Resilience and Complexity

A Bibliometric Review and Prospects for Industrial Ecology

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Summary

Resilience is an increasingly popular concept in academic research and public discourse and is closely connected to complex systems theory. This article reviews research on resilience and complexity in industrial ecology and the broader academy by conducting a bibliometric analysis of the academic literature over a 40-year period (1973–2014). The review revealed a large body of scholarship composed of five clearly identifiable intellectual communities, with resilience theory from ecology especially influential. Based on the study of ecosystems, these scholars conceptualize resilience as a dynamic and adaptive property of systems with multiple stable states that evolve over time. In comparison, resilience research in industrial ecology is limited and underdeveloped. Bibliometric analysis of this literature yielded just 37 publications and a scholarly network with no well-formulated research communities. This contrasts with industrial ecology scholarship on sustainability; a similar search yielded 1,581 publications. Given the emerging importance of the resilience concept and its relevance for sustainability issues, industrial ecology should expand research efforts in this area. The growing body of industrial ecology scholarship on complex systems provides a foundation to do so, as does the field's long-standing practice of using ecological principles to inform the study and design of industrial ecosystems. The article concludes by discussing how industrial ecology would benefit from incorporating principles of dynamic resilience and, conversely, how industrial ecology approaches could advance broader resilience scholarship.

Introduction

In the academy and in public discourse, there has been a remarkable rise in the use of the term "resilience" (figure 1). Referring to the ability to recover from or adjust to a disturbance or change, resilience thinking is permeating an ever-broadening array of disciplines and thought traditions, including social-ecological systems (Folke et al. 2002; Carpenter et al. 2001; Walker et al. 2004), psychology (Bonanno 2004; Luthans et al. 2006), disaster and risk management (Coaffee 2008; Cutter et al. 2008; Gaillard 2010; Rose 2007), hazards research (Godschalk 2003; Klein et al. 2003), climate change adaptation (Nelson et al. 2007; Tyler and Moench 2012; Tanner et al. 2009), urban planning (Ahern 2011; Wilkinson 2011), international development (Perrings 2006; Brown and Westaway 2011), engineering (Fiksel 2003, 2006; Hollnagel et al. 2006), and energy systems and planning (McLellan et al. 2012; Molyneaux et al. 2012). This proliferation is apparent in policy arenas as well, including within agencies of the United Nations (UN), networks of local governments, such as ICLEI (International Council for Local Environmental Initiatives), and nongovernmental organizations, such as the World Wildlife Fund (Evans 2011).

In this era of tremendous social, ecological, and technical change and uncertainty, highlighted by the wide-ranging effects of globalization processes and climate change, the notion

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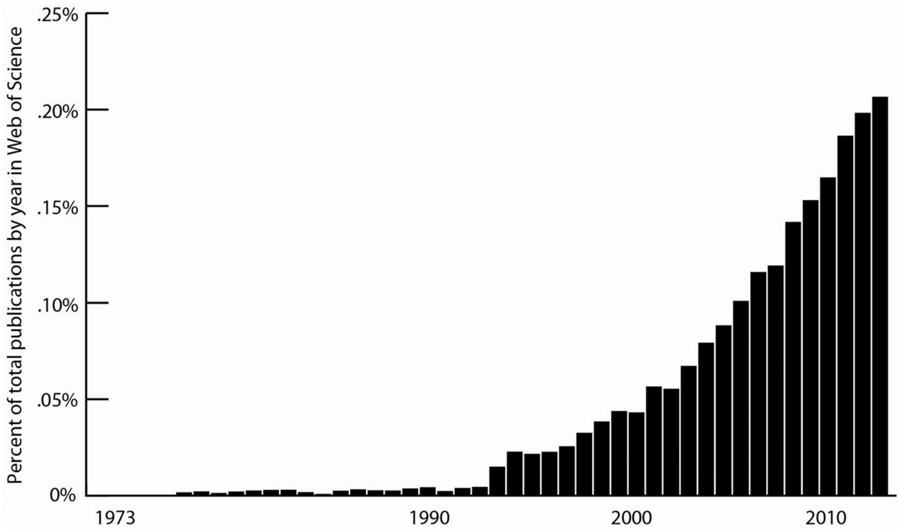

Figure 1 Rise of resilience in the literature (1973–2014). The figure represents the percentage of publications per year containing "resilience or resilient or resiliency" in the title, abstract, or keywords. *Data from*: Web of Science (2014).

of resilience has become an especially attractive feature of a wider sustainability agenda (Fiksel 2006; Vale 2014). As Cascio (2009, 92) writes, resilience theory "accepts that change is inevitable" and therefore it focuses attention "on the need to be able to withstand the unexpected." In contrast to similar terms that relate to coping with uncertain or changing futures, such as vulnerability or adaptation, resilience has a more positive societal connotation and is therefore arguably more politically tractable (Shaw and Maythorne 2012; McEvoy et al. 2013; Swim et al. 2011; O'Hare and White 2013).

There is also growing recognition that many systems, from ecosystems to expanding megacities to an increasingly interconnected global economy, are highly adaptive and complex (Anderies et al. 2013). More than simply being complicated, complexity refers to how systems exhibit patterns that emerge from interactions between individual components in unexpected and nonlinear ways. Complex adaptive systems are thus aggregations of diverse components connected by flows (Levin 1998) and can self-organize into multiple stable configurations that shift unpredictably if a threshold is exceeded (Berkes et al. 2003). This science of complexity has influenced many disciplines, from physics to political science (Ottino 2004; Miller and Page 2007) and, increasingly, the field of industrial ecology (IE). As evidenced by this special issue, as well as the 2009 edition, scholars within the community are infusing complex systems science into traditional areas of inquiry, including industrial symbiosis (IS), industrial metabolism, and input-output (I-O) analyses (Dijkema and Basson 2009; Zhu and Ruth 2013).

Although resilience is often cited as an important attribute of complex systems, its applicability hinges on how it is conceptualized. A clear division exists in the literature between so-called engineering resilience and ecological resilience (Holling 1996). Engineering resilience is a measure of the speed at which a system can return to its previous equilibrium. This is a static conception of resilience. Ecological resilience, meanwhile, postulates that bouncing back to a previous equilibrium may be impossible in complex ecosystems because they can shift between multiple stable states (Gunderson 2000). This dynamic conception of resilience is now widely accepted by the ecological community (Ahern 2011). It follows that as complexity science expands, more fields will adopt a dynamic conceptualization of resilience.

