2018

Enhancing quantitative approaches for assessing community resilience

W. C. Chuang
U.S. Environmental Protection Agency

A. Garmestani
U.S. Environmental Protection Agency, garmestani.ahjond@epa.gov

T. N. Eason
U.S. Environmental Protection Agency

T. L. Spanbauer
U.S. Environmental Protection Agency

H. B. Fried-Peterson
Swedish University of Agricultural Sciences

See next page for additional authors

Authors
W. C. Chuang, A. Garmestani, T. N. Eason, T. L. Spanbauer, H. B. Fried-Peterson, C. P. Roberts, S. M. Sundstrom, J. L. Burnett, D. G. Angeler, B. C. Chaffin, L. Gunderson, D. Twidwell, and C. R. Allen

Journal of Environmental Management 213 (2018) 353–362

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

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W.C. Chuang [a], A. Garmestani [b,*], T.N. Eason [c], T.L. Spanbauer [a], H.B. Fried-Petersen [d], C.P. Roberts [e], S.M. Sundstrom [e], J.L. Burnett [e], D.G. Angeler [d], B.C. Chaffin [f], L. Gunderson [g], D. Twidwell [h], C.R. Allen [i]

[a] National Research Council, U.S. Environmental Protection Agency, 26 W. Martin Luther King Drive, Cincinnati, OH, 45268, USA
[b] U.S. Environmental Protection Agency, Office of Research and Development, 26 W. Martin Luther King Drive, Cincinnati, OH, 45268, USA
[c] U.S. Environmental Protection Agency, Office of Research and Development, 109 T. W. Alexander Drive, Research Triangle Park, NC, 27711, USA
[d] Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Uppsala, SE-750 07, Sweden
[e] School of Natural Resources, University of Nebraska-Lincoln, 103 Hardin Hall, 3310, Holdrege St., NE, 68583, USA
[f] W.A. Franke College of Forestry & Conservation, University of Montana, 32 Campus Drive, Missoula, MT, 59812, USA
[g] Department of Environmental Sciences, Emory University, 201 Dowman Drive, Atlanta, GA, 30322, USA
[h] Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE, 68503-0984, USA
[i] U.S. Geological Survey, Nebraska Cooperative Fish and Wildlife Research Unit, University of Nebraska-Lincoln, 103 Hardin Hall, 3310 Holdrege St., Lincoln, NE, 68583, USA

A R T I C L E I N F O

Article history:
Received 15 August 2017
Received in revised form
29 January 2018
Accepted 30 January 2018

Keywords:
Ecological resilience
Community resilience
Social-ecological systems

A B S T R A C T

Scholars from many different intellectual disciplines have attempted to measure, estimate, or quantify resilience. However, there is growing concern that lack of clarity on the operationalization of the concept will limit its application. In this paper, we discuss the theory, research development and quantitative approaches in ecological and community resilience. Upon noting the lack of methods that quantify the complexities of the linked human and natural aspects of community resilience, we identify several promising approaches within the ecological resilience tradition that may be useful in filling these gaps. Further, we discuss the challenges for consolidating these approaches into a more integrated perspective for managing social-ecological systems.

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1. Introduction

For over 40 years, resilience has become a major focus for academics and professionals responding to rapid changes in environmental, social, technological, and economic systems. Resilience is directly tied to the sustainability of human and natural systems and accordingly, has resulted in diverse approaches to its measurement and estimation across scientific domains. While opportunities now exist to learn from the quantitative methods used in different disciplines, the rise in popularity of the concept also means that resilience is often oversimplified and applied incorrectly (Angeler and Allen, 2016). Since the concept of ecological resilience was introduced to study social systems, there has been inadequate development of quantitative approaches for assessing community resilience. In addition, the absence of some key components of resilience in the existing community resilience literature, such as the identification of thresholds and cross-scale interactions limits the application of resilience science.

Community resilience is implicit in social-ecological resilience studies, and although there have been studies with detailed models of coupled social-ecological systems and defined measures (e.g., lakes - Martin and Schlüter, 2015; rangelands - Brunson, 2012, McAllister et al., 2006), these studies did not make community resilience explicit in the analysis. In this paper, we make community resilience explicit in our conceptualization of social-ecological systems and add to the literature by 1) synthesizing promising quantitative approaches for assessing ecological and community resilience, 2) identifying gaps and limitations in the existing literature of community resilience, and 3) highlighting areas where quantitative methods developed in ecological resilience can be used to expand the scope of community resilience. Moreover, we discuss the challenges of combining these approaches to provide a

* Corresponding author.
E-mail address: garmestani.ahjond@epa.gov (A. Garmestani).

https://doi.org/10.1016/j.jenvman.2018.01.083
0301-4797/Published by Elsevier Ltd.

more holistic assessment of social-ecological systems.

