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Review

A social-ecological systems approach for environmental management

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ABSTRACT

Urgent environmental issues are testing the limits of current management approaches and pushing demand for innovative approaches that integrate across traditional disciplinary boundaries. Practitioners, scholars, and policy-makers alike call for increased integration of natural and social sciences to develop new approaches that address the range of ecological and societal impacts of modern environmental issues. From a theoretical perspective, social-ecological systems (SES) science offers a compelling approach for improved environmental management through the application of transdisciplinary and resilience concepts. A framework for translating SES theory into practice, however, is lacking. In this paper, we define the key components of an SES-based environmental management approach. We offer recommendations for integrating an SES approach into existing environmental management practices. Results presented are useful for management professionals that seek to employ an SES environmental management approach and scholars aiming to advance the theoretical foundations of SES science for practical application.

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1. Introduction

It is well recognized that natural resource and environmental issues occur at the intersection of complex natural and social systems (Berkes et al., 2003). Despite this recognition, conventional approaches to environmental management continue to follow disciplinary lines to address challenges. Solving environmental problems more effectively requires increased integration of social and natural sciences, novel governance approaches, and a new culture for environmental stewardship. An articulated framework is needed to engender such characteristics into an environmental management approach.

Transdisciplinary approaches and resilience objectives are rapidly developing across science and practice to inform and improve environmental decision-making (PCAST, 2011; NSTC, 2014). Transdisciplinary approaches merge interdisciplinary efforts together to address complex temporal, spatial, and organizational scales and build conceptual bridges between disciplines to solve real world challenges (Schensul et al., 2006; Tress et al., 2005; Van der Leeuw et al., 2011). Resilience is defined by the capacity of a system to adapt to disturbances and changes in the environment (Berkes et al., 2003; Young et al., 2006). With goals to enhance a system's ability to withstand disturbances, transdisciplinary science and resilience concepts are applied to challenges in many fields, including healthcare (Crow, 2011), food security (Hunt and Thornsbury, 2014), disaster risk reduction (UNISDR, 2012), and environmental management (Pohl, 2005; Schensul et al., 2006).

In the field of environmental management, Social Ecological Systems (SES) science can bring these concepts together by exploring the theoretical underpinnings for transdisciplinary science and resilience through development of conceptual and empirically based models and frameworks. SES science frames relationships between human and ecological components as part of a complex system with multi-scale feedbacks and dependencies (Berkes et al., 2003; Liu et al., 2007; Walker et al., 2006). There is rich opportunity for SES theory and practical application to partner in meeting the shared goals of advancing transdisciplinary approaches, improving system resilience, and increasing success of environmental management outcomes.

In this paper, we seek to bridge theory with practice by defining a framework for an SES approach to environmental management in the United States (U.S.) through synthesis of literature and presentation of real world examples. First, we define SES science concepts that are relevant to environmental management. Then, we describe the current challenges faced by environmental managers. We identify key components of an SES environmental management approach that are distinguishable from prevalent environmental management frameworks, and offer recommendations for integrating an SES approach into existing environmental management practices. Results of this study are useful for management professionals that seek to employ an SES environmental management approach in their work and scholars that aim to advance the theoretical foundations of SES science for practical application.

