

Applying resilience thinking to production ecosystems

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Abstract. Production ecosystems typically have a high dependence on supporting and regulating ecosystem services and while they have thus far managed to sustain production, this has often been at the cost of externalities imposed on other systems and locations. One of the largest challenges facing humanity is to secure the production of food and fiber while avoiding long-term negative impacts on ecosystems and the range of services that they provide. Resilience has been used as a framework for understanding sustainability challenges in a range of ecosystem types, but has not been systematically applied across the range of systems specifically used for the production of food and fiber in terrestrial, freshwater, and marine environments. This paper applied a resilience lens to production ecosystems in which anthropogenic inputs play varying roles in determining system dynamics and outputs. We argue that the traditional resilience framework requires important additions when applied to production systems. We show how sustained anthropogenic inputs of external resources can lead to a “coercion” of resilience and describe how the global interconnectedness of many production systems can camouflage signals indicating resilience loss.

Key words: agriculture; aquaculture; coerced resilience; fisheries; forestry; sustainable development.

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INTRODUCTION

While human ingenuity has made possible large increases in production and economic development it has also resulted in significant

environmental costs and has transformed the face of the planet (Raudsepp-Hearne et al. 2010). There is growing scientific consensus that the scale of human impacts requires the definition of a new geological era, referred to as the ‘Anthro-



Fig. 1. Production systems have enabled highly efficient production of particular ecosystem services (primarily food and fiber), yet they have also radically altered the provision of other ecosystem services: (a) intensive forestry involves trade-offs between biomass and other forest goods and services, (b) intensive agriculture can lead to unwanted export of sediments and nutrients into coastal waters, (c) sustained overfishing has resulted in substantial changes in species composition and biodiversity in many marine ecosystems, and (d) intensive aquaculture can cause significant pollution as a result of waste products and the use of chemicals and antibiotics. Image credits: Anders Esselin, Twoblueday (CC BY-NC 2.0), J Lokrantz/Azote, Ivan Walsh.

pocene' (Crutzen 2002). The Anthropocene is characterized by land cover transformation, biodiversity loss, pollution and climate change, all with global implications (Steffen et al. 2004). Evidence suggests that such impacts are at, or beyond, planetary capacity to support human existence under current standards of living and social structures (Rockström et al. 2009, Barnosky et al. 2012).

The magnitude and scale of anthropogenic impacts on the environment is determined by the demand for provisioning ecosystem services from a variety of production systems, and this demand is expected to increase further as a

consequence of a growing human population and increasing affluence (Tilman 1999). Production systems (e.g., fisheries, plantation forestry or row-crop agriculture) are characterized by the provisioning of food or fiber via primary or secondary production, often with high dependence on supporting and regulating ecosystem services (e.g., crop pollination, the maintenance of soil fertility, or biological control). At the global level, these systems have thus far managed to sustain considerable growth, yet often at the cost of externalities imposed on other systems and locations (e.g., Godfray et al. 2010; Fig. 1). The challenge is to ensure that current and future

Table 1. Key resilience concepts.

Resilience	The capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks (Walker et al. 2004).
Resilience thinking	Describes the collective use of a group of concepts to address the dynamics and development of complex social-ecological systems; resilience, adaptability and transformability are central (Folke et al. 2010).
Social-ecological systems	Emphasize that humans must be seen as a part of, not apart from, nature and that the delineation between social and ecological systems is artificial and arbitrary (Berkes and Folke 1998, Walker and Salt 2006).
Alternative stable states	Emphasize that systems may exist in two or more alternative states, each characterized by a different structure and sets of processes and feedbacks. Evidence for the existence of truly alternative stable states (i.e. a system can exist in multiple contrasting states under the same external environmental conditions) (Lewontin 1969) is the topic of some controversy (e.g., Mumby et al. 2013).
Regime shift	An abrupt change in a system state from one regime or stability domain to another (Scheffer et al. 2001, Folke et al. 2010)
Threshold	A breakpoint between two regimes of a system (May 1977, Walker and Salt 2006).
Basin of attraction	A region in which the system tends to remain unless perturbed. These regions are separated by a threshold; thus when a system crosses a threshold it is said to cross into another regime or “basin of attraction” (Walker et al. 2004).
Coerced resilience	Resilience that is created as a result of anthropogenic inputs such as labour, energy and technology, rather than supplied by the ecological system itself. In the context of production systems, coercion of resilience enables the maintenance of high levels of production.
Threshold cascade	Can occur when a regime shift in one system triggers regime shifts in others as a consequence of close interactions between those systems.