But to what extent is the IE community adopting dynamic resilience? Given the infusion of complex systems approaches in IE and the clear resonance with principles of sustainability, one would think that the concept would be highly relevant. Moreover, both IE and resilience are, in essence, ecological metaphors, reflecting attempts to apply ecological principles to human, coupled, and engineered systems (Ashton 2009; Pickett et al. 2014). Thus, it seems logical that IE should draw on the latest ecological theories (Ehrenfeld 2004).

The aim of this article therefore is to take stock of the research on resilience in IE, as well as the other disciplines. First, we describe how resilience is defined in the various fields, elaborating on the distinction between static and dynamic resilience. Second, we use bibliometric techniques to identify the influential research communities and scholars in resilience scholarship over a period of 40 years (1973–2014). Bibliometrics are used to quantify and map relationships and intellectual communities within academic literature and trace development of a research domain (Noyons 2001; Yu et al. 2014).[1] The analysis includes two bibliometric data sets—one on the resilience and complexity literature in the academy and a smaller one focused on resilience research within IE.

Our review reveals that resilience—static or dynamic—has not been a research focus of IE. This contrasts markedly with a large and rich body of literature on resilience and complexity in other disciplines, in which a number of clearly defined research communities and topics have emerged. These communities are heavily influenced by a handful of particularly prominent scholars in ecology and social-ecological systems. We argue that the IE community needs to tackle the issue of resilience, especially the version that stems from the "new ecology," which characterizes systems as dynamic, emergent, and adaptive (Pickett et al. 2004). Toward that end, we conclude the article by briefly recommending how the IE community can engage with resilience by testing theorized characteristics of resilient systems, probing the relationship between resilience and sustainability, and fostering interdisciplinary scholarship around the concept of a *resilient urban metabolism*.

From Static to Dynamic Conceptions of Resilience

The etymological origins of resilience, which date back to at least 1620, stem from the Latin term "resilio," which literally means "to spring back" (Klein et al. 2003). Comparatively, the modern-day dictionary definition of the term is more expansive: "(1) the capability of a strained body to recover its size and shape after deformation caused especially by compressive stress; or (2) an ability to recover from or adjust easily to misfortune or change" (Merriam Webster 2014). Scholars have used the concept of resilience in a range of disciplines and topical contexts, leading to varying definitions (table 1).

Our literature review revealed multiple conceptual tensions in its use (Meerow et al. 2015). Most germane for this article is the division between static equilibrium and dynamic nonequilibrium resilience. Early uses of resilience in engineering and ecology generally adopted a static understanding, with resilience defined as the ability of natural and human systems to maintain a state of equilibrium (Folke 2006). This was based on the dominant ecological theories of the time, which portrayed ecosystems as inherently stable and predictable (Clements 1936). But, in recent decades, this perspective has given way to a "new ecology" based on a more complex model of ecosystem dynamics (Cote and Nightingale 2011). In particular, Holling's (1973) study contributed to this transition by demonstrating that because ecosystems are complex adaptive systems, they have multiple stable states and therefore can be fully functional without bouncing back to their previous equilibrium postdisturbance. Holling then presented his notion of dynamic ecological resilience, in which not all aspects of the system have to stay the same as long as the system remains within a given "basin of attraction" (Holling 1973, 20).

With colleagues, Holling expanded on this theory by articulating, through the concept of panarchy, how systems constantly change when moving through adaptive renewal cycles (Gunderson and Holling 2002). These cycles consist of four stages: "conservation" (stability); "release" (a disturbance); "reorganization" (change after the disturbance); and "growth" (settling into a new stable state) (Walker et al. 2004, 2). Moreover, these scholars demonstrated that complex social-ecological systems are actually made up of multiple nested adaptive cycles with cross-scalar dimensions (Gunderson and Holling 2002). Thus, the popular concept of ecological resilience has evolved into "an intellectual framework for understanding how complex systems self-organize and change over time" (Anderies et al. 2013, 3). These insights led to a dynamic characterization of social-ecological resilience, defined 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" (Walker et al. 2004, 6).

These contrasting interpretations of resilience have implications for how systems are designed and managed (Folke 2006). A static resilience perspective seeks to create "fail-safe" systems that are stable, efficient, and predictable, whereas a dynamic resilience approach accepts change and unpredictability and designs systems to be safe to fail (Holling 1996, 33). Our review of the literature indicates that dynamic resilience predominates in studies related to complexity. However, research in engineering, disaster management, and economics still tends to follow the equilibrium model of resilience (Pendall et al. 2010). To elucidate which conceptualization predominates in IE and the academy, we conducted a bibliometric analysis of the literature, a method we now describe.

Bibliometric Methods

This study uses three well-known bibliometric techniques: direct citations; cocitations; and weighted direct citations. Direct citation analysis elucidates relationships within a data set directly and identifies which publications cite one another. Cocitation analysis assesses all references cited within a data set of publications[2] (usually representing a discipline or research area), whereas weighted direct citations also take into account relationships between the publications themselves. More specifically, cocitation analysis measures how many times two references have been cited together in publications in the data set. Assuming that if two references are cited together they are related, this cocitation count serves as an indicator of the strength of their relationship (Small 1973). The cocitations are then combined to create a cocitation network representing the "intellectual structure" of the data set (Yu et al. 2013). The network shows the references (nodes) and frequency with which each one is cited together in the data set (edges). Weighted direct citation (WDC) analysis, meanwhile, combines cocitations with direct citations. WDC analysis weights direct citations based on the number of references the two publications share and the number of times they are cocited. Although WDC is used to provide a more nuanced measure of the strength of the relationship between publications, WDC and cocitation maps for a set of publications are usually very similar (Persson 2010).

