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Review

Ways forward for resilience research in agroecosystems

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A R T I C L E I N F O

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A B S T R A C T

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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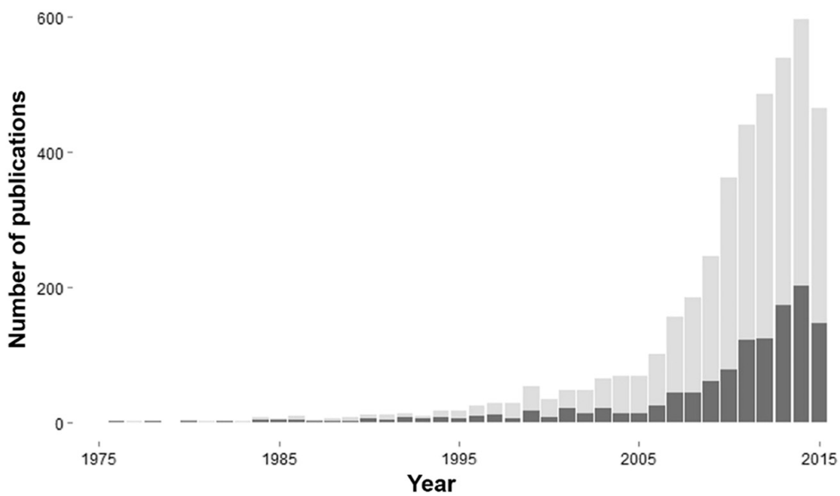

Fig. 1. Number of resilience-related publications (light shaded area) and number of agriculture-related resilience publications (dark shaded area) per year in the CAB and Agricola databases from 1970 to 2015.

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.

