Chapter 4

Scales of Coercion: Resilience, Regimes, and Panarchy

David G. Angeler and Craig R. Allen

The Anthropocene is the current geologic epoch in Earth's history and is characterized by human domination of biophysical processes at the planetary scale (Steffen et al. 2018). The ubiquitous influence of humans on planetary processes poses major challenges for the future trajectory of ecological and social-ecological systems at subplanetary scales (Rockström et al. 2009). A primary concern is that these human activities will lead to crossing one or more known, or unknown, critical thresholds, resulting in regime shifts at the local, regional, and global levels (Hughes et al. 2013).

Alternative regimes are characterized by different structures, functions, processes, and feedbacks in a system that result in a new, dynamically stable (fluctuation within a given basin of attraction) state (Holling 1973; Scheffer et al. 1993; Beisner et al. 2003). Alternative regimes are ubiquitous, as indicated by numerous examples across a range of ecological, social, social-ecological, geopolitical, economic, and climatic systems (Miller and Williamson 1988; Biggs et al. 2018; Steffen et al. 2018). Examples include grasslands rapidly becoming encroached by woodland, marine fisheries shifting from cod to lobster dominance, or democracies shifting to authoritarian regimes.

Regimes may be desired or undesired by humanity, reflective of the multiple social values or goals attributed to that regime or services, products, or outputs associated with a particular regime. Undesired regimes provide fewer benefits, such as food or fiber for humans, or they may generate more undesired effects such as extreme weather events, increase in diseases, or geopolitical conflicts (Homer-Dixon 1991; Folke et al. 2004; McMichael et al. 2008). While desired regimes are perpetuated and conserved, much work has focused on transforming undesirable system states into more desired regimes. The need to harness desired system functioning for human welfare leads to an increased examination of alternative system regimes and their management through the lens of resilience (Angeler et al. 2016a). Therefore, ecosystem restoration, rehabilitation, and mitigation (Society for Ecological Restoration [SER] 2004) have all been described through a resilience lens in the context of adaptation, transformation, or stabilization of regimes (Angeler and Allen 2016).

In this chapter, we build on the concepts of coerced resilience and coerced regimes, novel ideas derived from applying resilience theory to regime management (Angeler et al. 2020b). Coerced resilience reflects the types and degree of management actions needed to maintain a regime that has lost the capacity for self-organization and renewal. Such external subsidies may maintain a set of ecosystem services, such as provisioning, associated with a regime. Coercion of a desired regime is the inverse of ecological resilience, ecological resilience being defined as the amount of disturbance needed to shift a system between alternative regimes (Holling 1973; Angeler and Allen 2016. A desired regime with low resilience will require stronger coercion to maintain weak feedbacks of that regime. The trajectory of the current global climate regime, for example, will require substantial societal adaptation and mitigation to avoid a potentially catastrophic regime shift (Steffen et al. 2018). Conversely, a highly resilient degraded regime will also need a high degree of coercion to move the system into a desired regime. Turbid shallow lakes and wetlands can require significant nutrient control, food web manipulation, and technological interventions to mimic the conditions of clearwater lakes (Annadotter et al. 1999; Angeler et al. 2003).

In complex systems of people and nature, coerced resilience clearly has a multiscale connotation. In the following sections we will review the concepts related to resilience coercion and introduce a cross-scale extension of coercion ideas to highlight how management at discrete levels of the system may result in a coerced panarchy. Such a coerced panarchy is discussed theoretically and presented with the current global climate regime as an example.

Concepts

Coerced regimes and coerced resilience are two terms recently introduced into resilience literature. Though similar, there are fundamental, and operationally important, differences between the two. Below, we define both terms, and differentiate between them.

Coerced resilience

Coerced resilience is a phrase that arose from studies of the resilience of highly managed production ecosystems, such as forestry, agroecosystems, and aquaculture. It refers to resilience that is created as a result of anthropogenic inputs (labor, energy, technology), rather than supplied by the ecological system itself. Such coercion of resilience focuses on and enables the maintenance of high levels of production services from these systems (Rist et al. 2014). Conceptually, coercion has a main focus on maintaining high production output; that is, it targets only the parts of the ecosystem that are related to desired productivity. Coerced resilience can therefore be regarded as a management form that focuses on specific resilience rather than the broader or general resilience of the ecosystem that supports productivity. Indeed, optimizing outputs from a system is antithetical to managing a broadly resilient system; naturally resilient systems provide (less than optimal) outputs under a variety of conditions, whereas optimizing system outputs focuses on maximizing one or a few outputs under ideal conditions. Thus, coerced resilience is more aligned with command and control management (Holling and Meffe 1996), which recognizes that managing parts of the system can in the long run lead to the erosion of system resilience and potentially cause regime shifts (Gunderson 2000). Coercion of this type can reduce resilience of the system under management (Holling and Meffe 1996; Rist et al. 2014).

Coerced regimes

Contrary to coerced resilience, coerced regime management targets the entire system rather than focusing on specific aspects or outputs. Coerced regimes involve management activities that create artificial, non–self-sustaining feedbacks in a system through constant intensive interventions and subsidies that mimic the conditions of a desirable regime (Angeler et al. 2020b). Examples of coerced regimes are omnipresent and occur in diseased human subjects in need of permanent medication for full functioning (Angeler et al. 2018), lake management to mitigate acidification (Angeler et al. 2017), mechanical removal to remove trees from grasslands (Garmestani et al. 2019), or mitigation to preserve the climate (Steffen et al. 2018), for example.