human demands can be satisfied, while also transforming production systems into those that sustain desired yields, minimize (and reveal) net losses of ecological capital, and are resilient to increased frequencies and magnitudes of disturbance resulting from environmental change (Bennett and Balvanera 2007, Foley et al. 2011).

Resilience and ‘resilience thinking’ (Table 1; Appendix) have been described as frameworks for addressing sustainability challenges, or as a way to operationalize sustainability (Folke et al. 2002). Despite important theoretical contributions to the understanding of ecosystem dynamics (e.g., coral reefs, lakes, or grasslands; Rietkerk and Van de Koppel 1997, Nyström et al. 2000, Scheffer et al. 2001), resilience concepts have to date not been systematically applied across systems that are focused on production of food or fiber (but see Bennett and Balvanera [2007], Fisher et al. [2007], and Anderies et al. [2004] for related discussions on ‘robustness’). Here, we investigate the application of resilience concepts to the challenges associated with sustainability in key production systems (namely forestry, agriculture, fisheries and aquaculture), looking specifically at the substitution of human and human-made capital for natural capital and processes. We present three propositions for expanding the resilience framework to accommodate specific characteristics of these systems, highlight inter-

connectedness between them, and discuss the limits to which production systems can sustain global production of food and fiber.

CHARACTERISTICS OF PRODUCTION SYSTEMS

Production systems are primarily characterized by their capacity to provide provisioning services (namely food and fiber). While they depend on internal supporting and regulating ecosystem services to varying degrees, anthropogenic inputs (e.g., fossil fuel, technology, nutrients, pesticides and antibiotics) are often fundamental in determining the overall structure, function, and outputs from these systems. Put differently, resource users as well as infrastructure interact with the ecological system to meet desired production outcomes (Anderies et al. 2004). Increasing demand for food and fiber has, to a large extent, been met in many production systems with the replacement of specific ecosystem processes by anthropogenic inputs of labor and manufactured capital (e.g., the internal recycling of plant nutrients being replaced by fertilizer application). This change has been facilitated by access to external capital, namely technology and fossil fuel based energy (Tilman et al. 2002, Bennett and Balvanera 2007).

Globally, this transition has occurred for multiple types of production systems, but has

