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Perspective

Conceptualizing Climate Vulnerability in Complex Adaptive Systems

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This Perspective develops a novel approach for assessing the vulnerability of complex adaptive systems to climate change. Our characterization focuses on the dynamic nature of vulnerability and its role in developing differential risk across multi-dimensional systems, communities, or societies. We expand on past conceptualizations that have examined vulnerability as processual rather than a static or binary state and note the necessary role of complexity and complex adaptive systems theory as a basis for effective vulnerability assessment. In illustrating our approach, we demonstrate the importance of factors such as modulation (connectedness), feedback mechanisms, redundancy, and the susceptibility of individual components within a system to change. Understanding the complexity of potentially vulnerable systems in this manner can help unravel the causes of vulnerability, facilitate the identification and characterization of potential adaptive deficits within specific dimensions of complex adaptive systems, and direct opportunities for adaptation.

Introduction

Climate change has been identified as a major global challenge of the 21st century.[1] Current warming trends and their associated impacts represent a complex problem, which cannot be understood independently of their socioeconomic, political, and cultural contexts or without an appreciation of the broad heterogeneity of agents, communities, and environments that comprise them.[2–4] The ways through which climate change interacts with societies, ecosystems, and the environment are of particular interest when asking why and in what ways some communities or regions, and the people within them, are more or less susceptible to the impacts of climate change.

Over the past 30 years, vulnerability approaches have emerged as a critical means of better understanding differential susceptibilities to the impacts of a warming planet.[5–12] "Vulnerability" as a relational and organizing concept has highlighted the role of multiple interacting stressors and their influence on variable magnitudes of exposure sensitivity and adaptive capacity,[13–15] illustrated the role of multi-scalar, nested, and teleconnected vulnerabilities in affecting change at both proximal and distal scales,[16,17] and demonstrated the importance of assessments themselves in promoting capacity building and decision making through participation.[18,19] However, such approaches have not also been without controversy.[20] Some authors have questioned the epistemological basis of vulnerability, its potential to reinforce hegemonic power structures, or its perceived "deficit" focus[21] (see Ford et al.[22] for a review); others have highlighted a failure in past research to produce a comprehensive understanding of the ways through which the dynamic and multi-scale nature of climate change affects societies and livelihoods.[23] Symptomatic of studies has been a reliance on limited methodological toolkits,[24,25] which have inadequately evaluated or tracked the nuances of vulnerability or its constituent dimensions across time.[22,26] This has resulted in characterizations of vulnerability as a static, immutable, and a binary state as opposed to a process of interlocking exposures, sensitivities, and adaptive capacities that operate over a range of spatiotemporal scales.[27–31]

This Perspective develops an innovative, generalizable approach for vulnerability assessment in complex adaptive systems (CASs). Our framing conceptualizes CASs as composed of multiple dimensions, categorized according to function, whose subsequent operability is determined by the strength of smaller, interdependent "exposure units" that are contained within them. Exposure units are understood as subcomponents within dimensions with the aim of highlighting the non-linearity of vulnerability within different parts of the CAS across time and space. The relative viability and vulnerability of exposure units are governed by the interaction of multiple stressors operating across a range of sociopolitical, economic, cultural, and biophysical spheres. The novelty and utility of such an approach are evident through (1) its ability to identify transient or persistently at-risk components within CAS, which can then be prioritized to streamline decision making for adaptation; (2) its visualization of time as a continuous variable; and (3) its focus upon not only pinpointing areas of vulnerability but also assessing their relative magnitude and causality. Our framing is not tied to a set of methods per se but has been designed with the use of longitudinal, real-time monitoring methodologies in mind in order to better characterize the role of additive or non-linear stimuli, adaptive learning, and feedback mechanisms over time.

We begin by reviewing the concept of vulnerability and its use in the literature, placing it in the wider context of theories surrounding CASs. This is followed by a presentation of the approach itself, an example of how it might be used, and a more in-depth discussion on the approach's utility, potential application, and contribution to current scholarship within vulnerability and the sustainability sciences.

Conceptualizing Vulnerability

The Evolution of Vulnerability Thinking

Vulnerability is often defined as the degree to which a system, individual, or other entity is susceptible to the impacts of a hazard or adverse event. Such a framing is evident in past assessment reports of the Intergovernmental Panel on Climate Change (IPCC)[32,33] and remains part of a common vernacular adopted by much academic and scientific discourse aimed at informing policy and decision making around climate change. However, the fundaments underlying vulnerability as a concept represent far more than a mere simplification into ambiguous terminologies and short definitions.[29,34–36] Past and contemporary political ecology critiques of vulnerability demonstrate that many notions of what it means to be "vulnerable" are often dissonant and pluralistic.[29,35,37,38] Contention abounds as to the ways through which vulnerability manifests, which constituent components of vulnerability exist, and the methods through which vulnerability might be classified or better understood.[34,36,39] At the same time, more nuanced debates center around the ways in which vulnerability is considered to develop and alter through social, institutional, and political contexts; the breadth and precedence that is afforded to climate as a driving factor; and the concept of multiple as opposed to double exposures as drivers in susceptibility.[29,40–43]

