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TPOR: an integrated socio-ecological framework to inform management toward resilience

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Socio-ecological resilience recognizes that humans and nature are inextricably connected, and humans play an increasingly central and active role in determining the fate of ecosystem resilience. For decades, managers and scientists have sought effective approaches for managing forest composition, structure, and processes to improve resilience properties. Management actions that encompass large landscapes tend to engage a broad spectrum of stakeholders and perspectives about resilience. Translating resilience concepts into concrete and measurable objectives and outcomes and effectively communicating landscape management strategies presents many practical and conceptual challenges. Climate change is increasing the burden faced by managers to increase the pace and scale of management actions in an attempt to enhance the resilience of forested landscapes to more extreme environmental conditions. Through a process that engaged a diversity of stakeholders, we developed a framework for socio-ecological resilience intended to support, quantify and expedite a range of landscape resilience management activities. The Ten Pillars of Resilience (TPOR) Framework is an operational method to organize, evaluate, inform, guide, monitor, and document socio-ecological conditions across landscapes. The Framework's information hierarchy consists of three levels: 1) Pillars, which represent the primary constituents of resilient socio-ecological systems across landscapes; 2) Elements, which reflect the core features of each Pillar; and 3) Metrics, which represent the characteristics of each Element that directly or indirectly have bearing on resilient outcomes. The TPOR Framework has been used to support large-scale restoration policies, planning, assessments, and accomplishments. We discuss how the Framework can serve as a construct for integrating past, current, and future conditions as a function of management, climate, and other disturbances. It has demonstrated value in supporting the needed pace, scale, and effectiveness of management investments by providing a consistent and scientifically robust foundation for quantitatively representing the spectrum of facets of resilience in socio-ecological systems in balancing near-term gains and long-term resilience objectives.

KEYWORDS

climate change, collaborative decision making, ecosystem services, environmental restoration, landscape planning, Planscape, ten-legged stool

1 Introduction

Humans have increasingly influenced wildland ecosystems across the globe over the past century (e.g., Keeley, 2002; Klimaszewski-Patterson and Mensing, 2016; Roos et al., 2021). There is growing concern that the effects of past, present, and future stressors on wildland ecosystems are compromising their resiliency to disturbance, particularly as climate change progresses (Coop et al., 2020), calling into question their ability to support native species, recover their functionality, and provide the full array of essential ecosystem services (Barrett and Robertson, 2021). In terrestrial environments, reduced extent and function of forest ecosystems are particularly of concern given the substantial ecosystem services they provide and the lengthy recovery process of a century or more for mature and old forests to develop.

Forest ecosystem responses to past management practices (Stephens et al., 2016; Hessburg et al., 2019) have altered plant species composition, species interactions, and forest structural characteristics making them more vulnerable to high intensity fire (Abatzoglou and Williams, 2016; Kane et al., 2017), drought stress, and beetle-caused mortality (Bentz et al., 2010; Hicke et al., 2016; Berner et al., 2017). Concomitantly, a rapidly changing climate over the past few decades and the next century to come is increasingly affecting forest ecosystems and associated biota (e.g., Westerling et al., 2006; Harvey, 2016; Weiskopf et al., 2020), with fire and bark beetles becoming significant sources of tree mortality (Meddens et al., 2012; Hicke et al., 2016). Although fire and bark beetles are intrinsic and necessary disturbance processes in dry forest ecosystems, increasing temperatures and extended droughts are resulting in direct tree mortality and extensive high severity fire that threaten forest persistence across much of the western U.S (Abatzoglou et al., 2021). For example, in the temperate forests of California, United States, the area burned by wildfires approximately doubled in the first two decades of the 21st century (approximately 2.8 million ha per decade) compared to the two decades prior (approximately 1.1–1.3 million ha per decade) (Buechi et al., 2021).

Pressure is mounting to increase management across landscapes toward greater resilience before ecosystems are so compromised that they cannot recover from disturbances (e.g., Maxwell et al., 2022), resulting in a loss of forests (North et al., 2019; Stephens et al., 2020; Ager, 2022; Tyukavina et al., 2022; Legge et al., 2023). The push to treat expansive landscapes over short periods of time with the potential for both beneficial and detrimental consequences, puts additional pressure on managers and stakeholders to have a robust and common scientific foundation–and a common language–for defining resilience and evaluating outcomes. Decision support tools are becoming increasingly necessary to help managers, stakeholders, and policymakers grapple with the complexity of rapidly changing climate and landscape conditions and the fate of essential ecosystem services that hang in the balance. Managers need a consistent foundation to transition from the conceptual goal of resilience to operational and tactical aspects of project design and implementation (e.g., Tampekis et al., 2023). They also need to evaluate management effectiveness to support adaptive management through all facets of management (Halofsky et al., 2018). As a result of the increasing complexity, pace, and uncertainty in land management, managers, scientists, and communities are working more collaboratively than ever to characterize and manage landscapes in pursuit of long-term resilience to disturbance (e.g., Mansourian, 2021; Tampekis et al., 2024). Landscape management planning has shifted to more stakeholder engagement and model-driven, science-based approaches that attempt to design management to improve resilience to current and future disturbances (Kelly et al., 2019).

Despite these intentions, the ability to effectively apply this burgeoning quality and quantity of information planning across large landscapes, while attempting to reconcile multiple stakeholder interests, can impede progress by overwhelming managers and stakeholders (e.g., Gunderson et al., 1995; Urgenson et al., 2018). Climate change is precipitating a triple bind consisting of the need to act quickly across large landscapes, incorporate available information across multiple and diverse resources, and cope with substantial uncertainty in the ability for management to improve ecosystem resilience (e.g., Triepke et al., 2019). In short, the stakes are high, the complexity can be overwhelming, and uncertainty exists in sustaining functions over large regions. This combination of challenges commonly leads to time lags at best and the inability to act at worst (Bradshaw and Borchers, 2000).

An emerging hurdle that increasingly presents early in the planning process is the ability to translate the concept of resilience into concrete values, measures and outcomes that can be applied to consistently inform and support management investments and actions. Stakeholder collaboratives commonly seek consensus on methods and motivations to achieve short-term risk reduction goals while improving the prospect of longer-term resilience (McDermott et al., 2011; Fischer and Charnley, 2012; Seidl et al., 2016; Urgenson et al., 2018). However, getting to a clear, shared definition of resilience can greatly slow the process of moving into assessment and planning. Furthermore, working across ownerships and land jurisdictions can create conflicts in terms of restoration goals, investments, and desired outcomes (DellaSala et al., 2003).

Frameworks are an essential component of decision support systems, providing useful mental or conceptual constructs to make complex problems or processes more tractable and easier to translate into action (e.g., Binder et al., 2013; Cumming et al., 2005; Hessburg et al., 2015). They also provide a shared construct and a common vocabulary to structure individual applications, thereby expediting problem definition and inquiry, and building knowledge about higher level patterns and processes (McGinnis and Ostrom, 2014). Many frameworks have been developed to help translate the complexity of resilience and restoration as they apply to socio-ecological systems (Mumby et al., 2014; Díaz et al., 2015; Truchy et al., 2015; Baho et al., 2017). Most of them outline an analysis process–steps to answer questions pertaining to conditions and/or management opportunities for improving conditions - as opposed to serving as a working tool (e.g., Ostrom, 2009; Binder et al., 2013; Garmestani and Benson, 2013; Díaz et al., 2015; Baho et al., 2017). Furthermore, numerous conceptual models have been forwarded to represent socioecological systems (e.g., Redman, 1999; Ostrom, 2009; Pahl-Wostl, 2009), some of which depict systems as having independent and interacting or overlapping domains (e.g., Kalaba, 2014; Díaz et al., 2015) with broad recognition of their interdependence (Díaz et al., 2015). These existing frameworks provide structure for system mechanics to varying degrees. For example, the IPBES conceptual framework for connecting nature and people (Díaz et al., 2015) focuses on relationships between people and nature. It is broadly accepted and applied to shaping conversations and approaches for conserving biodiversity around the globe. In essence, it (and most of the other existing frameworks) serves as a precursor to a condition-based representation of people and nature. A framework for socio-ecological resilience focused on conditions and outcomes that can be incorporated directly into decision support systems to provide integrated project planning and evaluation of treatment success towards achieving local and regional objectives is still needed.

Recent frameworks have been developed to help practitioners characterize resilience and the challenges that future climate conditions and uncertainties may pose to long-term resilience objectives (e.g., Sterk et al., 2017; Lynch et al., 2022; Schuurman et al., 2022; Williams, 2022). However, few are designed to quantitatively evaluate status and change in the context of resilience (e.g., Povak et al., 2024). For example, the Resist-Accept-Direct (RAD) framework acknowledges the differential responses of specific systems to ongoing climate change and provides managers with three distinct restoration options to assess plausible future outcomes and to determine how they may or may not comport with ecological, societal, and policy objectives (Schuurman et al., 2022; Williams, 2022). Similarly, the Resistance-Resilience-Transformation (RRT, Peterson St-Laurent et al., 2021) provides a larger gradient with finer, more specific class definitions along the resistance to transformation scale to better communicate potential outcomes of management actions. While forward looking, these frameworks don't provide an informational model with which to structure the data necessary to evaluate landscape conditions, nor do they provide quantitative methods to inform proposed management actions.

Our objective was to develop an operational framework that could: 1) expedite and enhance a paradigm shift from more singular systems of evaluation to a socio-ecological foundation; and 2) support the full arc of management including setting objectives, identifying management options, evaluating potential outcomes, selecting treatment plans, monitoring change, and evaluating management effectiveness. Through a collaborative process with landscape planners, scientists, and other interested parties we determined there was a need for a comprehensive framework to enable effective management responses to the rapidly changing environmental circumstances currently challenging socio-ecological resilience. We applied principles of socio-ecological systems to create a structured framework called the Ten Pillars of Resilience (TPOR) for characterizing and evaluating socio-ecological resilience across landscapes. We describe an example of the TPOR Framework in action including a step-by-step guide of how it was applied to operationalize resilience in forest management. Finally, we demonstrate the utility of the TPOR Framework through an existing set of planning and policy applications across California and the western United States.

