other effects on water supplies, as well as significant and lasting impacts on vulnerable and isolated aquatic populations (see chapter 6.1, "Watershed and Stream Ecosystems"). Because climate change is expected to increase the incidence of severe wildfire and possibly rainstorms, and because human populations are increasing, the threat posed by post-wildfire debris flows is expected to increase. Debris flows can be difficult to mitigate, and few options exist beyond reducing the potential for severe fires. (See chapter 4.3, "Post-Wildfire Management.")

- **Set adaptable objectives and revisit them,** because there may be a lack of clear solutions, certain options may prove unrealistic, and new opportunities may become apparent as conditions change.

Eighty-five percent of known California spotted owl sites occur in moderate- or high-risk fire areas in the Sierra Nevada. Uncertainty exists regarding how increasing trends in the amounts and patch sizes of high-severity fire will affect California spotted owl occupancy, demographics, and habitat over longer timeframes. Barred owls have replaced or displaced northern spotted owls over large areas of their range. Management needs to consider effects of multiple stressors on at-risk species, especially because conditions may change which options are prudent or feasible over time. (See chapter 7.2.)

Given expectations for climate change, increased use of prescribed fire and managed wildfire at large scales would help to restore resilience in many forests. (See chapter 1.3, "Synopsis of Emergent Approaches.")

In the face of climate change, proactive conservation strategies for trout and amphibians should consider not only direct effects of climate, such as ameliorating high temperatures or low flows, but also reducing interactions with introduced species and other stressors. In some situations, there may be enhanced opportunities to deal with introduced species as climate change or wildfires alter conditions. (See chapters 6.1 and 6.4, "Lakes: Recent Research and Restoration Strategies.")

Although climate change may be a chronic stressor, the catalyst through which its effects will be expressed is likely to be wildfire.

Approaches to promote resilience following severe wildfires should consider landscape context and the changing climate to help to identify desired conditions, target treatments, and associated monitoring, and to identify species and genotypes appropriate for postfire planting efforts. (See chapters 3.1, "Genetics of Forest Trees," and 4.3.)

- **Rely more on process-based indicators than static indicators of structure and composition, while recognizing that restoration of structure and process must be integrated.**

Sierra Nevada managers have been experimenting with PSW-GTR-220 principles, using topography as a template to vary treatments while meeting fire hazard reduction, wildlife habitat, and forest restoration objectives. Although climate change may be a chronic stressor, the catalyst through which its effects will likely be expressed is wildfire. (See chapter 1.3, "Synopsis of Emergent Approaches.")

Manipulation of current forests to resemble historical forest conditions may not be the best long-term approach when considering future climates. In many places, such an approach may represent a useful short-term goal, but climates and climate-driven processes are heading in unprecedented directions. Given the likely novelty of future climates, a prudent approach for maintaining forest ecosystems is to restore key processes such as wildfire that have shaped forest ecosystems for millennia, and associated structure and composition that are resilient to those processes and aid in their restoration. (See chapter 4.1, "Fire and Fuels.")

Climate patterns strongly influence soil development and nutrient cycling processes. As elevation and precipitation increase, soil pH and base saturation tend to decrease as a result of greater leaching and decreased evapotranspiration. (See chapter 5.1, "Soils.")

Climate change effects on flood regimes could alter sediment storage in floodplains, terraces, and colluvial hollows, which would in turn influence channel stability. Climate change is also expected to diminish summer low flows that could threaten aquatic life, especially cold water species. (See chapter 6.1.)

Because foundational ecological processes, such as soil water storage and vegetation evapotranspiration, may not have explicit targets, there may be a tendency to undervalue—or even ignore—them in decisionmaking. Forest treatments have the potential to enhance system resilience to multiple stresses by reducing evapotranspiration and increasing soil water availability. In addition, such treatments have the potential to enhance the yield, quality, and timing of downstream water flows and resulting ecosystem services. (See chapter 6.1.)

- **Integrate valuation tools, decisionmaking tools, modeling, monitoring, and, where appropriate, research** to evaluate responses and better account for the risks and tradeoffs involved in management strategies.

Climate change may become a chronic stressor in red fir forests in the lower parts of their present distribution; reductions in the extent of true fir forests could be particularly detrimental to martens; consequently, the potential influence on terrestrial and aquatic ecosystem processes in the fir zone constitute an important cross-cutting research gap. (See chapters 1.5, "Research Gaps: Adaptive Management to Cross-Cutting Issues," 2.1, and 7.1.)

Post-wildfire management increasingly involves evaluating impacts of wildfire and potential benefits of treatment using decision support tools, developing broad-scale and long-term restoration strategies to influence ecological trajectories and promote desired conditions; and to design and implement programs that feed back into adaptive management frameworks. (See chapter 4.3.)

