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Forum

Multiscale adaptive management of social–ecological systems

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Abstract

Adaptive management is an approach for stewardship of social–ecological systems in circumstances with high uncertainty and high controllability. Although they are largely overlooked in adaptive management (and social–ecological system management), it is important to account for spatial and temporal scales to mediate within- and cross-scale effects of management actions, because cross-scale interactions increase uncertainty and can lead to undesirable consequences. The iterative nature of an adaptive approach can be expanded to multiple scales to accommodate different stakeholder priorities and multiple ecosystem attributes. In this Forum, we introduce multiscale adaptive management of social–ecological systems, which merges adaptive management with panarchy (a multiscale model of social–ecological systems) and demonstrate the importance of this approach with case studies from the Great Plains of North America and the Platte River Basin, in the United States. Adaptive management combined with a focus on the panarchy model of social–ecological systems can help to improve the management of social–ecological systems.

Keywords: ecosystem management, adaptive management, ecosystems, social–ecological systems, natural resources

Throughout the course of human history, local to regional scale ecosystems have been modified for humankind's benefit (Gunderson et al. 2022). Such modifications sought to and are successful at controlling and altering key biophysical processes and reducing variability. For example, dams are placed in the large river systems of the United States and elsewhere to provide consistent water supplies and flood protection. But modifying key biophysical processes often leads to unwanted ecosystem changes at multiple scales, including the loss of biodiversity, the endangerment of species, and the disruption of food webs (Gunderson et al. 2017). In response to these unwanted changes, ecosystem managers have attempted to restore key attributes by manipulating ecosystem processes amenable to high levels of control, both physical and ecological, at regional or watershed scales. For example, dam operations can be manipulated to control downstream flows, or a dam can be removed entirely. Such ecosystem restoration efforts, however, also involve complicated governance by government agencies, nongovernment organizations, other stakeholders, and the laws, regulations, and policies that affect a social–ecological system (SES; Green et al. 2015). These institutions and organizations operating at multiple jurisdictional levels with differing scopes and scales of authority has important ramifications for SES governance and management (e.g., water quality, fisheries management; Cash et al. 2006). The interacting governance and biophysical processes of SESs are identified at a fixed geographical scale, such as an SES defined by a watershed (for the purposes of a management authority's decision-making), but an SES defined at one particular scale is connected to larger and smaller SESs (Gunderson et al. 2017). Therefore, governance and management of multiscale SESs is one of the grand challenges facing humankind in the Anthropocene (Garmestani and Benson 2013, Gunderson et al. 2022). A powerful approach for managing SESs is adaptive management, and governance plays an essential role in facilitating adaptive management, as well as influencing social–ecological processes and structures across scales (Allen et al. 2011, Clement 2021).

Social–ecological systems are complex, in part, because of the high number of components and interactions among those components that operate at different scales (Gunderson and Holling 2002). The consideration of scale isn't trivial and can lead to undesirable environmental outcomes if not properly accounted for (Biggs et al. 2017). For example, the cumulative effects of small-scale habitat disturbances can, over time, deteriorate the large-scale suitability of a habitat corridor used for species migrations (e.g., migratory birds). Such cross-scale effects are encompassed in the concept of panarchy (Gunderson and Holling 2002). Panarchy was developed as a model to better understand linked systems of humans and nature, incorporating multiple scales, cross-scale interactions, and SES dynamism. Panarchy has proven particularly useful as environmental change has begun to scale up its impacts for humankind (e.g., climate change effects on coral reef SESs; Eddy et al. 2021). The more we understand the

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cross-scale effects in SESs, the better we can govern and manage SESs at multiple scales.

In this Forum, we introduce multiscale adaptive management and explain how panarchy shapes the framework, encompassing and accounting for scale, cross-scale interactions, and social–ecological dynamics. We also demonstrate the utility of our approach with examples that have complex spatiotemporal issues to overcome for effective SES management from the Great Plains of North America and the Platte River Basin in the United States, clearly showing that accounting for cross-scale interactions and scale-specific processes and structures is necessary for successful SES management. The structured, iterative process of adaptive management, when combined with panarchy (Gunderson et al. 2022), can accommodate different stakeholder priorities and multiple ecosystem attributes to generate better social–ecological trajectories.

