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S. Sundstrom

C. Allen

J. Hodbod

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Chapter 2
Resilience of Working Agricultural Landscapes

Shana M. Sundstrom, Jennifer Hodbod, and Craig R. Allen

Abstract Many alternative agricultural approaches have been developed as a response to the social and ecological costs of modern industrialized agriculture. These include diversified, organic, sustainably intensified, and ecologically intensified farming systems, each of which addresses different aspects of agriculture as a social-ecological system. However, clear theoretical models that account for human-nature coupling and the importance of scale are lacking. Global change, including climate change, land use change, and other human activities influencing social-ecological systems, is exacerbating uncertainty regarding agriculture system dynamics and increasing the need for comprehensive models that include a dynamical integration of socio-ecological-economic influences. Resilience theory and related ideas such as panarchy have begun to actively inform agricultural science and practice in ways that should help enable current agricultural practices to become more sustainable – and resilient. However, there are several key resilience concepts that have yet to be fully developed within the agricultural research community. In this chapter, we briefly present resilience and its relevance to agriculture, and then we focus on three interrelated resilience ideas that have received less attention in the agriculture literature: (1) the functional attributes which underpin resilience; (2) the possibility of alternative regimes in agricultural systems and the implications for both continued agricultural production and the ecological landscapes in which agricultural systems are embedded; and (3) the relevance of scale for understanding and managing complex agricultural systems. We finish by discussing a path forward for the continued development of theories that can adequately encompass the full complexity of agricultural systems.

S. M. Sundstrom · C. R. Allen (✉)
Center for Resilience in Agricultural Working Landscapes and School of Natural Resources,
University of Nebraska-Lincoln, Lincoln, NE, USA
e-mail: allencr@unl.edu

J. Hodbod
Department of Community Sustainability, Michigan State University, East Lansing, MI, USA

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2.1 Introduction

Two axioms about the future of modern industrial agriculture have become clear in the last decade. The first is that current levels of energy and chemical inputs, and waste outputs, are unsustainable (Patzek 2008). The second is that climate change poses a singular and potentially catastrophic risk to the future of food production globally (IPCC 2019). Working agricultural landscapes are complex social-ecological systems that integrate food, water, and energy sub-systems. For example, within working agricultural landscapes, food, feed, energy, and fibre are often the production goals (depending on social, economic, and environmental context), but simultaneously these landscapes are dependent on land, water, and energy (along with capital and labour) to form the resource base. Therefore, there are multiple independent but interacting components, and focused management actions that ignore this complex reality are likely to both generate unintended consequences that negatively impact other components and reduce the likelihood of achieving their own focused goals over the long-term. Unfortunately, the reality is that these complex systems are often managed as if they are stable, predictable, simple, stationary engineered systems tending towards equilibrium conditions (Chapman et al. 2017). The shortcomings of this approach have been well documented (Weis 2010; Malézieux 2012). Alternative paradigms to modern agriculture emerged as early as the 1970s when the environmental impacts and increased vulnerability of farmers to the post-WWII development of synthetic fertilizers, herbicides, and pesticides started to become apparent (Carson 1962; Wezel et al. 2009; Gliessman 2013). Disciplines such as agroecology seek a return to multifunctional and sustainable agricultural systems that rely more on natural ecological processes and less on ecologically destructive fossil fuel-based inputs (Garibaldi et al. 2017). A multiplicity of alternative agricultural approaches have been developed, including diversified, organic, sustainably intensified, and ecologically intensified farming systems, each of which addresses different aspects of agriculture as a social-ecological system (Doré et al. 2011; Kremen et al. 2012; Malézieux 2012; Loos et al. 2014). However, clear theoretical models that account for human-nature coupling and the importance of scale are lacking. Global change – including climate change, land use change, and other human activities influencing social-ecological systems – is exacerbating uncertainty and increasing the need for comprehensive models that include a dynamical integration of socio-economic influences. Resilience theory and related ideas, such as panarchy, have begun to actively inform agricultural science and practice in ways that should help enable current agricultural practices to become more sustainable – and resilient (Bennett et al. 2014; Sinclair et al. 2014; Lengnick 2015; Schipanski et al. 2016).

Resilience is an idea emerging from the recognition that ecological and social-ecological systems may exist in alternative states (or “regimes”) (Fig. 2.1). The development of resilience concepts gives rise to a number of questions relevant to the management of social-ecological systems. If ecosystems are complex adaptive systems, then what are the implications for assumptions regarding behaviour and

