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Panarchy theory for convergence

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Abstract

Coping with surprise and uncertainty resulting from the emergence of undesired and unexpected novelty or the sudden reorganization of systems at multiple spatio-temporal scales requires both a scientific process that can incorporate diverse expertise and viewpoints, and a scientific framework that can account for the structure and dynamics of interacting social-ecological systems (SES) and the inherent uncertainty of what might emerge in the future. We argue that combining a convergence scientific process with a panarchy framework provides a pathway for improving our understanding of, and response to, emergence. Emergent phenomena are often unexpected (e.g., pandemics, regime shifts) and can be highly disruptive, so can pose a significant challenge to the development of sustainable and resilient SES. Convergence science is a new approach promoted by the U.S. National Science Foundation for tackling complex problems confronting humanity through the integration of multiple perspectives, expertise, methods, tools, and analytical approaches. Panarchy theory is a framework useful for studying emergence, because it characterizes complex systems of people and nature as dynamically organized and structured within and across scales of space and time. It accounts for the fundamental tenets of complex systems and explicitly grapples with emergence, including the emergence of novelty, and the emergent property of social-ecological resilience. We provide an overview of panarchy, convergence science, and emergence. We discuss the significant data and methodological challenges of using panarchy in a convergence approach to address emergent phenomena, as well as state-of-the-art methods for overcoming them. We present two examples that would benefit from such an approach: climate change and its impacts on social-ecological systems, and the relationships between infectious disease and social-ecological systems.

Keywords: Convergence science, Emergence, Resilience, Adaptive cycles, Transdisciplinary research, Social-ecological systems

Many of the immediate and complex problems facing humankind (e.g., pandemics, climate change) are difficult to address, because they unfold across social-ecological systems (SES) comprised of many components distributed across scales and often operating in a non-linear manner. Although the emergence of undesired and unexpected novelty (e.g., COVID-19) or of a new regime due to the sudden reorganization of systems at multiple spatiotemporal scales (i.e., regime shifts) are broadly expected (Drijfhout et al. 2015), the particulars will always remain difficult to predict because of the fundamental challenge of anticipating unknowns in interacting complex adaptive systems (CAS). This can pose a significant challenge to the development of sustainable and resilient SES (a type of CAS). Anticipating and coping with the surprise and uncertainty resulting from emergence requires

methods and approaches that are appropriate for assessing the dynamics and behavior of systems which are both SES and CAS. Six core organizing principles of SES/CAS and their implications for methods and approaches were recently put forward (Preiser et al. 2018), and this paper proposes a novel combination of approach and methods that accounts for several core attributes of SES as CAS (see de Vos et al. 2019 for a review of previously used methods in this arena). These are the need for scientific processes that can incorporate diverse expertise and viewpoints, a scientific framework that can account for the multi-scaled structure and dynamics of interacting SES, and a goal of addressing emergence as a fundamental feature of SES/ CAS. We argue that combining a *convergence* scientific process with a *panarchy* framework provides a pathway for improving our understanding of, preparation for, and response to emergence, and ultimately how global environmental change unfolds in the Anthropocene.

A characteristic of CAS is that collapse is endemic to system dynamics (Gunderson and Holling 2002). During collapse, bound resources and energy are released and thus available as the system reorganizes and then enters a new period of accumulation and growth (Allen et al. 2003; Jorgensen and Fath 2004; Beinhocker 2006). Collapse is often confined to smaller spatial and temporal scales within a system, as opposed to entire civilizations or ecosystems collapsing, but that may be changing with planetary-scale changes of social-ecological baselines. The increase in complexity in SES over the course of human history has tended to be beneficial for humankind, leading to increased human life expectancy, the technological transformation of societies, and the emergence of democratic governance systems. However, the increasing complexity of modern civilization has also been accompanied by a tighter coupling between complex systems (e.g., food production, energy supply) that were previously only weakly linked, if at all (Liu 2017). This increase in complexity leads to two potential outcomes. First, the increased frequency and strength of interactions between previously weakly coupled systems and the overall increase in complexity across systems heightens the fundamental uncertainty of what future system characteristics might emerge. Emergent phenomena can be serendipitously beneficial or undesirable surprises depending on social-ecological contexts, making it crucial to understand how emergence ultimately affects sustainability in the Anthropocene

(Blythe et al. 2018). Second, there is an increased likelihood of collapse at larger spatial and temporal scales when the resilience of a system is exceeded (Havlin et al. 2014; Valdez et al. 2020); the global economic collapse in 2007 and the COVID-19 pandemic serve as recent examples (Darnhofer 2021). Collapse can lead to an alternative regime (new processes and structure) when systems have lost the necessary means to revert into a similar configuration post-disturbance (Scheffer 2009). Both collapse and unintended regime shifts as a function of reduced resilience contribute to highly uncertain system dynamics that challenge human and environmental systems.

Convergence science is a new approach for tackling complex problems confronting humanity that works across disciplinary boundaries and deeply integrates multiple perspectives, expertise, knowledge, methods, tools, and analytical approaches (National Science Foundation 2016). It was developed over the past 20 years by U.S. federal agencies in collaboration with international partners to address the rapidity and irreversibility of change in science and technology (Roco et al. 2013). Since 2010, convergence has been distinguished by ‘a purposeful focus on supporting societal values and needs’ (Roco et al. 2013). Convergence science expands on transdisciplinary research by aiming to not just conduct cross-disciplinary research, but more fully and meaningfully integrate diverse and multiple fields of science into synthetic, high-level frameworks in order to solve complex problems and ‘address complex intellectual questions underlying emerging disciplines’ (National Research Council 2014). In other words, the fundamental goal of convergence science is to stimulate the emergence of something larger than the sum of the parts, through the process of bringing together and integrating bodies of specialized knowledge (National Research Council 2014). Convergence has been applied across disparate realms of inquiry such as psychiatry and neuroscience (Eyre et al. 2021), technology development inspired by quantum physics (Dowling and Milburn 2003), the application of games to education, transportation and business management (Kim 2015) and is well-suited to the challenge of emergence.

As currently proposed by the U.S. National Science Foundation (2016), a convergence approach is meant to address two salient features: (1) the need for, but difficulty of, successful transdisciplinary

research processes that strive for a deep integration across disciplines; and (2) a focus on “solving vexing research problems, in particular, complex problems focusing on societal needs”. There is no prescription for building this integrative, collaborative process, and the people, approaches, and methods that are integrated may vary widely for different complex social-ecological challenges. However, there are few scientific frameworks or well-developed schools of thought with the capacity to address both the deep complexity of problems suited to convergence research and the many types of interacting complex systems. Convergence approaches that focus on problem solving, rather than discovery, run the risk of focusing on solutions to complex problems that may be efficient only in the short term. This may lead to spurious certitude, where ‘solutions’ are arrived at through a convergence process that only addresses one apparently tractable component of a ‘problem’ that is merely the tip of the proverbial iceberg. Utilizing broad theories of change is more likely to provide insight into the problem at hand, to be useful to other similar, but unanticipated challenges, and to provoke serendipitous discoveries (Johansson 2017). Thus, we argue that the study of emergence would benefit not only from a convergence approach as put forward by the U.S. National Science Foundation (2022), but also from a scientific framework predicated on understanding change in complex systems, which clearly involves dynamics at multiple scales of space and time.