Social–ecological systems, adaptive management, and panarchy

In the United States, and elsewhere, SES management is primarily based on laws that assume that SES dynamics are easily predicted and mitigated (Craig and Ruhl 2014). Social–ecological system management using this premise has met with mixed success because managers must make decisions within the context of laws (such as the US Endangered Species Act, ESA) that are based on species and population levels of organization, with little or no consideration of an SES perspective (Garmestani et al. 2020). Consequently, SES management is often based on simple metrics to assess the status of one or more endangered species and their habitats. Simple measures for SESs (e.g., number of an endangered species) neglect ecosystem-scale metrics of change (e.g., ecosystem processes and structures), contributing to management failures (Clement and Standish 2018). Practiced in the confines of such legal mandates, SES management has also had a difficult time accounting for scale, which is an inherent aspect of SES dynamics (Garmestani and Benson 2013). Managing for single variables is problematic because such approaches often do not account for potential interactions across scales in SESs (Gunderson and Holling 2002). Furthermore, the spatial and temporal scale at which management is applied is often chosen arbitrarily or is limited by law or administrative jurisdictions (Green et al. 2015). Management of SESs often assumes that data can be directly upscaled, as if one can add up the pieces to describe the whole, which, in turn, can lead to adverse SES management outcomes (Angeler et al. 2016). Adaptive management was developed to address some of these limitations in SES management (Holling 1978).

The process of adaptive management tests predictions against observations by monitoring and evaluating social and ecological responses to management actions. Adaptive management assesses possible management interventions for a specific natural resource or social condition at the inception of a project (Allen et al. 2011). In particular, the initial process of adaptive management creates and evaluates possible management interventions with stakeholder input, conceptual models, and simulation models (Allen et al. 2011). Although adaptive management can be applied in many settings, it has the greatest chance of success when there is high uncertainty regarding SES dynamics but high controllability over management interventions (Herrmann et al. 2021). Adaptive management historically has only addressed a single or small set of environmental variables, with spatial and temporal bounds on management interventions. However, not accounting for scale in adaptive management risks missing important cross-scale effects, including those that may cascade to larger scales across the SES. The panarchy model of SESs provides an approach for this issue.

Panarchy was developed to explain cross-scale interactions and dynamics of SESs (Gunderson and Holling 2002). It posits that SESs defined by specific spatial and temporal scales, such as an urban watershed, rural national forest, or large-scale biome, cycle through periods of stability and instabilities (e.g., forest fires, trophic cascades, or invasion of nonnative species) that occur at multiple spatial and temporal scales. As such, panarchy is being applied to emerging SES management issues where conventional governance and management, which typically uses fixed geographical units (a forest, a lake) and static equilibrium models, have failed to take into account the dynamics of SESs including their cross-scale effects (Angeler and Hur 2023). Panarchy acknowledges the inherent uncertainty in SESs, and therefore more flexible forms of governance and management have been proposed in contrast to those that are based on rigid prescriptive regulations (known as *command and control*; Garmestani and Benson 2013). Moving forward adaptive management must evolve and account for actual and potential cross-scale effects, as is envisioned in panarchy (Garmestani et al. 2020).

In this Forum, we describe the development of multiscale adaptive management on the basis of two large-scale grand challenges confronting SES management in the Great Plains of North America: invasion of grasslands by Eastern red cedar (*Juniperus virginiana*) and other woody species and management of the overappropriated Platte River basin by invasive herbaceous and woody species, focusing on invasion by the common reed (*Phragmites australis*). Both case studies represent large-scale emergence of undesired alternative regimes and help to demonstrate the importance of our multiscale adaptive management framework (Gunderson et al. 2022).

SES management challenges: Two case studies

Loss of grasslands and emergence of a woodland regime in the Great Plains of North America

Tree cover encroachment into the rangelands of the State of Nebraska (in the United States) has doubled since 2000 and is now approaching 1 million acres (Fogarty et al. 2022). Woody plant invasions are currently the dominant threat to grasslands in the Great Plains (Engle et al. 2008), and grassland transitions have been identified as the primary issue for conservation in Nebraska by the Conservation Roundtable and the Nebraska Invasive Species Advisory Council. Eastern red cedar (*Juniperus virginiana*) invasion now occurs throughout the Great Plains of North America. Historically, Eastern red cedar was kept at low population levels in isolated locations by frequent human- and lightning-ignited fires and thrived primarily in places where individual trees could escape fire damage (Briggs et al. 2002). The removal of this historical controlling process (fire), coupled with ubiquitous planting and distribution of Eastern red cedar, set the stage for widespread invasion and emergence of woodland domination in vast expanses of the Great Plains. The transition of grasslands to woodlands has significant social, ecological, and economic impacts on both the people and the ecosystems of the Great Plains.