In coerced regimes, because feedbacks are artificial, they mask rather than break the natural feedbacks of undesired system regimes. In practice this means that management often aims but fails to transform degraded regimes to desired regimes (e.g., eutrophic lakes resisting restoration efforts) and therefore only imitates the desired functioning of an untenable prior regime (i.e. the "ghost of a desired regime"). As soon as management is discontinued a system rebounds to the full manifestation of the degraded regime (e.g., a lake returning from clearwater conditions to the degraded aspects of its turbid regime). This notion is well aligned with ecological restoration and resilience theory (Suding et al. 2004; Suding and Gross 2006; Angeler and Allen 2016). Also inherent in coerced regimes is the aim to conserve desirable system regimes that are no longer viable (e.g., the current climate regime) that would flip to an alternative, often undesired regime if management were discontinued (figure 4.1).

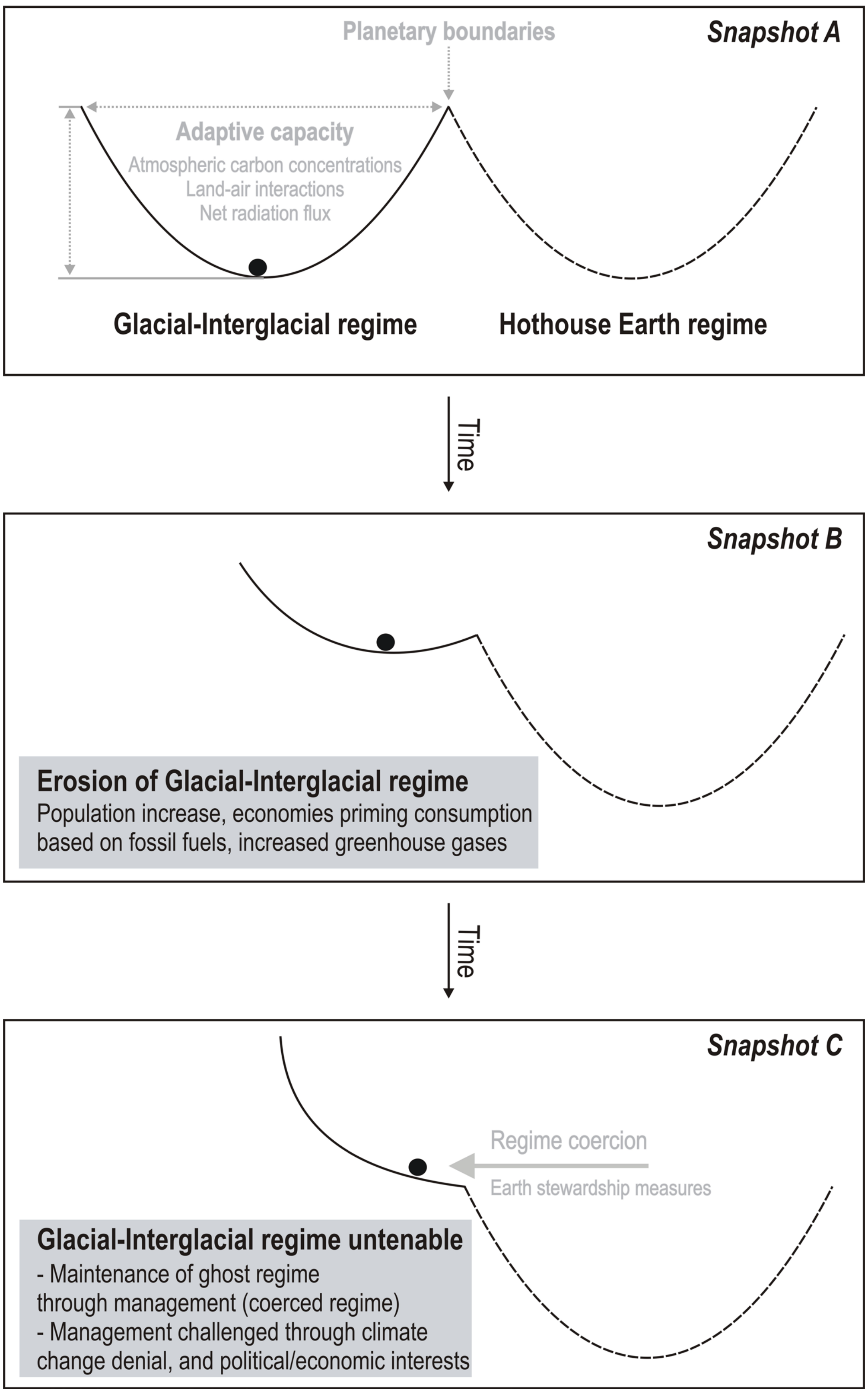

Figure 4.1: Illustration of the global climate system with a current (purple) regime and a potential future hothouse (red) regime. The changing shapes of basins of attraction over time (red arrow) show that the current regime becomes increasingly untenable (further emphasized with the area that warps the current regime and that fades from green into red). Transformation of societies (green arrow) is needed to coerce the system (symbolized with ball) into a desired regime.

Although the concepts of coerced regimes and coerced resilience focus on different aspects—the former imitating systemic conditions of untenable regimes and the latter improving the functioning of a few system variables (e.g., production output)—they are sometimes not mutually exclusive as in some managed ecosystems. For example, lake liming mimics circumneutral conditions within an acidified regime and at the same time targets the enhancement of recreational fisheries (Angeler et al. 2017). Similarly, agroecosystems such as corn, wheat, or soy fields have little or no self-organization, and lost resilience is offset by pesticides and fertilizers, because the management target is enhanced productivity (Rist et al. 2014).

