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Insight, part of a Special Feature on Panarchy: the Metaphor, the Theory, the Challenges, and the Road Ahead

Fourteen propositions for resilience, fourteen years later

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ABSTRACT. In 2006, Walker et al. published an article titled, "A Handful of Heuristics and Some Propositions for Understanding Resilience in Social-ecological Systems." The article was incorporated into the *Ecology and Society* special feature, Exploring Resilience in Social-Ecological Systems. Walker et al. identified five heuristics and posed 14 propositions for understanding resilience in social-ecological systems. At the time, the authors hoped the paper would promote experimentation, critique, and application of these ideas in resilience and social-ecological systems research. To determine the extent to which these propositions have achieved the authors' hopes, we reviewed the scientific literature on social-ecological systems since the article was published. Using Scopus, we identified 627 articles that cited the Walker et al. article. We then identified and assessed the articles relative to each proposition. In addition, we conducted a more general Scopus review for articles that did not cite the Walker et al. article specifically but incorporated a proposition's concepts. Overall, articles often cite Walker et al. as a reference for a definition of a heuristic or ecological resilience generally and not to reference a specific proposition. Nonetheless, every proposition was at least mentioned in the literature and used to advance resilience scholarship on social-ecological systems. Eleven propositions were tested by multiple articles through application of case studies or other research, and 7 of the 11 propositions were substantially discussed and advanced. Finally, three propositions were heavily critiqued either as concepts in resilience literature or in their application.

Key Words: *adaptive cycle; heuristics; propositions; resilience; social-ecological systems*

INTRODUCTION

Social-ecological system (SES) resilience is a well-established framework for understanding the dynamics between human and natural systems. At the beginning of the 21st century, multiple scholars built on C. S. Holling's original 1973 definition of ecological resilience to make it applicable to social-ecological systems (Adger 2000, Carpenter et al. 2001, Holling 2001, Gunderson and Holling 2002, Walker et al. 2004). Although the definitions of SES resilience vary, resilience is commonly defined as the ability of a given system to be disturbed and yet still provide the necessary feedbacks and functions while retaining a similar structure and identity (Carpenter et al. 2001, Walker et al. 2004, Folke et al. 2010). However, this definition does not elaborate on which factors are important for creating or ensuring that a system is resilient.

In 2006, *Ecology and Society* released a special feature entitled Exploring Resilience in Social-Ecological Systems Through Comparative Studies and Theory Development. The feature was a culmination of research by members of the Resilience Alliance in order to build on the concepts set forth in the book *Panarchy: Understanding Transformations in Human and Natural Systems* (Gunderson and Holling 2002). The feature was created based on work conducted in 15 case studies across a variety of social-ecological systems, including lakes and wetlands, rangelands, irrigation systems, and coral reefs. The goal was for this work to be compared with and serve as the new baseline for research on resilience and social-ecological systems. As written in the opening editorial,

> *Our hope is that [this special feature] might serve as a platform for a greatly increased program of research in many countries and organizations, which will lead to a better basis for sustainable development and an approach that we might tentatively call "adaptive governance for resilient social-ecological systems.* (Walker et al. 2006a)

Through an examination of these 15 case studies, Walker et al. (2006b) distilled five heuristics related to the underlying mental models that drive research on social-ecological system resilience. The five heuristics that describe how a system may respond to a shock were as follows: the adaptive cycle, panarchy, adaptability, resilience, and transformability (Walker et al. 2006b). These five concepts provided the foundation for resilience research and the backbone for understanding the potential outcomes from a disturbance.

From these heuristics, Walker et al. developed 14 propositions about resilience (Table 1). These propositions "are useful in helping us understand and compare different social-ecological systems, [but] they are not sufficiently well defined to be considered formal hypotheses." Two of these propositions focus on the adaptive cycle, specifically the variations in the sequence of phases that are possible in the adaptive cycle. Another proposition relates to the role of cross-level interactions in a panarchy in shaping subsequent adaptive cycles. Five propositions are related to system composition, including the "rule of hand" for the number of variables needed to describe the important characteristics of a social-ecological system, and the roles of fast and slow variables, ecological and social domains, functional and response diversity, and multiple thresholds. Another four concern the components of adaptability, the roles of mental models and learning in adaptability, and the relationship between adaptability and resilience. Finally, two propositions relate to transformation and its determinants.