Loss of sandbars and emergence of an incised vegetated regime in the Platte River basin in the United States

The Platte River basin in the central United States drains east from the Rocky Mountains in Colorado and Wyoming and flows to join the Missouri River after traversing the State of Nebraska. The water laws, policies, and infrastructure of the central Platte River basin in south-central Nebraska have evolved during post-European settlement to optimize the needs of agricultural irrigation and flood control (Birge et al. 2014). Predevelopment, the Platte River was a braided, shallow stream with high connectivity to riparian wetlands and fluctuating sandbar islands. This ecosystem was structured by high flow events that redistributed sediments and biota. The changes in flow regimes have altered aquatic and riverine habitats leading to the endangerment of populations of whooping cranes (*Grus americana*), piping plovers (*Charadrius melodus*), least terns (*Sterna antillarum*), and pallid sturgeons (*Scaphirhynchus albus*). The Platte River has transitioned from a braided river with open sandbars and high nonstationarity (SES is changing rather than remaining the same as before) to an incised river with vegetated sandbars and banks and high stationarity (SES in a static state), an ecologically undesirable condition.

Applying a multiscale adaptive management framework

The multiscale adaptive management framework has several steps to be undertaken in sequential order. The steps are identifying the management problem and the focal scale for intervention with stakeholder input, conceptual models, and simulation models; assessing the trade-offs associated with management interventions; implementing the first management intervention, with alternative intervention options ready to implement if the first option is not meeting project expectations; and assessing the progress of the project at decision points (SES context determines decision points) and determining whether to continue with current management or implement an alternative strategy. Management intervention progress is assessed with monitoring data that feeds into the multiscale models of the SES.

The first step in the multiscale adaptive management framework is determining the focal scale of interest and articulation of competing hypotheses via stakeholder input, conceptual models, simulation models, and baseline monitoring. Modeling SESs is quite daunting and is further exacerbated by the challenges associated with scale: spatial, temporal, and cross-scale interactions (Suarez-Castro et al. 2022). Social–ecological processes and structures interacting at multiple scales create confounding factors for SES management, because many effects are manifested at different scales than the scale of implementation (Lehmann et al. 2022). Therefore, simulation models that can assess multiple scales in a cross-scale framework will require new tools different than those previously used for adaptive management. Integrated modeling (Angeler et al. 2021) and multiscale conceptual and simulation models (Zou et al. 2023), for instance, are useful for some cross-scale issues as multiscale models account for more than one spatial and temporal scale and allow for model systems to be perturbed and evaluated (Tao et al. 2022). Monitoring occurs at the focal scale but also of key variables at other critical scales identified at the beginning of a project that have the potential to affect or be affected by the focal scale. For Eastern red cedar invasion, the focal scale is the biome scale, whereas, for common reed invasion, the focal scale is the watershed scale.

Invasion of grasslands by Eastern red cedar (*Juniperus virginiana*) in the Great Plains of North America is often seen as a problem of management at the scale of ownership parcels, the most frequent focal scale for this problem (figure 1). However, controlling Eastern red cedar invasion requires controlling processes at multiple scales—for example, the tree scale, where individual trees drop millions of propagules within meters of the individual tree; the landscape scale, whereby birds disperse seeds to adjacent ranches; and the ecoregion scale (often constrained by political boundaries because policies differ even within states), because humans move trees and plant them as windbreaks (Garmestani et al. 2020). Failure to account for any of these scales, both above and below the level of the parcel scale, will result in a failure to control Eastern red cedar invasion. Like the social-ecological processes themselves, monitoring too should occur at multiple scales.