2 Framework development and conceptual foundation

2.1 The concept of socio-ecological resilience as a foundation for management

Resilience theory emerged over a half century ago as a response to the lack of equilibrium concepts to address observed ecosystem dynamics (Holling, 1973). Resilience itself is not a condition or a state, rather it is an emergent system-level property reflecting the ability to self-organize over time by retaining characteristic processes, structures, and functions following disturbance (Holling, 1973; Peterson et al., 1998; Thompson et al., 2009; Sundstrom et al., 2014). For centuries humans have shaped landscapes to intentionally alter environmental disturbance regimes to avoid or mitigate extreme events (e.g., flood control, fire suppression), reduce risks, and increase short-term and long-term benefits and services (e.g., Turner, 2010). Society's expectations regarding the capacity of ecosystems to provide specific benefits and services are based on disturbance regime characteristics that emerged under past climates and social and political settings, which can change considerably over time (Hilderbrand et al., 2005).

Socio-ecological resilience recognizes that humans and nature are inextricably linked, and that humans are an increasingly central and active determinant of ecosystem resilience. Managing to promote resilience translates to the protection and enhancement of ecosystem services in a sustainable manner over the long term (e.g., Daily and Matson, 2008). The maintenance of key ecosystem components, structures, and functions that translate to societal benefits and services requires thoughtful and consistent management investments informed by ecological resilience theory and secured through societal support. Ecosystem services are commonly categorized into one of four functions: supporting, provisioning, regulating, or cultural (Carpenter et al., 2009). In contrast to strictly ecological resilience, socio-ecological resilience emphasizes that human communities are part of the capacity of the system to cope with, adapt to, and influence change (Folke et al., 2005; Folke, 2006; 2007). As such, it expands the original concept of resilience and associated self-reinforcing functions from initially pertaining only to natural disturbances, to now more broadly including management investments that result in favorable and sustainable (and thus self-reinforcing) feedbacks. For example, a hypothetical scenario presents itself where forest management reduces the risk of high severity fire in a given management unit, then a wildfire event occurs, resulting in the forest burning primarily at low to moderate severity, which in turn provides the opportunity for some salvage logging (timber harvest and mill operations, marketable products), improved forest resilience (improved forest health, reduced risk of future tree mortality and habitat loss), and public support for future management toward similar objectives (available funding and staffing). These self-reinforcing mechanisms within socio-ecological systems are commonly characterized as "return on investment" (e.g., Boyd et al., 2015), and when economic returns are part of the equation, it is commonly referred to as "the triple bottom line" corresponding to people, planet and profit (Elkington, 1997; Schweikert et al., 2018).

2.2 Transdisciplinary stakeholder engagement

Managing socio-ecological resilience is inherently a transdisciplinary endeavor, requiring cooperation between different areas of scientific expertise and practitioners from various sectors of society to generate cohesive and expansive foundational constructs on how progress can be built (e.g.,

TABLE 1 Operating principles for management, planning, and project design and implementation commonly applied in historical, traditional approaches directed at one or a few near-term objectives compared to those applied in more forward-looking approaches directed at managing for greater resilience across landscapes.

Traditional limited objective management	Landscape management for greater resilience
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 management 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 integrating the shared vision for future landscape conditions with locally driven project design and implementation capacities and accomplished through on-going engagement of stakeholders, scientists, and managers
Projects focus on a few specific 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 may or may not engage 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 landscape outcomes affected by project treatments

Brandt et al., 2013; Fiksel, 2006). Management approaches now commonly emphasize not only conserving essential ecosystem processes and services but also integrating social values and benefits through transdisciplinary approaches to convene and develop a collective vision of desired outcomes (e.g., Biggs et al., 2012; Newton and Elliott, 2016; Sayer et al., 2017). These more expansive and inclusive approaches to land management processes and outcomes across large landscapes, including the adoption of resilience concepts, are precipitating wholesale changes to how land managers and their agencies conduct the business of planning and uncertainty at multiple scales (Table 1).

Our approach to developing a framework for socio-ecological resilience reflects the new era of how land managers and agencies are planning land management, and the importance of a transdisciplinary approach. Over the course of 2 years (2018–2019), the authors led a diverse team of scientists, land managers, and policymakers in California on behalf of a multi-agency collaborative partnership–the Tahoe Central Sierra Initiative (tahoecentralsierra.org) – to collaboratively generate a conceptual framework for resilience to serve as a socio-ecological foundation through a common conceptual and operational construct to inform and support resilience objectives and actions being pursued by land managers across the state. The initial objective was to provide a foundation for the 1-million hectare Tahoe Central Sierra Initiative landscape in central Sierra Nevada (California and Nevada, United States), but it was designed to be broadly applicable to any geography or spatial scale.

Initially, a small team of scientists with expertise in forest ecology, aquatic ecology, biodiversity, and resilience worked together for several months to establish a conceptual foundation for resilience that pertained to forested ecosystems and diverse landscapes with a high degree of social, cultural, and ecological interaction. We wanted to develop a conceptual and operational model that reflected the unique facets of socio-ecological systems but also provided the ability to portray and evaluate their interdependence and interaction. A 2-day workshop was held in 2018 to define the key components of resilience and how to effectively capture them in a framework. The workshop was attended by over 30 individuals from a diversity of institutions (University of California researchers, U.S. Forest Service scientists and managers, and scientists and leaders from multiple California State agencies, The Nature Conservancy, The National Forest Foundation, and the California Forestry Association). The workshop started with a suite of presentations from experts on resilience across a range of topic areas, including a review of existing frameworks (e.g., Millar et al., 2007), followed by a series of round table discussions focused on individual topic areas, which ultimately became the pillars. Post-workshop consultations with additional subject-matter experts helped refine and finalize the pillars and their elements.

2.3 Features of an outcome-based socio-ecological framework

The workshop identified key features of a socio-ecological framework to inform land management that included: 1) integrated representations of ecological and social components of ecosystems; 2) a hierarchical structure to facilitate summarizing conditions at different levels of specificity; 3) a spatially and temporally flexible approach to represent and evaluate past, present, and future conditions at one or multiple spatial scales; and 4) user-defined metrics to characterize landscape- and stakeholder-specific needs. Following the workshop, the lead author (Manley) and a handful of other attendees pursued multiple group discussions and consultations with additional subject matter specialists and leaders (including additional State and Federal agencies, as well as researchers from multiple Universities across the U.S.) to solidify the final Framework. These key features are explored in more detail below.

2.3.1 Hierarchical systems and decision support

Today, a variety of environmental and social factors, objectives, and priorities need to be considered in planning and assessment across landscapes (Reynolds et al., 2014; Krsnik et al., 2023). Traditional, narrowly focused planning approaches (e.g., singular objective, project-specific outputs) are no longer adequate in such circumstances (Table 1). Complex systems analysis requires decision support systems capable of evaluating a large number of metrics (i.e., spatial data), their relationships, and reflect stakeholder values. Decision processes regarding large and diverse landscapes involve many different stakeholders and perspectives on what facets of the socio-ecological system are important. The ability to move from specific metrics of interest to one group (e.g., state regulator interests in carbon sequestration rates) to overall conditions (e.g., conservation group interests in overall carbon storage) is an important function to support decision making in a complex system. Thus, information systems ideally are hierarchical, to enable information to be evaluated and summarized at multiple levels of specificity to speak to different audiences and concerns. Furthermore, informed decision-making requires tools capable of evaluating planning options against a variety of metrics of values and outcomes that address a range of objectives and interdependent resource conditions consistently across landscapes and over time (e.g., Mills et al., 1998).

2.3.2 Prospective and retrospective utility

Scientific investigations and management assessments both endeavor to look back in time (retrospective) to understand what conditions, events, and responses have occurred in the past, and then use those observed interactions to estimate what future conditions, events and responses are most likely given various sets of potential inputs (e.g., management activities, climate futures). From these investigations, answers to the following questions can be garnered from empirical data (retrospective) or modeled results (prospective): 1) what conditions are possible to achieve; 2) what conditions are most likely to confer resilience; 3) how well do current conditions reflect resilient conditions; 4) what set of resilient conditions are both desired and achievable; 5) where can management inputs be most effective in achieving and maintaining resilient desired conditions; and 6) where can natural disturbances alone achieve these same goals? The ability to look backward and forward in time to address such a broad topic area as resilience requires a flexible data system that can bridge differences in data availability, granularity, accuracy, and representation between the past data and modeled future outcomes.

2.3.3 User defined metrics and measures

It was important to this project that the framework be flexible such that users could select the metrics and measures most relevant to the landscape and scale(s) of interest. The strength of the representation of resilient outcomes depends on the quality, breadth, and complementarity of the metrics selected, including the degree to which their interactions affect resource responses to disturbances, including management. Emergence and persistence of resilience lies in the character and strength of the interactions among all the actors in the socio-ecological system (Sterk et al., 2017).

2.3.4 Facilitate adaptive management

Adaptive management is a concept that emerged in the 1970s, and it is broadly defined as "learning by doing" (Walters and Holling, 1990), with an original emphasis on prospective and active management (Gunderson and Holling, 2002) intended to expedite learning by embedding experimental designs into management applications. Despite its divergent interpretations, applications, and successes over the past 50 years (Rist et al., 2013; Holling and Sundstrom, 2015), the concept of adaptive management has become a well-accepted intention of management. We call out four key features of adaptive management that a framework ideally would support: 1) explicit definition of what management is attempting to achieve; 2) set the course for achieving and maintaining desired outcomes; 3) provide metrics and measures of status, change, progress, and success; and 4) provide a strong scientific foundation to inform and support adaptation. Active adaptive management is more important than ever given the increasing pace and magnitude of environmental change occurring around the globe due to changing climate and geopolitical environments. We wanted a framework that could effectively address landscape features of relevance to adaptive management, including monitoring conditions over time via the information hierarchy and data evaluation techniques embedded in the initial process that informed management investments (Allen and Starr, 2017).