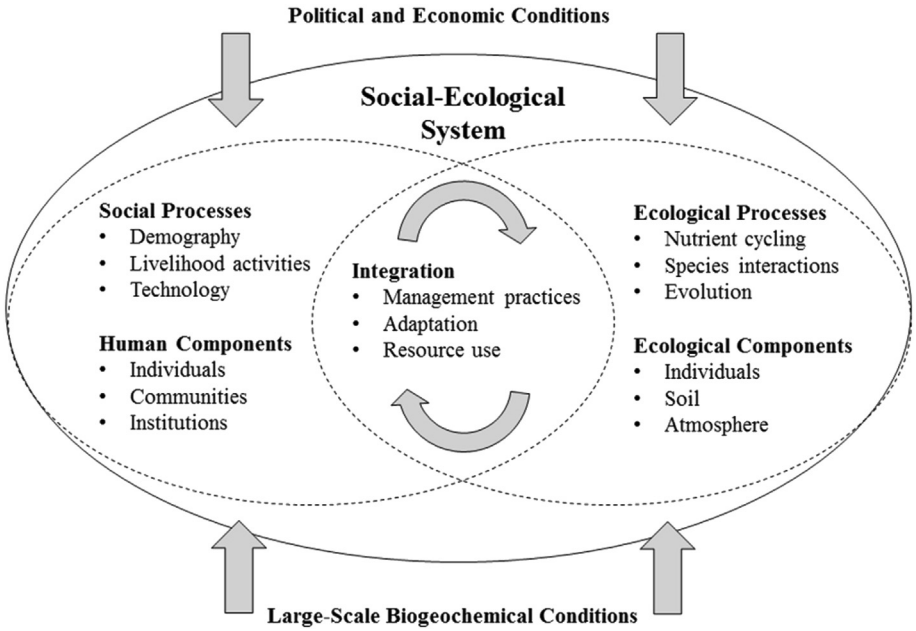

Fig. 1. Depiction of an SES (adapted from SNRE, University of Florida, (2015)).

2. SES science

SES science provides a theoretical framework that conceptualizes the environment as an open system consisting of ecological and social processes and components, including biomes, humans, and wildlife (Fig. 1). These processes are integrated through interactions such as management practices, adaptation, and resource use that occur on multiple scales and through cycles. As an open system, SES processes and interactions are influenced by broad scale forces such as political and economic conditions, and large-scale biogeochemical conditions (Chapin et al., 2009a, 2009b). System components interact within a dynamic, web-like structure that facilitates interdependencies and feedbacks influenced by direct and indirect drivers at different temporal and spatial scales (Berkes et al., 2003; Chapin et al., 2009a; Liu et al., 2007; Walker et al., 2006).

Within an SES, resilience and transdisciplinarity are concepts used to frame and influence the integration between social and ecological processes (e.g. management practices, adaptation, resource use). In SES science, resilience refers to a system's capacity to experience perturbations while retaining its essential functions, structure, feedbacks, and identity (Holling, 1973). SES resilience is described as continuous adaptive cycles that incorporate disturbance through a series of disruption, reorganization, and renewal. These adaptive cycles exist on multiple spatial and temporal scales (Gunderson and Holling, 2002; Walker and Meyers, 2004), and their transitions into new phases are determined by durability and persistence of the system (Curtin and Parker, 2014). In practice, decision makers and managers emphasize the need for enhanced resilience of natural resource systems (CNRWG, 2014) and human communities to environmental disturbances. For example, in response to a series of intensifying coastal storms and heat waves over the last twenty years, including Superstorm Sandy, New York City looked at new ways to construct buildings to resist storm damage, protect its occupants, and allow for faster evacuation (Urban Green Council, 2013). Through improved urban infrastructure, New York City planners sought to adapt using lessons learned from past environmental disturbances to increase their resilience to future environmental challenges.

Transdisciplinary approaches in SES science aim to integrate interdisciplinary sciences through collaborative and systemic mechanisms (Tress et al., 2005). By closely reflecting the complexity evident in environmental dynamics, transdisciplinary approaches are well suited for solving problems in environmental management (Pohl, 2005; Schensul et al., 2006). Transdisciplinary approaches address science and society's perception of an issue, produce practically relevant knowledge, and orient research inquiries toward common interests. In practice, transdisciplinary approaches go beyond interdisciplinary consultation and co-management by requiring a team of researchers and other interested parties, such as practitioners and managers, to address a problem collaboratively from initiation of a project (Stokols et al., 2008). A transdisciplinary approach to knowledge production allows for high adaptability of project goals and methods, and ensures that outcomes are sustainable and meet stakeholder needs. For example, a working group composed of university and U.S. Forest Service ecologists and social scientists addressed management of dry forests and rangelands in the Blue Mountains Ecoregion of eastern Oregon and Washington using transdisciplinary approaches. Over thirty years of research and management experience in the region and an active community of local stakeholders provided the foundation to successfully mobilize a collaborative group of managers, scientists, landowners, and resource users to develop social-ecological research initiatives, build new datasets, and address management issues relevant to the different stakeholders. The transdisciplinary approach was used to lead co-development knowledge for reducing vulnerability, fostering adaptation, improving resilience, and supporting sustainability of natural and human systems in the Blue Mountains region (MtnSEON, 2014a).