Panarchy theory is a well-suited framework for studying emergence, because it characterizes complex systems of people and nature as dynamically organized and structured within and across scales of space and time. It accounts for the fundamental tenets of complex systems (i.e., multiscaled, hierarchical, nonlinear, irreducible uncertainty, and adaptive behaviors) and explicitly grapples with emergence, including the emergence of novelty in complex systems, and the emergent property of social-ecological resilience. Resilience in social-ecological systems is about the capacity of SES to remain organized around one set of processes and structures by buffering and adapting to disturbances (i.e., avoiding a regime shift), or to deliberately transform into a more desired regime (Angeler and Allen 2016; Folke et al. 2021). This has clear implications for understanding the ways complex systems of people and nature adapt to or transform in relation to accelerating uncertain social-ecological change. This paper

presents panarchy theory as a framework for a convergence approach to address the challenge of emergence in social-ecological systems. We provide examples from climate change and zoonotic infectious diseases to illustrate the utility of this approach and suggest how future research can be developed to overcome limitations.

What is panarchy theory

Panarchy theory focuses on the dynamics of complex SES and their resilience on a rapidly changing planet. It is a branch of complexity science rooted in resilience theory and it accounts for hierarchical organization, connectedness of scales, and dynamic system structure (Gunderson and Holling 2002; Allen et al. 2014). Panarchy captures the cross-scale structure envisioned in hierarchy theory (Allen and Starr 1982) and acknowledges the transmission of information (matter, energy, knowledge) from higher to lower scales and vice versa by providing insight into the feedbacks and interactions occurring within and across system scales (**Fig. 1**). Such organization is ubiquitous and observed, for example, in lake food webs, regional ecosystem management, and the global climate (Garmestani et al. 2020; Angeler et al. 2021; Angeler and Allen 2022). This multi-scaled framing is

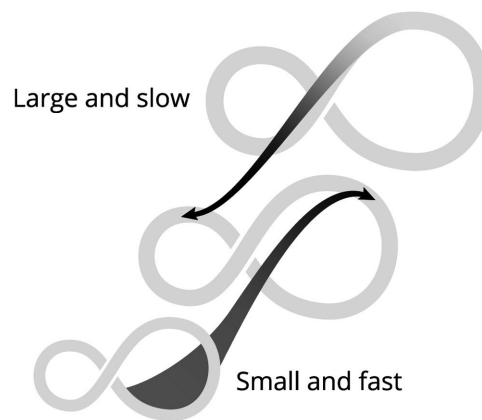


Fig. 1 The classic panarchy figure, showing nested adaptive cycles at three spatio-temporal scales. Dynamics at small and fast scales can cascade up to larger scales, and dynamics at larger scales both constrain possibilities at smaller scales and act as a source of memory in the event of disturbance. Adapted from Gunderson and Holling (2002)

critical for any analysis of emergence, as emergent phenomena generally manifest at scales larger than the small-scale components and processes from which they arise (Goldstein 1999).

Panarchy theory also explicitly grapples with systemic dynamics of change, including the possibility of collapse and the emergence of novel systems and the recognition that there can be high uncertainty associated with a new system trajectory during the reorganization phase (Allen and Holling 2010). Panarchy theory argues that complex adaptive systems have four primary phases of development which they move between; movement from one phase to the next may systematically follow the order shown in the adaptive cycle figure (**Fig. 2**), or may be more disordered (Gunderson and Holling 2002). These four phases are called an adaptive cycle and describe system movement through phases of growth (r), conservation (k), release (Ω), and reorganization (α) (Holling 1986). Different dynamics dominate each phase, and the reorganization phase is dominated by possibility—the possibility for new entities or processes to emerge, and the possibility for the system to shift to a new regime. Nested adaptive cycles

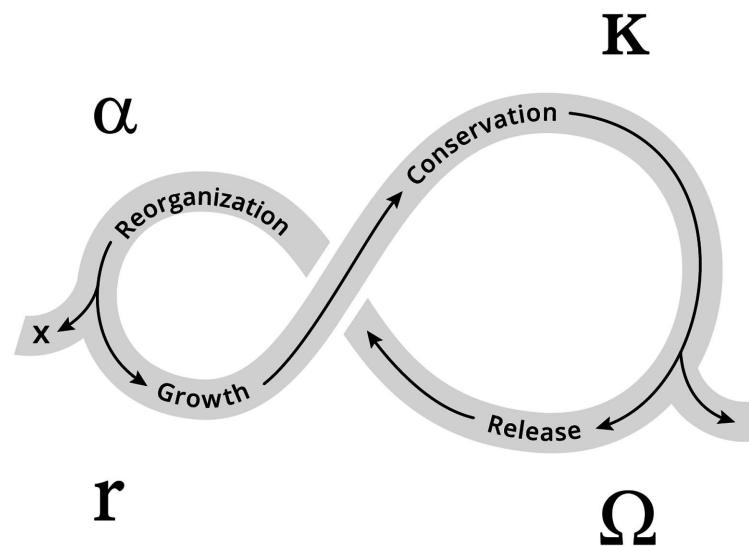


Fig. 2 A representation of the four stages of system development. The two front loop phases, exploitation and conservation, are the slow accumulation of capital (e.g., nutrients and biomass), whereas the two back loop phases occur when disturbance triggers the rapid release of accumulated capital and the reorganization of the system. The 'x' arrow is the possibility of the system undergoing a regime shift during the reorganization phase. From Gunderson and Holling.

comprise a panarchy. There have been successful and diverse applications of panarchy in SES (Gunderson et al. 2021) mainly in qualitative analyses (Allen et al. 2014; Sundstrom and Allen 2019). However, panarchy also offers broad potential for quantitative and mixed method empirical analyses (Allen et al. 2014; Angeler et al. 2021). It can, therefore, be useful for the development of theory and hypothesis testing focused on a critical analysis of emergence.

Emergence and panarchy theory

Anderson (1991) argued that the science of complexity was “a movement joining together into a general subject all the various ideas about ways new properties emerge,” an argument Goldstein (1999) refined by defining emergence as “the arising of novel and coherent structures, patterns, and properties during the process of self-organization in complex systems.” Thus we have the emergence of macro-level phenomena, like consciousness in humans and resilience in SES, where the phenomena are more than the sum of the parts and cannot be well deduced from an understanding of the individual system components. There are also emergent phenomena such as the creation of novelty as a result of the structure and dynamics of CAS (Goldstein 1999; Wilcox and Colwell 2005; Allen and Holling 2010). Examples of this include the reorganization of a CAS following collapse—the emergence of alternative stable states when the resilience of a system is exceeded—or the emergence of new things resulting from the dynamics of a panarchy, such as policies, norms, infectious diseases, biological invasions, technologies, novel behaviors, or novel systems. Sometimes, the emergence of a novel phenomenon can impact other emergent features, as in when invasive species outcompete native species, reducing both diversity and system-level resilience.