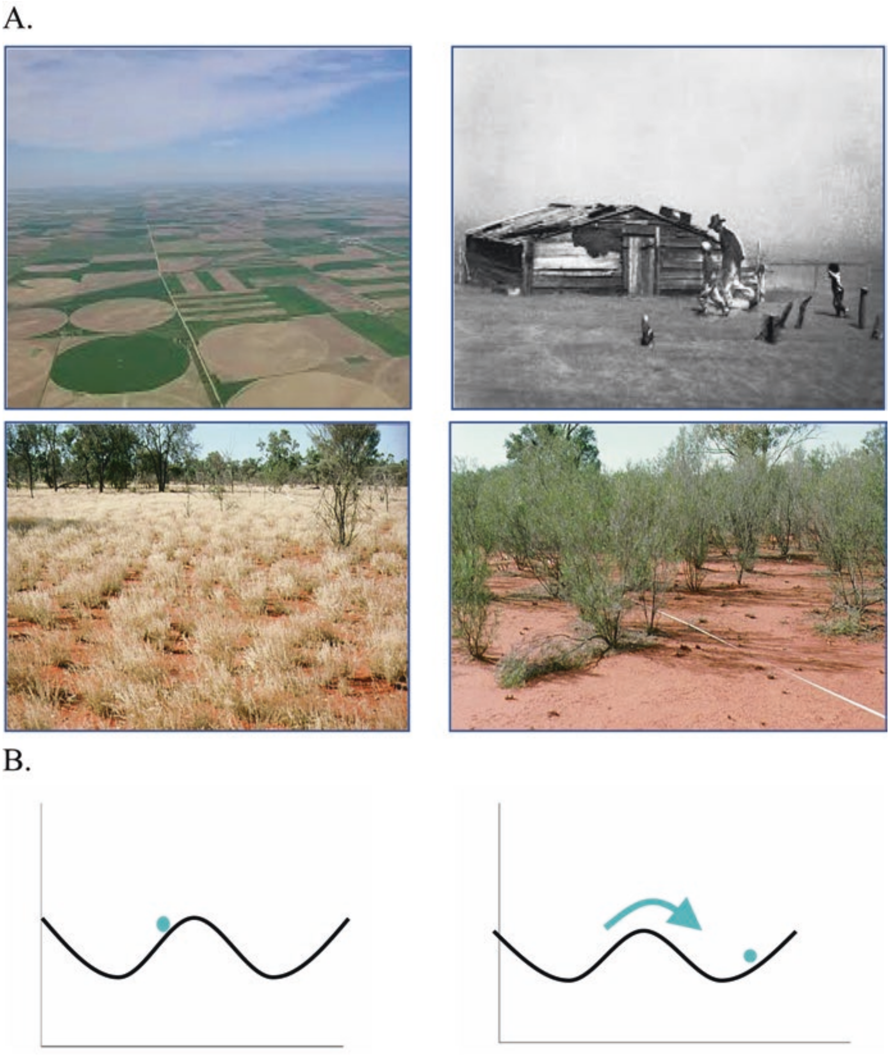

Fig. 2.1 Alternative states are alternative configurations of the same landscape. Shifts between states occur when the structuring "regime", that is, the processes and feedbacks that provide the characteristic structure of a system, changes as a result of a threshold in a key variable being exceeded. (**a**). Alternative regimes for farmland and rangeland. (**b**). Conceptual model or "cartoon" of the shift between alternative states (Allen et al. 2019)

dynamics? For management? For emergent phenomena? For ecological functions upon which humans rely? For the interactions between humans and ecosystems? Indeed, a rich panoply of theory, concepts, and management strategies addressing these questions have arisen over the decades which collectively comprise elements of the core of resilience theory and practice. Although resilience was originally developed within ecology and then expanded to encompass the human component of ecosystems, it has subsequently spread across scientific disciplines. Uptake of the theoretical content of resilience has not always occurred in tandem with the use of the verbiage, such as agriculture research papers that reference resilience in the title or body but never define the term (e.g. Gliessman 2013; Isaac et al. 2018). In that sense, it has also become a catchword, vaguely encompassing some theoretically desirable system trait and no more. Given the very real problems faced by agriculture and the rich utility resilience science offers to wicked problems such as the interactions between people, productions systems, and the environment, we argue that resilience science has much to offer beyond catchy verbiage.

Agricultural systems pose an interesting twist on social-ecological systems because rather than consisting of the interaction between people and a natural resource which is harvested, such as a fishery, modern agricultural systems exist *because of* people. The extent to which they are engineered means we can re-engineer them to be less environmentally costly and more resilient. Modern agricultural systems are coerced, in that the system being managed lacks self-organization to maintain itself in a particular regime, and without constant exogenous inputs would revert to some other type of system. In a lightly coerced system, such as native grassland used to graze cattle, the initial changes would be undetectable and/or minimal if humans were absent. In a highly coerced agroecosystem such as row crop monocultures, changes in the system would be dramatic, and the state of the system would rapidly change. Despite their intense coercion, industrialized agricultural systems still fundamentally rely on ecological components of soil, animal and plant species, water, and nutrients, each with multiple roles operating at multiple scales. These systems cannot be separated from their broader impacts on the environment and the social components of governance, policy, trade, livelihood security, and economics – i.e. they reflect all elements of the food-energy-water nexus and its complexities. In other words, despite the fact that agricultural systems only exist as a result of human agency, their dynamics and behaviour are those of a complex adaptive system where resource use and management decisions are based on highly uncertain conditions, and the limits and thresholds inherent to agroecosystems as complex adaptive systems are largely unknown. For example, our most productive irrigated agricultural systems have not yet stood the test of time, and their resilience is unknown, yet intensive irrigated agricultural systems continue to spread globally. In this chapter, we describe resilience science and the application of resilience and panarchy theories to complex working agricultural landscapes.

2.1.1 Resilience

Resilience is the capacity of social-ecological systems to buffer disturbances and remain within their current regime. A regime can be qualitatively described as a recognizable system state, such as a native grassland or mixed hardwood forest, where the system has self-organized around a key set of processes and functions and remains in that state (or regime), despite experiencing disturbances. There have been numerous explorations of what qualities of a system make them resilient (see Angeler and Allen 2016 and accompanying papers). A key model is the cross scale resilience model which posits resilience is derived, in part, by the distribution of function within and across scales, with the most resilient distribution characterized by high diversity within a scale and redundancy across scales (Peterson et al. 1998; Sundstrom et al. 2018). The contradiction this poses for modern agriculture is obvious, as the highly efficient production of food and fibre is dependent on a decreasing number of species, most of which are grown in massive monocultures (Khoury *et al.* 2014). Modern agriculture approaches to food production fail to consider both resilience and the full and differential dimensions of food system functions at appropriate scales: in other words, the multifunctionality of food (Hodbod and Eakin 2015). Critical functions offered by agricultural systems cross-cut economic, ecological, and social sustainability, and a high-performing, multifunctional landscape would achieve the following (Hodbod et al. 2016):

1. Support equitable provision and maintenance of livelihoods with fair wages and regional economic vitality.
2. Ensure food security, including physical, social, and economic access to sufficient, safe, and nutritious food which meets dietary needs and food preferences and supports an active and healthy life.
3. Regenerate a range of provisioning, regulating, and cultural ecosystem services, including those not directly used in agricultural systems.
4. Reduce greenhouse gas emissions throughout agricultural systems (including production, processing, distribution, consumption, and waste).
5. Does not compromise future productivity by degrading the required resource base (e.g. soil, water).