Coercion concepts in resilience science are valuable for envisioning the management challenges ecological, social-ecological, and other complex systems face in a rapidly changing world. Complex systems of people and nature comprise several essential system features, particularly adaptive capacity, thresholds, and scale (Baho et al. 2017; Angeler et al. 2019). These features can be incorporated into coercion concepts to facilitate the envisioning and management of social-ecological challenges. Scale-specific structures and processes inherent in the hierarchical organization of complex systems underpin their resilience because disturbances are scale specific and affect some scales more than others in the system (Nash et al. 2014). Impact-free scales can buffer against disturbances, confer resilience, and maintain the overall system configuration through cross-scale interactions and feedbacks. This resilience is conferred partly by the abundance, redundancy, and diversity of functional traits within and across the scales present in a system (Sundstrom et al. 2018). This suggests that examining coerced resilience and regime concepts through the lens of scale might provide a more detailed picture of potentials and pitfalls of management in an uncertain Anthropocene. In the next section, we discuss coercive regimes from a cross-scale or panarchy perspective.

Panarchy

Panarchy conceptualizes multiscale organization, interconnectedness of scales and dynamic system structure, and the collapse and reorganization inherent in adaptive cycles (Gunderson and Holling 2002). Panarchy is a model of complex systems that portrays the cross-scale structure envisioned in hierarchy theory (Allen and Starr 1982) and that acknowledges top-down and bottom-up processes that account for many observed nonlinear dynamics in ecosystems.

Panarchy also considers complex system dynamics such as adaptation, conservation, collapse, and reorganization, which are often portrayed as a nested set of adaptive cycles (Gunderson and Holling 2002) (figure 4.2). These adaptive cycles are related to extrinsic (climatic) and intrinsic (e.g., economy, governance) factors that influence, and are influenced by, important interrelated phenomena such as innovation, novelty, and regime changes in social-ecological systems (Allen et al. 2014). The theory can provide a heuristic to conceptualize different aspects of system organization (Allen et al. 2014) or can be formulated into hypotheses for individual premises and empirically tested (Angeler et al. 2015). There have been diverse and successful applications of panarchy in social and ecological systems and analyses (Green et al. 2015; Berkes and Ross 2016; DeWitte et al. 2017), and it can provide quantitative and qualitative underpinning for risk management and vulnerability and risk assessments (Angeler et al. 2016b). In this context, a panarchy may be a particularly suitable heuristic for framing coercive management from a multiscale perspective while accounting for the dynamism at each scale in a system. Specifically, panarchy can be useful for identifying points in adaptive cycles where management can be leveraged to enhance the coercion of a regime within a specific system configuration. In other words, a panarchy can be coerced through deliberate management of distinct phases of the adaptive cycles across hierarchies.