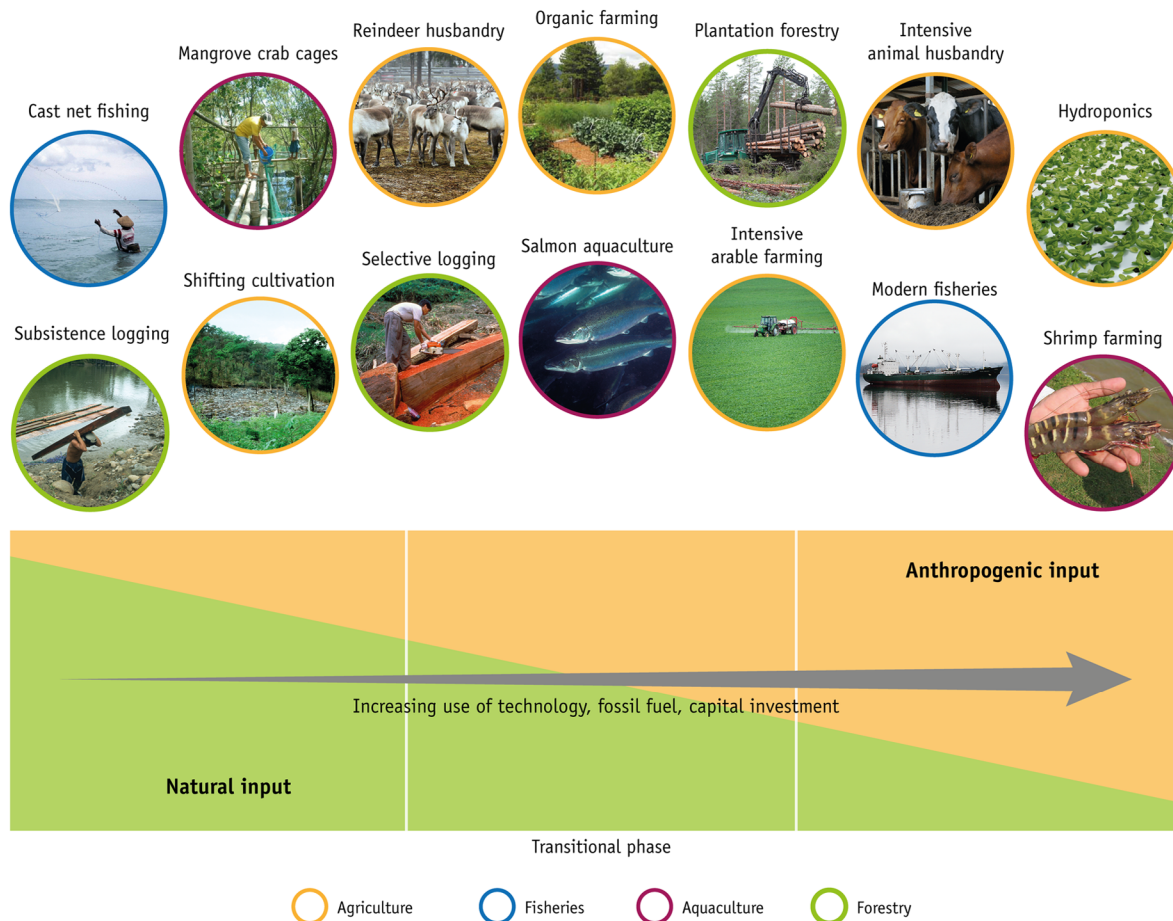


Fig. 2. A schematic illustration of the relative contributions of anthropogenic and natural inputs to key production systems. Production systems to the left side of the figure, rely on the maintenance of local ecological processes, retain a wider range of options for unforeseen future requirements, and thereby provide clearer feedbacks regarding proximity to ecological thresholds than do productions systems to the right, which require significant anthropogenic inputs. Example production systems illustrated are not arranged relative to each other, but in relation to the continuum of increasing anthropogenic inputs. It should also be noted that significant variation may be found within systems (e.g., Pelletier et al. 2011). Image credits: A Löf/Azote, J Lokrantz/Azote, N Kautsky/Azote, M Troell/Azote, M Almqvist/Azote, P Thiel/Azote, B Ekberg/Azote, Matt O'Hara (CC BY-NC 2.0), S Zeff/Azote, A Maslennikov/Azote.

taken place over different time scales and at different speeds (Fig. 2). For instance, agriculture began this process over a thousand years ago, industrial-scale forestry in the last couple of hundred years, and industrial fishing only after World War II. At the extreme, some systems are now principally supported by anthropogenic inputs to maintain the desired system state, for example intensive modern agriculture (Fig. 2 far right). At the other extreme, some systems

require very little anthropogenic input and are supported largely by ecological processes, such as some wild capture fisheries (Fig. 2 far left). Many systems are currently within the transitional phase where a former dominating reliance on natural processes is being replaced by anthropogenic inputs, often at the expense of externalities imposed elsewhere (Foley et al. 2005) (Fig. 2).