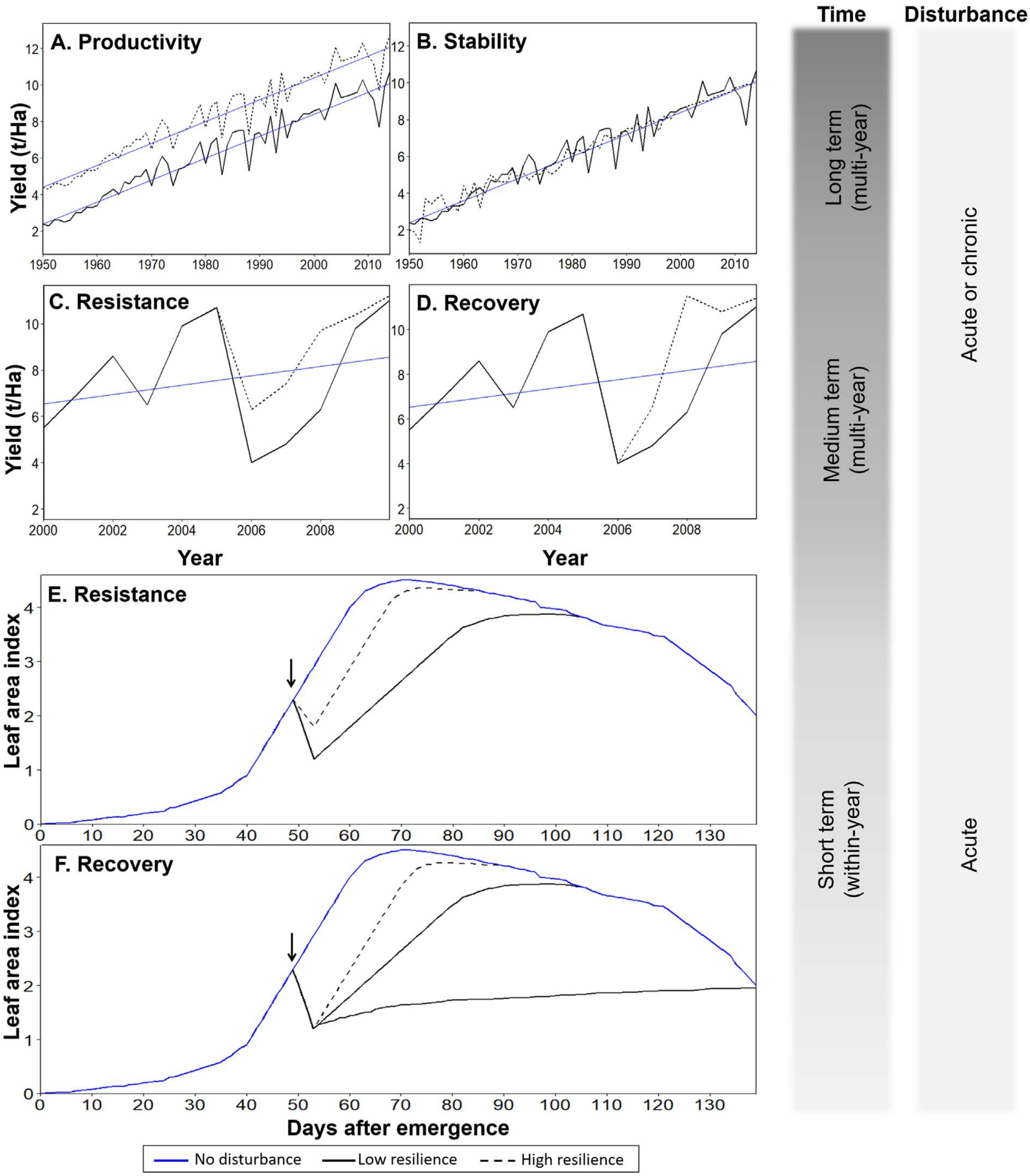

Fig. 2. The components of resilience as applied to agroecosystems. Dotted lines represent desirable attributes or responses to stress. Solid lines represent low resilience scenarios. For a multi-year variable such as crop yield, desirable resilience involves any or all of the following: higher average productivity (A); less variation around mean productivity levels (B); higher resistance, i.e. a less negative outcome during stressful years (C); or faster recovery after a disturbance (D). For a short-term variable such as Leaf Area Index, high resistance to stress (E) and/or fast recovery (F) are the desirable scenarios. Average annual corn yields for the U.S. (solid lines in A and B) from USDA-NASS (2007). Data for scenarios C-F generated by the authors. Concept modified from Conway (1986).

Furthermore, given that disturbances in intensive agroecosystems can be chronic (e.g. soil degradation, toxicity), acute (e.g. heat wave, pest invasion), high intensity (e.g. extreme weather), or low intensity (e.g. tillage), it is critical to carefully define disturbance and consider potential long-term, gradual changes when monitoring and measuring resilience. The mechanisms behind the disturbance – resource limitation or resource flooding, for example – also determine the components of resilience that are most appropriate to examine and the system responses that managers should aim to achieve. Great precision is thus required when answering the question, ‘Resilience of what, to what?’ (Carpenter et al., 2001).

In any case, management of externally-regulated agroecosystems is typically reactive and centered on productivity at a single scale and timeframe; field-scale problems are solved using field-scale solutions. On the other hand, internally-regulated agroecosystems require proactive management and consideration of long-term goals, multiple scales, and multiple services to maintain production when challenged by environmental stress. They resist moving into an unproductive state by relying on genetic and species diversity, complex trophic structures, and/or soil organic matter accumulation to buffer environmental adversity. Integrated crop-livestock systems, for example, capitalize on

