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Insight, part of a Special Feature on Panarchy: the Metaphor, the Theory, the Challenges, and the Road Ahead

Implications of Panarchy for ecosystem service research: the role of system dynamics in service delivery

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ABSTRACT. Panarchy illustrates the dynamic nature of social-ecological systems and their nestedness and interconnectedness through time and space. Although there have been great advances in ecosystem service (ES) research, it has only rarely integrated dynamic interaction of components in social-ecological systems (SES). We explore how Panarchy theory, and especially its detailed reflections on change and system dynamics, could help ES research to better capture the dynamics of change into its fundamental assumptions. We do this by outlining four main conclusions of Panarchy theory: multiple states, the adaptive cycle, variances of the adaptive cycle, and change and persistence for sustainability. We illustrate how these aspects can be incorporated in ES research and conclude with recommendations for the field.

Key Words: *change; complexity; resilience; spatial; temporal*

INTRODUCTION

The world is changing faster and more fundamentally than ever witnessed before by humans (Steffen et al. 2011, 2015). Although the well-being of many people around the planet has improved (Raudsepp-Hearne et al. 2010*a*, United Nations 2015), this improvement comes at a cost to our natural systems: habitat decline, biodiversity loss, climate change, and increased eutrophication and pollution of water systems. Because human and natural systems are closely interlinked in social-ecological systems (SES) that operate at multiple scales, changes to social systems affect natural ones, and changes to natural systems affect social ones. Such SES are complex, adaptive systems that are interdependent and interact at multiple scales (Bouamrane et al. 2016).

In their seminal book, Gunderson and Holling (2002*a*) introduce Panarchy as a term to reflect the adaptive and evolutionary nature of SES and to highlight their nestedness and interconnectedness through time and space. The authors stress that in SES, materials and information flow in multiple directions. As such, the concept of Panarchy helps to understand changes in SES, which are complex and dynamic, often featuring not only interactions of system components but changes in those interactions, and not a single consistent direction of flow.

Ecosystem services (ES) are the diverse ways nature contributes to human well-being (MEA 2005). Ecosystem services research was developed, in part, to document and understand the effects of environmental change on ecosystem function and human well-being, and the effects of human actions on the environment (Carpenter et al. 2009). It has been successful at bringing attention to the interlinked nature of SES not only through scientific papers, but also through international endeavors such as the Millennium Ecosystem Assessment (2005) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019). Although this work started with a focus on the effects of ecosystem change on ecosystem function and human well-being, more recent papers have featured bi-directional feedbacks between social and ecological systems, showing how human decisions and actions impact ecosystems as well (Raymond et al. 2013, Reyers et al. 2013, Mace 2014).

Despite great advances in ES research over the past decades, this work has only rarely investigated change in SES through time and space (Rau et al. 2018, Winkler et al. 2021*a*). Two decades ago, leaders of the Millennium Ecosystem Assessment found that the theories and models available at that time only poorly incorporated feedbacks between ecological and social systems, and thus often failed to anticipate thresholds of change, fundamental system changes, and regime shifts (Carpenter et al. 2009). Since then, multiple publications outlining research frontiers in ES science have repeatedly called for more consideration of uncertainty (Nicholson et al. 2009), temporal and spatial dynamics (Bennett et al. 2015), and non-linearities (Koch et al. 2009, Bennett 2017). Most recently, authors of the Global Assessment of IPBES concluded that biodiversity and ES are decreasing, and transformative change is needed, calling for research to pay more attention to drivers of change (Díaz et al. 2019). Currently, ES research's ability to inform decision makers on how to effectively govern our changing world is limited by the lack of integration of change into ES research (Abson and Termansen 2011, Reyers et al. 2013, Pascual et al. 2017, Rau et al. 2018, 2020, Stritih et al. 2019).

We explore how Panarchy theory, and especially its detailed reflections on change and system dynamics, could help ES research to better capture the dynamics of change. We do this by outlining four main conclusions of the book *Panarchy* (Holling and Gunderson 2002*a*) that relate to the dynamics of change in SES. We follow the order the conclusions are presented in the Panarchy book and discuss how each of these conclusions can be integrated into ES research. We acknowledge that some aspects related to change and dynamic systems have been studied in the context of ES, such as trade-offs (Raudsepp-Hearne et al. 2010*b*) and spatial interactions of ES (Schröter et al. 2018). However, Rau et al. (2020) found in their review of almost 300 ES research

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papers that only 2% covered temporal dynamics. Finally, we provide practical recommendations to help ES researchers incorporate and account for change in their research, allowing them to generate more nuanced findings about the dynamics of ES in complex SES.

