Framing management of social-ecological systems in terms of the cost of failure: the Sierra Nevada, USA as a case study

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Abstract

Managing complex social-ecological systems in an era of rapid climate change and changing human pressures represents a major challenge in sustainability science. The Sierra Nevada, USA is a large social-ecological system facing a tipping point that could result in major ecosystem changes. A century of fire suppression and climate change have set the stage for mega-disturbances that threaten biodiversity, human life and values, ecosystem services, and forest persistence. Stakeholders face multidimensional and often contentious trade-offs with costs and benefits that can be mismatched in space and time. If compromises cannot be reached, the status quo is likely to continue, resulting in the conversion of large portions of a 100,000 km² predominately mixed-conifer forest ecosystem to a chaparral-dominated ecosystem. We describe the outcomes of a continuation of the ecological status quo on biodiversity, cultural history, fire management, recreational value, and climate control, including indirect effects on water and food security and recreation. The social-ecological ramifications of such a future are undesirable for most stakeholders. Therefore, we contend that forest management conflicts should be framed in terms of the cost of failure of negotiations among stakeholders. Specifically, negotiations may benefit from (1) stakeholders quantifying their definitions of success and failure, (2) quantification of trade-offs and recognition of their multidimensionality, and (3) allowing for solutions that are heterogeneous in space and time. This approach may help stakeholders navigate the wicked problem of managing Sierra Nevada forests and other complex social-ecological systems.

Sustainable use of natural resources is predicated on management that recognizes the fundamental interconnectedness of ‘human’ and ‘natural’ systems as a cohesive social-ecological system (Berkes and Folke 2000). Rapidly growing human populations have increased demand for a wide range of ecosystem services, so improving the sustainability of society’s use of these services has become a central goal in the management of social-ecological systems (Clark and Dickson 2003, Rodríguez et al 2006, Wu 2013). However, the difficulty of identifying salient ecosystem services and stakeholders (Rodríguez et al 2006), the role of climate change in altering ecosystem function (Mooney et al 2009), and the large spatial scale (Wu 2013) and complexity (Liu et al 2007) of many social-ecological systems complicate the already-difficult challenge of sustainable ecosystem management (Defries and Nagendra 2017).

One such system is the Sierra Nevada, a complex social-ecological landscape that includes ~100,000 km² of primarily forested mountains in the US state of California (SNC 2019). Sierra Nevada forests are home to >600,000 people as well as thousands of species of plants and wildlife, many of which are endemic to the region (Murphy and Stine 2004). Via its snowpack, the Sierra Nevada provides water for nationally important agricultural production and tens of millions of people in California (Klausmeyer and Fitzgerald 2012, SNC 2019). Sierra Nevada forests also provide timber resources, cultural and recreational value, and climate control via carbon storage, among other ecosystem services (Kelsey 2019). With the
Table 1. Qualitative comparison of current and future features of the Sierra Nevada social-ecological system.

| Feature                        | Current                                      | Future                                      | Status-quo                  | Desired/reference condition |
|--------------------------------|----------------------------------------------|----------------------------------------------|-----------------------------|------------------------------|
| Dominant ecosystem type        | Forest (mixed-conifer)                       | Grass/shrub or chaparral forestry            | Forest (mixed-conifer)      |                              |
| Vegetation structure           | High densities of smaller trees              | Low tree density, high shrub/grass density   | Lower overall tree densities, higher abundance of large, old trees       |
| Landscape diversity/heterogeneity | Low                                          | Low                                          | High                        |                              |
| Resilient (disturbance regime reinforces system properties) | No                                           | Yes                                          | Yes                         |                              |
| Carbon storage                 | High (but volatile)                          | Low                                          | High (and stable)           |                              |
| Net carbon flux                | Sink                                         | Source                                       | Sink                        |                              |
| Water resource provisioning    | High (but volatile)                          | Low                                          | High (and stable)           |                              |
| Timber resources               | High yield                                   | Low yield                                    | Moderate yield              |                              |
| Disturbances                   | Frequent, high-severity                      | Frequent, high-severity                      | Frequent, low-severity      |                              |
| Level of management            | High                                        | Low                                          | Low                         |                              |
| required to sustain system     |                                              |                                              |                              |                              |
| Recreational value             | High (but volatile)                          | Low to Moderate                              | High (and stable)           |                              |
| Biodiversity                   | High (but declining)                         | Low                                          | High (and stable)           |                              |
| Firefighting/suppression costs | High                                        | High                                         | Low                         |                              |
| Risks to humans associated with disturbances | High risk of fire-related death, air pollution associated with unpredictable smoke exposure | Some risk of fire-related death, air pollution associated with unpredictable smoke exposure | Some risk of fire-related death, more predictable and less intense smoke exposure | |