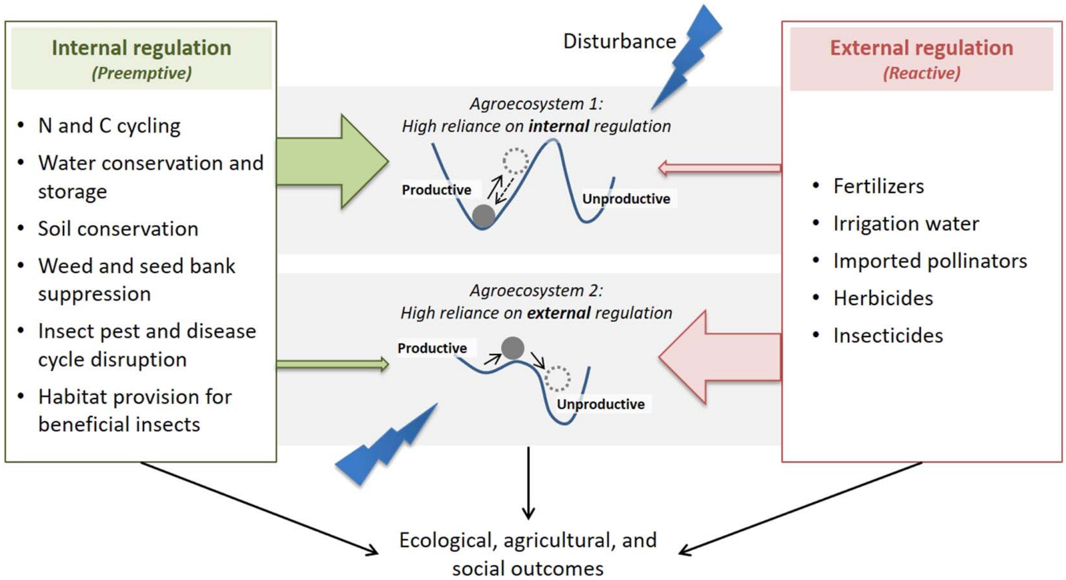

Fig. 3. Sources of regulation in an agroecosystem and the outcomes for regime resilience. High internal regulation results in high resilience of the desirable (productive) regime, whereas high external regulation results in low resilience and higher probability of flipping to an undesirable (unproductive) regime.

multiple kinds of diversity at different scales to influence internal buffering mechanisms and promote resilience to stress, as illustrated in Box 1.

These observations focus on agroecosystem resilience at the field scale, but it is important to note that resilience at this scale is a product of both smaller-scale biophysical mechanisms and complementary social and economic resilience of the greater landscape. Empirical results for crop yields at sub-field scales are not necessarily good predictors of performance at the field scale, and judicious placement of sampling plots to eliminate unwanted – but influential – heterogeneity has been shown to overestimate productivity for some systems (Kravchenko et al., 2017). Multi-scale processes influence baseline conditions and dictate the pathways and impetus for systemic changes; the field scale conveniently integrates both sub-field processes and landscape scale energy exchanges (Whisenant, 1999). We focus on the field scale to make resilience tractable for empirical tests and to pare down the vast number of competing influences on ecological resilience mechanisms while still informing agroecosystem management.

2.3. Examine scale and cross scale interactions

Input imbalances in agroecosystems are common because boundaries are porous, self-regulation is difficult to achieve, and the mechanisms that promote or hinder resilience are sometimes exogenous to the system (Rist et al., 2014), involving a mixture of off- and on-site factors of varying degrees of importance. Resilience can be simultaneously a function of entire regions and landscapes (Ponce Campos et al., 2013), watersheds (Walker et al., 2009), farms and their connected enterprises (Sinclair et al., 2014), or fields (de Moraes Sá et al., 2014).

Resilience at large spatio-temporal scales occurs in response to similarly-scaled disturbances (e.g. climate change, topsoil loss, regional drought) and must be managed accordingly, e.g. through landscape diversification or regional policy mechanisms (Chaplin-Kramer et al., 2011; Zhu et al., 2000). This fact makes resilience especially difficult to characterize empirically. On the other hand, small-scale, biophysical resilience is a response to heat, water scarcity, nutrient limitation or other stresses in individual plants or stands and their corresponding microclimates. Resilience management at this scale is directed at sub-field mechanisms, e.g. soil carbon storage or rhizosphere microbiome composition. Management options are also a function of system type: while extensive systems can capitalize on community assemblage characteristics and topographic or microclimatic heterogeneity to support internal regulatory cycles, intensive monocultural systems are often limited to other mechanisms such as improvement of soil organic matter content or water holding capacity (Box 1). Studying resilience at the field and sub-field scales presents its own considerable challenges. However, insights into resilience at the field scale especially offers the most directly relevant information and metrics for agroecosystem managers and researchers.

Box 1: Scales of resilience in integrated crop-livestock systems

Since the 20th century, mechanization, synthetic input production, and the resulting economies of scale have brought about the specialization characteristic of modern farming systems. Reincorporation of livestock production into cropping cycles is a strategy to bolster diversity and multi-functionality of modern agroecosystems. Integrated crop-livestock systems (ICLS) include stubble grazing, seasonal rotation of crops with sown pastures, or the inclusion of productive grasslands in the agricultural landscape mosaic.