MULTIPLE STABLE STATES ARE COMMON IN MANY SYSTEMS

> *Abrupt shifts among a multiplicity of very different stable domains are plausible in regional ecosystems, some economic systems, and some political systems.* (Holling et al. 2002*a*:395)

This conclusion highlights that social-ecological systems can exist in multiple stable states. Each state is characterized by a specific combination of ecological and social components that are expected to persist in the absence of perturbation. For example, shallow lakes can exist in a clear or a turbid form (Scheffer et al. 1993, Hilt et al. 2017; Box 1). Shifts between states can be gradual or can be sudden and dramatic (Scheffer et al. 2001, Scheffer and Carpenter 2003). Sudden shifts may involve tipping points or other nonlinear dynamics. Once a system has shifted to a new state, a return to the previous state may not always be possible (Walker and Salt 2006, Bohensky et al. 2015). The exact tipping point at which a system shifts into another state can be difficult to predict (Biggs et al. 2012).

This Panarchy conclusion suggests that ES researchers should keep in mind that an ecosystem may not stay in the same state and that this might change ES supply and demand in ES assessments (Table 1). Different states of an ecosystem may provide vastly different combinations of ES, often referred to as ES bundles (Raudsepp-Hearne et al. 2010*b*). For example, the change of a lake from an oligotrophic state to a eutrophic state is likely to have important consequences for multiple ES, such as fish (Willemsen 1980), drinking water (Palmstrom et al. 1988), or recreation (Keeler et al. 2015). So far, ES research has not addressed the effects of state shifts on ES bundles, or whether the supply of individual ES in ES bundles will change in parallel or in different directions when the state shifts (Table 1). Research on the provision of ES bundles through time suggests that each ES within any given bundle can change differently from other ES in the bundle because of the different drivers influencing its provision (Renard et al. 2015, Braun et al. 2018). There are a variety of studies that have assessed ES bundles occurring in related locations at the same time (e.g., Raudsepp-Hearne et al. 2010 a or b?, Su et al. 2012, Hamann et al. 2015, Qiu et al. 2021), which could give us indications on different stable states of ecosystems. However, there is no analysis on whether the different performances of the bundles are connected to different states of the system or other effects (e.g., different phases, different sets of drivers). Literature around space-for-time substitution in ecology have raised concerns about such approaches for over 30 years (Pickett 1989, Damgaard 2019).

To date, the vast majority of ES research has used static snapshots of ecosystems to assess ES supply or demand (e.g., the matrix approach developed by Burkhard et al. 2010). Few studies have examined the temporal changes (short- and long-term) of ES and this may have important impacts on findings. Tomscha and Gergl (2016) showed that assessing only one point in time compared to a time series could culminate in misleading results because reference data were missing. Those that have considered time have found interesting results of changing ES. For example, Laursen et al. (2021) found that in the winter, the spatiotemporal overlap of waterbirds and recreational activities is less than in the summer. Vierikko and Yli-Pelkonen (2019) researched the seasonality of supply and demand of recreational ES provided by a lake and showed that the supply remains similar while the demand changes. They also highlighted that the socio-cultural values change with seasons. Renard et al. (2015) looked at the changes of nine ES between 1971 and 2006 in the Canadian Monteregie region and found that all of them changed significantly over time. However, although some research exists on temporal change in ES, the research has generally not focused on multiple stable states, but rather on ES recovery after disturbance (Sutherland et al. 2016) rather than on how the ES supply and demand might change in different stable states of an ecosystem.

When ES research has accounted for ecosystem dynamics, it has typically been in the form of predictable and linear trends (Rau et al. 2018). However, this Panarchy conclusion reminds us that it is inappropriate to assume that a current state of ES supply and demand is a permanent property of the system and thus, we cannot assume in management and governance decisions a stable production of ES over long periods of time. The conclusion may be especially true in the case of “coerced regimes” (Rist et al. 2014, Angeler et al. 2020). Coerced regimes occur when people artificially hold a system in one state to provide specific ES. For example, agricultural systems are often coerced into a specific state that maximizes crop production through several interventions such as the addition of fertilizers, pesticides, and herbicides (Box 1). Coercion of this type can decrease the resilience of a system, increasing the need for continued human inputs or the chance that a system will flip into an alternate state that is less desirable in terms of the ES provided. More research is needed on the impact of such coercion on ES and on when coercion increases the likelihood of flipping to an alternate state with less preferable ES. (Table 1).