Instead, most commonly we see working agricultural landscapes managed solely for efficiency in profit and productivity, even though this means a reduction in resilience. While principles of comparative advantage may work well in enhancing economic efficiency, particularly in non-crisis years, there are trade-offs in terms of resilience to disturbance. Without some degree of functional redundancy, the loss of one critical system component can trigger dramatic changes in system dynamics. This is true in relation to agro-biodiversity at the farm level, diversity of nutrients in household diets, diversity in food supply sources and distribution networks for cities, and the diversity of modes of production, inputs, and economic strategies across all dimensions of food system activities (Hodbod and Eakin 2015). Efficiency approaches, such as maximum sustained yield, focus on producing maximum output under (rarely met) ideal conditions, whereas resilience focuses on guaranteeing (lesser) production under a variety of conditions, including unexpected conditions.

When Holling (1973) first introduced the concept of ecological resilience, he contrasted it with what he termed engineering resilience. Engineering resilience assumes that the system in question operates in a single state and at equilibrium. This can be true in ecosystems over small spatial scales and short timeframes, which are the scales at which much ecological research is conducted. Engineering resilience was the logical extension of a Newtonian worldview of nature as a clockwork mechanism, where one merely needed to understand the mechanistic relationships between the pieces in order to fully understand and predict future behaviour (Heylighen et al. 2007). The application of this worldview to the management of natural resources has led, inevitably, to system collapse (Holling and Meffe 1996). Consider fisheries, where harvest rates were set by overly simplified equations (Carpenter et al. 2002). The intense single-species focus ignored the larger ecological context of fish communities over time and space and assumed that any deviations from the expected equilibrium were temporary and indicated a need to tweak the equations. Holling (1973, 2001) argued that ecosystems and in fact most ecological, social, economic, and social-ecological systems are actually non-stationary, have alternative states, and possess critical thresholds that when exceeded may flip a system into a less-desirable alternative state (Allen et al. 2019). This approach derives from complexity theory and considers systems of people and nature, such as agricultural systems, as complex adaptive systems. As such they consist of many independent entities that interact locally and are capable of evolution or adaptive response to change, are hierarchical with scale-specific structure, and are characterized by critical thresholds, inherent uncertainty, non-equilibrium, multiple possible alternative stable states, and emergent phenomena that cannot be predicted by aggregating knowledge from smaller spatial and temporal scales (Levin 1998). One of those emergent phenomena is ecological resilience – the amount of disturbance a system can withstand before it collapses. Ecological resilience emerges at the system level and is a non-normative property, as even unproductive and undesirable system states, including agricultural systems, can be highly resilient and resistant to change. In the case of systems in undesirable states, managers can take actions to erode resilience and encourage system transformation to a more desired state (Chaffin et al. 2016). When a system is in a perceived desirable state, it is usually in policymakers' and managers' best interest to maintain and enhance resilience because the thresholds between alternative system states are often poorly understood, and regime shifts tend to occur abruptly.

System resilience is predicated on a small handful of interrelated and sometimes difficult to quantify attributes. Perhaps the best understood attribute is the contribution of species as functional organisms and their role in maintaining critical ecosystem processes (Folke et al. 2004; Soliveres et al. 2016). Resilience emerges when there is a diversity of functional attributes, a redundancy in the species contributing to a particular function, and response diversity, all *distributed in a non-random manner within and across system scales* (Peterson et al. 1998; Elmqvist et al. 2003). This provides buffering capacity in the face of disturbances, as disturbances rarely occur evenly across all spatial and temporal scales. Spatial and temporal heterogeneity in landscape structure is also critical and cannot be understood separately from the distribution of functions within and across system scales, as a homogenous landscape across multiple scales will necessarily support fewer functions (Tews et al. 2004; Fischer et al. 2008). Response diversity refers to species that perform a similar function but respond differentially to a specific disturbance such as drought or flooding (Elmqvist et al. 2003). The primary take-away is that highly simplified agricultural systems stripped of their diversity in the push for efficiency are the most vulnerable to unforeseen disturbances because the processes of internal system variability that buffer disturbances have been removed and replaced with external subsidies (Patzek 2008; Altieri et al. 2015). Ironically, while such streamlined agrosystems may be more productive in the short term, research is increasingly demonstrating that the competitiveness of more diversified farming systems in maintaining stable productivity over longer time periods is a result of its higher buffering capacity (Davis et al. 2012; Matsushita et al. 2016; Schrama et al. 2018). Hodbod and Eakin (2015) discuss different combinations of response and functional diversity, highlighting the trade-offs for food systems (Fig. 2.2).