The application of the vulnerability concept to society and the environment emerged in the 1970s and early 1980s, primarily through political ecology framings of natural hazards and a focus on the sociopolitical root causes of un-"natural" disasters.[44–46] This epistemology of vulnerability[47,48] saw further development in the 1980s and 1990s with broader application in food systems and international development discourse and thereafter to the issue of climate change and the role of its human dimensions in creating differential risk.[6,13,49,50] By the time the IPCC's Third Assessment Report[32] was published in 2001, vulnerability had become firmly established in the climate literature, and the mid-2000s then experienced a proliferation of debate examining what "vulnerability" was and proposed a variety of assessment frameworks from both "top-down" and "bottom-up" perspectives.[8,14,15,51–53]

O'Brien et al.,[40] among others,[7,51] contend that debate within post-1990s climate vulnerability discourse has arisen from two divergent research foci and ideologies stemming from the variable embrace of either biophysical-focused or political economy-focused approaches to vulnerability assessment. The biophysical tradition, sometimes equated with the "risk-hazard approach" in wider vulnerability literature, represents an empirical positivist-science basis for vulnerability analysis, which is concerned with vulnerability as the "outcome" of climate-environment interactions. Here, vulnerability is seen as an endpoint denoting the sum of projected impacts of climate change on a given set of exposure units once potential adaptations have been accounted for.[23,40,54] Such an approach is strongly event focused, and the role of humans in modifying impacts arising from climate change (beyond large-scale adaptations) receives little emphasis in such a characterization.[8,51,52,54]

An alternative framing to the outcome-oriented vulnerability assessments involves those that take a sociopolitically focused "contextual" approach.[15,23] In the contextual framing—also termed "second generation"[53]—vulnerability is considered through a "starting point," "social-ecological system," or "human security" lens, whereby risks are assessed from a linked and cyclically interacting social-biophysical perspective.[12,40,51] Contextual vulnerability looks at not only how individuals or groups may be vulnerable because of the way the biosphere interacts with humans and society but also the context through which this interaction occurs and how social constructs within societies might develop vulnerability across multiple hierarchical scales (e.g., through relative strength or weakness of political economy, wealth, or strength of social networks).[17,42,55,56] Assessments are primarily "place-based" because of the fact that contextual vulnerability assessments focus on "multiple stressors" and "micro-level" interactions. This allows for the appraisal of causal mechanisms that develop from the interface between climatic, socioeconomic, political, and cultural stressors and an exploration of how these create differential exposures, sensitivities, and adaptive capacities.[57–61] Importantly, stressors within contextual framings of vulnerability can act as both additive and deleterious factors in the development of exposures, sensitivities, and adaptive capacities; are not temporally discrete; and are liable to develop feedback mechanisms.[12,23,52] The incorporation of multiple stressors or exposures over time permits a better understanding of how differential vulnerability develops among populations.[8,43,52,62] Smit and Pilifosova,[63] among others,[52,64,65] have attempted to frame this contextual, social vulnerability approach through the following (or a similar) heuristic equation:

$$V_{sit} = f\,(ES_{sit} - AC_{sit})$$

Here, ES refers to exposure sensitivity, which describes the degree and magnitude of stress experienced within the system (*s*) in response to a stimulus or stimuli (*i*) in time (*t*) and the susceptibility of the system to the direct or indirect effects of that stimuli or stimulus. Adaptive capacity (AC) refers to the potential of the system (*s*) to adapt in response to applied stimuli (*i*) in time (*t*) and works to mediate the potential impact of exposure sensitivity.[63] Increasing adaptive capacity, therefore, improves the ability of a system to cope with a wider range of conditions and absorb a greater magnitude of exposure sensitivity.[63]

Despite a rapid growth and proliferation of contextual assessments, some scholars have critiqued the efficacy of the methodologies and methods associated with them, particularly their effectiveness at capturing the multiple, dynamic stressors that affect vulnerability and the nature of its evolution through time.[26,62,66] Tschakert et al.,[11] for example, contend that vulnerability assessments have "lost their way" in recent years first through having reduced their focus on structural and relational stressors, such as poverty and marginalization, and second through the application of social vulnerability indicators that continue to "reinforce the static notion of vulnerability." Further to this, Ford and Pearce[24] highlight an over-reliance on the retrospective documentation of climate hazards and coping strategies from interviews and focus groups over a short period of time in the Canadian Arctic when pointing to similarly fixed and "static" characterizations (see also Fawcett et al.[67]).