Box 1. Altiplano landscape, Bolivia

Due to the harsh climate of the Altiplano region of Bolivia, quinoa remains the only agricultural product that reliably grows there (Jacobsen 2011). Traditionally, quinoa production works on a two-year cycle in which the Altiplano landscape transitions through multiple states that provide different ecosystem services (ES). In the first year, the land is left unseeded so that rainfall accumulates in the soil providing a water reserve for the crops. In this state, the system provides ES such as erosion regulation, soil fertility, and pest regulation. In the second year, quinoa is planted, which involves land clearing, ploughing, sowing, fertilizing, harvesting, and cleaning (Jacobsen 2011, Winkel et al. 2016). In this state, the system’s main ES are quinoa as well as regulating ES such as erosion control.

In recent decades, global and local drivers have put pressure on the functioning of the quinoa system in the Altiplano region. Growing global demand for quinoa has led many farmers to reduce the length of time that the land is left unseeded to increase quinoa production (Jacobsen 2011). In addition, the influx of migrant workers has enabled quinoa production to intensify but has also led to land-use reforms that have forced the system to reorganize (Winkel et al. 2016). This has extended the length of the exploitation phase but also increased environmental degradation, which may lead to the eventual collapse of the ecosystem if changes in the management regime do not occur (Jacobsen 2011).

The quinoa production system of the Altiplano landscape provides different ES at different spatial levels. For example, quinoa is produced by individual plants, although cultural identity operates primarily at the landscape level. Many decisions, such as the length of the fallow period, occur at the farm level, but these decisions trigger changes at a variety of scales that influence non-target ES, including soil fertility, erosion regulation, and quinoa supply. The global demand for the one ES (quinoa) thus has negative impacts on the local ecosystem and the other services provided (e.g., erosion control, soil fertility), ultimately impacting the whole Altiplano ecosystem.

Identifying the stages of the adaptive cycle within the Altiplano system at different levels and how these adaptive cycles interact can help determine how to implement or alter the management practices to prevent the system from collapsing and the loss of ES that are crucial for the Altiplano landscape system.

Wildfires in the North American West

A well-known example of the adaptive cycle is the wildfires in the western United States (Higgins and Duane 2008, Allen and Holling 2010, Littell 2018). The exploitation phase is a period of growth for the early successional species. In the conservation phase, biomass accumulates over a longer time, which creates vulnerability to fire due to the increase in fuel loads and drought. This biomass includes not only the wood but also, for example, pinecones that get buried in the soil surrounding the trees. In the release phase, the degree of connectedness is high due to interdependencies of growing vegetation across forest floors and upward into tree canopies, which makes the system fragile to a collapse and resistant to new species and outside interventions (Higgins and Duane 2008). In parallel, through accumulation (e.g., biomass in a forest) the potential for change is increasing. This combination of fragility and potential change means that any disturbance can shift the system into a different state. Forest fire or pest/disease can be triggered in the release phase. The energy stored in extra fuel loads and drought during the conservation phase is unleashed. In the reorganization phase, the system restructures the ecosystem or people respond to the event with management actions (Littell 2018). The seeds of the cones in the soil allow new pine trees to grow back (Johnstone et al. 2016). This process describes the natural adaptive cycle in which naturally occurring fires happen in first-generation forests with multi-aged stands: the fire clears out the ecosystem and starts a new cycle.

The cycle also illustrates the different speeds of the four phases of the adaptive cycle. The lodgepole pines drop pinecones containing seeds in the soil surrounding them over a long time period, creating seed banks that act as a memory of the forest (Johnstone et al. 2016). Over short time spans, fires can burn through forests, entirely changing the composition of the system and melting the serotinous cones, which releases their seeds. The memory of the ecosystem in the form of the seed bank allows the short-term phase of fire recovery to proceed to a new exploitation phase. This ecosystem's sustainability relies on both short-term changes and disturbances that influence the long-term, persistent memory of the lodgepole pine landscape over time.

If humans alter the ecosystem, for example, through timber extraction or expansion of settlement, the parameters of the ecosystem shift to another state. When a fire comes through the ecosystem, the ecosystem is heavily influenced by humans. Certain types of forest management that clear-cut and remove trees from the system cause new generations of even-aged forest stands. Without prescribed/cultural burning or other fire management, this regrowth can cause the fuel loads to densely build up near human settlement. One reason for the lack of active forest management is that people live too close to the forested areas and thus prescribed/cultural burns, or other preventative management are not performed. This leads to a situation of collapse when a fire develops into an extreme or severe fire and comes close to human settlements. In the reorganization phase, the human system can restart with novel fire management and prevention techniques, however the loss in the release phase in both social and ecological capital might have been extremely high and make the recovery hard. Indigenous management regimes used small-scale fires to prevent larger scale fires from occurring (Russell-Smith et al. 2013), which shows that human management can be aligned with the natural adaptive cycle.