human population in California expected to grow by 25%-30% by 2040 (PPIC 2019), continued provisioning of ecosystem services and resources is a priority for public officials and land managers. Mismanagement of this social-ecological system therefore bears wide-reaching and potentially irreversible consequences for humans and nature.

Qualitative projection of the Sierra Nevada ecological status quo and its consequences

There has been increasing recognition in the scientific literature that Sierra Nevada forests likely face a tipping point (e.g. Hessburg et al 2016, Stephens et al 2018, Davis et al 2019, North et al 2019), defined as a 'situation where accelerating change caused by a positive feedback drives the system to a new state' (van Nes et al 2016). Accelerating changes in the Sierra Nevada include a rapidly warming and drying climate, increasingly large and severe forest fires, and megadroughts (Asner et al 2015, Diffenbaugh et al 2015, Abatzoglou and Williams 2016, Stephens et al 2018, Keyser and Westerling 2019). A century of fire suppression and land use legacies have increased tree densities and available fuels which, together with climate change, have contributed to the recent observed increase in mega-disturbances that threaten human life and values, biodiversity, and forest ecosystem persistence (McIntyre et al 2015, Hessburg et al 2016). Because Sierra Nevada forest ecosystems are adapted to a frequent, low-severity disturbance regime, uncharacteristically large and severe disturbances can lead to failed forest regeneration and ecosystem type conversion (Stevens et al 2017, Rissman et al 2018, Shive et al 2018, Young et al 2019). Over the next several decades, a continuation of this altered disturbance regime could result in the conversion of mixed-conifer forest to a chaparral-dominated ecosystem (table 1).

Such a scenario is a possible and perhaps even likely outcome of a continuation of the status quo in the Sierra Nevada (Stephens et al 2018), which would likely impair the provisioning of ecosystem services required to sustain the region’s existing and projected human population. Below we detail the potential consequences of ecosystem type conversion (from forests to a chaparral-dominated ecosystem) in the Sierra Nevada on (i) biodiversity, (ii) cultural history, (iii) fire and smoke management, (iv) recreational value, and (v) climate control, which could trigger further indirect effects on water and food security and recreation.

Biodiversity

Extensive decline of Sierra Nevada forests would raise the possibility of widespread extinction events. The California Floristic Province is a global biodiversity hotspot (Myers et al 2000), and Sierra Nevada forests are a hotspot of plant endemism within that region (Thorne et al 2009). Loss of forest cover is expected to exacerbate the existing threat of climate change to those species (Loarie et al 2008). Iconic species like the
giant sequoia (*Sequoiadendron giganteum*) as well as focal forest species of conservation concern that depend on large, old trees like the California spotted owl (*Strix occidentalis occidentalis*) and Pacific fisher (*Pekania pennanti*) would be threatened from forest loss/conversion (Scheller et al. 2011, Jones et al. 2018, Rissman et al. 2018), as would hundreds of other less prominent species, particularly plants (Thorne et al. 2009). Indeed, species from spotted owls to epiphytic lichens are already experiencing long-term declines, trends which are expected to continue if large, severe fires continue increasing in prevalence (Jones et al. 2016, Miller et al. 2018). Of course, some species may be expected to benefit from a loss of green forests and increased prevalence of early-seral and chaparral communities in the Sierra Nevada (Swanson et al. 2011). However, even species considered highly adapted to early-seral conditions associated with recent severe fire, such as the black-backed woodpecker (*Picoides arcticus*), have responded negatively to the extensive patches of severe fire (White et al. 2019, Stillman et al. 2019a, 2019b) that are becoming more common in the region (Stevens et al. 2017).