3 Ten Pillars of Socio-ecological Resilience (TPOR)

3.1 The TPOR framework information hierarchy

The transdisciplinary team and process described above developed the TPOR Framework. TPOR consists of three hierarchical levels of information: 1) the 10 *Pillars* of resilience serve as the primary structure of the Framework and represent the primary domains of socio-ecological systems, which can be synthesized to generate a representation of overall ecosystem resilience (Figure 1); 2) the *Elements* of each Pillar reflect core features, and they are a suggested set; and 3) the *Metrics*, represent

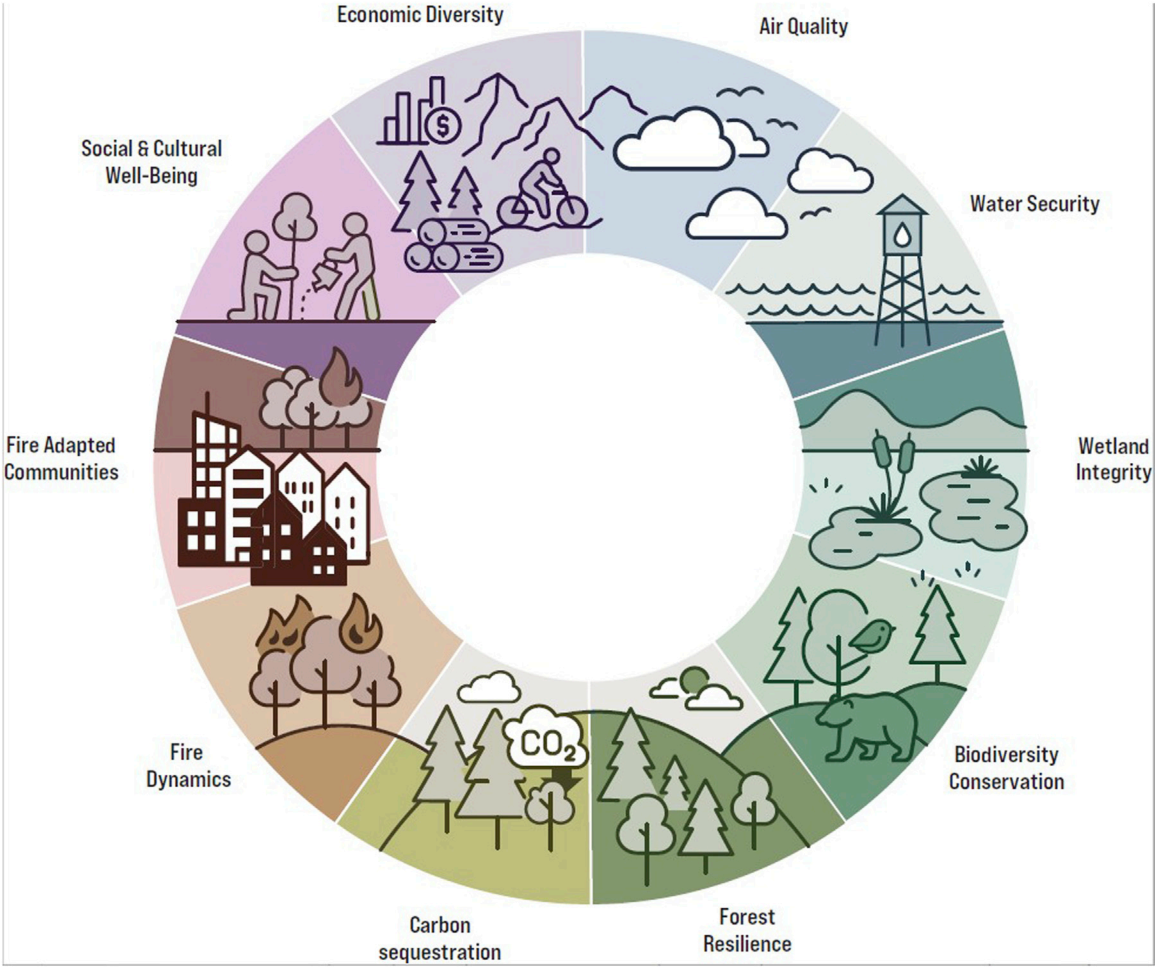

FIGURE 1
The Ten Pillars of Socio-ecological Resilience (TPOR) Framework representing the essential building blocks of socio-ecological resilience. Here the focal vegetation community is forest, but in other types of wildland-dominated landscapes, the Forest Resilience Pillar could be recast to reflect other or multiple dominant ecotypes.

the characteristics of each Element that have significant bearing on the resilience of the Pillar and they are user defined. The Pillars, Elements and Metrics offer a simple structured information hierarchy that can be used to reflect an identifiable set of desired outcomes reflecting resilient landscapes.

3.1.1 Pillars and elements

Pillars are the first order partitioning of the socio-ecological system. The 10 Pillars span ecological and social domains of native ecosystems, and although they are represented individually, we recognize that they are highly interconnected components of socio-ecological systems (Figure 1). The second order of the hierarchy is two or more Elements per Pillar, for a total of 30 Elements representing component features of the Pillars that reflect resilience (Table 2). The Pillars and their Elements are described below.

The Forest Resilience Pillar is measured by the persistence and consistency of primary producers and allies (i.e., vascular and non-vascular plants, fungi, lichen) and their functions in the face of recurrent or chronic disturbances. This Pillar addresses dominant vegetation life form(s); thus, although it is cast here as pertaining to forests, it could readily represent any individual or span multiple vegetation ecotypes (e.g., grassland, woodland savanna). This Pillar is comprised of three Elements: *structure*, *composition*, and *disturbance* (Table 2). Resilient vegetation communities are most likely maintain a range, amount, and distribution of vegetation conditions and dynamics (including processes) that will support a full suite of potential ecosystem services over time (e.g., Yapp et al., 2010). The desired outcome for the Forest Resilience pillar is, "Vegetation composition and structure align with topography, desired disturbance dynamics, and landscape conditions, and are adapted to climate change."

The Fire Dynamics Pillar pertains to the range of expected fire characteristics, whether fire occurs intentionally (prescribed fire and wildfire allowed to burn for resource benefits) or unintentionally. Fire Dynamics includes two Elements: *fire severity* and *functional fire* (Table 2). These elements address the character, location, and frequency of fire across the landscape. Fires that burn largely at low- and moderate-intensity and at a frequency to which forest ecosystems are adapted (Safford and Van de Water, 2014) are

TABLE 2 Hierarchical architecture of the Ten Pillars of Socio-ecological Resilience (TPOR) Framework, including the 10 pillars, their core elements, and example metrics that have bearing on resilience.

Pillars	Core elements	Example metrics
Forest resilience	• Structure • Composition • Disturbance	• Tree density, basal area, large tree density, structural heterogeneity • Vegetation community type, tree species composition • Time since disturbance, disturbance history
Fire dynamics	• Severity • Functional fire	• Risks of high severity fire, high severity patch size • Time since fire, proportion of fire by severity (low, moderate, high)
Carbon sequestration	• Storage • Stability	• Mass, sequestration rates • Persistence and variability over time
Wetland integrity	• Structure • Composition • Hydrologic function	• Stream channel and floodplain morphology, alluvium storage capacity, carbon content • Riparian and aquatic biological integrity • Surface flow, ground water recharge, stream channel discharge
Biodiversity conservation	• Focal species • Species diversity • Community integrity	• Species of conservation concern, culturally important species • Species richness, rarity, endemism • Functional diversity, trophic integrity
Water security	• Quantity • Quality • Storage and timing	• Ground water levels, water yield • Sediment, phosphorus, nitrogen, pollution • Stream flow volume, reservoir storage, snow water content and timing of melt
Air quality	• Particulate matter • Visibility • Greenhouse gases	• Wildfire and prescribed fire emissions • Visual quality • Ozone
Fire-adapted community	• Hazard • Preparedness	• Risk of high and moderate severity fire, threats to infrastructure • Community fire protection plans, established ingress/egress routes, response times, acceptance and support for the use of fire
Economic diversity	• Wood product industry • Recreation industry • Water industry • Economic health	• Biomass and small diameter wood supply and demand, wood processing capacity • Recreation diversity and demand • Water management infrastructure and market • Employment resilience, income diversity, workforce capacity
Social and cultural wellbeing	• Public health • Engagement • Recreation quality • Equitable opportunity	• Smoke-induced illness rates, public health susceptibility • Recreation access, recreation experience costs and benefits • Environmental justice

beneficial in most vegetation types. In contrast, fires that burn primarily at high intensity over large areas pose a threat to life, property, and the resilience of ecosystem processes (Stephens et al., 2020). The desired outcome for the Fire Dynamics Pillar is, "Fire burns in an ecologically beneficial and socially acceptable way that perpetuates landscape heterogeneity and rarely threatens human safety or infrastructure."

The Carbon Sequestration Pillar reflects the fundamental process of primary productivity and succession, which in turn supports the development of complex systems and associated ecosystem services. One of the critical services is the capacity of natural areas to contribute to reductions in greenhouse gas emissions and help mitigate climate change. Carbon Sequestration has two Elements: *carbon storage* and *carbon stability* (Table 2). The capacity of landscapes to make contributions to carbon sequestration is broadly of interest (Buotte et al., 2020), and some jurisdictions (e.g., States, countries) have set specific goals for carbon neutrality with specified reliance on natural and working lands–including native forests (Baker et al., 2020). Forest ecosystems are integral in achieving carbon and climate policy goals and environmental objectives (Moomaw et al., 2020). Carbon dynamics are complex, with many factors affecting sequestration rates, accumulation, and stable storage in living and dead plant biomass above and below ground. For example, all fire reduces sequestered carbon, but large, high severity wildfire pose substantial threats to carbon sequestration goals, as well as impacting other environmental quality goals (e.g., black carbon and methane emissions, old forest habitat; Hurteau et al., 2008; Law et al., 2022). The desired outcome for the Carbon Sequestration Pillar is, "Carbon sequestration is enhanced in a stable and sustainable manner that yields multiple ecological and social benefits."