Freshwater lakes

Shallow lakes, which can exist in either clear or turbid forms (Scheffer et al. 1993, Hilt et al. 2017), are classic examples of an ecosystem that can exist in multiple states. The presence of submerged vegetation is a key variable in determining the state of a lake. Vegetation enhances water clarity, leading to greater likelihood of clear water states, via suppression of algal growth and settling of particles. Thus, submerged vegetation often characterizes clear and shallow lakes. Perturbations such as storms can shift a lake without submerged vegetation into a turbid state. Additionally, at high-nutrient levels (tipping point), algal growth can no longer be suppressed by vegetation, and the lake shifts into a turbid state. In this state, submerged vegetation can no longer thrive due to light limitations. Nutrient levels (tipping point) must be dramatically reduced to return the lake to its clear state. Many studies focus on the factors that stabilize the different states. For example, Rip et al. (2006) studied the role of birds in the state of two shallow lakes in a nature reserve in the Netherlands, in which external phosphorus loads were reduced, finding that light was a more important factor than close-by grazing birds. However, very few studies look at the consequences for habitat, ES supply, and demand in and provided by these different states of an ecosystem (Hilt et al. 2017).

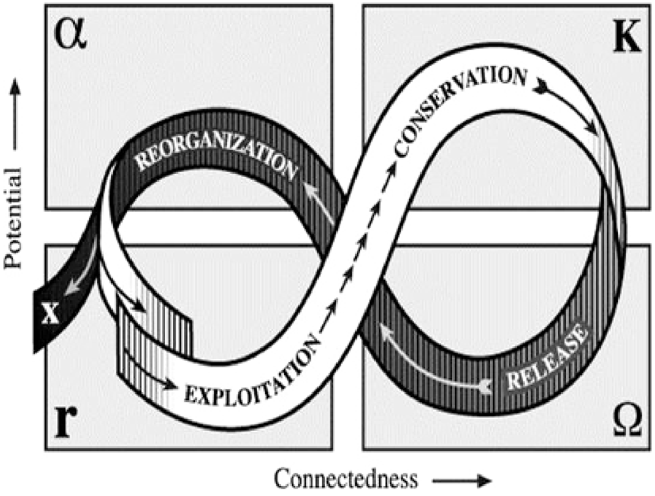
THE ADAPTIVE CYCLE IS A FUNDAMENTAL UNIT OF DYNAMIC CHANGE

> *An adaptive cycle that aggregates resources and periodically restructures to create opportunities for innovation is a fundamental unit for understanding*

> *complex systems from cells to ecosystems to societies to cultures.* (Holling et al. 2002*a*:398)

The second Panarchy conclusion stresses that the adaptive cycle is a key element of Panarchy that describes change in social-ecological systems through a sequence of four phases: exploitation (r), conservation (K), release (omega), and reorganization (alpha) (Fig. 1). Three properties shape how a system moves through the different phases of the adaptive cycle: (1) accumulation of potential (i.e., resources, such as biomass, social relationships, or economic capital), (2) the degree of connectedness of the system (i.e., the amount of influence the system can exert over external variability), and (3) the resilience of the system (i.e., a measure of a system's vulnerability to unexpected or unpredicted shocks; Holling and Gunderson 2002*b*). The interplay between these three properties and the four phases creates the dynamic change of a system.

Fig. 1: The adaptive cycle throughout its four phases: exploitation, conservation, release, and reorganization. The phases vary in the level of connectedness (x-axis) and potential (y-axis). From *Panarchy* edited by Lance H. Gunderson and C. S. Holling. Copyright 2002 Island Press. Reproduced by permission of Island Press, Washington, D.C. https://islandpress.org/books/panarchy



Different change processes play out in each phase of the adaptive cycle. The exploitation phase (r) is characterized by low connectedness between controlling variables and relatively low levels of resources (e.g., biomass, human capital). Low connectedness leads to relatively weak interactions between components within a system and to system behavior that is controlled more by external forces than endogenous ones. In the slow progression from the exploitation phase to the conservation phase (K), the connectedness of the system components increases, and resources accumulate. Increased connectedness means that system behavior is increasingly driven by interactions among internal system components and less by external variability. The other three progressions, from conservation to release (omega), release to reorganization (alpha), and reorganization to exploitation, are faster. Resources accumulated in the conservation phase (K) are suddenly freed in the release phase (omega), for example, by a fire, a pest, or an economic crisis. The low connectedness and the relatively high potential in the reorganization phase (alpha) increase the likelihood that the system develops in novel configurations as it moves into a new exploitation phase (r). North American forest fires exemplify the phases through time (Box 1).

