Framework for Promoting Socio-ecological Resilience across Forested Landscapes in the Sierra Nevada

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Final Report to the Sierra Nevada Conservancy for Tahoe Central Sierra Initiative

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Executive Summary

Forests and rangeland ecosystems cover over 80% of California and provide critical habitats and ecosystem services on which wildlife and humans depend. Scientifically sound strategies to promote resilience that account for the dynamic nature of forested landscapes are needed to maintain and restore crucial ecosystem services for which communities depend upon across the region. Despite significant effort and investment, forest management actions to improve the resilience of forested landscapes are not keeping pace with stressors that are mounting as a result of climate change, and in fact the gap between current conditions and target conditions may be widening, as opposed to narrowing (Coop et al. 2020). Collaborative efforts to promote resilience across large landscapes often struggle with developing a shared concept of resilience, which slows the pace of collaboration and the development of a shared vision that can be implemented.

A portfolio of socio-ecological conditions has been developed as the primary organizing feature of the framework for resilience pillars, elements, and metrics. There are 10 pillars of resilience that represent desired landscape outcomes that explicitly recognize the interdependence of ecological and social systems: forest resilience, fire dynamics, carbon sequestration, biodiversity conservation, wetland integrity, air quality, water security, fire-adapted communities, economic diversity, and social and cultural well-being. Each pillar is described by 2-4 elements that represent the primary features of each pillar. Metrics are measurable characteristics of each element that represent conditions associated with ecosystem resilience at relevant scales. The pillars, elements and metrics offer a simple yet readily identifiable set of desired and target outcomes that pertain to socio-ecological systems across forested landscapes, and can be used as a primary structure for making inferences about the degree to which conditions at various organizational levels (e.g., elements, pillars, and the socio-ecological system as a whole) are likely to be resilient to disturbance in a transparent and scientifically defensible manner. Monitoring and reporting on the metrics, elements, and pillars serve as a robust basis for continued adaptive management as climate change progresses.

Across the majority of landscapes, change is unavoidable, and resilience will depend on the ability of society to adapt management inputs in response to changing environments that are informed by a strong scientific understanding of ecosystem dynamics. The intention of management actions can be categorized into three strategies that represent a continuum of intended rates and degrees of change and novelty: resistance (low), adaptation (moderate), and transformation (high). Resistance strategies are intended to maintain the status quo or realign with current environmental conditions and maintain it for as long as possible. Adaptation strategies are intended to facilitate change and improve the ability of systems to flex and change incrementally over time. Transformation strategies are intended to facilitate transformation of existing conditions to a different, and often novel, state that will be more resilient to near-term disturbances and future environmental conditions while continuing to provide ecosystem services.

Large, regional areas in the 1-3 million acre range are the scale at which most outcomes of socio-ecological resilience are expressed, at least in the Sierra Nevada, since it is the scale at which large-scale processes operate and their benefits are realized (e.g., population viability, water security, fire dynamics, local markets and economies, community protection capacity). Planning across regional landscapes is highly effective at promoting greater resilience because: 1) they are large enough to have measurable ecosystem services and identified beneficiaries; and 2) planning at large scales provides for more options to accomplish multiple objectives across scales that might otherwise be in conflict at smaller scales. Regional-level planning across jurisdictions invokes an alternate set of operating principles. A collaborative vision for the future of the landscape across all jurisdictions requires a cohesive vision for the future of the landscape that integrates regional objectives, local capacities and opportunities, and stakeholder priorities, and which the land managers can then use to develop more localized project design and implementation.

Regional-scale planning has the potential to expedite planning and implementation by sharing resources, to work at a large enough scale to affect ecosystem service reliability as well as to enhance efficiencies of scale, to develop a sustainable work force with associated markets, and to address policy questions at scales that can inform state and federal policy discussions. Building blocks of regional landscapes are subsets of the landscape that are often defined by watershed or basin boundaries. A range of target conditions can be established for each building block based on the target conditions established for the regional landscape, the capacities of the facets within it, the priorities of local stakeholders, and the contribution they can make to the desired amounts and distributions of conditions targeted across the regional landscape. These intermediate building blocks are most commonly the scale at which individual projects are planned and implemented.

The complexity of multiple measures for multiple metrics across multiple elements and pillars can pose a challenge to interpreting what management inputs will be most effective in moving systems toward target outcomes. The concept of ‘risk reduction’ and ‘tradeoffs’ has traditionally been used to analyze options and portray costs and benefits associated with management scenarios. The interdependent nature of social and ecological systems results in a limit to the degree that any given pillar can be prioritized above others. Analytic tools are an essential component of weighing multiple benefits and risks to identify and quantify the most favorable combination of management actions based on stakeholder priorities and ecosystem dynamics.

Preface

This document is a product of the Tahoe-Central Sierra Initiative is a partnership of State, federal, and non-governmental partners (Table P-1) collaborating to increase the pace and scale of management to promote forest resilience across the 2.4 million acre (1 million hectare) landscape that encompasses the American River basin, Yuba River basin, and the Lake Tahoe basin in the central Sierra Nevada. The TCSI partnership is predicated on the shared perspective that the forests and watersheds of the Sierra Nevada are in peril due to threats from climate change, drought, and wildfire, and that time is of the essence. The TCSI landscape is one of seven regional landscapes recognized by the Sierra Nevada Conservancy, a state agency, as the building blocks for the Sierra Nevada Watershed Improvement Program.

Table P-1. Tahoe Central Sierra Initiative partner organizations.

Sector	Partner
State:	Sierra Nevada Conservancy
	California Tahoe Conservancy
	CalFire
	University of California
Federal:	U.S. Forest Service Region 5
	USFS Pacific Southwest Research Station
Private and Non-profit:	The Nature Conservancy
	National Forest Foundation
	California Forestry Association

A cornerstone of TCSI is a strong scientific foundation that serves to support and expedite progress toward greater resilience. TCSI established a science enterprise co-led by the U.S. Forest Service Pacific Southwest Research Station and The Nature Conservancy to develop a scientific foundation of information and tools that could be used by managers to expedite the pace and scale of project design and implementation to achieve greater landscape resilience. As an initial investment in the scientific foundation, the TCSI determined that a practical guide for resilience would support and expedite planning and implementation at all scales.

The Framework for resilience has been applied to the TCSI landscape in the form of an assessment of current conditions, potential future conditions resulting from different management scenarios modeled over nearly a century, and a blueprint for progress, a mapped interpretation and summary of management opportunities to promote resilience. These separate products were developed to support progress within the TCSI landscape and to serve as an example of how to accomplish regional landscape planning.

1. The Resilience Challenge

Forest ecosystem conditions in the Sierra Nevada have changed substantially over the past 150 years. Historically, the disturbance regime in dry- and moist-mixed conifer forests of the Sierra Nevada consisted primarily of frequent low to moderate intensity fire, with small patches of moderate and high severity fire. This historical fire pattern resulted in a heterogeneous forest structure consisting of a diversity of tree ages and seral stages. There was spatial variability with individuals and clumps of trees interspersed with openings. Large trees, snags, and logs that persisted for centuries served as biological legacies (Skinner and Chang 1996). Over the past century, forest ecosystem responses to the combination of historical clear cutting and a century of fire suppression have resulted in changes in plant species composition, species interactions, and forest structural characteristics that exacerbate the vulnerability of forests to high severity fire (Coppoletta et al. 2016), drought stress (Stephens et al. 2018) and insect mortality (Fettig et al. 2019). In addition, such forests have a much greater probability of propagating large, high severity fires that result in large areas of tree mortality. There is growing concern that the combined, long term effects of these stressors on forest ecosystems have compromised their ability to respond to and recover from future disturbances. As a result, significant uncertainty exists regarding the future extent of forested landscapes and their contributions to preserving native species composition as well as ecosystem structure, and function in the region (Stephens et al. 2018).