When Walker et al. (2006b) was published, the authors hoped that the propositions they put forth would be "augmented, modified, or rejected by future research." Fourteen years have now passed for resilience theory to evolve and for the scientific community to research, adopt, or reject these propositions. We review the use and development of these 14 propositions to investigate the work that has incorporated these propositions into their research,

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discuss how the concepts have been used, and suggest areas where the research could be expanded. To achieve this, we conducted a literature review based primarily on literature that cited the original Walker et al. (2006b) article.

Table 1. References to propositions in publications that cited Walker et al. (2006b). The rightmost column sums to more than the number of citing publications (627) because some articles mentioned more than one proposition.

Proposition	Number of publications that cite Walker et al. (2006b) and refer to this proposition
1: Modes of reorganization	14
2: Variations in the adaptive cycle	21
3: Cross-scale interactions	37
4: The "rule of hand"	18
5: Fast and slow variables	25
6: Ecological vs. social domains	41
7: Functional and response diversity	29
8: Components of adaptability	51
9: Mental models	10
10: Learning	32
11: Adaptability vs. resilience	19
12: Multiple thresholds	12
13: Transformation	18
14: Determinants of transformability	24
(Did not reference a specific proposition)	302
(Unable to discern which proposition was referenced)	33
(Unable to access full text)	29
(Removed due to incorrect reference entry)	10

METHODS

We focused our analysis on a review of articles that cited Walker et al. (2006b) supported by a non-exhaustive literature scan for other relevant publications. Using Scopus, we found 627 publications that cited Walker et al. (2006b) as of 24 July 2019 (Appendix 1). We coded each article for references to Walker et al.'s (2006b) 14 propositions (Table 1), then split into teams of two to review the papers associated with each proposition. We ignored 302 publications that referenced Walker et al. for general resilience definitions but did not refer to specific propositions (Table 1). We omitted an additional 72 publications because we were unable to discern which proposition was referenced or access the full text, or because they incorrectly referenced Walker et al. (2006b), leaving 253 publications that we recorded as referring to at least one proposition.

To support the review of citing publications, we also scanned the literature for publications that were relevant to each proposition but did not cite the original article. Search terms for the literature scan were designed separately for each proposition to balance coverage with time limitations (Table 2). It was beyond the scope of this work to systematically review entire fields of study, such as learning or mental models, for their relevance to the propositions. Where appropriate, we also incorporated publications from our own knowledge of the literature.

RESULTS AND DISCUSSION

We present the results of our literature review for each of the 14 propositions and place these results in the context of the broader literature on social-ecological resilience. Many of the papers citing Walker et al. 2006(a) relate to the five heuristics rather than the 14 propositions and are used for defining the core concepts of social-ecological system resilience. However, as hoped for by the authors in the special feature, researcher engagement with the 14 propositions continues to expand resilience thinking and highlight its utility for understanding social-ecological systems.

Proposition 1: Modes of reorganization

Proposition summary: Multiple modes of reorganization are possible during phases of release and renewal in a social-ecological system. Because of this, managers need to consider multiple approaches during such periods (Walker et al. 2006b).

Although Walker et al. (2006b) argued that multiple modes of reorganization are possible during phases of release and renewal, no papers citing the original paper discussed the potential for multiple modes. Most papers either adopted the adaptive cycle as a heuristic a priori or focused on specific phase transitions (for example collapse or reorganization), seeking to identify specific triggers or configurations of different variables or capitals (Baral et al. 2010, Hartel et al. 2017). Phase transitions were easier to identify after the fact (Abel et al. 2006), and the modes of reorganization did not always follow the initial theory. For instance, Abel et al. (2006) found that there was not always a "pre-release decline in resilience" before a collapse as implied in the adaptive cycle. Overall, published research focuses on using the heuristic of reorganization as a part of the adaptive cycle to explain how change occurs rather than focus on other parts of this proposition that are related to the non-linear, multimodal potential of reorganization.

Proposition 2: Variations in the adaptive cycle

Proposition summary: The four phases of the adaptive cycle appear to explain the dynamics of change in many systems. Nonetheless, exceptions to the adaptive cycle occur, particularly under the influence of large, external disturbances and a lack of critical forms of capital (Walker et al. 2006b).

Within the review for papers citing Proposition 2, many disciplines were represented such as environmental studies, archaeology, engineering, management, and mathematics. The papers focused on system change, transformation, or transition, but examined a wide variety of systems and types of change. This shows that the heuristic of the adaptive cycle has found its way into many disciplines and most publications used the adaptive cycle and its phases as a heuristic (i.e., for ecological analysis, Zurlini et al. 2006; for social system analysis, Courvisanos et al. 2016; for social-ecological analysis, Antoni et al. 2019).