The Biodiversity Conservation Pillar is directed at maintaining all native species and reducing the impacts of non-native species toward conserving the intrinsic and extrinsic values and benefits that depend on biological diversity and integrity. Biodiversity Conservation has three Elements: *focal species*, *species diversity*, and *community integrity* (Table 2). The Elements enable recognition of all levels of biological organization from the persistence and enhancement of genetic diversity, individual species of interest or concern, suites of species that perform critical ecosystem functions, and community interactions and interdependencies that support overall system resilience (e.g., Noss, 1990). Biodiversity is essential to forest resilience in many ways, including successful reforestation, post-disturbance recovery, and providing essential ecological and societal services, such as seed dispersal, pollination, and recreational activities (consumptive and non-consumptive) (Thompson et al., 2009). The desired outcome for the Biodiversity Conservation Pillar is, "The network of native species and ecological communities is sufficiently abundant and distributed across the landscape to support and sustain their full suite of ecological and cultural roles."

The Wetland Integrity Pillar encompasses meadow, riparian, and other wetland ecosystems that serve as key linkages between upland and aquatic systems across landscapes. Wetland integrity has three Elements: *structure*, *composition*, and *hydrologic function* (Table 2). Meadow and riparian ecosystems with functional hydrology are likely to serve increasingly important roles in buffering impacts from extreme climate phenomena (e.g., prolonged droughts, atmospheric river events) that are anticipated to increase, and from upland disturbances (e.g., wildfire, invasive species, restoration efforts and seasons) likely to increase through intentional management and natural disturbance processes. For example, 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, Carbon Sequestration, and Biodiversity Conservation (Naiman et al., 2010; Reed et al., 2022). The desired outcome for the Wetland Integrity Pillar is, "Meadow and riparian ecosystems provide multiple ecosystem services and are key linkages between upland and aquatic systems in forested landscapes."

The Water Security Pillar encompasses a broad array of important roles and functions that water and hydrologic processes have in socio-ecological systems. Water Security has three Elements: *quality, quantity,* and *storage and timing* (Table 2). These components are essential for forest health and resilience, terrestrial and aquatic biodiversity, recreation, industry, and human consumption (Tidwell, 2016). All Elements within Water Security are vulnerable to disturbances, particularly drought and other extreme weather events (flooding, mass erosion), but are also affected by changes in vegetation structure (e.g., density and canopy cover), ground cover, soil compaction, stream channel and floodplain integrity, and dams and diversions (e.g., Chang and Bonnette, 2016; Olson and Van Horne, 2017). The desired outcome for the Water Security Pillar is, "Watersheds provide a reliable supply of clean water despite wide swings in annual precipitation, droughts, flooding, and wildfire."

The Air Quality Pillar has a spectrum of socio-ecological benefits that can be substantially compromised by changes in vegetation conditions and land cover across landscapes, that in turn affect human communities in a multitude of ways. Air Quality has three Elements: *particulate matter, visibility,* and *greenhouse gases* (Table 2). Vegetation, particularly forests, can contribute to clean air by capturing particulates and removing them from the atmosphere (Nowak et al., 2014). Forests in particular play a key role in sequestering greenhouse gases, which are the primary cause of climate change by trapping heat in the atmosphere (Bonan, 2008). Fire, on the other hand, contributes particulates and gases to the atmosphere that, above certain levels, can impact forest health and human health (Liu et al., 2015). High intensity wildfires are particularly impactful in the amount and duration of toxic pollutants released. 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. The desired outcome for the Air Quality Pillar is, "Emissions from fires are limited to primarily low- and moderate-severity fires in wildland ecosystems. Forests improve air quality by capturing pollutants."

The Fire-adapted Communities Pillar addresses the integrated nature of communities in proximity to, or integrated within, wildland-dominated landscapes, and the threat of fire to human communities and infrastructure. In fire-adapted ecosystems, fire is an essential process and fire-adapted communities are an integral part of achieving and maintaining landscape resilience. In cases where fire is not a primary process in maintaining an ecosystem (e.g., chaparral ecosystems; Syphard et al., 2019), fire-adapted communities are more focused on minimizing the impact of fire as a negative event (e.g., Baker, 2017). Fire-adapted Communities has two Elements: *hazard,* and *preparedness* (Table 2). Fire-adapted communities are characterized by a reduced level of hazard associated with wildfire and smoke, high awareness and support for reducing vulnerability to fire (e.g., defensible space, fire resistant building materials), and well-developed and disseminated community plans to follow in the event of a fire (Stein et al., 2013). For example, Community Fire Safe Councils are an increasingly utilized approach to bring communities together to increase community adaptation to living with fire (Everett and Fuller, 2011). The desired outcome for the Fire-adapted Communities Pillar is, "Communities have adapted to live safely in forested landscapes and understand the significance of fire to maintaining healthy forests. They have sufficient capacity to manage desired fire and suppress unwanted fire."

The Economic Diversity Pillar represents the financial, industrial, and workforce capacities of a region to support, respond to, invest in, and benefit from natural resource-based needs and opportunities, as well as the flexibility, stability, and diversity of resource-based and resource-influenced economies in associated rural and urban communities (Ashton and Pickens, 1995). Economic Diversity has four broad Elements: *wood product industry*, *recreation industry*, *water industry*, and *overall economic health* (Table 2). They reflect the array of industry sectors that are likely to be directly affected by resource management within and across large landscapes with substantial extents of natural lands, as well as place-based community economics that are affected by these industries. More local, within-landscape outcomes and direct linkages from external factors to the landscape of interest are the primary focus, as opposed to wide ranging ripple effects that externalities could affect or be affected by outcomes in a given landscape. For particular applications, users could add or exchange one or more elements that better address the most relevant economic drivers and effects. The desired outcome for the Economic Diversity Pillar is, "Forest management and outdoor activities support a sustainable, natural-resource-based economy, particularly in rural communities."

The Social and Cultural Wellbeing Pillar spans a broad spectrum of societal benefits focused on the connection between landscapes and quality-of-life attributes, as well as the ability of communities to productively reconcile a diversity of goals and objectives. Elements of the Social and Cultural Wellbeing Pillar include *public health* (including safety), *engagement* (across multiple governments, levels of government, communities, and issues of importance), *recreation*

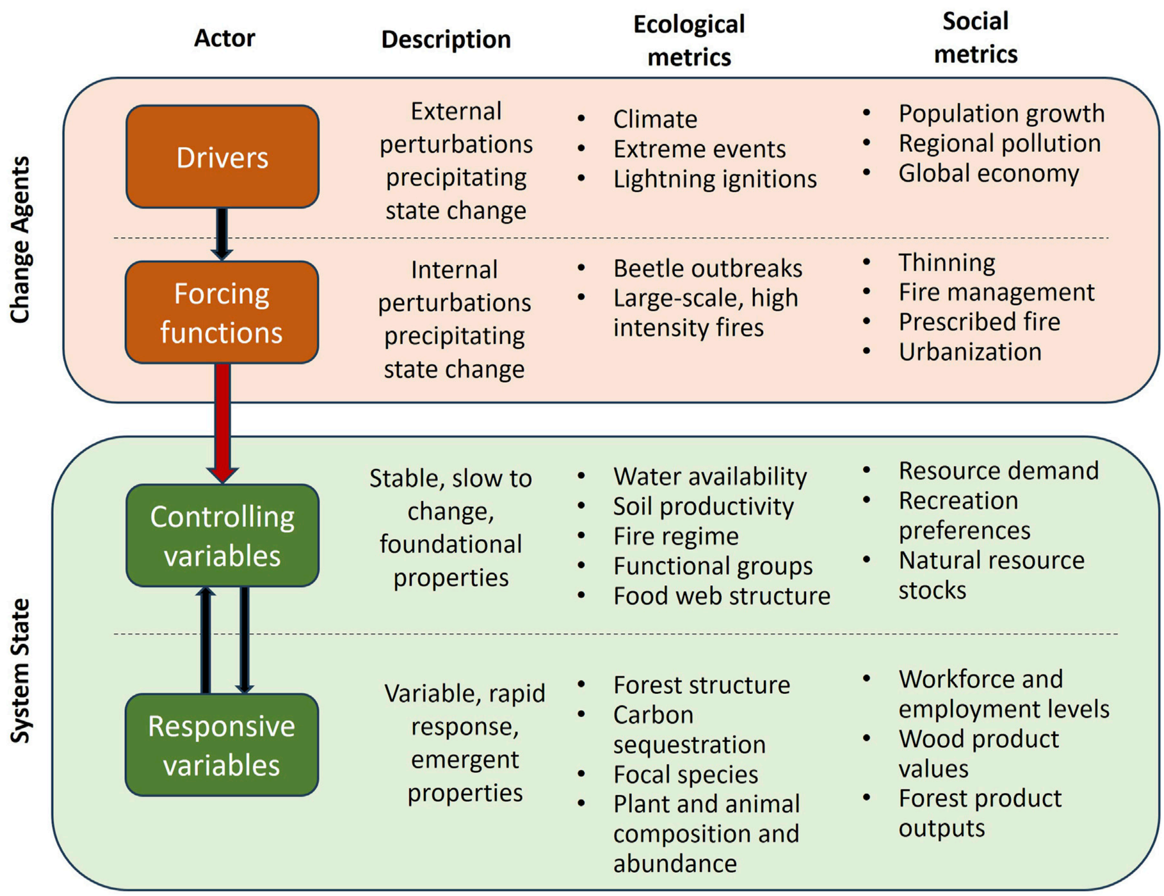

FIGURE 2
Change agents and system state interactions as they pertain to socio-ecological ecosystem resilience, with example ecological and social metrics.

quality, and *equitable opportunity* (including environmental justice) (Table 2). The desired outcome for the Social and Cultural Wellbeing Pillar is, "The landscape provides a place for people to connect with nature, to recreate, to maintain and improve their overall health, and to contribute to environmental stewardship, and is a critical component of their identity."