**Cultural history**

The transformation of the Sierra Nevada forest ecosystem would result in the loss of cultural ecosystem services and sociocultural history. Drastic ecological changes could be detrimental to indigenous communities whose intimate relationships with the Sierra Nevada ecosystem date back at least 11,000 years (Safford and Stevens 2017). The Sierra Nevada also imbues the works of iconic American artists John Muir, Ansel Adams, and Gary Snyder, and has influenced many others. Even substantial change short of total ecological transformation would be sufficient to radically change the human experience of the Sierra Nevada. Just as we are left with Muir’s words and Albert Bierstadt’s sketches as an elegy to the Hetch Hetchy Valley, we could eventually be left with mere memories of the Sierra Nevada humankind has known for many millennia.

**Fire and smoke management**

Large, severe fires are increasing in the Sierra Nevada as a result of climate change and fuel accumulation due to fire suppression, and are projected to continue increasing (Liu et al. 2013, Stephens et al. 2013, Westerling 2016, 2018, Jones 2019). Increased severe fire extent potentially threatens the estimated $140 million of timber value in the Sierra Nevada (USDA 2019) and the financial viability of institutions tasked with responding to fire. The USDA Forest Service (USFS) now spends over half its budget on fighting fires, increasingly at the expense of other programs (North et al. 2015, USDA 2015), including programs that seek to reduce fuels and prevent severe wildfires from occurring. In 2018, the California Department of Forestry and Fire Protection budgeted $434 million for fire suppression, but spent over $670 million, and private insurance claims exceeded $845 million (Shoot 2018). Continued increases in severe wildfire activity and continued growth of the wildland-urban interface will further increase firefighting costs. Large, severe fires also pose public health risks via air pollution. Smoke exposure from wildfire has been associated with increased asthma attacks (Reid et al. 2016), particularly in children (Delfino et al. 2009), as well as increased reporting of emergency room visits for cardiovascular events (Wettstein et al. 2018).

**Recreational value**

The recreational value of Sierra Nevada forests and alpine areas is exceptional, and is increasing. Yosemite is the country’s fifth-most visited national park, and annual visitation has exceeded 2 million since 1967, 3 million since 1987, and 4 million since 2015 (NPS 2018). Extreme wildfire events and sustained losses of iconic forest landscapes could affect forest recreation opportunities and their perceived recreational value. For example, the 2013 Rim Fire burned >100,000 ha, approximately 30% of which occurred within Yosemite National Park, converting some forested areas into invasive grasslands and shrub-dominated ecosystem types (Rissman et al. 2018). The cost of that fire in terms of lost recreation and tourism were estimated to be as high as $211 million (Batker et al. 2013). In late July 2018, during peak tourist season, Yosemite closed for two weeks during the ~39,000 ha Ferguson Fire with important impacts to the local tourism-dependent businesses (Branch et al. 2018, Hughes 2018). Furthermore, an accelerated decline in the snowpack resulting from climate change (see below) would jeopardize California’s $1.2 billion winter sports industry, threatening the economic viability of many mountain communities (Hagenstad et al. 2018).

**Climate control and cascading effects**

If current trends in forest loss due to wildfire and ongoing climate change continue, Sierra Nevada forests may become a carbon source and create a positive feedback with cascading effects (Liang et al. 2017a, 2017b). The Sierra Nevada will be influenced by climate change whether it is a carbon source or sink, but if it becomes a carbon source, the acceleration of climate change would have important regional ramifications. Loss of snowpack and forest cover would have wide-reaching agricultural and food security implications for California and the United States. It would threaten California’s $50 billion agricultural industry, which depends on water provisioning from the Sierra Nevada, and which provides one third of the country’s vegetables and two thirds of its fruit and nuts (CDFA 2018). The Sierra Nevada provides clean water for 25 million people (Klausmeyer and
Fitzgerald 2012, and demand for clean water will only rise with a growing human population. Large, severe wildfires can introduce pulses of sedimentation into affected watersheds, which can result in millions of dollars of damages to water treatment facilities (Edelson and Hertl 2019).