González-Hidalgo et al. (2014) emphasized that the release and reorganization phase is a natural part of an ecosystem often hampered by policies and management in the context of forest fire management. In a study on Sahelian agro-pastoral systems, Vang Rasmussen and Reenberg (2012) illustrated that the adaptive cycle helps reveal that systems might get stuck in a phase if the parameters are not well aligned. This is a "rigidity trap," where a system stuck in one phase of the adaptive cycle becomes

Table 2. Search terms for the literature scan. We applied each search term to the "Article title, abstract, keywords" field in Scopus. We limited the search results to the years 2006-2019. The search terms were adapted for each proposition. Additionally, in each search, (_SES_) was replaced by ("social-ecological system" OR "socio-ecological system" OR "human-environment system" OR "human and natural system" OR "socio-environmental system").

Proposition	Search terms for literature scan
1: Modes of reorganization	transition AND reorganisation OR collapse AND _SES_
2: Variations in the adaptive cycle	"adaptive cycle" AND pattern OR variation OR phase OR condition
3: Cross-scale interactions	_SES_ AND ("cross-scale" OR memory OR revolt)
4: The "rule of hand"	"rule of hand"
5: Fast and slow variables	"slow variable" OR "fast variable" AND resilience
6: Ecological vs. social domains	regime-shift OR attractor OR threshold AND modelling OR conceptual OR theoretical AND _SES_
7: Functional and response diversity	("functional diversity" OR "response diversity") AND _SES_
8: Components of adaptability	adaptability AND _SES_
9: Mental models	"mental model" AND _SES_ OR natural-resource-management OR regime-shift OR policy-development
10: Learning	learning AND "adaptive management" OR "adaptation" OR "adaptability" AND _SES_
11: Adaptability vs. resilience	(resilience AND adaptability) AND _SES_
12: Multiple thresholds	"multiple thresholds" OR "interacting thresholds" OR "interacting regime shifts" OR "thresholds" OR "regime shifts" AND _SES_
13: Transformation	transformation AND cross-scale AND _SES_
14: Determinants of transformability	"transformability" AND _SES_

highly connected, rigid, and inflexible. System capacity for novelty is diminished, leading to a decrease in adaptive responses to shocks (Vang Rasmussen and Reenberg 2012). Only Bradtmöller et al. (2017) questioned if the adaptive cycle is the best way to characterize change in archaeology if the inherent spatio-temporal units are not distinct to identify each phase of the adaptive cycle. Others found variations in their case studies compared to the suggested heuristic, mainly in the social system (i.e., Bunce et al. 2009, Daedlow et al. 2011). Overall, the ideas embedded in Proposition 2 appear to be used in a wide array of disciplines in a variety of social-ecological contexts, and only a few papers, primarily Bradtmöller et al. (2017) mentioned above, questioned the utility of the adaptive cycle in their respective fields.

Proposition 3: Cross-scale interactions

Proposition summary: Cross-scale interactions critically determine the form of the subsequent adaptive cycle at any one focal scale (Walker et al. 2006b).

Proposition 3A: Reiterations of adaptive cycles are driven by higher-scale influences, such as memory (Walker et al. 2006b).

Proposition 3B: Synchronization of adaptive cycles at lower levels influences the potential for upscale "revolt" (Walker et al. 2006b).

Of the 35 papers citing Walker et al. (2006b) that we initially thought related to Proposition 3, only 21 referred to cross-scale interactions. References to cross-scale dynamics usually concerned issues of governance (i.e., scale mismatch or politics of scale) or to scale used generically to mean size (e.g., small-scale unit). Six of the articles focused directly on effects that cross-scale interactions have on the adaptive cycle. Concepts such as memory (the idea that reiterations of adaptive cycles are driven by higher scale influences) or revolt (the effect that lower levels have on change at higher levels) were rarely explicitly discussed. Linkages between higher and lower levels were explicitly discussed by seven of the articles that directly cited Walker et al. (2006b). In summary, although mentions of cross-scale interactions have permeated the academic discourse, they have not necessarily referred to the way that cross-level interactions have been conceived in the panarchy literature. Although a few articles have focused on cross-scale interactions analytically to infer how these would influence future trajectories of an adaptive cycle, most articles used cross-scale interactions descriptively to explain how dynamics of change are interrelated within and between systems.