Thus far, most ES research has not directly engaged with how supply and demand might change across phases of the adaptive cycle (Table 1). The four phases of the adaptive cycle might affect the provision of and demand for ES if ES are provided and demanded in varying amounts depending, in part, on the interaction among accumulation of potential, connectedness of the system, and resilience. There are reasons to suspect that ES supply and demand may behave differently in the slower exploitation and conservation phases compared to the rapid phases of release and reorganization. For example, during forest fires, timber is no longer supplied although the heat helps cones to release their seeds (Box 1). We speculate that the human demand for certain essential ES (e.g., food) remains relatively stable throughout the different phases, whereas the supply varies. Special attention should be given to the question of how to ensure that essential ES are maintained in the phases of change (release and reorganization phase). Underlying stocks (e.g., natural and human capital) might be potential indicators for the phase in which the system is. Through natural resources management, ES supply might be stable but deplete ecosystems and thus threaten the potential for future supply. Thus, the system might be moving to the edge of the conservation phase into the release phase (Isbell et al. 2015).

A key step in increasing understanding of ES would be to develop measurements that help to assess which phase of the adaptive cycle a system is currently in, and how this affects ES supply and demand. This calls for ES research to consider more complex and dynamic interactions that can exist in a system with different phases. Although in the first Panarchy conclusion the state of the system is at play (e.g., clear vs. turbid lake), a system in different phases of the adaptive cycle is more likely to see changes in ES supply and demand (e.g., after a wildfire; Box 1). With more understanding about ES supply and provision across different phases of the adaptive cycle, we can also learn about ES bundles in the different phases and if and how essential ES services are provided in all phases (Table 1).

Moving from mapping to monitoring ES over time can help to identify the phase a system is in and allow adaptive management strategies that can buffer and prepare for potential changes. For example, monitoring of phosphorus over a century allowed not only phosphorus management to change their way of doing things, but also showed that the effects were reduced phosphorus levels (MacDonald and Bennett 2009). Monitoring ES might also allow us to understand if ES play a role in the process of the adaptive cycle in natural, but also coerced states (Table 1). Lautenbach et al. (2012) analyzed data on global pollination benefits between 1993 and 2009 and identified early warning signs of conflict between pollination services for food production and other land uses that could create turmoil in food production systems. Human and non-human perturbations can affect the supply and demand of ES, which in turn can influence the process

Table 1. Potential research questions occurring for ecosystem services (ES) research based on the four Panarchy conclusions.

Multiple stable states are common in many systems	Which ES are supplied and demanded in different stable states of an ecosystem? How do bundles of ES change over time? Can ES in the same bundle change independently, or does the whole bundle come and go together? Is the timing of the shift in ES the same for all ES in a bundle? What are the mechanisms behind shifts in ES that accompany a shift between different stable states? For how long can a system be held in a coerced state to provide particular ES? Are there any implications of the ES lost during coercion for the resilience of the overall system?
The adaptive cycle is a fundamental unit of dynamic change	How does ES supply and demand change in the different phases of the adaptive cycle? Can we learn from the ES bundle being supplied and from changes in this supply over time; what phase of the adaptive cycle are we in or get clues about how the system and its ES might change in the future? What does this imply for management of SES? Which ES are essential for people in each phase of the adaptive cycle? Do ES supply and demand (and their interactions) play a role in the progression of the adaptive cycle?
Not all adaptive cycles are the same; some are maladaptive	Which ES are supplied by which variation of the adaptive cycle? How do human intentions collide with the intentions of other living beings concerning natural capital and the potential for ES supply? How can management and governance ensure ES are supplied in phases of release and reorganization? What role does ES management play in creating traps in maladaptive systems? Which variables should be monitored to cover drivers of ES change and to describe the context of the system?
Sustainability requires both change and persistence	How can we foster diversity in the management and governance of ES supply? How are ES part of the memory of an SES? What is the role of memory and of revolt in the supply and demand for ES? To what degree can cultural ecosystem services hinder systems to overcome maladaptive cycles?

of the adaptive cycle. Forest management might remove understory and forest floor vegetation and with it the cones that are essential for the reorganization phase after a fire (Box 1).