It has been argued that, in addition to ineffectual indicators and methods, many assessments fail to capture the complex

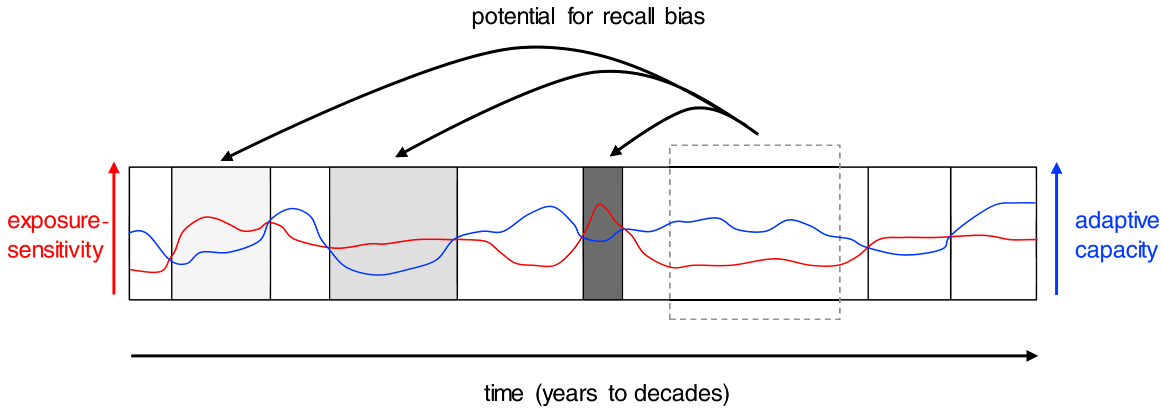

Figure 1. Diagrammatic Representation of the Challenges Encountering "Static" Place-Based Vulnerability Assessments
Here, the dotted box represents the period over which fieldwork is conducted and is superimposed over the area of research interest (often called the "exposure unit"). Shaded boxes represent manifestations of excess vulnerability, where exposure sensitivity (red line) is greater than adaptive capacity (blue line). The length of boxes refers to the time over which vulnerability is manifest. The degree of shading represents likelihood of recall bias, where the lightest represents the most susceptible.

subtleties and plurality of stressors that affect, and are affected by, vulnerability and adaptation temporally as a result of short data collection periods and a methodological dependence on "word of mouth" as opposed to direct observation.[24,26,68] Not only have these methods historically generated an inadequate accounting of recall bias as a factor (Figure 1), but they also preclude wider understandings related to the onset of slow versus fast variables as stressors, the concept of accumulative stressors, and the potential that adaptations at the time of study could in fact develop into maladaptive responses.[69,70]

Fawcett et al.,[67] among others,[24,57] suggest that long-term, longitudinal approaches to vulnerability assessment can provide a more dynamic, in-depth understanding of how communities or regions experience and respond to change in the context of multiple climatic and non-climatic stresses. Real-time monitoring can provide in-depth insight on fast (e.g., week-to-week or year-to-year changes in exposure, sensitivity, or adaptive capacity) versus slow (e.g., long-term, cumulative structural trends and effectors) variables[62,71,72] as underlying determinants of vulnerability and improve the tracking of maladaptive adaptation trajectories.[24,73] Moreover, in assessing human-environment relations over a prolonged period, the interrelated and compound nature of converging stressors can be evaluated for different contexts and across multiple scales. By extension, this facilitates a stronger understanding of the nuanced, dynamic ways in which vulnerability might manifest itself differentially between individuals.[67] Despite their utility and application to multiple core components of vulnerability research, longitudinal vulnerability assessments—particularly those utilizing real-time monitoring—remain uncommon.[66] McDowell et al.,[74] for example, note that between 1990 and 2015 just 6% (n = 17) of papers assessing climate vulnerability at the community level utilized real-time monitoring, and the application of longitudinal methods overall decreased from 2005 onward.

Complexity, Complex Adaptive Systems, and Vulnerability

Notwithstanding its broad application to the study of geography and the environmental sciences, complexity theory has been infrequently drawn upon in the vulnerability assessments relating to climate change. This comes despite the clear applicability of its insights, drawn from resilience and adaptation literature, which have utilized the concept for improving the understanding of the causal factors in systemic change and linked behavior and feedback mechanisms and for supporting decision-making and adaptation initiatives.[75,76]

Complexity theory is concerned with non-linear relationships in changing, disordered systems whose stability is transient.[77] It seeks to understand "how complex behavior evolves or emerges from relatively simple local interactions between system components over time."[78] Complexity theory therefore aligns strongly with the place-based focus of many vulnerability studies given that, unlike a conventional systems theory grounding, complexity theory postulates that structures are not in a constant state of equilibrium and are constructed relationally.[79] This prevents the static characterization of interrelated processes and products by focusing on factors such as the development of feedback loops, the crossing of thresholds, and the diversity of actors and processes involved.[77,80] To understand the system as a whole as well as its emergent properties in complexity theory, it is therefore necessary to examine changing relationships between different elements of a system with time as well as the movement of stocks and flows between its components.[78]