Proposition 4: The "rule of hand"

Proposition summary: critical changes in social-ecological systems are determined by a small set of three to five key variables, i.e., the "rule of hand." To understand change in systems, it is important to identify this small set of variables (Walker et al. 2006b).

Our literature review found several articles that used the proposition to justify their work but little evidence of testing or development of the proposition. Nine citing publications used the rule of hand to justify implementing a small number of key variables in their modeling, analysis, conceptual approach, or management recommendations. One citing publication critiqued the rule of hand as reductionist (Olsson and Jerneck 2018) and another argued it was reliant on educated guesses about the appropriate variables and blind to the variability of individuals within a population (Brand 2009). Other citing publications referenced the rule of hand but showed little use or discussion of the proposition. The literature scan revealed one additional publication that discussed the importance of the rule of hand for model building (Holling and Sundstrom 2015). We conclude that some researchers have found the rule of hand useful but there remains substantial scope to test and develop the proposition. For example, we speculate that the rule of hand could be tested by applying methods based on Takens' Theorem that estimates the number of dimensions of an attractor (Deyle and Sugihara 2011) to social-ecological time series. Such a test would be of novel theoretical interest, but the limited uptake of the rule of hand to date suggests that any result may be of little practical impact.

Proposition 5: Fast and slow variables
Proposition summary: Slowly changing variables control ecological resilience, whereas social resilience is controlled by either fast or slow variables (Walker et al. 2006b).

Although there has been a great deal of research on fast and slow variables generally (Holling 1986, Crépin 2007, Walker et al. 2012), of the 20 articles that cite Walker et al. (2006b) and refer to Proposition 5, only three have engaged with the content of the proposition itself. Anderies (2014) discussed the role of fast and slow variables in built environments, particularly as they pertain to the natural spaces they occupy. The authors emphasized the need to plan and consider a variety of social and ecological variables occurring at different speeds and times when constructing environments and spaces, which should help increase desirable and resilient states. Williams et al. (2019) took a similar approach and discussed the need to use a complex systems perspective to organizational development in built environments, particularly focusing on the interactions between slow and fast variables and their impact on resilience. A case study by Wrathall (2012) investigated the role of slow and fast environmental variables that result in environmental migration in the Garífuna Villages of Northern Honduras. In this study the outcome of these interactions was the disruption of society resulting in out-migration to urban spaces because of untenable living situations in the villages due to extreme flooding. In summary, within the articles that cite Walker et al. (2006b), there has been little engagement with this proposition, which is a surprising oversight considering the level of discussion about fast and slow variables in the resilience literature. We acknowledge that there has been work conducted on the role of slow and fast variables in social-ecological resilience; however, it is not connected to the original article and, as such, Proposition 5 has room to be better linked to the original publication.

Proposition 6: Ecological vs. social domains
Proposition summary: The ecological and social domains of social-ecological systems can be addressed in a common conceptual, theoretical, and modeling framework (Walker et al. 2006b).

Forty-one of the papers that cite Walker et al. (2006b) were related to this proposition. Many of the publications utilized the concept of social-ecological systems to discuss specific systems as SESs (Smith and Stirling 2010 [socio-technical regimes]; Moffatt and Kohler 2008 [built environment]; Hossain and Szabo 2017 [wetlands]) or to build on and expand the concept of SESs (Tyler and Quinn 2013) rather than explore the nuances of ecological and social domain frameworks. Others focused on the application of individual social attributes to overall system resilience (Gooch et al. 2012, Keys et al. 2014). A few found that ecological and social domains can be explored using a common framework (Malkamäki et al. 2016).

Notably, some papers pushed back against Proposition 6, particularly in its application to the social domain. This includes Stojanovic et al. (2016), who were concerned about the exclusion of non-quantitative social research, and Blythe (2015), who stated the social domain is different enough from the ecological domain to require a separate framework. Our literature scan in Scopus yielded 93 related, peer-reviewed articles, which either discussed the same topics as the publications mentioned above (such as specific SESs or social attributes) or were not relevant. One of note was Milkoreit et al. (2018), who explored resilience framework concepts in both ecological and social domains particularly whether "tipping point" as currently defined is appropriate for social domains. Ultimately, Proposition 6 is still highly relevant in academic discourse through the application of SESs as a concept and ensuing critical pushback. More work is needed to confirm that the ecological and social domains do have a common framework.