3.2 Guideposts for metric selection

The selection of metrics is entirely the prerogative of the user and what is best suited to their application. A large body of literature is dedicated to the subject of environmental indicators and their selection (Heink and Kowarik, 2010), which certainly is relevant to selecting metrics to populate the Framework. A broad range of criteria can be applied to the selection of metrics ranging from scientific rigor to cost effectiveness (Czucz et al., 2020). For the purpose of addressing socio-ecological resilience, we suggest focusing on metrics that are strong and reliable reflections of ecosystem conditions, processes, and functions.

The inclusion of metrics from multiple types of response variables is likely to strengthen the representation of a given Element or Pillar in terms of the pace and character of change over time and improve our understanding of complex system dynamics. Change agents and the conditions they affect, to the degree they are understood, are foundational for orchestrating effective management and tracking change (Carpenter et al., 2001), and as such make strong candidates as metrics of resilience (Figure 2). Two types of change agents are commonly recognized in systems ecology: 1) controlling or slow variables; and 2) responsive or fast variables (Carpenter et al., 2001; Walker et al., 2012; Morelli et al., 2020; Figure 2). Controlling variables have a major influence on system conditions, are relatively stable through time (meaning they are generally "slow" to change), and typically consist of foundational processes and properties, such as site productivity, fire regimes, and human population demands for resources (sensu Walker, 1992; 1995). Modification of controlling variables has significant effects on ecosystem dynamics, specifically on a system's vulnerability to a significant state change (i.e., lack of resilience). Responsive variables, alternatively, tend to be the more tangible and variable system conditions, such as vegetation structure, populations of individual species, annual fire cycles, management costs, and market valuation. Both stabilizing (negative) and amplifying (positive) feedbacks among state variables affect the magnitude of system responses to change agents (Chapin et al., 1996).

Resilience dynamics are contingent upon interactions between biotic and abiotic processes operating across a range of scales

(Angeler et al., 2011). To the degree possible, the suites of metrics selected to represent each Element and Pillar reflect interacting parts of the system, to refine our understanding of ecosystem interdependencies (direction of change) and vulnerabilities (early warning). For example, the response of a given forested area to a disturbance event (e.g., fire, beetle outbreak) reflects the interaction of three environmental factors: the environmental context set by external drivers (e.g., climate), the inherent site capacity to absorb disturbance (determined by physiographic features such as topography, aspect, slope, soil type), and the condition of controlling (e.g., water availability, natural resource stocks) and responsive (e.g., species composition, forest structure, resource market value) variables (e.g., Walker et al., 2012; Figure 2). The strongest responses occur when an external driver modifies an important controlling variable, in an area that has limited site capacity, which in turn influences numerous fast variables, and may amplify forcing functions, such as a beetle outbreak. For example, reduced snowfall (Klos et al., 2014) impacts water availability, particularly in shallow montane soils, which in turn can increase drought stress on mature trees, leaving them more vulnerable to bark beetle-related mortality (Bentz et al., 2010) and increased risk of high-intensity fire (e.g., Stephens et al., 2022). Including metrics from a range of change agents and responses operating within system dynamics helps build a strong foundation of understanding of interactions among change agents, processes and ecosystem responses to provide the critical underpinning informing desirable outcomes and how management investments are most likely to improve future resilience.

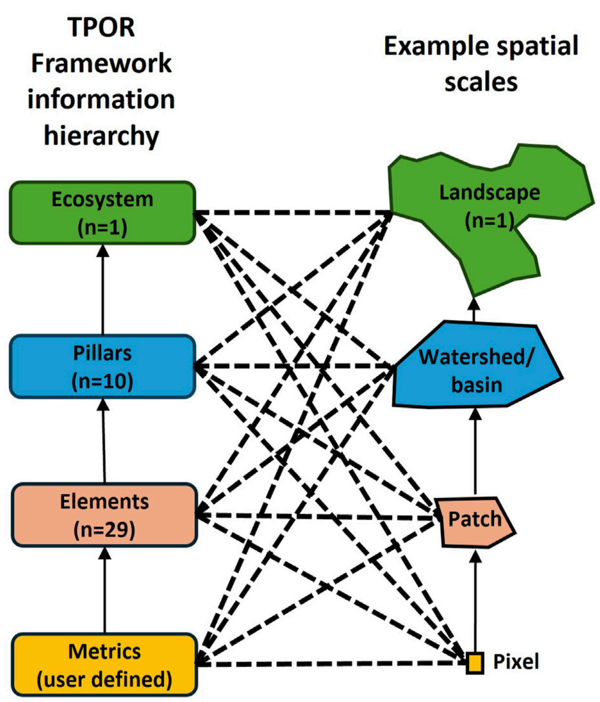

FIGURE 3
Options for summarizing and evaluating conditions across landscapes based on the interplay of spatial scale and the four-level information hierarchy of the TPOR Framework.

3.3 Putting the framework to work: Interpreting resilience

To make inferences about resilience at different scales and provide a measure of progress toward resilience over time requires the translation of metric values (e.g., trees per hectare, smoke emissions in parts per million, biomass tons per hectare) into a normalized range of values that also represents an interpretation of conditions (1.0, most favorable; 0.0 least favorable) (e.g., Enea and Salemi, 2001; Wu et al., 2024). The end product is more precisely a 'translation' of a metric value into a representation of anticipated resilience, with 1.0 being the most resilient (Manley et al., 2023; Povak et al., 2024). Often, fuzzy logic is used in the translation step where the raw data are evaluated against one or more benchmark or target values above/below which conditions are considered more/less favorable depending on the form of the logic function (Reynolds et al., 2014). For example, large tree density needs to meet or exceed a threshold in order to support their associated functions in old forest ecosystems (e.g., Jones et al., 2017). The threshold commonly varies depending on the forest type and site productivity, thus the interpretation of favorable and unfavorable values would be site specific. For a highly productive mixed conifer forest, 0 large trees per ha could be considered least favorable (0.0) and >5 large trees per ha could be considered most favorable (1.0), with a linear increase in values from 0.0 to 1.0 for the intervening range of tree densities. In other forest types, the threshold density for most favorable could be higher or lower.

Interpreting conditions as desired or favorable is a necessary component of all environmental assessments (e.g., Feld et al., 2010). The determination of what is considered favorable or desired can be informed by a variety of relevant contexts and data sources (e.g., percentiles of current ranges, historical ranges, modeled future ranges, empirically observed or derived thresholds), as can be the character of the transition between the two end points (e.g., linear, curvilinear, stepped; Manley et al., 2023). Translation makes it possible to address and coevaluate a range of resilience objectives from metric-specific outcomes to overall ecosystem resilience outcomes, which in turn supports management needs to address specific near-term needs (e.g., reduce risk of fire to communities–a metric pertaining to the Fire-adapted Communities Pillar) while working toward broader, long-term outcomes (e.g., enhanced ecosystem resilience based on conditions across all Pillars; Manley et al., 2023).

Ideally, each Element is represented by multiple metrics, which serves to capture the breadth and complexity associated with each Element and Pillar. Translated values for each metric can be combined in a variety of ways to represent conditions at higher order levels (Element, Pillar, ecosystem) of the Framework, as well as a range of spatial scales (Figure 3). Summarizing multiple metrics to generate an overall representation of a place or feature on landscapes is not a new challenge, and a large body of literature exists from the field of environmental monitoring on mechanisms for accomplishing summary statistics (e.g., Rooney and Bayley, 2010). A straightforward approach to represent multiple metric conditions as favorable or unfavorable may entail averages or the minimum or maximum value, based on how best to represent the suite of metrics. More complex approaches may include multivariate representations (e.g., Riitters et al., 1995; Wu et al., 2024), optimized weighting (Rooney and Bayley, 2010), or AI-based approaches (Chisom et al., 2024).

Using the Framework, one can interplay the levels of organization in the Framework with spatial scales within and among landscapes to address the needs of a myriad of applications (Figure 3). For example, conditions at each level of the Framework hierarchy (metric, Element, Pillar, and ecosystem) may be characterized at the pixel (smallest unit) scale first, and then conditions of each level of the hierarchy summarized across successively larger spatial scales (e.g., pixel to patch to watershed to landscape). This approach provides insights into the degree to which favorable Pillar outcomes are spatially compatible among Pillars. For example, fire dynamics and carbon sequestration may not be highly compatible given that higher carbon levels can include above ground dead woody biomass, which fuels higher impact fires. Alternatively, it may be more useful for some applications to summarize individual metrics at successively larger spatial scales, and then generate multiple metric representations at each spatial scale. This approach provides insights into the spatial heterogeneity and distribution of favorable and unfavorable metric conditions, which in turn can inform the spatial configuration of management investments. Achieving favorable conditions across all Pillars everywhere is not a realistic expectation or objective, given that favorable conditions in one Pillar (e.g., carbon sequestration) may commonly conflict with favorable conditions in another Pillar (e.g., fire dynamics) at the pixel or patch scale. Setting targets for desired and resilient landscape outcomes is an important step in landscape management that requires careful consideration of how to define and achieve a dynamic balance of favorable conditions across Pillars, spatial scales, and time (Mori, 2011).