For the bibliometric analysis, we used Thomson Reuters' (2014) Web of Science™ (WoS) citation index to construct two literature data sets: one on resilience and complexity generally and one on resilience in IE. For the resilience-complexity data set, we searched the titles, abstracts, and keywords of all English citations in the WoS database published between 1973 and February 2014, using the search terms "resilience or resilient or resiliency" and "complex*."[3] This query yielded 3,931 publications, which we reduced to 2,221 by excluding articles in the medical and health science research areas (e.g., psychology,

Table 1 Representative definitions of resilience, by field

Author	*Field*	*Definition of resilience*	*Static or dynamic conceptualization*
Holling (1973, 17)	Ecology	"The ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist"	Dynamic
Pimm (1984, 322)	Ecology	"How fast the variables return towards their equilibrium following a perturbation"	Static
Carpenter and colleagues (2001, 765)	Social-ecological systems	"The magnitude of disturbance that can be tolerated before a socioecological system (SES) moves to a different region of state space controlled by a different set of processes"	Dynamic
Adger (2000, 347)	Geography	"The ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change"	Dynamic
Rose (2007, 384)	Economics	"The speed at which an entity or system recovers from a severe shock to achieve a desired state"	Dynamic
Fiksel (2006, 16)	Systems engineering	"The capacity of a system to tolerate disturbances while retaining its structure and function"	Dynamic
Zhu and Ruth (2013, 74)	Industrial ecology	"The ability [for industrial ecosystems] to maintain their defining feature of eco-efficient material and energy flows under disruptions"	Dynamic
Zeng and colleagues (2013, 12)	Networks	"The critical threshold . . . at which a phase transition occurs from normal state to collapse"	Static
Ouyang (2014, 53)	Engineering	"The joint ability of a system to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation"	Static

internal medicine, medical ethics, and so on) and conference proceedings, letters, meeting abstracts, notes, and software reviews. Although we found the WoS to be the most comprehensive database, it still excludes many books and is limited to journals registered by it.

To construct the IE-resilience data set, the following keywords were used: "resilience," "resiliency" or "resilient" and "industrial ecology," "industrial symbiosis," "industrial ecosystem*," "urban metabolism," "socio-economic metabolism," "industrial metabolism," "life cycle analysis," "material flow analysis," "life cycle assessment," or "input output." This broad range of keywords helped to ensure that inclusion of as many publications within the field as possible, even if "industrial ecology" did not appear in the title, abstract, or keywords. This search yielded 81 publications, of which 44 were excluded one by one based on a determination of whether or not they were broadly within the IE field. The final data set included 37 publications (table 2).

Both data sets were imported into Bibexcel, software designed specifically to analyze bibliographic data (Persson et al. 2009), where cocitation network files were generated. A similar process was used to create network files of WDCs. However, for the IE data set, there was insufficient co-occurrence to generate an interesting WDC network.

The cocitation and WDC network files were then visualized and analyzed based on degree centrality, edge weight, and modularity using Gephi, an open-source network analysis software program (The Gephi Consortium 2014; Bastian and Heymann 2009). The Force Atlas algorithm, which clusters nodes closer together if they have more links, was used for the layout. Node size was set to reflect degree centrality (i.e., the more edges that link to a node, the larger its size). However, for the WDCs, node size only reflects the number of times that article is cited by others ("indegree"). Thicker lines connecting nodes in the networks indicate more links (i.e., higher edge weight).

To identify scholarly communities within these networks, we used the community-detection algorithm (Blondel et al. 2008) in Gephi to measure modularity and determine community size and number. High modularity indicates that a network is readily divided into subnetworks or communities whose nodes are much more densely connected to one another than to others (Newman 2006). A default resolution of one was used for all networks. To increase readability, only prominent nodes were labeled (resilience-complexity data set cocitation degree values over 75, the WDC network over 15, and the IE-resilience data set over 30).

Results

The bibliometric analysis reveals that communities within the two networks are divided by topic (i.e., social-ecological systems vs. ecosystems), rather than by field of study (figure 2).

Table 2 Influential publications in industrial ecology on resilience

Authors	*Journal/book*	*Citation count*	*Subject*	*Analytical tools*
Haberl and colleagues (2004)	*Land Use Policy*	72	Material and energy flow accounting and sustainability science	MFA
Zhang and colleagues (2010)	*Environmental Science & Technology*	49	Ecosystem services in LCAs	LCA
Koellner and Scholz (2008)	*International Journal of Life Cycle Assessment*	39	Land-use impacts on biodiversity	LCA
Moore and Manring (2009)	*Journal of Cleaner Production*	27	Sustainability in SMEs	Supply-chain management
Garcia-Serna and colleagues (2007)	*Chemical Engineering Journal*	26	Green engineering	Cradle to cradle
Ashton (2009)	*Journal of Industrial Ecology*	20	Regional industrial ecosystems	Industrial symbiosis
Crowther (2010)	*Systems Engineering*	13	Spatially explicit input-output models of regional economic interdependency	Input-output modeling
Brandão and Canals (2013)	*International Journal of Life Cycle Assessment*	12	Land-use impacts on biotic production	LCA
Allenby (2009)	*Journal of Industrial Ecology*	7	Complex sociotechnical systems and industrial ecology	—
Agudelo-Vera and colleagues (2012)	*Resources Conservation and Recycling*	6	Urban harvesting, water, energy	Urban metabolism
Georgiadou and colleagues (2012)	*Energy Policy*	5	Future-proofing the energy performance of buildings	LCA
Geng and Côté (2007)	*International Journal of Sustainable Development and World Ecology*	4	Diversity in industrial systems	Industrial symbiosis
Li and colleagues (2011)	*Journal of Industrial Ecology*	4	Optimization of recyclables sorting	Optimization models
Chang and colleagues (2012)	*Journal of Environmental Management*	3	Drinking water infrastructure planning	LCA
Coats and colleagues (2013)	*Biofuels, Bioproducts and Biorefining-BIOFPR*	2	Biofuel production from anaerobic digestion in dairy farms	LCA
Ouyang (2014)	*Reliability Engineering and System Safety*	2	Critical infrastructure systems	Review of various methods
Dangerman and Shellnhuber (2013)	*Proceedings of the National Academy of Sciences of the United States of America*	2	The global energy system	—
MacKillop (2012)	*Cities*	2	Climate science in urban planning (history in Manchester)	—
Vogt and colleagues (2010)	*Handbook of Sustainable Energy*	2	Energy systems	—

Note: Citation counts as of August 1, 2014. LCA = life cycle assessment; SMEs, small- and medium-sized enterprises; MFA, material flow analysis.

For the resilience-complexity data set, five distinct research communities can be identified in the cocitation network: (1) ecological resilience; (2) social-ecological systems; (3) marine ecosystems; (4) complexity and networks; and (5) organizational risk and resilience. The first three communities are tightly clustered, suggesting that they are highly linked and thus closely related, whereas the fourth and fifth are more loosely connected. The most influential scholars in this data set are ecologists (i.e., Folke, Holling, Gunderson, and Walker) and they feature most prominently in communities 1 and 2. In particular, Folke is featured as an author or coauthor in communities 1, 2, and 3. These findings are supported by the results of the WDC analysis (figure 3). With the exception of scholars in community 4, our review suggests that the most prominent publications define resilience in more dynamic (rather than static) terms.