Proposition 7: Functional and response diversity
Proposition summary: Two types of diversity are important for social-ecological systems: (1) functional diversity, which influences system performance, and (2) response diversity, which influences resilience (Walker et al. 2006b).

Of the 29 papers related to Proposition 7 that cite Walker et al. (2006b), six papers provided case studies or literature reviews that encourage diversity in social-ecological systems, and two papers suggest that diversity is generally good but do not specifically refer to resilience (Quaranta and Salvia 2014, Baird et al. 2019). Many studies used the proposition to justify aspects of their own research without building on the proposition. One review paper (Biggs et al. 2012) noted that positive associations between diversity and resilience are well documented in ecological literature, but less work has been conducted in the social sciences. In operationalizing the concept, researchers have assessed diversity in at least three ways, as follows: concurrent diversity (diversity in components at a given moment within a specific region), temporal diversity (change in components over time), and spatial diversity (change across space; Goulden et al. 2013).

These recent papers provide two important conceptual considerations. First, an inverted U-shaped relationship between diversity and resilience may arise if too much diversity and redundancy cause stagnation and prevent a system from adapting quickly to change (Biggs et al. 2012). Second, managing for resilience should focus not only on the diversity of components, but also on diversity in connections between these components (Anderies 2014). Overall, the application of functional and response diversity for system performance and building resilience has been well received and adopted in the scholarship.

Proposition 8: Components of adaptability
Proposition summary: Adaptability is primarily determined by (1) the absolute and relative amounts of all forms of capital: social, human, natural, manufactured, and financial, and (2) the system of institutions and governance (Walker et al. 2006b).

Proposition 8 has been applied across a wide array of studies and contexts, including ethnographic research (Baird and Gray 2014) and archaeological studies (Bradtmöller et al. 2017), as well as through diverse approaches to social-ecological research across continents and contexts (e.g., Mcclanahan and Cinner 2008, Speelman et al. 2014). Proposition 8 is mostly cited on a superficial level, where the components' contribution to adaptive capacity are assumed to be true, rather than engaging in an in-depth analysis. There are citing papers that do develop the proposition, however. Investigating the role of different components of adaptability in the adaptive cycle generally (Bradtmöller et al. 2017) or specifically in relation to persistence and transformations (Daedlow et al. 2013) is one way the proposition has been used;

another is for adaptive governance or management (Gooch et al. 2012, Ayre and Nettle 2017). Some studies have analyzed the necessity and/or sufficiency of the components to build resilience (e.g., Akamani et al. 2015, Missimer et al. 2017) and others present new components such as innovation (Dennis et al. 2016) and livelihood diversification (Goulden et al. 2013, Baird and Gray 2014). These developments indicate the proposition's specific components and their relations are evolving and dynamic. For example, there is no absolute answer, even within specific communities, to what facets of social capital are important, how, and for whom. However, a large amount of scholarship on adaptation and social capital has does not cited Proposition 8 but nonetheless has discussed ideas and themes embedded within the proposition (Malakar et al. 2018).

Proposition 9: Mental models
Proposition summary: Mental models drive change in social-ecological systems, and adaptability is enhanced through partially overlapping mental models of system structure and function (Walker et al. 2006b).

In the initial scan of the articles that cite Walker et al. (2006b), 10 were related to Proposition 9. Three papers cited Walker et al. (2006b) and mentioned the general idea of the proposition (Beymer-Farris and Bassett 2012, Curtin 2014, Karadzic et al 2014), while Anderies (2014) mentioned all of the propositions verbatim and notes their application to built environments. Similarly, Arias-Yurisch (2019) utilized the idea of Walker's mental model, calling it a "schemata," to note how culture influences a public network. Convertino et al. (2016) similarly used the concept of mental models generally, but added innovation in the analysis of the mental models. Van Riper et al. (2018) primarily focused on multilevel values in a collective, suggesting that the more diverse mental models in a group, the higher the cost of investment in communication.

The secondary literature scan in Scopus revealed an additional 26 relevant articles. Most used mental models to learn about or better understand a system, but eight papers used mental models to examine the potential for adaptation or transformation in the system through policy changes or management actions. For example, Curtin (2014) assessed three components of the adaptive decision-making process—equity design, process design, and outcome design—in order to help managers create more effective policies that build resilience. Overall, the mental model concept has been widely adopted to assess stakeholder perspectives in SESs, but the citing articles seldom directly assessed or developed the original proposition.