Commercial ICLS are illustrative of the implications of scaling as they involve both intensive and extensive management styles and the disturbance regimes and human objectives that correspond to each. ICLS exhibit ecological resilience in the form of decreased susceptibility to pest outbreaks (Khumairoh et al., 2012) and drought (de Moraes et al., 2014). At the field scale, the drivers of this resilience include the taxonomic diversity of both target (for harvest) and non-target species achieved by introducing forage crops into rotation and providing habitat and alternative feeding sites for beneficial organisms. At the sub-field scale, resilience is supported with improved soil organic matter dynamics and higher fungal:bacterial ratios in microbial communities (Acosta-Martínez et al., 2010). At the farm and regional scale, spatial and temporal diversity are achieved through increases in the heterogeneity of land cover types and the complexity of multi-year crop/pasture rotations (Lemaire et al., 2014).

These multi-scale effects and interactions result in a high degree of self-regulation driven by microbial associations and organic matter deposition. Despite doubling the management intensity of a similar-sized extensive grazing operation, ICLS do not typically require corresponding input increases. They do, however require a high degree of managerial adaptability and social and economic capital. The interacting effects of crop type, tillage, water management, and climate complicate understanding the underlying mechanisms of ecological resilience, while tradeoffs among social, economic, and ecological resilience influence the calculus of overall system outcomes.

The time scales under consideration in agroecosystems range from decades, e.g. for some soil physical properties, to a matter of seconds, e.g. for plant physiological responses to stress. Therefore, temporal scales and hysteresis are equally important when considering the consequences of past poor management on resilience mechanisms. Hysteresis describes transitions between system states that are sudden and non-linear rather than smooth and reversible, usually with slower time to recovery than to degradation. The resulting "system memory" in intensive agroecosystems is evident in soil structural and biological processes such as soil organic matter turnover, microbial community function, or bulk density changes that are a function of past land use regimes.

For instance, a longstanding justification for more diverse crop rotation schemes is the positive residual effects of previous crops on the yield of subsequent crops due to improved soil properties and weed and pest control, especially when diverse plant functional groups are incorporated (Lin, 2011; Gaudin et al., 2015). On the other hand, a system affected by memory of prolonged past adverse conditions may be unable to capitalize on positive hysteretic outcomes and fall into a poverty trap (Carpenter and Brock, 2008; Tittonell and Giller, 2013).

Furthermore, the effects of management actions can spill over to the scales either above or below the focal scale (Rist et al., 2014). These "crossover effects" can occur when management practices in one system intentionally or unintentionally alter the resilience of downstream systems (Table 1). The tradeoffs involved in crossover effects have clear implications for agroecosystems, especially when management for resilience to one type of disturbance (e.g. fertilizer application) affects resilience to other types of disturbance (e.g. stress tolerance response). Negative crossover effects are evident, for example, where heavy application of livestock manure as a soil amendment improves soil organic matter content at the focal scale but contributes to widespread eutrophication and hypoxia in freshwater and marine ecosystems (Boesch et al., 2001).

A positive crossover effect may result from the integration of hedgerows and other non-crop vegetation in a field or farm, which can enhance provision of biocontrol services not only for the target fields but also for fields in the surrounding agricultural mosaic (Chaplin-Kramer et al., 2011). For instance, planting mixtures of susceptible and tolerant varieties helps control pests and pathogens more effectively when implemented over an entire region rather than at small, within-field scales (Zhu et al., 2000). Similarly, an agricultural field may be currently unaffected by erosion, but management actions at small scales – e.g. inappropriate tillage practices leading to stable aggregate breakdown, crusting, and highly localized runoff – can directly trigger a transition into a degraded state when preferential water flow multiplies to carve out rills and gullies. The resilience of the un-eroded regime can be further impacted indirectly by policy environments and resulting incentives for soil conservation practices. Resilience is a characteristic of complex systems; regardless of whether crossover is positive or negative, management recommendations always run the risk of producing unintended consequences.

3. Current approaches to monitoring resilience

Detailed indicator frameworks have facilitated the ranking and evaluation of agroecosystem types in terms of their relative resilience (e.g. Milestad and Darnhofer, 2003). Indicators of resilience that have

Table 1
Examples of internally and externally regulated agroecosystems and the related cross-scale interactions, indicator variables and research approaches used to study their resilience to stress events.