1.1. Ecological resilience

Ecological resilience is a measure of the amount of change an ecosystem can absorb before it shifts from one regime to a new regime characterized by a different set of processes and structures (Holling, 1973). Thus, ecological resilience expands upon the idea of single equilibria to include multiple regimes. Over the past several decades, there has been an increased focus on research in ecological resilience and many other concepts closely related to resilience (Donohue et al., 2013). One of the terms confused with ecological resilience is recovery, which is the time required for a system to return to equilibrium after a perturbation. Recovery was termed 'engineering resilience' by Holling (1996) to differentiate it from ecological resilience. Although recovery is an important component of resilience, it does not fully encompass ecological resilience, because it leaves out the essential property of multiple regimes and thus the possibility of regime shifts and transformations among different regimes. This point is critical, as this difference in understanding of the dynamics of social-ecological systems is one of the key differences between ecological and community resilience. In the literature, characterizations of community resilience typically do not account for the possibility of multiple regimes in social-ecological systems, and therefore reflect an engineering resilience perspective.

Engineering (and community) resilience can be depicted by a single regime (Fig. 1a), where the system condition varies within a "steady-state" represented by one basin of attraction, while ecological resilience is depicted as a complex landscape (Fig. 1b), with multiple basins representing alternate regimes. Although there has been theoretical and empirical development of the concept of ecological resilience (e.g., Gunderson, 2000), quantitative measures of resilience and the factors that contribute to its erosion are necessary for it to be valuable as a tool for ecosystem management (Angeler et al., 2016). Observations of regime shifts in social-ecological systems (see Gunderson and Pritchard, 2002) have served as case studies of ecological resilience, which resulted in a push to develop quantitative methods to assess ecological resilience (Folke et al., 2004). For example, many systems have been examined quantitatively using early warning signals (EWSs) of regime shifts in time series data (e.g., Carpenter and Brock, 2006; Dakos et al., 2008; Spanbauer et al., 2014), and in empirical studies in the lab (e.g., testing EWSs in microcosm experiments; Drake and Griffen, 2010), as well as assessing EWSs in whole lake ecosystem manipulations (Carpenter et al., 2011).

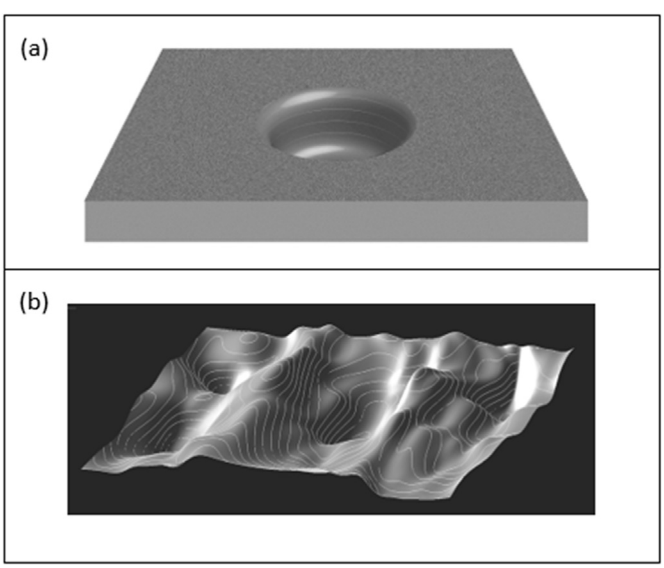

Fig. 1. A stability landscape heuristic illustrating the concept of resilience. a) A social-ecological system with only one possible regime (i.e., engineering resilience). b) A social-ecological system with many possible regimes (i.e., ecological resilience).

1.2. Community resilience

Timmerman's work on society's resilience to the impacts of climate change described resilience as "the measure of a system's or parts of a system's capacity to absorb and recover from the occurrence of a hazardous event" (Timmerman, 1981 P.21). Since then, this concept has been used to study aspects of resilience in human and social systems (Janssen, 2001; Manyena, 2006; Vogel et al., 2007). Later research expanded the definition of perturbation from natural hazards to any impact that may change the functions and structure of human society. Resilience at the human community level is therefore treated "as the ability of groups or communities to cope with external stress and disturbances when undergoing any social, political or environmental change" (Adger, 2000). In addition, some studies of community resilience largely focus on normative criteria. For example, Norris et al. (2008) defined resilience as "a process linking a set of networked adaptive capacities to a positive trajectory of functioning and adaption in constituent populations after a disturbance."

The general focus of community resilience has been to understand how individuals, households, and communities deal with internal or external forces of change without compromising their well-being. Berkes and Ross (2012) identified two major research strands of community resilience: psychological and social-ecological. In the psychological interpretation, "environment" often refers to the social, rather than the biophysical environment (Berkes and Ross, 2012). The majority of the literature emphasizes psychological well-being at the individual level, and a community member's ability to adapt under extenuating circumstances. In this context, the social-ecological approach to community resilience refers to the capacity of a system to continually change and adapt, and yet remain within specific (desirable) regimes (Berkes and Ross, 2012). Likewise, Walker et al. (2004) defined the term as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks." The central concerns of the social-ecological strand of community resilience include sustainable livelihoods and disaster resilience. In general, disaster resilience focuses on a set of capacities and strategies for disaster readiness (Norris et al., 2008). The purpose of disaster resilience research is to enhance the ability of a community to prepare and plan for, absorb, recover from, and adapt to adverse events in a timely and efficient manner, including the recovery and improvement of basic functions and structures of social systems (Cumming, 2011a; Cumming et al., 2005; Cutter et al., 2014; Gunderson, 2010; Manyena et al., 2011). In this realm of study, system impacts (perturbations) are usually natural hazards in general (Klein et al., 2003a), extreme events (Cutter et al., 2006, 2008, 2010, 2014) or coastal disasters (Adger et al., 2005; Klein et al., 2003b). Disaster resilience scholars are also concerned with the uneven adaptive capacities among populations and communities (e.g., lack of resources and financial and social capacity to cope with change).