Panarchy theory has primarily grappled with emergence in three ways: (1) the emergence of novelty during processes of self-organization; (2) understanding resilience as an emergent phenomenon; and (3) the way dynamics within and across system scales directly impact resilience and thus vulnerability to a regime shift, where a new regime can emerge after the collapse of the previous one (Garmestani et al. 2020). Complex systems such as SES are said to self-organize,

because there is no global controller or top-down authority dictating dynamics and behavior (Levin 1998). Instead, CAS are comprised of many individual entities that are the subject of selective forces, that experience localized interactions with other entities, and that are to a degree interchangeable (individual entities come and go, but continuity of function is often maintained) (Levin 1998). Collectively, these features of self-organization result in the constant production of novelty as entities respond to disturbances. Examples of this in ecological systems include the clustering of phenomena such as invasion, extinction, nomadism and migration at transition zones between scales in complex systems (Allen and Holling 2008).

Transitions between scales (“scale breaks”) occur when system phenomena do not change continuously across a broad range of scales, but rather manifest at a limited range of spatial and temporal scales. These scale breaks define the levels of a panarchy (Wiens 1989; Angeler and Allen 2016). Ecological processes such as photosynthesis, for example, occur at very small spatial and temporal scales (e.g., at a cellular level in plants), whereas the processes that structure a forest biome manifest at much greater spatial and temporal scales (hundreds to thousands of kilometers and from centuries to millennia). The scale breaks between structuring processes are areas of high variability (Wiens 1989), as one set of structuring processes is replaced by another, and they appear to generate novelty (Allen and Holling 2010) and to allow rapid adaptation at the system level. Species that operate at the scale breaks are more likely to successfully invade, go extinct, have a higher population variability in both space and time, and are more likely to have behavioral attributes that allow them to take advantage of that variability (such as being nomadic or migratory) (Allen et al. 1999; Forsys and Allen 1999; Allen and Saunders 2002, 2006; Wardwell and Allen 2009). There is potential for these concepts to help us more broadly understand the conditions for the generation of emergent novelty in CAS, both where it is beneficial to humans (novelty as a source of adaptive capacity) and harm (novelty that reduces resilience or causes harm, like infectious diseases).

The second way panarchy has grappled with emergence has been through the mechanistic explanation it provides for the emergence of resilience, which is a system-level emergent property of complex systems and can be understood for each adaptive cycle within a panarchy.

A primary source of resilience is the distribution of functions both within and across scales (Holling 1992; Peterson et al. 1998; Nystrom and Folke 2001). Having a diversity of functions present within one scale domain and a redundancy of functions providing functional reinforcement across scale domains allows for buffering and compensation in the event of disturbance since disturbances rarely impact all system scales equally at the same time. These scale domains can be objectively identified, thus providing a quantitative measure of resilience via the distribution of the diversity and redundancy of function across scales (Gunderson 2000; Sundstrom et al. 2012; Nash et al. 2014).

The third primary application of panarchy theory to emergence has been the focus on regime shifts, which occur when a system's resilience is exceeded. Though regime shifts are typically tracked at the system-level, they can occur at any scale within the system (consider the difference between a coral reef system with spotty bleaching of individual corals, versus widespread bleaching across the entire reef). When resilience is exceeded, even a small disturbance can drive widespread collapse, because the system no longer has the capacity to buffer or adapt to the disturbance. After collapse, a system undergoes a rapid reorganization during which it may follow a generally predictable trajectory (Clements 1916) by simply resetting into a similar configuration, or under certain circumstances, may undergo a regime shift where novel processes or components emerge and the system assumes a structure fundamentally different from that which previously existed. Forests, for example, usually regrow following wildfire. However, two alternative trajectories have become increasingly likely—forests shifting to a grassland or shrubland due to soil and moisture changes from the fire intensity and from climate change driven shifts in the precipitation and thermal patterns, or a different type of forest emerging in response to the shifting climate drivers (Jiang et al. 2013; Allen 2014). Our ability to predict the most likely system trajectory remains poor.

There is significant potential for the panarchy framework to make further contributions to our understanding of emergence and novelty in CAS. For example, the circumstances leading to collapse in complex systems are reasonably well understood (Gunderson and Holling 2002; Boettiger et al. 2013; Lindenmayer and Sato 2018; Holstein et al. 2021), but the reorganization phase, in which emergent

phenomena can manifest or a system can undergo a regime shift, remains little studied. Examples of emergent phenomena that are poorly understood include the emergence of novel diseases. It is imperative that we develop a better understanding of the ways in which interactions of complex systems of people and nature give rise to emergent processes and phenomena, which requires the integration of convergence research and panarchy theory. The complexity of systems of people and nature cannot be understood using siloed approaches to research. Convergence approaches involving, for instance, the ecological, social, and economic sciences, including modelers, climate scientists, spatial planners, public health experts, politicians and decision makers, and other private (farmers, interest groups, commerce) and public (consumers, research funders) stakeholders will be needed to better understand the complexity dictating emergence dynamics in systems relevant to sustainable human existence, including agriculture, health, food security, a changing climate and increasing environmental catastrophes. There are always going to be limitations in our ability to predict what we do not know that go beyond challenges of data limitations—the emergence of novelty, after all, is fundamentally a process of surprise, and there will always be surprises that are completely unanticipated (Angeler et al. 2020). Although uncertainty cannot be eliminated, it can be reduced through an improved understanding of how novel system elements manifest across spatiotemporal scales. Using panarchy theory to frame and quantify issues of great societal importance provides learning opportunities about how system components and the system at large may adapt to change, and their likely trajectory should they fail to. Accounting for such scenarios can help to build preparedness for future shocks and inform policy. The manifestation of dynamic system patterns across scales suggests that an explicit consideration of the multi-scale patterns that steer such complex dynamics will have implications for research, management, and policy.

Convergence and panarchy theory

Convergence science is a recent advancement in the movement away from siloed, discipline-specific research, and is an expansion on multi-,

inter-, trans-, and other types of cross disciplinary research collaborations (National Research Council 2014). Convergence science is an explicit recognition of the need to broaden the space not just for who is in the room, but how a ‘problem’ is defined. Many, if not all problems of compelling interest to humankind require such an approach to avoid the lure of tractable solutions that may provide short-term relief, but risk deepening the problem in the long-term. A central tenet of resilience science, from which panarchy emerged, is that system-level resilience or the ability to respond to disturbances without collapsing and undergoing a regime shift, is often eroded by decision-making that focuses on short-term and small-scale fixes (Holling and Meffe 1996). In that vein, convergence science, which requires deep collaboration across disciplines, is not just useful but necessary to avoid a myopic focus that fails to account for how human practices and endeavors at small spatial and temporal scales can interact with each other within and across systems to drive often unexpected and abrupt changes at much larger scales.