Theories of complex systems have been applied to sustainability sciences and the study of human-environment interactions through the lens of CASs.[77,79] CAS and complexity theory more often than not share a number of general rules: both argue that systems are composed of diverse components that are independent but whose micro-interactions and properties develop emergent wider behaviors.[80,81] CASs, however, have a strong focus upon adaptation and the ability of systems to self-organize and modify their behaviors; in doing so, they can acclimatize to changes in their environment and develop co-evolutionary potential.[77,82] In addition, CAS theory postulates that systems are inherently governed by economies of scale and that small interactions are often also governed by

Table 1. Definitions Adopted by This Conceptual Approach

Approach Terminology	Definition	References
Adaptive capacity	a prerequisite for adaptation; adaptive capacity refers to the total sum of relationships, expertise, and entitlements and their ease of mobilization and utilization, which allow for individuals, households, or institutions to prepare, cope, adjust, or alter a system to mitigate against an applied stimulus or stimuli and the potential for damage that might arise from this application	Ford et al.,[9] Ford and Smit,[52] Engle[94]
Adaptation	the practice of implementing or utilizing adaptive capacity to alter behavior or remove drivers in order to decrease vulnerability and to cope with possible impacts of adverse change	Bennett et al.,[12] Fazey et al.,[18] Kates et al.[90]
Exposure	the rate and nature through which individuals, communities, or regions differentially experience multi-scalar changes, trends, or shocks; it is intrinsically linked to, and almost inseparable from, sensitivity	Bennett et al.,[12] Ford et al.,[52] Luers,[64] Smit and Wandel[89]
Exposure units	the specific components of a human-environment system, including its actors and social, technological, and natural components, which in total form the focus of a vulnerability framework or assessment	Eakin and Luers[95]
Sensitivity	describes pre-existing and developing conditions within an entity that govern its susceptibility to the effects of an exposure	Bennett et al.,[12] Füssel and Klein,[53] Debortoli et al.[65]
Coping capacity or range	the range over which a system might deal with or accommodate the application of stresses, perturbations, or applied stimuli; although it is typically presented as a positive value, which also serves as a proxy for a component of adaptive capacity (see references), we visualize that the coping range could be either positive (able to cope) or negative (unable to cope) (see also “adaptive surplus or deficit” below)	Smit and Pilifosova,[63] Smit and Wandel[89]
Slow variables	variables that emerge from broader, long-term trends and result in gradual changes to exposure, sensitivity, or adaptive capacity within a system (e.g., currency inflation, alteration to interest rates, and sociocultural transformations); these are determined by factors and processes external to the system	Fawcett et al.,[67] Chapin et al.,[71], Ford et al.[73]
Fast variables	variables that are superimposed over, and governed by, slow variables and result in rapid changes to exposure, sensitivity, or adaptive capacity within a system (e.g., pests in agropastoral systems and day-to-day financial income); these are determined by factors both internal and external to the system	Fawcett et al.,[67] Chapin et al.,[71] Ford et al.[73]
Adaptive surplus or deficit	the degree to which a system has a positive or negative coping range; adaptive surplus represents a positive coping range brought about by an adaptive capacity that exceeds present exposure sensitivity; adaptive deficit represents a circumstance whereby exposure sensitivity is greater than adaptive capacity and represents a circumstance of excess vulnerability	Ford et al.,[9] Smit and Pilifosova[63]

larger broad-scale trends.[79] Key concepts within CAS theory include modulation (i.e., the degree to which nodes of a system can be decoupled into relatively discrete components and reassembled), redundancy (i.e., the degree to which nodes can substitute for one another), hierarchical endogenous-exogenous interaction (i.e., the system is open and can interact with external factors), and emergence (the origin and development and of unexpected or unpredictable phenomena).[79,83] CASs are also seen to have the ability to not only adapt but also learn, comprehend, and respond to feedbacks both institutionally and ecologically.

CAS theory is drawn upon within some framings of risk,[84–87] and some basic tenets underlying it are ubiquitous enough to fit within almost any vulnerability approach or framing. Examples include the principle that a system can self-organize after a perturbation to reprise its initial role[88] or can develop a new role when a stressor is applied, which reduces its subsequent susceptibility through an increase in its coping range.[89,90]