Community resilience, with an explicit emphasis on social dimensions, recognizes that "human community relies on ecosystem services and natural resources for livelihood" (Adger, 2000). That is, a resilient community depends on sustainable livelihoods, and the loss of resilience is associated with negative impacts on livelihoods.

Therefore, this type of study focuses on identifying the factors (e.g., institutions and organizations that affect natural resource management) and linkages across organizational levels that could damage, sustain, or promote a community's livelihood. Research in this area is often linked to the vulnerability of agricultural/food systems to climate change. Examples include studies of livelihood security of farm communities in the developing world given the impact of economic and environmental change on a global scale (Eakin et al., 2009), and the study of economic returns (as thresholds) of dryland grain production systems with and without adaptation to climate change (Antle et al., 2004).

2. Measuring resilience

2.1. Approaches to assessing community resilience: conceptualization of community resilience

In the field of community resilience, researchers from different intellectual traditions frame the research questions and measure community resilience with a variety of metrics and approaches (Gallopín, 2006). Accordingly, the definition and measurement of community resilience remains contested in different academic disciplines (Adger, 2000; Angeler and Allen, 2016; Gunderson, 2010) and there is a lack of consensus on the methods for operationalizing community resilience. Due to the divergence, two major issues emerge: (1) there are no widely accepted or commonly used quantitative approaches for assessing community resilience; and (2) the existing quantitative methods are limited and do not reflect the dynamic and multifaceted characteristics of social-ecological systems. Before listing the quantitative methods for assessing community resilience, one must understand that community resilience is conceptualized using these metrics:

(a) Place-based resilience metrics: Some researchers have acknowledged the spatial aspects of community resilience and attempted to quantify a so-called “place-based” resilience index within a particular spatial unit (e.g., county, city) across various spatial extents, such as a nation or a state (Cutter et al., 2014; Frazier et al., 2013). Cutter et al. (2008) proposed a model to improve the comparative assessment of disaster resilience at the local or community level. The disaster resilience of place (DROP) model, especially its dynamic aspect, has remained an untested theoretical framework. Building on the DROP model, Cutter et al. (2014) created an empirically-based resilience metric known as Baseline Resilience Indicators for Communities (BRIC), and geographically visualized the sum of the resilience scores (Cutter et al., 2014; Frazier et al., 2013). The approach is useful to theoretically illustrate temporal changes in the resilience landscape by presenting time-series snapshots. However, other key aspects of social-ecological systems, such as thresholds, cross-scale interactions, and interrelationships between each component within scales, are not taken into consideration.

(b) Coupled social-ecological metrics: To conceptualize how components of social-ecological systems interrelate with each other at different scales, scholars have introduced tools from system dynamics and system complexity (i.e. Lewison et al., 2016) to study community resilience (Sendzimir et al., 2008, 2011). In a local-scale case study, Sendzimir et al. (2008) used data collected from participatory group discussion to identify stakeholder worldviews and the factors that supported or blocked the transformation from conventional river management. Ideally, the system dynamics approach offers a prototype to build quantitative models or simulations to better understand resilience. However, to date, the approach remains narrative-based, for it conceptually analyzes and describes the system's response to disturbances and shifts between regimes (Filatova et al., 2016; Sendzimir et al., 2008, 2011).

(c) Teleconnection metrics: To address non-linear dynamics in a nested system (Adger et al., 2009), Eakin et al. (2009) researched how vulnerabilities and responses of farm households in distinct geographic locations are linked through spatial and temporal cross-scale processes, called teleconnections. Although the concept of teleconnected vulnerability comprehensively engages the broader complexity of all cross-scale interactions, this approach is mainly assessed qualitatively, which limits the research's capacity to explore and quantify the magnitude of reinforcing and stabilizing feedbacks in a system. In addition, Akamani (2012) proposed a theoretical model of community resilience for understanding and assessing the sustainability of forest-dependent communities. The model captures external and internal drivers of change, which is useful for studying how factors interact across multiple scales to influence the process and outcomes of resilience between and within communities.

Community resilience has been deeply influenced by the intellectual debates framing vulnerability, global change and studies of natural disaster preparedness. Each of the aforementioned knowledge domain has its own research frame and set of methods to conceptualize community resilience, which has led to the lack of consensus on the quantitative approaches for assessing community resilience. In the following section, we discuss existing quantitative approaches for assessing community resilience.