A simplified example of metric translation and multiple pillar representations of current conditions at Pillar and ecosystem levels of the informational hierarchy of the TPOR Framework is provided in Box 1. The example portrays the Tahoe Central Sierra Initiative (TCSI) Landscape is sufficiently large to encompass a wide array of socio-ecological conditions and interactions, and concomitantly decision support tools have an important role in capturing and representing the complexity and its associated contributions to resilience. The translation of a single metric, total carbon, to a condition score (ranging from 0.0 to 1.0) is illustrated as a function of the range of observed values across the TCSI landscape and a simple fuzzy logic ramp from zero carbon (score of 0.0) to the ≥90th percentile of the maximum value in the current landscape (score of 1.0). Condition scores for three Pillars - Carbon Sequestration, Forest Resilience, and Water Security - are then averaged to generate an ecosystem-level representation based on the three Pillars. The ecosystem-level representation reflects the spatial alignment of favorable conditions for Forest Resilience and Water Security along the eastern flank of the landscape, and illustrates the opposing spatial distribution of favorable conditions for carbon, which becomes less apparent in the ecosystem representation.

3.4 Case studies of framework applications in policy and planning

The Framework is intended to provide a flexible system to support a wide range of management applications across a diversity of landscape characteristics and dynamics. Management applications directed at resilient outcomes commonly seek to address four basic questions about a given landscape: 1) What conditions are possible (capacity) and most likely to confer resilience?; 2) How well do current conditions reflect resilient conditions?; 3) Where is management most likely to be effective in affecting desired conditions and outcomes across the landscape?; and 4) How effective were management actions in contributing to or achieving desired outcomes? The TPOR Framework already has been used as the foundation for multiple research studies to evaluate outcomes resulting from various management options and future climates by providing inputs to and interpreting outputs from dynamic models (e.g., LANDIS-II, Scheller et al., 2007), optimization models (e.g., ForSys, Ager et al., 2021; Manley et al., 2025), climate analog models (Povak and Manley, 2024), and the development of decision support tools (e.g., PROMOTe, Povak et al., 2024) across California and the western U.S. Here, we provide four example applications of the TPOR Framework for socio-ecological resilience that structure evaluations, facilitate accountability, inform policy, and enable and expedite the ability of managers and collaboratives to conduct assessment and planning across socio-ecological considerations and take future climate vulnerabilities and constraints into account.

3.4.1 Tahoe Central Sierra Initiative action plan

The TPOR Framework was adopted by the TCSI partnership in 2020 (tahoecentralsierra.org/use-the-tools) and used as a foundational feature of their roadmap for management (Blueprint, Manley et al., 2023) and culminating in a 10-year action plan. The Blueprint for TCSI resilience was based on 15 metric data layers representing five of the 10 Pillars in the Framework (Manley et al., 2023). The metric raw values were first interpreted and then translated to represent favorable (1.0) to unfavorable (0.0) conditions based on published literature on ecological integrity and system resilience associated with each metric and element, and represented using fuzzy logic principles (Reynolds and Hessburg, 2014; Reynolds et al., 2014). They then evaluated and mapped current conditions, as well as the climate-informed potential to reach and/or maintain favorable conditions into the future using the PROMOTe model (Povak et al., 2024). Mapped representations of Metric, Element, Pillar and overall ecosystem conditions were evaluated to inform the development of a 10-year regional plan (2023–2033) for the TCSI landscape. The existence of the TPOR Framework and associated Blueprint enabled the rapid development of a 10-year plan with management targets and expedited investments towards its two main goals common to many large landscape management efforts: 1) restore and maintain social and ecological resilience; and 2) build institutional capacity to restore resilience (https://www.tahoecentralsierra.org/wp-content/uploads/2023/09/1.-TCSI-10-Year-Regional-Plan.pdf). It was subsequently applied in multiple landscape planning projects within the TCSI landscape to inform the pace and location of treatments to accomplish near-term and long-term management objectives across multiple Pillars (e.g., Manley et al., 2025).

3.4.2 California's Wildfire and Forest Resilience Action Plan

In 2018, the Governor of California created the Wildfire and Forest Resilience Task Force (Task Force; wildfiretaskforce.org/about) to confront the threat of large-scale, high intensity wildfires and the additional impacts of changing climates across forest-dominated landscapes across the State. For 2 years, the Task Force convened dozens of interagency and stakeholder-led

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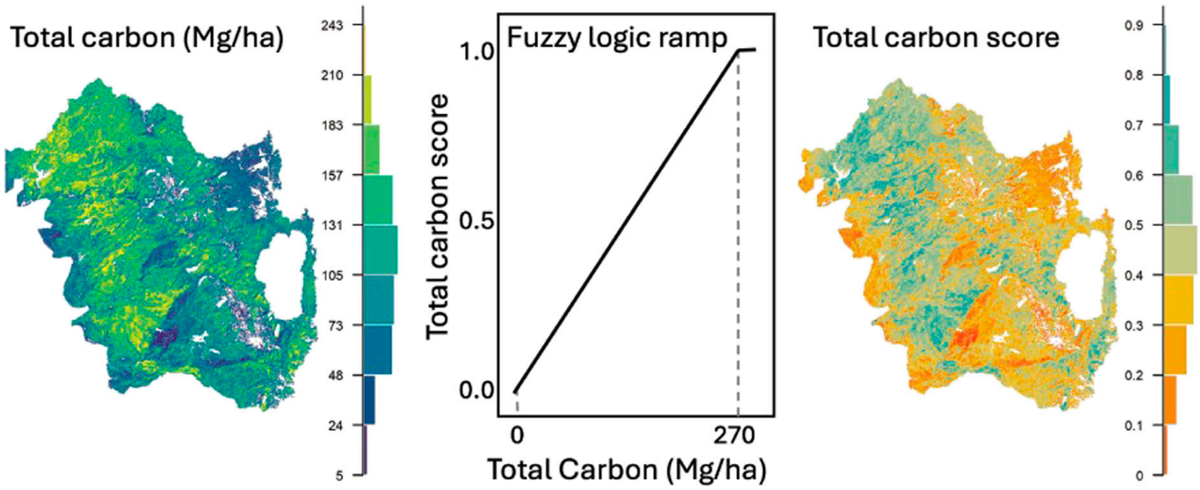
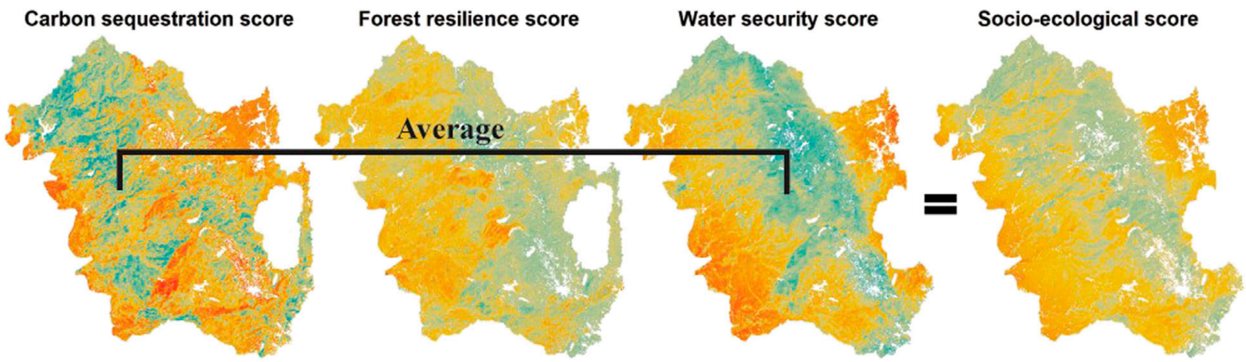
BOX 1 Example application of the TPOR Framework to the Tahoe Central Sierra Initiative (TCSI) landscape.

1. Members of the TCSI partnership convened with federal and university scientists to develop a landscape resilience roadmap for planners and managers in their 1-million-hectare landscape located in the central Sierras of California.
2. A set of metrics for each of three Pillars (forest resilience, carbon sequestration, water security) were selected based on the best available data relevant to socio-ecological resilience and available across the entire landscape (remotely sensed data and modeling results), identified and developed with engagement of the partnership.
3. Each metric was then evaluated using fuzzy logic methods to translate raster values of resource condition to condition scores ranging from 0 (unfavorable condition) to 1 (favorable) using a fuzzy logic ramp. In the example below, the distribution of total aboveground carbon is depicted in the left pane with low carbon stocks in dark blue and high stocks in yellow. The statistical distribution of condition values was evaluated to determine the upper and lower bounds of the fuzzy logic ramp (middle panel) for the condition score, where C Mg/ha of carbon was considered unfavorable, and 270 Mg/ha was considered favorable based on the distribu-tion of the majority of values (90th percentile). The right panel shows the distribution of resource condition scores with red indicating unfavorable and blue indicating favorable conditions.



4. This process was repeated for all metrics, ranging from one to four metrics per pillar. Pillar-level scores were derived through an optimized weighted averaging of metric scores. From the Pillar-level scores, a final socio-ecological score was developed by averaging scores across the Pillars (figure below). Multiple options exist for summarizing across multiple metrics and Pillars to develop composite representations of condition scores.
5. The interim and final results of resource condition values and scores can be brought into decision support tools, some of which are available through fully-functional online decision support platforms (e.g., Plan-scape.org) where users have access to raw and scored condition maps, and can then apply raw or interpreted data products to assessment and planning for management.



workshops to inform and populate an action plan (sensu Biggs et al., 2012; Folke et al., 2016). The Task Force produced the Wildfire and Forest Resilience Action Plan (California Department of Natural Resources, 2021; wildfiretaskforce.org/action-plan) that articulated four specific goals: 1) increase the pace and scale of forest health projects; 2) strengthen protection of communities; 3) management forests to achieve the State's economic and environmental goals; and 4) drive innovation and measure progress. Goal 4 specifically recognized the importance of having a strong scientific foundation for monitoring, reporting, and decision support tools, including adopting the POR Framework for socio-ecological resilience. The TPOR Framework pillars served as the backbone for assessing condition and progress across environmental, social and economic goals of the Action Plan.