Resilience of crop to:	Internally-regulated agroecosystem		Externally regulated agroecosystem		Cross-scale interactions	Important variables	Research approaches	References
	Mechanisms	Management actions	Mechanisms	Management actions				
Fertility loss	Microbial activity (especially fungal)[1,2], N fixation[3], biomass turnover[4], soil micro-aggregation[5]	Complex crop rotations, conservation tillage, livestock integration, cover cropping	Management intervention	Fertilizer application, soil amendments	N leaching and watershed quality, natural resource availability, maintenance of alternative stable states	Soil microbial community resistance and recovery, historical yield stability, land-use patterns, economic tradeoffs	Laboratory incubations, meta-analysis,	[1](Rivest et al., 2013); [2](Acosta-Martínez et al., 2010); [3](Gaudin et al., 2013); [4](Turmel et al., 2014); [5](Six et al., 2002)
Drought	Plant response diversity[6], soil water holding capacity[7], soil organic matter[8]	Building soil organic matter (e.g. through organic inputs, cover cropping)	Management intervention	Irrigation, genetic resources, avoidance (fallow)	Water policy environment, climatic variability, riparian habitat conservation, climate change, soil compaction, canopy cover	Relative dry-down or green-up times, microbial resistance and recovery, plant stress responses	Greenhouse, experimental disturbance, deficit irrigation, thermal or multispectral remote sensing	[6](Elmqvist et al., 2003); [7](Williams et al., 2016); [8](Pimentel et al., 2005)
Heat	Microbial symbionts[9], soil water holding capacity[10], microclimate provision[11]	Intercropping, crop rotations, building soil organic matter, genetic resources	Management intervention	Protected agriculture (shade structures), avoidance, genetic resources	Climate change, GHG emissions from agriculture	Plant stress response	Growth chamber, experimental disturbance, thermal remote sensing	[9](Singh et al., 2011); [10](Williams et al., 2016); [11](Rao et al., 2007)
Pest/pathogen outbreak	Diversity and abundance of natural enemies[12], spatial and temporal crop diversity[13]	Habitat provision (e.g. hedgerows), crop rotations, intercropping (e.g. "push-pull")	Management intervention	Pesticide application, hormone interruption, trapping	Landscape diversity, climate change, actions of neighboring producers, acquired pesticide resistance	Stress hormone levels, insect community composition	Hyperspectral remote sensing	[12](Chaplin-Kramer et al., 2011); [13](Lin, 2011)

been employed in agricultural systems include soil health parameters such as total and mineralizable N and total C (Song et al., 2015), soil organic matter (Van Apeldoorn et al., 2011), mineral P and K (Berzsenyi et al., 2000), pH and cation exchange capacity (Verhulst et al., 2011), soil physical properties (Trabaquini et al., 2013), texture (Delmotte et al., 2011), structural stability (Mallory and Porter, 2007), and soil-water relations (Rusinamhodzi et al., 2012). Indicators such as pest (Khumairoh et al., 2012) and weed pressure (Smith et al., 2008), frequency of landslides (Holt-Giménez, 2002), severity of erosion (Rockström et al., 1999), and within-field topography (Kravchenko et al., 2005) have also been measured to support understanding of agroecosystem resilience mechanisms.

However, data on the kind of dynamic indicators and surrogates that permit active resilience monitoring or predictive analysis are still lacking. In some cases, incorporating resilience into agroecosystems research may simply be a matter of asking better, more precise questions. In other cases, particularly when active monitoring or prediction are required, tracking responses to experimental disturbances or tapping into long-term or intensive datasets can yield useful insights (Scheffer et al., 2015).

3.1. Analyzing multi-location, long-term trials

Long-term or intensive datasets capitalize on large numbers of observations with high temporal and spatial variability to capture resistance and recovery of key indicators of resilience. Crop yield and yield stability are foundational indicators of performance in the agronomic (e.g. rotation diversity, tillage trials) and breeding literature (e.g. variety trials), and though most pre-2010 studies examine these metrics without explicitly relating them to resilience, there is certainly room to interpret them through a different lens. Applying resilience approaches to standard yield and yield stability analysis can bring much-needed perspective and emphasize whole-system attributes, cycles, and associations among interconnected scales. Since 2010, comparative studies at the field scale have examined agroecosystem attributes such as fertility management strategy (i.e. organic amendments; Song et al., 2015), temporal diversity (i.e. crop rotation; Gaudin et al., 2015), and agroforestry (Jacobi et al., 2013), among many others, for their potential to support biophysical and socioeconomic resilience to stress.