Although SES science seems like an obvious choice for understanding environmental issues, there is much to learn about applying these theories in practice. SES's emphasis on transdisciplinarity has great potential for developing novel solutions to overcome environmental management challenges, such as by enhancing environmental and community resilience. To understand the value that can be added by SES management approaches, however, we must identify how environmental management has evolved thus far and the current challenges facing this field.

3. A shifting paradigm for environmental management

3.1. Evolution of management approaches in the U.S.

From its earliest days, U.S. management of natural systems was based on a utilitarian and exploitative worldview that assumed limitless resources and human dominion over nature. At that time and through to the mid-20th century, most environmental management focused on steady-state resource management, maximum sustainable yield of resources, and single-species models that were managed primarily through reactionary, top-down hierarchal processes (Born and Sonzogni, 1995). In the 1980s, growing awareness of finite natural resources led to a global social movement of sustainability (Westley et al., 2011). To support such a philosophical transformation, a new environmental management model was needed.

In the 1990s, a paradigm shift in management was stimulated through new theoretical perspectives that environmental systems were highly complex, dynamic and therefore unsuitable for conventional, prescriptive management approaches. As a result, holistic, adaptive, and inclusive approaches were developed to manage resources as part of fluid human-environmental processes (Chapin et al., 2009a). Integrated environmental management recognized that effective governance of complex environmental systems required the participation and collaboration of diverse stakeholders in environmental decision-making (Margerum, 1999). Similarly, co-management was developed as an approach to further emphasize the importance of shared power and responsibility of environmental stewardship between governing bodies and local resource users (Berkes, 2009). Adaptive management also emerged to use a learn-by-doing approach for overcoming the challenges of uncertainty and complexity present in human-environmental systems.

More recently, a combined adaptive co-management approach has developed to emphasize knowledge generation and learning as essential for adapting management actions and goals over time to optimize their relevancy (Armitage et al., 2010; Olsson et al., 2004). Adaptive co-management is a bottom-up, emergent, and self-organizing process aimed towards problem solving (Buck et al., 2001). Due to its emphasis on local stakeholder collaboration, adaptive co-management is best for addressing a well-defined, small-scale resource system with clear property rights, social entities, and leaders prepared to champion the effort (Armitage et al., 2008). Adaptive co-management has offered a solution that improves upon earlier utilitarian and exploitative views of natural resources in America. Today's decision makers and managers, however, are presented with environmental challenges that are often not well defined and represent large-scale problems that are not ideal for an adaptive co-management approach. A new approach that addresses today's challenges for environmental

management is needed.

3.2. Current challenges for environmental management

3.2.1. Addressing broader scales

Environmental management today is challenged to address such complexities as multiple scales, effects of distal drivers on local systems (e.g., telecoupling, Liu et al., 2013), and open system issues (Polasky et al., 2011). Examples of contemporary environmental challenges include globalization, climate change (IPCC, 2014), an exponentially growing human population, and a public increasingly interested in consistent two-way dialogue with natural resource management agencies (Reed, 2008). Human well-being, which is now considered an essential component of successful environmental management (McShane et al., 2011), is dependent not only on local social and environmental resources, but also on global system interactions, such as the capacity for distant regions to provide sustaining resources to local communities. Local environmental management goals can no longer be considered in isolation from broader scale forces and systems (Hecht, 2010).

3.2.2. Conflicting stakeholder worldviews

Many environmental management initiatives do not encompass the diversity of stakeholder perspectives, and this disconnect can threaten the success of these initiatives. Lack of attention to stakeholder perspectives is often linked to feedback loops of power imbalances. Success metrics for management outcomes are often determined by powerful stakeholders who are more successful at driving their own environmental management agendas than less powerful groups (Krott et al., 2014). For example, government agency land managers, such as the U.S. Forest Service, often view the landscape and its value in terms of resources. In contrast, local land users, such as tribal groups, value cultural and spiritual aspects of the land, which are rarely considered as metrics in agency driven management plans. This discrepancy in perspectives and cultural constructions subsequently undermines intended collaborative processes. New approaches are needed if inclusion of diverse stakeholders is to be used to overcome problems with accountability for management outcomes, power imbalances, cultural miscommunication, and exclusion of the general public (Bryan, 2004; Conley and Moote, 2003; Frame et al., 2004). Strategies that identify where power comes from are critical for improved environmental management (Krott et al., 2014).