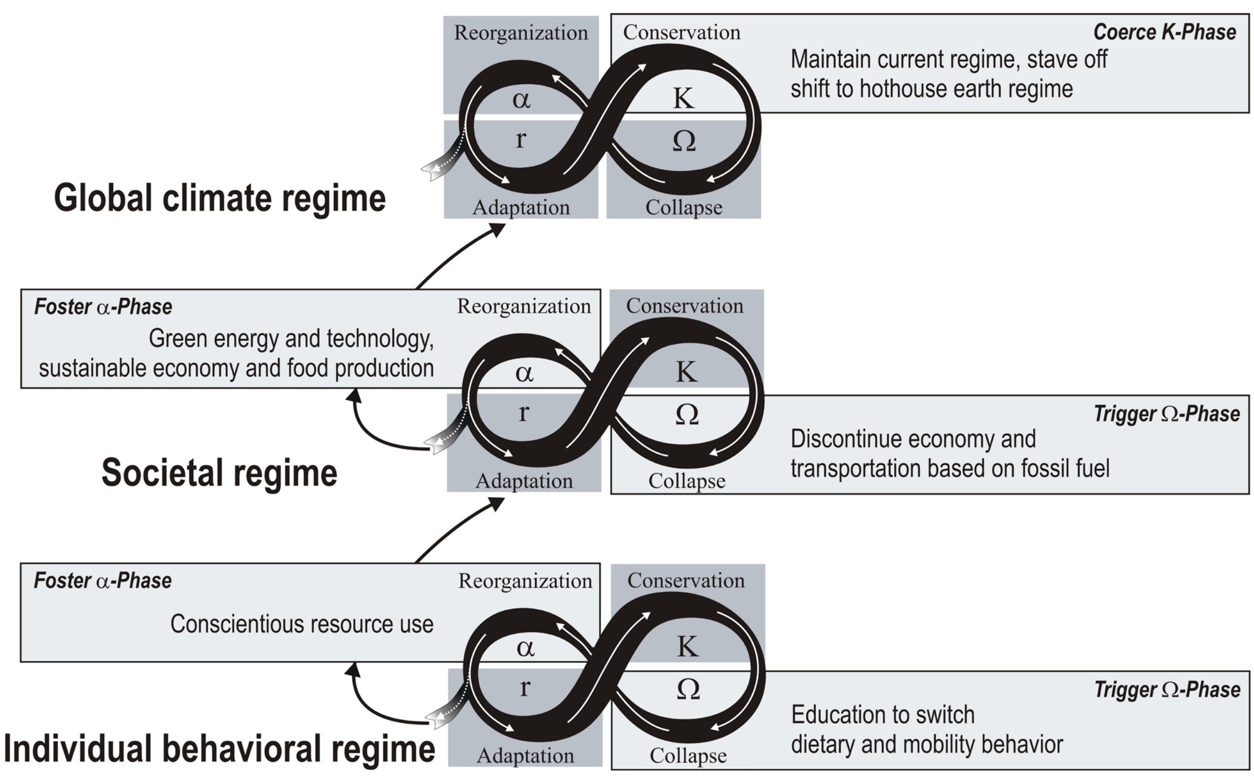

Figure 4.2: Schematic illustration of a climate system as a coerced panarchy. Highlighted are leverage points (green squares) for management in different phases of the adaptive cycles at the scale of individuals and society with the aim to stave of the triggering of the Omega phase at the highest level (global climate). General examples of interventions are given.

We next discuss coercive management of a panarchy (coerced panarchy) from a conceptual perspective. This will be followed by a real example using the global climate to discuss the practical implication of cross-scale management of dynamic systems.

Coerced Panarchy

Because of the interconnectedness of scales and the dynamic nature of these scale domains, captured by the processes within adaptive cycles, coercive management of a panarchy may have essentially a vertical (cross-scale) and horizontal (within-scale) component. Regarding the vertical component, management interventions at one scale can propagate up or down the entire panarchy. Such cascades are often desirable because not all scales in a panarchy are amenable to direct interventions or actions, that is, they are not manageable. Imagine a large eutrophic lake with recurring, broad-scale toxic algal blooms. Managing the blooms through direct interventions at the scale at which phytoplankton operates (i.e., fishing of the blooms) is impossible and therefore requires other interventions such as nutrient or top-down food web control. That is, interventions at higher trophic levels (fishing of planktivorous fish or stocking of predatory fish) can induce effects that cascade down the food web and eventually manifest at the trophic level of algal primary producers (Carpenter and Kitchell 1993). Similarly, inducing change at the top level of a panarchy often is impossible and requires a major change induced from below, as demonstrated by the massive revolts during the Arab Spring that lead to the toppling of corrupt authoritarian regimes (Sadiki 2014).

Ideally, management of a panarchy can be facilitated if interventions at a single scale propagate throughout other scales. We speculate that single-scale management of a panarchy might include the need for low coercion of a system in which the resilience of a desired regime is still high or the resilience of a degraded regime low. Building on this line of reasoning, we speculate that single-scale interventions will become insufficient the more eroded the resilience of a desired regime or the more stable the resilience of a degraded regime has become. In such cases management interventions at multiple scales will be needed to strengthen the coercion potential and thus the strength of artificial feedbacks in a panarchy. Again, for example, very resilient eutrophic (degraded) lake regimes need multiple biological and technological management interventions both within the lakes and in their catchments to abate the effects of nutrient enrichment (Annadotter et al. 1999; Madgwick 1999; Søndergaard et al. 2000). The climate example below provides another example of the need for multiple management interventions for maintaining the climate system in its current regime because of its low resilience.

Regarding the horizontal components of a panarchy (e.g., different habitat patches operating within their own adaptive cycles that may or may not be in synchrony), management can exploit the dynamic adaptive cycling of patterns and processes and intervene in the different adaptive cycle phases (from α to Ω) by either freezing, destroying, or boosting the reorganization of these phases. For example, nutrient precipitation in a lake may trigger the Ω phase for phytoplankton and facilitate the growth of submerged plants that contribute to clearwater conditions. Minimizing disturbances to macrophytes, such as sediment resuspension, may consolidate the α phase. As is the case with vertical components of coerced panarchies, redundant interventions within a single phase or across different phases of an adaptive cycle would probably increase the coercion success.

The lake example shows that the management of vertical and horizontal structures in a panarchy can be informed by a coercion analogue of the cross-scale resilience model (Peterson et al. 1998). The cross-scale resilience model posits that the relative resilience of a system is increased with an increasing redundancy of functions within and across scales. An analogous “cross-scale coercion model” suggests that an increasing redundancy of management interventions within and across scales is needed to artificially maintain a system in a desirable regime with low resilience (i.e. a system facing an imminent regime shift) or to mitigate degraded regimes that are highly resilient.

We next discuss the global climate regime as an example of a coerced panarchy, that is, a system that needs to be coerced into the current desirable climate regime by the implementation of mitigation measures with the aim of preventing it from tipping over into a hothouse Earth regime (Steffen et al. 2018). We particularly highlight how the redundancy of Earth stewardship measures within and across scales in the climate panarchy may influence the coercion potential.

Global Climate Panarchy

Modeling evidence suggests that continuation of past and present human activities will lead to ongoing climate change, as indicated by higher global average temperatures, accelerating rise in sea level, weakened marine jet streams, and shrinking polar ice sheet cover (Intergovernmental

Panel on Climate Change [IPCC] 2014). Such changes are expected to occur abruptly and nonlinearly, potentially leading to a new regime in which the climate is substantially and persistently changed. Profound changes in the global climate are already under way and supported by empirical evidence. Examples include regime shifts in forest fire regimes (Westerling et al. 2006), groundwater systems (Figura et al. 2011), arctic marine environments (Kortsch et al. 2012), and other ocean regions in the Northern Hemisphere (Beaugrand et al. 2015).