The IE-resilience cocitation network (figure 4) is much smaller and the topical focus of the communities is less cohesive. We identified five communities in this network: (1) topically diverse; (2) risk and resilience in technical systems; (3) IE and resilience; (4) urban systems; and (5) agricultural systems.

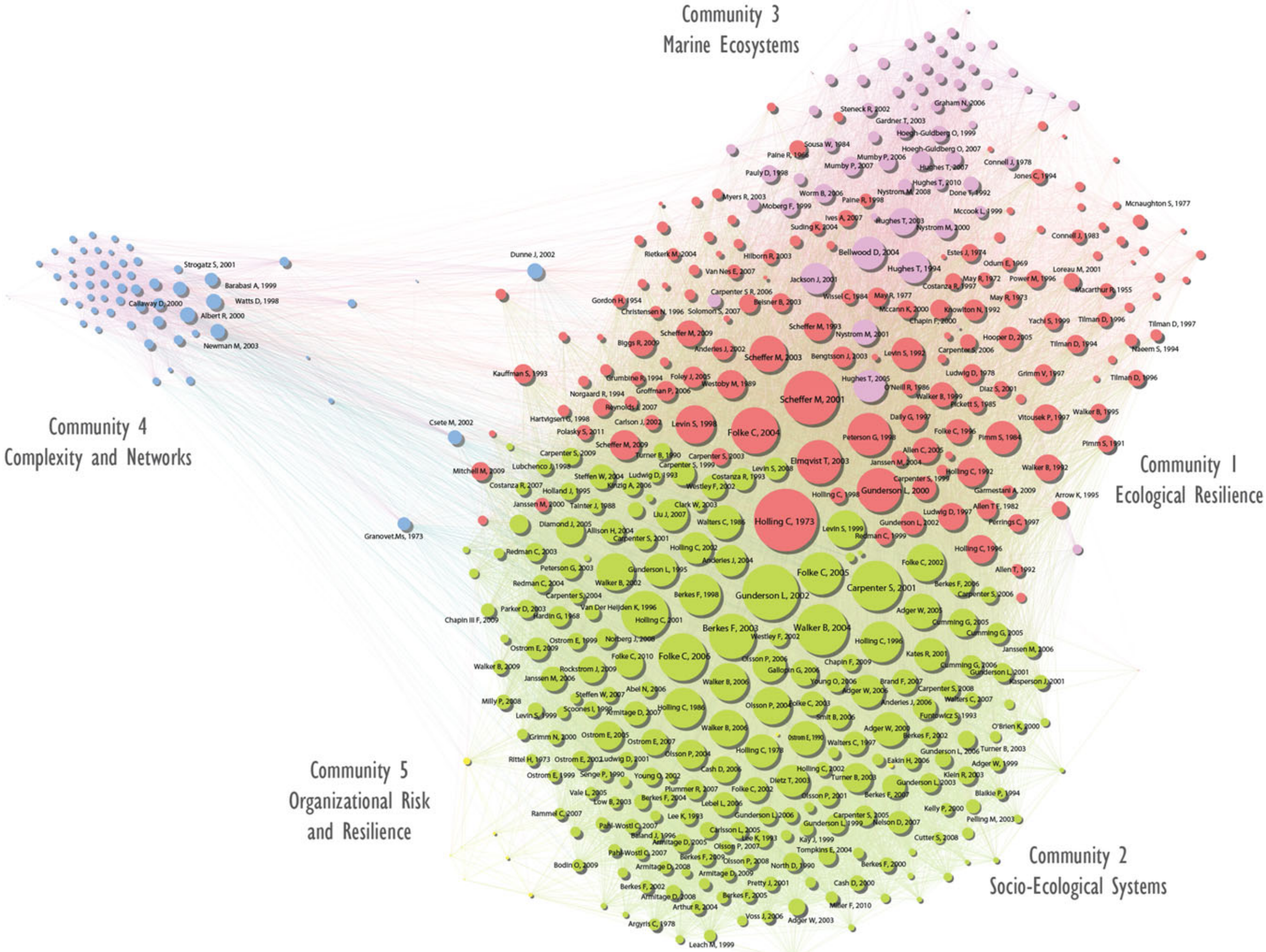

Figure 2 Cocitation network of literature on resilience and complexity. The nodes represent individual references cited in the publications within the data set and a connecting edge means the two references are cited together. Node size reflects degree centrality; edge weight shows how many publications the two references are cited together in. Colored communities highlight different research themes. Nodes with degree values >75 are labeled with the lead author's first initial, last name, and year of publication.

Resilience and Complexity

Ecologists dominate the most central community (community 1: ecological resilience) in the cocitation network for the resilience-complexity data set. Holling's 1973 article is the most central node (i.e., most frequently cocited publication) in the entire network (figure 2). Other important publications (as indicated by node size and high degree of centrality) include Scheffer and colleagues (2001), Gunderson (2000), Folke and colleagues (2004), Elmqvist and colleagues (2003), and Levin (1998). Although these scholars are all ecologists, their research spans ecosystem types, from marine to forest to savannah. Other prominent topics include ecosystem complexity (Grimm and Wissel 1997), ecological regime shifts (Biggs et al. 2009), and the dependence and impact of humans on the environment (Norgaard 1994; Vitousek et al. 1997). Not all scholars within community 1 are ecologists. Norgaard (1994), for example, is an economist. Scholars in this community generally base their definitions of resilience on Holling's (table 1), with the notable exception of ecologist Pimm (1984), who adopts a static interpretation.