3.2.3. Managing for abrupt change and adaptability

Previous management approaches considered only steady-state interactions, or gradual, continuous change, so they had limited capacity to predict and manage for abrupt changes of vulnerable systems (Gunderson and Holling, 2002). Identifying the thresholds for change, or boundaries between alternate regimes, and drivers that lead to abrupt change are a challenge for environmental management (Groffman et al., 2006; Scheffer et al., 2012). An example of crossing thresholds into abrupt change is demonstrated through the explosive spread of wildfires, which is stimulated through a perfect storm of fuel load, connectivity of patch mosaics, and atmospheric feedback dynamics (Peters et al., 2004). Individually, these factors do not lead to ideal fire conditions, but together, they drive a system to cross a threshold (i.e. tipping point) that makes the environment conducive for wildfire. Understanding the cross-scale interactions and components that lead to abrupt environment change is needed to predict and prevent catastrophic events (Drijfhout et al., 2015), so that adaptability can be enhanced.

3.2.4. Scale mismatch

Scale mismatches are evident in both theory and application, and these mismatches can have negative implications on management predictions and outcomes. Spatial and temporal scale mismatches become abundantly clear when working across multiple disciplines, such as between the natural sciences and social sciences where researchers may design projects and collect data at different, incompatible scales. For example, to address the same problem, natural sciences may work at the watershed level that is defined by ecological components, while social sciences work at spatial scales defined by political boundaries. Scale compatibility issues can affect the ability to integrate, aggregate, and disaggregate data, and result in imperfect cross-disciplinary coupling. Temporal scale mismatches are often evident when managers and stakeholders have different time constraints or expectations for completion of a project. A study on the Clark Fork River cleanup in western Montana (Metcalf et al., 2015) found a mosaic of perspectives about the river restoration due to temporal, spatial, and institutional scale issues. The public became increasingly frustrated with the project due to the time lag between project initiation and the actual restoration. Similarly, spatial inconsistencies were evident with regard to locations where restoration was emphasized. Such scale issues can erode trust with the public and frustrate environmental managers and stakeholders.

3.2.5. Institutional limitations

In the U.S., it is challenging to integrate resilience theory into environmental management because of limitations within existing legal and institutional frameworks (Benson and Garmestani, 2011a). U.S. natural resource laws and regulations focus on minimizing human impact on the environment to preserve the present (or past) state of the environment, even though large-scale environmental issues like climate change are based on theories (e.g., resilience theory) that assume dynamic and adaptive processes (Craig, 2010). U.S. management agencies give even less attention to social resilience, or the ability of society to learn and adapt to change. Managers that do seek to embrace and implement resilience concepts, may find themselves unable to overcome core statutory and regulatory requirements (Benson and Garmestani, 2011b). One such attempt towards institutional integration of resilience concepts in the U.S. Forest Service (Benson and Garmestani, 2011a) is demonstrated through the proposed utilization of a 2010 Forest Service manual entitled, “Ecological Restoration and Resilience.” Policies outlined in this manual have yet to be interfaced with other primary management directives of the Forest Service (e.g., Multiple Use-Sustained Yield Act of 1960; National Forest Management Act 1976), which assume ecological equilibrium and stable systems. As a result, the manual has yet to have any significant impact on the ground. This example demonstrates that there is still much to be done to reform institutionalized assumptions and regulations on many levels in order to incorporate SES concepts into environmental management in the U.S. Currently, there are few defined enforcement standards to regulate resilience management and to ensure that it takes place (Benson and Garmestani, 2011a).

3.2.6. Lack of empirical evidence

Empirical evidence is needed to improve and assess success of new and integrated management approaches (Plummer and Fitzgibbon, 2004). For an SES management approach to be developed with success, empirical data on both social and ecological processes in systems are needed. Although it is often challenging to collect a balance of these datasets, they are needed to populate frameworks that enable testing and development of new SES approaches. Particularly, there is a lack of long-term datasets available

Table 1
A framework of an SES approach for environmental management. Matrix demonstrates the current environmental management challenges that can be addressed by specific SES concepts ("X" indicates linkage between challenge and concept).