2.1.1. Agent-based modeling and economic simulations

Agent-based modeling can be used to represent social-ecological systems (Hare and Deadman, 2004). Agent-based models are described as “robotic aggregates responding to a variable environment, or they simulate complex behavior of humans in social networks” (Jopp et al., 2011, p. 164). These models attempt to give researchers a coherent picture of how particular organisms would act under specific conditions (Jopp et al., 2011). As an extension, multi-agent models emphasize the interactions of a larger number of autonomously acting agents in a system (Jopp et al., 2011). This method has been used to inform ecosystem management (Janssen, 2001) and decision making in coupled human-natural systems (An, 2012). An advantage of agent-based modeling is that it can include the spatial dimension of community resilience by simulating the change of spatial patterns over time. This approach has been applied to study the collapse of an ancient society in northeastern Arizona, as determined by a sharp decline in human population (Axtell et al., 2002), and to explore social and biophysical dynamics that contributed to deforestation and forest regrowth (Evans and Kelley, 2008). The simulation scenarios can also help researchers identify the drivers that lead to regime shifts (Filatova et al., 2016). Similarly, Antle et al. (2004) used economic simulation models and coupled process models to explore the economic returns of farming, and use these returns as the threshold of a regime shift. Though simulation models can be a useful tool to gain a better understanding of social-ecological resilience, they do not fully represent reality, and validating model results can be challenging (Evans and Kelley, 2008).

2.1.2. Quantitative and mixed-methods approaches

Some research efforts assess community resilience using a mixed-methods approach, which combines quantitative and qualitative methods. Akamani and Hall (2015) used quantitative survey data of 209 households to test a resilience model for a forest-dependent community and investigated how type of institution, capital assets, and other social variables influenced households' participation in collaborative forest management (Akamani and Hall, 2015). Kelly et al. (2015) analyzed data from surveying twelve stakeholders at different spatial levels of representation and areas of expertise. Using published statistical data and historical records of land degradation, they were able to explain the complex interrelationships between community resilience, forest ecosystems and land degradation. Perz et al. (2012) assessed social-ecological resilience in the southwestern Amazon region using a similar approach. In addition to interviewing community members to gather information on their livelihood diversity, adaptive capacity (a community's emergency response to crisis, such as wild fire caused by drought), and collective memory of migration, they included the spatial assessment of connectivity (defined as proximity to markets and access to paved roads) as a measure of community resilience. Perz et al. (2012) quantitatively compared community resilience by region using 229 survey samples; however, this approach does not consider the changing status of a system, nor its feedbacks, thresholds, and regime shifts.

2.2. Quantitative approaches for assessing ecological resilience

Quantifying resilience has proven challenging, as much of the research on quantitative approaches for assessing ecological resilience has focused on the detection of EWSs that indicate an impending regime shift, rather than directly measuring the innate degree of system resilience at a given point in time (see Carpenter and Brock, 2006; Scheffer et al., 2015); however, a number of these approaches may be useful for assessing aspects of community resilience. In this section, we do not treat all the methods available, but rather methods for quantifying ecological resilience that appear promising for managing social-ecological systems.

2.2.1. Early warning signals

Early warning signals (e.g. critical slowing down and flickering) have shown great promise for quantifying ecological resilience. Critical slowing down is a measure of the recovery time of a system after it has been perturbed (Dakos et al., 2008). Detection methods for flickering, and other associated dynamics, have also been developed for assessing ecosystems. A system may "flicker" between alternative regimes far from any identifiable thresholds, meaning that critical slowing down is less likely to be detectable or present because the system is far from the equilibrium around which the slowing down happens (Dakos et al., 2013). Measurements of skewness, kurtosis, and mean exit time reflect flickering dynamics of highly stochastic systems.

Early warning signals can be univariate (e.g. a single species) or multivariate (e.g., a network of interacting species). These indicators can be either metric or model-based, with both approaches attempting to quantify changes in variance properties of a time series but differing in whether or not they attempt to fit the data with a specific model structure (Dakos and Bascompte, 2014). Many of the indicators developed to identify critical slowing down and flickering have been univariate in nature; they have focused on a single (or very few) variables that were known to respond to a particular disturbance (Brock and Carpenter, 2012). However, when the response variable is either unknown or chosen incorrectly, type I or II errors may result (Burthe et al., 2015). Indeed, there is much criticism in the ecological resilience literature of EWSs because many only reliably detect regime shifts after their onset (and thus too late for effective management), and their applicability to more complex systems is questionable (Biggs et al., 2009; Scheffer et al., 2009; Seekell et al., 2011, 2012; Spears et al., 2016). These problems have led to a new frontier of resilience research that emerged in an attempt to address some of the aforementioned issues. Multivariate indicators such as the Variance Index (VI) and Fisher Information (FI) were developed to assess change in complex systems using multivariate data combined into a single index, thus avoiding the need to know *a priori* which variable best captures the ecosystem dynamics driving a regime shift (Eason et al., 2014). The VI captures the dominant component of variance, while FI is more integrative and tracks the overall variability in system dynamics (Brock and Carpenter, 2006; Eason et al., 2016). FI is based on information theory which has proven useful in assessing ecosystem functioning, stability, complexity and diversity (Fath et al., 2003), retrospectively identifying regime shifts (e.g., Eason et al., 2016; Spanbauer et al., 2014) and more recently in examining spatial and temporal patterns in terrestrial and aquatic ecosystems (Eason et al., 2016; Sundstrom et al., 2017). Additionally, there is evidence that FI is capable of detecting impending regime shifts with more clarity and advanced warning when compared to traditional EWSs in complex, multivariate systems (Eason et al., 2014).