Forests and rangelands are extensive ecosystems covering over 80% of California and providing critical habitats and ecosystem services on which wildlife and humans depend (Cal Fire 2017). Scientifically sound strategies to promote resilience that account for the dynamic nature of forested landscapes are needed to maintain and restore crucial ecosystem services for which communities depend upon across the region. Several important ecosystem services are time sensitive, such as carbon sequestration and biodiversity conservation. The State has a goal of becoming carbon neutral by 2045 to meet is climate readiness goals (Executive Order B-55-18), and the forest management and reforestation accounts for approximately 16% of the carbon sequestration (20.4 M tons/yr of carbon) needed to accomplish this goal (Baker et al. 2020). The State also has ambitious biodiversity conservation goals, as reflected in the 2017 Biodiversity Initiative and subsequent Executive Order B-54-18, as well as the 2017 Safeguard California Plan and the 2015 State Wildlife Action Plan.

For the past 20 years, forest managers and scientists have worked to develop effective approaches to the restoration of forest composition, structure, and processes in pursuit of ecosystem resilience in the Sierra Nevada. Yet, despite significant effort and investment, forest management actions to improve the resilience of forested landscapes are not keeping pace with stressors that are mounting as a result of climate change, and in fact the gap between current conditions and target conditions may be widening, as opposed to narrowing. Best practices and clear steps forward have been identified by many, but they primarily address scale and process, while pace remains a challenge: increase the scale of project planning and implementation, shift to a more collaborative and science-based process; and shift to targeting forest conditions that are better able to cope with future climates through the use of ecological forestry practices (Box 1).

Box 1. Key changes in operating principles for management planning and project design and implementation to address forest management challenges and increase the pace and scale of activities that promote resilience.

Conventional Forest Management Approach	**Regional Resilience Approach**
Regional level:	
Management plans are developed separately for each land ownership/jurisdiction	A cohesive landscape vision is developed across ownership/jurisdictions
Management plans are led by individual agencies, and individual stakeholder input is solicited and addressed	Landscape management approaches are evaluated and developed in collaboration with stakeholders
Management planning and design engages scientists in review of draft plans for science consistency	Management planning and design engages scientists in resource assessments (current and future) to collaboratively and proactively to develop a resilience strategies based on landscape-specific analysis
Implementation of plans across the landscape is dependent upon the internal priorities and resources of each institution	Implementation of plans across the landscape are coordinated and collaboratively resourced
Local level:	
Management is designed to produce individual outputs and conditions	Management is focused on desired outcomes locally and across jurisdictions at regional landscape scale
Local management objectives are accomplished by the design and implementation of individual projects led by a single agency	Local management objectives are accomplished by integrating shared goals for landscape conditions with locally driven project design and implementation capacities and accomplished through on-going engagement of stakeholders
Projects focus on a few goals, and non-target conditions in the project area are avoided	Projects are designed to move the local landscape toward desired conditions that address the full array of multiple integrated benefits for ecosystems and communities
Projects tend to avoid or limit treatment in sensitive areas or habitats	Management plans address the entire local landscape to improve health of sensitive areas and species
Project planning and design engages scientists in review of individual projects after they are planned	Project planning and design engages scientists collaboratively and proactively to design projects to accomplished desired outcomes for local landscapes
Monitoring addresses implementation and effectiveness of individual projects	Monitoring and adaptive management addresses the whole landscape

2. Socio-Ecological Resilience and Benefits

Collaborative efforts to promote resilience across large landscapes often struggle with developing a shared concept of resilience, which slows the pace of collaboration and the development of a shared vision that can be implemented. The lack of a clear and definitive definition of resilience can also make it difficult to develop measureable target conditions for management outcomes. A common framework for resilience is needed to help expedite the development of science-based, measureable and achievable target conditions that will promote resilience across large landscapes, and to make it possible to track progress toward State goals and objectives across multiple landscapes.

Resilience theory emerged over 40 years ago as a response to the lack of equilibrium concepts to address observed ecosystem dynamics (Holling 1973). Resilience is a dynamic state that represents the capacity of a system to recover from disturbance and retain the same set of processes, structures, and functions (Holling 1973, Peterson et al. 1998, Thompson et al. 2009). Disturbances (perturbations) act on ecosystem conditions and precipitate change. Resilience dynamics are often depicted graphically in terms a 'basin-of-attraction' or 'cup'. The basin represents the range of conditions that are characteristic of the system in terms of ranges of composition, structure, and function over the course of disturbances whose frequency, intensity, and character routinely occur as part of system dynamics. The ball represents the combination of characteristics that a system may have at a given time, as a function of its disturbance history (recent or long-term). In a resilient system, a disturbance will effect changes in composition, structure, and function (i.e., move the ball around in the cup), but they will remain within the range of conditions that are characteristic of the system.

A recent science synthesis of the status of ecosystems in the Sierra Nevada called for shifting the goals of improving forest resilience from a purely ecological focus with a strong emphasis on fire, to a more comprehensive focus on socio-ecological resilience and management strategies that focus on a broad suite of interdependent ecological and social outcomes and apply to large landscapes and longer term outcomes (Long et al. 2014). Such an approach focuses not only on facilitating the preservation of essential ecosystem processes and conservation of native species, but also on the generation of social benefits. Given the interdependence among social and ecological systems, threats facing the well-being of our forested landscapes are also threats to communities and economies. It follows, then, that robust solutions need to reflect ecological, social, and economic facets of the problem. Socio-ecological resilience emphasizes the capacity of human communities to cope with, adapt to, set targets for, and influence change in environmental and social conditions toward desired outcomes (Folke 2006). Objectives to sustain a wide array ecosystem services and benefits will depend on the function and integrity of both ecological and social systems.

Resilience is an attractive concept based in part on a commonly held set of implicit expectations: 1) there is a latent expectation that resilient ecological systems will intrinsically yield services of value to people and society; and 2) once conditions resilient to disturbance have been achieved, they do not require substantial additional management input to be maintained; and 3) historical conditions, if restored, will be resilient into the future. In reality, a wide range of human inputs are, and will continue to be, required to maintain desired ecosystem conditions and services (Hilderbrand et al. 2005). People increasingly shape landscapes and intentionally alter disturbance regimes, with particular emphasis on avoiding or mitigating extreme events (e.g., flood control, fire suppression), to reduce risks and increase short-term and long-term benefits (e.g., Turner et al. 2010). As a result, the maintenance of key components, structures, and functions and the benefits that they can provide to society will require thoughtful and consistent investments of management inputs and societal behaviors to shape and adapt to change.

Ecosystem services and benefits from forested landscapes are essential and management to promote resilient conditions can be designed to enhance a wide range of services and benefits. Services and benefits are commonly categorized as supporting, provisioning, regulatory, and cultural. Supporting services are those underlying natural processes, such as photosynthesis, nutrient cycling, the creation of soils, and the water cycle, upon which all life depends. They are not commonly the direct focus of management because they are slow to change, but their function is an underlying objective of management. Without supporting services, provisional, regulating, and cultural services wouldn't exist. Provisioning services are the most commonly identified benefits, and in forested landscapes include a wide array of wood products, non-wood forest products (e.g., mushrooms and cultural materials), water, and hunted animals. Regulating services including clean air, water purification, pollination, decomposition, erosion and flood control, and carbon storage and climate regulation. Finally, cultural services are non-material benefits that contribute to the development and cultural advancement of people and communities, including environmental quality and safety, recreation, cultural uses and practices, and creativity inspired by nature, such as music and art.

Managing to promote resilience is an effective and sustainable means of protecting and enhancing ecosystem services. Management directed at the greatest risks will yield the greatest impacts, however management directed at a range of risks and enhancements will yield the most robust suite of services, given the highly interdependent nature of ecosystems. For example, large scale high intensity fires pose a risk to many ecosystem services, and forest management efforts directed at reducing the risk of such fires will have broad ecosystem benefits. Direct benefits gained by reducing the risk of large, high intensity fires include reduced threat to communities and infrastructure, increased old forest habitat security, increased carbon sequestration stability, and reduced risk of toxic wildfire emissions, among others. In contrast, management efforts directed promoting resilience in meadow ecosystems will benefit an array of water-related benefits, as well as enhanced carbon sequestration, both of which may be essential to meeting target conditions that will achieve some degree of security and adaptability to climate change.