SES concept	Management challenge					
	Addressing broader scales	Conflicting stakeholder worldviews	Managing for abrupt change and adaptability	Scale mismatch	Institutional limitations	Lack of empirical evidence
A systemic worldview	X	X	X	X		
Transdisciplinary approaches		X	X	X		
Adaptive governance		X	X		X	
Monitoring systems	X		X	X		X
Education and training		X			X	

to support resilience management, which is defined by a large temporal scale. It is also difficult to select the right indicators for resilience monitoring, because it is necessary to monitor both indicators of immediate relevance and indicators that are anticipated to be important in the future (Carpenter et al., 2001). Overall, monitoring and evaluation must play an important role within management initiatives so that better environmental management strategies can be developed.

Today, we are more aware than ever of the importance of balancing components of human systems, such as livelihoods, equity, and economics, with natural systems to build environmental resilience. Applying such a systemic perspective to management initiatives is a challenge, but SES science offers an approach to help encompass this new paradigm in environmental management.

4. An SES approach to environmental management

An SES approach to environmental management broadly guides systems toward high levels of human and environmental resilience through management of their adaptive cycles, so that resources and ecosystem services can be sustained at multiple scales (Folke et al., 2005). Management programs can contribute to broad objectives of SES environmental management by placing their smaller scale management goals (e.g., regional recreation and multi-use plans) within a systems lens. Managers can benefit from this approach by being able to better anticipate how relationships and feedbacks within their system, intended or unintended, affect their achievement of management objectives.

Here, we present a framework for SES environmental management by describing key SES concepts (i.e., a systemic worldview, co-development of knowledge, stakeholder engagement, monitoring systems, and education and training) and how they address current environmental management challenges (Table 1). By implementing these concepts within a management plan, a management initiative can gain a systemic understanding of the integrated social and ecological components that interact within the domain of an environmental management target. Within the explanation of these SES concepts, we also offer suggestions as to how these components can be integrated into existing management approaches.

4.1. Systemic worldview

A systemic worldview entails viewing a case study as connected to interconnected, multiple scales (e.g., temporal, spatial, and institutional) and large-scale issues (e.g., environmental change, globalization), so that the needs and perspectives of different stakeholders are integrated together as a comprehensive picture of a system. A systemic worldview also allows for consideration of how components may interact with various external systems to better predict both intended and unintended consequences. Systemic and resilience thinking can help to expand our knowledge of potential scenarios and outcomes to reduce the high uncertainty associated with large scale issues (Polasky et al., 2011). A systemic worldview calls for managers to exert less control over the system and accept more decentralization of guidance and decision-making. Doing this requires a large degree of trust and confidence that the system will self-organize, and such cultural change in environmental stewardship is not easy.

Management of bison in the Greater Yellowstone Ecosystem offers an example of how implementing a systemic worldview might be helpful in management initiatives. Stakeholders in the Greater Yellowstone Ecosystem are concerned that free roaming bison transmit *Brucellosis* to cattle. *Brucellosis*, a bacteria that causes failed pregnancies among cattle, can cause ranchers to lose their 'Brucellosis free' status for beef sales and consumption and negatively affect their economic sustainability. Bison are not solely to blame for transmission of the disease, however, as empirical evidence shows that elk is also a culprit. To try to solve this problem, the Interagency Bison Management Plan (2010), which is a cooperative effort led by state, federal, and tribal entities, was formed to bring together its multiple agency stakeholders to meet regularly over the past decade. This group aimed to synergistically develop a systemic worldview of the problem and new strategies for bison and *Brucellosis* management. It is uncertain if 100% eradication of *Brucellosis* is possible. However, the IMBP has made great strides in other areas like bringing together stakeholders, providing an outlet for concerned citizens, and keeping the issue at the forefront of agencies.