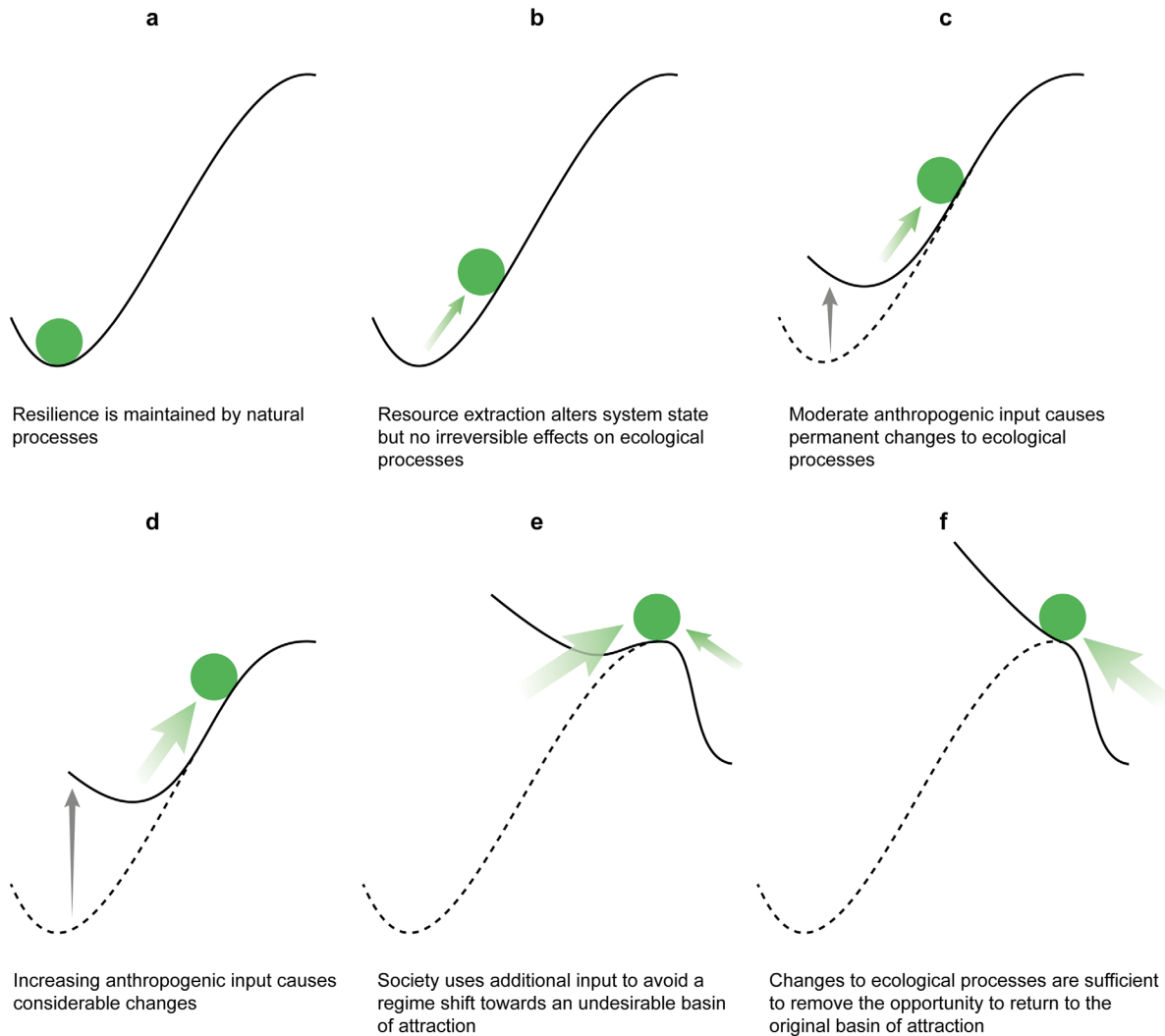


Fig. 3. Coerced resilience and regime shifts in production systems. Coercion (anthropogenic input) is indicated by an arrow holding the ball in an otherwise unstable state, the size of the arrow indicating the magnitude of input necessary to maintain this position. The dotted line represents the “original” basin of attraction. Note that this sequence is used to illustrate relevant potential system states and regime shifts, and is only one of many possible outcomes.