3. The Framework Socio-Ecological Resilience: Pillars, Elements, and Metrics

The ability to measure current and future conditions relevant to socio-ecological resilience and to interpret them in terms of resilience is a significant positive contribution to increasing the pace and scale of management. Over the course of three years, a series of workshops, conversations, and document reviews were held involving a wide array of scientists, land managers, and policy makers to create a conceptual framework for resilience that could be used to inform, structure, and measure resilience-based landscape management and planning.

The framework consists of two parts: 1) *a portfolio of conditions* for evaluating socio-ecological resilience; and 2) *an assessment process* of current and future conditions that results in the identification of opportunities to effectively promote greater resilience across the landscape.

Portfolio of Conditions: Pillars and Elements

The portfolio of socio-ecological conditions three main components: 1) 10 pillars of resilience, desired landscape outcomes that encompass the suite of desired benefits from resilient socio-ecological systems across forested landscapes and explicitly recognizes the interdependence of ecological and social systems (Figure 1); 2) a set of 30 elements that represent core features of the 10 pillars that directly affect resilience (Table 1); and 3) metrics that are measurable characteristics of the elements at various relevant scales (Appendix A). The metrics selected to represent each element may vary from landscape to landscape, depending on available data, stakeholder preferences, and the unique features of each landscape.

A consistent framework for current and future target conditions provides a strong foundation for prioritization, accountability, monitoring, and adaptive management. The pillars, elements and metrics offer a simple yet readily identifiable set of desired outcomes that pertain to socio-ecological systems across forested landscapes, and can be used as a primary structure for making inferences about the degree to which conditions at various organizational levels (e.g., elements, pillars, and the socio-ecological system as a whole) are likely to be resilient to disturbance in a transparent and scientifically defensible manner. Monitoring and reporting on the metrics, elements, and pillars can serve as a solid basis for continued adaptive management as climate change progresses. Each pillar is described in more detail below.

Forest resilience pertains to the persistence of forest vegetation and its ability to be disturbed and remain a forest. Forest resilience is comprised of three elements: structure, composition, and disturbance. Disturbances include both natural disturbances, such as wildfire, beetles, and extreme weather events, and human disturbances, such as forest management (e.g., timber harvest, prescribed fire, thinning) and recreational activities. The response to these disturbances will be a function of forest vegetation structure, composition, and the characteristics of disturbance (type, intensity, scale, frequency). The outcomes of resilient forests across landscapes are the ability to maintain the desired range, amount, and distribution of forest conditions (including processes) over time – such as forest heterogeneity, seral stage diversity, and large trees, snags and logs – and that these conditions provide the desired ecosystem services.

Fire dynamics pertains to the range of characteristics of fire, whether it occurs intentionally (prescribed fire and wildfire allowed to burn for resource benefits) or unintentionally. Fire dynamics is comprised of two elements: fire severity, and functional fire. Fire is a key process in forest ecosystems, particularly in dry forests. The desired outcome is that fire is allowed to function as a primary disturbance agent in forests, and that its characteristics are compatible with the ability of forests to persist and maintain desired ecosystem services, and consist primarily of low to moderate severity fires that cover large areas and occur every few decades. Elements pertain to the character, location, and frequency of fire across the landscape. Large, high severity fires are a concern given that they pose a significant threat to life, property, and forest persistence.

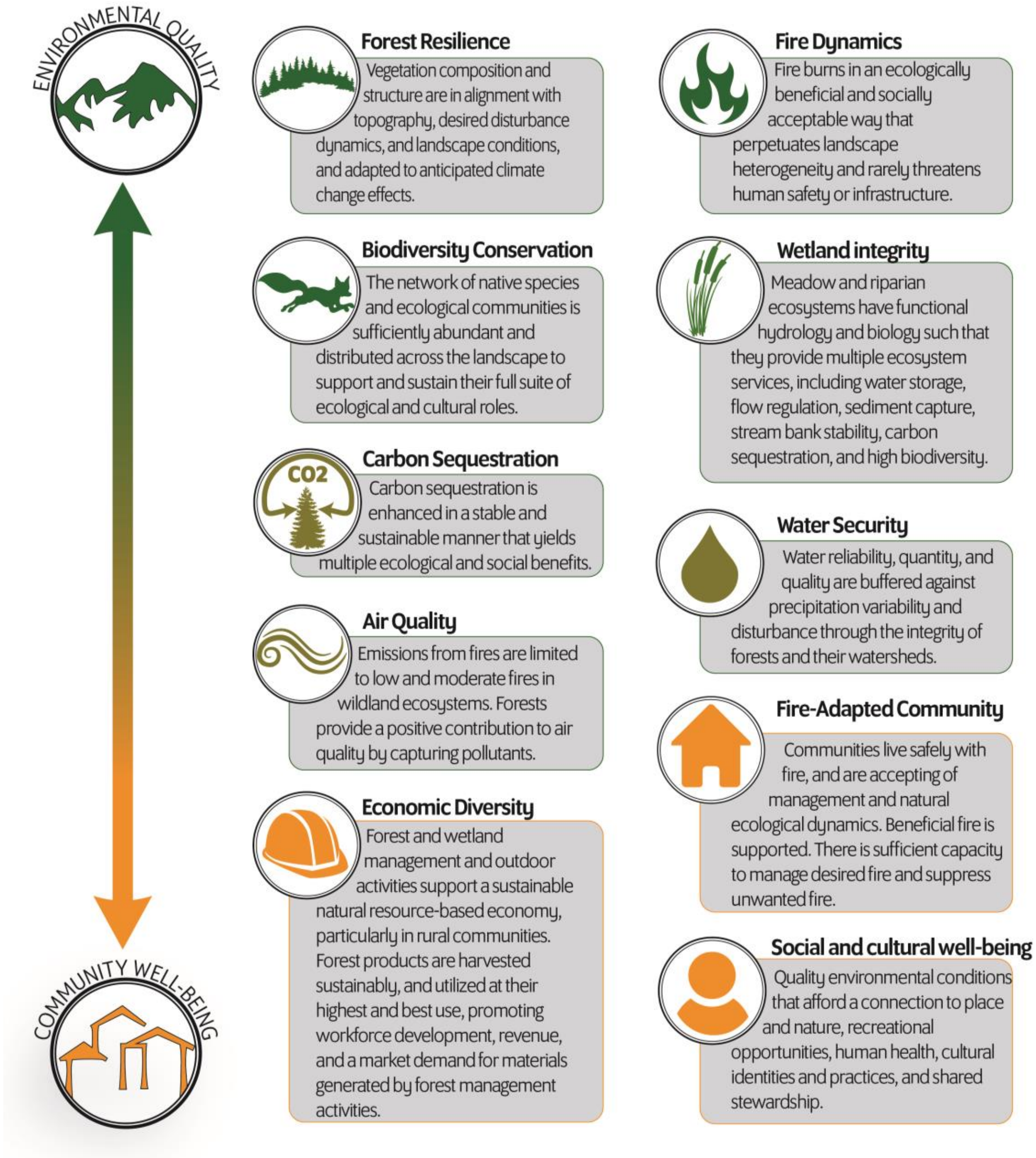

Figure 1. Pillars of resilience that represent desired outcomes and the suite of benefits that are expected as a result of investments to enhance the resilience of forested landscapes.

Table 1. Pillars of resilience that represent desired landscape outcomes and their associated core elements and examples of benefits that are aligned with resilience.