To build a systemic worldview, managers must first understand their system and its potential future transformations in order to think beyond their traditional system boundaries. One process that has been proposed (Cumming et al., 2005) entails first defining the current system to conceptualize system attributes and selecting the variables most likely to change in response to identified drivers. This information is collected through diverse stakeholder input (e.g., workshops, interviews, focus groups). Scenario planning (Peterson et al., 2003) is then used to identify a set of future identities of the system. The final steps of this process includes clarifying change trajectories, assessing likelihoods of alternate futures, and identifying mechanisms for adaptability to support resilience of a desired state.

4.2. Transdisciplinary approaches

Transdisciplinary approaches can be used to improve management by increasing capacity for managing adaptability, reducing isolation between management initiatives, and resolving mismatches between scales. Transdisciplinary approaches are often difficult and challenging to perform in the real world because integration efforts are complex to facilitate, and there are human resource limitations, institutional biases, and lack of adequate

networking and communication among the public, managers, and researchers. Transdisciplinary approaches hinge on co-development of new knowledge and processes with a diverse group of experts and stakeholders. Engaged stakeholders are key to successful transdisciplinary processes, so managers must be well-versed in collaborative techniques and allocate time in their projects specifically for building trust between stakeholders.

4.2.1. Co-development of knowledge

Managers are now asked to change their role from that of an external specialist with a pre-defined agenda to being one of the many actors within a system that contributes to the learning and knowledge generation process (Kates et al., 2001; Waltner-Toews and Kay, 2005). Managers must be facilitators and community-builders by connecting local groups (i.e., holders of local knowledge), key individuals, tribal governments and their membership, and relevant organizations and agencies to address management challenges. Such efforts to connect local knowledge to scientific knowledge within institutional frameworks can lead to co-development of knowledge for enhanced sustainability of interventions and more efficient problem-solving. Indeed, local communities that have stood the test of time are likely the most experienced at self-organizing for adaptation to environmental change (Gadgil et al., 1993). Incorporation of traditional ecological knowledge with conventional/scientific knowledge is a mechanism useful for enhancing resilience. Co-development of knowledge can improve power dynamics, lead to transdisciplinary development, improve adaptive capacity, collect more comprehensive and relevant information about the environment, and address scale issues (Alessa et al., 2015). It is also useful for identifying management goals and achieving more sustainable outcomes.

For co-development of knowledge, participants work together to establish meaning through analysis of empirical observations. Flexibility in understanding all perspectives must be exercised throughout the whole process to enable co-development of knowledge. For example, a natural resource management program that focuses on the Coeur d'Alene Tribe's stream restoration integrates indigenous knowledge with scientific knowledge by facilitating beavers' habitat creation of dams. Coeur d'Alene elders and the Tribe's non-indigenous, external natural resource specialists co-developed a plan to focus resources on facilitating beavers' ecological role as opposed to concentrating efforts solely on streambed restoration. Elders' indigenous knowledge about beavers, observed effects on local ecosystems, and notions of streambed restoration contributed to the co-developed management project. Adaptive learning took place as collaborators learned from lessons shared among participants. Success of the management project was evident on the landscape and to stakeholders (Zedalis, 2014).

4.2.2. Stakeholder engagement

For transdisciplinary processes to occur, diverse stakeholders must be included at the onset of an initiative. Different stakeholder perspectives must be identified and acknowledged before any management decisions are made, and preferably before specific management goals are finalized. Building these stakeholder partnerships requires an understanding of each other's culture to consider the pros and cons of each action and anticipate reactions among the different stakeholders. To be effective, stakeholder engagement must lead with defining management success collaboratively and interactions among stakeholders must occur consistently throughout the process. Such attempts can increase stakeholder commitment to, and ownership of, co-developed strategies and the execution of projects to help ensure long-term sustainability of management outcomes.

