Exploring resilience with agent-based models: state of the art, knowledge gaps and recommendations for coping with multidimensionality

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Abstract

Anthropogenic pressures increasingly alter natural systems. Therefore, understanding the resilience of agent-based complex systems such as ecosystems, i.e. their ability to absorb these pressures and sustain their functioning and services, is a major challenge. However, the mechanisms underlying resilience are still poorly understood. A main reason for this is the multidimensionality of both resilience, embracing the three fundamental stability properties recovery, resistance and persistence, and of the specific situations for which stability properties can be assessed. Agent-based models (ABM) complement empirical research which is, for logistic reasons, limited in coping with these multiple dimensions. Besides their ability to integrate multidimensionality through extensive manipulation in a fully controlled system, ABMs can capture the emergence of system resilience from individual interactions and feedbacks across different levels of organization. To assess the extent to which this potential of ABMs has already been exploited, we reviewed the state of the art in exploring resilience and its multidimensionality in ecological and socio-ecological systems with ABMs. We found that that the potential of ABMs is not utilized in most models, as they typically focus on a single dimension of resilience by using variability as a proxy for persistence, and are limited to one reference state, disturbance type and scale. Moreover, only few studies explicitly test the ability of different mechanisms to support resilience. To overcome these limitations, we recommend to simultaneously assess multiple stability properties for different situations and under consideration of the mechanisms that are hypothesised to render a system resilient. This will help us to better exploit the potential of ABMs to understand and quantify resilience mechanisms, and hence support solving real-world problems related to the resilience of agent-based complex systems.

Keywords: agent-based models, model development, multidimensionality, review, social-ecological systems, stability properties

1 Introduction

In a world undergoing unprecedented change, understanding the resilience of agent-based complex systems, i.e. their ability to absorb change while maintaining functioning and thus persist, is of utmost importance (Biggs et al., 2012, 2015; Holling, 1973). Resilience has therefore become an increasingly popular concept in ecology, socio-ecology and other environmental sciences, as well as in many international bodies and conventions such as the CBD, the OECD and Wetlands International (Donohue et al., 2016). Increasing the capacity of agent-based complex systems (Grimm et al., 2005) to sustain their functioning and services under disturbances and ongoing change is of prime interest (Biggs et al., 2012; Oliver et al., 2015).

However, putting resilience into practice is challenging. Inconsistent terminology keeps hampering communication and understanding among theoreticians, empiricists and policy-makers (Baggio et al., 2015; Brand and Jax, 2007; Donohue et al., 2016; Grimm and Wissel, 1997; Pimm, 1984). In particular, the meaning of the term “resilience” differs widely between social and natural sciences. In social-ecological research, “resilience” is primarily an integrated and holistic approach within sustainability science, which emphasizes social-ecological feedbacks, change as inherent element of social-ecological systems, and the capacity of such systems to adapt (Biggs et al., 2015). Quantification of resilience was so far not a major issue, which might be one of the reasons why putting resilience into practice is still difficult.

In contrast, in ecology “resilience” originally referred to the recovery of certain state variables to pre-disturbance levels (Pimm, 1984). More recently, ecologists use “resilience” as a multidimensional umbrella for the specific stability properties, or dimensions, recovery and resistance (Oliver et al., 2015; Standish et al. 2014), which are quantifiable (Table 1). Indeed, a few experimental studies quantified resilience by measuring its multiple dimensions

(Donohue et al., 2016; Hillebrand et al., 2018). Biodiversity research, in particular, is focussing on the (in)variability of state variables as a proxy for "stability" (Wang and Loreau, 2016), because a system showing lower variation usually has higher chances that state variables remain within the ranges required for the persistence of a system. In this interpretation, resilience, defined as the ability to function and persist despite disturbances and change, is the consequence of recovery and resistance, which in turn may be determined by mechanisms such as adaptive capacity or learning which are also discussed in social-ecological research. In addition to the multidimensionality of resilience, assessments of its properties also depend on the levels of organization, state variables, reference states, types of disturbance and scales considered (Biggs et al., 2012; Carpenter et al., 2001; Grimm and Wissel, 1997). Consequently, in ecology a reductionist interpretation of resilience prevails as resilience research often ends up in more or less unrelated assessments of specific properties in specific ecological situations (Grimm and Wissel, 1997).