Such an abundance of field-scale agronomic data is useful, as this is precisely the scale at which resilience has been neglected. Furthermore, these trials are critical to understanding the smaller-scale, mechanistic variables that contribute to productivity and potential management actions. The challenge remains to knit these valuable resources into mineable, comparable long-term datasets across climates and crops to be able to trace and predict longer-term resilience in response to past and future environmental variations.

3.2. Manipulating experimental disturbances

Some of the most interesting insights that resilience can bring to agroecosystems research arise from a focus on dynamic variables, or variables that can produce traceable trajectories in response to a stress period or disturbance (Todman et al., 2016). Examples are relatively scarce in the literature owing to the difficulty of collecting data with the temporal resolution necessary to construct an accurate response curve. However, subjecting a system to an artificial stress whether in a lab incubation setting or in the field gives researchers the ability to cope with the unpredictability of acute stress events, control the duration and intensity of the stress, and frequently monitor the chosen indicator (e.g. vegetation reflectance indices, microbial respiration, growth rate) before, during, and after the disturbance.

In managed grasslands or pastures for example, methods to produce artificial disturbances have included repeated mowing, fire, grazing exclosures (López et al., 2013), and rain shelters (Zwicke et al., 2013) to represent overgrazing, water, and temperature stresses. Similar effects have been simulated in intensive agricultural fields using modified tillage regimes (Carter et al., 2009) and deficit irrigation treatments (Verhulst et al., 2011). These experimental approaches are suitable for characterizing the response and recovery aspects of resilience and thus giving more direct indications of the underlying slow biophysical variables that define a system's current state.

The study of soil ecosystem resilience has lent another interesting perspective to agroecosystem resilience in which the resistance and recovery aspects in response to experimental disturbances have been particularly well described (Grandy et al., 2012). Functional soil attributes examined with explicit reference to their capacity for resistance or recovery have included bacterial or fungal biomass (Acosta-Martínez et al., 2010), microbial community evenness and richness (de Vries et al., 2012), and nutrient cycling (de Moraes Sá et al., 2014), while structural factors have included bulk density, aggregate stability, and porosity (Carter et al., 2009; Trabaquini et al., 2013).

Similarly, microbial ecology studies tracking the resistance and recovery rate of microbial activity and community composition after acute (tillage, flooding) and chronic (toxicity) disturbances have lent great insight into the dynamics of soil resilience. Such studies have compared different management types and disturbance histories, such as managed forest soils with either retention or removal of litter (Zhang et al., 2013), agricultural soils with either organic or synthetic fertility management (Kumar et al., 2014), or native grassland vs. adjacent agricultural soil (de Vries et al., 2012), for their relative soil microbial resilience characteristics. Most importantly for understanding the contribution of microbial dynamics to overall agroecosystem resilience are the few studies that complete the picture by making direct connections between microbial resilience, soil processes, and crop performance under stress (e.g. Rivest et al., 2013).

3.3. Monitoring with remote sensing

The versatility of remote sensing tools makes them well-suited to quantifying resilience surrogates and indicators across scales (e.g. Lobell et al., 2013). At the global scale, historical satellite imagery has given insight into the resilience of entire biomes by tracking recovery of net primary production after dry years, (Ponce Campos et al., 2013) while at the regional scale canopy reflectance has been used to measure the dynamics of vegetation cover in managed and unmanaged ecosystems throughout the growing season in response to weather variables (Ares et al., 2001).

The use of remote sensing at the field scale has been more limited. However, the increasing availability of handheld and ground-level optical sensors, unmanned aerial vehicles, and high-resolution satellite imagery for precision agriculture presents opportunities for examining within-season resilience metrics. Handheld reflectance sensors have been used to show differences in growth trajectories under different tillage and irrigation schemes in wheat (Verhulst et al., 2011), a method that could be adapted to monitor resistance and recovery for other disturbances and systems. Furthermore, the increasing popularity of thermal imaging and multispectral or infrared sensors in high-throughput phenotyping for crop breeding suggests similar applications for near-real-time detection of crop stress and recovery.