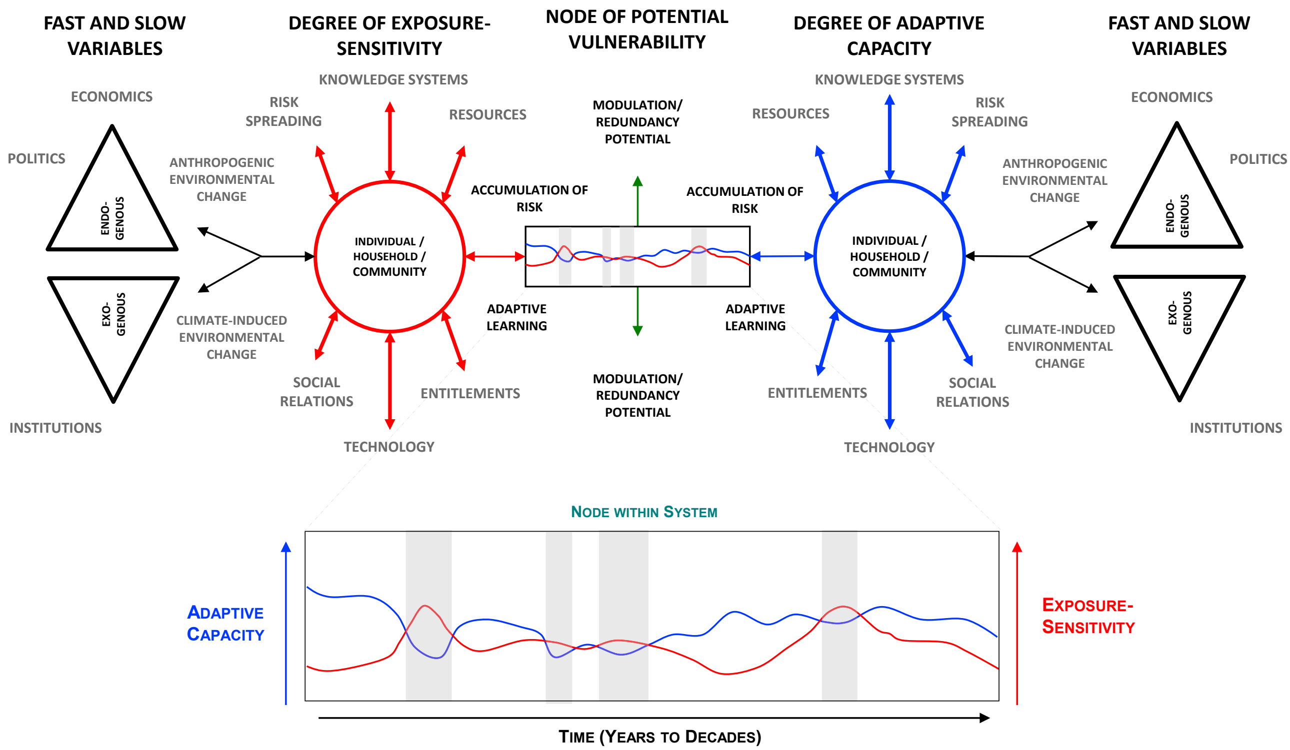

Figure 2. Diagram of the Evaluation of Vulnerability within Differing Exposure Units or Nodes within the CAS

Gray sections within the "vulnerability profile" highlight periods of vulnerability experienced over the course of a study period—in this case, years to decades. For definition of concepts, see Table 1 and the section Complexity, Complex Adaptive Systems, and Vulnerability.

Other CAS concepts, however, are less frequently drawn upon in vulnerability work. For example, the principles that (1) systems exist in a majority-disequilibrium state, (2) can exhibit stochasticity, or (3) can experience rapid and immediate, or slow and transitional, changes in state as a result of emergent interactions remain infrequently incorporated into contemporary vulnerability research.

Moreover, studies of vulnerability commonly fail to adequately address issues related to adaptive learning within their approaches[24] or theories pertaining to feedback loops, webs of specific causality, variable thresholds of change, or exogenous versus endogenous stimuli.[41,91] This comes despite the fact that (1) adaptive learning is considered a primary driver in sustaining adaptive capacity and developing suitable adaptive strategies and derives from interactions between subjects that commonly form foci within vulnerability discourse, including systemic processes and structures and institutions of knowledge;[24,92,93] and (2) feedback can have significant multi-scale, hierarchical effects that can be location specific and/or have wider exogenous impacts.[17,93] All of the above provide rationale for critiques on the viability of contemporary vulnerability approaches, particularly with regard to their frequent characterization of climate-society interactions and their associated risks as "static."[22,67]

Climate Vulnerability in Complex Adaptive Systems

In this section, we propose an innovative conceptual approach to vulnerability assessment that draws upon thinking from CAS theory, including exogenous and endogenous hierarchies of risk, feedback loops, and intercomponent interactions. Our CAS vulnerability approach focuses on the notion that vulnerability derives from, and cannot be separated from, a pluralistic context of multiple, synchronously acting stressors (origins of stress) and perturbations (spikes in stress). These are considered to operate over non-linear trajectories, with differing spatial and temporal scales, and have variable magnitudes of impact that affect both the totality of a system and its subcomponents. Although it is possible to understand or appraise vulnerability at a particular time or in a particular place through a number of pre-existing approaches,[52,53] our conceptualization builds upon wider perspectives, primarily from the disaster sciences, that vulnerability is a dynamic state of susceptibility to harm that is process driven and is therefore, over time, a process in and of itself.[29–31] Through compartmentalizing a system to assess the vulnerability of its specific dimensions before reconstructing it and appraising it as a whole, our approach allows for the tracking of vulnerability and adaptation across specific exposure units and can pinpoint priorities for adaptation (refer to Table 1 for a complete list of definitions for terms used in our framing).