These outcomes are plausible consequences of a continuation of current trends in Sierra Nevada forests. The social-ecological ramifications of such a future are expected to be undesirable for most stakeholders (table 2), and prompt, effective forest management is likely necessary to avoid it.

**Multidimensional trade-offs and spatiotemporal mismatches**

In their attempts to avoid that future, stakeholders face multidimensional and often contentious trade-offs (table 2) whose costs and benefits can be mismatched in space and time and are often scale-dependent (Cumming et al. 2013, 2006). Following Euro-American genocide of indigenous populations and a century of highly effective fire suppression (Taylor et al. 2016), reducing accumulated forest fuels has become a major conservation conflict in the management of Sierra Nevada forests. Tools for fuel reduction include mechanical thinning (i.e. selective removal of smaller and medium-sized trees), mastication, and increased use of prescribed and managed fire, each of which can be applied in a variety of ways and combined with other approaches (figure 1) (Agee and Skinner 2005). Determining if, how, where, and when such treatments are implemented is a core challenge of Sierra Nevada forest management. An incomplete list of possible outcomes of different fuel reduction treatments includes: increased forest resilience (Collins et al. 2014); reduced tree mortality from drought stress (van Mantgem et al. 2016, Restaino et al. 2019); potential declines in spotted owl site occupancy and reproduction (Stephens et al. 2014, Tempel et al. 2014); diversification of forest structure and thus the small mammal community (Kelt et al. 2013), which in turn influences spotted owl populations (Hobart et al. 2019a); changes to bird community species richness (White et al. 2013); changes to the carbon budget (Wiechmann et al. 2015) and thus broader changes in global atmospheric chemistry, which have been linked to changes in the small mammal and bird communities of the Sierra Nevada (Moritz et al. 2008, Tingley et al. 2009). Below we describe two issues in more detail to better illustrate trade-off complexities: (i) the challenge of incorporating managed and prescribed fire into forest management and (ii) the conservation of the spotted owl.

Managed wildfires and prescribed fires (collectively ‘managed fires’) have lower emissions than escaped or unplanned fires (collectively ‘unmanaged fires’) (Ahuja 2006), but air quality regulations constrain the use of managed fires, which can ultimately result in the more intense effects of unmanaged fires (North et al. 2012). Managers face the difficult choice of imposing lower present-day emissions on California residents by managing and even starting fires, or awaiting greater future emissions when larger, unplanned fires occur. A retrospective analysis suggests that prescribed fire may result in better health outcomes for children in California than unmanaged fires (Prunicki et al. 2019). There are also legal and financial risks associated with managed fire, because the risk of damage from escaped fires can be minimized but not eliminated. For example, a jury found the Nevada Division of Forestry guilty of gross negligence after a prescribed burn destroyed 23 homes worth an average of $1.4 million each (Hidalgo 2018). This risk is increasing because residential development in the Sierra Nevada is projected to grow (Mann et al. 2014). Managed fires may reduce the risk of highly destructive megafires (e.g. damages related to the 2014 King Fire exceeded $60 million; Vives 2016), but entail legal exposure that simply waiting and hoping currently does not.

The Sierra Nevada is the core range of the declining California spotted owl, and decisions related to fire management and other complex, interconnected processes will play an important role in determining its long-term viability. Large, severe fires lead to population declines through loss of nesting habitat (Jones et al. 2016), but, as noted above, fuel reduction treatments may also exert negative population effects through habitat alteration (Stephens et al. 2014). However, there is increasing evidence that the potential long-term benefits of treatment (reducing fire-related habitat loss) may exceed short term costs to owls from habitat alteration, meaning that owl conservation and ecosystem restoration might be compatible (Tempel et al. 2015, Wood et al. 2018, Jones 2019). Though large-tree logging has mostly ended on public land in the Sierra Nevada, the absence of those trees may have contributed to ongoing spotted owl population declines (Jones et al. 2018), illustrating the temporal mismatch between decision and consequence. Those mismatches are further illustrated by the manner in which the differential forest management histories on private lands (intensive timber extraction), national forests (large tree logging and fire suppression), and national parks (limited logging history and increased use of fire) in the Sierra Nevada have mediated spotted owl territory survival via its influence on their small mammal prey (Hobart et al. 2019b). Importantly, the Sierra Nevada population of the California spotted owl is threatened by other processes, notably (i) a rapidly growing barred owl population (Wood et al in review) that could cause further spotted owl population declines through conspecific aggression and competition (Yackulic et al. 2019), and (ii) the possibility of widespread and persistent environmental toxicity via anticoagulant rodenticides that can cause direct
Table 2. Comparison of stakeholders and examples of their potential values in the Sierra Nevada social-ecological system. Note that the stakeholders included in this table and their characteristics are not intended to be comprehensive/exhaustive, but illustrative.