To move on in resilience research, the holistic and reductionist interpretation of resilience need to be reconciled. Although the old management slogan "If you can't measure it, you can't manage it" might represent a too narrow "command-and-control" notion of management, we argue that some quantification of resilience is needed to assess the state of a system in response to changes or actions, and to uncover the major resilience mechanisms. Therefore, we would ideally perform controlled experiments within entire systems and simultaneously measure recovery, resistance, and persistence, as well as (in)variability. To learn about the mechanisms underlying resilience, we would implement possible mechanisms, such as those listed by Biggs et al. (2012, 2015) or Desjardins et al., (2015), and measure the different dimensions of resilience for different levels of organization, state variables, reference states, types of disturbances, and spatial and temporal scales (Grimm and Wissel, 1997). However, except for artificial systems in ecology such as micro- and mesocosms or extremely simplified settings such as in behavioural economics, this is hardly possible.

Consequently, modelling plays an important role for understanding agent-based complex systems as it complements empirical research. Ecology in particular has a long tradition in modelling because ecological systems are complex, large, and often develop too slowly to be understood via short-term studies. Modelling also plays an increasing role in social sciences (Gilbert and Troitzsch, 2005). If a model captures multiple patterns describing the system in reality, it can be used to systematically explore resilience mechanisms. Model predictions then can be tested in targeted surveys or experiments, so that models informed by observations, and observations motivated by model predictions, are truly integrated. Accordingly, modelling could facilitate the consideration of the multidimensionality of resilience and thereby foster the integration of the holistic and reductionist approaches to resilience.

Agent-based models (ABM) play a particularly important, but certainly not exclusive, role in this context because decision-making agents, for example humans, individuals of other species, or institutions, are the building blocks of agent-based complex systems such as ecological systems, land-use systems, cities, or financial markets. ABMs have been widely used to understand observed system-level patterns mechanistically, because these patterns emerge from individual variation, local individual interactions and adaptive behaviour (An, 2012; DeAngelis and Grimm, 2014; Matthews and Gilbert, 2007). In social-ecological systems (SES), which are characterized by feedbacks between ecological and social processes (Biggs et al., 2015; Ostrom, 2009; Parker et al., 2008), ABMs are often used to better understand resource use and its consequences for humans and ecosystems (e.g. Rammer and Seidl, 2015; Schlüter et al., 2009; Walker and Janssen, 2002).

ABMs have a great potential but their development, testing and analysis is challenging, and the corresponding methods and strategies are complex. The corresponding methodology developed slowly but also significantly over the last two decades (Grimm et al., 2010, 2005; Grimm and Berger, 2016a; Heppenstall et al., 2012; O'Sullivan and Perry, 2013; Robinson et al., 2007; Tesfatsion, 2006), but the common practice of model analysis in terms of sensitivity, uncertainty, understanding of emergence, and robustness is still quite limited (Schulze et al., 2017).

Facing the high relevance of resilience research and the potential of ABMs to advance this field by integrating holistic and reductionist approaches to resilience, an overview on how resilience, and in particular its multidimensionality is operationalized in ABMs is needed. Therefore, we aimed to summarize the state of the art, identify possible knowledge gaps, and suggest ways forward for a more effective use of ABMs for resilience research. We first provide relevant definitions and concepts and then conduct a review of ABMs assessing resilience. Based on this we formulate general recommendations that might help developing and analysing ABMs in a way that delivers more comprehensive insights into resilience.

Table 1 Definitions, assessment, implications and examples of the stability properties related to resilience.

Stability property	Definition / assessment	Implications	Example
Recovery	Process of a state variable returning to the values prior to a disturbance. / Time needed until the state variable reaches pre-disturbance levels (dashed arrow Fig. 1).	Measuring recovery for different variables may lead to different conclusions.	Abundance after disturbance through a pesticide might recover quickly, but age and size structure might take much longer to return to pre-disturbance levels (Galic et al., 2017; Martin et al., 2014).
Resistance	The change of a state variable after a disturbance (“amplitude”, solid arrow Fig. 1).	Just referring to the amplitude is merely descriptive.	
	Comparison of amplitude with and without mechanisms that are assumed to affect resistance.	Better understanding why resistance emerges.	Productivity of a low diversity system might be more affected by species loss (Fig. 1 B) compared to a diverse system (Fig. 1 A).
	Buffer mechanisms: Require observing the variable of interest and a variable that measures buffer capacity.	If a buffer works, the variable of interest is hardly affected by a disturbance, but the buffering capacity is reduced. One disturbance might be buffered well but reduces buffer capacity for another disturbance.	Size structure of *Daphnia magna* populations buffered against pesticides that mainly affected small individuals and against predators focusing on larger ones. Combination of both disturbances leads to extinction (Gergs et al., 2013).
Persistence	Existence of a system through time as an identifiable unit, described by specific state variables remaining within a certain range (shaded area Fig. 1).	Cannot only be directly assessed if a system definition exists and functional and/or if structural criteria for quantifying when a system has lost its identity are available (Jax et al., 1998).	Savannas are characterized by both a tree cover of not more than 20% and a scattered distribution of trees (Calabrese et al., 2010).
Variability / invariability	Change of a state variable over time (Arnoldi et al., 2016). Often used as a proxy for persistence, because it is assumed that a system showing lower variation has higher chances that state variables remain within the ranges required for the persistence of a system.	Continuous variation might increase resilience, as it supports reconfiguration in response to disturbance (Holling and Gunderson, 2002).	