A convergence approach by itself, however, is insufficient if the scientific framework binding together the expertise of multiple disciplines and perspectives does not accommodate the reality of the dynamics of complex systems—namely, multi-scaled, nonlinear, adaptive, and capable of abrupt regime shifts. Panarchy theory provides a well-developed theory explicitly embedded in these dynamics and is equally applicable to any type of complex system of interest to humans—from social to biological—and the interactions between them. Perhaps most importantly, panarchy theory explicitly considers the scales at which key processes unfold, the interactions and feedbacks within and across scales, and how system resilience changes as a function of those interactions. Panarchy, therefore, helps to overcome limitations of conventional approaches to research, because scale is not implicit, subjective, or ignored. Scale is an objective and quantifiable central component and thus incorporates the biophysical reality of complex systems where large-scale top-down drivers (e.g., climate change) constrain behavior at smaller scales and small-scale dynamics (e.g., earth stewardship measures) can, under the right circumstances, cascade up to drive change at much larger spatial and temporal scales, as well as in other, even distant, complex systems (Liu et al. 2013; Liu 2017). Some of the more vexing problems confronting humanity are challenging because of the scale and/or speed or rate

with which they are unfolding (i.e., climate change), the complexity accruing from the intersection of multiple systems (i.e., agriculture interacting with economics, geopolitics, land use change and climate change), and heterogeneous human values.

Despite the varied contexts in which we argue a convergence approach is useful and even necessary, panarchy theory is broadly applicable, because it is not discipline dependent and lends itself well to convergence approaches that bring together people from disparate backgrounds with different language sets and tools. As long as collaborative teams contain participants experienced with panarchy theory, it can be applied to any type of system or mix of interacting systems, because the basic dynamics and behaviors of complex systems, including those underpinning the panarchy model, are universal (**Fig. 3**).

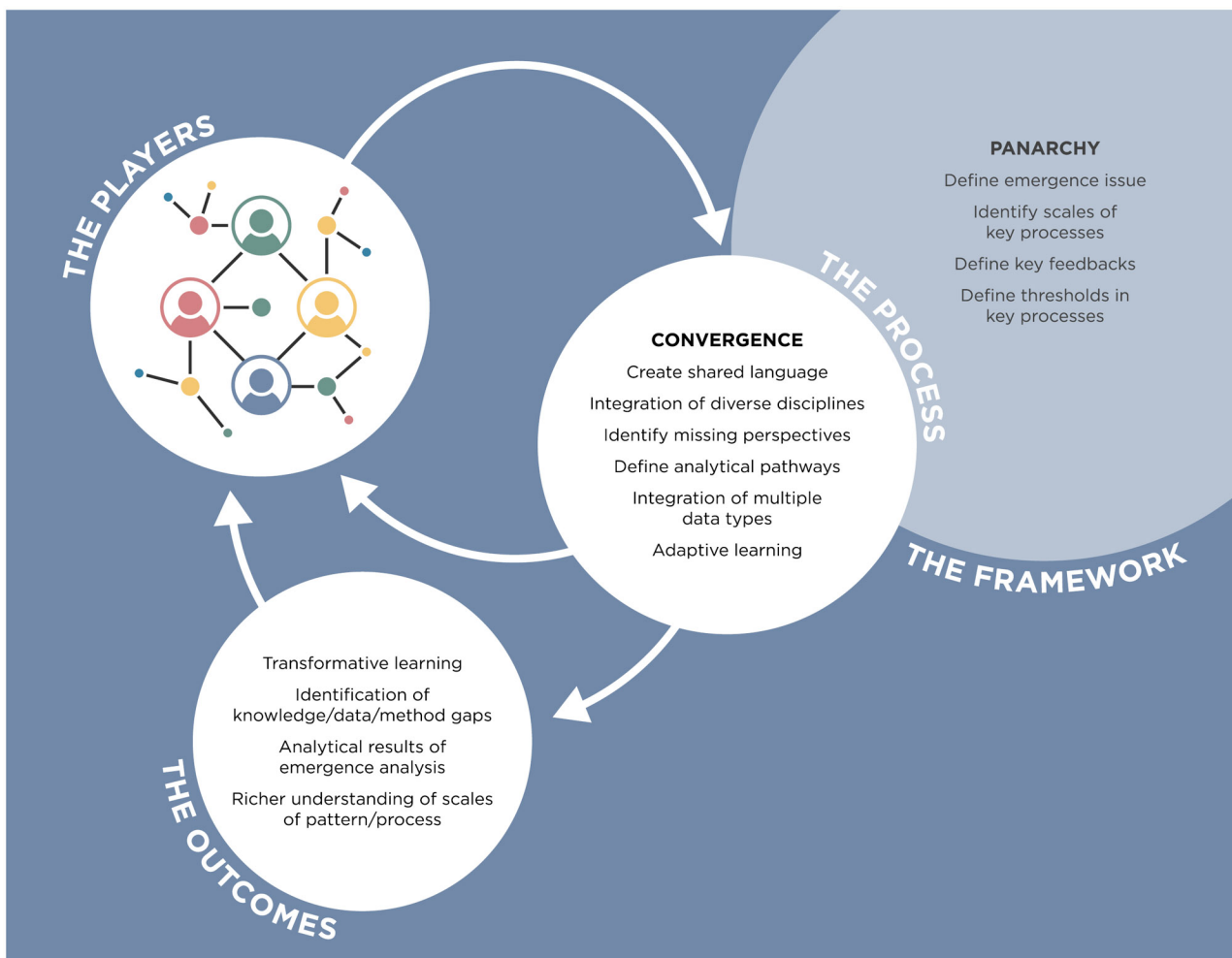


Fig. 3 The key components of applying a panarchy framework to a complex SES problem via a convergence science approach

Challenges of applying panarchy and convergence to emergence

Panarchy theory was originally used as a heuristic in descriptive studies, requiring an understanding of dominant system processes and interactions, rather than data per se (i.e., McAllister et al. 2006). Approaches to quantify and/or track system movement through adaptive cycles at multiple scales via biophysical variables have been proposed, but data limitations are always a challenge, and these proposals also typically neglect social variables (Burkhard et al. 2011; Sundstrom and Allen 2019). Some recent studies have used mixed quantitative and qualitative forms of primary and secondary data to analyze trends and themes rather than statistical analyses (Teuber et al. 2017; Jimenez et al. 2020; Hodbod and Wentworth 2021). They have been useful because they broaden the scales, processes, and feedbacks under consideration and provide a substantially richer understanding of change in complex systems (e.g., see Abrahams and Carr 2017). However, they have also been limited to relatively small communities, in both population size and diversity of stakeholders, because of data limitations that prohibit studying more complex systems (Wentworth et al. 2022).