The focal scale for addressing common reed invasion (*Phragmites australis*) is driven by species of concern (e.g., threatened and endangered species) in the Platte River basin, which require open sandbars over river reaches (figure 2; NRC 2005). The listed status of these species (whooping cranes, piping plovers, least terns, and pallid sturgeons) by the US Fish and Wildlife Service led to litigation and compromise during the relicensing of the Kingsley Dam in the State of Nebraska (in the United States), and the creation of the Platte River Recovery Implementation Program (PRRIP). The PRRIP includes representatives from three states, federal agencies, and other stakeholders and was mandated to use adaptive management for system-wide ecological restoration. The PRRIP is an adaptive management approach to restoration at the watershed or multiple-States scale, as well as small-scale habitat enhancement (Birge et al. 2014). The ESA is the mechanism driving the PRRIP as the recovery of threatened and endangered species and their habitat is the thrust of ESA. In the Platte River basin, the adaptive management plan primarily revolves around habitat requirements for least terns and piping plovers, species protected under ESA (Birge et al. 2016). The focal scale of interest and indicator of management success is nighttime roosting habitat for these species (daytime habitat in the Platte River basin includes meadows and corn fields, currently effectively unlimited), but faster and smaller scales are critical too, such as the movement of sand grains by the river and processes leading to vegetation establishment (seed spread). Similarly, monitoring should occur at multiple scales as well, for seedlings, incipient patches, and at large scales to map extent and movement of the invasion front.

Assessing trade-offs

Once the focal scale of management intervention is identified, the next step is to evaluate trade-offs associated with the use of the intervention at each scale and the governance structure that will enable management of those trade-offs. Assessing trade-offs is undertaken via a qualitative method that compares ecosystem services provided at different scales for different system regimes and was specifically developed for adaptive management (see Birge et al. 2016 and figures 3 and 4 for more detail on scale-dependent monitoring and management guidance). Ultimately, trade-offs are primarily based on human preferences and benefits from a particular SES. We illustrate this issue in the following examples.

In the Great Plains of North America, minor management differences, such as haying versus burning, create a simple set of direct trade-offs. More complex trade-offs with more fundamental differences occur when the SES under management can occur in alternative regimes. In the Great Plains, grasslands can

Figure 1. Eastern red cedar (*Juniperus virginiana*) invasion in the sandhills of Nebraska, in the United States. Prescribed fire, shown in the background, is one of the management interventions used to limit spread of Eastern red cedar.

Figure 2. Common reed (*Phragmites australis*) invasion of a riparian zone in the United States. Photograph: Wes Bickford, US Geological Survey.

be grasslands but, given the right perturbation, may also transition to woodlands (Eastern red cedar) or to moving sands (in the Sandhills, specifically). These regime shifts completely alter the suite of ecosystem services derived, but even these trade-offs are fairly straightforward to quantify. Understanding cross-scale trade-offs can be more difficult, because such trade-offs can be across time or across space. The invasion of grasslands by woody invasive species (Eastern red cedar) illustrates both types of cross-scale trade-off. An example of a spatial trade-off occurs when a rancher plants a windbreak of invasive trees, often Eastern red cedar. This provides a local benefit in terms of livestock protection from wind, but, at larger scales than the individual ranch, this same windbreak provides ecosystem disservices in the form of invasive propagules spreading from the planting, which can invade neighboring ranches and reduce grassland productivity. The same example illustrates temporal trade-offs. That same

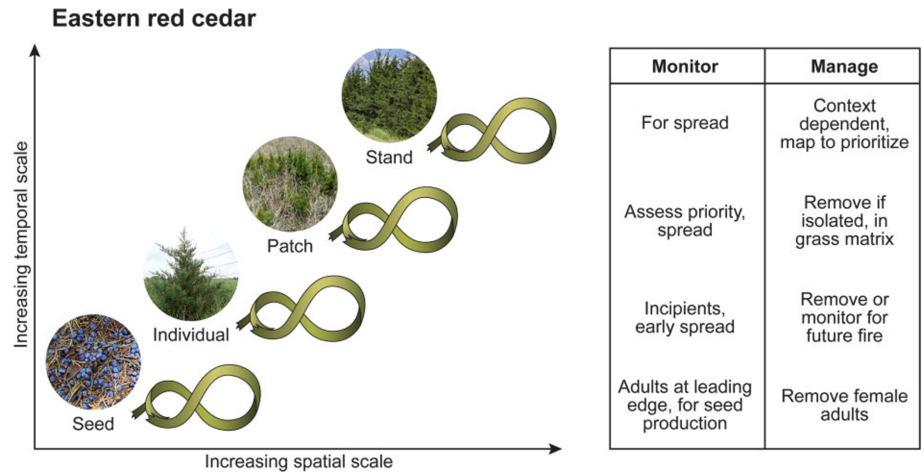

Figure 3. Panarchy of Eastern red cedar (*Juniperus virginiana*) invasion in the Great Plains of North America with monitoring and management guidance at multiple scales.