Community 2 (social-ecological systems) is closely connected to community 1, as evidenced by its spatial proximity, the interlinkages, and the shared prominent lead authors (i.e., Gunderson, Folke, Levin, Carpenter, Holling, and Walker). This community is differentiated by research that focuses on complex social-ecological systems (SESs) or social systems, as opposed to just natural ecosystems. Gunderson and Holling's (2002) book on panarchy is the most prominent publication. Also influential is the article by Carpenter and colleagues (2001) on measuring resilience and Walker and colleagues' (2004) on the relationship between resilience, adaptability, and transformability. Research in community 2 is more focused on governance, with prominent articles by applied ecologists on managing SESs for resilience (Berkes et al. 1998, 2003; Lebel et al. 2006; Olsson et al. 2004, 2006; Walters 1997; Armitage et al. 2007). There is also work by social scientists, and they

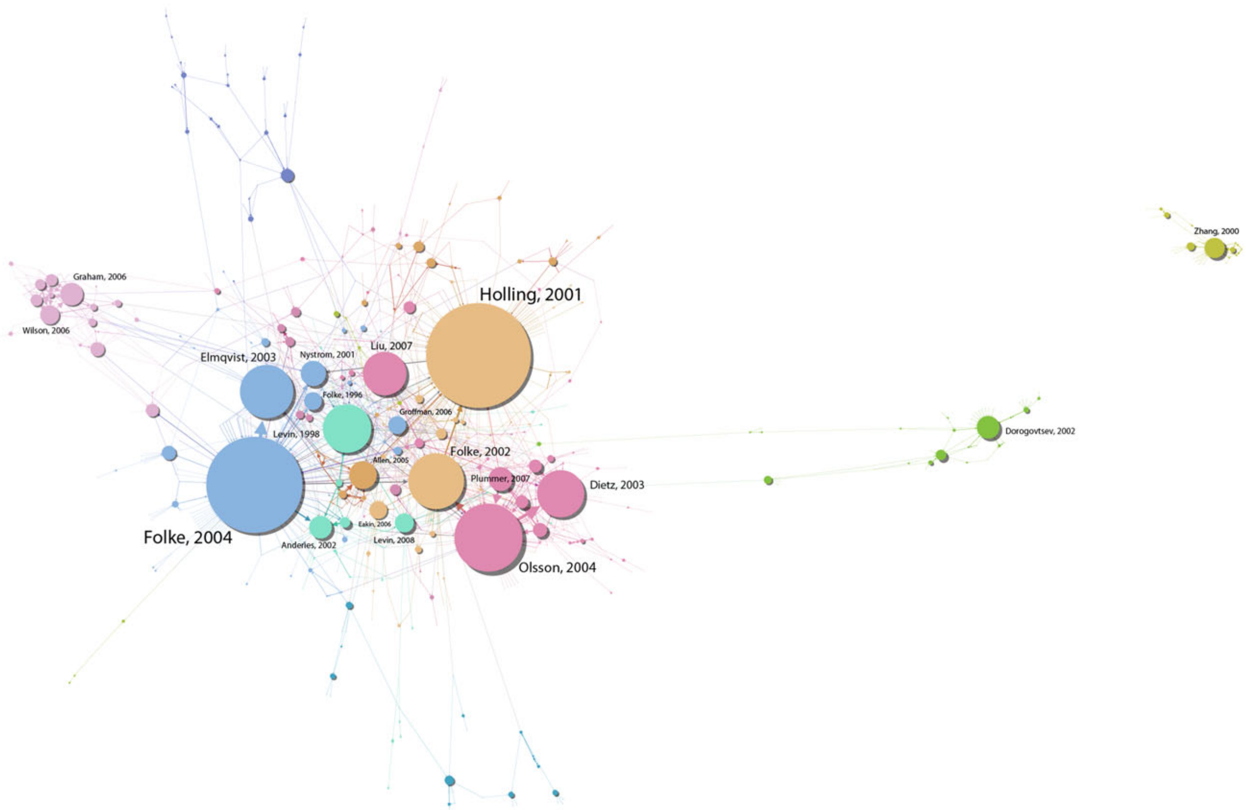

Figure 3 Weighted direct citation network of the literature on resilience and complexity. Nodes represent publications. An arrow connecting nodes means one publication cites the other. Node size reflects the number of times other publications in the data set have directly cited a publication. Edges are weighted by cocitations and shared references. Nodes with degree values >15 are labeled with the lead author's last name and year of publication.

are further from community 1 than the ecologists. Scholars include the economist Ostrom (1990, 2005, 2007) and sociologist Dietz and colleagues (2003) on institutional approaches to managing the commons, as well as the work of geographers who occupy the right side of the network and focus on issues of sustainability, adaptation, and vulnerability. Key publications include those by Adger (2000, 2006), Smit and Wandel (2006), Kates and colleagues (2001), Turner and colleagues (2003), Blaikie and colleagues (1994), Cutter (2008), and Diamond (2005). The nodes in the bottom right of community 2 are generally focused on resilience (of communities, cities, and so on) to climate change, natural disasters, or hazards (figure 2). This last group of publications does not necessarily identify the systems they examine as SESs (Cutter et al. 2003, 2003; Füssel 2007; Pelling 2003; Klein et al. 2003). As with community 1, community 2 generally adopts a dynamic conception of resilience.

Community 3 (marine ecosystems) is smaller, with fewer prominent publications. However, it is also the most tightly knit, with the largest nodes consisting of work by just four different lead authors—Hughes and colleagues (1994, 2003, 2005, 2007), Jackson (2001), Nyström and colleagues (2000, 2001, 2008), and Bellwood and colleagues (2004)—and frequent coauthorship between them. The research focuses on the resilience of marine ecosystems, especially coral reefs. Within this community, static resilience has traditionally dominated, but more dynamic conceptions are being adopted (Nyström et al. 2008).

Community 4 (complexity and networks), far off to the left, is much more loosely connected to the first three communities (figure 2). The largest nodes (i.e., most cocited) are articles that focus on complex networks: Newman (2003); Watts and Strogatz (1998); Erdõs and Rényi (1960); Barabási (1999); Callaway and colleagues (2000); and Strogatz (2001). This community uses the term resilience in relation to networks, but in a manner distinct from the others. Resilience refers here to the ability of the network to function when vertices or nodes are removed (either randomly or in a targeted fashion) (Newman 2003; Callaway et al. 2000). Although isolated, some articles link to the other communities, such as Granovetter's (1973) work on social networks, Csete and Doyle's (2002) article on biological complexity and networks, and Dunne and colleagues' (2002) research on food webs as networks. This is logical given that they all focus on networks of some kind. Mitchell's (2009) book introducing complexity science and Kauffman's (1993) work on self-organization in complex biological systems link this community with community 1.