NOT ALL ADAPTIVE CYCLES ARE THE SAME AND SOME ARE MALADAPTIVE

> *Variants to the adaptive cycle are present in different systems. These include physical systems with no internal storage, ecosystems strongly influenced by external pulses, and human systems with foresight and adaptive methods to stabilize variability. Some are maladaptive and trigger poverty and rigidity traps.* (Holling et al. 2002*a*:401)

In this conclusion, Holling et al. (2002*a*) identified four variations of the adaptive cycle that differ in their levels of complexity. First, there are physical systems, which, in the view of Western science, have no ability to create and no intention to change a system in a specific way: (1) a chemical reaction proceeds in the same way every time provided it occurs under the same conditions, (2) living systems in which individuals do not control or predict changes in their environment, but have evolved ways to passively adapt to variations in their environment, such as in semi-arid savannas that come to a bloom during rainy seasons; (3)living systems with components that adapt and create novel responses in reaction to changing conditions. These components of a system actively influence the system itself. Beavers, birds, and reef-building corals are examples in that they all influence the processes of their ecosystems. And (4) human systems with components of agency, like foresight and intentionality (i.e., people have objectives), which both create and control change. In this case, humans act as the drivers of change in the system by self-organizing, generating novel responses to anticipated or imagined changes, and actively adjusting the adaptive cycle through their actions and decisions. For example, farmers can prolong the growing seasons of crops through their management actions (i.e., coerce the system to remain in the exploitation phase; Box 1).

This conclusion points to the value for ES research to investigate different types of drivers of change and to consider the potential for those drivers to change the system itself. Although human drivers (fourth variation) are considered often in social-ecological systems, other factors also function as drivers of ES supply and human well-being. Drivers originating from the first and second variations of the adaptive cycle (physical systems and systems without control) are seemingly controllable for humans. For example, humans have altered soil composition for agricultural exploitation. Although people have felt in control of these drivers for a long time, Panarchy suggests that we might have underestimated the power of these non-human drivers. For example, forest fires can massively change ES supply (Pausas and Keeley 2019). The third variation (living systems with intention) can even ultimately undermine human interests. Sea otter populations along the North American Pacific Coast directly affect carbon sequestration and food provision (shellfish) to local communities (Levine et al. 2017, Thierry et al. 2021). Depending on human preferences and needs, the activities of the sea otters can compete with human needs for food and economic development. Consequently, it is important to consider a range of different potential drivers of change in ES assessments.

Different types of drivers are reflected in ES frameworks such as the IPBES framework, which recognizes three types of drivers: nature, anthropocentric assets, and institutions (i.e., rules, regulations; Díaz et al. 2015). The combination of different drivers shapes the context in which ES are provided. Thus, changes in the drivers have consequences for the ES. Consequently, assessing ES supply alone is not enough. Indicators for the different potential drivers of change are important to understand change in relation to ES better (Table 1).

People are probably the main indirect and direct drivers of change in environmental systems. The ES literature increasingly acknowledges this by not only focusing on the assessment of ES, but also on management and governance of ES (Sattler et al. 2018, Winkler et al. 2021*b*). Management and governance have repeatedly been identified as a major driver of changes in ES provisions (e.g., Renard et al. 2015, Garrah et al. 2019). However, questions remain concerning the role of management and governance of system's shifts in states or the process through the adaptive cycle and the stable provision of essential ES (Table 1). One way forward is to implement adaptive and anticipatory management and governance that have the possibility of (unexpected) change as a cornerstone of their thinking (Guston 2014, Boyd et al. 2015).

This third Panarchy conclusion also highlights maladaptive cycles, which are conditions that maintain a system in an undesired state (Carpenter and Brock 2008). This definition highlights the normative dimension of the concept because probably in most maladaptive cycles, entities exist that benefit from the current cycle. Certain drivers (in this context also called traps) are powerful enough to keep systems in maladaptive cycles. The drivers can be human (e.g., poverty) or non-human (e.g., returning or invasive species). Systems in a maladaptive cycle lack the properties to shift into another cycle. Thus, the properties of the system reinforce the system in the maladaptive cycle.

