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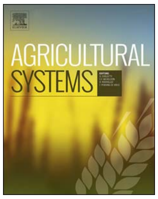

Review

Ways forward for resilience research in agroecosystems

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ABSTRACT

Agroecosystems are on both the receiving and contributing ends of increasingly demanding climatic and environmental conditions. Maintaining productive systems under resource scarcity and multiplicative stresses requires precise monitoring and systems-scale planning. By incorporating ecological resilience into agroecosystems research we can gain valuable insight into agroecosystem identity, change, responsivity, and performance under stress, but only if we move away from resilience as a mere touchstone concept. Using the productivity, stability, resistance, and recovery of system processes as a basic framework for resilience monitoring, we propose quantitative research approaches to tackle the continuing lack of biophysical, field-scale indicators needed to lend insight into dynamic resilience variables and mechanisms. We emphasize the importance of considering productive functions, sources of system regulation and disturbance, and cross-scale interactions when applying resilience theory to agroecosystems. Agroecosystem resilience research requires understanding of multiple scales and speeds of influence both above and below the focal scale. When these considerations are addressed, resilience theory can add tangible value to agroecosystems research, both for the purposes of monitoring current systems and of planning future systems that can reconcile productivity and sustainability goals.

1. Introduction

Specialization – and the economies of scale that it enables – has led to impressive gains in productivity and labor-use efficiency in commercial agroecosystems. However, the long-term sustainability of highly specialized systems and concentrated agricultural landscapes is in question. Increasing dependence on a small number of agricultural commodities (Khoury et al., 2014), unsustainable mining of water and soil resources (Foley et al., 2011), and the biological simplification of agricultural systems (Tilman et al., 2006) are potential sources of instability and vulnerability to climate change and unpredictability, endangering critical ecosystem services to and from agriculture. On the other hand, complex agroecosystems that rely on spatial, temporal, and or biological diversity to support self-regulating feedbacks and synergisms can lend resilience to adverse climate conditions while maintaining productivity and ecosystem service provision (di Falco and Chavas, 2008; Gaudin et al., 2015; Khumairoh et al., 2012). Recently, interest has turned to applying ecological resilience theory to agricultural systems to identify management practices and the underlying mechanisms that support agricultural production in the face of environmental stresses (Allen et al., 2014).

Holling (1973) first defined ecological resilience as the ability of natural systems to retain their original function and organization when subjected to a disturbance. Various active definitions of resilience now exist in the current literature, spanning from Holling's descriptive ecological concept to more normative interpretations characterizing the ability of a natural system to maintain a desired identity or valued services. Since Holling's, 1973 paper the number of ecological studies referencing the term resilience has steadily increased, with a notable spike after 2005 (Fig. 1). Much of the focus of resilience research has been on unmanaged systems' response to anthropogenic forces. Agriculture-related studies, on the other hand, make up about 30% of resilience literature. Much of the latter group deals with extensively managed ecosystems (e.g. fisheries and rangelands) that rely on internal regulation of ecosystems to drive dynamics of persistence, transition, or collapse, and that closely mimic the dynamics of unmanaged systems. These include studies conducted at all scales from sub-field to regional/landscape, but mostly concentrate on scales larger than the field.

Resilience applications in intensively managed orchards, horticultural crops, or cereal-based systems – the foundation of the global food system (Cassman, 1999) – are more elusive, partly because noticeable fluctuations in state parameters are actively mitigated by human intervention. Furthermore, confusion in the definitions and metrics of resilience caused by the proliferation of studies in disparate fields of inquiry, along with the fundamental differences between agricultural and natural systems, complicate the application of the theory to agroecosystems research. Resilience must be used carefully to

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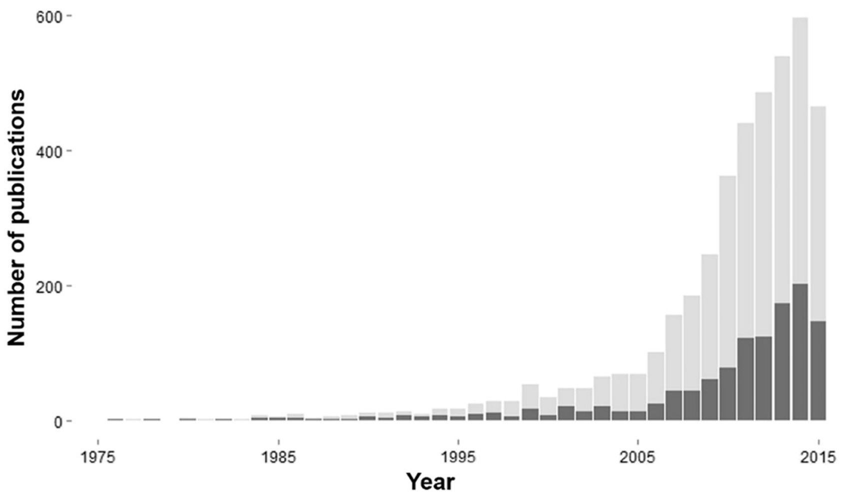

Fig. 1. Number of resilience-related publications (light shaded area) and number of agriculture-related resilience publications (dark shaded area) per year in the CAB and Agricola databases from 1970 to 2015.

be applicable to intensive agroecosystem management, to remain informative to researchers and policy makers, and to avoid turning into an ambiguous, catch-all term (Brand and Jax, 2007).