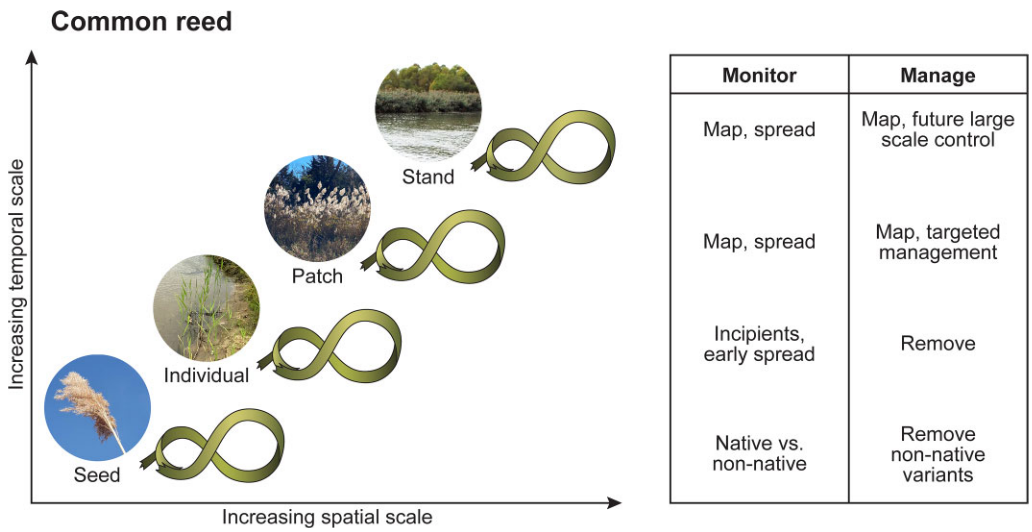

Figure 4. Panarchy of common reed (*Phragmites australis*) invasion with monitoring and management guidance at multiple scales. Photograph: Mike Eggleston, US Geological Survey.

windbreak providing local ecosystem services to a ranch over time becomes a disservice; Eastern red cedar when mature produce millions of seeds per year, and, over time, that windbreak becomes a source of seeds not only to adjacent ranches but to the focal ranch as well. Therefore, the ecosystem services desired by various stakeholders and their trade-offs can be assessed through monitoring and surveying stakeholder expectations (figure 3).

Despite the focus of adaptive management in the Platte River basin being on threatened and endangered species (i.e., at the population level), in the PRRIP, learning opportunities for how to maintain, restore, and create bare, vegetation-free sandbar habitat are provided, thereby accounting for the ecosystem processes and structures of the Platte River. To achieve this, current approaches include plowing riverine islands, removing vegetation from islands mechanically and with herbicides, and putting more sand into the river channel upstream, so that river processes can create new sandbars. A governance committee including stakeholders provides oversight to adaptive management activities. Cross-scale interactions occur in this context as well—for example, when the common reed rapidly invaded the river (smaller scale) or when basin-wide water management decisions were made (larger scale). Alternative regimes in the Platte River basin present hard trade-offs, the river is managed in a way that has resulted in two different regimes, one managed primarily for human benefit resulting in a wooded river and a section managed for endangered species, resulting in a more braided, open sandbar regime that is better ecologically. In this case, the Platte River is managed for both regimes, but the human-desired regime is self-organizing (its resilience is an emergent property of the SES; see Allen et al. 2019) whereas the ecologically desirable regime is coerced; that is, it needs constant (human) external intervention to maintain its resilience (figure 4; Angeler et al. 2020).

Once stakeholder input and the modeling process has been completed, adaptive management intervention can proceed, with multiscale monitoring, which allows for empirical data to feed back into the adaptive management process and generate learning about the SES over time. With adaptive management, management actions are treated as hypotheses and are put at risk with monitoring data. Decision points, where monitoring over time eventually refutes or sustains the working hypotheses, are necessary but context dependent in the structured, iterative process of adaptive management.