Steffen et al. (2018) considered the present climate regime as a glacial–interglacial limit cycle with a 100,000-year cycle. This cycle has been self-organizing and maintained during the past 1.2 million years. An alternative regime is described as a hothouse Earth that might have catastrophic consequences for humanity should planet Earth fully shift and stabilize in this regime. Steffen et al. (2018) contended that we need to consider deliberately coercing the Earth system into the glacial–interglacial regime to stave off a regime change to a hothouse Earth (figure 4.1). However, forcing the Earth system artificially into this glacial–interglacial regime would require sustained, massive management efforts and external subsidies by humans because such a regime would no longer be self-organizing. A series of Earth stewardship measures have been identified that could be used to coerce the Earth system to remain in the current glacial–interglacial regime (table 4.1). These measures include a global economy uncoupled from fossil fuels, augmentation of global carbon sinks, technology innovations, new governance agreements, behavioral transformation, and changes in social values.

Measure	**Redundancy**	**Scale**
Geo-engineering	Solar radiation management. Carbon capture and storage (enhanced weathering, direct air capture; reforestation, afforestation)	Society
Technology	Development of cleaner technology and improved efficiency	Society
Economy	Emission taxes, investments, subsidies, carbon emission trading	Society
Governance	Polycentric; international policy and law	Society
Emission reduction	Low carbon energy (renewable; biomass, solar, wind, geothermal) and transportation (electric cars, hybrids)	Individual, societies
Urban transformation and building design	Provide and encourage public transport, facilitate walking and bicycling, promote green areas	Individual, societies
Live style and behavior	Dietary shifts to plant-based diet, reduced use of car and air travel, family planning	Individual, societies

Table 4.1: Examples of partly interdependent management measures that can be mapped onto different phases of the adaptive cycle (AC) for coercing the climate panarchy (Fig. 4.2). Shown are also selected redundancies of these measures and their potential application across scales in the panarchy for enhancing their coercive force.

The global climate provides an example where the resilience of the current glacial–interglacial regime has been increasingly eroded, mainly by the decades-long overexploitation of fossil fuel. Specifically, fossil fuel has become the main subsidy of economic growth and human welfare. The results of externalizing the costs of carbon from the economy has led to increases in the concentrations of carbon dioxide and other greenhouse gases to the atmosphere. The accumulating gases have changed the energy budget of the planet, leading to the effects mentioned above. As Steffen et al. (2018) suggested, the pathological overuse of fossil fuel has exhausted the resilience of the glacial–interglacial regime, and significant management efforts are needed to mitigate the potential devastating consequences of a shift to a hothouse Earth regime. That is, the conditions of the glacial–interglacial regime must be conserved, necessitating the artificial coercion of the entire glacial–interglacial regime. Such coercion currently involves failed attempts to limit inputs of carbon and nitrogen into the atmospheric and oceanic realms of the planet. However, there are indications that the global social–ecological–climatological system is hysteretic. In other words, the path leading to degradation of the system is not the same as the pathway needed to reverse it. That is, management for coercing the current climate regime differs substantially from the human activity that eroded its resilience over time: Simply limiting the use of fossil fuels is unlikely to reverse the warming of the climate.

That the way out of the current delicate situation is extremely challenging is manifested in the complex, insufficient, and ineffective implementation of many Earth stewardship measures in the short and longer term. This may be due to, for example, inflexible policy that is mismatched with environmental challenges (Green et al. 2015), the weak adherence by many countries to international initiatives such as the Paris climate agreement, potential side effects of atmospheric carbon mitigation that can offset potential benefits (e.g., soil carbon sequestration; Powlson et al. 2014), and the speed by which global warming unfolds, manifested in an all-time high of CO_2 emissions at the time this chapter was written in 2018 (Global Carbon Project 2018). Although Earth stewardship measures (table 4.1) are a minimal requirement to effectively maintain a coerced climate regime trajectory, they allow examination of the complexity of coercion of the global climate from a panarchy perspective. Specifically, examining a coerced climate panarchy may be particularly suitable for envisioning the management challenges (e.g., cross-scale interactions) that are inherent in dynamic wicked problems, such as climate change (Angeler et al. 2016b).

Twidwell et al. (2019) made a clear case that the application of coercive force to management occurs within the bounds of existing policies, which further underscores the need for adaptive law and transformative governance to manage essential structures and functions for maintaining the current Earth system regime (Green et al. 2015; Chaffin et al. 2016; Garmestani et al. 2019). Maintaining structures and functions is critical for the resilience of a system (Holling 1973), especially if management aims to avoid regime changes, such as the shift of the current climate regime to a hothouse Earth regime. In panarchy theory, resilience relates to the adaptive cycling of nested systems through phases of reorganization and collapse. The interconnectedness of hierarchical scales in a panarchy further contributes to system resilience through feedbacks that can stabilize or destabilize system configurations through cross-scale interactions. Accounting for both the adaptive cycling and the interconnectedness of scales provides the potential to envision and implement management under constant system change.

Consider a simplified example of a coerced climate panarchy consisting of three arbitrary scales: the human individual, societies, and the global climate regime (figure 4.2). Each scale shows points in the adaptive cycle at which mitigation measures can be leveraged. At the highest level, the global climate regime, management aims are to freeze the Ω phase to maintain the current glacial–interglacial system and avoid a regime shift and reorganization to a hothouse Earth regime. However, it is clear that at this scale direct management cannot be leveraged to control the Ω phase. Building on interconnectedness as a major tenet of panarchy theory, management interventions at the societal and individual scales can be designed to percolate up to the highest scale in the global climate regime and force the maintenance of the Ω phase and avoid system collapse.