2 The multiple dimensions of resilience

In ecology, the multidimensionality of resilience or stability has been acknowledged for a long time (Grimm and Wissel, 1997; Pimm, 1984), although the term "multidimensionality" has become more popular only recently (e.g., Donohue et al., 2016). Recent reviews on resilience in ecology agree that resilience per se is not quantifiable, but only its different dimensions, or components: recovery, resistance, and variability (Oliver et al., 2015; Standish et al., 2014; Table 1; Fig. 1). More generally, also the persistence of systems can, at least in microcosms or models, be quantified in terms of population persistence (e.g. Drake and Lodge, 2004), or characteristic patterns in organization or spatial structure (Cumming and Collier, 2005; Jax et al., 1998). Because these different stability properties are not always correlated (Dey and Joshi, 2013; Tung et al., 2016), just looking at one of them only gives limited insights into the emergence of resilience.

A second level of multidimensionality that is also increasingly acknowledged lies in the fact that recovery, resistance, persistence and variability can only be applied to specific situations, which are defined by the considered level of organization, state variable, reference state, disturbance, and spatial and temporal scale (Grimm and Wissel, 1997; they originally referred to "ecological situation", but here we use the more generic term "specific situation"). The assessment of the stability properties does not only depend on the system of interest itself and its mechanisms, but also on how we observe it. Different state variables and levels of organization (e.g. individual agents vs. communities) may react differently to disturbances (Fig. 1 A, B vs. E, F). Likewise, the way we define the reference state determines how close a variable returns to its "normal" state after a disturbance. For example, comparing the state variable against a dynamic reference (temporal development of the state variable without disturbance) may indicate slower recovery and larger amplitude (Fig. 1 C, D) than when compared to a static reference (Fig. 1 A, B). Virtually all stability properties, in particular variability and persistence, will depend on the spatial and temporal scales considered (Cumming et al., 2016). For example, in metapopulations the local existence of populations does not inform about regional persistence (Hanski and Gilpin, 1991). Disturbances of populations by toxicants or predators may affect different size classes so that consequences for resilience are not captured by only considering total abundance (Gergs et al., 2013). In mesocosm experiments addressing the response of aquatic invertebrate communities to a pulse exposure of an insecticide, species composition changed strongly while two ecosystem functions (primary production and respiration) hardly changed (Radchuk et al., 2016). In all these cases a multidimensional view, considering several state variables, levels of organization or disturbance type, provided insight into the internal organization of the system and, hence, its resilience mechanisms.