APPLYING RESILIENCE CONCEPTS TO PRODUCTION ECOSYSTEMS

We present three propositions for expanding the resilience framework to accommodate specific characteristics of production systems. These propositions highlight the fundamental roles played by human and human-made capital in substituting for natural capital and processes and the associated risks.

(1) *Ecological resilience is being replaced by*

“coerced resilience,” and in some systems a permanent, but masked, loss of alternative regimes may have occurred.

Anthropogenic inputs in intensive production systems maintain these systems in an “artificial” ecological state that probably otherwise would not exist (Fig. 3b–f). A removal of anthropogenic inputs is likely to result in a shift towards a different basin of attraction, presumably at the expense of desired production outputs (Foley et al. 2005). Anthropogenic inputs thus maintain an

otherwise unstable state, and through sustained intervention may generate a capacity to absorb disturbance while the system retains essentially the same structure and function, although different feedbacks may be operating (e.g., where soil impoverishment is mitigated by the use of fertilizers). This raises an apparent paradox, whereby highly modified production systems can, through anthropogenic efforts rather than ecological processes, mimic the response of resilient natural systems to a specified disturbance, in their capacity to return to pre-disturbance system states. To separate these different forms of resilience, we refer to resilience that emerges at the system level as a consequence of anthropogenic input or action as ‘coerced resilience.’ In such cases, supporting ecological processes have been replaced to varying degrees by human-controlled processes that maintain a system in a particular desired state.

The extent of anthropogenic input necessary to maintain a system in an intensive production state may increase over time (Fig. 3c–d) due to negative impacts on supporting ecological processes. For example, even systems in states of coerced resilience (e.g., intensive agriculture, plantation forestry, and aquaculture) benefit from natural support processes, such as those provided by biodiversity. However, as the natural processes and capital that sustain them are lost, the capacity to benefit from these supporting processes may diminish (e.g., recent declines in both wild and domesticated pollinators, and the reported parallel declines in the crop plants that rely upon them [Potts et al. 2010]). Moreover, such a progression, whereby species and interactions contributing to supporting processes are lost during intensification, ultimately removes opportunities for returning to previously available ecological basins of attraction, and thereby reduces options for the future (Fig. 3f). Consequently, coerced resilience (Fig. 3b–e) implies a potential masking of changes in ecosystem dynamics that may be critical in evaluating the long-term viability of these systems. It is important to note that in this transitory stage when resilience is coerced, ecological controls alone are not sufficient to hold a system in its position, this can only be maintained through a variety of anthropogenic forces designed to achieve particular properties (e.g., high levels of production)

and dynamics. The metaphor of Sisyphus pushing a boulder up a mountain is useful to convey the pivotal role of societal inputs in maintaining the current state of many production systems. In most cases, these ecosystems would revert to some other configuration in the absence of these efforts, emphasizing the necessity for continued and potentially increasing intervention to maintain intensive production states. A similar challenge has been identified by Anderies et al. (2013) from a governance perspective whereby resilience is achieved by combining different types of capital, which, via a regulatory feedback network, generate a basin of attraction for the desired system state, in this context often intensive management of a production system.

(2) *Maintaining production systems in states of coerced resilience increases cross-boundary interactions between production systems with major implications for sustainability.*

Maintaining a high yield in one production system often requires external inputs that derive from a much wider (and generally distant) supporting resource base (Fig. 4). In addition, the movement of water, air or species may link two or more production systems with a distant system acting as a recipient of materials (e.g., wastes, pollutants, pathogens, species) (Fig. 4). In both cases, the external effects imposed by one system can undermine the capacity for long-term production and resilience of another. Thus these frequently global connections—also referred to as “teleconnections”—have major implications for system sustainability and vulnerability (Adger et al. 2009).