Additionally, while historical analyses that include recall data, literature review, and incomplete datasets are more robust convergence studies than purely quantitative analyses, the trade-off is that managing and integrating multiple forms of data requires more time and labor. This highlights the practical reality that it likely takes one or more dedicated data specialists to cope with integrating data originating from different domains and for noncongruent purposes and that this may have limited earlier studies. Therefore, while the integration of multiple data types is a positive from a convergence perspective, there are two main challenges for using panarchy in a convergence science approach: data scarcity and the need for methods to address limitations of existing datasets, and the need for methods to model multiple scales and feedbacks in individual and interacting complex systems.

Data scarcity and the need for methods to address limitations of existing datasets

With respect to data scarcity and methods to address such data limitations, analyses using secondary data sources may be challenged by the lack of data at desired spatiotemporal scales. Social-ecological studies exploring longitudinal patterns often struggle with a lack of congruence between the spatial and temporal extents of the available ecological data, and the relative lack of social data. There are datasets that provide open-access social-ecological data—for example, comparing food systems is done using standardized quantitative datasets (such as census, agricultural census, food security, and socio-economic indicators) to compare outcomes. However, these data are often unavailable at the appropriate scale or consistently across time. For example, Wentworth et al. (2022) found multiple elements of data limitation in a study of a city-scale food system: first, that secondary data were limited at smaller focal scales (i.e., food security data was available at the county scale, not the city scale); second, that data collection protocols changed over time for available longitudinal data (i.e., how the US census calculates poverty rates has changed multiple times in the past 60 years); and finally, that analyses are limited by the lack of primary data and are forced to rely on quantitative secondary data collected for other purposes.

There have, however, been recent advances in methods capable of addressing the limitations of existing datasets. Limited resources for the collection of primary data are a perennial problem in research, requiring innovative ways of using secondary data collected for other purposes. Recent advancements in capturing and publishing data, and computational infrastructures along with algorithmic advancements in data engineering and prediction, have created unprecedented opportunities for novel approaches for the imputation of missing data (using available data to calculate a missing value) or using surrogates for different purposes. The use of passively collected data, such as data from social media, satellites, or Big Data collected from Internet of Things shows hope and can be one pathway to meet the data challenge of modelling a panarchy (Moreno-Cano et al. 2015; Ivan et al. 2020; Epstein et al. 2020). Advancements

in Machine Learning provide new methods to develop datasets or facilitate data preparation. Machine Learning refers broadly to computational algorithms that classify data, recognize patterns, and create predictive models from data. These tasks are achieved through repetitions known as training that improve performance or minimize predefined cost functions.

Examples of these methods are the Active Learning methodology to reduce the human workload in labeling raw data, Generative Adversarial Networks to create artificial datasets (Prince 2004; Goodfellow et al. 2020), and different data augmentation techniques to use already available but scarce data to produce new data sets for training the models (van Dyk and Meng 2012). Jean et al. (2016) provides a novel approach whereby they apply a three-step Transfer learning methodology to predict poverty in Africa from easily available but noisy daytime and nighttime satellite imageries and sparsely available survey datasets. Another considerable advancement in their model is that it can learn by itself through several steps of applying Convolutional Neural Networks to relate satellite images to economic levels. This advances similar works that use human labeling to create training datasets (Jean et al. 2016). These above-mentioned methodologies are just some of the tools that can be used to provide datasets for a complex panarchy model when primary data are scarce or unavailable. From traditional statistical models for missing data imputation, to different methods of using surrogate variables, and recent advanced machine learning methods, there are a variety of cutting-edge methods that can help address challenges of data scarcity. Furthermore, as the shift towards more quantitative fixes to these challenges continues, it will be important to remember that convergence research needs to explicitly incorporate the social component of SES, and that the data challenges are especially high with regards to longitudinal social data. To that end, we encourage researchers to consider the value of the additional context that comes from historical and qualitative data and to be creative in the exploration of workarounds in the pursuit of multi-scaled and cross-scale panarchy research using a convergence approach to questions of fundamental interest to humankind.

The need for methods to model multiple scales and feedbacks in individual and interacting complex systems

The second primary challenge in convergence-based panarchy analyses stems from the lack of methods to conduct quantitative panarchy analyses (though see Angeler et al. 2015, 2021; Sundstrom and Allen 2019). Quantitative modeling methods are challenging for any analysis that explicitly includes processes that occur at multiple spatial and temporal scales. For example, Turner (2021) uses dynamic systems models in a soil complex system to model feedbacks across multiple scales. The impressive integrative methodology captures core elements of complex systems behavior, but the equations driving the model come from several decades of soil science studies. Such equations are not available for many systems, where the rates of critical processes are often unknown.

Clearly, methods that let the data tell the story are needed, as is the case with multivariate ordination techniques that have been applied to ecological monitoring data (Angeler et al. 2021), or the multivariate Fisher information, an information theory approach that evaluates order (a measure of the amount of information about a particular parameter or group of parameters that can be obtained by observation) in time-series or spatial data and is agnostic to the type of variables inputted (Karunanithi et al. 2008; Sundstrom et al. 2017). Machine Learning tools and methods are increasingly used in quantitative research and problem solving. They have a long record of application in biology (Tarca et al. 2007; Jumper et al. 2021), and have recently been used in agriculture (Liakos et al. 2018) and drug discovery (Chodera et al. 2020). Rolnick et al. (2019) argued their utility in filling the existing gaps in different climate change solution domains such as disaster management, smart grids, supply chain management, and more. They can also provide quantitative methods for challenging problems in modeling, such as those posed by panarchy because Machine Learning can ‘learn’ from captured datasets of study subjects, obviating the need for extensive equations that define the system.

For example, Bury et al. (2021) implemented a deep learning model that can predict a regime shift in natural systems such as ecological, climate, and epidemiological. Their model produces early warning

signals of tipping points (thresholds demarcating a regime shift) that are more sensitive than traditional methods, with fewer false positive results and learns from collective possible models, rather than dynamical equations from the study system. This new method can also predict some qualitative characteristics of the new system that was not possible with generic early warning indicators. They used outputs of randomly generated dynamical systems that contained sufficient instances of tipping points and regime shifts to train deep learning models, which offers an example of how advancements in Artificial Intelligence can provide tools to predict system behavior. Given sufficient simulations or observed data sets, its utility in a multi-scaled panarchy is clear, and may allow researchers to identify when crossing a tipping point at one scale can cascade to other scales within the system. In another study, Deep Reinforcement Learning algorithms in conjunction with other machine learning methods was used to create a virtual soccer environment in which individual players progress from learning tiny micro joint movements derived from video of real soccer players to movement and ball control, and finally to interactions with other teammates (Liu et al. 2021). Billions of training cycles allowed the system to learn movements at multiple spatial and temporal scales, with feedbacks across scales. Most promising of all is that the program did not require mechanistic equations but relied on captured video footage. A panarchy model encompassing multiple temporal and spatial scales with feedbacks may also benefit from such methodology. This can potentially provide a quantitative solution for the many systems for which dynamic system equations are not yet available but captured behaviors can be fed into the models to learn.