There is broad consensus for using common garden experiments or provenance tests to prepare for projected conditions by better understanding how genetic variability can improve ecological restoration. (See chapter 3.1, "Genetics of Forest Trees.")

Rigorous assessment of the effects of future climate change on spotted owls will require dynamic models that incorporate vegetation dynamics and effects of competitor species. (See chapter 7.2.)

Further research is needed to evaluate how nitrogen deposition and ozone affect carbon sequestration both aboveground and in the soil. This information will be critical to climate change mitigation efforts in the region. During severe fires, accumulated nitrogen in vegetation, litter, and surface soils will be released, and both thinning and prescribed fire can be used to proactively reduce the amount of plant matter available for combustion. However, long-term ecosystem protection and sustainability will ultimately depend on reductions in nitrogen deposition, and this is the only strategy that will protect epiphytic lichen communities. (See chapter 8.1, “Air Quality.”)

- **Consider the integrated nature of socioecological systems;** approaches that address only one dimension of a problem are less likely to succeed in the long run than strategies that consider ecological, social, economic, and cultural components.

Addressing diverse viewpoints and perceptual divides regarding climate change by focusing on more immediate and local issues and potential impacts to public health and socioeconomic well-being, is important for generating support for mitigation and adaptation. (See chapter 9.3.)

Anticipated shifts in the hydrologic cycle are expected to detract from spring and summer water-based recreation and tourism, may reduce water supplies, and may increase risks of floods. These projections highlight the importance of advance planning as well as efforts to restore degraded systems so they will be less vulnerable. (See chapters 6.1; 6.3; 9.1, “Broader Context for Social, Economic and Cultural Components;” and 9.3, “Sociocultural Perspectives on Threats, Risks, and Health.”)

Adjusting management approaches based upon long-term monitoring and feedback loops becomes increasingly important as climate change induces effects on systems. (See chapters 9.1 and 9.6, “Collaboration in National Forest Management.”)

An important opportunity to mitigate climate change while promoting broader objectives lies in utilizing biomass generated from restorative forest treatments for energy production, especially in lieu of pile burning. (See chapter 9.5, “Managing Forest Products for Community Benefit.”)

- **Use participatory and collaborative approaches to facilitate adaptive responses and social learning.**

Rural communities in the United States tend to be more vulnerable to climate change than urban communities, and people residing in the wildland-urban interface are particularly vulnerable to fire, making the concept of community resilience especially relevant in these contexts because of its focus on a community’s ability to cope with change. (See chapter 9.4, “Strategies for Job Creation Through National Forest Management.”)

Interactions with holders of traditional and local ecological knowledge could be particularly valuable in understanding impacts of climate change. (See chapters 4.2, “Fire and Tribal Cultural Resources,” and 9.6.)

Science-management partnerships can facilitate dissemination of scientific information to help confront the challenges associated with climate change (see chapter 1.2, "Integrative Approaches: Promoting Socioecological Resilience"). The California Landscape Conservation Cooperative (CA LCC) is an example of a partnership that aims to address impacts of climate change and has held recent workshops for the synthesis area.

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Chapter 1.5—Research Gaps: Adaptive Management to Cross-Cutting Issues

Jonathan Long,[1] *Carl Skinner,*[2] *Malcolm North,*[3] *and Lenya Quinn-Davidson*[4]

Summary of Cross-Cutting Research Gaps

- High-elevation forests, including the upper montane and subalpine zones, warrant increased attention and research owing to the projected effects of climate change. These forests provide important habitat and biodiversity values, and they face novel threats from shifts in precipitation patterns and increased likelihood of uncharacteristically severe wildfire.
- Forested riparian areas are highly valued, yet they have not been a focus for restoration research. Conducting experimental projects over extended periods and across the synthesis area, in combination with large-scale modeling, would help to guide practices to restore riparian areas and downstream aquatic resources.
- Long-term effects of wildfire, with and without various pre- and postfire treatments, remain a significant research gap for many socioecological values. Increased understanding of long-term effects of repeated fires across upland, riparian, and aquatic systems would help to promote socioecological resilience.
- Key questions remain concerning removal of burned trees and woody debris as part of post-wildfire treatments, given limited understanding of fuelbed succession following fires of different intensities. Both social and ecological research are needed to evaluate the outcomes of accepting or influencing ecological trajectories of severely burned areas through salvage and other kinds of treatments.

[1] Research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

[2] Geographer (emeritus), U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002.