In this review, we first highlight unique features of agroecosystems that must be considered when applying resilience theory and review past attempts to identify the biophysical drivers, management practices, and system designs that sustain productivity under environmental stress. We then propose approaches to quantitatively monitor and assess resilience that consider the characteristics and goals of intensive agriculture and identify research priorities and knowledge gaps. By reconnecting resilience theory with agricultural outputs and focusing on measurable ecological and biological indicators to complement sociological and economic indicators, we hope to make resilience a tool that adds value to applied agroecosystems research and adaptive management.

2. Applying resilience in agroecosystems

Resilience in unmanaged systems is often described as the product of several complementary features: 1) latitude, or the maximum pressure a system can undergo before losing its ability to recover, 2) resistance, or the degree to which a system withstands pressure, 3) precariousness, or the proximity of the system to a threshold, and 4) panarchy, or the interactions among multiple scales and speeds (Walker et al., 2004). In agroecosystems, resilience is intimately connected with the objectives and limitations of each system. To be relevant, especially in intensive agroecosystems, analysis of resilience must therefore use a modified framework where the productive functions, regulatory mechanisms, and scales important to these systems are made explicit.

2.1. *Integrate productive functions*

We propose an operational version of resilience in agroecosystems adapted from Conway (1986) and Folke et al. (2002) that considers productive functions by focusing on outcomes such as crop yield, farm income, or provision of ecosystem services and that is centered around four main system aspects: 1) productivity, or total agricultural production or service provision, 2) stability, or the magnitude of variation around mean production levels, 3) resistance to declines in yield components or growth parameters and their supporting mechanisms in the face of disturbance (ecological resilience), and/or 4) rapid recovery to baseline functionality when conditions improve (engineering resilience) (Fig. 2).

Productivity and stability provide the contextual basis as to the desirability of a particular state in an agroecosystem in the long term, i.e. the ability to reliably produce enough food, fuel, and fiber without detrimental effects on the broader agricultural landscape. Resistance and recovery, on the other hand, span temporal and spatial scales to help characterize system response to disturbances and the biophysical mechanisms associated with the long-term maintenance of ecosystem services and commodities. For instance, managers of extensive systems like rangelands or pasture may value fast recovery times after disturbance to maintain system function (e.g. Vogel et al., 2012), whereas managers of intensive systems are more concerned with the resistance component of resilience, recovery becoming important only when efforts to minimize productivity loss are insufficient.

2.2. *Consider loss of self-regulation and type of disturbance*

Shifts away from internal regulation through reliance on external inputs impact the way that resilience must be conceptualized, defined, and measured in intensive agroecosystems (Fig. 3). Resilience-building aims to boost system regulatory mechanisms by creating the conditions necessary for persistence of a desired regime through internal feedbacks (Biggs et al., 2012). Specialized, intensive agroecosystems are externally-regulated and depend on exogenous inputs to withstand disturbance and coerce the system into a desirable state (Rist et al., 2014). Although such systems are theoretically resilient when conditions are favorable, especially from a productivity standpoint, they are often vulnerable to acute stress or suboptimal input levels (Table 1). For example, when irrigation water is limited during a drought, systems are often pushed into an undesirable state with considerable yield loss if internal buffering mechanisms (e.g. high soil organic matter and adequate aggregation for water conservation) are lacking. In fact, because intensive practices often degrade the internal mechanisms of resilience (e.g. water infiltration and storage capacity) (Rist et al., 2014), stress could occur even in the absence of meteorological drought (Mishra and Singh, 2010).

If a system is already in an unproductive state, resilience is an undesirable trait and steps must be taken to coerce the system regime toward more favorable metrics. In this case, external regulation may be a necessary part of desirable resilience building, especially where inputs are unbalanced and already chronically low, such as in many agroecosystems in Sub-Saharan Africa and the semi-arid tropics (Tittonell and Giller, 2013). Continued cultivation in these systems without first addressing water and soil health further mines limited resources and entrenches the system in a “poverty trap” of cyclical degradation and collapse (Carpenter and Brock, 2008). The question of input balance is therefore just as important as input source; external inputs that stabilize natural resource bases and transform unproductive regimes can improve resource use efficiency (de Wit, 1992), boost favorable resilience characteristics, and reduce exposure to disturbances.