We define maladaptive systems in the context of ES supply as situations in which the ES supply is negatively changed either relating to equitable access to ES or for the natural ecosystem to maintain ES supply. Invasive species with no natural enemies spread in ecosystems, potentially leading to a shift of the stable state of the system. These species can be understood as drivers that reinforce a maladaptive cycle. Another example are disservices arising from "redlining," a racially motivated designation of low-income, African-American neighborhoods as "high investment risks" by the US Federal Home Owner Loan Corporation (HOLC) in the 1930's (Nardone et al. 2020). Redlining has triggered a maladaptive cycle of urban development. Today, extreme disparities exist in the supply of ES and disservices between neighborhoods considered high or low investment risk in the early 20th century. In 94% of US cities studied, historically redlined neighborhoods have significantly higher summertime temperature anomalies, increased the urban heat island effect, and reduced potential for urban greening (Hoffman et al. 2020). As such, ES management and governance function as traps for a maladaptive cycle. For this reason, it is important to continue research on questions such as environmental justice, power, and equity related to ES (e.g., Daw et al. 2011, Jenerette et al. 2011, Laterra et al. 2018) to identify maladaptive systems and find strategies to overcome them (Table 1).

SUSTAINABILITY REQUIRES BOTH CHANGE AND PERSISTENCE

> *Sustainability is maintained by relationships among a nested set of adaptive cycles arranged as a dynamic hierarchy in space and time - the Panarchy.* (Holling et al. 2002*a*:402)

This conclusion states that sustainability is maintained through the interactions between spatial and temporal scales. In the Panarchy book, sustainability is defined as "the capacity to create, test, and maintain adaptive capability" (Holling et al. 2002*b*:76). This conclusion and the definition of sustainability differ from more common definitions (e.g., the Brundtland definition) in that it underlines the importance of interaction and change for the maintenance of any stable state (or to shift to another more desired state) rather than the maintenance of a certain equilibrium. Adaptive cycles on higher levels of the Panarchy as well as slowly changing variables maintain the memory of the system to maintain adaptive capacity. Cycles on lower levels and more quickly changing variables allow for innovation and fast recovery after disturbances. Together, these nested adaptive cycles maintain sustainability within the SES.

The idea of sustainability presented in this conclusion means that we cannot assume an ability to hold a system in a constant stable state. Thus, we cannot aim to identify a set of conditions that will provide a specific (desired) amount of ES over medium and long time periods without change. When acknowledging constant change, two implications reveal themselves for ES research. Ecosystem services researchers need to be able to understand ES and SES in a way that allows for changes at small scales by promoting diversity and innovation, while preserving those parts of the system that provide the memory needed for a successful reorganization phase to conserve critical and irreplaceable natural capital and cultural institutions.

This poses a fundamental challenge when managing ecosystems for the delivery of ES. Ecosystem services demand is relatively fixed because people need certain ES like food or clean water, and they cherish cultural ES such as sense of place. This means that systems are typically managed to ensure a steady and predictable supply of specific ES, which is likely to create a coerced system (Rist et al. 2014). However, as this fourth conclusion states, systems change, and as changes occur, the provision of ES might also change, which creates problems for the relatively static human systems that rely on consistent ES supply. Diversity and innovation in management can be pathways to react to changing conditions (Table 1). For example, finding ways to foster diversity and innovation in the management systems might help maintain appropriate levels of ES supply while allowing system change. Traditional uses of ecosystems were often much more adapted to local conditions than today's homogenized management, and thus may offer a wider variety of potential pathways to deliver desired ES during system change, or pathways for human systems to adapt to changes in the ES provided (Barthel et al. 2010). Research is needed to better understand which traditional and local approaches are useful and transferable to other contexts, and whether it is possible to move knowledge and traditions among places in an ethical and responsible manner.

In ES research, there has been relatively little attention given to changes in people's underlying values toward ES over time. Other environment related studies have found changes in attitudes of people over time, e.g., attitudes toward wind energy (Eltham et al. 2008) and human-made climate change (Milfont et al. 2017). However, most of this work has been conducted in developed Western countries, and results might be different in other places or cultures, such as communities practicing subsistence agriculture or Indigenous cultures with centuries-long connections to land and water. In the same vein, we should also consider how slow variables connected to ES (like sense of place) might keep systems from overcoming maladaptive cycles (Table 1) and with which means processes can be designed that nourish adaptation or transformation. For example, strong place attachment has been identified as one factor that hampers people's willingness to adapt or change despite looming climate conditions that will be untenable for continuous agricultural production (Marshall et al. 2016). It may be possible to use this knowledge to develop techniques to overcome the challenges of slow variables or even find processes that make a strength out of the weakness (Lyon 2014, Masterson et al. 2017).