Following the release of California's Wildfire and Forest Resilience Action Plan, the Task Force invested in developing metric data layers for each of the 10 Pillars across the 13-million hectares of forested ecosystems and four forest-dominated ecoregions (Sierra Nevada, Southern California. Central Coast, and Northern California) in the state of California (wildfiretaskforce.org/regional-resource-kits-page; Andreozzi et al., 2022; Andreozzi et al., 2023a; Andreozzi et al., 2023b; Andreozzi et al., 2023c). Each region's Resource Kit housed 80 to 100 metrics across the 10 Pillars, selected by *insitu* regional technical experts, and the data were freely available for anyone to access and download from public websites, including data dictionaries) that described their source data, derivation, and suggested interpretations of favorable and unfavorable benchmark values (Clark et al., 2023a; Clark et al., 2023b; Clark et al., 2023c; Young-Hart et al., 2023). The Framework definition and structure (i.e., Pillar outcomes and elements) provided a consistent and available construct, terminology, and interpretation of metrics across the expansive and highly diverse state of California, resulting in the intended effect of supporting and expediting planning efforts across the state (e.g., Upper Mokelumne River Watershed Authority forest project planning; umrwa.org/forest-program assessment), and providing a stable foundation for reporting progress over time toward improved conditions (e.g., Eitzel et al., 2024).

3.4.3 Outcome condition metrics for public lands

The U.S. Forest Service has a long history of measuring performance in the form of *outputs* (e.g., area treated, timber harvested), but more recently the agency has expanded its representation of land management accomplishments to include ecological, social, and cultural *outcomes* in recognition that the positive impact of work does not necessarily correspond to area treated or products produced. In response to the wildfire crisis facing landscapes across the western U.S. (U.S. Forest Service, 2025), the U.S. Forest Service applied outcome-based condition metrics that reflected the TPOR pillars across nearly 20-million hectares of lands across the western US at high risk of wildfire impacts to provide an assessment of positive management benefits to ecosystem resilience across large landscapes. They are also intended to help the U.S. Forest Service and its partners document progress being made toward shared goals. The ability to demonstrate accountability and progress toward desired outcomes are core to collaborative forestry, successful trust building, and effective partnerships (e.g., Stern and Coleman, 2015; Davis et al., 2017; Butler and Schultz, 2019).

3.4.4 Planscape planning and assessment tool

Managing for socio-ecological resilience by definition requires managers to assess current conditions and the ability of areas to achieve and maintain favorable conditions into the future, with climate being a primary uncertainty and driver of change (Adger and Hodbod, 2014; Seidl et al., 2016). Arriving at climate-informed management strategies for socio-ecological resilience requires the ability to generate three products: 1) a spatially and temporally specific representation of current conditions; 2) a representation of projected future climate and resource specific (Metric, Element, or Pillar) responses to climate change; and 3) potential impacts and benefits that could result from management actions.

Planscape is a wildfire resilience planning support and collaboration tool designed to support any user to plan and prioritize management treatments by leveraging the latest data and climate models (Planscape.org). It is an open-source, web-based software tool that was initially developed through a collaboration between the state of California and Google.org, with more recent investments including a collaboration between Spatial Informatics Group and the U.S. Forest Service. The geographic scope of Planscape is currently the continental United States.

Spatial data in Planscape can be organized by the TPOR Framework, and planners can then leverage these data to evaluate current and potential future conditions (e.g., resource vulnerability to future climate based on the PROMOTe model; Povak et al., 2024) and use them to prioritize or optimize management investments (https://www.planscape.org/documentation/user-guide). The Planscape application using the TPOR pillars can be scaled geographically to meet needs across a wide user-base, thereby contributing to the goal of increasing the pace and scale of informed and effective management (e.g., ForSys; Ager et al., 2021).

An example of how Planscape uses the Framework to generate climate-informed representation of conditions to inform management investments is depicted in Figure 4. Multiple representations are illustrated. Current conditions for the Mosquito Creek drainage (8134 ha) of the North Fork Feather River in the northern Sierra Nevada, California are depicted for two different Elements (Focal Species and Species Diversity) of the Biodiversity Conservation Pillar, each based on the average condition of a set of composite metrics. The condition scores at each level range from favorable (blue) to unfavorable (red) with regard to resilience based on primary disturbances expected to occur in the landscape (Figure 4). The Focal Species (Element 1) is in a neutral to favorable condition across most of the landscape, whereas Species Diversity (Element 2) is generally in a neutral to unfavorable condition. These two Elements are then combined (e.g., averaged) to represent current conditions (i.e., species-level representations of biodiversity) at the Pillar level, indicating that much of the landscape is in less than favorable condition at this upper level of the Framework hierarchy. Future climate impacts then can be introduced into the evaluation, combining the condition scores of current and anticipated future potential to generate climate-informed management strategies, with Figure 4 depicting the four PROMOTe strategies (monitor, protect, adapt, and transform; see Povak and Manley, 2024).

4 Discussion

4.1 The value of operational frameworks

Framework systems are broadly popular, but practitioners are still left with the task of identifying ecosystem components of interest, and then how to structure and interpret information about those components to then move through the process or concept framework. The TPOR Framework comports with contextual factors of Ostrom's (2009), Ostrom's (2011) foundational institutional analysis and development (IAD) framework, as well as more recent strategic approaches to framing and climate-adapted resilience strategies for land management (e.g., RAD, Shuurman et al., 2022). The TPOR Framework goes a step further than most socio-ecological frameworks in being operational as a quantitative tool in management applications, offering a discrete suite of socio-

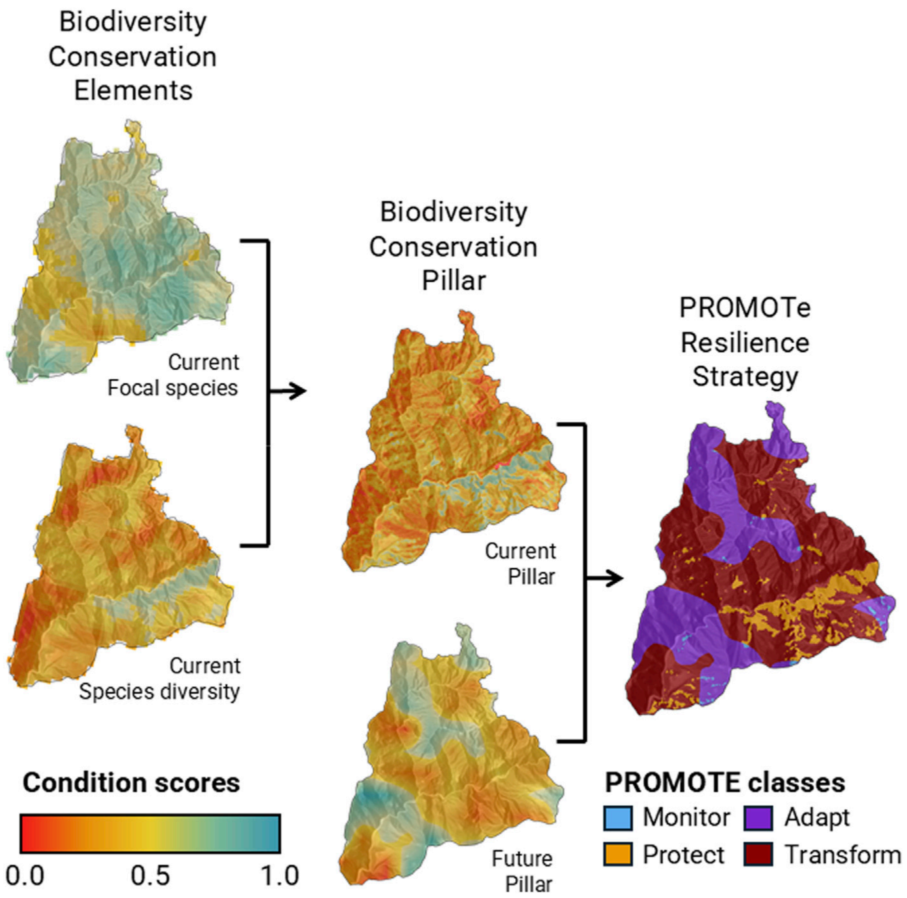


FIGURE 4
Graphical illustration of multiple metric representations of current and future conditions at Element and Pillar levels of the informational hierarchy of the Ten Pillars of Socio-ecological Resilience Framework for the Mosquito Creek drainage of the North Fork of the Feather River in the northern Sierra Nevada, California. Two elements of current condition for the Biodiversity Conservation Pillar are summarized up to the Pillar level, and then combined with a Pillar-level future climate condition representation to derive one of the four, spatially explicit climate-informed PROMOTe management strategies for each pixel (Povak and Manley, 2024; Povak et al., 2024).

ecological topic areas (Pillars), each with a high-level resilient outcome description, and a set of specific components (Elements) that are characterized by relevant user-selected metrics. The TPOR Framework can be used to conduct assessments at a point in time (status), from the past to the present (retrospective change), and from the past or present to the future (prospective analysis, anticipatory). Therefore, it provides a mechanism for quantifying conditions within a socio-ecological context and informing future management investments and expectations (Cole et al., 2019).