Other attributes that contribute to social-ecological resilience include adaptive capacity, system memory, and internal self-regulation. Adaptive capacity is typically understood to represent the combination of genetic, epigenetic, behavioural, and acclimation processes contained within species and populations, be they the species cultivated for productions or humans (Angeler et al. 2019). It can also be a system-level property related to the system's ability to respond to change, which more readily translates to the social components of agroecosystems (Cabell and Oelofse 2012; Koohafkan et al. 2012; Bennett et al. 2014). System memory refers

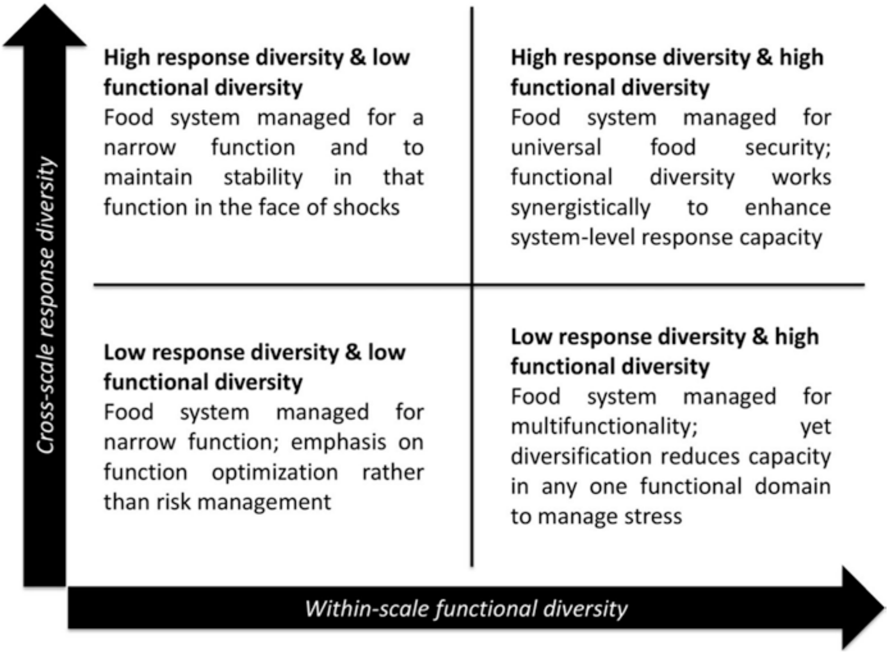

Fig. 2.2 Different combinations of response and functional diversity in food systems, highlighting the trade-offs between the two types of diversity. Monocultures fit into the bottom left quadrant, as the management for efficient optimization of production creates low response and functional diversity. In contrast, working agricultural landscapes managed for high response and functional diversity will fulfil a wider range of functions (Hodbod and Eakin 2015)

to the ability of the system to draw upon stored information or material in order to reorganize post-disturbance (Power et al. 2015; Newman et al. 2019). This may come in the form of seed banks, nearby populations with dispersal ability, local expertise, or other forms of institutional capital (Nystrom and Folke 2001). Finally, internal self-regulation depends on feedbacks and stabilizing mechanisms and requires key processes to unfold unimpeded, such as the regenerative relationship between fire and grasslands. The primary focus of agroecology is movement towards increased self-regulation through the restoration of agro-ecological processes such as nutrient recycling and retention, water storage, pest/disease regulation, and pollination such that fewer external inputs are required, especially those based on fossil fuels. The primary methods for doing so rely on building ecological resilience through a focus on the attributes just described (Cabell and Oelofse 2012; Nicholls and Altieri 2018). Such methods have been successfully implemented on individual farms and small communities since the 1970s, before the language of agroecology expanded to incorporate the theory of resilience science (Wezel et al. 2009; Koohafkan et al. 2012; Gliessman 2013; Casimiro Rodríguez and Casimiro González 2018).

Translating the attributes of ecological resilience beyond small-scale agroecosystems to industrialized agricultural systems, which provide a significant portion of the world's calories through the maximization of the efficient and stable production of a small handful of species, is clearly more challenging. There is a glaring contradiction between ecological resilience and the objectives of industrialized agriculture. Resilience is concerned with regime shifts, or the long-term persistence of a system in a recognizable configuration of structure and function. This is also a goal of agricultural systems. However, resilience is predicated on the persistence of relationships, processes, and functions, rather than stability or stationarity in either species presence or species abundance (Sundstrom et al. 2018). In fact, resilience is to a large extent *dependent* on variability in species presence and abundance, in obvious contradiction to stable agricultural row crop production. Regardless of the environmental costs of coercing industrialized agricultural systems through human inputs of energy, water, nutrients, and pesticide/herbicides, industrialized agriculture often fails to account for the possibility of large-scale regime shifts and the collapse of agricultural systems. In the quest for increased efficiency and maximization of yields, industrialized agriculture has removed the system attributes that provide resilience to disturbances, whether they be small-scale pest outbreaks or large-scale climate change, and in doing so has rendered such systems highly vulnerable to the possibility of large-scale regime shifts (Patzek 2008; Altieri et al. 2015). While an increasing number of agricultural researchers have recognized this problem and incorporate resilience science as a critical tool for developing and expanding new types of agricultural systems, few researchers take into account the possibility of not just small-scale regime shifts in the form of a farm (farmer) adapting to changing socio-economic-ecological conditions but the possibility of large-scale shifts in the ability of landscapes to maintain food production services.