Proposition 10: Learning
Proposition summary: Learning is a key component of adaptability and is enhanced by careful experimentation in the form of active adaptive management (Walker et al. 2006b).

Conducting a review of the articles that cite Walker et al. (2006b) yielded 31 journal articles and one book chapter related to Proposition 10. It quickly became apparent that the articles citing Walker et al. (2006b) were simply citing Proposition 10 without engaging in much debate. Article topics include experimentation, knowledge creation, and adaptive management with a focus on governance. Of the 32 sources, 21 were research articles that studied the role of learning in adaptive management, particularly adaptive co-management between resource users and government. Seven of the citations were review articles that tended to focus on the need for learning and adaptive co-management in the face of climate change, and four were thought pieces that developed a new theoretical framework to be used to incorporate learning into research being conducted on social-ecological systems. The overarching theme is that increased adaptability is desirable and will increase resilience in the system. By promoting learning, adaptive governance, and polycentricity, the articles have suggested it will be possible to create adaptive systems.

The secondary search in Scopus for any literature related to the terms in the proposition yielded 199 results. These articles, like Walker et al. (2006b), encouraged experimentation, co-management, and adaptability as key components to incorporate learning into management (Ehrhart and Schraml 2018, Trimble and Plummer 2019).

Proposition 11: Adaptability vs. resilience
Proposition summary: Efforts to deliberately enhance adaptability can (unintentionally) lead to loss of resilience (Walker et al. 2006b).

Most papers that referred to Proposition 11 cited it in passing, without developing the proposition further. Nelson et al. (2007) and Nelson (2011) explicitly but broadly supported the proposition, and Yletyinen et al. (2019) specifically focused on the role of optimization in reduced adaptability. Huai (2017) illustrated a spatial displacement: increased drought adaptability in one location can decrease resilience in another location. The case analyzed in Karadzic et al. (2014) reflects a displacement of resilience loss across a fishery social-ecological system, where social adaptation led to environmental resilience loss.

Domptail et al. (2013) advanced the discussion by applying the framework developed by Scoones (2007) and Leach et al. (2010) to distinguish resilience (i.e., maintaining system structure and function) from robustness (i.e., a change in system structure to maintain function). Domptail et al. (2013) suggested that efforts to enhance resilience may undermine robustness. Like part three of the Walker et al. proposition, Domptail et al. (2013) argued that command and control policies may decrease the flexibility and variability of management responses within a social-ecological system and thereby lead to decreased resilience. Ultimately, the literature review indicates that most papers cited Proposition 11 to define adaptability or resilience without further discussion. Nonetheless, a few papers do discuss in-depth adaptability vs. resilience and the implications for social-ecological resilience.

Proposition 12: Multiple thresholds
Proposition summary: Social-ecological systems have multiple interacting thresholds, giving rise to multiple pairs of alternate regimes, only a few of which are feasible (Walker et al. 2006b).

Out of 627 articles that cite Walker et al. (2006b), 13 were related to Proposition 12 and focused on research areas such as social-ecological systems, ecology, social systems, energy, and the built environment. A common theme has been the need to focus on slow variables of change and the integration of multiple stakeholders and scales of analysis. Frequently missing from the literature were mentions of possible regime pairs that are not currently feasible and discussions of interacting thresholds as a concept. Walker's own later work acknowledged that it is "wrong

to focus research and management attention only on identifying thresholds" for agricultural systems because the focus can instead be on "building general resilience" to maintain structure and function in these systems (Walker et al. 2010).

The secondary scan revealed the abstracts of 240 related, peer-reviewed articles but few engaged with the idea of multiple states (not all of which are feasible at a given time). An exception was Biggs et al. (2018) who formed a database of regime shifts and noted "research tends to focus on individual regime shifts rather than comparisons across regime shifts." Sigdel et al. (2017) also acknowledged a fluctuating number of possible regimes based on elements considered in their model of conservation dynamics and social norms, and some work in socioeconomic and political systems acknowledged multiple thresholds to engage and build human capacity for planning and action (Blythe 2015). Overall, the Proposition 12 review suggests that the concepts of thresholds and regime shifts have been widely and successfully adopted. Nonetheless discussions of potential interacting thresholds and non-feasible regime pairs have not yet been fully investigated and are an area for potential exploration in other work.