Pillars	Core Elements	Benefits
Forest resilience	• Structure • Composition • Disturbance	• Increased drought tolerance – reduced risk of drought induced tree mortality • Increased large tree occurrence • Increased old forest habitat security • Maintain or increase tree species diversity
Fire dynamics	• Severity • Functional fire	• Reduced risk of large high severity fires • Reduced threat of fire to communities and infrastructure • Increased role of fire in creating and maintaining desired conditions • Increased capacity to contain landscape fire (wild or prescribed)
Carbon sequestration	• Storage • Stability	• Maintained or increased carbon storage to help meet GHG emission objectives • Maximized stability of stored carbon • Maintained or increased carbon refugia
Wetland integrity	• Structure • Composition • Hydrologic function	• Maintained or increased sediment, water, and carbon holding capacity • Maintained or restored native species diversity • Maintained or restored wetland occurrence
Biodiversity conservation	• Focal species • Species diversity • Community integrity	• Maintained or increased focal species habitat • Maintained or increased functional group ability to provide ecosystem services • Maintained or increased community diversity and adaptive capacity
Water security	• Quantity • Quality • Storage and timing	• Maintained or increased water storage to support human uses • Maintained or improved water quality • Maintained or enhanced healthy river systems • Maintain or enhanced flood control
Air quality	• Particulate matter • Visibility • Greenhouse gases	• Reduced risk of high output, toxic wildfire emissions • Reduce risk of very poor air quality days • Reduced ozone
Fire-adapted community	• Hazard • Preparedness	• Reduced threat of wildfire to human communities • Enhanced capacity to respond to immanent threat from fires • Increased acceptance and support for the use of managed and prescribed fire as the most effective tool to reduce the threat of fire to communities
Economic diversity	• Wood product industry • Recreation industry • Water industry • Economic health	• Increased capacity to process wood biomass and small diameter woody material • Increased revenue from natural resource-based industries that support local communities

		• Increased workforce diversity to support forest management activities
Social and cultural well-being	• Public health • Engagement • Recreation quality • Equitable opportunity	• Reduced public health impacts • Maintained or improved availability of culturally valued resources • Maintained or improved public and tribal engagement in natural resource management and conservation • Maintained or improved recreation experiences

Carbon sequestration pertains to the ability for forest management to contribute to greenhouse gas emissions reduction to mitigate climate change. Carbon sequestration has two elements: carbon storage and carbon stability. The State of California has set ambitious goals for greenhouse gas emission reductions, including promoting carbon neutrality by 2045. Forests are integral to meeting carbon and climate policy goals and environmental objectives. Although many projects may only be able to address above ground carbon (based on forest inventory data), the elements recognize the importance of below ground carbon and the stability of carbon over time. All fire reduces sequestered carbon, but large-scale high severity wildfire poses the greatest threat to carbon sequestration goals, as well as impacting other environmental quality goals (e.g., black carbon and methane emissions, old forest habitat).

Wetland Integrity pertains to meadow, riparian, and other wetland ecosystems that are key linkages between upland and aquatic systems in forested landscapes. Wetland integrity has three elements: structure, composition, and hydrologic function. Meadow and riparian ecosystems with functional hydrology will serve increasingly important roles in buffering impacts from extreme climate events that are anticipated to increase, and from upland disturbances that will increase by design toward achieving desired forest conditions. Meadow and riparian ecosystems capture and slow the release of sediment, water and carbon, which in turn promotes and enhances multiple pillars of resilience including water security (amount, quality, temperature), carbon sequestration, energy generation, and biodiversity.

Biodiversity conservation pertains to maintaining all native species and reducing the impacts of non-native species on native species and other ecosystem conditions and services. Biodiversity conservation has three elements: focal species, species diversity, and community integrity. Biodiversity is essential to forest resilience in many ways, including reforestation, post-burn recovery, and essential services of ecosystems to ecology and society, such as seed dispersal and pollination, recreational activities (consumptive and non-consumptive), and adaptation to change over time. Elements of biodiversity range from genetic diversity and population persistence of individual species of particular interest or concern, to suites of species that perform critical ecosystem functions, to community interactions and interdependencies that support the persistence of individual species.

Water security pertains to the broad array of important roles and functions that water plays in ecological and social systems. Water security has three elements: quality, quantity, and storage and timing. Water reliability, quantity and quality is essential for forest health and resilience, terrestrial and aquatic biodiversity, recreation, industry, and human consumption. Water security is closely tied to forest conditions, and is vulnerable to disturbances, particularly drought and extreme weather events (flooding, mass erosion), but can also be affected by forest structure (e.g., tree density and canopy openings), fire, thinning, and timber harvest. Elements of water security pertain to quantity and availability (yield), quality, and the timing and rate of water delivery (storage) from upland forest ecosystems to downstream functions and uses.

Air quality has a spectrum of ecological and social values. Air quality has three elements: particulate matter, visibility, and greenhouse gases. Forests contribute to clean air by capturing particulates and removing them from the atmosphere. Fire, on the other hand, contributes particulates and gases to the atmosphere that above certain levels can impact forest health, human health, and carbon sequestration targets. High intensity wildfires are particularly impactful in the amount and duration of toxic pollutants release. In contrast, low and moderate intensity fires contribute pollutants, but are the most effective tool for reducing the risk of high intensity fires and their timing and extent can be controlled to minimize human health impacts from smoke. Elements of air quality include particulate matter, greenhouse gas emissions, and visual quality. Greenhouse gases are the primary cause of climate change by trapping heat in the atmosphere, and include carbon dioxide, methane, nitrous oxide and fluorinated gases (such as ozone).

Fire-adapted communities pertains to the integrated nature of communities and fire, including an understanding and appreciation of the important role of fire in dry forest ecosystems, support for the use of fire as an important tool in managing forest condition and the risk of fire. Fire-adapted communities has two elements: hazard and preparedness. Smoke and impacts to visual quality can be managed, and they are a necessary aspect of living in proximity to wildland ecosystems. Fire-adapted communities have reduced hazards associated with wildfire and smoke, awareness and progress toward reducing vulnerability to fire (e.g., defensible space, fire resistant building materials), and have a well-developed and disseminated community response to fire (e.g. ingress and egress). Community Fire Safe Councils are an effective and increasingly utilized approach to bringing communities together to take positive action to increase community adaptation to living with fire.

Economic diversity pertains to the degree to which a region reflects a broad mix of economic activities that create and sustain long-term employment opportunities for rural communities, and is related to how flexible and stable an economy is likely to be in response to social, and ecological events or changes that impact economic activities in some manner. Economic diversity has four elements: wood product industry, recreation industry, water industry, and overall economic health. Natural resource-based economies are a particular focus, including forest management workforce, wood product industries, water agencies, recreation industries, and fire-related workforce needs and activities. In addition to elements pertaining to these primary sectors, overall elements of economic diversity and health are valuable to capture change and adaptation that will occur over time.

Social and cultural well-being pertains to a broad spectrum of societal benefits with the primary focus being the connection between forested landscapes and quality of life attributes. Elements of social well-being in forested landscapes, which are clearly linked to all other resilience pillars, include public health, engagement, recreation quality, and equitable opportunity. Specifically, each metric of social well-being is linked to multiple other pillars: public health is linked to air and water quality directly and indirectly to carbon sequestration; public engagement is linked to economic diversity, fire-safe communities, fire dynamics, and is greatly influenced by the status of all the other pillars (e.g., poor environmental quality or poor economic health would precipitate high engagement but perhaps low overall social well-being); and recreation quality is linked to forest resilience, biodiversity, water security, air quality, and economic diversity.

Portfolio of Conditions: Metrics

Describing, measuring, and monitoring resilience using a core set of metrics that are widely used is an important aspect of adaptive management and ecosystem performance, particularly when working toward large scale outcomes, and when uncertainty is high, as it is in terms of the future of ecosystems as climate changes. Socio-ecological systems exist and function at multiple scales of space, time and organization, and the interactions across scales ("panarchy") are fundamentally important in determining the dynamics of the system and future target landscape outcomes necessary to achieve resilience objectives (Gunderson and Holling 2002). The pillars, elements, and metrics provide a structure that can be used to address four critical questions at the relevant scale(s): 1) what are the current conditions?; 2) what are the target conditions for each landscape outcome and the associated ecosystem services?; 3) what conditions are possible (capacity) and most probable (tendency) into the future?; and 4) what is the relative importance of any given place on the landscape to achieving target conditions and outcomes across the landscape? (Figure 2).