[3] Research plant ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

[4] Staff research associate, University of California Cooperative Extension, 5630 South Broadway, Eureka, CA 95503.

- There is a great need for more integrated research that evaluates how ecological restoration efforts affect important socioeconomic and cultural values. Although science suggests that there are opportunities for forest treatments to enhance water supply and mitigate some of the potential effects of climate change, research is lacking in the Sierra Nevada on the longevity of treatment effects on water yield and the extent to which water quality can be maintained or enhanced.
- Benchmarks and performance criteria can be valuable tools for evaluating progress toward meeting broad restoration goals, and there are large efforts to develop integrated indexes of ecosystem health that consider ecological and social conditions. However, at a broad strategic landscape level, it can be problematic to emphasize quantitative targets. More research and joint consideration by managers and scientists of these types of benchmarks and criteria would help to inform management goals and strategies.

Building on Adaptive Management Efforts

A number of studies undertaken by the Forest Service within the synthesis area have been designed and implemented to better understand both more immediate and long-term effects of treatments, including the Blacks Mountain Ecological Research Project (Oliver 2000); Goosenest Adaptive Management Area Project (Ritchie 2005); Long-Term Soil Productivity Study (Powers 2006); National Fire and Fire Surrogate Study (McIver and Fettig 2010); the Teakettle Experiment (North 2002); the Kings River Experimental Watersheds (KREW) (Hunsaker and Eagan 2003); the Plumas-Lassen Administrative Study, which includes the Meadow Valley study area; and the Sierra Nevada Adaptive Management Project (SNAMP), a joint project spearheaded by the University of California (fig. 1 and table 1). These studies have generally had difficulty maintaining funding after initial implementation, so the resulting information from the studies has been limited to responses over relatively short time periods. In a few situations, researchers have been able to study some long-term questions by taking advantage of a well-designed study that had been dormant or abandoned for some time but had been well archived by the original researchers (Dolph et al. 1995, Knapp et al. 2012). These examples provide a valuable precedent for future research.

Progress made on previous research topics will help to inform development of landscape strategies. Synthesis of research on the effects of forest fire hazard reduction treatments suggests that the threat of high-intensity fire can be significantly reduced with relatively benign impact on most wildlife species at project scales