Community 5 (organizational risk and resilience) is also isolated and has very few citations and a low degree of centrality. This community consists primarily of organizational scientists

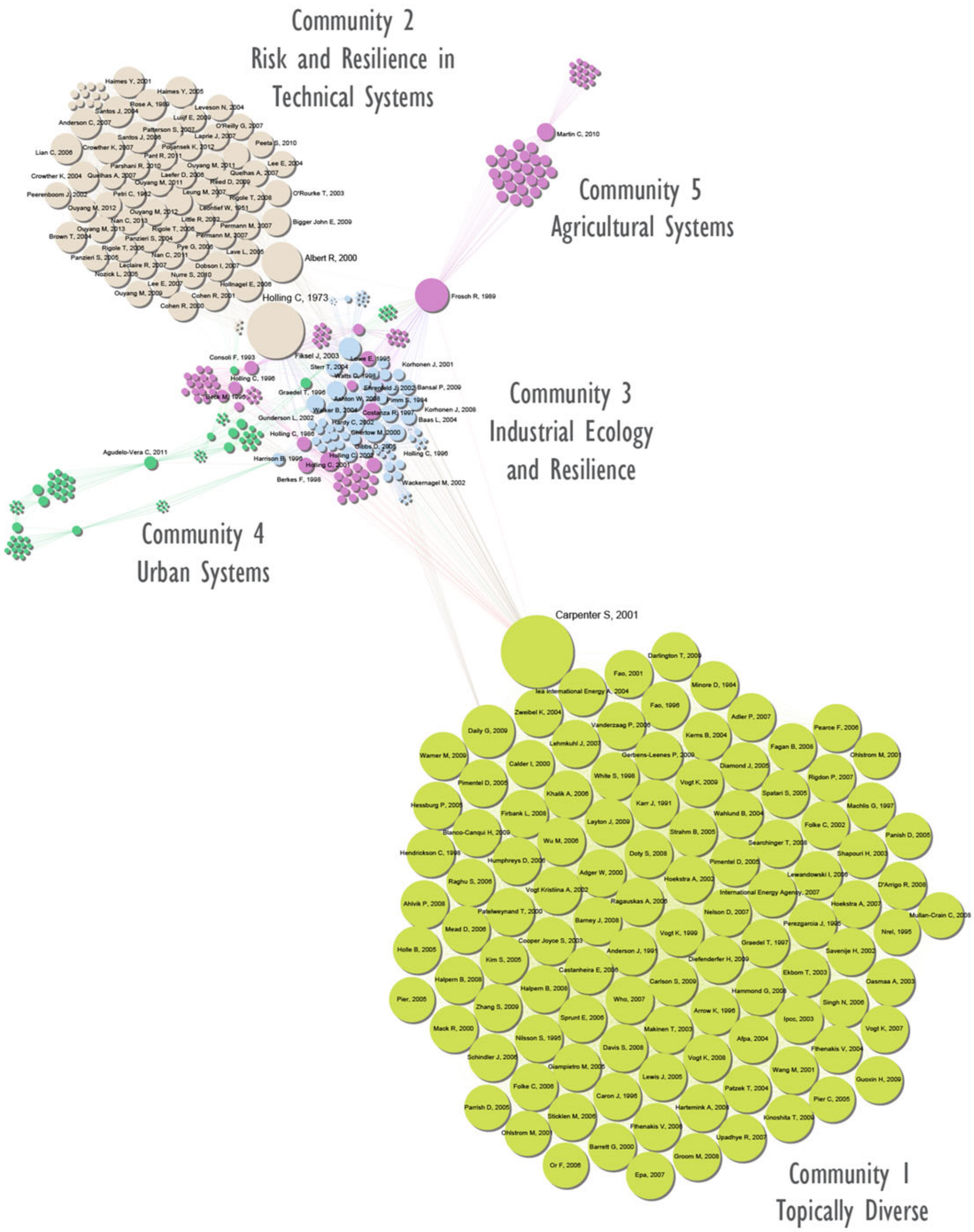

Figure 4 Cocitation network of the literature on industrial ecology and resilience. Nodes with degree values >30 are labeled with the lead author's first initial, last name, and year of publication.

studying resilience in relation to risk, safety, and accidents. The most prominent node is Hollnagel and colleagues' (2006, 6) book on engineering resilience, which proposes a "new paradigm for safety management," and defines resilience as "the ability of systems to prevent or adapt to changing conditions in order to maintain (control over) a system property" (Hollnagel et al. 2006, 95). That this definition allows for adaptation and change suggests that these scholars also take a more dynamic perspective, and this book is cocited with prominent ecology and SES resilience literature and articles in the complexity and networks scholarly community. D. D. Woods (Hollnagel et al. 2006), a coauthor of the book, represents another prominent node. Other notable nodes include Weick and Roberts (1993) and Weick and Sutcliffe (2001), Vaughan (1996), Reason (1997), and Snook (2000).

The weighted direct citation analysis for the resilience-complexity data set (figure 3) generally confirms findings from the cocitation analysis. Large nodes indicate that the publication is highly cited by other scholars doing similar work, and the thicker the arrows connecting two nodes the more likely it is that the two articles are more similar in topic (Persson 2010). The same lead authors (most notably Folke and Holling) are very large and central nodes, further confirming their importance to resilience and complexity research. Ten communities were detected and these topical delineations closely resemble those of the cocitation analysis. Particularly prominent communities include: ecosystem resilience (Folke et al. 2004; Elmqvist et al. 2003; Folke et al. 1996); socioecological systems (Folke et al. 2002; Holling 2001; Eakin and Luers 2006); ecosystem resilience and management (Levin 1998, 2008; Anderies et al. 2002; Janssen et al. 2004); adaptive governance of social-ecological systems (Olsson et al. 2004; Dietz 2003; Plummer and Armitage 2007); and coral reef resilience (Graham et al. 2006, 2007; Wilson et al. 2006). Off to the right are two more isolated research communities: complex networks (Dorogovetsev and Mendes 2002) and electrical and telecommunication engineering (Zhang et al. 2000).

Industrial Ecology and Resilience

The most striking finding from cocitation network analysis of the IE-resilience data set (37 publications in total) is just how infrequently the resilience concept has been used in the field. A more restrictive WoS search using "industrial ecology" without the additional nine IE-related keywords and "resilience OR resiliency OR resilient" yielded just 13 publications, with five appearing in the *Journal of Industrial Ecology* (*JIE*). This is in stark contrast to usage of sustainability, which yielded 226 publications (based on the terms "industrial ecology" and "sustainability") and 1,581 publications with all the keywords used.[4] This represents a 1:43 ratio of IE publications on resilience to those on sustainability, whereas the ratio of "resilience" to "sustainability" publications in the entire WoS database is less than 1:2.[5]

We classified all 37 IE and resilience publications based on topic, methodological tool, discussion of complexity, and conceptualization of resilience (static or dynamic) (table 2). Topics include eco-industrial parks, urban ecology, the built environment, recycling, and energy, water, food, economic, and agricultural systems. In this literature, the most commonly employed IE approaches are life cycle assessment (LCA) (nine publications in total), material and energy flow analysis (six publications), and IS (four publications). Various other methods (i.e., I-O modeling and network analysis) are cited in the remaining publications, but many do not specify a particular tool or approach, being primarily theoretical articles or literature reviews.