Each element could be described by a wide range of metrics. For the purposes of the framework, we have identified a core set of metrics that are strong representatives of elements and pillars and that if characterized would enable the State to address progress toward regional and State-wide goals and objectives (Appendix A). In addition, a wide variety of data sources are available to quantify these characteristics. Technological advances in remote and in-field data collection, such as Light Detection and Ranging (LiDAR), satellite imagery, and automated field data collection, and advances in data processing, such as data imputation and neural networks, are making it possible to characterize conditions with greater accuracy, precision, and coverage than ever before. Advances will continue to proceed and improve data quality and access over time.

The use of consistent data sources is not needed to summarize conditions at high levels across large landscapes. For example, LiDAR data is becoming increasingly available across landscapes, and it provides high resolution data on forest structure. However, it may become dated over time (rarely collected more than once every 5 years) and it may not be available across the entire landscape. The highest quality data source for each metric may not be available to every project area or across the entire project area, particularly when attempting to move toward assessment and opportunity mapping across large landscapes that are millions of acres in size.

Most importantly, the framework provides a structure that landscape collaboratives and stakeholders can use to hit the ground running. Stakeholders have specific notions about what is important in their landscape, what the barrier are to promoting resilience, what important resources are at risk and their relative importance, and what data are useful and available to characterize conditions. The pillars, elements, and core metrics set the stage, which then enables regional landscape groups to address as full an array of pillars and elements as possible, select and add metrics as they see fit, and use the best available information to conduct assessments, and identify needs and opportunities for management to promote resilience and reduce risk.

4. Contending with a Novel Future

Across the majority of landscapes, change is unavoidable, and resilience will depend on the ability of society to adapt management inputs in response to changing environments that are informed by a strong scientific understanding of ecosystem dynamics. Target conditions may be the same as current, they may reflect an historical condition that is expected to be more resilient than current conditions, or they may reflect a condition that has never existed before but is expected to be best suited to future environmental stressors. The intention of management actions can be categorized into three strategies that represent a continuum of intended rates and degrees of change and the novelty: resistance (low), adaptation (moderate), and transformation (high) (Figure 2; Box 2). These strategies can be associated with conditions of interest (e.g., protection of ancient trees = resistance strategy), or places of value (e.g., low risk of fire in defense zone = transformation strategy). Each strategy is described in more detail below.

Resistance strategies are intended to maintain the status quo or realign with current environmental conditions and maintain it for as long as possible. It is most appropriate and feasible for elements of ecosystems that (directly or indirectly) are high value, difficult or impossible to replace, able to persist for the foreseeable future with a feasible investment in protective measures, such as ancient trees, rare plant communities, and houses in the wildland-urban interface. For example, disturbance and climate refugia, areas that are least subject to major changes in the near future (Krawchuk et al. 2020, Morelli et al. 2020), are good candidate locations for resistance strategies.

Adaptation strategies are intended to facilitate change and improve the ability of systems to cope over time. Adaptive responses intentionally enhance or otherwise modify ecological conditions (e.g., forest structure, fuel conditions) and social conditions (e.g., collaborative forest and fire management) to facilitate the ability of the system to flex and change incrementally in response to environmental pressures and disturbance. For example, reducing the density of trees in overstocked forest stands will help the remaining trees be more resilient to drought stress.

Transformation strategies are intended to facilitate transformation of existing conditions to a different, and often novel, state that will be more resilient to future environmental conditions while continuing to provide ecosystem services. Transformation strategies are most appropriate when existing conditions are not resilient to disturbance, the response to disturbance is likely to push it into an alternative state that is less desirable (e.g., reduced ecosystem services, non-forested) and potentially detrimental (e.g., ecologically diminished, increased social risk). For example, translocating individuals of a given species outside its current and historical range in anticipation of changing climate would be a transformative action. It would be creating a novel community of species, but it might be deemed a positive contribution to the maintenance of the species or the ability of the area to maintain forested conditions several decades in the future.

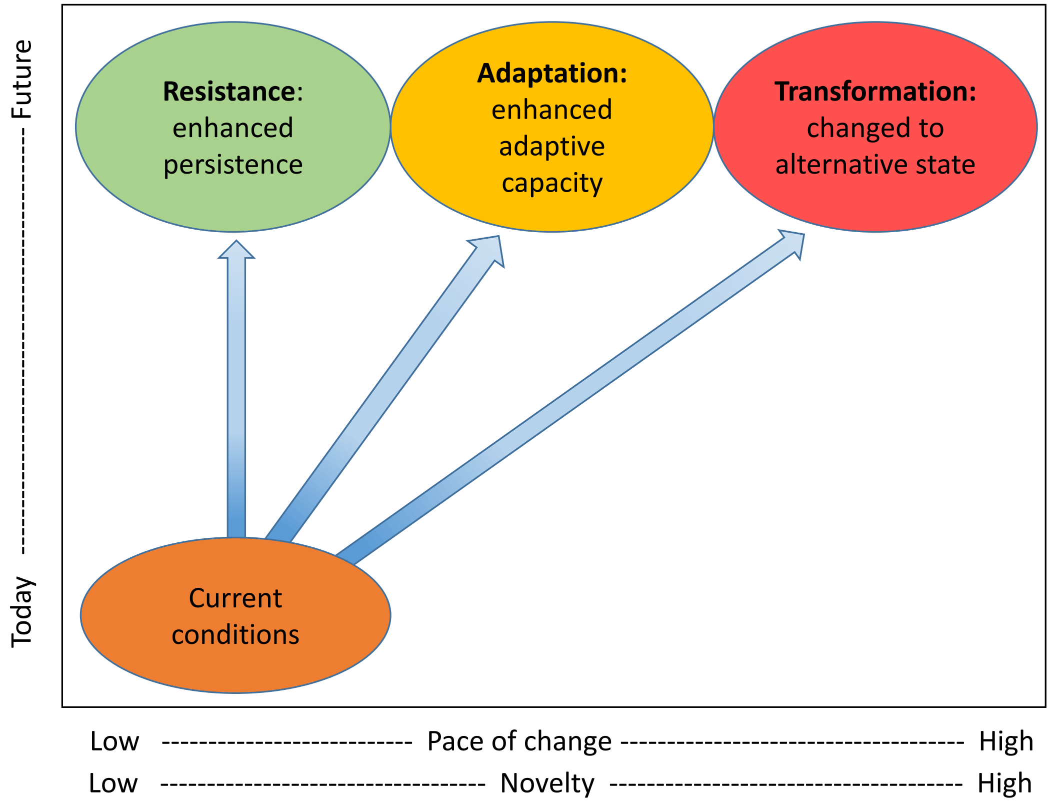

Figure 2. Three intervention strategies to promote future resilience are distinguished by their intended pace and degree of change: resistance, adaptation, and transformation.