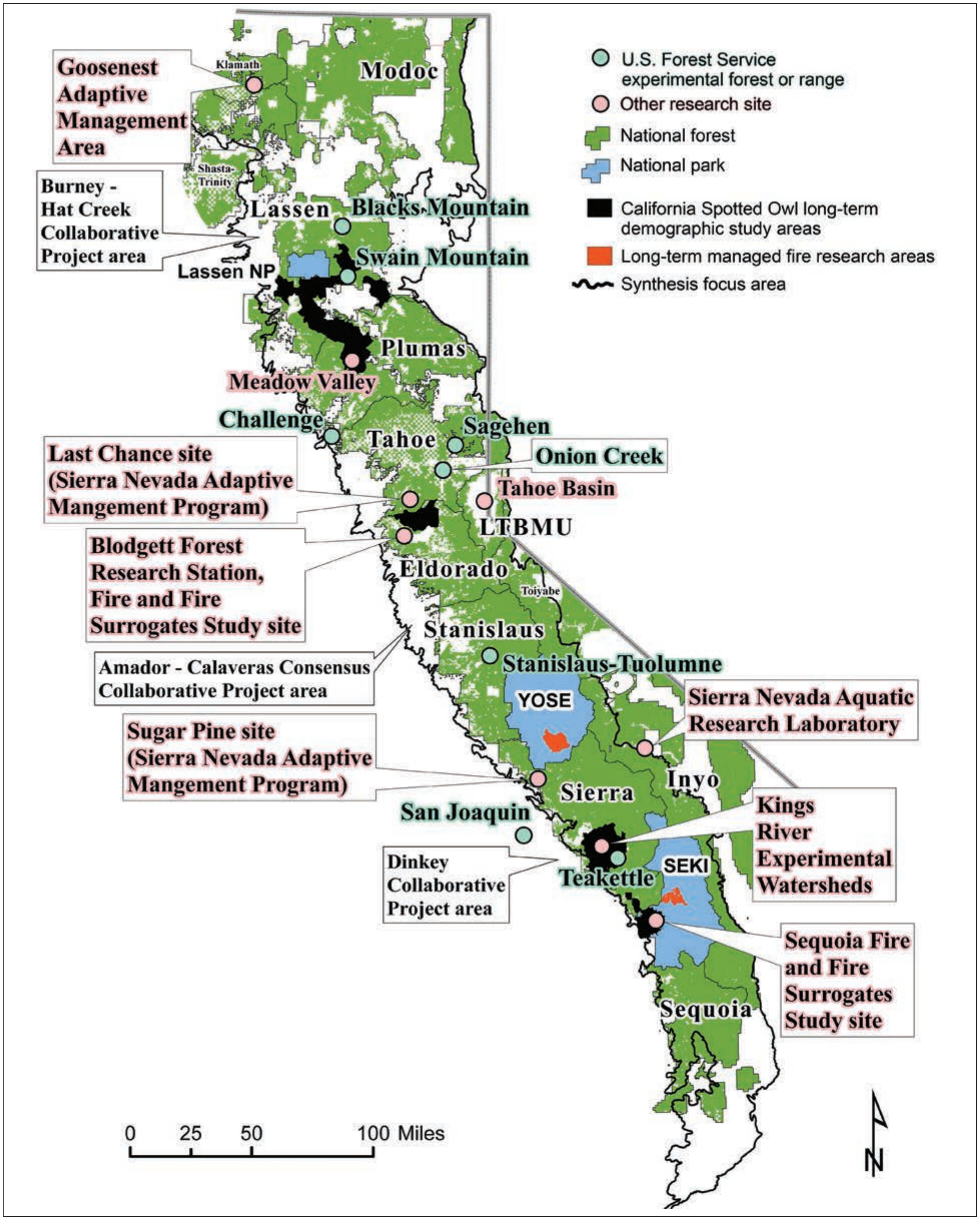

Figure 1—Map of experimental areas in the Sierra Nevada and southern Cascade Range, highlighting various adaptive management projects featured in this synthesis. LTBMU = Lake Tahoe Basin Management Unit. YOSE = Yosemite National Park. SEKI = Sequoia-Kings Canyon National Parks. NP = national park. Map by Ross Gerrard.

Table 1—USDA Forest Service experimental forests and adaptive management areas within the Sierra Nevada and southern Cascade Range synthesis area

Research area	Acres	Hectares
Blacks Mountain Experimental Forest	9,180	3715
Challenge Experimental Forest	3,573	1446
Goosenest Adaptive Management Area	172,000	70 000
Goosenest Ecological Research Study Area (also the southern Cascade Range Site of the National Fire and Fire Surrogates Study)	3,000	1200
Kings River Experimental Watersheds	46,604	18 860
Onion Creek Experimental Forest	2,965	1200
Sagehen Experimental Forest	20,016	8100
Stanislaus-Tuolumne Experimental Forest	1,500	607
Swain Mountain Experimental Forest	6,158	2492
Teakettle Experimental Forest	3,212	1300

Treatment areas within these studies have often not been large enough to make strong inferences about species with large home ranges, address patterns of habitat suitability and connectivity at the landscape scale, and evaluate the synergistic effects of treatments and wildfires on wildlife. Additionally, these research projects generally have not been in place long enough to evaluate long-term effects.

(Stephens et al. 2012). However, many of the less common species have not been a focus of study primarily because of statistical limitations with studying small populations or large home ranges. Most research associated with priority species, such as California spotted owl, has been on the small mammals that are their prey. Treatment areas within these studies have often not been large enough to make strong inferences about species with large home ranges, address patterns of habitat suitability and connectivity at the landscape scale, and evaluate the synergistic effects of treatments and wildfires on wildlife. Additionally, these research projects generally have not been in place long enough to evaluate long-term effects. Adaptive management studies must overcome the challenge of maintaining long-term capacity and resources in order to promote social learning and system resilience.

Many experimental forests and other areas dedicated to adaptive management experiments offer opportunities to improve understanding of how to design strategies to restore forests. A number of other large projects have been supported through the Collaborative Forest Landscape Restoration Program, including the Dinkey Landscape Restoration Project, the Amador Calaveras Consensus Group Cornerstone Project, and the Burney-Hat Creeks Basin Project. In particular, the Dinkey project is examining effects on fishers, and it has already yielded insights regarding approaches to promote successful collaboration (Bartlett 2012). A number of these projects are discussed throughout chapters of this synthesis; the following examples highlight projects in Forest Service experimental forests and adaptive management areas (fig. 1 and table 1).

The Teakettle Experiment improved understanding of the ecological effects of widely used forest treatments, such as understory and overstory thinning with and without prescribed fire (North 2002). Dozens of studies examined how these treatments affected different ecosystem components. Collectively, the research suggested that in fire-suppressed mixed-conifer forest prior to treatment, many ecological processes were impeded by competition for limited soil moisture and uncharacteristically high fuel and duff loading (North and Chen 2005). After treatment, patchy heterogeneity of forest conditions was associated with the greatest increases in species diversity and restoration of ecosystem functions (Ma et al. 2010, North et al. 2007, Wayman and North 2007). The researchers concluded that fire was essential to restoring many ecological processes but that understory thinning could play an important role in facilitating greater variability in burn effects and post-treatment forest heterogeneity (North 2006).