In this literature, inconsistencies exist with respect to how complexity is addressed. One third of the publications (12 total) explicitly label their systems as complex, coupled, or adaptive. Crowther and Haimes (2010) and Xu and colleagues (2011) point out that regional economies are complex and interdependent. Similarly, Agudelo-Vera and colleagues (2011) and Shi and Yang (2014) highlight the complexity of urban systems.

The publications also differ on whether resilience is static or dynamic, if defined at all. Seven publications use a static definition, 12 dynamic, and 18 either unclear or only mention resilience in passing. To illustrate how these opposing perspectives are conveyed, Ouyang (2014, 53) defines resilience of critical infrastructure systems as the capacity to "resist," "absorb the initial damage, and recover to normal operation." This static conception reduces resilience to resistance and bouncing back, as does Shi and Yang's (2014, 440) material flow analysis (MFA) study where resilience is defined as "the restoration ability" of a system. Exemplifying the dynamic perspective by noting that ecosystems have multiple stable states, Ashton (2009) uses Holling's adaptive cycle model to understand industrial ecosystems, and Garcia-Serna and colleagues (2007, 28) contrast resilience with resistance and specifically argue that green engineering "cannot be static."

In the cocitation network of the IE-resilience data set (figure 4), Holling (1973) and Carpenter and colleagues (2001)—among the most foundational studies in the larger resilience-complexity literature—are the two largest nodes. This suggests that industrial ecologists are, at least in theory, drawing on dynamic resilience. Although the analysis indicated ten communities within the IE-resilience cocitation network, no studies were cited more than three times and less than half of all the articles cited together co-occurred in more than one document. Thus, this network structure is highly influenced by each additional co-occurrence. Of these ten, five somewhat substantive community clusters can be delineated: (1) topically diverse; (2) risk and resilience in technical systems; (3) IE and resilience; (4) urban systems; and (5) agricultural systems. We have labeled community 1 "topically diverse" because it contains foundational resilience publications (e.g., Carpenter et al. 2001; Folke 2006; Adger 2000; Diamond 2005), as well as others covering a range of topics, such as ecosystem service valuation (Daily et al. 2009), impact of wind turbines on birds (Layton 2008), biofuel development (Hammond et al. 2008), and agriculture and biodiversity (Firbank et al. 2008). Some work within this community is written by scholars associated with IE, either by methodology (Hendrickson et al. 1998) or by the fact that they publish in the *JIE* (e.g., Cooper 2003; Graedel 1997). But the bulk of it is not. Community 2 features publications in the resilience-complexity data set (Holling 1973; Hollnagel et al. 2006), as well as research on errors in complex networks (Albert et al. 2000), I-O risk analysis (Anderson et al. 2007), and vulnerability in interconnected urban infrastructure systems (Little 2002). Community 3 is quite a bit smaller than the first two and includes publications primarily on resilience (Pimm 1984; Walker et al. 2004; Gunderson and Holling 2002; Fiksel 2003) as well as work by well-known industrial ecologists (e.g., Graedel 1996; Chertow 2000). The publications in community 4 relate to agricultural systems (Martin et al. 2010; Phong et al. 2011). With their early influential work on industrial ecosystems, Frosch and Gallopoulos (1989) link community 4 with the rest of the network. Last, publications in community 5 share a general focus on urban systems and include research on urban water systems (Lundie et al. 2004; Lundin and Morrison 2002), urban metabolism (Kennedy et al. 2007), and resource management in urban planning (Agudelo-Vera et al. 2011).

Industrial Ecology and Resilience: Moving the Field Forward

In light of the concept's proliferation in the academy and in public discourse, research on resilience in IE has been limited. This contrasts markedly with IE research on complex systems, which is blossoming in subfields such as industrial symbiosis (Chertow and Ehrenfeld 2012; Baas 2008), industrial ecosystems (Ashton 2009; Zhu and Ruth 2013), I-O modeling (Wood and Lenzen 2009), sustainability transitions (Rotmans and Loorbach 2009), LCA (Davis et al. 2009), and supply chains (Christopher and Peck 2004). This is a significant and welcome development given that, in 2007, just six articles in IE focused on agency, complexity, or complex systems theory (Dijkema and Basson 2009). This shift is perhaps in response to calls for more research in this area from scholars such as Spiegelman (2003). Given that resilience is an important attribute of complex systems, this literature provides the basis for greater engagement with resilience thinking. This section briefly discusses how IE can move this agenda forward by addressing a major gap in resilience scholarship: the lack of quantification and testing of theorized characteristics of resilience. This will necessitate making IE tools less static so as to better approximate the complexity inherent to dynamic resilience. Finally, we propose using "resilient urban metabolism" as a "boundary object" to enable multiple disciplines to collaborate and more fully characterize urban systems.

Testing Resilience Characteristics

Despite the recent proliferation in resilience publications, most studies lack metrics or empirical assessments of system resilience (Carpenter et al. 2001; Weichselgartner and Kelman 2014; Haberl 2004). In particular, resilience scholars have identified a large number of theorized *characteristics* of resilient systems, such as adaptability, diversity, efficiency, flexibility, learning, and redundancy (Godschalk 2003; Rose 2007; Eraydin and Taşan-Kok 2013; Fiksel 2003; Bahadur et al. 2010; Walker and Salt 2006). IE tools and approaches could significantly advance efforts to quantitatively measure these characteristics. Some work by IE scholars has already been done in this area. For example, Ashton (2009) illustrates how diversity is important for assessments of the sustainability (and resilience) of regional industrial ecosystems. Bristow and Kennedy (2013) identified stored energy and flexibility in demand as important indicators of resilience. LCA research might be extended to quantify environmental impact in terms of how these impacts affect the adaptive capacity of a system, or its capacity to "adapt to change in factors such as climate, water availability and diseases" (Van der Werf et al. 2014, 7). Spatially explicit I-O modeling could help assess urban resilience by characterizing economic interdependencies, including system function if a perturbation severed these connections (Crowther and Haimes 2010). Similarly, Haberl and colleagues (2004) point out that material and energy flow accounting provides a useful methodology to quantify system thresholds, although, admittedly, such calculations may be difficult in nonlinear systems (Haberl et al. 2004).