2.1.2 Regime Shifts

Regime shifts occur when a critical threshold in a key system variable is exceeded (Scheffer 2009). Such shifts often occur abruptly and therefore as an unpleasant surprise but are often the result of a long, slow change in a key driver (Scheffer and Carpenter 2003). An important point is that these shifts can be highly unpredictable because system behaviour doesn't outwardly appear to change despite the slowly changing driver, until the system suddenly collapses. Once a threshold in a key system parameter has been reached, even a very small disturbance can be sufficient to exceed the capacity of the system to buffer the disturbance, triggering a regime shift (Crépin et al. 2012). Thresholds which when crossed trigger movement to a new regime are called critical thresholds or critical transitions and are to be distinguished from linear or nonlinear thresholds along which a system can move both forward and backward (Scheffer 2009). The development of the underlying theory with its origins in physics and its application to ecosystems and social-ecological systems has been substantive, generating a robust literature that is now being applied to many other system types (Karunanithi et al. 2011; Lenton and Williams 2013; Lansing et al. 2014; Vance et al. 2017; Rocha et al. 2018). The cutting edge of regime shift science is the search for early warning indicators of impending regime shifts, in order to improve our ability to monitor system movement towards a critical threshold (Dakos et al. 2010; Carpenter et al. 2011; Hughes et al. 2013b; Eason et al. 2014; Clements and Ozgul 2018). In ecological systems, regime shifts have proven problematic for several reasons: the difficulty of reversing such shifts, the fact that such shifts often result in degraded system states that produce fewer ecological goods and services upon which humanity depends, and the possibility of not just hysteresis but irreversibility. Hysteresis occurs when the path that led to a regime shift cannot be followed backwards to induce a regime shift back to the prior state (Scheffer et al. 2001). For example, slowly increasing phosphorus loading in a shallow lake over time can trigger the shift to a eutrophic, nutrient-rich, and turbid state, but reducing phosphorus inputs to levels lower than what triggered the shift is not sufficient to move the lake back to an oligotrophic, or clear-water, algae-free state. Movement back to a previous regime can be extremely challenging, and in some cases impossible, as the underlying conditions that permitted the original regime are no longer present. The continued collapse of the Grand Banks cod fishery as a result of overfishing despite a decades-long fishing moratorium and the contamination of groundwater with nitrates throughout much of the Midwest are sobering examples (Crépin et al. 2012), and the possible collapse of the entire Great Barrier Reef coral system a grim prospect (Wolff et al. 2018). Because regime shifts can occur abruptly, without obvious warning, and be irreversible, managers and policymakers should be highly motivated to avoid them. This is especially true for production systems, because much of humanity is reliant upon the foods produced by these systems. The critical need to maintain resilient agricultural systems cannot be overstated.

Agricultural systems, despite being engineered by humans, are not immune to regime shifts, as nonlinear and abrupt change is a feature that cannot be engineered away. In fact, the degree to which industrialized agriculture has attempted to engineer such systems to reduce variability and uncertainty actually renders the system more vulnerable to a regime shift because resilience has been stripped out in favour of efficiency (Patzek 2008; Altieri et al. 2015). Instead of self-organized processes that buffer insect outbreaks, periodic droughts, or heat waves, humans must engineer responses to every new disturbance, whether it is soil loss and soil degradation from tilling, herbicide-resistant weeds, pesticide-resistant pests, or diminished groundwater for irrigation. It is an arms race that cannot be won, and it results in environmental degradation beyond the borders of the field. Others have documented the various ways in which industrialized agriculture contributes to local and regional environmental degradation (Mooney et al. 2009; Bailey and Buck 2016). Regime shifts, however, have received less attention in agricultural research.

There are three basic ways in which regime shifts can be addressed by scientists: (a) qualitative descriptions of case studies, such as in Kinzig et al. (2006); (b) equation-based modelling, as in Vandermeer and Perfecto (2012), where they describe shade and no-shade coffee growing regimes as an example and then create a generalized model of regime shifts in production systems and find that the conditions for hysteretic regime shifts are easily generated; and (c) predictive modelling which seeks to understand the proximity of a system to a critical threshold (see Rockström et al. 2009; Hughes et al. 2013a for the conceptual outline of this approach at the global level). These basic approaches can be applied in combination at different levels of organization within agriculture and at different spatial and temporal scales. The agricultural literature is quite sparse, however. That is not to say that there is no research warning of the risk of large-scale change on par with the US Dust Bowl of the 1930s (i.e. Cook et al. 2009), but that such risk is rarely discussed specifically with regard to working agricultural landscapes in terms of a regime shift and the implications for long-term dynamics and behaviour – potentially hysteretic, irreversible system movement to a new basin of attraction defined by fundamentally different functions, processes, and structures. There remains vast uncertainty regarding such shifts – not just in terms of when and where and why they might happen but with regard to what the new system might look like. Furthermore, dust bowl conditions, as distinguished from desertification by Romm (2011), are not the only kind of regime change at risk in the Great Plains and other irrigated working agricultural landscapes. Woody invasion, permanent loss of soil carbon, salinization, and desertification are among some of the other risks of not just climate change, but modifications to biodiversity, the soil, and the hydrological cycle as a result of industrialized agriculture (Amundson et al. 2015; Sanderman et al. 2017; Zou et al. 2018). Our understanding of whether there are critical thresholds leading to a hysteretic regime shift, the cross scale feedbacks between key processes, or how close we are to such thresholds is extremely poor. Although some authors have addressed two issues that are encapsulated by regime shift science, namely, the possibility of a regime shift and the need to consider spatial and temporal scales much larger than the field-farm level of organization (Chaplin-Kramer and

Kremen 2012; Tittonell 2014; Bailey and Buck 2016; Landis 2017), few do both at the same time (though see Gordon et al. 2008; Müller et al. 2014; Chapman et al. 2017). Muller et al. (2014) used land use survey data and qualitative descriptions to create land use transition curves they visually inspected to detect linear and nonlinear regime shifts in type of production system in China, Laos, Vietnam, and Indonesia (e.g. shifting cultivation, plantation crops, intensive agriculture). Gordon et al. (2008) documented the ways in which agricultural modifications to the quality and quantity of hydrological flows have increased the risk of regime shifts to three parts of the hydrological cycle, which they list as “interactions between agriculture and aquatic systems, agriculture and soil, and agriculture and the atmosphere”, each of which play out at different spatial and temporal scales. For example, agriculture-soil shifts manifest at field to landscape scales, whereas agriculture-aquatic shifts tend to occur at watershed to river basin scales (Gordon et al. 2008).