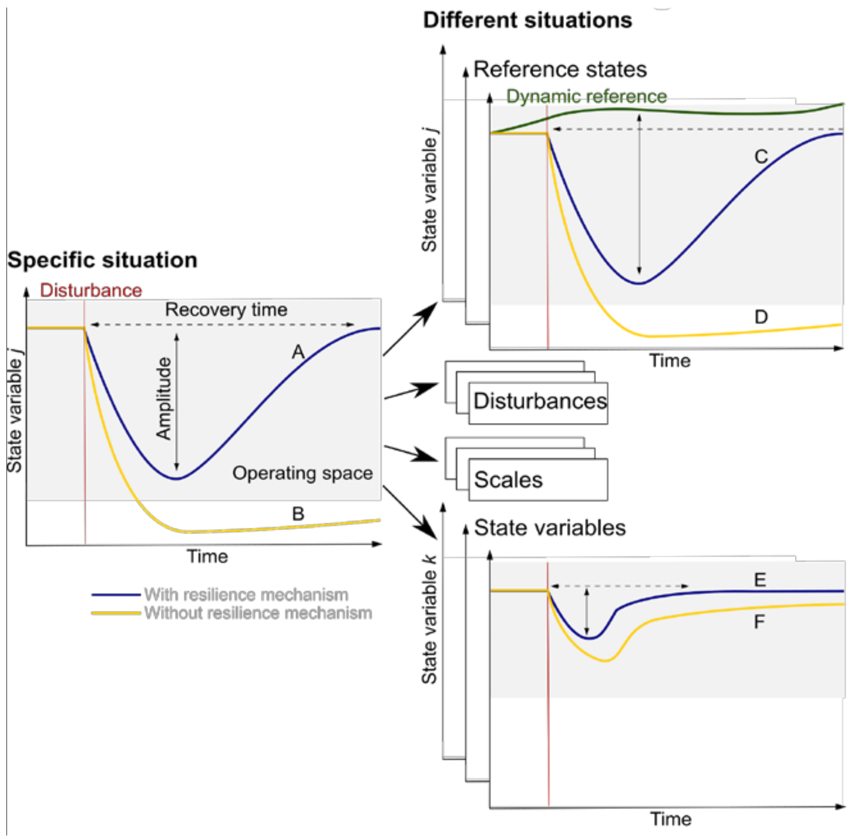

Fig. 1. Schematic illustration of the three stability properties recovery, resistance, and persistence assessed across the different dimensions of specific situations. A multidimensional view is needed to learn more about the mechanisms underlying resilience, i.e. the stability properties need to be assessed for different state variables, levels of organization, disturbances, and spatial and temporal scales. Curves show the response of a state variable to a disturbance (red line) in a system with (purple) and without (orange) a resilience mechanism. The dashed arrow indicates recovery time, the solid arrow the amplitude, which might indicate resistance. The operating space (shaded area) defines a desired range, within which a state variable should remain that a system persists. The green curve indicates a dynamic reference, i.e. the temporal development of the state variable without disturbance. The different dynamics A-E are referred to in the main text.

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3 Literature review

3.1 Methods

We conducted a Web of Science Topic Search (TS) using the search term TS = ("individual* based* model*" OR "agent* based* model*") AND resilience*. Our search yielded 118 articles (3 July 2017). We excluded 29 papers, because no ABM or results were presented, or because the ABM was not used to study resilience. Since we were only interested in model applications to ecological and social-ecological systems, we excluded articles investigating systems related to economy (n=10), technology and human safety (n=10), sociology (n=3), medicine (n=2) or other systems (n=3). We additionally included four articles that were reviewed in Parrott et al. (2012) and An et al. (2014), but did not appear in our topic search. We evaluated the retained 65 articles with respect to the modelled system, their operationalization of multidimensionality of resilience and the representation of resilience mechanisms. Methodological details and the definitions underlying our evaluation, and detailed results can be found in the Supplementary materials.

3.2 Results

Stability properties

The reviewed models, mainly investigating socio-ecological systems (Fig. 2a), usually studied specific stability properties in isolation. Only 15 studies included one (n=13) or two (n=2) stability properties in addition to variability (Fig. 2b). Of all reviewed articles, 94% measured the variability of one (n=18) or more state variables (n=43), while the other three stability properties where typically quantified with only one state variable. Recovery was measured in eight studies and persistence in nine studies, while resistance was hardly quantified (n=4).

Specific situations

Of the 65 studies, 46 addressed multiple dimensions of specific situations. Out of these, 38 studies used different state variables corresponding to different levels of organization (Fig. 2c). Around half of the studies defined static (n = 9, e.g. value of a state variable prior to a disturbance; Fig. 1 A, B) or dynamic reference states (n = 27, e.g. baseline scenario; Fig. 1 C, D), of which two included more than one reference state. While the majority of the reviewed studies explicitly modelled disturbances (Fig. 2d), only ten studies included more than one disturbance. Press disturbances, altering the system permanently, were investigated in 13 studies. Most studies included a pulse disturbance which either occurred once (n = 10) or multiple times (n = 24). Of all reviewed articles, ten assessed resilience at more than one spatial scale and 13 focused on more than one temporal scale.

Resilience mechanisms

While the assessment of stability properties could be related to resilience mechanisms in 56 articles, they were explicitly communicated in only 40 articles. About one quarter of the studies investigated potential resilience mechanisms directly, e.g. by contrasting system behaviour with and without a proposed mechanism.

3.3 Discussion

Our literature review shows that most existing models focus on a single dimension of resilience; i.e. they use variability as a proxy for persistence or resilience, and are limited to one reference state, disturbance type and scale. Less than one fourth of the reviewed studies varied more than two dimensions of specific situations, and only 15 studies assessed multiple stability properties. Moreover, relatively few studies explicitly test the ability of different resilience mechanisms to support resilience. Accordingly, the potential of ABMs for rigorous manipulation of relevant interactions and feedbacks across the dimensions of specific situations, and the subsequent assessment of different stability properties to identify resilience mechanisms has been exploited to a limited degree. This confirms previous findings, e.g. regarding the lack of incorporation of alternative theories of human-decision making (Groeneveld et al., 2017) or the limited analysis of ABMs developed for social-ecological systems (Schulze et al. 2017).