More broadly, quantifying some resilience characteristics would help us expand our knowledge of the relationship between resilience and sustainability, which needs to be more clearly articulated theoretically, empirically, and practically. Resilience is often cited as a component, or even prerequisite, for sustainability. At other times, the concepts are presented as synonymous, and, in still other cases, resilience is lauded as a more suitable paradigm for an increasingly risky and uncertain world (Derissen et al. 2011). IE can help elucidate the sustainability-resilience relationship. As an example, consequential LCA could be used to investigate potential synergies and trade-offs between designing for eco-efficiency and designing for resilience. Theorized resilience characteristics include redundancy and flexibility, which may come at the expense of resource-use efficiency. Reducing efficiency might appear less sustainable in the short term, but from a long-term perspective, it may actually make the system more sustainable by being able to withstand a range of perturbations (Zhu and Ruth 2013; Korhonen and Seager 2008; Walker and Salt 2006).

As these examples intimate, more interplay between IE and resilience scholars would mutually benefit both communities. One research area where this would be especially useful is in the study of urban systems, which, because of their complexity, require multidisciplinary approaches, and for which there is no consensus on how to characterize or measure their resilience (Leichenko 2011). Toward this end, we now provide a brief example of how interdisciplinary coupling can occur, using "resilient urban metabolism" as a boundary object (Brand and Jax 2007).

Toward a Resilient Urban Metabolism

Many disciplines are calling for "urban resilience" in the face of climate change (Leichenko 2011) and natural disasters and hazards more generally (Coaffee 2008; Godschalk 2003). Municipal governments are developing adaptation strategies in response to rapidly growing urban populations, rising sea levels, increased drought, and storm surges (Ahern 2011; Davoudi et al. 2012). The unpredictability of these challenges has led to a focus on building general system resilience, rather than trying to plan for all possibilities (Tyler and Moench 2012). A body of so-called urban ecological resilience literature has emerged, which conceives of cities as complex adaptive systems and, consequently, applies the dynamic form of resilience to them (Lhomme et al. 2013; Jabareen 2013; Resilience Alliance 2007).

The notion of a resilient urban metabolism can support multidisciplinary urban resilience research by serving as a "boundary object" (Star and Griesemer 1989). A boundary object is a "malleable" concept that enables communication across disciplines through use of shared terminology, even though conceptualizations of the term will vary by discipline (Brand and Jax 2007). By facilitating collaboration between scholars from different fields, boundary objects are useful devices to leverage their respective disciplinary expertise (Newell and Cousins 2015).

Previous studies have documented the effectiveness of using "resilience" and "urban metabolism" individually as boundary objects (Beichler et al. 2014; Brand and Jax 2007; Cousins and Newell 2015), but not in combination as we propose here.

Bibliometric analysis of the urban metabolism literature reveals that three "ecologies" have emerged: industrial ecology; political ecology; and urban ecology (Newell and Cousins 2015). Given their particular strengths and foci, these three thought traditions collectively provide an excellent interdisciplinary foundation for how to theorize, model, and foster more resilient urban systems. Through quantification of material and energy stocks and flows, IE urban metabolism has significantly advanced our understanding of the (un)sustainability of cities (Kennedy et al. 2007). These approaches have been largely static, and less attention has been given to the dynamics within and between the stocks and flows, spatial-temporal scales of cities, or socioeconomic and ecological dimensions of the metabolism (Newell and Cousins 2015). In political ecology, research has primarily focused on the social dynamics and governance of the urban metabolism and the methods are predominately qualitative (Newell and Cousins 2015). In urban ecology, the term ecosystem is increasingly preferred to urban metabolism as a characterization of urban system complexity (Golubiewski 2012). Nevertheless, from ecology, the pioneering work on metabolism by E.P. and H.T. Odum has influenced generations of urban metabolism scholars in IE. In addition, urban ecology has incorporated conceptions of dynamic resilience into the theorization and modeling of urban systems (Alberti et al. 2003). Each perspective offers a useful window into the complex, dynamic nature of cities. If these three "ecologies" can find ways to collaborate by using "resilient urban metabolism" as a boundary object, it could result in a far more comprehensive assessment of resilience and its characteristics. This would include the interdependent subsystems and sectors that compose urban systems as well as the ways in which they are embedded in global resource, commodity, communication, and multilevel governance networks (Seitzinger et al. 2012; Hodson and Marvin 2010; Godschalk 2003).

Conclusion

This article has used bibliometric techniques to document a large and growing body of scholarship on resilience and complexity that has been strongly influenced by theories of ecological and social-ecological systems that embrace resilience as dynamic and operating in nonequilibrium. In contrast, the review reveals that research on resilience in IE is limited. But if one agrees with Ehrenfeld (2007, 74) that "the primary source for industrial ecology, as the name suggests, is ecology," then it logically follows that the field needs to engage with widely accepted theories of resilience in this "new ecology."

IE tools can be used to address the lack of metrics in resilience research by quantifying theorized characteristics of resilient systems. This engagement with dynamic resilience is likely to reshape understanding and approaches in our respective research domains, from IS to socioeconomic metabolism to LCA. It will also lead to a deeper, more nuanced understanding of the relationship between resilience and another transformative metaphor of our time, sustainability. This is critical, because as Fiksel (2006, 16) writes, "Sustainability will arguably require the development of resilient, adaptive industrial and societal systems that mirror the dynamic attributes of ecological systems." So, we leave you with a final question to ponder: How is dynamic resilience likely to reshape our notions of sustainability given the implication that steady-state equilibrium is just not a realistic model of our world?

Notes

1. "Communities" refers to clusters of publications in the cocitation and weighted direct citation networks. These communities are defined by the fact that the nodes (publications) within them are more densely connected to one another (implying a stronger relationship) than to the other communities. In bibliometric analysis, these network clusters represent subdomains or themes within the field (Persson 2014; Yu et al. 2013).
2. "Publication" refers to an academic article, book, review, editorial, and so on, not the specific journal it was published in.
3. The asterisk after complex is a wildcard symbol used in searches to ensure inclusion of all variations of it (i.e., complexity, complexities).
4. We also found a growing use of concepts related to complexity in IE; a search produced 2,080 publications when "complex*" and the IE keywords were used.
5. A database-wide search using the same search terms ("resilience OR resiliency OR resilient" and "sustainability") and years (1973–2014) used for the IE literature yielded 40,789 citations on resilience and 56,639 on sustainability.

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