One example of these connections can be seen with livestock production. Historically production of meat relied upon farm-based resources where feed and manure were produced and used within the same farm. Today, global meat demand is met by industrialized production systems where livestock and feed are geographically decoupled (Naylor et al. 2005). The transport of soybean feed produced in Brazil to Europe is illustrative of this trend. This has several consequences: Firstly, manure from the farm is often leached into the environment, rather than considered a resource for on-site crop production. Secondly, production of livestock feed purchased outside the farm may require high inputs of synthetic mineral fertilizers in an

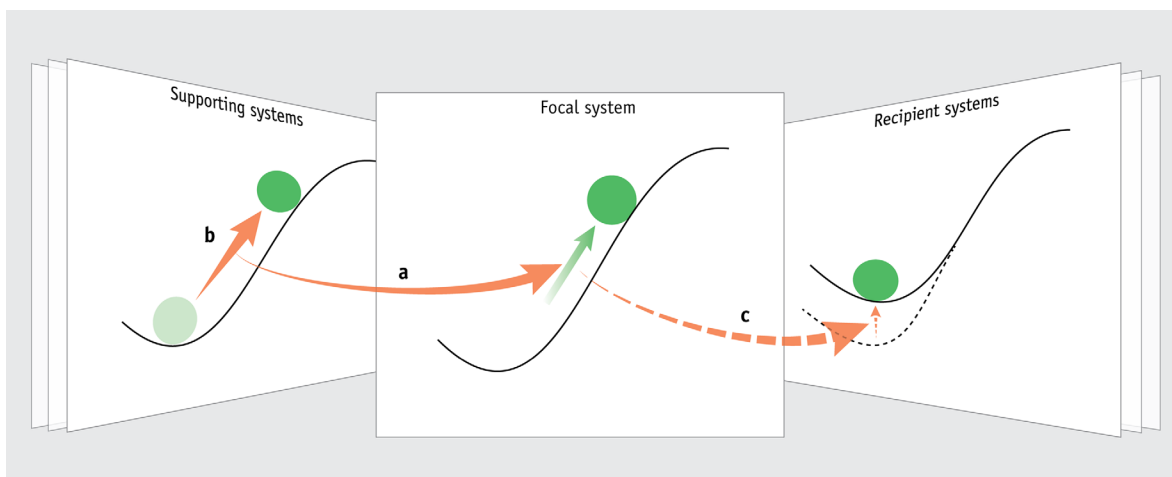


Fig. 4. Cross-boundary interactions between production and supporting and/or recipient systems. The focal system may receive resources from a distant supporting systems (arrow a); these subsidies are also potentially obtained with resultant state shifts in the supporting systems (arrow b); further the focal production system may produce waste products which impact the resilience of recipient systems elsewhere (arrow c).

area often distant from where the cattle are raised. Finally, long distance, fossil fuel-dependent transport is often required to distribute livestock feed and fertilizer.

Similar to terrestrial livestock farming, aquaculture such as salmon farming in Norway or shrimp production in Asia depends on feed containing fish products (fishmeal or fish oil) that typically originate from smaller pelagic wild or mixed fisheries in South America, the North Sea, or Asia, respectively (Deutsch et al. 2007). The impact of drawing on such resources can include negative effects on marine ecosystem structure and function (Cury et al. 2011, Deutsch et al. 2011). Demonstrating a further link, waste products from land-based production systems frequently impact supporting marine ecosystems. For example, global intensification of agriculture has generated excessive nutrient run off, leading to widespread eutrophication and oxygen depletion of freshwater and coastal environments (Rabalais and Nixon 2002), thereby representing a vicious feedback between terrestrial and marine production systems. With such global connections, the potential for synergisms between impacts, or for such impacts to be superimposed on vulnerabilities relating to, for example, climate change, are also of concern (O'Brien and Leichenko 2000).