Proposition 13: Transformation
Proposition summary: Transformation involves changing the state space of the system and the scales of the panarchy (Walker et al. 2006b).

As originally defined in the summary by Walker et al. above, transformation differs from adaptation in that transformation is the fundamental change to the state space of the system, potentially including changes to scale and cross-scale relationships within the panarchy. When we assessed the literature, we found 21 papers within Scopus that used the term transformation and cited Walker et al. (2006b). Of the 21, eight did not refer to Proposition 13 specifically but instead referenced the "transformability" heuristic discussed elsewhere in the paper. Among papers that did discuss or apply Proposition 13, transformation in governance was a recurring theme. Topics included transformation in natural resource governance (Cundill and Fabricius 2010), habitat planning (Choi et al. 2017), and agriculture productivity (Walker et al. 2010).

However, the term "transformation" has evolved since Walker et al. (2006b) was published, which is reflected in some recent articles. Three papers cited Proposition 13 to critique either Walker et al.'s definition of "transformation" or general usage of the term in resilience theory (Olsson et al. 2015, Glaser et al. 2018, Hayashi and Walls 2019). A search for papers that did not cite Walker et al. (2006b) but discussed transformation found a wider range of topics than the direct references, though there was also overlap in topics between the citing and non-citing papers. New topics included transformation in municipalities (Ziervogel et al. 2016), ecological restoration (Janssen et al. 2017), and climate change (Käyhkö et al. 2020). Whereas citing papers linked transformation to resilience theory, non-citing papers linked transformation to other concepts such as sustainability. Ultimately, though transformation is still an important and discussed concept in resilience theory, the original definition proposed by Walker et al. (2006b) has not stood the test of time, as later articles demonstrated through critique and new applications of the term.

Proposition 14: Determinants of transformability
Proposition summary: Determinants of transformability include incentives, awareness, experimentation, reserves, and governance (Walker et al. 2006b).

Walker et al. (2006b) proposed four elements that can determine the transformability of a system: (1) incentives to change vs. not change; (2) cross-scale awareness and reactivity; (3) willingness to experiment; and (4) governance capacity because of large assets in human, natural, and built capital. The primary review of the literature yielded 14 references related to Proposition 14 in Walker et al. 2006b. These papers applied Proposition 14 to a specific case study, for example river basin management (Sendzimir et al. 2007) and non-governmental organizations (Akamani 2016), while three also provided additional in-depth discussion of the determinants of transformability (Olsson et al. 2006, Walker et al. 2009, Wilson et al. 2013). Like Proposition 13, these papers largely focused on assessing governance; however, one major difference was the application of Proposition 14 to adaptive management and experimentation (Gunderson et al. 2006, Plummer 2009). We also examined the literature to assess whether papers used Proposition 14 concepts without directly referencing Walker et al. (2006b). Like the direct references, these papers explored ideas embedded in Proposition 14 such as experimentation (Pant et al. 2015) and capital assets (Lengnick et al. 2015). Overall, key components for system transformability appear among both the citing and non-citing literature, but the technical language and overarching focus, such as resilience versus sustainability, may differ.

CONCLUSION

Our analysis of the last 14 years of research on the propositions outlined in Walker et al. (2006b) shows that all 14 propositions contributed to scholarship on social-ecological systems and resilience. However, not all propositions have been engaged with equally. Some propositions have only been mentioned in the literature, while others have been tested in case studies or other applications, and a few have been thoroughly critiqued (Table 3). All propositions were mentioned by articles in the scientific literature, and for each proposition we found at least one article that used the concept to advance the scholarship on the resilience of social-ecological systems. All propositions, except 1, 3, and 4, have multiple articles that test the concepts by applying them to case studies or other research; this engagement spans multiple academic disciplines and includes novel applications. A smaller set of propositions (5–8, 10, 11, and 13) were substantially advanced by citing articles through either theoretical models or case studies. Finally, Propositions 4, 6, and 13 have articles that critique either the theory behind these concepts or their application.