Our approach is visualized through two key stages. The first subdivides the CAS that is the object of study into "dimensions," which represent groups of exposure units within the system that share a common function. Exposure units, also referred to as "nodes" in our approach, denote specific sites within system dimensions where vulnerability has the potential to manifest (Figure 2). The exact number of nodes or

Box 1. Inuit Traditional Food System in Arctic Canada

Indigenous traditional food systems describe networks of agents, actors, and stakeholders within a specific area who are involved in the production, distribution, processing, preparation, and exchange of foods that derive from short, localized supply chains and a have cultural and spiritual importance beyond simply their nutritional value.[97,98] In the context of the Canadian Arctic—a region warming at more than twice the global annual average[1]—climate change has come to represent a significant threat to Inuit traditional food systems.[9,73,99] However, the challenge of an altered climate extends far beyond simply its physical effects; research highlights the compound and pluralistic nature of how climate change interacts with social, political, cultural, and economic stresses to affect individuals, households, and communities.[73,100,101] To this end, we outline a hypothetical Inuit traditional food system representing a CAS of coupled human-environment interactions. Using examples from Figure 3 and working left to right, the table subdivides the system into dimensions that are commonly considered key to its function and outlines potential exposure sensitivities, adaptive capacities, and interactions that might otherwise affect the vulnerability of nodes. Conceptualization in this way would track current and future threats to system stability and, by extension, threats to potential food security. Moreover, through focusing on the causal factors underlying vulnerability within the system and understanding their interactions, such an approach would have the potential to improve the success of targeted adaptations and interventions.

		Dimension (Figure 3)					
		I	II	III	IV	V	VI
Indigenous food system dimension		quality and health of subsistence species	availability of subsistence species	access to hunting, fishing, and harvesting grounds	traditional and non-traditional methods of food preparation	traditional and non-traditional methods of food storage	methods of food distribution
Nodes (Figure 3)		A–I	A–I	A–C	A–B	A–B	A–B
Indigenous food system nodes		specific subsistence species (e.g., B = caribou)	specific subsistence species (e.g., B = caribou)	specific land access types (e.g., A = sea ice, B = open water, C = land)	A = traditional; B = non-traditional	A = traditional; B = non-traditional	A = inter-community; B = intra-community
Possible exposure sensitivities	fast	seasonal variation in edibility (e.g., caribou rutting season); human-induced environmental changes and contaminants; anomalous land, sea, and ice conditions	possible over-hunting; knock-on effect of decline in species health and food quality from dimension I; predation from invasive species	affordability of, and cash flow for, equipment required for access (e.g., purchasing and maintaining machinery, ammunition, and gasoline); inter-annual and inter-seasonal land conditions (e.g., early ice breakup); time constraints of engaging in waged employment or full-time education	conditions becoming too warm for drying racks or food fermentation	cost of purchasing personal freezer; power cuts; access to community freezers dependent on social networks	ability to distribute foods between communities according to weather conditions
	slow	increase in climate- or temperature-sensitive zoonotic diseases and parasites	changes to seasonal migration routes as a result of climatic changes	attrition of indigenous knowledge of the land; centralization and sedentarization of semi-nomadic population	attrition of indigenous knowledge of food preparation; architecture of housing results in lack of space for butchering meats	melting of permafrost insulating ice cellars	changing ethos and culture surrounding sharing

(*Continued on next page*)

Box 1. Continued

		Dimension (Figure 3)					
		I	II	III	IV	V	VI
Possible adaptive capacities	fast	harvesting at different types of year; selective harvesting of specific animals	traveling increased distances to access hunting grounds	creation of new routes and trails; sharing equipment and resources; uptake of technology for navigating in poor conditions	country food preparation programs and nutrition education	community freezers	purchasing of traditional foods; development of country food markets
	slow	environmental controls and regulation	harvest quotas	harvester assistance programs	transition to store-bought alternatives	transition to store-bought alternatives	transition to store-bought alternatives
Redundancy potential		high (able to substitute which species are hunted)	high (able to substitute which species are hunted)	moderate (lack of access to ice, overcome by access to open water, dependent on breakup)	moderate (system can operate with only one node but might have implications for food preference)	high (system can still operate with traditional or non-traditional storage)	moderate (some relationship between sharing and monetization of country food)

dimensions is not fixed and can vary depending on the CAS or even the time scale over which research takes place. The classification of nodes within the system is based on the following criteria:

(1) They exhibit a degree of modulation (i.e., the nodes can be decoupled into relatively discrete components, allowing individual appraisal, and then recombined to reconstruct the system).
(2) They have definable but porous boundaries that allow them to be interconnected with other (often multiple) exposure units (thereby allowing feedbacks, webs of causality, and redundancy between nodes).
(3) They are liable to experience adverse impacts when a set of system-wide or exposure unit-specific stressors are applied.