2.2.2. Cross-scale resilience model, discontinuity hypothesis and time series modeling

Early warning indicators and integrated multivariate indicators are intended to predict/identify regime shifts based on generic signals that occur across ecosystems. It has been argued that the reason some EWSs do not provide adequate warning is because they are not scale-specific, or they focus on the wrong scale (Nash et al., 2014). That is, EWSs do not account for the hierarchical organization of ecosystems, an inherent property whereby patterns and processes are manifested and operate at different scales of space and time.

Perhaps the simplest and most common method to quantify resilience is that of the cross-scale resilience model and its attendant discontinuity hypothesis, which explicitly incorporates scales (Angeler at el. 2016). Current approaches to identify scales based on the discontinuity hypothesis (Holling, 1992) complement EWSs. Aggregations of species (or modes) in body mass distributions reflect the scales at which resources and structure are available to organisms that have evolved to exploit resources at those specific scales (Nash et al., 2013; Stirnemann et al., 2015). In contrast, gaps (discontinuities or troughs) in the distribution reflect the transition between structuring processes and thus scaling regimes (Wiens, 1989). At these transitions, there is no ecological structure or resource pattern with which animals can interact, or there is great variance and instability in the structures or patterns (Allen and Holling, 2008). Countless systems have been successfully examined for discontinuities and/or multimodalities in animal body mass distributions, in line with the discontinuity hypothesis (Nash et al., 2013; Raffaelli et al., 2016; Sundstrom et al., 2012; Thibault et al., 2011; Wardwell et al., 2008).

Once discontinuities are identified, the distribution of functional groups within and across these aggregations can reveal the relative resilience of a system (of delimited spatial and temporal bounds) (Allen et al., 2005). A system with high within-scale diversity of function and high cross-scale redundancy of function is expected to have a higher capacity to buffer disturbances and remain in the same regime (Allen and Holling, 2002). Evidence continues to accumulate showing that it is functional richness across multiple scales rather than species richness that is critical for buffering capacity and the long-term persistence of ecosystems (Soliveres et al., 2016). Using discontinuity analysis to identify the intrinsic scales of biological communities may be combined with EWSs to pinpoint sensitive scales that may provide early warning signals of an impending threshold (Spanbauer et al., 2016).

Time-series modeling approaches to quantify resilience build upon discontinuity analysis and are designed to quantify the specific resilience of a particular community, such as a phytoplankton community's response to liming (Angeler et al., 2011; Baho et al., 2014). Discontinuity analysis can be used to make the within and cross-scale distribution of organisms explicit, which is the first step towards the quantification of resilience in the time-series modeling approach. Subsequently, dominant temporal frequencies in a community are identified and the distribution of species (and consequently their functions) within and across these scales can indicate the community's ability to buffer against disturbances and thus its resilience (Angeler et al., 2013).

2.2.3. Spatial resilience

Spatial resilience is the contribution of spatial attributes to the feedbacks that generate resilience in ecosystems and other complex systems, and vice versa (Allen et al., 2016). Where long-term data are not available or inference broader than a local case study is desired, spatial resilience is an important means of assessing resilience. Ecosystems have inherent spatial components and processes that influence resilience at multiple spatial scales (Allen et al., 2016; Cumming, 2011a, b; Nyström and Folke, 2001; Zurlini et al., 2014). Cumming (2011b) posited that spatial resilience is governed by interacting spatial characteristics across scales, such as spatial diversity and heterogeneity of components and processes that comprise systems, spatial connectivity within and outside the system, and how components and processes interact across spatial scales. The concept of system memory also plays a role: after a disturbance, restoration to the previous state will be more likely if spatially-connected areas maintain pre-disturbance components and processes (Cumming, 2011b; Nyström and Folke, 2001).

Although approaches to quantifying spatial resilience are relatively unexplored, several methods appear promising (e.g., Angeler and Allen, 2016; Cumming, 2011a, b; Sundstrom et al., 2017). In landscape ecology, metrics such as spatial heterogeneity, fragmentation, and cross-scale structure influence the persistence of ecosystems in space and could serve as resilience indicators (Cumming, 2011b; Nyström and Folke, 2001). Metrics estimating connectivity of land cover/land use types can also indicate spatial resilience. For instance, Zurlini et al. (2014) showed that resilience eroded in an Italian rural-urban socio-ecological system as connectivity and homogeneity of intensive agricultural and urban cover types increased. Network theory has potential for assessing spatial resilience at local scales (i.e., at individual nodes such as cities) and at broad scales (i.e., between nodes such as cities within a region; Allen et al., 2016). Estimating cross-scale resilience and discontinuity patterns in space can assess the distribution and scale at which ecological functions occur across spatial extents (Göthe et al., 2014) and provide warnings of low resilience when functional redundancy across scales is reduced (Göthe et al., 2014; Peterson et al., 1998). Spatial modeling can also untangle the relative importance of dominant and rare species, and it has been suggested that this contributes to a more detailed picture of resilience as rare species can maintain critical functions in ecosystems by replacing dominant species after perturbations (Angeler et al., 2015).