Examples of emergence that would benefit from the integrated application of panarchy and convergence

The following examples highlight societal problems where the explicit consideration of multiple spatio-temporal scales from a convergence approach is both critically important and difficult to do. The climate change example presents climate change as an emergent phenomenon driving unpredictable change in SES, and focuses on the challenges of data collection, missing data, synthesis, and modeling as pertains to a

convergence/panarchy approach. The infectious disease example emphasizes process-based challenges around conceptualizing a panarchy in a SES and highlights the shift already occurring in the health sector towards convergence science. Both arenas could benefit from the application of a panarchy approach to emergence.

Climate

Current progress in climate research must inform future panarchy/convergence research as climate change, itself an emergent phenomenon, becomes increasingly responsible for catalyzing emergence across all scales to the detriment of Earth's SES. Climate variability and extreme climate events have long affected the Earth's complex SES and have been a leading driver of collapse in civilizations, especially where agricultural production has been affected (Weiss and Bradley 2001; Cheng et al. 2015; Sinha et al. 2019). As a large, relatively slow variable, climate change can manifest and cause non-linear change at multiple scales, ranging, for example, from physiological impacts on individual plants to causing extensive and rapid shifts in vegetation at continental scales (Knapp et al. 2008; Roberts et al. 2019). Anthropogenic climate change is now creating significant stress on SES by altering water and carbon cycles (Bell et al. 2010), the spatio-temporal distribution of precipitation, and increasing climate variability.

Interactions between climate and the function and evolution of SES manifest at multiple spatial and temporal scales, with feedbacks within and across scales (**Fig. 4**). Changes to these relationships can be framed in the context of a panarchy to expose the key scales at which processes and patterns emerge, and the cross-scale feedbacks that could accelerate a particular trajectory of changes within the SES (e.g., individual decisions influence habitat change at the local scale, which influences climate variability at regional and global scales). Climate and its state variables (temperature, precipitation, and humidity) are historically critical slow drivers of SES that can lead to rapid change when tipping points are passed; whether SES can keep pace with and adapt to accelerated climate warming or are driven into a novel regime remains a source of great uncertainty. Although potential Earth-scale regime shifts have been envisioned (Steffen et al. 2018), current research is agnostic about scale-specific



Fig. 4 Schematic example of the interactions between climate and SES across multiple scales. The symbols represent human activities, land surface features, and monitoring approaches at different scales in the panarchy. Adaptive cycles (stylized figure eights) occur at each of the four scales

impacts and reactions to climate change in SES in part because much is dependent on human choices. The potential to reduce this uncertainty and more accurately anticipate the emergence of a novel or undesired SES trajectory based on climate change has obvious utility for preparing for the future. Considering the multiscale, dynamic features of panarchy can guide future research into how complex systems dynamics, including novelty and innovation, may emanate from multi-scalar dynamics.

To understand the impact of changing climate on SES using panarchy, global climate models are increasingly useful because of their improved biological, physical, and chemical representations. Over time, the reliability and accuracy of predicting future climate conditions with these models has improved but at relatively coarse spatio-temporal scales so their prediction reliability at finer spatio-temporal scales such as sub-seasonal and regional remains poor. To address this issue, the scientific community has been using regional- and meso-scale models that use the coarser data of the global climate models but produce finer scale information that may be appropriate for predicting the trajectories of regional SES and emergence in a panarchy framework, though care must be taken to account for the propagation of uncertainties through the datasets (e.g., Bukovsky et al. 2013). Also useful to scientists is observed climate data to understand and quantify interactions between climate change and its impacts on SES at multiple scales. Over the last several decades, the spatio-temporal density of observations has increased globally and could be used for near-real time assessments of SES and emergence (e.g., Menne et al. 2012). For example, Schmidt et al. (2017) used 3 decades of time series satellite imagery, including vegetation cover, human population size, and rainfall to understand Ebola spillover intensity and its relationship to seasonal, interannual and decadal spatiotemporal variation in climate and landcover.

Despite improvements in the scale and coverage of climate data, a large swath of the land surface still lacks *in situ* observations, as well as much of the oceans. To overcome some of the challenges tied to poor spatial density and inconsistencies related to observation frequency differences between regions, the climate community has developed finely scaled reanalysis climate datasets (hourly estimates at a few kilometers resolution) (Hersbach et al. 2020) that integrate observations from various platforms (e.g., *in situ*, weather balloon, etc.) and model data in a gridded format. Remotely sensed data from satellites have also become increasingly valuable in capturing climatological, ecological phenomena, and other related processes and their spatiotemporal changes (Wickham et al. 2018). In addition, satellites can provide global, hemispheric, or continental data. This type of large spatial coverage also assists in filling the voids in data sparse regions. For example, many human-forced changes in the Amazon and the

Arctic and Antarctic have been captured by satellite data. Availability of critical data from these remote locations can also assist in the detection of emergence in areas/regions, which would not have been possible in the past.

Access to climatological, biophysical, and remote sensing data has allowed scientists to develop a variety of indices that better describe physical conditions, which can play an important role in capturing and summarizing complex processes and conditions and can potentially assist in understanding change and feedbacks at multiple spatial and temporal scales. For example, the Palmer Drought Severity Index (PDSI) is one climate index originally designed to capture complex climatological–hydrological–vegetation interactions associated with the devastating Dust Bowl drought in the United States during the 1930s (Palmer 1965). The PDSI remains a key index for examining ecological droughts and the consequent long-term and complex SES impacts that result (Crausbay et al. 2020). Similarly, proxy data such as tree-rings, ice cores, and sediment cores provide invaluable information about paleoclimatic conditions, which can also provide insight of past emergence and potentially help to envision future emergence. Collectively, these data sources can be used in combination with other social-ecological data sets to ask broader questions about thresholds, regime shifts, and emergence as a function of climate-driven impacts on SES within a convergence approach.

Emerging zoonotic disease

Existing and emerging zoonotic diseases (diseases that are transmitted to humans from an animal reservoir) present a complex global challenge connecting people, animals, and SES across multiple temporal and spatial scales. Throughout the world, humans share habitat and interact with diverse domestic and wild animals that play a critical role in culture, food security, and sustainable livelihoods. However, companion animals, livestock, and wildlife can serve as reservoirs for zoonotic pathogens (viruses, bacteria, parasites, fungi, and prions) with the potential to spillover to people with devastating human health and economic impacts (Rahman et al. 2020). The majority of emerging infectious diseases are zoonotic (Taylor et al. 2001), and even before COVID-19 heightened global awareness of zoonotic

pathogen spillover, epidemics due to pathogens linked to wildlife hosts (e.g., Ebola, Avian Influenza, and the first SARS coronavirus) raised concern about known and unknown emerging pandemic threats (Morse et al. 2012). Understanding the emergence of zoonotic infectious diseases in multiple hosts and at multiple temporal and spatial scales is critical to protect the well-being of people, animals, and our shared environments.