Such coerced panarchy shows that management can target different phases of an adaptive cycle. Such management can be sequential and implement a gale of creative destruction, as described by Austrian economist Josef Schumpeter (2010). In the broadest sense of the climate debate this means that current unsustainable behavior (fossil fuel–based economy) must be destroyed and replaced through the creation of sustainable (green energy) livelihoods at both the societal and individual levels. Such change is necessary because incremental adaptation measures to climate change may be insufficient, necessitating transformation (Kates et al. 2012). In our example, we provide a simplified demonstration of the coercion of the panarchy with Earth stewardship measures that target the α and Ω phases at the individual level. Such measures include changes in current alimentation (e.g., meat-based diet) and transportation habits (e.g., air travel, car). These habits have a high carbon footprint, which should be reduced (inducing the Ω phase). Sustainable livelihoods through the reorganization of their behavior and resource use (reduced consumption, plant-based diet, use of green energy and transportation) resulting from transitioning to a low carbon footprint can then be created and spur the α phase of the cycle (figure 4.2). Similarly, at the societal level, economies, technologies, and production systems that rely on fossil fuels should be replaced (Ω phase) by alternative models that are cleaner and more efficient (α phase) (figure 4.2, table 4.1).

Our model of coerced climate panarchy shows that many Earth stewardship measures, such as those related to green transportation, could be implemented across scales in the panarchy (table 4.1). Specifically, the provision of infrastructure that facilitates green transportation operates mainly at the societal level, whereas the use of such infrastructure depends on the individuals within societies. The model also shows that several categories of Earth stewardship measures are redundant, such as solar radiation management and carbon capture and storage as geo-engineering measures (table 4.1). These examples show that Earth stewardship measures can be redundant within and across scales in the climate panarchy. Within-scale and cross-scale redundancies are critical elements of system resilience (Peterson et al. 1998) and may therefore play a critical role in effectively coercing the current climate in the glacial–interglacial regime. Because the resilience of a system is expected to increase with increasing within-scale and cross-scale redundancy (Allen et al. 2005), we speculate that effective coercion of the glacial–interglacial regime will increase with increased redundancy of climate mitigation measures within and across scales in this particular climate system. Multiple coercion measures are needed in the face of the rapidly eroding resilience of our current climate regime in order to stave off an undesired, catastrophic shift to a hothouse Earth regime.

Conclusions

Unprecedented rates of environmental change in the Anthropocene require management models that guarantee the sustainable development of an increasing human population. The concept of coerced panarchy allows envisioning the leverage of management interventions in a complex system, such as the global climate, to optimize the potential to adapt to or transform in response to societal challenges (Angeler et al. 2020a). Successful long-term stewardship of the Earth will require interdisciplinary efforts involving global partnerships that link researchers, managers, policymakers, and citizens (Chapin et al. 2011). The coerced climate panarchy example identifies the scales and phases of the adaptive cycles that these partnerships could target for the implementation of mitigation measures. This example shows that within-scale and cross-scale aspects will be critical for effectively coercing the climate in the current glacial–interglacial regime. That is, it is likely that the potential for successful coercion increases with an increased redundancy and diversity of Earth stewardship measures within and across scales in the climate regime. Multiple interventions are probably needed to keep the current climate regime in its present low-resilience state. However, although theoretically a series of mitigation measures are available, the implementation of these may face societal rejection (e.g., fewer children) or reluctance to change habits and behavior in the short term. That is, cultural, in addition to economic, political, and technological aspects may potentially limit the application of the full arsenal of Earth stewardship measures and potentially weaken the mitigation of global warming.

A coerced panarchy has the potential to clarify the complexity associated with artificially maintaining desired system conditions. It remains to be seen how effective the coercion of the current climate regime can be in the long term given that atmospheric CO_2 levels continue to increase. Global warming may soon reach levels that exceed our potential for coercion of the climate panarchy even if Earth stewardship measures are implemented at multiple scales.

Acknowledgments

This study was supported by a sabbatical professorship to D.G.A. through the University of Nebraska–Lincoln.

Literature Cited

Allen, C.R., D.G. Angeler, A.S. Garmestani, L.H. Gunderson, and C.S. Holling. 2014. Panarchy: Theory and applications. *Ecosystems* 17: 578–589.

Allen, C.R., L. Gunderson, and A.R. Johnson. 2005. The use of discontinuities and functional groups to assess relative resilience in complex systems. *Ecosystems* 8: 958–966.

Allen, T.F.H., and T.B. Starr. 1982. *Hierarchy: Perspectives for Ecological Complexity.* University of Chicago Press, Chicago.

Angler, D.G., and C.R. Allen. Quantifying resilience. 2016. *Journal of Applied Ecology* 53: 617-624.

Angeler, D.G., C.R. Allen, C. Barichievy, T. Eason, A.S. Garmestani, N.A.J. Graham, D. Granholm, L. Gunderson, M. Knutson, K.L. Nash, R.J. Nelson, M. Nyström, T.E. Spanbauer, C.A. Stow, and S.M. Sundstrom. 2016a. Management applications of discontinuity theory. *Journal of Applied Ecology* 53: 688–698.

Angeler, D.G., C.R. Allen, and A. Carnaval. 2020a. Convergence science in the Anthropocene: Navigating the known and unknown. *People and Nature* 2: 96–102.