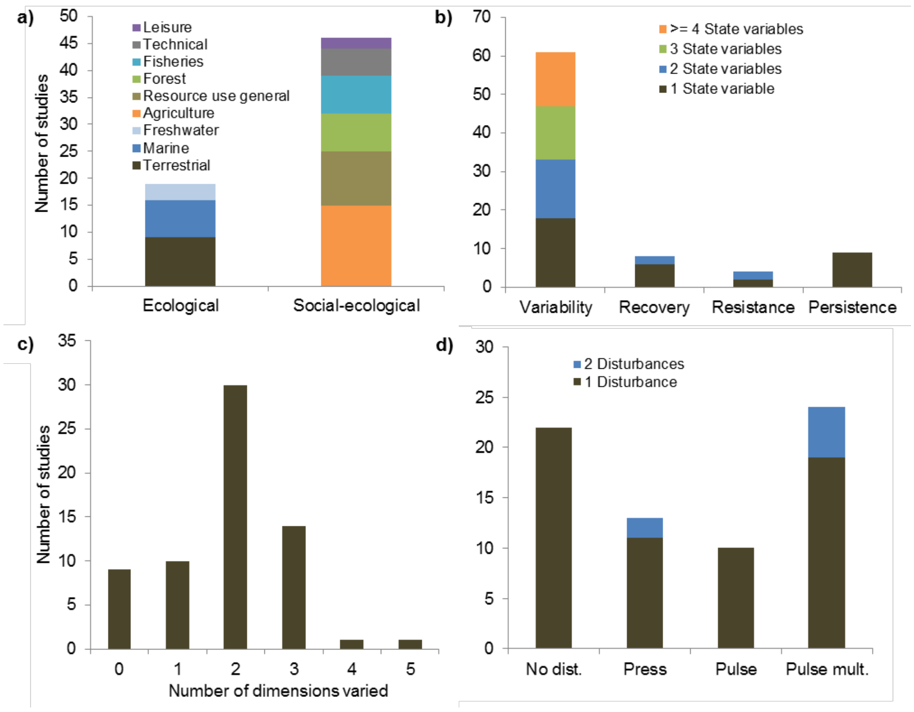

Fig. 2. (a) Overview of the systems investigated in the 65 reviewed articles. (b) The number of studies measuring the stability properties variability, recovery, resistance and persistence. (c) The number of dimensions of specific situations varied in each study. (d) The number of studies investigating no disturbance, press, pulse or multiple pulse disturbances.

4 Discussion and recommendations

Using the concept of resilience to guide the sustainable management of complex ecological and social-ecological systems is attractive and has been called for by international organizations. However, there are two main challenges. First, resilience is a multidimensional concept necessitating the measurement of several stability properties for different state variables, reference states, disturbance types and spatio-temporal scales (Carpenter et al., 2001; Grimm and Wissel, 1997). Second, measurement of several stability properties is prohibitively costly in empirical and experimental conditions. In this context, ABMs provide a solution by allowing for an extensive exploration of the multidimensionality underlying resilience at relatively low costs.

Despite the suitability of ABMs to study resilience, agent-based modelling is not a panacea to resilience research and has to overcome several challenges. ABMs have been criticized for their high complexity and uncertainty, and the consequent lack of predictive power, validation and verification (Bankes, 2002; Grimm and Railsback, 2005; Lempert, 2002; Matthews and Gilbert, 2007; Parker et al., 2003). ABMs and models in general cannot capture the full complexity of real agent-based systems. Therefore, reality checks with targeted empirical research and observations, narratives of events and mechanisms that are not captured in data sets, and “expert judgements” can be critical (Millington et al., 2012; Topping et al., 2015). Moreover, tools and approaches have been developed to increase rigor and comprehensiveness of agent-based modelling (Grimm et al., 2005), as well as to improve modelling practice to better inform decision making (Grimm et al., 2014; Schmolke et al., 2010).

Our review demonstrates that ABMs studying most dimensions of resilience and specific situations have been developed, which provides insight into the resilience of the modelled systems as well as the mechanisms underlying it. However, our review also indicates that most of these dimensions have been studied in isolation. Therefore and based on the overall progress that has been made in agent-based modelling over the last 20 years, or so (An, 2012; Epstein, 2006; Farmer and Foley, 2009; Grimm and Berger, 2016a, 2016b; Matthews and Gilbert, 2007), we here make three recommendations to advance ABM as a tool for resilience research in ecology and socio-ecology (Table 2). These are heuristics rather than specific methods or techniques, but we nevertheless hope that they help broadening the scope of future studies.