Upon subdivision of the CASs, vulnerability is examined for each dimension's constituent nodes on the basis of the notion that multiple stressors interact and augment to affect exposure sensitivity and adaptive capacity within the exposure units. The role of these stressors can be either fast or slow onset, characterizing the ways through which stakeholders experience exposure sensitivity and adaptive capacity across time, and can derive from sources both exogenous and endogenous to the system. Examples of multiple stressors might include, among other things, economics, resource availability and use, entitlements, technology, and social relations and knowledge systems (Figure 2).

Much like the number of nodes or dimensions and the structure of their interactions within the CASs, our approach does not designate specific stressors *a priori* because they are mose likely system and situation dependent. Therefore, although Figure 2 provides examples, the stressors included therein should not be considered exhaustive. Moreover, the primary purpose of this approach is as a heuristic to highlight areas both of significant deficit in coping capacity and of manifestations of compound vulnerability across multiple dimensions within a CAS. As such, we do not propose specific indicators to assess variables because they are context dependent on available data, chosen methods, and the quantitative tangibility of certain characteristics within dimensions and nodes of the system in question. We do, however, note that numerical ratings for vulnerability could theoretically be applied to our approach through the calibration of tangible and intangible vulnerability indicators for a specific system.[96]

In assessing vulnerability for constituent nodes and dimensions of the CASs, with iterative reappraisal it is possible to track specific adaptive capacities and exposure sensitivities with time. This facilitates the creation of node-specific and dimension-specific vulnerability profiles with longitudinal scope for all entities within the system. This is done with the objective of highlighting surpluses (where adaptive capacity exceeds exposure sensitivity) or deficits (where adaptive capacity is less than exposure sensitivity) in adaptive capacity in terms of both magnitude and time scale across both specific dimensions, as well as within the system as a whole. Furthermore, it allows for the identification of the most impactful drivers of potential vulnerability on individual aspects of the system in time, pinpoints priorities for capacity building and adaptation, and highlights possible slow versus fast variables in vulnerability and maladaptive trajectories.[90]

After the accounting of manifestations of vulnerability within individual exposure units and dimensions of the system, the second stage of our approach develops a whole-system composite temporal vulnerability profile, or "fingerprint," for the CAS by combining the vulnerability profiles created for its constituent parts and accounting for their interconnectedness and