Angeler, D.G., C.R. Allen, A.S. Garmestani, L.H. Gunderson, O. Hjerne, and M. Winder. 2015. Quantifying the adaptive cycle. *PLoS One* 10: e0146053. doi:10.1371/journal.pone.0146053

Angeler, D.G., C.R. Allen, A.S. Garmestani, L.H. Gunderson, and I. Linkov. 2016b. Panarchy use in environmental science for risk and resilience planning. *Environment Systems and Decisions* 36: 225–228.

Angeler, D.G., C.R. Allen, and M.-L. Persson. 2018. Resilience concepts in psychiatry demonstrated with bipolar disorder. *International Journal of Bipolar Disorders* 6: 2.

Angeler, D.G., B.C. Chaffin, S.M. Sundstrom, A. Garmestani, K.L. Pope, D.R. Uden, D. Twidwell, and C.R. Allen. 2020b. Coerced regimes: Management challenges in the Anthropocene. *Ecology & Society* 25(1):4. https://doi.org/10.5751/ES-11286-250104

Angeler, D.G., P. Chow-Fraser, M.A. Hanson, S. Sánchez-Carrillo, and K.D. Zimmer. 2003. Biomanipulation: A useful tool for freshwater wetland mitigation? *Freshwater Biology* 48: 2203–2213.

Angeler, D.G., S. Drakare, R.K. Johnson, S.J. Köhler, and T. Vrede. 2017. Managing ecosystems without prior knowledge: Pathological outcomes of lake liming. *Ecology and Society* 22: 44.

Angeler, D.G., H.B. Fried-Petersen, C.R. Allen, A. Garmestani, D. Twidwell, W. Chuang, V.M. Donovan, T. Eason, C.P. Roberts, S.M. Sundstrom, and C.L. Wonkka. 2019. Adaptive capacity in ecosystems. *Advances in Ecological Research* 60: 1–24.

Annadotter H., G. Cronberg, R. Aagren, B. Lundstedt, P.Å. Nilsson, and S. Ströbeck. 1999. Multiple techniques for lake restoration. In *The Ecological Bases for Lake and Reservoir Management*, ed. D.M. Harper, B. Brierley, A.J.D. Ferguson, and G. Phillips, 77–85. Developments in Hydrobiology 136. Springer, Dordrecht, The Netherlands.

Baho, D.L., C.R. Allen, A. Garmestani, H.B. Fried-Petersen, S.E. Renes, L.H. Gunderson, and D.G. Angeler. 2017. A quantitative framework for assessing ecological resilience. *Ecology and Society* 22: 17. https://doi.org/10.5751/ES-09427-220317

Beaugrand, G., A. Conversi, S. Chiba, M. Edwards, S. Fonda-Umani, C. Greene, N. Mantua, S.A. Otto, P.C. Reid, M.M. Stachura, L. Stemmann, and H. Sugisaki. 2015. Synchronous marine pelagic regime shifts in the Northern Hemisphere. *Philosophical Transactions of the Royal Society B* 370: 20130272.

Beisner, B.E., D.T. Haydon, and K. Cuddington. 2003. Alternative stable states in ecology. *Frontiers in Ecology and the Environment* 1: 376–382.

Berkes, F., and H. Ross. 2016. Panarchy and community resilience: Sustainability science and policy implications. *Environmental Sciences and Policy* 61: 185–193.

Biggs, R., G. Peterson, and J.C. Rocha. 2018. The regime shifts database: A framework for analyzing regime shifts in social-ecological systems. *Ecology and Society* 23: 9.

Carpenter, S.R., and J.F. Kitchell. 1993. *The Trophic Cascade in Lakes*. Cambridge University Press, Cambridge, UK.

Chaffin, B.C., A.S. Garmestani, L. Gunderson, M. Harm Benson, D.G. Angeler, C.A. Arnold, B. Cosens, R.K. Craig, J.B. Ruhl, and C.R. Allen. 2016. Transformative environmental governance. *Annual Review of Resources and Environment* 41: 399–423.

Chapin, F.S., S.T. Pickett, M.E. Power, R.B. Jackson, D.M. Carter, and C. Duke. 2011. Earth stewardship: A strategy for social–ecological transformation to reverse planetary degradation. *Journal of Environmental Studies and Sciences* 1: 44–53.

DeWitte, S.N., M.H. Kurth, C.R. Allen, and I. Linkov. 2017. Disease epidemics: Lessons for resilience in an increasingly connected world. *Journal of Public Health* 39: 254–257.

Figura, S., D.M. Livingstone, E. Hoehn, and R. Kipfer. 2011. Regime shift in groundwater temperature triggered by the Arctic Oscillation. *Geophysical Research Letters* 38: 1–5.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Reviews in Ecology, Evolution and Systematics* 35: 557–581.

Garmestani, A., J.B. Ruhl, B.C. Chaffin, R.K. Craig, H.F. van Rijswick, D.G. Angeler, C. Folke, L. Gunderson, D. Twidwell, and C.R. Allen. 2019. Untapped capacity for resilience in environmental law. *Proceedings of the National Academy of Sciences* 11: 201906247.

Global Carbon Project 2018. https://www.globalcarbonproject.org/index.htm

Green, O.O., A.S. Garmestani, C.R. Allen, J.B. Ruhl, C.A. Arnold, L.H. Gunderson, N.A.J. Graham, B. Cosens, D.G. Angeler, B.C. Chaffin, and C.S. Holling. 2015. Barriers and bridges to the integration of social-ecological resilience and law. *Frontiers in Ecology and the Environment* 13: 332–337.