First, we recommend quantifying two or more stability properties simultaneously. The fact that resilience cannot be addressed with a single metric needs to be better addressed in ABMs because the different stability properties are not necessarily correlated (Dey and Joshi, 2013; Hillebrand et al., 2018; Tung et al., 2016), and measuring only one stability property can mislead the management actions. For example, Naghibi and Lence (2012) found that the impact of high flow events due to river management on salmon population during the spawning period materialized much earlier regarding recovery than regarding resistance. Therefore, just looking at resistance would underestimate the long-term impacts of high flow events, e.g., as a result of opening a floodgate.

Regarding variability, instead of only looking at the change of a variable over time, the coefficient of variation can be better compared among studies as it is independent of the magnitude and allow for a closer integration of modelling and empirical research, where this metric is commonly used (Donohue et al., 2016). On a related note, we encourage modellers to address resistance in their resilience assessments, which is often measured in empirical and experimental studies, albeit mostly in laboratories and simplified, small systems. Only combined efforts and the use of identical stability properties by empiricists and modellers will truly advance our understanding of resilience and its application. Moreover, we suggest to not only looking at the change of the state variable, but also at the behaviour of the underlying buffer mechanisms, which has been hardly done in the reviewed studies. These buffers may typically respond slowly, but can lead to nonlinear changes or regime shifts once a certain threshold is exceeded (Biggs et al., 2012).

Regarding persistence, a system definition is required. For population this is straightforward in principle, because extinction clearly defines how long a population persisted. For real populations however, quasi-extinction may be more relevant (Holmes et al., 2007), because it is usually impossible to show that a population really went extinct, so that detection thresholds need to be defined. Also for communities and ecosystems, the definition of such thresholds is required. The arbitrariness of such thresholds can be reduced by their systematic variation, while looking for abrupt changes in characteristics, functions, or services of a system. For semi-arid savannas, for example, 20% tree cover is a generally accepted threshold, because higher values indicate bush encroachment due to overgrazing, which will lead to the loss of the service “rangeland” (Jeltsch et al., 1997).

Second, we propose to assess stability properties from different perspectives, i.e. under different specific situations. This is important for both an improved understanding of resilience, and the reconciliation of different management and policy objectives (Donohue et al., 2016). Our review revealed that most models only consider a few specific situations. Once a model of adequate complexity exists and has proven to be structurally realistic (Grimm and Railsback, 2012; Wiegand et al., 2003), many specific situations can be assessed, which will provide more comprehensive insights into resilience. For example, a static reference state may be appropriate for a pulse disturbance, but including a press disturbance requires a dynamic reference. Moreover, several state variables describing different levels of organization often respond differently to changes and may require different reference states. For example, Cordonnier et al. (2008) applied a management perspective to assess the protective ability of managed forests stands against avalanches and rock falls, by measuring how long several threat-specific state variables stayed within favourable reference states. They found that only relatively low thinning intensities protect against both threats, i.e. multiple dimensions needs to be observed to guide proper management. Similarly, only a systematic combination of various disturbances, potentially acting on different scales, allows to disentangle multiplicative, synergistic and antagonistic effects (Belarde and Railsback, 2016). Likewise, varying the spatial scale, in particular the size, of the modelled system is a simple but often rewarding exercise, which is often ignored. Exploring variability, recovery, or persistence for different system sizes can lead to surprises because certain mechanisms may unfold only at larger scales, or break down at smaller ones (Cumming et al., 2016).

Third, we advocate starting model-based resilience analysis with hypotheses about underlying resilience mechanism and how one could quantify their effects. Many resilience mechanisms have been proposed, but if, how and when they render a system resilient remains often unclear (Biggs et al., 2012; Desjardins et al., 2015), for instance, regarding the role of biodiversity for the resilience of complex systems (Cardinale et al., 2012). Since many of the assumed mechanisms, such as learning and adaption, are related to individual variation, interactions, decision-making and feedbacks, ABMs offer a promising tool to uncover them. To this end, we manipulate, or even deactivate a given mechanism, for example recolonization, social influence on land use practices, or learning, and explore how the different dimensions of resilience change, across different situations. Ten Broeke et al. (2017), for example, found that adaption through inheritance of specific traits (harvesting and moving rates) could prevent the collapse of a stylized common-pool resource system.

A stronger focus on resilience mechanisms can, in principle, reconcile the reductionist and holistic interpretations of resilience to some degree: adaptive capacity, for example, would no longer only reflect a way of thinking or dealing with agent-based complex systems, but we could quantify the effects of adaptive capacity on resilience (measured by the three stability properties) and compare it with other possible resilience mechanisms.