3. Applying ecological resilience methods to community resilience assessments

There is limited consensus on the methods for assessing critical aspects of resilience and accordingly, there is a prevalent need to clarify the concepts and approaches to maximize the utility and application of the concept. In this work, we discussed the theory and some of the quantitative approaches from ecological and community resilience that may be useful for assessing social-ecological systems (Table 1). Since there is limited development and application of approaches for quantifying community resilience, we synthesize our findings by considering quantitative approaches primarily employed in ecological resilience. These quantitative approaches developed in ecological resilience appear useful for assessing the complexities inherent in community resilience, and articulating active ways of bridging ecological and community resilience to better assess and manage change in coupled human and natural systems.

3.1. Employing EWSs in community resilience

Although ecological resilience was defined more than forty years ago (Holling, 1973), the exponential increase in related research only began in the early 2000s. Previous studies have provided helpful conceptual frameworks to study community resilience, but their application, and quantitative methods that facilitate early intervention, remain rare. Though statistical methods have existed for decades in ecological resilience, their application has been primarily limited to assessment of ecological regime shifts (Andersen et al., 2009; Filatova et al., 2016). However, it is important to understand that social-ecological systems can exist in alternative regimes, which has important implications for community resilience as well (Allen et al., 2014). Despite the challenges presented by insufficient data or the desire for long term temporal studies (Hicks et al., 2016; Nyström and Folke, 2001), some EWSs have been applied to assess aspects of resilience including regime shifts in coupled human and natural systems (e.g. Eason and Cabezas, 2012; Gonzalez-Mejia et al., 2014; Karunanithi et al., 2011; Spielmann et al., 2016; Vance et al., 2017). For example, Spielmann et al. (2016) used EWSs for research on the change of human settlement size and social institutions under the impacts of climate change and population relocation in the prehistoric U.S. Southwest from 1050 AD to 1375 AD. They detected critical slowing down before social transformation and concluded that EWSs are useful for anticipating social change. While these studies capture inherent change in community dynamics and structure (e.g., population growth, land and energy use, economic activity), most of them do not include many of the factors of concern within the community resilience literature (e.g., vulnerability, diversity, hazard management).

Indicators developed to identify and predict these thresholds in ecosystems need to be easily interpretable and broadly applicable if they are to serve a practical and not just purely theoretical purpose. While EWSs are powerful tools due to their ease of application, the outstanding questions regarding their utility indicates that there is still more research needed in this area. Some of the challenges include the fact that: (1) depending on the dynamics of the system, some EWSs fail to produce a signal prior to a regime shift (Dakos et al., 2015), (2) regime shifts can occur with no EWSs (Hastings and Wysham, 2010), and (3) EWSs may produce a signal when no critical transition has occurred (Burthe et al., 2015). To combat some of these challenges, Eason et al. (2016) recommend the use of multiple quantitative approaches to compare, validate and augment system evaluations. Moving forward, managing resilience in social-ecological systems will require novel characterizations of system behaviors, and will need to take into account the various actors involved in buffering disturbances (Green et al., 2015).

3.2. Accounting for scale in community resilience

Within regimes, ecological and social systems are characterized

Table 1
Similarities and differences between ecological resilience and community resilience.

Theme	Definition	Characteristics	Focus on	Context	Approaches and example references
Ecological resilience	Measure of the amount of change needed to change an ecosystem from one set of processes and structures to a different set of processes and structures (Holling, 1973; Angeler and Allen, 2016)	Diversity, variability, modularity (scales), cross-scale interactions	Multiple regimes, multiple scales, adaptive and transformative capacity	Alternative regimes, ecosystem change	EWS, regime detection (Eason et al., 2014; Dakos et al., 2015; Spanbauer et al., 2016; Sundstrom et al., 2017), discontinuity analysis (Nash et al., 2013; Raffaelli et al., 2016)
Community resilience	Many definitions, examples include: 1. "The measure of a system's, or part of a system's capacity to absorb and recover from the occurrence of a hazardous event" (Timmerman, 1981). 2. "Qualities of a community, stemming from everyday processes, that might enhance or detract from its ability to prepare for, respond to, recover from and mitigate environmental hazard events" (Cutter et al., 2014). 3. "The ability of groups or communities to cope with external stress and disturbances when undergoing any social, political or environmental change (Adger, 2000)." 4. "...involves a regime change in which the structures, processes, and identity of a community either evolve into a more desired configuration or developed into a less desirable state (Gunderson, 2010)"	Diversity, variability, maintaining system functions, vulnerability	Recovery of human systems, sustainable livelihoods, disaster preparedness, the ability to cope with change	Disaster management, global environmental change, collapse of societies	Agent-based modeling (Janssen, 2001; Axtell et al., 2002), conceptual frameworks (Cutter et al., 2014); EWSs (Spielmann et al., 2016), economic simulations (Antle et al., 2004)

by multiple spatial scales and processes operating at different speeds (temporal scales) (Allen et al., 2014). Furthermore, regimes can exhibit multiple scales in the structure of their components, as for example, cities cluster into discrete size classes within regions (Garmestani et al., 2009). A fundamental difference between ecological and community resilience is the manner in which each treats scale (Gunderson, 2010). In practice, community resilience has only been concerned with one level in a system; the scale of a community (e.g., city; neighborhood) (Berkes and Ross, 2016) (Fig. 2) and is specifically focused on return time to a former regime post-disturbance. On the other hand, ecological resilience accounts for the possibility that return may not be possible, and a system may reorganize into a completely different regime. Without explicit consideration of scale, cross-scale interactions, or regime shifts, the impacts go unnoticed and unchecked until the consequences manifest.