Gunderson, L.H. 2000. Resilience in theory and practice. *Annual Review of Ecology and Systematics* 31: 425–439.

Gunderson, L.H., and C.S. Holling. 2002. *Panarchy: Understanding Transformations in Human and Natural Systems.* Island Press, Washington, DC.

Holling, C.S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4: 1–23.

Holling, C.S., and G.K. Meffe. 1996. Command and control and the pathology of natural resource management. *Conservation Biology* 10: 328–337.

Homer-Dixon, T.F. 1991. On the threshold: environmental changes as causes of acute conflict. *International Security* 16: 76–116.

Hughes, T.P., S. Carpenter, J. Rockström, M. Scheffer, and B. Walker. 2013. Multiscale regime shifts and planetary boundaries. *Trends in Ecology & Evolution* 28: 389–395.

Intergovernmental Panel on Climate Change (IPCC). 2014. *Climate Change 2014: Synthesis Report*. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Core Writing Team, R.K. Pachauri and L.A. Meyer. IPCC, Geneva, Switzerland.

Kates, R.W., W.R. Travis, and T.J. Wilbanks. 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the USA* 109: 7156–7161.

Kortsch, S., R. Primicerio, F. Beuchel, P.E. Renaud, J. Rodrigues, O.J. Lønne, and B. Gulliksen B. 2012. Climate-driven regime shifts in Arctic marine benthos. *Proceedings of the National Academy of Sciences USA* 109: 14052–14057.

Madgwick, F.J. 1999. Restoring nutrient-enriched shallow lakes: Integration of theory and practice in the Norfolk Broads, UK. *Hydrobiologia* 408/409: 1–12.

McMichael, A.J., S. Friel, A. Nyong, and C. Corvalan. 2008. Global environmental change and health: impacts, inequalities, and the health sector. *British Medical Journal* 336: 191–194.

Miller, M.H., and J. Williamson. 1988. The international monetary system: An analysis of alternative regimes. *European Economic Review* 32: 1031–1048.

Nash, K.L, C.R. Allen, D.G. Angeler, C. Barichievy, T. Eason, A.S. Garmestani, N.A.J. Graham, D. Granholm, M. Knutson, R.J. Nelson, M. Nyström, C.A. Stow, and S.M. Sundstrom. 2014. Discontinuities, cross-scale patterns and the organization of ecosystems. *Ecology* 95: 654–667.

Peterson, G., C.R. Allen, and C.S. Holling. 1998. Ecological resilience, biodiversity, and scale. *Ecosystems* 1: 6–18.

Powlson, D. S., C.M. Stirling, M.L. Jat, B.G. Gerard, C.A. Palm, P.A. Sanchez, and K.G. Cassman. 2014. Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* 4: 678.

Rist, L., A. Felton, M. Nyström, M. Troell, R.A. Sponseller, J. Bengtsson, H. Österblom, R. Lindborg, P. Tidåker, D.G. Angeler, R. Milestad, and J. Moen. 2014. Applying resilience thinking to production systems. *Ecosphere* 5: 73.

Rockström, J., W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley. 2009. Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society* 14: 32.

Sadiki, L. 2014. *Routledge Handbook of the Arab Spring*. Routledge, New York.

Scheffer, M., S.H. Hosper, M.L. Meijer, B. Moss, and E. Jeppesen. 1993. Alternative equilibria in shallow lakes. *Trends in Ecology & Evolution* 8: 275–279.

Schumpeter, J.A. 2010. *Capitalism, Socialism, and Democracy.* Routledge, New York.

Society for Ecological Restoration (SER) International Science & Policy Working Group. 2004. *The SER International Primer on Ecological Restoration*. Society for Ecological Restoration International, Washington, DC.

Søndergaard, M., E. Jeppesen, J.P. Jensen, and T. Lauridsen. 2000. Lake restoration in Denmark. *Lakes & Reservoirs: Research & Management* 5: 151–159.

Steffen, W., J. Rockström, K. Richardson, T.M. Lenton, C. Folke, D. Liverman, C.P. Summerhayes, A.D. Barnosky, S.E. Cornell, M. Crucifix, J.F. Donges, I. Fetzer, S.J. Lade, M. Scheffer, R. Winkelmann and H.J. Schellnhuber. 2018. Trajectories of the Earth system in the Anthropocene. *Proceedings of the National Academy of Sciences USA* 115: 8252-8259.

Suding, K.N., and K.L. Gross. 2006. The dynamic nature of ecological systems: Multiple states and restoration trajectories. In *Foundations of Restoration Ecology*, ed. D.A. Falk, 190–209. Island Press, Washington, DC.

Suding, K.N., K.L. Gross, and G.R. Houseman. 2004. Alternative states and positive feedbacks in restoration ecology. *Trends in Ecology & Evolution* 19: 46–53.

Sundstrom, S.M., D.G. Angeler, C. Barichievy, T. Eason, A. Garmestani, L. Gunderson, M. Knutson, K.L. Nash, T. Spanbauer, C. Stow, and C.R. Allen. 2018. The distribution and role of abundance in cross-scale resilience. *Ecology* 99: 2421–2432.

Twidwell, D., C.L. Wonkka, H.H. Wang, W. Grant, C.R. Allen, S.D. Fuhlendorf, A. Garmestani, D. Angeler, C.A. Taylor, U.P. Kreuter, and W.E. Rogers. 2019. Coerced resilience in fire management. *Journal of Environmental Management* 240: 368–373.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. *Science* 313: 940–943.