In conclusion, we found that that the reviewed studies typically focus on a single dimension of resilience by using variability as a proxy for persistence, and are limited to one reference state, disturbance type and scale. Moreover, only few studies explicitly test the ability of different mechanisms to support resilience. Therefore, we suggest that it is time to move on from focusing on a single attribute of resilience to reveal the multidimensionality of resilience, especially given that ABMs provide a unique opportunity for doing so backed up by increasing computational power. In particular, we propose using ABMs to systematically assess multiple stability properties for different situations, while explicitly testing the effect of potential resilience mechanisms. The recommendations presented here will hopefully promote a more systematic and comprehensive exploration of the multiple dimensions of resilience in ABMs. Such advancement will foster the understanding of the mechanisms determining resilience, which is fundamental to safeguard ecosystem services and to ultimately ensure sustainability.

Table 2 Main recommendations to advance agent-based modelling as a tool for resilience research in ecology and socio-ecology.

Aspect	Recommendations
Stability properties	• Quantify multiple stability properties simultaneously, because they are not necessarily correlated • Consider to measure variability as coefficient of variation (ratio of standard deviation to mean) for better comparison among studies and closer integration of empirical research • Measure the behaviour of the underlying buffer mechanisms, as they can lead to nonlinear changes or regime shifts • Define systems to assess persistence, e.g. by systematically identify thresholds to measure quasi-extinction
Specific situations	• Assess stability properties for different situations to foster a more comprehensive understanding of resilience • Assess the stability properties for several state variables describing different levels of organizations to account for different conclusions about resilience • Use a dynamic reference state for press disturbances to account for long-term changes • Systematically combine various disturbances with different strengths and acting on different scales to disentangle multiplicative, synergistic and antagonistic effects • Explore stability properties for different temporal and spatial scales, because certain mechanisms may unfold only at larger scales, or break down at smaller ones

Resilience mechanisms	• Identify potential resilience mechanisms • Explicitly test and manipulate mechanisms to see if, how, and under what conditions they render a system resilient

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Supplementary materials

6.1 Review methods and definitions

While we included some additional articles (see main text), we did not attempt a full "snow ball search", i.e. checking the reference lists of all articles found for further relevant publications. The list of all evaluated and excluded papers is provided in the Supplementary material. For the purpose of this review we define scenarios as various instances of the same model used to assess system's response to targeted changes (e.g. contrasting policies, structural and procedural changes, and targeted parameter changes). We disregarded scenarios only varying disturbances, to clearly distinguish scenarios and disturbances. Regarding disturbance, we differentiate pulse disturbances following Pickett and White (1985, p. 7), multiple pulse and press disturbances. A pulse disturbance has a beginning and an end, is short relative to the typical time scale of change of the system considered, and has consequences beyond its duration. Multiple pulse disturbances overlap with "disturbance regimes" (e.g. continuous vs. rotational grazing), which are characterized by the frequency and spatial extent of disturbances in a certain region (Turner, 2010). Contrastingly, a press disturbance permanently changes system drivers or structure. For all disturbance types, we only considered physical changes, while socioeconomic changes (e.g. price shocks, policy changes) were considered in scenarios.

6.2 Supplementary results

Stability properties

If excluding variability, only two studies investigated more than one stability property. Naghibi and Lence (2012), for example, assessed different properties of fish population size; population variability, the time until the initial population recovered after a high flow event, and the population differences between the disturbed and undisturbed state (amplitude, which may indicate resistance). Recovery was quantified mostly via return time to pre-disturbance conditions, except for Balbo *et al.* (2014), who quantified the maximum amplitude allowing for recovery of hunter-gatherer populations under climatic changes. Resistance was measured as the amplitude between a disturbed and non-disturbed state (Naghibi and Lence, 2012), as the reaction time relative to the appearance of a disturbance (Dressler et al., 2016), as the deviance from a baseline scenario under different mechanisms potentially enhancing resistance (Rasch et al., 2016; Smith, 2014), or as economic buffer capacity (Rasch et al., 2016). Persistence was typically determined by the rate or probability of extinction of the population of interest in the entire system, except Cordonnier et al. (2008), who measured the time spend within favourable ranges of different state variables ("permanence"), and Johnson (2009), who interpreted changes in characteristic length scales as range shifts.

Specific situations

In total, 30 studies varied two dimensions of specific situations, typically the level of organization and state variable (n=24). Only 14 studies varied three dimensions, of which all, except two, included level of organization and state variable. Four and five dimensions were varied in one study each. Johnson (2009) used different window sizes to assess natural length scales of complex systems (landscape level) and species composition (community level) across two different disturbances (patch clearing and species invasion). Cordonnier et al. (2008) defined different reference states for three different state variables on different levels of organization, which were used to assess the response of forests to two different disturbances (random and gap thinning) acting on different spatial extents.