Emerging zoonotic diseases are influenced by diverse factors and scales, ranging from cellular interactions and host ecology to landscape and climate that shape pathogen transmission at the interface of people, animals, and SES. Routes of transmission within and among domestic animal, wildlife, and human populations vary, ranging from direct contact among these groups to vector-borne disease transmission and indirect contact with pathogens in shared environments (Plowright et al. 2017; Rahman et al. 2020). These diverse transmission routes as well as regional and global spread of disease in animal and human hosts can be influenced by ongoing environmental change, including land-use change and climate change. Modeling and empirical research demonstrate that climate change and our alteration of landscapes for agriculture, urbanization, and natural resource extraction reduces biodiversity, changes patterns of interaction among species, and facilitates emergence of infectious diseases (Johnson et al. 2020; Plowright et al. 2021; Carlson et al. 2022). Environmental change also shapes broader animal and human disease risks that are challenging to anticipate and assess. For example, livestock losses associated with drought can drive migration of livestock-keepers to urban areas and refugee camps, potentially exposing new populations to zoonotic and human pathogens (FAO and UNCCD 2021).

The One Health approach offers an example of convergence science in practice to investigate complex health issues, including emerging infectious diseases. Reflecting the goals of convergence science, the One Health approach brings together diverse disciplines, methods, tools, perspectives, and stakeholders to solve complex challenges to health and well-being at the interface of people, animals, and their shared environments. One Health is a systems approach, with the potential and goal to integrate expertise and data on humans, animals, and the environment from molecular to planetary scales (Rabinowitz et al. 2018). Like the broader call for convergence science, One

Health is aspirational, because it seeks to nurture the development of new insight and solutions to complex, or even intractable, problems of deep concern to humanity by making space for many different perspectives and ways of understanding the world. To address complex health threats, there is a call for One Health teams and projects that fully integrate the social sciences, arts, and humanities and prioritize meaningful stakeholder or community-based engagement, particularly with Indigenous and other marginalized partners (Lapinski et al. 2015; Jack et al. 2020).

Integrating panarchy theory with a One Health convergent science approach offers a novel path to enhance prediction of emergent phenomena like zoonotic disease. Diverse connections and feedbacks across spatio-temporal scales can shape spillover and spread of a zoonotic disease in complex SES (**Fig. 5**). By explicitly focusing on nested adaptive cycles from individual to planetary levels as well as forces acting at rapid (e.g., local weather patterns) to slower (e.g., global climate change) temporal scales, panarchy theory offers a framework for incorporating the influence of cross-scale processes on disease emergence. For example, climate affects tick distribution and abundance and the emergence of tick-borne diseases at multiple interacting levels. At the individual vector or host scale, microclimate at a given site influences tick reproduction, survival, and activity (Estrada-Pena et al. 2012; Dumas et al. 2022). On a local scale, weather patterns influence local habitat as well as reproduction and population size in key rodent hosts, impacting the potential for ticks to reach and feed on these animals and shaping potential for pathogen spread to other wildlife hosts, domestic animals, and people (Estrada-Pena et al. 2012; Ogden and Lindsay 2016; Ogden et al. 2021). Regional climate patterns can shape host movement to access habitat and resources as well as larger scale migration and human landscape use, allowing ticks and pathogens to be carried to new environments or hosts. Climate change can also influence the geographic range of vectors, including expansion of tick populations to new environments (Ogden et al. 2021). These forces may also be synergistic, for example if largescale climate change introduces new tick species to a given area while also creating a more favorable local and microclimate for their establishment and survival. Processes and feedback across spatial and temporal scales also facilitate the emergence of non-vector-borne pathogens, as the world has

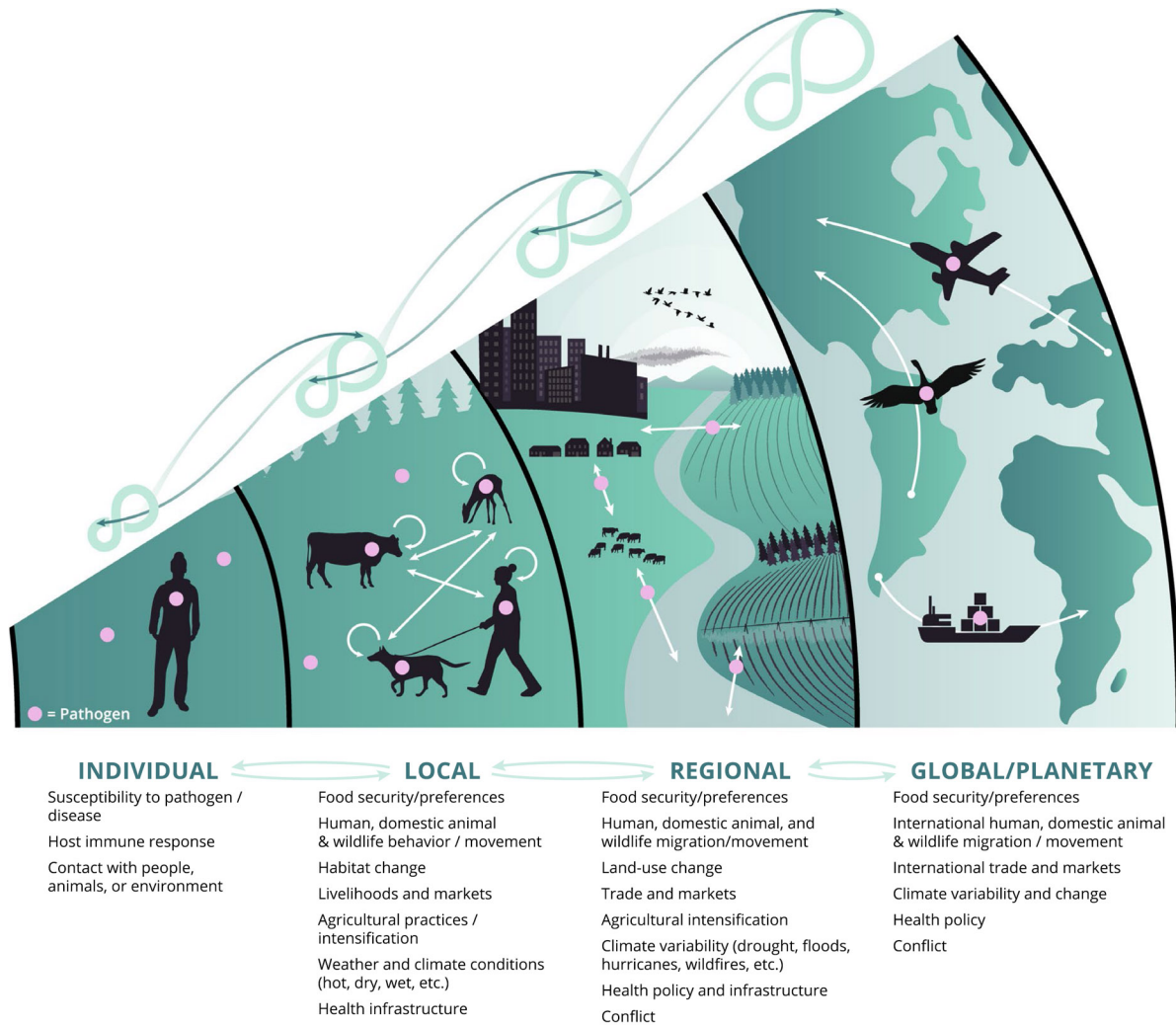


Fig. 5 Schematic example of the interactions between health and SES across multiple scales. The symbols represent pathogen transmission at the human-domestic animal-wildlife interface, human and animal activities, and land surface features, at different scales in the panarchy. Adaptive cycles (stylized figure eights) occur at each of the four scales.