The objectives of several other experimental areas were to test particular hypotheses. For example, the Challenge and Blacks Mountain Experimental Forests are included in the Long-Term Soil Productivity (LTSP) study, which looks at effects of different treatments on long-term soil productivity (see chapter 5.1, “Soils”). Currents efforts on the Sagehen Experimental Forest are looking at the ecological effects of strategically placed treatments on a landscape. In addition, the Sagehen fuels reduction project was planned to protect and restore forest landscape heterogeneity, reduce fuels, and maintain and restore habitat for the Pacific marten. The consideration of habitat for a rare forest carnivore, early in a collaborative planning process, was viewed as key to the favorable prognosis for this project. Monitoring of martens and forest conditions as the treatments are implemented and beyond will help evaluate whether the expected outcomes develop.

The high-diversity treatment at Blacks Mountain Experimental Forest (BMEF) is one of the most established efforts to study heterogeneity in forest structure and fuels through variable-density thinning based on species composition and other factors. The primary objective of the BMEF study was to compare differences in ecological effects between stands treated for high structural diversity and stands treated for low structural diversity (Oliver 2000). Comparisons between the two types of treatments at the BMEF showed a large difference in short-term financial returns; the high-diversity treatment yielded less revenue because it maintained most large legacy trees, whereas the low-diversity alternative was based on a prescription that cut most larger trees while maintaining intermediate-sized trees (Hartsough 2003). However, both types of treatments reduced fire behavior considerably when affected by an otherwise severe wildfire (Ritchie et al. 2007, Symons et al. 2008). Although an analysis of carbon outcomes of alternative treatments in the study area has not been done, Pacific Southwest Research Station researchers have data available to do so.

Treatments in the Stanislaus-Tuolumne Experimental Forest were designed to mimic historical reference conditions, including density, species composition, and age distribution (Knapp et al. 2012). To achieve these objectives, treatments based on stand conditions described by original detailed data and old maps have extended into some riparian areas and moved away from diameter caps in favor of selecting trees for removal to achieve the desired structure and spatial pattern. Future analyses of these treatments will facilitate a number of important comparisons of the effects of creating different stand structures to achieve both restoration and fire hazard reduction objectives, including a comparison of timber volume and economic returns between variable-density thinning and a more conventional even density thin. An extension of this research is examining effects of the experimental treatments on water yield.

The Goosenest Ecological Study Project (including its associated Fire and Fire Surrogate Study) was focused on finding ways to accelerate late-successional conditions through mechanical thinning and prescribed fire, including a comparison of a treatment that emphasized retention of pine trees and an alternative that emphasized retention of any large trees including firs; the study assessed treatment effects on fire hazard, vegetation, soils, small mammals, beetles, and birds.

Research Gaps

Appendix E of the Sierra Nevada Forest Plan Amendment (SNFPA) provided a list of priority questions for monitoring and research to support adaptive management. Several of those priorities have yielded outcomes highlighted in this synthesis, including but not limited to the following:

- Effects of fuel treatments on wildfire risk reduction (chapter 4.1, “Fire and Fuels”);
- Continuation of watershed research at the Kings River Experimental Watershed (chapter 6.1, “Watershed and Stream Ecosystems”);
- Expansion of aquatic invertebrate monitoring (chapter 6.1);
- Study of grazing effects on amphibians (chapter 6.3, “Wet Meadows”);
- Expanded monitoring of fishers, particularly in the southern Sierra (chapter 7.1, “The Forest Carnivores: Marten and Fisher”); and
- Continuation of the owl demographic study (chapter 7.2, “California Spotted Owl: Scientific Considerations for Forest Planning”).

Other topics recommended in SNFPA appendix E are likely to have been under-addressed. In addition, some important areas discussed in this synthesis, such as social and economic components of resilience, were not emphasized in that document. Revisiting and revising the list of questions from SNFPA appendix E would help to develop a long-term strategy for research to address management challenges. The various chapters of this synthesis highlight gaps in knowledge from their respective disciplines and focal areas. The topics that follow emerged as important concerns across multiple chapters. In addition, chapter 1.3, "Synopsis of Emerging Approaches," highlights the importance of adaptive management to evaluate the effects of treating large landscape areas to achieve integrated resource objectives, including promotion of wildlife species of concern, promotion of water quality, and reduction of wildfire risks. The premise that a strategic landscape approach can promote resilience by avoiding potential traps of stand-scale perspectives and constraints is a particularly important hypothesis to test through simulation modeling and an adaptive management framework. Another topic that is related to understanding interactions between treatments and wildlife species of special concern is the issue of limited operating periods (see box 1.5-1).