Stakeholder engagement must move beyond traditional forms of one-time feedback, such as public comment periods, to more multi-directional, collaborative communication strategies (Steelman, 1999), so that a foundation is built and trust can develop between stakeholders. Leadership, trust, social networks, and social memory are essential for increased adaptability of SESs (Folke et al., 2003). It is not easy to build a foundation for trust, however. Long periods of trust building and activities that foster respect among collaborators are often needed before successful management can occur (Pretty and Ward, 2001). Trust may be eroded through lack of communication, lack of engagement, and temporal and scale issues. Some ways to build a foundation of trust are through public meetings; one on one interactions between stakeholders and agencies; field trip demonstrations of project successes; collaborating with NGOs as bridging organizations to cross between local actors, communities, a multi-scaled institutions (Folke et al., 2005); and relying on existing networks with trusted agents as a place of dialogue. In the example of the Clark Fork River in western Montana (Metcalf et al., 2015), trust was built early in the process of a dam removal in the Milltown community. Stakeholders were engaged through public meetings, by NGOs and agencies engaging in one-on-one interactions, and through the use of citizen action groups. The end result was a successful restoration project that created a sense of place for residents and was marked by a mutual respect between community members and agencies. The long-term sustainability and efficacy of high collaborative initiatives are worth the risk of investing resources in trust mechanisms (Reed, 2008).

4.3. Adaptive governance

Adaptive governance is crucial for supporting the self-organizing aspects needed for improved resilience and adaptability. Adaptive governance refers to social agency for reorganization, in which key individuals, groups, and institutions self-identify, form, and connect together at multiple organizational levels (Folke et al., 2005) to make decisions and share power (Lebel et al., 2006). If adaptive governance is done successfully, costs for collaboration and conflict resolution can be reduced, and beneficial outcomes can include enhanced equity among stakeholders, efficiency of decision-making, legitimization for actions, and increased local-level capacity (Plummer and Fitzgibbon, 2004). Adaptive governance can help equalize power dynamics among stakeholders, with regard to how it manifests and influences collaboration and learning (Armitage et al., 2008) to allow for enhanced transdisciplinary capabilities (e.g., co-development of knowledge, stakeholder engagement) and institutional change. By decentralizing some decision-making, it is possible to be more reactive and adaptive to change.

Adaptive governance has theoretical foundations in the field of participatory approaches that still debates which factors lead to sustained change and success of a participatory process (Hickey and Mohan, 2004). Participatory approaches emphasize that stakeholders must demonstrate a high-level of mobilization (e.g., self-mobilization, Pretty et al., 1999), including having the leadership and support for that leadership to develop a shared vision, resolve conflict, and guide the self-organizing process. Adaptive governance, therefore, is most successful in contexts where considerable work has been done to empower stakeholders, and the stakeholders themselves seek to create change and transformation in their community. To provide capacity for individuals to learn and act on their experiences, particularly within the framework of institutions, social networks are helpful for increasing access to resources and conserving social memory, which stores experience and knowledge useful for adapting to change. High flexibility in social arrangements allow for adaptation of rules, institutions and

incentives in the face of change (Brown, 2003). Legislation must create social space for adaptive governance of environmental management, so that it can be more flexible to broader stakeholder perspectives and participation, and manage for adaptive capacity and resilience (Olsson et al., 2004).

4.4. Monitoring systems

Consistent social and ecological monitoring is needed to collect reliable datasets for informing theory and application, and assessing success of interventions. Monitoring standards must be developed to consider scales across disciplines, so that coupling between different disciplinary monitoring efforts can occur. For example, monitoring of fish populations must be done at the same spatial scale that fishing regulations are enforced. Scenario building to understand future trajectories for a system can help with selecting the best indicators for monitoring that is informative for supporting resilience goals (Cumming et al., 2005). Indicators must be cost-effective and efficient to monitor, as well as reflective of environmental feedback dynamics (Olsson et al., 2004). Greater institutional investment is needed to support monitoring that is necessary for increased capacity for adaptability (Benson and Garmestani, 2011a). Creating databases of standardized information about social-ecological systems is also valuable for efforts seeking to scale up and across broad scales.

Community-based monitoring, citizen science programs, and collaborative efforts are potentially powerful ways to monitor environmental systems.Community-based monitoring relies on non- scientist, local users to engage in monitoring activities, which may also include determining the goals of a monitoring project, specific monitoring methods, and of environmental change (Alessa et al., 2015). Many agencies and organizations across the nation are adopting such community-based monitoring strategies. Examples range from Community Based Observing Networks for Situational Awareness (CBON-SA) by the University of Idaho with the Arctic Domain Awareness Center in Alaska to bird counts initiated by the National Audubon Society. Another example within land management is the site steward program whereby U.S. Forest Service personnel train and rely on citizens to help monitor the conditions of cultural resources in their surrounding national forests. Community-based monitoring and citizen science are helpful for producing, incorporating, and sharing both top-down and bottom-up knowledge in management of social-ecological systems. Incorporating stakeholders in data collection and co-development of knowledge can make co-management of SESs and dissemination of management tools and techniques possible. Collaborative networks, like the Mountain Social-Ecological Observatory Network of the U.S. Intermountain West region (MtnSEON, 2014b), are useful for connecting dispersed monitoring efforts together to build capacity among monitoring initiatives, standardize approaches, cover greater spatial scales, and allow for broad datasets to be collected faster and more efficiently than most monitoring efforts (Peters et al., 2014).