| Stakeholder                                | Definitions of success                                                                 | Possible conflicting stakeholders                                                                 | Definitions of failure                                                                 | Minimum acceptable outcome (starting place for compromises) |
|--------------------------------------------|----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|-------------------------------------------------------------|
| Land management agencies                   | Multi-use forests—provisioning of timber, wildlife habitat, ecosystem services          | Environmental groups (e.g. timber extraction), Conservation groups (e.g. wildlife habitat)       | Ecosystem type conversion                                                              | Maintain forested ecosystems                                 |
| Environmental and/or conservation groups   | Conservation of biodiversity, ecosystem service provision, and natural landscapes for intrinsic and recreational value | Timber industry (e.g. wildlife habitat), Land management agencies (e.g. wildlife habitat)       | Ecosystem type conversion                                                              | Maintain forested ecosystems                                 |
| Timber industry                            | Revenue from timber sales (both from timber industry lands and purchases of timber offerings on public lands), long-term economic growth and sustainability of revenue | Regulatory agencies (e.g. diameter limits, ESA), Environmental groups (e.g. wildlife habitat) | Ecosystem type conversion                                                              | Maintain forested ecosystems                                 |
| Regulatory agencies                        | Public safety, adherence to state and federal laws (e.g. Endangered Species Act [ESA]) | Land management agencies (e.g. smoke exposure from prescribed fire)                              | Ecosystem type conversion                                                              | Maintain forested ecosystems                                 |
| Members of the public (Sierra Nevada residents) | Safety (reduced smoke exposure and wildfire risk), sustained property values, recreational opportunities | Land management agencies (e.g. smoke exposure from fire, severe fire risk)                     | Ecosystem type conversion                                                              | Maintain forested ecosystems                                 |
| Members of the public (ex situ)            | Safety (reduced smoke exposure), water provisioning (downstream), agricultural production, recreational opportunities | Land management agencies (e.g. smoke exposure from fire, provisioning of ecosystem services) | Ecosystem type conversion                                                              | Maintain forested ecosystems                                 |
owl mortality through food chain contamination (Franklin et al 2018, Gabriel et al 2018). These threats can interact, but, importantly, the return on management investments may be realized on very different time scales (Yackulic et al 2019), incentivizing a cautious and comprehensive approach to spotted owl conservation.

An important consequence of the complexity of the social-ecological system that is the modern Sierra Nevada is the propensity for the ramifications of forest management decisions to ripple in space and time. Continued fire suppression may yield short-term benefits in terms of avoiding property damage and legal exposure for management agencies, but result in long-term costs to residents, insurers, and other agencies because continued fuel accumulation is likely to lead to even larger, severe fires that are difficult to control (North et al 2012). The managed fires that may help prevent the Sierra Nevada from becoming a carbon sink bear costs for California residents in terms of air quality (albeit potentially less severe costs than those posed by wildfire; see Frumicki et al 2019) and benefits for residents of the United States as a whole in terms of sustained agricultural productivity (CDFA 2018). Individually, these examples represent conservation conflicts, or situations in which stakeholders with differing levels of power disagree about conservation objectives (Thomas 1992, Redpath et al 2013). Together, this network of stakeholders whose goals and desired outcomes are linked asymmetrically in space and time makes forest ecosystem management in the Sierra Nevada a ‘wicked problem’ (Defries and Nagendra 2017, Mason et al 2018). As a result, there is a serious risk that endless negotiation and protracted litigation will result in gridlock (e.g. Gutiérrez et al 2015) and thus a continuation of the status quo towards a nearly universally undesirable future.