Knowledge about what components provide memory in SES that deliver ES remains scant despite the fundamental role of memory in sustainability. Social-ecological memory links the physical (ecological) qualities to the social qualities (e.g., meaning of a place) with consequences for ES (Raymond et al. 2018). In the tradition of Panarchy thinking, memory is created and maintained through slow variables and through adaptive cycles at larger scales. Scale can imply temporal as well as spatial scale. Stocks such as natural capital, biodiversity, and human knowledge could be the components that hold the memory for ES supply. However, we argue that certain ES might be able to provide memory themselves if they are slower variables, e.g., erosion regulations or sense of place. The nestedness of the speeds of change for system components and services provides memory for different adaptive cycles.

WAYS FORWARD AND CONCLUSION

The four conclusions of the Panarchy book provide suggestions about how to explore and engage with the dynamics of ES and may help ES researchers to work on key knowledge gaps and questions for ES research (Table 1). The adaptive cycle implies a strong need for more dynamic approaches in ES research. Widening the scope from ES to other variables describing the social-ecological context will help identify the phase of an adaptive cycle a study system is in. In addition, taking the adaptive cycle seriously implies that management and governance of ES must prepare for change rather than focus on stabilizing systems that might be coerced or maladaptive. If the objective of ES research is not only to assess the potential for ES supply, but also to assess the realized supply of ES and learn how to govern ES supply sustainably (Abson et al. 2014), it would be short-sighted not to acknowledge normative objectives in our human activities and their effects on ES. Last, the interactions of different scales (e.g., local to international, short- to long-term) need our attention because they influence each other and create an additional level of complexity in SES.

Effective monitoring of ES can provide critical information for scientists to track temporal trends, to uncover spatial patterns, and to understand how multiple, interacting variables influence the supply and demand of ES in SES (Tallis et al. 2012). International organizations such as IPBES and GEOBON aim to identify and monitor essential ES variables to build common approaches for collecting data about ES over time. These big, internationally orchestrated efforts are needed because otherwise it will be challenging to obtain comparable data across many locations (Geijzendorffer and Roche 2013). Nevertheless, Panarchy suggests that in addition to collecting data on ES, scientists should also collect information about variables that describe the context of the system. These additional variables might help to identify patterns of causes across different systems that drive ES supply and demand. With the information about ES, ES drivers, and the SES, researchers will be able to not only assess ES as a snapshot, but also have information to start understanding the drivers and identifying patterns of change.

Another approach to start understanding dynamic effects in ES research is to produce long-term social-ecological data either by repeating existing studies or by implementing long-term monitoring. Ecosystem services researchers could examine the rich body of literature produced over the last 20 years (Costanza et al. 2017) and start repeating empirical studies in the same location with the same methods, which would enable researchers to identify changes in ES supply, flow, or demand across time in greater detail. Also, remote sensing could help to understand temporal changes (Braun et al. 2018). Long Term Ecological Research (LTER) sites can function as inspiration on how to set up research over long time periods in specific case studies (Mirtl et al. 2018). However, the specifics of how to assess social-ecological change vs. purely ecological change needs more academic consideration. Understanding the factors that led to previous changes might give scientists critical knowledge to project how different management scenarios could influence the delivery of ES in the future.

Finally, scenarios, both quantitative and qualitative ones, help researchers and decision makers consider potential future change. Both types of scenarios have been used in various research activities to think about the future of ES from the local (e.g., Hashimoto et al. 2019) to the global level (Chaplin-Kramer et al. 2019). Although a variety of scenario-based modeling tools exist, their relevance for policymaking is not always explicit (Rosa et al. 2020). Some quantitative, scenario-based models for ES integrate local knowledge, but then produce a static view into the future (e.g., Koo et al. 2018). Scenarios were presented in the Millennium Ecosystem Assessment; however, they did not explore social-ecological feedback and dynamic interactions. Currently, a task force at IPBES is developing new scenarios that take dynamic interactions and feedbacks into consideration (Rosa et al. 2017). Such scenarios can then illustrate that the future will hold unpredictable conditions for ES and point to the need to embracing change (Pereira et al. 2021).

We know that the world is changing, but the concrete consequences of change often seem to surprise us. Panarchy highlights the importance of thinking about systems as dynamic with components interacting in non-linear ways throughout adaptive cycles on different scales and provides new opportunities for ES researchers to offer meaningful insights for decision making in SES. Ecosystem services research should consider dynamic interactions, slow and fast changes, and consequences for management and governance to increase the resilience of SED and of the long-term, sustainable delivery of ES.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13254

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No data were collected or code written for this paper.

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