The dearth of longitudinal data and lack of consistently measured social variables makes the detection of cross-scale patterns of change a difficult task in community resilience. One way to address this problem is to take advantage of existing methodologies that explicitly incorporate scale (Angeler et al., 2016). Discontinuity analysis uses proxies such as population size to identify scales in relevant systems, and account for cross-scale interactions in social-ecological systems. To date, there have only been a few studies which attempted to detect discontinuous patterns in human systems; the key system variables used in those studies included city size measured by population (Garmestani et al., 2005, 2007, 2008), firm sizes and their functional richness (Garmestani et al., 2006), and gross domestic product (GDP) (Sundstrom et al., 2014) with temporal coverage from a single year to several decades.

To study community resilience comprehensively, researchers need to consider a community's capacity to respond to change and where possible, the mechanisms and processes that drive regime shifts in these social-ecological systems. Ideally, these core concerns should be addressed across spatial and temporal scales. Ecological resilience is useful for describing social-ecological interactions at multiple scales, but hasn't been explicitly employed in most studies of community resilience. Applying discontinuity analysis in community resilience studies offers a way to gain a better understanding of changes in structure and function of social-ecological systems. With sufficient time-series data, future studies can explore spatial patterns in the analysis including possible spatial autocorrelation (clustering), and observe how the spatial and temporal distribution of results adjusts to disturbance and loss from natural disasters. Future studies could apply scale-dependent discontinuity analysis in analyzing, for example, farm lot size, farm size (i.e., amount of labor and investment), diversity of agricultural products, or productivity per land area or per capita, as a way to move beyond the limitations of current community resilience approaches. Identifying discontinuous distributions in social-ecological systems may provide early opportunities for managers to intervene or develop the ability to reorganize before a system passes a critical threshold (Spanbauer et al., 2016).

3.3. Considering spatial connectivity in community resilience

One of the key tenets of systems thinking is the idea that no action exists in isolation; hence, it is possible for events/actions to have cascading effects through processes, time and particularly in this context, space. The inherent spatial connectivity and

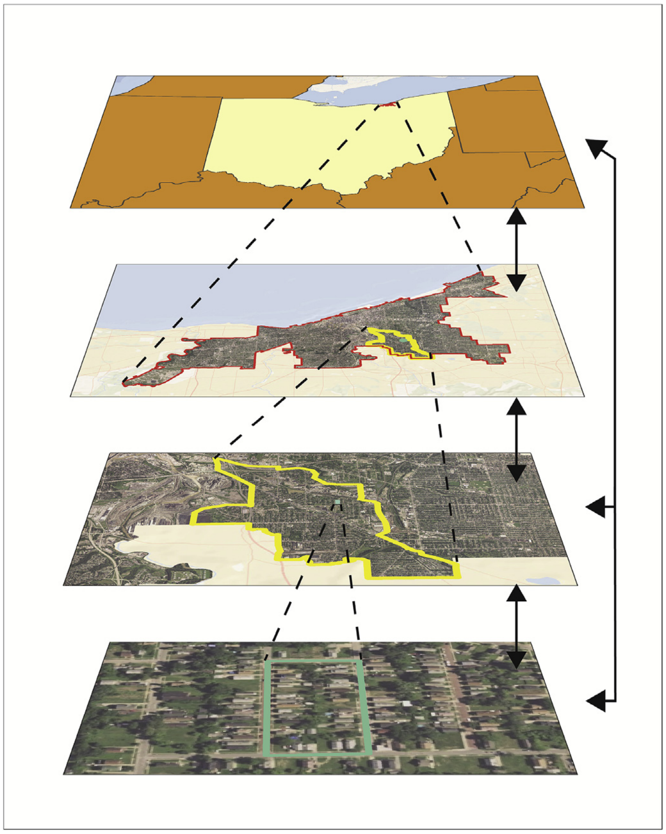

Fig. 2. Illustration of cross-scale effects. Ideally, assessment of community resilience should consider multiple scales and cross-scale interactions in a social-ecological system. The finest scale to the largest scale in this figure are: A city block in the Slavic Village neighborhood, the Slavic Village Neighborhood, Cleveland, Ohio, and the State of Ohio, USA.

interactions of human communities across city, regional, and national scales (Marcus et al., 2014; Perz et al., 2012), the cross-scale spatial structure of communities (Fig. 2), and the spatially intertwined nature of social and ecological systems make considering spatial aspects of community resilience essential (Angeler and Allen, 2016). However, many resilience indicators rely on high resolution long-term data which, for many systems, is neither available nor a reasonable expectation in the near future. This has restricted the scale and scope of the quantification of resilience in the field (i.e., small freshwater lakes, coral reefs, and grasslands), and has resulted in experimental studies focused on simple organisms (Dai et al., 2012). Holling and Goldberg (1971) pointed out that the current state and range of responses of both ecological and social systems are driven, in part, by a succession of historical events and the system's spatial linkages.