Remote sensing approaches are currently limited by the availability of quality imagery at the temporal and spatial scales necessary to examine short-term changes in crop physiological status. However, when supplemented by collective effort in the development of open-access, minable data repositories, they could supply the intensive datasets necessary to make predictions regarding resilience of single or multiple system states (Scheffer et al., 2015).

3.4. Modeling agroecosystem resilience

Modeling tools can help tease out the impacts of many interacting factors, under a number of conditions and at many scales (Kahiluoto

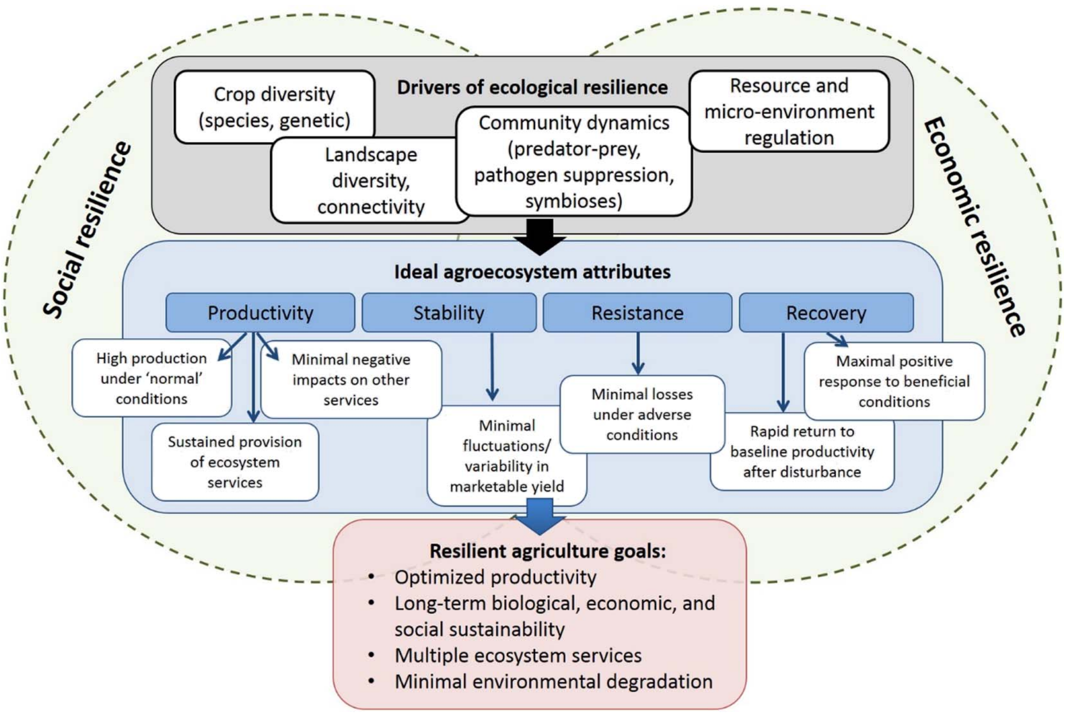

Fig. 4. The concept of ecological resilience as it applies to agroecosystems, demonstrating the multi-scale ecological, social, and economic dynamics driving resilience. The ecological outcomes of a resilient, desirable system regime feed into the overall goals of sustainable agriculture.

et al., 2014b). Statistical model simulations have been used to quantify the effects of cropping system, management, and environmental variability on economic and/or agronomic performance of livestock, crop, or integrated crop-livestock systems (e.g. Martin and Magne, 2015), including under future climate and market scenarios. For example, di Falco and Chavas (2008) used cereal yield data to model the effect of extreme rainfall years on yield stability under varying degrees of spatial crop diversity, while Kahiluoto et al. (2014a) used a mixed model approach to show that diversity of responses to rainfall and market shocks, rather than diversity of cultivar types, was most likely to support resilience in the barley-producing landscape of Finland. In an innovative approach from soil science, Todman et al. (2016) used a model based on an analogy with a mechanical spring and damper system to quantify resilience metrics for soil respiration responses to disturbance.