Changes in Upper Montane and Subalpine Forests

The management recommendations for the mixed-conifer forests presented in North et al. (2009) were not intended to extend to higher elevation forests with less frequent fire regimes. Considerations for red fir forests, which fall into that category, are discussed in chapter 2.1, "Forest Ecology." Pacific marten (*Martes caurina*), which depend on relatively high-elevation forests, are thought to be particularly vulnerable to habitat loss as a result of climate change (Purcell et al. 2012, Wasserman et al. 2012).

The zone of transition from wet mixed-conifer forests into red fir (*Abies magnifica*) is a particularly important focal area for forest management in the synthesis area. Multiple sections of this synthesis note that red fir forests are an important subject for research because they are broadly distributed in the region; they support important values, such as habitat for priority species and water supply; and they have not been extensively researched. Projected warming and shifts in precipitation from snow-dominated to rain-dominated, as well as associated increases in the incidence of severe wildfire, could result in disturbance effects that push systems in this transition zone beyond important ecological thresholds. Trujillo et al. (2012) noted that forest productivity and composition in the elevation zone between 1800 and 2100 m in the Sierra Nevada appears particularly sensitive to changes in snowpack. Streams in this zone are expected to experience increases in and changes in seasonal timing of peak flows, and the freezing level in winter storms, which coincides with the moist mixed conifer/red fir transition, is expected to rise (Herbst and Cooper 2010, Safford et al. 2012a). As temperatures warm, trees in this zone are less likely to go dormant in winter, so their evapotranspiration will increase and

Projected warming and shifts in precipitation from snow-dominated to rain-dominated, as well as associated increases in the incidence of severe wildfire, could result in disturbance effects that push systems in this red fir transition zone beyond important ecological thresholds.

Box 1.5-1

Limited Operating Periods

Limited operating periods (LOPs) are typically seasonal restrictions on certain activities that are thought to disturb wildlife. Although special management zones typically impose spatial constraints on treatments, sets of LOPs impose additional temporal constraints. As a result, science that improves understanding of species' habitat associations does not resolve the LOP constraint. Although noise is often a primary concern, burning also generates heat and gases that could be harmful under certain conditions, such as when denning animals are unable to relocate (Dickinson et al. 2010). Many LOPs designated for raptors and carnivores of concern in the Sierra Nevada Forest Plan Amendment extend for 6 or 7 months through spring and summer, whereas LOPs for sensitive amphibians and wintering bald eagles run from fall through winter and into spring. Restrictions on spring burning in particular could constrain management especially in a near-term phase designed to render landscapes more resilient to fire. Paradoxically, LOPs may conflict with larger strategic recommendations to benefit wildlife species; for example, spring burning may have less effect on predicted fisher resting habitat than fall burning (see chapter 7.1, "The Forest Carnivores: Marten and Fisher"), yet spring burning is difficult to implement under the current LOP around fisher dens. Out-of-season burning may be a critical tool to reduce accumulated fuels, especially while trying to accommodate air quality constraints. Future listings of species under the Endangered Species Act could reduce management options to implement restorative landscape treatments; this possibility presents another incentive to transition toward the long-term phase outlined in chapter 1.2, " Integrative Approaches: Promoting Socioecological Resilience."

Limited operating periods constitute an important opportunity for research to address a practical management challenge. Synthesizing existing information and conducting additional research on effects of treatment operations on particular species of concern would help to narrow restrictions to the most ecologically relevant conditions (considering treatment effects and interactions with weather and animal development). Research to refine smoke modeling could also help to gauge potential impacts more precisely.

likely reduce soil moisture and stream discharge (Bales et al. 2011). In addition, competitive interactions between martens and fishers may increase with decline in snowpack, which is projected to continue in the northern Sierra Nevada (Safford et al. 2012a). Major changes in subalpine forest structure have occurred over the last century, and increasing tree densities may promote higher continuity of fuels, which could increase the future role of more intense fire, and greater density-related stress, which could increase forest susceptibility to outbreaks of insects and disease (Dolanc et al. 2012). Continued monitoring and research are needed to evaluate whether declines in whitebark pine (*Pinus albicaulis*) forests in California represent change that is indicative of a resilient ecosystem, or instead a "catastrophic" outcome (or transformation) resulting from the synergy of climate change, native insect pests, and novel stressors (Millar et al. 2012).