Box 2. Examples of actions consistent with three different resilience strategies pertaining to ecological (a) and social (b) systems.

a) Ecological systems

Strategy	Outcome	Action	Examples
Resistance	Retention	Protection measures	Refugia, large trees, reference areas, biodiversity hotspots, rare and/or at-risk populations and communities, barred owl removal
Adaptation	Enable and promote flexibility	Conservation measures	Landscape connectivity, genetic diversity conservation measures, reforestation with climate adapted seed stock, PODs for fire management
Transformation	Directed change	Intervention measures	Species translocations, strategic distribution of forest conditions to affect landscape-scale fire behavior, intentional shifts in community composition

b) Social systems

Strategy	Outcome	Action	Example
Resistance	Retention	Community protection measures	Fire protection and response for homes and critical infrastructure, hardening homes, defensible space management
Adaptation	Enable and promote flexibility	Individual and community incentives	Exemptions to regulatory restrictions, collaborative planning, regulatory reform, condition-based management, shared regional resilience visions
Transformation	Directed change	Societal expectations and norms	Changing land use policies, changing wildfire management policies, changing financial policies to promote and support biomass and small wood utilization industries

5. Using the Framework to Assess Conditions and Management Opportunities

We outline a step-wise approach for determining target conditions and actions across spatial scales (Figure 3): 1) set regional landscape resilience goals based on a combination of regional and local landscape desired benefits and capacity and shape target contributions across stakeholders; 2) determine target conditions for each local patch or facet based on the combination of capacity of the facet to support conditions of interest and the importance of that location to meeting regional and/or local goals; 3) determine how local target conditions roll up to target conditions for intermediate-scale building blocks; and 4) identify commitments to action at the regional scale, and a plan for action through stakeholders associated with intermediate-scale building blocks (watershed or basin-scale units that are subsets of the regional landscape) (Figure 3).

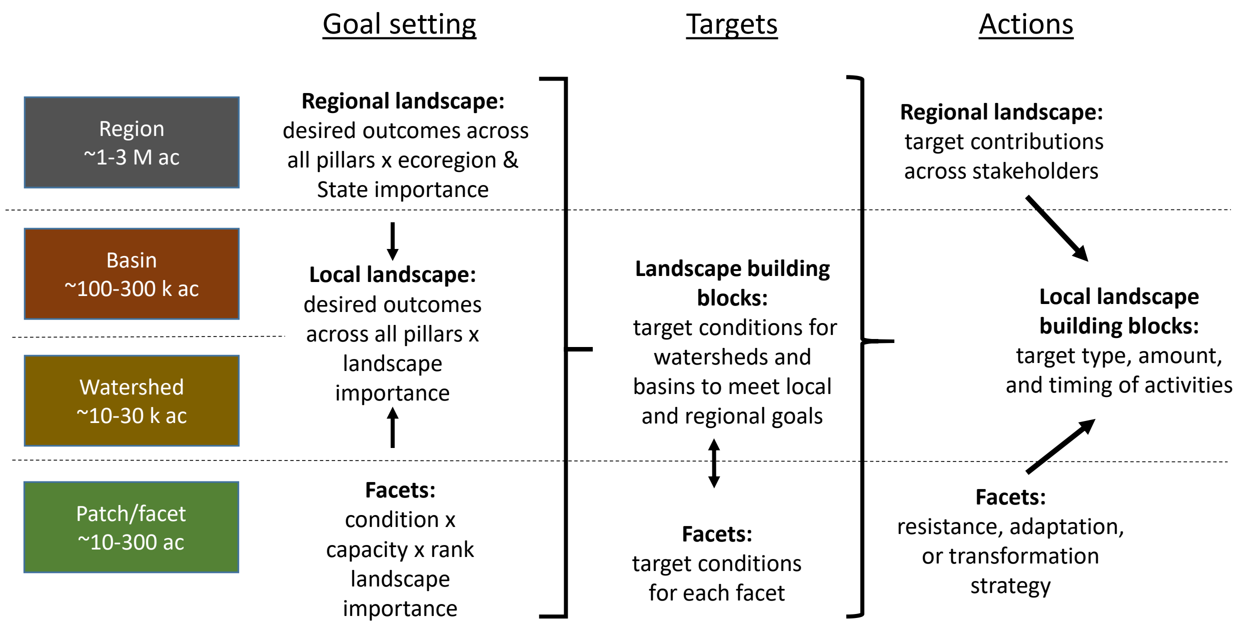

Figure 3. Application of the framework for socio-ecological resilience to regional landscapes for setting outcome goals, target conditions, and actions to promote resilience.

The Foundational Role of Regional Landscapes

Large, regional areas in the 1-3 million acre range are the scale at which most outcomes of socio-ecological resilience are expressed, at least in the Sierra Nevada, since it is the scale at which large-scale processes operate and their benefits are realized (e.g., population viability, water security, fire dynamics, local markets and economies, community protection capacity). For example in the past decade, wildfires burned large areas ranging from 100,000 to over 250,000 acres, and drought-induced tree mortality affected large areas of the Sierra Nevada. There is a need to increase the scale of planning and forest restoration projects to affect change at the scale of recent fire and drought disturbances. Social, economic, and environmental solutions to forest management challenges are more readily achieved across large regional landscapes and across all lands because there are more options and flexibility to balance multiple objectives over space and time (McKinney and Kemmis 2011, Hessburg et al. 2015). Concomitantly, they serve as an organizing feature to both guide and demonstrate how community-driven projects can add up to accomplish broad-scale outcomes (e.g., ecosystem services and benefits) that can be readily quantified and monitored over time.

Many State and Federal policies set goals and objectives for a more resilient future, including improved forest health and drought resilience, reduced the risk of destructive wildfire, reduced greenhouse gas emissions, improved water security, and conservation of biodiversity. Regional landscape boundaries vary among most State plans and programs, and while a single set of regional boundaries for each ecoregion would be ideal (e.g., Figure 4), it not a necessity to realize the primary benefits of regional assessment and planning as long they are guided by a consistent scientific foundation, which the Framework helps to accomplish.

Traditionally, forest management plans were developed by a single institution with input being solicited by interested parties (stakeholders), scientists were consulted on an ad-hoc basis as needed, and implementation was conducted by individual institutions acting independently, As we contend with increasingly complex challenges and possibly irreversible loses of ecosystem services, the design and implementation of management is moving toward multi-institutional collaborations and funding, and solutions that have a solid scientific foundation. Such collaboration requires additional time to accomplish project design, but it greatly enhances the ability to achieve broadly supported benefits across large geographic areas.

Planning across regional landscapes is highly effective at promoting greater resilience because: 1) they are large enough to have measurable ecosystem services and identified beneficiaries; and 2) planning at large scales provides for more options to accomplish multiple objectives across scales that might otherwise be in conflict at smaller scales.

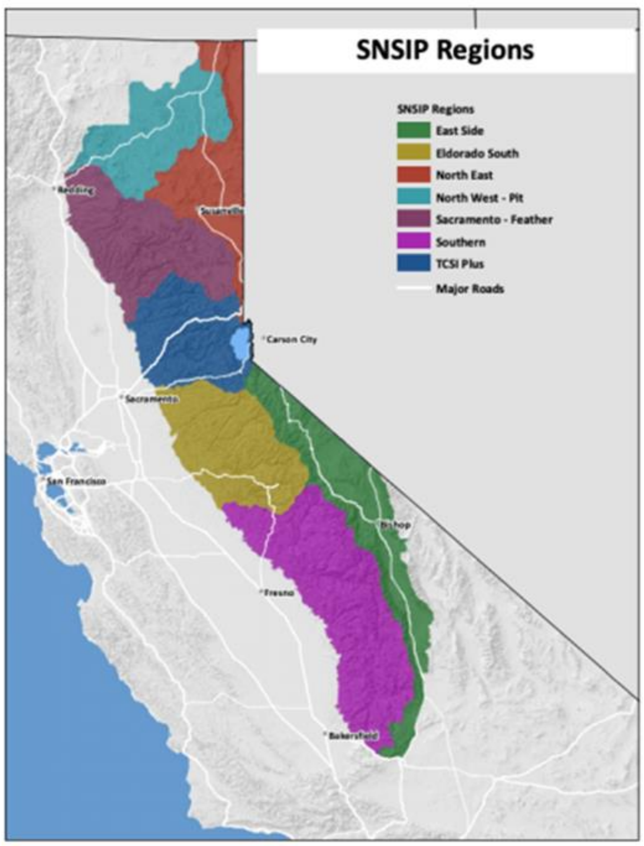

Figure 4. Sierra Nevada ecoregion and example ecologically driven boundaries of regional landscapes, including the Tahoe Central Sierra Initiative (TCSI) landscape.