Process-based models can provide further insight into the mechanisms behind environment- and management-related effects on crop response to climate variability (Kahiluoto et al., 2014b). They also avoid the difficulties associated with the long-term nature of most resilience studies and allow large, complex datasets to be analyzed under various simulation scenarios relatively quickly and thoroughly. Despite the uncertainty inherent in dynamic agricultural modeling tools, they can provide valuable guidance as to the direction of future experimental research and potential adaptation mechanisms. Modeling techniques can thus be considered a launch pad for further inquiry in the field or as a testing site for otherwise untestable questions.

4. Research priorities and knowledge gaps

The most recent resilience literature reveals that despite growing interest in applied resilience research and increasingly novel approaches in fields such as soil and microbial ecology, significant gaps still exist in understanding the consequences of disturbance-induced changes on regulatory agroecosystem services, the biological drivers of resilience across management systems, and the cross-scale implications of resilient systems or lack thereof. Translating resilience into measurable entities has been a perennial challenge in many fields and especially in agroecosystems research, as effective characterization requires understanding the various scales and speeds across which disturbances and resilience drivers can interact. Properly characterizing resilience remains time-consuming and expensive due to the multidisciplinary nature and broad-reaching implications of such studies. While studying ecological resilience at manageable scales is a good starting point for learning how to ask answerable questions about resilience drivers, the interactions and tradeoffs among different kinds of systems resilience (e.g. social resilience, economic resilience, and ecological resilience) at all scales must eventually be considered to arrive at relevant conclusions about overall, long-term system outcomes.

Although the approaches highlighted above offer ideas for how we may actively integrate resilience concepts into agroecosystem research, further work is required to reach a consensus on appropriate metrics. While abundant information exists on productivity- and stability-related agricultural and ecological indicators across spatial and temporal scales, studies that adequately characterize the resistance and recovery aspects of resilience are still relatively rare. There is also room for more creativity in the selection of resilience surrogates and indicators: crop variables such as evapotranspiration rates (e.g. Zwicke et al., 2013), chlorophyll fluorescence (e.g. Sinare and Gordon, 2015), and plant stress volatile emissions (e.g. Aksenov et al., 2013), among others, have yet to be investigated in much detail. Existing frameworks should be subject to empirical testing and cross-validation to determine linkages between resilience indicators and conventional agronomic performance metrics and to identify potential tradeoffs in resilience management options at scales both larger and smaller than the agricultural field.

Both experimental and model-based approaches can help to understand feedbacks in plant, soil, and rhizosphere dynamics under stress and how they relate to system resilience. Data-intensive methods such as remote sensing and precision agriculture-related research can deliver information with the temporal resolution necessary to understand near-instantaneous changes in response to disturbance, whereas long-term, historical datasets can address larger scale fluctuations in system indicators. These approaches, among others, represent opportunities to better operationalize resilience theory for intensive agroecosystems.

This review stresses the importance of understanding field-scale biophysical dynamics, whether to form the basis for larger-scale assumptions about agroecosystem resilience, explain the relative resilience of different management systems, or address the difficulties of capturing agronomic resistance and recovery to environmental stressors at field scale. However, mechanistic indicators cannot stand alone; social and economic contexts, policy environments, unintended management consequences and externalities at scales above the field or farm scale must be considered in conjunction to biophysical metrics due to the many interactions among scales and system components that influence overall agroecosystem resilience. Data on field-scale biophysical indicators of resilience should also be complemented by stakeholder-driven indicator development to help ensure that results at the field scale are translatable to local socio-economic and political contexts (Holt-Giménez, 2002).

When these considerations are addressed, resilience theory has much to offer not only as a comparative metric of system performance under stress, but also as a monitoring tool to prevent agroecosystem degradation and loss of function from maladaptive management practices or environmental adversity. Ultimately, it can keep agroecosystems research in sight of the long-term goals of sustained productivity and provision of ecosystem services even in a volatile environment. More research is needed to identify actions that build resilience and sustainable performance of systems with high productivity, stable yields, maximal resistance to negative disturbances, and maximal positive response to favorable conditions while achieving long-term economic and social sustainability, provision of multiple ecosystem services, and minimal environmental impact (Fig. 4). Integrating resilience concepts might reveal complementary measures of agricultural sustainability or performance that can be leveraged to benefit both agricultural and ecological objectives.

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