Recent connections between spatial resilience and the ecological sub-discipline of landscape ecology offer opportunities to quantify resilience with available, high-resolution spatial data. In landscape ecology, spatial heterogeneity, fragmentation, and cross-scale structure are known to influence the persistence of ecosystems in space (Mayer et al., 2016; Cumming, 2011b). Landscape connectivity can also aid in restoration to previous regimes following a disturbance via dispersal, gene flow, demographic rescue, nutrient/habitat replacement, flow of resources/knowledge, etc. (McRae et al., 2012). Because social systems often have implicitly spatial components and processes, such as social networks and urban morphology, using these same landscape ecology spatial metrics could help in quantifying spatial community resilience (Cumming, 2011a; Marcus et al., 2014). For instance, greater spatial connectivity between marginalized communities and social resources can lead to increased resilience; but greater connectivity between marginalized and dominant cultures can also lead to social turnover and loss of traditional knowledge, which can lead to degraded resilience as social systems lose their identity and homogenize (Cumming, 2011a; Perz et al., 2012). Thus, connectivity within and across social-ecological landscapes can indicate spatial resilience; however, over-connectedness and homogeneity in some social-ecological systems (e.g., urbanized and intensely-managed agricultural lands) may signal a loss of resilience and the potential for natural disturbance to push both the social and ecological parts of the system into an alternate regime (e.g. desertification; Zurlini et al., 2014).

4. Conclusion: connecting ecological and community resilience

The interaction between ecological and social factors is key to understanding the resilience of coupled systems of humans and nature, and many studies of the resilience of social-ecological systems attempt to integrate social and ecological systems. For instance, scholars have described how the increase of nutrient loads and reductions in oyster populations due to human activities and human population growth caused a shift from a clear water benthic ecosystem to a plankton-dominated ecosystem regime in Chesapeake Bay (Curtin et al., 2001; Hicks et al., 2016; Kemp et al., 2005). However, there has been little effort made to integrate ecological components into community resilience (or view them in context with each other). Incorporating biophysical (or environmental) variables into current community resilience studies is essential to enhancing our understanding of the complex interactions between humans and the environment. Examples of variables for supplementing community resilience could include: biodiversity, % of land conversion over time (i.e., from rural, or from natural landscape to the built-up environment), and land fragmentation metrics.

In this paper, we treated some promising quantitative approaches for assessing ecological and community resilience. Significant research has been conducted on understanding resilience in the context of ecosystems and communities separately. A critical step now is bridging our understanding between and amongst disparate resilience disciplines. We have attempted to illuminate some of those differences, and suggested ways for moving resilience research and application forward. Moreover, we acknowledge limitations and opportunities within these disciplines. While the literature on ecological resilience is well established, there are a number of open research questions on measuring and operationalizing the approaches that are critical for advancing the application to emerging challenges (e.g., harmful algal blooms). Though there is no consensus on the definition and approaches for assessing community resilience, the concept continues to evolve from a single-state, equilibrium-based definition (e.g., "recovery" from Timmerman, 1981) into a more dynamic, and non-equilibrium-based viewpoint, influenced by research on social-ecological systems (e.g., Adger, 2000; Walker et al., 2004; Spielmann et al., 2016). By assessing relatively well-developed methods for quantifying ecological resilience, we identified approaches that can be used to quantify community resilience based on a more holistic view of social-ecological systems. These approaches include applying consistent and quantifiable metrics to assess community resilience, establishing long-term monitoring and data collection efforts, and considering scale and cross-scale dynamics in system evaluations.

In an effort to respond to an expanding suite of global challenges, we submit that it may be possible in future research to catalyze the convergence of ecological and community resilience into an integrated approach by facilitating a deeper understanding of coupled human-natural systems, and we hope this paper has moved us closer to that goal. Human societies and the environments they inhabit are incapable of being disentangled, therefore, it is essential that we gain a holistic understanding of how the resilience of each is deeply intertwined. This research effort is not intended to be exhaustive but is indicative of the type of synergy and cross-disciplinary cooperation needed to manage problems and promote sustainability in our increasingly complex and interconnected world.

Acknowledgements

The authors would like to thank Michael Harrison from the University of Nebraska–Lincoln for creating Fig. 1b. This research was performed while TLS and WC held NRC Research Associateship awards at the U.S. EPA. Financial support from the Swedish Research Councils FORMAS (2014-1193) and VR (2014-5828), and the August T. Larsson Foundation of the Swedish University of Agricultural Sciences is acknowledged. The Nebraska Cooperative Fish and Wildlife Research Unit is jointly supported by a cooperative agreement between the United States Geological Survey, the Nebraska Game and Parks Commission, the University of Nebraska–Lincoln, the United States Fish and Wildlife Service, and the Wildlife Management Institute. The views expressed in this manuscript are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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