Framing management debates in terms of the cost of failure

We contend that forest management debates in the Sierra Nevada should be framed in terms of the cost of failure of negotiations among stakeholders. Such a failure could result in the continuation of the status quo, and thus the widespread conversion of Sierra Nevada forests to a chaparral-dominated ecosystem which could result in the consequences we described above. This may serve as a potent and perhaps ominous reminder of what is at stake. However, it should not be used as a cudgel to expedite the implementation of policies that have not been properly evaluated. We outline three specific actions that can help keep the cost of failure appropriately present in negotiations.

First, we believe negotiations can be improved if stakeholders explicitly define the outcomes they are trying to achieve (success), the outcomes they are trying to avoid (failure), and the acceptable space between (potential compromises) (table 2). The important distinction here is between failure and the minimum acceptable outcome, as this may highlight underlying commonalities between groups. It is our understanding that the widespread conversion of Sierra Nevada...
Atuo et al. 2019), identifying promising new pathways in the conservation and management of the spotted owl resource use and population ecology, thus recently began collaborating and were able to document the results. However, in the Sierra Nevada, the two groups historically had adversarial undertones. The timber industry has historically had adversarial relationships with academic researchers and the relationship between stakeholders has historically had adversarial undertones. However, in the Sierra Nevada, the two groups recently began collaborating and were able to document previous unknown elements of California spotted owl resource use and population ecology, thus identifying promising new pathways in the conservation of that subspecies (Hobart et al. 2019a, 2019b, Atuo et al. 2019). Unsurprisingly, the absence of trust can impede the management process. The erosion of trust can be an ongoing process, as can occur if stakeholders engage in agenda-driven science, defined as the misuse of the scientific process or violation of scientific norms to advance a particular management outcome (Peery et al. 2019). Parties engaging in agenda-driven science compromise their own credibility (thus undermining their own objectives) and impede the accurate evaluation of management proposals by adding potentially unsound information to the scientific literature. The absence of trust can also be a residual outcome of historical events. For example, the Quincy Library Group, a group of northern Sierra Nevada stakeholders engaged in a congressionally-mandated collaboration with the USFS to develop forest management policy, was notably incomplete because some environmentalists refused to participate because a major timber industry group was participating (Gutiérrez et al. 2015, Cheng et al. 2016). This illustrates the potentially generational effects of broken trust: if individual representatives of stakeholder groups feel their trust has been betrayed, they may be unlikely to engage in future discussions, even if the personnel and institutional culture at the aggrieving groups have changed.

Second, relevant trade-offs should be quantified and potential multidimensionality should be explored and stated. This is a natural extension of defining a range of acceptable outcomes, because it allows for the explicit testing of the feasibility of proposed solutions. Such efforts will be facilitated by studies conducted at spatiotemporal scales sufficient to capture the relevant ecological processes (e.g. Wiens 1989, Wood et al. 2019). Incorporating the multidimensionality of many, if not most, potential management actions in the Sierra Nevada would be an important acknowledgment of the inherent complexity of the social-ecological system. It could also improve negotiations: the more multifaceted a debate, the less it can be conceived as a zero-sum game, and the more parties may be able reach mutually beneficial (or at least tolerable) solutions.

Empirical testing via experimentation is a powerful way to assess potential trade-offs. For example, a 10-year, full-factorial experiment with three levels of forest thinning and two levels of burning quantified the trade-offs between CO2 emissions generated by fire, generated and averted by forest management activities, and sequestered by forest growth (Wischmann et al. 2015). When experimentation is not feasible, simulations have proven valuable. Spotted owl protected activity centers (PACs) are often considered an impediment to fuel reduction treatments in the Sierra Nevada, but fire models including and excluding PACs from simulated treatments suggested that the two can be compatible (Dow et al. 2016). Subsequently, owl population projections quantified the relationships between owl population change and treatment frequency and extent if hypothetical fuel reduction treatments of different intensities were conducted in PACs that had been vacant for different durations (Wood et al. 2018). We acknowledge that funding, executing, and sustaining ecological experiments and long-term studies is very expensive and notoriously difficult. For example, an insufficiently large spotted owl population and delays in implementing fuel treatments across the landscape necessitated substantial alteration of a planned before-after control-impact design of the spotted owl/fuel reduction treatment study component of the Sierra Nevada Adaptive Management Project (Peery et al. 2014). Quantifying management trade-offs and identifying multidimensionality with an ideal experimental design will not always be possible, and when it is the cost may be daunting. Yet such work is integral to the evaluation of potentially contentious management decisions, and those costs should be considered in the context of the potential costs of failing to develop sound management. This mindset will not obviate budgetary constraints, but it may place them in an appropriate context.