Restoration of Forested Riparian Areas

Forested riparian areas are highly valued yet have not been a focus for restoration research. Chapter 6.2, "Forested Riparian Areas," suggests that more active use of mechanical thinning and prescribed fire would help to restore riparian ecosystems in the synthesis area, but effects on water quality, riparian soils, and priority riparian and aquatic species (including Sierra yellow-legged frog, mountain yellow legged-frog, and Yosemite toad) may warrant special consideration in experimental studies. However, for the Sierra Nevada, few research experiments on prescribed fire have been conducted in riparian areas, and only one recent wildfire study has been published for stream riparian areas (see chapter 6.1.) In the Tahoe basin, there have been studies on pile burning in streamside zones (see chapter 5.1, "Soils") and pending research on silvicultural treatments in aspen stands, which are commonly found in riparian areas. The KREW study will provide new data from one experimental area in the southern Sierra Nevada over the next few years. Meanwhile, work as part of SNAMP will provide additional information on hydrologic effects in the central Sierra Nevada. Conducting experimental projects over extended periods (at least 10 years) and across the synthesis area, in combination with large-scale modeling, would help to guide practices to restore riparian areas and downstream aquatic resources.

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Effects of Wildfires, Particularly Long Term

Long-term effects of wildfire and treatments both pre- and post-wildfire remain a significant research gap (see chapter 4.3, "Post-Wildfire Management"). Safford et al. (2012b) noted that the effectiveness of fuels treatments in reducing wildfire severity in frequent-fire forest types has been well established. There remains a need to evaluate effects of fires (along with effectiveness of forest treatments) in other ecosystem types, including riparian and montane hardwood forests. The Fire and Fire Surrogates Study (McIver and Fettig 2010, McIver et al. 2013), which includes three research sites within the assessment area, was designed for this purpose and would continue to provide important information if these sites were again emphasized. Moreover, the effects of fires (and postfire treatments), especially in large severe patches over long periods, are not well understood.

Research on the effects of severe wildfire on aquatic systems has been quite limited in the Sierra Nevada (see chapter 6.2). Researchers have noted the importance of identifying thresholds at which high-severity burns have negative impacts on aquatic organisms (Minshall 2003). Given the particular importance of water quality as an ecosystem service, the potential impacts of increasingly severe wildfire on aquatic systems are an important research gap (see chapter 4.3). One particular threat from wildfires that has been recognized in the Sierra Nevada is sedimentation of reservoirs, which can degrade water quality in the short term and reduce storage capacity in the long term (Moody and Martin 2004, 2009).

A recent study by Buchalski et al. (2013) surveyed nightly echolocation activity of bats in riparian and upland areas one year after the McNally fire in the southern Sierra Nevada. They concluded that some species were selecting burned areas for foraging; a finding which reinforces the value of fire-created habitat heterogeneity for biodiversity. However, it did not examine roosting habitat, which could be more sensitive to effects of severe wildfire, especially for species that roost in large trees and snags, such as pallid bats (*Antrozous pallidus*) (Baker et al. 2008).

Recent wildfires, such as the 2012 Chips Fire on the Plumas and Lassen National Forests, present opportunities to learn how severe wildfires affect spotted owls and their habitat, because there is a decade-long monitoring dataset in the burned area. The Chips Fire burned through large areas previously burned by the 2000 Storrie Fire. The availability of data from existing plots in the Storrie Fire area will allow study of the effects of the reburn (see chapter 4.3). Among other objectives, these types of studies could help to evaluate the extent to which down woody fuel loads remaining from the Storrie Fire may have affected severity of the reburn. The Reading Fire 2012 within the southern Cascade Range portion of the synthesis area presented an opportunity to evaluate impacts of fire to sensitive wildlife species such as the Pacific marten, northern goshawk, California spotted owl, and native trout.

Effects of Post-Wildfire Treatments

Key questions remain concerning treatment of burned trees and woody debris in high-severity burn patches, given limited understanding of fuelbed succession following fires of different intensity. These questions are especially important given that the warming climate appears to be lengthening the fire season (Westerling et al. 2006), with associated increases in fire activity expected (Lenihan et al. 2003). Chapter 4.3 identifies a number of important gaps in socioecological research, including effects on channel processes (fig. 2), use of dead trees by wildlife such as black-backed woodpecker (*Picoides arcticus*), and outcomes of accepting or influencing ecological trajectories of severely burned areas through salvage, replanting and other kinds of treatments. In particular, novel approaches may be needed to encourage regeneration of conifers and hardwoods where widespread patches of high-severity burn may inhibit recovery of desired conditions.

Brent Skaggs

Figure 2—Aerial view of the Lion Fire of 2011, which was managed for resource benefits.