(3) *There are global limits and thus trade-offs in our capacity to coerce resilience in production systems, and in the extent to which such systems can be relied upon to meet global demand.*

Coerced resilience is only possible as long as society has the skill, capacity, and willingness to provide the necessary anthropogenic inputs to maintain the functional attributes of a production system. Additionally, at the global scale, there are fundamental ecological limits to the capacity to coerce resilience in production systems (Rockström et al. 2009). This is because continued inputs are largely dependent upon, and ultimately limited by, globally finite resources, such as fossil-fuel based energy and phosphorus (e.g., Elser and Bennet 2011). The sustainability of strongly coerced states is further constrained by the capacity to absorb or treat waste products, with resultant trade-offs in our ability to gain resilience at one location (through anthropogenic input) without losing it in associated supporting and recipient systems elsewhere (Fig. 4).

This description of limits to coerced resilience parallels capital theory within economics where production system outputs are only possible (whether used to stabilize a system or in terms of resource production) when the requisite inputs (in this case human capital or human-made capital for example) are connected in a network.

In addition, the potential pitfalls of sustained coerced resilience have similarities with the concepts of 'robustness' and 'robust control', which have been used to explain potential fragilities or dysfunctions within complex systems (Csete and Doyle 2002, Anderies et al. 2007, Doyle and Csete 2011), including within a resource management context (e.g., Cifdaloz et al. 2010, Rodriguez et al. 2011).

Given the cross-boundary interactions detailed above, supporting and recipient systems, as well as the production system themselves, may be jeopardized in the face of ongoing human intervention to maximize production (Fig. 4). Continued coercion of key production systems thereby risks causing threshold cascades, whereby the crossing of thresholds in supporting or recipient systems in turn drives other production systems over critical thresholds or vice versa. For example, increased demand for fishmeal and fish oil by an expanding aquaculture industry may create further incentives for overfishing in capture fisheries and push these supporting marine systems closer to thresholds, that, once passed, may drastically decrease their production capacity. If they were to undergo a regime shift, the effect of a loss of a vital input would have corresponding implications for the aquaculture systems they support. The aquaculture system may then be maintained only by transitioning to alternative supportive systems in a form of sequential exploitation, which may readily obscure underlying environmental costs. This 'masking' of environmental implications for end-users and policy makers may be aided by the remoteness of such impacts in terms of geography, distance along the supply chain, and by the classification of some environmental costs as externalities.

Increased global reliance on production systems heavily dependent on anthropogenic inputs has the capacity to perpetuate a process which—thanks to the efficiencies of globalized trade—reduces the costs to producers of degrading supporting systems, by allowing for transitions to alternative sources of required inputs. In the absence of policy incentives to do otherwise and governance structures that recognize connections between supportive and recipient systems, little stands in opposition to the continuation of this process, other than the eventual lack of surrogate

systems.

CONCLUSIONS

Contemporary production systems face enormous sustainability challenges. Coerced resilience has allowed the maintenance of high levels of production at the likely expense of ecological resilience in supporting systems. The nature of global interactions supported through trade and mobility often mask or camouflage the ecological signals of resilience losses and thus the true underlying constraints to production (Berkes et al. 2006). Analysis of anthropogenic inputs to production systems reveals that coercion is currently holding many systems in otherwise unstable states, potentially leading to the loss of alternative options for the future. If regime shifts in key production systems are to be avoided, the global nature of markets, and their capacity to enable coerced resilience in some systems at the expense of reduced resilience in others, must be recognized and accounted for in international policy. Furthermore, there is a risk that similar global inequities that are inherent to international trade will be mirrored if the degradation of resilience in some systems is permitted to the benefit of maintaining coerced resilience in others.