In 74% of the studies, at least two state variables were quantified. Most studies considered demographic (e.g. population size, sex ratio), ecological (e.g. diversity, plant cover, biomass) and economic (e.g. income, yield) variables. In total, 38 studies assessed more than one level of organization. Fujii et al. (2009), for example, investigated the resilience of subtropical forests on three different levels. They measured diameter at breast height (individual level), species diversity and composition (community level), and biomass (ecosystem functioning).

Reference states were not defined in almost half of the studies (n=29). Eight studies defined static reference states (e.g. landscape configuration before a disturbance), one study included static and dynamic states, while the remaining 27 studies compared the simulations against a dynamic reference (e.g. baseline scenario). Only two studies included more than one reference state; Cordonnier *et al.* (2008) defined favourable value ranges of three indicators in addition to a dynamic baseline scenario, while Jenkins *et al.* (2017) compared eight experiments of insurance schemes and technical protection measures to reduce flood damage under future climatic conditions against the respective experiments under current climate (baseline).

Of the reviewed studies, 43 explicitly modelled disturbances, but only ten studies included more than one disturbance (nine studies included two and one study three). For example, Rammer and Seidl (2015) studied the impacts of multiple forest thinning, a single clear cut and global warming on timber production. Press disturbances, altering the system permanently, were investigated in 13 studies, such as climatic changes (Balbo et al., 2014; Janssen, 2010; Jiang et al., 2012; Perez et al., 2016; Rammer and Seidl, 2015; Rebaudo and Dangles, 2015; Reed et al., 2011; Smith, 2014), the exclusion of fish (Doropoulos et al., 2016; Mumby et al., 2016), invasion of a new species (Johnson, 2009), and exposure to chemicals and salt (Bi and Liu, 2017; Gabsi et al., 2014). Most studies assessed multiple pulse disturbances, e.g. multiple natural disasters (Charnley et al., 2017; Jenkins et al., 2017; Naghibi and Lence, 2012; Vincenzi et al., 2008; Vogt et al., 2014), climatic shocks (Dieguez Cameroni et al., 2014; Rogers et al., 2012), clearing or thinning (Cordonnier et al., 2008; Fujii and Kubota, 2011; Johnson, 2009; Kubicek et al., 2012; Rammer and Seidl, 2015; Soussana and Lafarge, 1998; Wakeford et al., 2008; Wild and Winkler, 2008), and fishing events (Kubicek and Reuter, 2016; Lindkvist and Norberg, 2014; Morrison and Allen, 2015; Piou et al., 2015; Schlüter and Pahl-Wostl, 2007; Vergnon et al., 2008).

Of the reviewed articles, only ten assessed resilience at more than one spatial scale. Of these studies, five varied the spatial extent of disturbances, for example, Kubicek et al. (2012) studied the effects of different diameters of a mechanistic disturbance on a coral reef community. Four studies applied the same model to different study sites (Dressler et al., 2016; Fujii et al., 2009; León and March, 2014; Vincenzi et al., 2008). In contrast, Ye et al. (2013) tested the effect of the configuration and number of habitat patches on population dynamics in fragmented landscapes. Johnson (2009) used different window sizes to assess natural length scales of complex systems.

Temporal scales were varied in 13 studies, of which eleven tested various durations of disturbances. Kanarek et al. (2008), for example, introduced a climatic disturbance leading to resource degradation for one, five or ten years to study its effects on foraging behaviour of geese. In contrast, Balbo *et al.* (2014) used precipitation models on different temporal scales to investigate scale-dependent disappearance of hunter-gatherers, and Christie and Knowles (2015) tested if different time scales affect their conclusions regarding the resilience of habitat corridors. Three studies combined both spatial and temporal scales. Wild and Winkler

(2008), for example, systematically varied the proportion and interval of krummholz removal to study its coexistence with grassland.

Resilience mechanisms

Resilience mechanisms could be identified in 56 articles, but were explicitly communicated in only 40 articles. Only about one quarter of the studies investigated potential resilience mechanisms directly. Bohensky (2014), for example, found that learning improved the success of water management strategies under variable water availability. Decelles *et al.* (2015) showed the importance of geographical connectivity for successful transportation of larvae transport. Schlüter et al. (2009) and Schlüter and Pahl-Wostl (2007) found that the use of multiple ecosystem services (response diversity) increased the economic and ecological performance of a river ecosystem providing fish and irrigation for agriculture. ten Broeke *et al.* (2017) revealed that adaption through inheritance of specific traits (harvesting and moving rates) could prevent the collapse of a common-pool resource system.

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