Large-scale regime shifts and the risk of irreversible change in non-production systems have received attention, and these results make it clear that should similar shifts occur in production landscapes, humanity will likely be unpleasantly surprised, despite some level of inevitability given the scope and scale of climate change and other human modifications to the environment. For example, researchers have identified large-scale climate-mediated shifts in inland Arctic ecosystems that involve shifts in hydrological cycles and vegetative cover (Karlsson et al. 2011), and Desie et al. (2019) document regime shifts in topsoil carbon processing in forests converted to spruce monocultures. Solomon et al. (2009) point out that the 1930s Dust Bowl was associated with average rainfall decreases of only ~ 10% over ~10–20 years and that climate modelling suggests that if carbon dioxide levels peaked at ~450 ppm, irreversible decreases of precipitation of ~10% would be expected over large regions of the world. While these studies have only indirect bearing on production landscapes, the point is that climate-mediated and human-mediated land use changes can cause profound shifts in hydrology, soil chemistry, and other critical parameters that have direct implications for working agricultural landscapes and our ability to feed increasing numbers of people and that these drivers of change may interact in surprising ways to produce unanticipated outcomes. The potential for large-scale regime shifts ought to be a significant cause for concern and a focus of agricultural research (Rocha et al. 2018).

2.2 Scaling, Adaptive Cycles, and Panarchy

A key component of resilience theory is that it explicitly accounts for scaling and hierarchies, feedbacks across scales, and the coupling of human and nature. To manage for resilience in any system type, it is as critical to identify the key processes and functions that maintain a system in a desired (or undesired) state as it is to understand the scales and cross scale feedbacks of those processes and functions. In a resilient system, functional diversity and redundancy, be it provided by organisms, people, or institutions, are not just randomly sprinkled throughout a system. It emerges through feedbacks between adaptive and evolutionary processes of niche specialization, cooperation, and competition and the species and the scales at which resources are present and disturbances occur. For example, if you are a very large farmer, growing grain that is sold to a distributor for global markets, there is still ample room for a farmer growing subsistence crops or perhaps selling excess within the local community or at a farmer's market. In ecosystems, many species can co-exist despite using the same resources because they do so at different spatial and temporal scales separated by nonlinear shifts between domains of scale. These scales are not just convenient levels of organization but are quantifiable, objectively identified scale domains separated by nonlinearities. It is the ecological theatre on which pattern and process play out. This theatre is structured by key processes that operate at distinct ranges of spatial and temporal scales. Consider the difference between the process of photosynthesis, driven by a diurnal cycle, and geologic climatic processes that determine the location of biomes on earth. The scaled nature of structuring processes creates scaling in structure itself – from soil to biomes – and this is reflected in the species that interact with that ecological structure. The discontinuity hypothesis (Holling 1992) was proposed as a way to quantitatively test the proposition that both ecological structure and the species that interact with it will occur at distinct, discontinuous domains of scale. A great deal of testing has borne this out (Stow et al. 2007; Nash et al. 2014; Sundstrom et al. 2014). Applications of this research to other types of complex adaptive systems has shown similar space-time structuring where processes scale structure and create domains of scale of resource opportunity for the entities that interact with that structure (Garmestani et al. 2006, 2007; Sundstrom et al. 2014). The end result of this feedback between processes, scales, and system entities is that all are scaled discontinuously, with nonlinearities between scale domains. In other words, the species in a community do not occur in a continuous range of size but in lumps of similarly sized creatures that interact with their environment at similar spatial and temporal scales. Not only is this the basis for quantitatively measuring resilience by assessing the distribution of species functions within and across these scale domains, these scale domains are also the basis for understanding the scales at which adaptive cycles play out (Peterson et al. 1998; Allen et al. 2014).

Adaptive cycles and panarchy were developed by Holling (1986, 2001) as a construct to understand how "specific nonlinear processes interact on multiple time and space scales" (Holling 1986). System dynamics and behaviour are neither rigid and stationary nor fully chaotic, in the dynamical systems theory sense. Plants sprout, grow, conserve matter, and then senesce and die. Annuals do this quickly over the course of one growing season, while long-lived trees do so over centuries and even millennia (e.g. bristlecone pine (*P. longaeva*). Gunderson and Holling (2001) described these cycles of change as adaptive cycles and detailed four stages of development and change over time: *exploitation* of resources and thus fast growth, *conservation* of matter, *collapse* and release of accumulated energy and matter, and *renewal* where the system reorganizes (Fig. 2.3). The time scales of each stage differ, as the growth and conservation stages are the slowest and longest, whereas collapse and renewal occur rapidly. Resilience also differs across each stage, as the