4.5. Education and training

Changing the culture and institutional norms for environmental stewardship and governance requires education and training that specifically builds capacity among environmental management practitioners in regards to using systems thinking and SES approaches in management. As SES management is a new and quickly evolving concept, education initiatives can serve as a medium to bring together diverse partners to further develop SES tools and techniques for addressing environmental challenges. Educational and training programs are available to address specific aspects of an SES environmental management framework, such as community mobilization to support adaptive governance (e.g., Village Earth, 2016), systems thinking (e.g., Donella Meadows Institution, 2016), facilitation and conflict resolution (e.g., Natural Resource Leadership Initiative, 2014), community-based management (The Center for People and Forests, 2011), and SES for environmental managers (e.g., Social-Ecological Systems Training and Education Program, MtnSEON, 2014c). Facilitation, leadership, and community building skills are needed to maintain collaborative relationships through the life of a management project (Goring et al., 2014), but such skills are rarely taught in graduate education for environmental management or through formal job training (Blickley et al., 2012). Skills for collecting data for indicators useful for monitoring social-ecological systems, such as complementary social and biophysical variables at the same scales, are also needed.

5. Conclusion

In this paper, we emphasize the importance of utilizing systems thinking, transdisciplinary approaches, and resilience science to help address current challenges in environmental management. We have outlined a framework for an SES approach to environmental management by describing the major concepts that can be applied to management situations. We highlight that the SES concepts of a systemic worldview (e.g., transdisciplinary approaches, adaptive governance, monitoring systems, and education and training programs) can help meet specific environmental challenges. Stakeholder engagement is well-emphasized in our framework, as we believe that isolation between different initiatives, expectations, and priorities is often the underlying cause of many current challenges in achieving successful and sustained results in environmental management. By providing a framework that integrates both social and biophysical components into one management approach, SES environmental management offers great potential for more sustainable outcomes of interventions.

Implementing SES theory in practice can help environmental managers predict and adapt to environmental change (e.g., preparedness), so that the unintended consequences of management decisions can be avoided. An SES environmental management approach can assist managers to address complex systems holistically by considering multiple, interacting variables, and reduce compartmentalization of knowledge and resource areas by including diverse stakeholders in making management decisions. By implementing SES concepts in an integrated way, a management initiative can gain a systemic understanding of the social and ecological components that interact within the domain of an environmental management target. For example, engaging stakeholders in co-development of knowledge through transdisciplinary approaches can improve the systemic worldview of an initiative and lead to a more comprehensive plan for monitoring outcomes of an intervention (e.g., collection of complementary biophysical and social data). The improved understanding produced by integration of SES concepts allows managers to better predict both the biophysical and social reactions of the system (i.e. consequences) to management intervention. For sustainability of these approaches and intervention outcomes, education and training in SES approaches are needed to build capacity among environmental management practitioners. Taken together, the SES concepts presented in this paper can be integrated into a management approach to better understand, and thus avoid, unintended system reactions and consequences of management decisions.

Overall, the true value of an SES approach to environmental management is to develop a new culture for science. By adopting new approaches, such as co-development of knowledge, transdisciplinary processes, and stakeholder engagement, as part of the

standard workflow of research and management, we can change the overall context for how science is done. Developing such fundamental cultural aspects among both scientists and environmental managers can help to cross bridges between scientific knowledge and decision-making, and provide a supportive framework to help environmental management towards overcome its current challenges. By using an SES science approach, environmental managers can meet their specific goals, while still achieving the broader resilience objectives of large-scale social-ecological resilience and environmental sustainability.

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