Regional-level planning is not new, but planning across jurisdictions toward a cohesive landscape outcome is an emerging approach, and it invokes an alternate set of operating principles (Box 2). A collaborative vision for the future of the landscape across all jurisdictions is the first step, which becomes the cohesive vision for the future of the landscape that integrates regional objectives, local capacities and opportunities, and stakeholder priorities, which the land managers can then use to develop more localized project design and implementation. A primary incentive and goal for innovating regional planning is to remove barriers to implementation that cannot be resolved at smaller scales. One major barrier is the high cost of treatments in part due to the lack of a market for non-timber woody materials. A regional approach could facilitate investment in infrastructure, equipment and expertise to make economic use of the lower value material that is the byproduct of thinning treatments to reduce the risk of fire, such as biomass energy or small diameter wood mills. It could also potentially reduce treatment cost by securing a supply of material from a larger regional area. Regional-scale planning has the potential to expedite planning and implementation by sharing resources, to work at a large enough scale to affect ecosystem service reliability as well as to enhance efficiencies of scale, to develop a sustainable work force with associated markets, and to address policy questions at scales that can inform state and federal policy discussions.

Setting Regional Landscape Resilience Targets

Three factors act at the regional landscape scale to shape target outcomes: 1) the inherent capacity of the landscape given the current composition, structure, and function of elements that are relatively immutable over at least several decades; 2) future climate and urbanization trends; and 3) priorities that emerge from institutional stakeholders as desired or required to accomplish a shared vision for a resilient landscape. The inherent capacity of the landscape is primarily dictated by existing conditions that are not readily changed (i.e., difficult or slow to change), as opposed to features that can change quickly (e.g., tree density). For example, life zones are one aspect of relatively fixed conditions, in that they reflect species and physiognomic responses across broad climatic conditions. While climate and associated biota will shift over decades, those shifts can be taken into account in strategic measures to adapt to changing environments. Other examples of relatively fixed elements include a range of high value social and ecological elements: private and public land ownership, public land use allocations (e.g., wilderness, roadless areas, general forest), urban development and infrastructure (social assets), large patches of large trees, ecologically intact old forests critical habitat for species at risk or concern, and fens (ecological assets).

In contrast, identifying priorities for future conditions will reflect targeted changes that can be made over the course of 5-10 years (or longer) toward more resilient conditions. More pliable elements in forested ecosystems may include tree density, tree species composition, seed sources adapted to future climate, amount and distribution of seral conditions, and amount and distribution of habitat for focal species. More pliable elements in social systems may include job training opportunities, tax incentives for business investments, and defensible space and public safety campaigns.

Determining Local Landscape Capacity and Importance

Landscape facets are individual geophysical units that share the same set of abiotic features, such as parent material, soil type, temperature and precipitation regimes, solar radiation, slope, and aspect (Underwood et al. 2010, North et al. 2012, Comer et al. 2015). Abiotic conditions set the stage for abiotic and biotic processes, and as such play pivotal role in biotic responses to changing environmental conditions. Existing conditions will vary widely across pillars, elements, and the metrics that are relevant at the local facet scale. Potential ecological conditions for a given facet are a function of the combination of geophysical site conditions (bottom-up environmental drivers) and broad-scale environmental conditions, namely climate change over the next 50-100 years and urbanization (top-down environmental drivers). Some facets will have the potential to support a broad array of conditions (e.g., productive soils, wet sites, low topographic position, north facing slopes), including forest conditions that take a long time to develop such as complex forests with large trees, multilayered canopies, and high species diversity. In contrast, other facets will only be able to support a limited array of conditions (e.g., less productive soils, drier sites, ridge tops, south facing slopes, frequent fire ignitions, tendency to burn at high severity), resulting in less complex forests with simpler structures and generally lower species diversity.

External drivers put further constraints on what a site can support into the future, namely climate change and urban development. Given that forests grow over several decades and centuries, 50-100 year climate projections are important considerations for future planning. For example, future climates are predicted to be warmer and with more variable precipitation with extended periods of drought interspersed with wet years that may or may not also exhibit extremes (Bedsworth et al. 2018). Drought tolerance is enhanced by reduced competition for water, so predicted future climates might suggest that target tree densities would move toward the lower end of referenceranges, particularly for site types that are drier and more responsive to climate variability (e.g., Restaino et al. 2019).

Urban development over the next 100 years is predicted to directly affect the character of private lands, but it will also affect public lands through proximity to the built environment, and recreational use (US EPA 2017). Urban development, including recreational use, also carries with it an increased probability of fire ignitions, which increase fire risk, particularly in areas that may be difficult to manage or suppress fire. Forests adjacent to (i.e., within 1/4 mile) houses or critical infrastructure are considered the first line of defense for reducing the risk and threat of fire, and as such, will be substantially more limited in the range of conditions that a site will be able to support. Regardless of the ecology of these patches, target forest conditions in defense zones typically emphasize a low probability of supporting moderate and high intensity fire and a low probability of drought stress, both of which are enhanced by low tree density and limited woody material on the ground.

Attributing Opportunity by Landscape Building blocks

Watershed-based subunits of regional landscapes, typically 20,000 to 40,000 ha (50,000 to 100,000 ac; Hydrologic Unit Code 8 to 10), are effective building blocks of regional landscapes. They are an effective means by which cross-scale linkages between regional landscape goals and local goals, capabilities, priorities, and thresholds are achieved and expressed. Specifically, a range of target conditions can be established for each building block based on the target conditions established for the regional landscape, the capacities of the facets within it, the priorities of local stakeholders, and the contribution they can make to the desired amounts and distributions of conditions targeted across the regional landscape. Intermediate-scale building blocks can be defined in a number of ways, but are most often defined by watershed or basin boundaries, with other factors, such jurisdictional boundaries, influencing their geographic extent. These intermediate building blocks are the scale at which individual projects are planned and implemented.

6. Interpreting Multiple Metrics, Elements and Pillar Outcomes

The complexity of multiple measures for multiple metrics across multiple elements and pillars can pose a challenge to interpreting what management inputs will be most effective in moving systems toward target outcomes. The concept of 'risk reduction' and 'tradeoffs' has traditionally been used to analyze options and portray costs and benefits associated with management scenarios. Increasingly analytic tools are used to take multiple, sometimes competing, objectives into account simultaneously in an effort to optimize outcomes across multiple target conditions. A growing number of planning tools are available (e.g., Reynolds et al. 2014, Ager et al. 2017) to evaluate the relative performance of management scenarios across multiple desired outcomes (pillars). In the process of using multiple outcome evaluation tools, users can determine how they want metrics, elements, and outcomes to be evaluated. For example, individual elements may be evaluated equitably across the spectrum of pillars, such that each element (regardless of the number of metrics used to describe it) carries equal weight in determining the degree to which a pillar outcome has been achieved, and each outcome carries equal weight in determining the degree to which resilient conditions have been achieved.

The evaluation of metrics, elements, and pillars can be configured in any manner that suits stakeholders and informs management for a given landscape, and can be significantly more complicated than the example shown here. Specifically, metrics, elements, and pillars may be evaluated in a more hierarchical manner, such that some metrics and elements may carry more weight than others in evaluating individual outcomes, and pillars may be parsed first by social and ecological conditions, before being combined to reflect overall resilient conditions. The evaluation process embodies the relative value that stakeholders place on the different pillars.

The interdependent nature of social and ecological systems results in a limit to the degree that any given pillar can be prioritized above others (Figure 5). For example, prioritization might entail setting target improvements for the highest priority outcomes – let's say forest resilience, fire-adapted communities, and biodiversity conservation - and setting targets of neutral or positive change for other outcomes – let's say air quality, wetland integrity, water security, and economic diversity and social and cultural well-being – and acknowledged potential short-term negative change in carbon sequestration. Analysis of relationships among the elements and pillars might show that in order to meet the target biodiversity conservation and air quality conditions, forest resilience gains would fall short of target conditions, and carbon sequestration would be slightly impacted. However, with an increased use of fire as a management tool, and an additional investment in wetland integrity above target, the target outcomes for forest resilience would be met, and targets for fire dynamics, wetland integrity would be exceeded, and air quality and carbon sequestration would not be reduced below current conditions. In short, analytic tools are an essential component of weighing multiple benefits and risks to identify and quantify the most favorable combination of management actions based on stakeholder priorities and ecosystem dynamics.