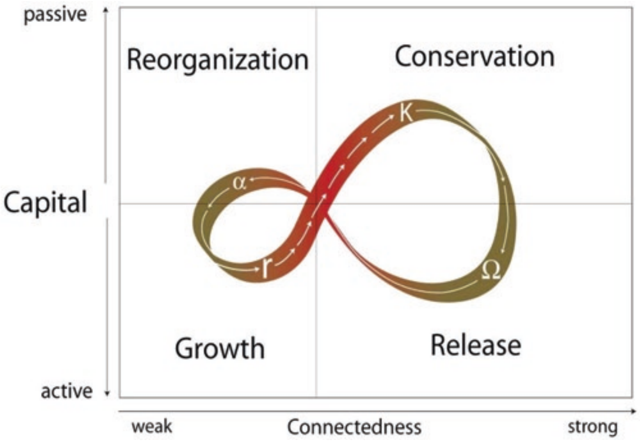

Fig. 2.3 The phases of growth, collapse and renewal within an adaptive cycle (Gunderson and Holling 2002)

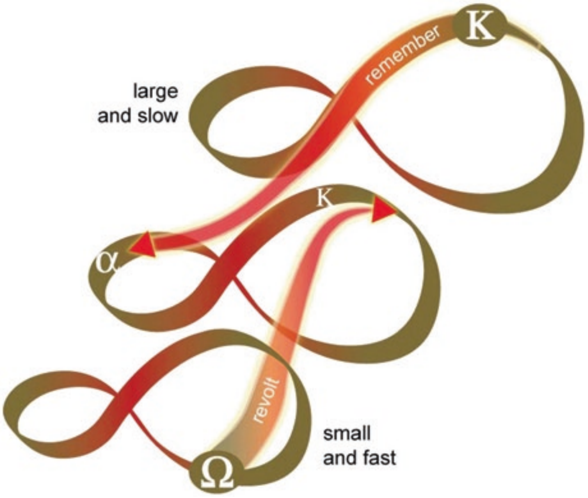

Fig. 2.4 A conceptualized panarchy, a set of nested adaptive cycles (Gunderson and Holling 2002)

organization or connectedness between organisms increases throughout the conservation phase until the system becomes so over-connected or energy and material are so bound up that the system's ability to flexibly respond to a disturbance renders it vulnerable to collapse (e.g. its resilience is low). Perhaps the most oft-ignored part of this theory, however, is that just as systems are multi-scaled and hierarchical, adaptive cycles occur at *each scale domain within the system* (these are the scale domains identified by the discontinuity hypothesis (Gunderson and Holling 2002)). The full suite of nested adaptive cycles is called a panarchy (Fig. 2.4). Slower processes such as climatic change (prior to the Anthropocene) and geomorphology unfold over geological time scales but constrain the development of biomes and ecosystems. Tropical forests, for example, do not occur at the poles. Faster and smaller processes such as fire, disease, and insect outbreaks can act contagiously, spreading across system scales and driving larger-scale changes (Holling 1986). Cross scale feedbacks can either reinforce resilience, such as when species that are impacted by a disturbance at one scale are compensated for by species that perform a similar function at a different scale, or can reduce resilience, as in when an invasive species such as eastern red cedar (*Juniperus virginiana*) crosses a threshold and shifts from being localized and patchy to driving an ecosystem-wide regime shift from grassland to woody shrubland. Feedbacks are more likely to propagate across scales when adaptive cycles across levels in the panarchy are in the same stage of development, that is, they are synchronized. Human management actions often act to artificially keep systems in the conservation phase, such as forests where fire has been suppressed and fuel loads have accumulated. This greatly increases the risk that when a small fire is ignited, it can rapidly spread to crowns and thus through forests, transforming what might have been a minor patchy disturbance into a catastrophic and widespread fire. It is a general truism that the regular "collapse" and release of bound up material at smaller spatial scales enhances resilience at larger spatial scales, as it maintains heterogeneity, diversity, and asynchrony across scales.

Adaptive cycles, panarchy, and the discontinuity hypothesis have been explored at length in social-ecological systems, where the organisms or system entities range from humans, to farms, institutions, firms, economies, and more. These concepts of scaling, hierarchy, feedbacks, and cycling dynamics are basic and inherent features of complex adaptive systems, including agricultural systems (Sundstrom and Allen 2019). They are useful to agriculture and other systems because they provide a way to frame dynamics that takes into account the complex reality of these systems. While it may be easier to conduct a study at the field-farm level and ignore the larger-scale ecological, political, and economic factors that constrain and impact what happens at the farm level, it is not conducive to providing real-world solutions to the challenges that face agriculture. While microscale changes to soil microbiota and carbon storage may seem to occur on time scales too fast and small to have relevance to a farm or the world, the consequences of various land management practices such as tilling, fertilizer use, and shifting cultivation on global carbon budgets are likely to be profound (Houghton et al. 2012).

The application of adaptive cycles and panarchy to agricultural systems as social-ecological systems is a largely unexplored territory because the movement from description to quantification or application is understandably challenging. As Darnhofer (2010) writes, "More research to operationalize resilience thinking will be necessary, as key interactions have been a neglected area of study". Thus far, it has been presented in detail as a useful way to capture and tease out complex social dynamics and interactions (Darnhofer et al. 2010; Sinclair et al. 2014) or briefly discussed as an example of a possibly useful heuristic (Malézieux 2012; Pant 2016). Patzek (2008) and Van Apeldoorn et al. (2011) discuss in greater detail the biological and environmental consequences of the way in which industrialized agriculture curtails the natural adaptive cycling that occurs in ecosystems. In particular, industrialized agriculture puts the system in a “short-cut loop”, from the rapid growth to the reorganization phase (Apeldoorn et al. 2011). Patzek (2008) describes in detail the difference between a full adaptive cycle in ecosystems, where exergy (free energy referenced to the environmental conditions) stored in dead biomass is recycled within the system and decomposition processes in the reorganization stage release “previously stored exergy to provide feedstock for the next stage”. In a thorough quantification of the entropy associated with a corn monoculture in the USA, he demonstrates empirically how “all agricultural processes that rely on external inputs are not cyclic and cannot be sustainable” with or without tilling the soil, as it takes 6–13 times more energy to remediate soil degradation than the direct energy inputs to corn agriculture. Soil degradation takes the form of the death and/or weakening of soil flora and fauna, acidification, build-up of insoluble metal compounds, and build-up of toxic residues from field chemicals. Furthermore, some of the entropy generated is exported both as atmospheric pollution and as toxic runoff into surface and groundwater, contaminating water as far as the Gulf of Mexico and “causing eutrophication of remote ecosystems embedded in the environment of the agrosystem” (Patzek 2008). It is an outstanding example of how translating the dynamics of nested adaptive cycles to agricultural systems can elucidate the degree to which agricultural practices are or are not resilient or sustainable.