directly witnessed during the COVID-19 pandemic. Wilcox et al. (2019) highlighted the utility of CAS frameworks and resilience theory, which are integrated into panarchy theory, in considering hierarchical SES and cross-scale interactions in zoonotic disease emergence and management. In a retrospective analysis of Avian Influenza outbreaks in the Mekong River Basin in southeast Asia, both smaller scale fast variables (i.e., pathogen mutation, local animal trade and migration) and

larger scale slow variables (i.e., a regional increase in intensive poultry production without policy for increased biosecurity) influenced disease emergence (Wilcox et al. 2019).

While panarchy theory provides a lens for retrospective analysis of zoonotic disease outbreaks, it also has potential to provide qualitative and quantitative tools for predicting zoonotic disease emergence. By explicitly incorporating hierarchy (e.g., organization of human and animal groups), connectedness of scales (e.g., local to global movement of pathogens), and dynamic system structure (e.g., different types and frequency of human–animal–environment interactions in different seasons and sites), panarchy theory can provide both a conceptual and analytic framework to model the within and across system scale feedbacks and interactions that impact zoonotic disease emergence. Panarchy can also help to strengthen focus on and tools for understanding emerging zoonotic disease in systems undergoing regime shifts. For example, woody species invasions in parts of the North American Great Plains ecosystem is shifting landcover from grassland to woodland and forest, which has facilitated tick expansion in some areas (Noden et al. 2021). The impact on tick-borne pathogen spread in these changing environments is unknown but understanding how regime shifts in SES influence zoonotic disease emergence and management is critical for protecting interdependent health. While some regime shifts may increase zoonotic disease vectors or pathogens (as in the ecological example in the Great Plains), societal regime shifts also have the potential to reduce zoonotic disease emergence, such as a radical shift in current human land-use to an approach that decreases degradation or conversion of habitats for agricultural and natural resource extraction (Plowright et al. 2021). One Health approaches offer an example of convergent science in action to investigate zoonotic disease emergence as well as other complex health challenges at the human-animal-environment interface. This approach would be enriched by integrating team members with training and perspective in panarchy theory and complex systems to investigate multiscale connections and processes in novel ways.

We hope these examples (climate change and emerging zoonotic diseases) highlight the increasing complexity of the societal challenges we face. These challenges often involve the intersection of multiple complex adaptive systems; agriculture, for example, features in both

Figs. 4 (climate example) and 5 (zoonotic disease example). Agriculture is an excellent example of an arena in which society needs to acknowledge and anticipate the deep uncertainty of what might emerge in agricultural systems as climate and land use change increasingly disrupt stable food production, yet the current science is not particularly well-positioned to do so (Darnhofer 2021). For example, until recently, much agricultural research was reductionist, focused on plot and field-scale research to efficiently increase reliable agricultural production. This facilitated siloed research based on singularly focused disciplines such as plant genomics, soil science, etc. Even those disciplines are often subdivided into sub-fields. Soil scientists tend to research either the physical, chemical, or biological components of soil, and few view these varied processes and feedbacks as an integrated system, making it highly challenging to understand the dynamics of soil as a complex system in and of itself, much less consider the interactions of a soil system with the other components of an agricultural system, their surrounding ecosystem, or impacts on society or human health (Turner 2021). Furthermore, as soon as the research focus moves to the farm level, socio-economic, policy, education, and other factors play a direct role in farmer decision-making regarding production practices, which in turn has direct feedbacks at multiple scales on the soil, plants, and surrounding watershed. Research into farm-level agriculture ideally requires expertise on soil dynamics, plants, hydrology, farmer values, the impact of social networks on decision-making, and economic and trade policymaking at multiple scales, among many others. In addition, the effects of climate change are already here, with measurable impacts on individual farms through changes in temperature and precipitation, as well as an increase in extreme weather events (Hughes et al. 2011; Sheng and Xu 2019; Wheeler and Lobley 2021). Thus, any research on the uncertain future of reliable large-scale agricultural production faces formidable challenges integrating knowledge across multiple scientific fields, many of which remain fragmented, siloed, data-challenged and inherently reductionist (Turner 2021). This makes the need for convergence science not just compelling, but urgent. Panarchy offers the necessary framework for envisioning worst-case and best-case scenarios that may emerge due to the interaction of social-ecological factors and offers possibilities for working towards resilient agricultural systems.

Conclusion

Many of the challenges confronting humanity involve novel phenomena emerging from multiple complex social-ecological systems interacting across spatial and temporal scales. Problem solving that seeks to break these challenges into discrete and more manageable components run the risk of ‘solving’ a problem at one scale and for a limited timeframe, but with unexpected and potentially devastating impacts at other scales or on other interacting systems. We need frameworks that can capture the dynamism of multi-scaled systems with cross-scale feedbacks that experience nonlinear change. We suggest that panarchy is such a framework. We also need scientific approaches that explicitly recognize the value of transcending disciplinary perspectives for complex emerging societal challenges, along with funding streams to support more holistic scientific approaches. The current push by the U.S. National Science Foundation to prioritize collaborative research through convergence is one such positive example. The complex challenges we face are non-stationary and involve interacting SES with competing values, norms, knowledge, dynamics and behavior that cannot be adequately dealt with by conventional siloed disciplinary approaches. Convergence science is an important step forward in designing scientific discourses and processes meant to incorporate and transcend multiple scientific disciplines and perspectives for knowledge co-creation, all of which has been identified as important for treating SES as CAS (Preiser et al. 2018). Though there are clear data challenges with regards to the quantification and implementation of panarchical framing of complex SES, we argue that both panarchy and convergence are useful tools for tackling the challenges of emergent phenomena and processes, which have the capacity to continually disrupt and even collapse social-ecological systems upon which humankind are dependent. The three arenas touched on in this paper—climate research, emerging zoonotic diseases, and agriculture—highlight the need for and value of new approaches and methods to tackle the challenge of sustainability and resilience of SES in the Anthropocene.

Conflict of interest The authors have no competing interests to declare.

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