Science suggests that there are opportunities for forest treatments to enhance water supply and mitigate some of the potential effects of climate change, although research is lacking in the Sierra Nevada for how much and how long restoration treatments are likely to influence water yield and water quality.

Effects of Restoration Treatments on Ecological Services and Other Social Values

A common thread throughout this synthesis is the need for more integrated research that evaluates how ecological restoration efforts affect important socioeconomic and cultural values (see chapter 9.2, "Ecosystem Services"). Chapters 4.2, "Fire and Tribal Cultural Resources; 4.3, "Post-Wildfire Management;" and 6.3, "Wet Meadows," all highlight the gap in understanding effects on ecosystem services associated with wildlife, culturally important plants, and water resources. Science suggests that there are opportunities for forest treatments to enhance water supply and mitigate some of the potential effects of climate change, although research is lacking in the Sierra Nevada for how much and how long restoration treatments are likely to influence water yield and water quality (see chapter 6.1). The use of geospatial modeling tools to prioritize landscape treatment strategies (see chapter 1.1) can explicitly integrate social values by mapping overlap between the use, provision, and vulnerability of ecosystem services to disturbances (Beier et al. 2008).

Performance Criteria

Benchmarks and performance criteria can be valuable tools for evaluating progress toward meeting broad restoration goals. However, at a broad strategic landscape level, it can be problematic to emphasize fixed quantitative targets. For one reason, such targets may lead to raising standards inappropriately high for some areas, reducing expectations for others, with an overall tendency to reduce heterogeneity in the landscape (Bisson et al. 2009). As a result, resilience-based approaches tend to de-emphasize fixed production targets in favor of plans to reduce vulnerability and strengthen capacity to respond and adapt. The properties of a socioecological system that confer resilience can change over time, with spatial configuration, and depending on the people involved, so the selection of useful surrogates or metrics needs to be similarly diverse and dynamic (Carpenter et al. 2005). By considering various policy constraints on management and other contextual factors, evaluation systems may yield more informative findings that promote social learning (for example, availability of burn windows, see chapter 9.3, "Sociocultural Perspectives on Threats, Risks, and Health"). As an example of how metrics could be used, Fire Return Interval Departure metrics can serve as an initial measure of restoring fire as an ecological process, but they should be considered within a broader context of the reference fire regime (Sugihara et al. 2006) and the larger socioecological system in terms of vulnerability and desired conditions (see chapter 4.1). In addition, the choice of metrics should be reviewed and may need to be revised as the system evolves and presents new opportunities and constraints.

Accordingly, restoration designed to promote broader societal interests will strive to include a mix of ecological and social criteria for evaluating success (see chapter 9.4, "Strategies for Job Creation Through Forest Management," for examples of socioeconomic indicators). There are many efforts to develop integrated indexes of ecosystem health that consider ecological and social conditions (Rapport and Maffi 2011, Rapport and Singh 2006) (see also chapter 9.2). Although efforts to quantify social criteria, such as cultural significance and community well-being, also entail a risk of being too reductionist (Higgs 1997), such indicators can provide valuable guides for identifying potential vulnerabilities and opportunities that may help promote resilience in socioecological systems (Cabell and Oelofse 2012). A key consideration is to incorporate feedback loops to evaluate whether the indicators appear to be working as intended and revise them especially to account for confounding factors.

Chapter 1.3, "Synopsis of Emergent Approaches," considers the hypothesis that treatments initially implemented across a relatively small proportion of a landscape in a short number of years could avert the most undesirable effects of wildfires while avoiding deleterious impacts to priority wildlife species. This example identifies a guideline that could be tested for particular landscapes in an adaptive management framework involving managers, stakeholders, and researchers. This type of reflective approach would engage the public and communities in evaluating the particular ecological and social characteristics of their landscapes, identifying vulnerabilities and appropriate indicators, and strengthening capacity to adapt to future disturbances and stressors by promoting a long-term view towards risks (see chapter 9.3).

Management Implications

- There are a number of important and potentially controversial topics for which science suggests that treatment approaches might be warranted, but further study in an adaptive management framework would be helpful to evaluate social and ecological tradeoffs and suitable contexts, including:
    - treatment of red fir forests,
    - treatment of riparian areas, and
    - removal of burned trees following severe wildfires.
- Management plans might be particularly well-informed through adaptive management or targeted research to evaluate effects of treatments and unmanaged wildfires on wildlife habitat, water supply, and other high-value ecological services.

- Collaborative review by scientists and managers of past efforts to implement adaptive management, including monitoring plans in the SNFPA appendix, could help to inform management plans.

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