Biological invasions are dependent on processes at multiple scales; the processes responsible for introduction, establishment, and spread all differ and occur at different scales, and management too should address the scale and progress of the invasion. With respect to Eastern red cedar invasion, different stages of invasion and the degree of invasion by red cedar call for different actions (see figure 3). Preventing dispersal or preventing establishment requires management substantively different from removing patches and preventing reinvasion. Monitoring should occur at the scale of parcels for the presence of propagules, in relevant subwatersheds for incipient invasion (seedlings), within watersheds for patches of red cedar, and across the biome to track the invasion front and patches of red cedar.

Small-scale monitoring in the Platte River basin will involve monthly assessments for propagules of nonnative, invasive species. At larger scales, monitoring becomes more difficult, but spatial regimes provide indicators of larger scale change, which can help detect a potential parcel-level surprise or one driven by a broader scale driver (e.g., climate change; Sundstrom et al. 2017). In this context, spatial regimes provide an objective delineation of relevant spatial extents for larger scales in the multiscale adaptive management framework (Sundstrom et al. 2017).

When multiple, interacting scales define ecosystem processes and structures in an SES, there are explicit cross-scale trade-offs among different management interventions for restoring habitat for wildlife and adaptive management of the SES (Birge et al. 2016). For example, herbicide is a strategy used to control vegetation on islands in the Platte River basin, but, as a nontargeted control, there are impacts on native vegetation and invasive vegetation (common reed and purple loose strife, *Lythrum salicaria*, are better at colonizing after treatment). Therefore, control of vegetation at island scales can result in higher invasive species densities, producing more propagules, leading to basin-wide invasions and changing community composition from native to nonnative. Herbicide control of invasive species on Platte River islands has a local benefit for a short period of time but exacerbates the local problem over longer time scales and leads to more downstream invasion over broader spatial scales. Traditional adaptive management does not consider these types of cross-scale trade-offs (e.g., windbreaks provide local ecosystem services but landscape ecosystem disservices).

Unexpected events such as the invasion of the Platte River basin by the common reed often originate from scales above or below the focal scale, and scales above or below may provide early warning signals of collapse at the focal scale. A collapse of least tern and piping plover habitat occurs rapidly when islands are invaded by the common reed, which can grow as much as 12 inches per day. In this case, smaller-scale monitoring could have been focused on incipient invasion and the appearance of colonizing propagules on the sandbar islands of interest. Similarly, context (larger scales) can preface change at smaller (and focal) scales (figure 4). Upstream basin monitoring with remote sensing could have indicated an increasing invasion problem in the watershed, allowing managers time to plan for change rather than simply reacting to it. New approaches for detecting emergent phenomena (e.g., common reed invasion), such as screening approaches (regime shift screening; Uden et al. 2019) are welcome additions to tools for monitoring of SESs.

The next step in the framework is an assessment of the management intervention and cross-scale interactions (i.e., assessing for unexpected effects emanating from scales above and below the focal scale; Gunderson et al. 2022). Accounting for processes and structures at multiple scales is necessary to cope with large-scale grand challenges, especially those that involve alternative regimes that exhibit hysteresis. At large scales, a process is implemented that initially searches for patterns and then winnows mechanisms if a pattern is detected at multiple scales allowing for the benefits of adaptive management of SESs (adaptive inference; Holling and Allen 2002). As well, because SES organization is compartmentalized largely by scale, smaller scale uncertainties can be addressed through the adaptive management process while waiting for larger-scale patterns to resolve. If multiple experiments at different scales occur simultaneously, the cross-scale interactions and relative degree of compartmentalization of those scales must be assessed.

Another issue to be taken into account in the assessment stage of the framework (and many if not all other forms of SES management) that is rarely considered is nonstationarity. Nonstationarity means that baseline norms, expectations and reference points become, sometimes rapidly, obsolete (Pauly 1995). Climate change has been a driver of expanding nonstationarity across many SESs (Milly et al. 2008). Incorporating double-loop learning (identifying causality and taking action to address the issue), whereby objectives and hypotheses are revisited given monitoring data, is explicitly focused on assessing nonstationarity in SESs. If after a loop of learning in the adaptive management cycle the system has been found to be appreciably nonstationary, as is the case in the Platte River basin (see below), then the multiscale adaptive management process should be initiated anew; if the system operates at time scales where there is stationarity and learning has occurred, then managers can shift to a refinement of goals, and shift from a reduction of false negatives (type II errors) to false positives (type I errors) as uncertainties are minimized and the inquiry reduced, in the sense of being more focused with less uncertainty (Holling and Allen 2002). That is, as key uncertainties are eliminated, experiments should shift from simply identifying patterns and trends to identifying mechanisms and causes and tightening the statistical threshold used for the rejection of null hypotheses.