Why are some propositions, such as Propositions 1, 3, and 4, only mentioned in the scientific literature, while others are tested and applied (e.g., Proposition 8) and still others directly critiqued (e.g., Proposition 13)? The difference likely reflects the evolution of resilience thinking over time. Some propositions, such as Proposition 1 (Modes of reorganization) have emerged as foundational or at least noncontroversial in the resilience field. On the other hand, propositions that have been tested and applied to case studies and other research reflect greater interest among scientists excited by their potential in applied resilience research. Finally, heavily critiqued propositions have not stood the test of time because of changes in research priorities. The critique of Proposition 13 (Transformation), for example, demonstrates how

Table 3. Proposition engagement. Propositions were placed into categories depending on the level of engagement with that proposition in the scientific literature. "Mentioned" – referred to by citing articles, "Used" – used to justify claims or methods, "Tested" – proposition examined through theoretical models and/or case studies to assess utility or applicability, "Advanced" – proposition was substantially advanced through theoretical models and/or case studies, "Critiqued" – citing articles critical of the propositions' utility or validity.

Proposition	Mentioned	Used	Tested	Advanced	Critiqued
1: Modes of reorganization	Yes	Yes	No	No	No
2: Variations in the adaptive cycle	Yes	Yes	Yes	No	No
3: Cross-scale interactions	Yes	Yes	No	No	No
4: The "rule of hand"	Yes	Yes	No	No	Yes
5: Fast and slow variables	Yes	Yes	Yes	Yes	No
6: Ecological vs. social domains	Yes	Yes	Yes	Yes	Yes
7: Functional and response diversity	Yes	Yes	Yes	Yes	No
8: Components of adaptability	Yes	Yes	Yes	Yes	No
9: Mental models	Yes	Yes	Yes	No	No
10: Learning	Yes	Yes	Yes	Yes	No
11: Adaptability vs. resilience	Yes	Yes	Yes	Yes	No
12: Multiple thresholds	Yes	Yes	No	No	No
13: Transformation	Yes	Yes	Yes	Yes	Yes
14: Determinants of transformability	Yes	Yes	Yes	No	No

the meaning of the term has evolved since 2006 and, as such, the original proposition has served its purpose of furthering the literature on resilience. However, the Walker et al. (2006b) article is no longer the authority on this topic because it has been adopted and altered to be applicable to a wide variety of disciplines outside of the SES literature.

Overall, there has been substantial interaction with the original article, and we suggest that some of the propositions have served their purpose and been adopted by a host of academic disciplines. Other propositions have not stood the test of time and have become so generalized it is difficult to study. This includes, in particular, Propositions 1 (Modes of reorganization), 4 (Rule of hand), and 13 (Transformations). Propositions 2 (Adaptive cycle), 3 (Cross-scale interactions), 7 (Functional and response diversity), 10 (Learning), 11 (Adaptability vs. resilience), and 12 (Multiple thresholds) have been widely adopted and have spurred their own body of literature beyond just the suggestions in the Walker et al. (2006b) article. As such, Walker et al. (2006b) is no longer the main source or citation for information on these propositions. However, there is still work to be done on the propositions that reference social domains. At the time of writing the original paper, the focus of resilience was more related to ecological systems; applying these concepts to social systems was relatively novel. Propositions 5 (fast and slow variables), 6 (ecological vs. social domains), 8 (components of adaptability), and 9 (mental models) have been adopted by social science literature but frequently do not cite back to the original article and were co-produced in other disciplines. For example, Propositions 5, 6, and 8 have been applied in ecological resilience literature but have not found a stronghold in the social domains of resilience thinking. These blurry lines and overlaps are one likely reason for the lack of engagement of the social-ecological resilience literature and the reason there appears to be little social engagement with these propositions.

This literature review investigated publications that have incorporated propositions from Walker et al. (2006b) into their research, discussed how the concepts have been used, and suggested areas where the research could be expanded. Based on the findings of this review, we posit that in 14 years these 14 propositions have greatly contributed to scientific discourse. They have successfully facilitated the growth of the five heuristics (adaptive cycle, panarchy, resilience, adaptability, and transformability) and have encouraged scholars to think beyond the box and apply the ideas in novel ways. Given this expansion and growth, we conclude that Walker et al. (2006b) will be happy to know that, 14 years later, these propositions have been "augmented, modified, or rejected by future research" (Walker et al. 2006a) and the scholarship on social-ecological system resilience is continuing to grow and evolve. In line with those authors, we hope that, over the following 14 years, this review article will be critiqued, applied, and interacted with as extensively as Walker et al. (2006b).

Responses to this article can be read online at:
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Data Availability:

The data and code that support the findings of this study are available within the text of the document and supplementary materials.

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Appendix 1. Appendix A1: Full list and coding of the publications that cited Walker et al. (2006).

Please click here to download file 'appendix1.xlsx'.