Enhancing resilience in production systems will require a mixture of interventions dependent upon the current position of a particular system along the trajectory of change. In some cases, it may be possible to alter the system's current basin of attraction using locally, regionally, or nationally available sources of natural capital and processes, drawing on ecological engineering and ecosystem restoration techniques (Lin 2011, Nyström et al. 2012). A 'local' example might be increasing forest adjacent to agricultural fields such that the ecosystem services provided by the forest buffer those that may be lacking elsewhere, thus creating a resilience 'ledge,' an area of greater stability on an otherwise downward slope (Fig. 3e left of current system state). Even systems maintained in highly unstable states (e.g., intensive agriculture or aquaculture) will benefit from attempts to use natural processes to enhance system resilience. In other cases, techno-fixes (e.g., the use of synthetic organisms) may be required, including building

novel states where the current regime is beyond the point of return (e.g., Redford et al. 2013, Graham et al. 2014). However these would likely involve trade-offs where resources must be taken from elsewhere. In such cases where coerced resilience is desired, the impacts on supporting and recipient system resilience must be considered. We argue that the ultimate goal is to retain or enhance the provision of global production system resilience through bolstering natural supporting processes rather than an increased reliance on anthropogenic inputs.

Resilience concepts have been put forward as a guiding framework for addressing sustainability challenges. In order to deal adequately with system where anthropogenic inputs drive system dynamics, we have expanded upon the current resilience framework. Specifically, this expansion accommodates key features typical of many intensive production systems: coercion of resilience and the potential for cross-boundary interactions to mask the costs for supporting, recipient, and other production systems. The current resilience framework primarily takes an ecological system-centered view, focusing on the ecological response and feedback of system components. This is less applicable to intensive production systems where the resilience of multiple systems is often connected and interdependent as a result of anthropogenic inputs. The concepts and insights highlighted here contribute to acknowledging the fundamental roles played by anthropogenic inputs in the resilience of key global production systems, and their associated risks. For example, while ecosystem-based approaches have been proposed as a promising avenue for managing linked ecosystem dynamics and resilience, the identification of coerced resilience in production systems highlights the need for a broader approach that embraces international policy and governance.

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SUPPLEMENTAL MATERIAL

APPENDIX

SYSTEM STATES, REGIME SHIFTS AND RESILIENCE

The focus of resilience is on the dynamics of a system once disturbed (Walker et al. 2004). To illustrate responses to a disturbance, a simple resilience landscape diagram, or ‘ball-in-cup model,’ is often used (e.g., Holling et al. 1995). The ball, representing the current system state, exists in a cup-shaped landscape where any point along that landscape surface represents a possible system state (Fig. A1). In the simplest model, the landscape consists of two valleys separated by a hill (representing a threshold). Each valley represents a ‘basin of attraction’ (Walker et al. 2004). In reality, however, there exists a potential range of alternative states and thus multiple valleys (Norström et al. 2009) (Fig. A1).

The potential for a regime shift is dictated by the presence of alternative states, as well as by the magnitude of disturbance necessary to cross a threshold between states (e.g., Beisner et al. 2003). The resistance to regime shifts is referred to as “resilience” (Holling 1973).

Shifts between states may follow two principal pathways. Firstly, if the system (ball) is perturbed by a pulse disturbance (e.g., fire, storm or disease outbreak, drought) severe enough to push it across a threshold, the system will shift to an alternative state. A smaller perturbation may

dislocate the system from its current position, but controlling ecosystem processes and feedbacks remain in place allowing the system to return to its original position. Secondly, the topography of the landscape may change as a consequence of altered environmental conditions, for example changes in nutrient concentrations, temperature or precipitation, which slowly erode the threshold separating different states, and/or reduce resilience of the present state, for example through the loss of groups of functionally important organisms (Nyström et al. 2000). In such situations even a small perturbation may push the system into an alternative state (Van Nes and Scheffer 2004).

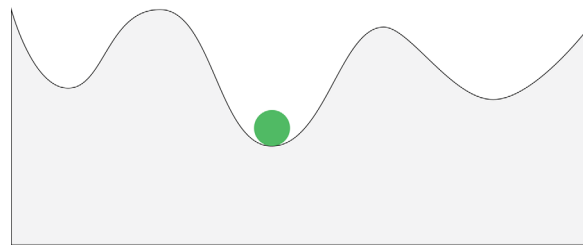


Fig. A1. Alternative system states of a resilience landscape.

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