For example, the spread of the common reed (*Phragmites australis*) into the Platte River basin is an example of nonstationarity in the SES. In the early 2000s, the PRRIP encountered an unexpected event: invasion of the watershed by the common reed. This biological invasion forced a reconsideration of the PRRIP and initiated double-loop learning. The immediate reflexive response was to deal with the common reed as a complication for adaptive management but to proceed with the original plan. Over time, managers recognized that because of nonstationarity of the system, the adaptive management plan would have to be revised to incorporate the new conditions (with *Phragmites australis* as part of the SES) of the Platte River basin.

Recent advances can help to overcome many of the limitations that have hindered multiscale assessment and modeling in the past. For example, artificial intelligence (AI), advances in cyberinfrastructure, and automated data collection have greatly increased the ability to manage SESs and show promise for improving simulation models for multiscale adaptive management (Galaz Garcia et al. 2023). Leveraging technology can help to harmonize and rapidly produce empirical and remotely sensed data (Suarez-Castro et al. 2022) by increasing access to cyberinfrastructure and technical expertise, greatly empowering the capacity of AI for use as a tool for multiscale modeling and assessment of SESs (Galaz Garcia et al. 2023). The multiscale adaptive management process will then confirm or refute the model outputs, on the basis of monitoring data, and continue with the current intervention or switch to the next management intervention. Despite uncertainties in multiscale models, assessing cross-scale interactions will improve the adaptive management process and may generate more desirable outcomes for society (Gunderson et al. 2022).

Summary

These cases of ongoing regime shifts discussed in this Forum are occurring at large spatiotemporal scales. Both examples presented in the present article, like all SES challenges, transcend single scales and reflect change within a panarchy—that is, at multiple scales of time and space with different processes and structures dominating at different scales. Adaptive management has been used for decades as a powerful tool for managing ecosystems around the world (Allen et al. 2011). When employed in cases where there is high uncertainty and high controllability, adaptive management is an appropriate framework for SES management. However, adaptive management (and SES management in general) has done a poor job of accounting for the problem of scale (both spatial and temporal) and cross-scale interactions in SESs. Social and ecological dynamics of SESs, within and across scales, present significant challenges for scientists, policymakers, and practitioners (Garmestani and Benson 2013). Understanding these dynamics and how to manage them is of increasing importance in the face of accelerating environmental change.

In this Forum, we discussed the importance of accounting for SES dynamics when adaptive management is guided by panarchy. We provided background for these two extensions of social–ecological resilience (adaptive management and panarchy; Jozaei et al. 2022) and described a multiscale adaptive management framework, part of which was developed from addressing Eastern red cedar invasion in the Great Plains of North America (Garmestani et al. 2020). The framework was further strengthened by assessing common reed invasion of the Platte River basin in the United States, which highlighted issues with SES management that could be improved with our multiscale adaptive management framework. Ultimately, this new multiscale adaptive management framework will need to be further tested in order to refine the framework and assess how it can be improved for managing and governing SESs in an era of rapidly accelerating environmental change.

Policy implications

We offer the following policy recommendations:

- Use multiscale adaptive management for an SES where uncertainty is high and controllability of management interventions is high. Management and monitoring should account for the key scales present, because only managing the focal scale is inadequate for managing the cross-scale aspects of environmental change.
- Engagement of stakeholders should communicate the cross-scale nature of the management challenge and identify and address the key scales involved, using the panarchy model to develop multiscale conceptual models and simulation models of the SES.
- Implementation of multiscale adaptive management of SESs is a structured, iterative process, and requires communication of goals and the need for management and monitoring at multiple scales.
- Different monitoring and management are needed at different scales and is a challenge in existing governance frameworks. Tapping recent innovations in AI, data collection and modeling are critical for governing and managing multiscale SESs.

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