Framing complex systems with many interacting parts as nested scale domains at which adaptive cycle dynamics unfold has proven a useful heuristic for many different fields (Allen et al. 2014). As in the agricultural examples given here, it has proven more difficult to use the concept quantitatively. It has the potential to be particularly relevant for agricultural systems for several reasons: (1) The model incorporates not just top-down, large-scale processes that constrain what agricultural products can be produced and where but small and mesoscale processes that can, under certain conditions, cascade up to impact agricultural production at larger scales; (2) the model readily incorporates the biological, ecological, and socio-economic-political components of complex agrosystems; and (3) the discontinuity hypothesis provides a methodology for the objective identification of relevant scale domains of pattern and process in systems. Investigating agricultural systems within the framework of panarchy may provide insights regarding the resilience of these systems to global change.

2.3 Where to from Here?

Working agricultural landscapes are complex systems whose inputs and outputs, be they human-sourced or more naturally derived, both impact and are impacted by multiple biophysical and social processes occurring at multiple spatial and temporal scales. Whether we consider tropical forests where naturally occurring foods and fibre are harvested in a sustainable way or monoculture row crop grain production, it is to our long-term detriment to view them as anything other than highly complex and increasingly fragile systems. Even before the potentially catastrophic risk posed by climate change, human modifications to natural systems and the creation of strongly coerced agricultural systems has come with mounting environmental costs that imperil our future ability to produce sufficient foodstuffs. We need frameworks with which to address these wicked problems that adequately account for the innate complexity of working agricultural landscapes as complex adaptive systems. Resilience science provides such a framework for agricultural researchers and has begun to be applied in some compelling and insightful ways (e.g. Darnhofer et al. 2010; Cabell and Oelofse 2012; Sinclair et al. 2014; Bailey and Buck 2016). Nonetheless, we feel that the particular concepts of regime shifts, adaptive cycles, and panarchy have a value for agricultural systems that has not yet been fully realized.

As other researchers have pointed out, it is crystal clear that over the long-term, the heavy dependence of industrial agriculture on external inputs is not sustainable (Patzek 2008). Part of the movement towards more sustainable working agricultural landscapes will require increasing the self-organization of the processes that are the lifeblood of food, energy, and water production, namely, soil health and nutrient recycling, pollution-free hydrological cycles, and maintaining high levels of biodiversity that provide these and other supporting services such as pollination and pest control. Furthermore, the capacity to respond to shocks within such landscapes will require a shift from optimization and efficiency to accepting somewhat reduced but more consistent production over time and under a variety of conditions.

Even if row crop monocultures are themselves not eliminated, they are nonetheless embedded in a larger ecological context that is critical for the maintenance of these ecological processes in the wider landscape. Agroecology is already an advanced science with highly prescriptive methodologies for improving self-organization and reducing external inputs within a farm. Resilience science can help shape the search for ways to facilitate these processes across larger spatial and temporal scales. In particular, it is imperative that we have an improved understanding of threshold behaviours and the risk of regime shifts in the ecological processes that underpin agriculture. Given the likelihood of climatic regime shifts that profoundly alter the thermal and precipitation attributes of working agricultural landscapes, what are the risks to these landscapes of experiencing contagious disturbances that further push them into regimes unsuitable for agriculture? The woody invasion of the Great Plains is an example of a disturbance that began as the planting of individual eastern red cedar to act as windbreaks and has spread across spatial scales in a contagious manner in part because fire, a key process in maintaining grasslands in a grass-dominated state, has been actively suppressed for decades. The Plains are now experiencing a large-scale regime shift to a new state dominated by eastern red cedar, which has less utility as rangeland, provides fewer ecological services such as sustaining a rich native flora and fauna, and is driving undesirable changes in the local and regional hydrological cycles (Zou et al. 2018).

Other possible thresholds, particularly in soil characteristics and carbon storage, are likely, but our understanding of where they might be, and what kinds of changes might cascade up and down scales, is poor. It is critical that we begin managing working agricultural landscapes, rather than parcels, and focus on the key ecological structuring processes that support these landscapes as agricultural production systems (Winfree et al. 2018). Processes such as fire, water management, pollination, and pest control do not respect the boundary of the farm and operate at specific spatial and temporal scales with cross scale feedbacks. In order to manage across these artificial boundaries, we need to understand the scales at which these processes occur so that we can intelligently redesign management actions to account for the reality of multi-scaled, hierarchical systems that can operate in multiple basins of attraction. Burning across landowner and parcel boundaries, creating corridors to facilitate native biodiversity and prevent the spread of invasive species, and managing natural drainage systems to assist natural hydrological cycles and reduce pollution to said waters will all be important management actions that need to be informed by a clear understanding of the scales and cross scale feedbacks of these key processes.

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