The TPOR Framework, combined with climate-informed strategy-based systems like PROMOTe (Povak et al., 2024), provides users with support functions that span planning processes (e.g., scaled down from programmatic to project specific and/or serial planning over time) and measuring progress over time, creating positive feedback among investment needs, actions, accomplishments, and policies. The TPOR Framework can be employed to inform and expedite management investments toward greater resilience in four important ways: 1) *pace* - large landscape efforts can move right to goal setting for desired conditions associated with each of the Pillars, as opposed to wrestling with the concept of resilience and how to represent it; 2) *scale* – *large* landscapes with complex socio-ecological facets can use these constructs for establishing a shared vision, including spatially explicit data and climate-informed management strategies, that expedite project design and implementation; 3) *impact* - large-landscape planning efforts with spatially explicit management strategies and the ability to evaluate the associated ecosystem services through Pillar conditions will result in more effective investments in the near term that are more likely to yield resilience dividends over time; and 4) *monitoring and accountability* – the push to increase the pace and scale of management requires social and financial capital, which in turn demands measures of success that are tangible and meaningful.

4.2 Tackling the resilience imperative in a changing climate

Declaring resilience as the ultimate management objective for landscapes sets a high bar, and one that a changing climate is making even more challenging (e.g., Ummenhofer and Meehl, 2017). Given that resilience is an emergent system property, the effectiveness of management investments toward the goal of greater resilience can only be confirmed retrospectively; and even proven strategies do not guarantee protection against high-impact disturbances (e.g., Maxwell et al., 2022). Scientists, managers, and policymakers are compelled to push for a greater understanding of what future climate and disturbance dynamics hold in store, what constitutions and configurations of landscape conditions will be resilient to them, and how management investments can be most effective in enhancing resilience.

Managers, policymakers, and other interest-holders are being challenged to evaluate options and operate across increasingly large landscapes that convey substantial ecological, social, cultural, and economic consequences based on uncertainty about potential management outcomes that may take decades or even centuries to unfold. Climate is increasingly impacting all aspects of socio-ecological systems, and capturing the complexity of these systems to improve our understanding of their capacity to achieve and maintain resilient conditions will be crucial for their stewardship (Nelson, 2011). Land management needs to match the spatial and temporal scales at which climate impacts are emerging to yield effective resource outcomes. At broad scales (e.g., ecoregion, state, country, continent), climate change is transforming ecological and social systems (Linnér and Wibeck, 2021), precipitating the need to "rewire" how we approach problems and envision feasible and sustainable outcomes (West et al., 2020; Davelaar, 2021; Horcea-Milcu, 2022). These circumstances call for holistic, transformational adaptative approaches (Kates et al., 2012) that encompass the diversity, complexity, and interconnectedness of socio-ecological systems across landscapes and over time (Gunderson and Holling, 2002), as opposed to historical land management approaches that were more singular in their objectives (e.g., timber volume) and narrow in their spatio-temporal evaluations (e.g., near-term site-based effects analysis). As such, current circumstances call for wholesale reconsideration of the scientific and conceptual foundations of land management toward a sustainable and resilient future.

The TPOR Framework provides a conceptual structure that is designed to carry the complexity of dynamic socio-ecological systems through assessment, planning and decision-making processes. The TPOR Framework also provides an operational tool to address the deepening complex global challenge: a) socio-ecological systems are highly interdependent, b) a changing climate is precipitating impactful environmental change across the globe, and putting vital ecosystem services in peril, and c) human systems, behaviors, and investments are now essential to meeting the global resilience challenge. The TPOR Framework has already demonstrated effectiveness and enabled users to address greater complexity and facilitate movement toward investing in climate-informed strategic management approaches. We acknowledge that it is not possible (or even desirable) to represent all facets of the complexity of ecosystems, and certainly the 10 Pillars of the Framework are not a panacea for addressing complex system dynamics, uncertainties and tradeoffs. Rather, the Framework is offered as a scalable tool and vessel for representing and evaluating the Pillars and their components that are most relevant to a particular application using a construct that can serve any user at any scale, making it readily integrated into decision support tools and across diverse applications.

4.3 Decision support now integral to land management

Tools like the TPOR Framework and applicable decision support models such as Planscape (planscape.org), are increasingly necessary to help scientists, managers, and policymakers retain and account for the complexity of socio-ecological systems and the uncertainty of climate impacts at multiple scales in planning management activities (e.g., Liu et al., 2007; Long et al., 2014). Advances in remotely sensed data have greatly improved the ability to characterize forest ecosystem conditions across landscapes, including extant conditions (Gonzalez et al., 2010), historical reference conditions (e.g., Balaguer et al., 2014; Seidl et al., 2016; Lydersen and Collins, 2018; North et al., 2022), contemporary reference conditions (e.g., Jeronimo et al., 2019; Rudge et al., 2022), and future climate-informed projections (e.g., Pierce et al., 2016; Shackelford et al., 2021). Significant progress has also been made in understanding the relationships among fire, forest structure, drought tolerance as primary disturbances in forest ecosystems, and their effect on ecosystem resilience (e.g., Schmidt et al., 2008; North et al., 2009; Lydersen and North, 2012) and sustainability (e.g., Franco-Gaviria et al., 2022). Thus, information on the composition, structure and function of landscapes is greater and more available than ever, but so is the challenge of integrating the complex information into scientifically robust representations of resilience that are informative, actionable, and trackable over time.

Multiple-outcome evaluation tools can be used to help managers understand options for achieving multiple desired outcomes across a landscape and the socio-ecological systems it supports. In fact, analytic tools are becoming an essential component of understanding (or at least representing) interdependencies, evaluating multiple costs, benefits, and risks (e.g., Uhde et al., 2015). A growing number of decision support and planning tools (e.g., Reynolds et al., 2014; Ager et al., 2021) can evaluate the relative performance of management scenarios across multiple desired outcomes (i.e., Pillars). For example, multi-criterion decision making (MCDM) is a hierarchical structured decision process that enables users to set relative priorities to individual metrics and then summarize outcomes across multiple metrics to express higher order outcomes (Srdjevic et al., 2013; Reynolds et al., 2014; Marques et al., 2021; Krsnik et al., 2023; Reynolds et al., 2023). Such tools enable managers to retain the complexity in their assessment of management options, as opposed to over simplifying landscape dynamics to derive interpretations of outcomes. Thus, the complexity represented within and among Pillars in the Framework can be readily brought into the decision-making process to identify the most favorable combination of management actions to improve benefits across Pillars.

4.4 The Siren's song to optimize

The TPOR Framework provides a broad foundation on which to build a representation and interpretation of conservation, restoration, and management opportunities and benefits. The concepts of "risk reduction" and "tradeoffs" are commonly used to analyze options and portray costs and benefits associated with management options (e.g., Stern et al., 2014). Managers may naturally gravitate toward more traditional approaches of giving greater or even singular consideration to Pillars that are perceived to be at the greatest risk of degradation or loss (Table 1; e.g., Scott et al., 2013; Blennow et al., 2014). However, the integrated nature of socio-ecological systems indicates that management directed at overall system function is likely to have the greatest yields and reduction of overall risk in the long run (e.g., Berkes, 2017; Manley et al., 2025). Furthermore, socio-ecological systems have social, economic, and cultural tolerance thresholds (known and unknown) that will constrain the degree to which any given Pillar can be impacted to accomplish a singular or narrow set of desired outcomes.

Determining optimal outcomes can be a slippery slope, particularly if the scope of the expected outcome is narrow (e.g., reduced fire risk) and there is an expectation of profit or avoided economic loss to justify or compensate for investments. The interdependent nature of social and ecological systems (e.g., triple bottom line of people, planet, and profit; Ragazou et al., 2024) limits the degree to which any given Element or Pillar can be realistically prioritized or optimized above others. Economics can drive decisions toward less expensive treatment options (profit) that may have positive but lesser ecological benefits (planet), leaving more expensive but ecologically more beneficial treatments to accrue for some future investment that may not be feasible or justifiable. The triple bottom line concept is increasingly being applied to public land management investments, particularly as conservation finance programs become more prevalent as a means of bridging the gap between public sector funding and management needs (e.g., Seipp et al., 2023). In fact, it has been expanded in various applications to quadruple and quintuple bottom line approaches, adding “purpose” and “place” to people, planet, and profit (e.g., Panneels, 2023). However, in conservation applications, the equation is flipped, where a premium is put on ‘planet’ outcomes that can be sustainably supported through outcomes for the other two or four ‘legs of the stool’. Using the information hierarchy provided by the Framework, management investments can be quantified in terms of their impacts to one or more Metrics, Elements, and all 10 Pillars, and this information in turn can help optimize the return on investment by comparing financial and ecological outcomes across multiple management scenarios. In essence, the TPOR Framework enables and supports managers in addressing a comprehensive “ten-legged stool” upon which socio-ecological resilience rests. Optimization models such as ForSYS (Day et al., 2023) and Mixed Integer Programming (Pascual et al., 2022) can ingest data from the Framework to support such efforts and prioritize treatment allocations toward a comprehensive suite of outcomes.

5 Conclusion

The TPOR Framework serves to remind us that humans are part of a highly interdependent socio-ecological system, and as a result, the fate of any part of it affects every part of it. The concept of socio-ecological systems inherently drives conversations among managers, practitioners, and scientists toward the long view – the persistence of quality – and all the facets of these systems that need to be functional to achieve that end. The ability to connect past performance (retrospective evaluations), with current conditions and prospects for creating future conditions through informed management investments (prospective evaluations) provides an opportunity to realize the promise of adaptive management. Putting an essential emphasis on long-term outcomes helps to reduce the draw of short-term gains that may come at a long-term cost. Expanding the context for how society gauges the value of investments to include some measure of persistence of quality, and thereby resilience, is an integral step in the transformation from managing the present to managing for the future. The notion of persistence as a tangible measure of resilience hopefully serves to make decision-making processes less transactional, and more integrated, thoughtful, and humble.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: there are no data per se. It is a methods paper.

Author contributions

PM: Resources, Writing – review and editing, Conceptualization, Visualization, Methodology, Funding acquisition, Validation, Supervision, Project administration, Writing – original draft. NP: Formal Analysis, Writing – review and editing, Visualization. KW: Writing – review and editing, Conceptualization, Methodology.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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