Third, consistent with the multidimensionality of many forest management trade-offs, stakeholders should allow for solutions that are heterogeneous in space and time. Solutions that fail to account for the complexity of the problems they purport to solve are unlikely to be fully successful. Particularly in large ecosystems like Sierra Nevada forests—entailing tens of thousands of square kilometers of forest spanning four
degrees of latitude and a 4000 m elevational gradient—substantial variation is likely necessary to accommodate the range of conditions (North 2012). From a negotiating perspective, heterogeneous solutions may facilitate the creation of mutually acceptable solutions by providing more axes for compromise. From an implementation perspective, such solutions are likely to be expensive, and there may be disagreement among stakeholders regarding the relevance of some costs. For example, a county-level environmental NGO and the USFS may be mandated to weigh the potential effects of a forest management plan on national food production via changes in California’s hydrology quite differently. To whom such costs are relevant and whether they can be internalized in formal cost/benefit analyses is difficult to determine. In light of such complexities and of increasing budgetary constraints, we suggest again that the costs of potentially complex and heterogeneous management plans be compared not only to those of simpler plans, but also, to the greatest extent possible, to the potential costs of the consequences of not employing the optimal management plan.

The constraints that California spotted owl habitat conservation may impose on ecosystem restoration planning illustrate both the complexity and promise of multidimensional trade-offs. Although California spotted owls are primarily associated with old-growth forest conditions, the strength of forest associations and relative importance of different forest types varies across their range (Tempel et al. 2016, Jones et al. 2018). Likewise, the level of ecological departure from historical conditions varies across the Sierra Nevada (North 2012). Therefore, different types and intensities of fuel reduction/restoration treatments are likely necessary in different places even though they are generally necessary across the range, and the subsequent effects of fuel treatments on spotted owl populations will likely vary in direction (positive, negative, or neutral effects) and magnitude (weak or strong effects) and will also vary in space and time (Jones 2019). This variation may allow for more flexible and heterogeneous solutions to landscape-scale fuel treatments. At finer scales (~4 ha), heterogeneity in the application of fuel reduction treatments can also allow flying squirrels—a key prey item for spotted owls in Sierra Nevada national forests (Hobart et al. 2019b)—to move in response to loss of preferred habitat such that the population density does not change at the scale of an individual spotted owl territory (~400 ha) (Sollmann et al. 2016). Communicating these necessarily complex solutions to stakeholders and the public, as well as translating these solutions into on-the-ground action, is likely to be challenging. The addition of communication professionals to science and management teams could be beneficial (Enquist et al. 2017).

There is considerable evidence that Sierra Nevada forests face a tipping point, and that without potentially substantial management they could be drastically reduced in extent. The many cascading consequences of such change are nearly universally undesirable (tables 1 and 2). Yet managing this social-ecological system entails the navigation of multidimensional trade-offs whose complexity and spatiotemporal asymmetry can impede the implementation of solutions that could help avert that future. Our three proposals, (i) explicitly defining success, failure, and a range of acceptable outcomes, (ii) quantifying trade-offs and acknowledging their multidimensionality, and (iii) developing solutions that are heterogeneous in space and time, incorporate the social-ecological realities of the Sierra Nevada and may help improve negotiations of forest management policy by keeping the steep cost of failure appropriately present. This may help urge stakeholders towards the development of solutions to the wicked problem of managing Sierra Nevada forests and other social-ecological systems.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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