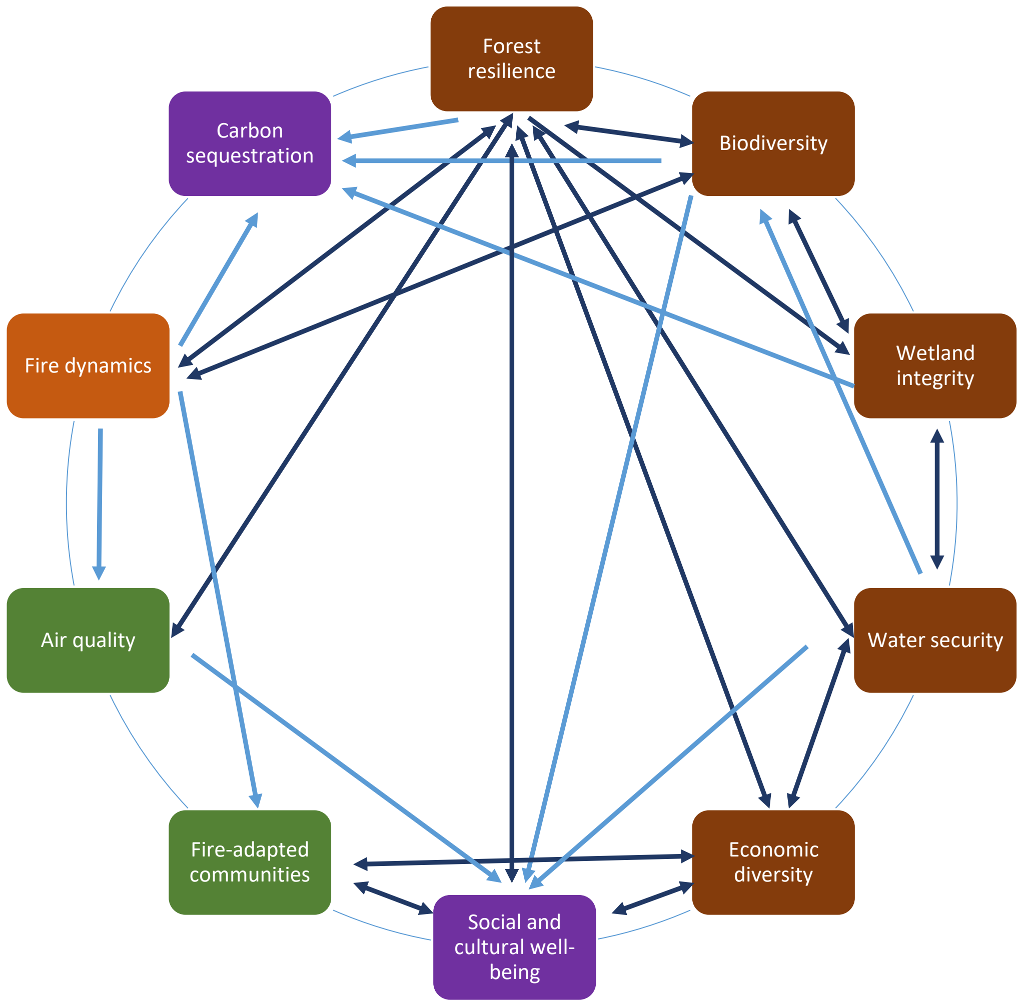

Figure 5. Pillars are highly interdependent and outcomes for each pillar affect outcomes for multiple other pillars. Interactions can be one direction (light blue) or bi-directional (dark blue) between pillars. Pillars fall into four functional categories based on their interactions with the other pillars: *drivers* (brown colored boxes = many connections coming in and going out), *influencers* (orange boxes = many connections going out, fewer coming in), *integrators* (purple boxes = many connections coming in, fewer going out), and *niches* (green boxes = few connections in or out).

7. Conclusions

This Framework for Resilience is intended to expedite, guide, and document progress toward greater socio-ecological resilience. Understandably, regional and intermediate-scale landscape planning efforts may not be able to address all the pillars or all the metrics. Nonetheless, the Framework will expedite progress toward greater resilience in the following ways: 1) Pace - large landscape efforts that adopt the Framework for resilience will enhance their progress because collaborative efforts can move right to goal setting relative to the pillars; 2) Scale - efforts that reach toward regional landscape scales in their goal setting and planning will enhance the ability of accomplishing meaningful change in socio-ecological resilience, and 3) Impact - larger landscape efforts that represent their goals and target conditions in the form of the pillars and metrics will enhance the ability to assess the cumulative effects of management actions on resilience and ecosystem services within and across landscapes by jurisdiction, by ecoregion, and across the State, which also creates a positive feedback between policies, actions, and accomplishment.

8. Acknowledgements

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Appendix A. Core metrics for the condition of each element and pillar of socio-ecological resilience.

Pillar	Elements	Core Metrics
Forest resilience		
	Structure	Tree density
	Structure	Basal area
	Structure	Large/tall tree density
	Structure	Clump/gap structure
	Structure	ICO composite index
	Structure	ICO composite index
	Structure	Seral stage (early, mid, late)
	Structure	Large snag density
	Composition	Vegetation community type
	Composition	Tree species diversity
	Disturbance	Time since disturbance
	Disturbance	Recent disturbance return interval
Biodiversity		
	Focal species	Suitable habitat for focal species
	Focal species	Critical habitat for listed species
	Species diversity	Species diversity
	Species diversity	Non-native species distribution
	Community integrity	Functional group diversity
	Community integrity	Community diversity
Fire dynamics		
	High intensity	Risk of high severity fire
	High intensity	HIgh intensity patch size
	Functional fire	Time since fire and frequency
	Functional fire	Proportion of fire as high severity
Water security		
	Quantity	Ground water
	Quantity	Water yield
	Quantity	Snow accumulation
	Storage and timing	Stream flow volume
	Storage and timing	Reservoir storage
	Storage and timing	Snow water content
	Storage and timing	Snow melt
	Quality	Nitrogen
	Quality	Phosphorus
	Quality	Sediment
	Quality	Pollution

Appendix A cont.

Pillar	Elements	Core Metrics
Wetland integrity		
	Structure	Stream channel morphology
	Structure	Alluvium storage capacity
	Composition	Carbon content
	Composition	Benthic invertebrates
	Hydrologic function	Surface water flow
	Hydrologic function	Stream channel discharge
Carbon		
sequestration	**Above ground carbon**	Mass
	Below ground carbon	Mass
	Stability	Persistence
Air quality		
	Particulate matter	Wildfire emissions
	Particulate matter	Prescribed fire emissions
	Visibility	Visual quality
	Greenhouse gases	Ozone
Fire-adapted		
communities	**Fire hazard**	Risk of high and moderate severity fire
	Fire hazard	Threat to infrastructure
	Fire preparedness	Community fire protection plans
	Fire preparedness	Egress/ingress plans
	Fire preparedness	Fire management plans
Economic		
diversity	**Wood product industry**	Biomass supply and demand
	Wood product industry	Small diameter tree supply and demand
	Wood product industry	Processing capacity
	Recreation industry	Recreation diversity
	Recreation industry	Recreational use
	Water industry	Water management infrastructure
	Economic health	Job market in natural resources
	Economic health	Employment resilience
	Economic health	Income diversity
Social and cultural		
well-being	**Public health**	Smoke-induced illness
	Public health	Public health susceptibility
	Public engagement	Natural resource knowledge
	Recreation quality	Costs and benefits to recreation
	Equitable opportunity	Environmental justice