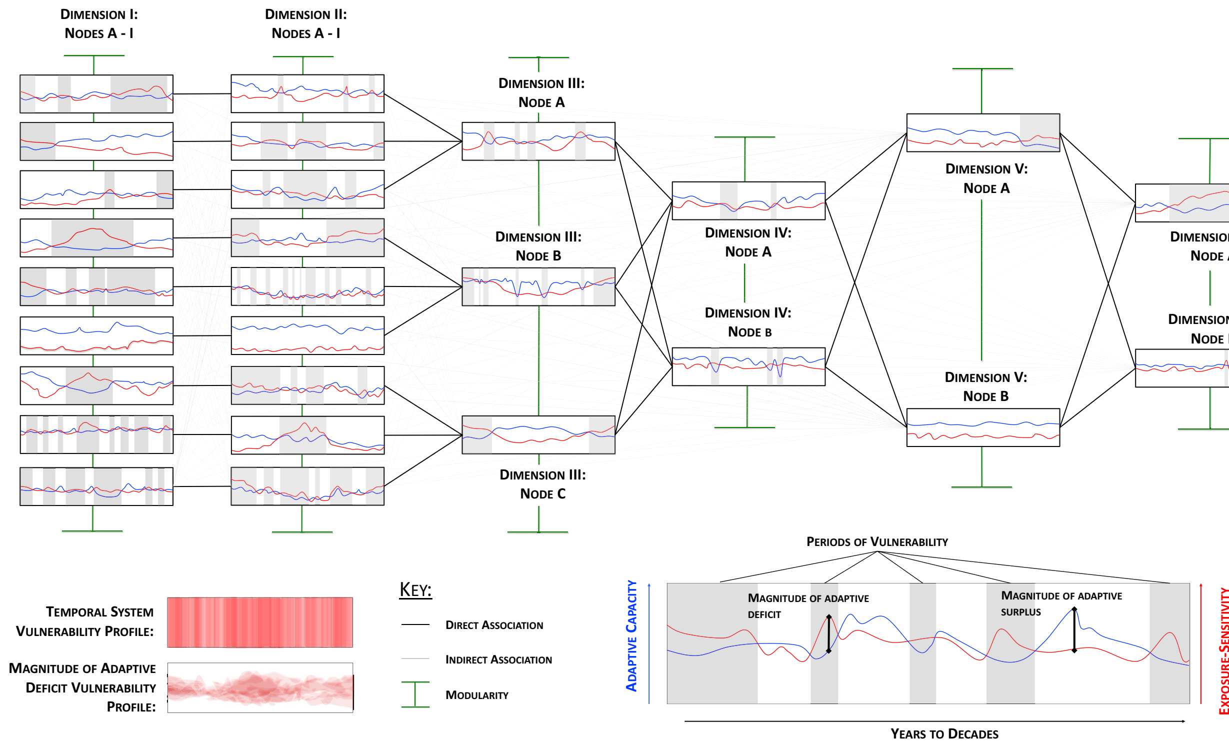

Figure 3. Composite Vulnerability Profile of an Idealized Human-Environment System

Here, the system is seen to comprise a CAS of multiple dimensions and nodes, which relate to areas where vulnerability has the potential to manifest. Through assessing the vulnerability of specific dimensions and nodes and accounting for their interlinkages and associations through time, it is possible to develop a whole-system vulnerability profile. This composite profile can highlight both the vulnerability of the overall system in time and the relative magnitude of its adaptive deficit or surplus in this time. The vulnerability of the system is further influenced by the redundancy potential of components that perform similar functions (e.g., dimensions V:A and V:B, whose linkages are demonstrated with green lines) and the degree to which components can be separated or disconnected from other vulnerable components within the system.

relationships. When accounting for interactions, the approach should also consider nodes within the reconstructed system for feedback (both positive and negative), their redundancy potential, and their modularity (see Complexity, Complex Adaptive Systems, and Vulnerability). Redundancy potential is critical in determining the overall vulnerability of the system because it permits specific nodes within the network to be placed outside of their coping capacity while still maintaining overall system stability.[77] Modularity describes the degree to which nodes within the system can be detached and separated from one another and therefore is a measure of the degree to which risks might cascade or transfer across nodes.[77]

By focusing explicitly on the temporal, process-based nature of vulnerability, adoption of this approach can help address concerns directed at previous vulnerability assessments discussed in Conceptualizing Vulnerability, particularly that they have had an overt focus on single, static points in time and have privileged the biophysical impacts of climatic change at the expense of other exogenous and endogenous sociopolitical drivers.[11,24,29] Figure 3 outlines a network of node interactions within a hypothetical system and provides a composite vulnerability profile for all of the system's exposure units. A worked example of a CAS in Box 1—in this case the traditional food system of Inuit in the Arctic—illustrates how the approach might be applied.

Knowledge surrounding *why* vulnerability occurs is an essential springboard for identifying and understanding opportunities for adaptation.[102] Our CAS vulnerability approach, catered to a specific system in the manner outlined in Box 1, directly addresses the question of why vulnerability manifests in a specific area and for certain people, is of a specific magnitude, and occurs at a specific time. From this, it is possible to gain an understanding of adaptation opportunities (e.g., direct economic investment, entitlements, and building social cohesion). The identification of entities with a high modulation potential, in conjunction with knowledge of the causal factors underlying potential vulnerability, will highlight nodes where an adaptive response might have a lower likelihood of maladaptive effects than other areas of the system or where an increase in vulnerability might have fewer knock-on impacts. In addition, through iterative reappraisal of exposure units and their interactions across time, the likelihood of capturing the role of feedback in affecting vulnerability between dimensions, and within the system as a whole, is increased. Construction of a total system vulnerability profile (or subdivisions therein based on modularity) and the creation of a "vulnerability fingerprint" are important in our framing because they allow for the tracking of vulnerability across an entire system across any given period of time. Furthermore, producing a vulnerability fingerprint also identifies "quick-win" areas where the magnitude of an adaptive deficit is small and, by extension, so too is the increase in coping capacity required to overcome it. Alternatively, in areas where it becomes evident that significant increases in adaptive capacity are required to overcome excess exposure sensitivity, the approach can identify "weakest link" areas within a CAS.[103]

Conclusion

This Perspective outlines an innovative conceptual approach for assessing climate-change vulnerability. Our approach builds upon previous scholarship that has conceptualized vulnerability as a function of relative exposure sensitivities and adaptive capacities and incorporates wider perspectives that vulnerability is dynamic and contextual rather than outcome based to emphasize that vulnerability is a *process* rather than a static or binary state. Vulnerability is therefore seen to be determined by the continuous interaction of multiple exogenous and endogenous stressors, in addition to the interconnectedness of components that interact with them.

To this end, we emphasize the need for climate vulnerability assessments to recognize systems as complex, adaptive, and comprising multiple dimensions and nodes. Each node is considered interrelated to a greater or lesser degree and has interoperability that facilitates overall system function. It is within nodes that potential manifestations of excess vulnerability arise, and these are tempered by their potential modularity and redundancy and have an effect on the net vulnerability potential of the system as a whole.[77,80] The dynamic state of vulnerability within the CAS, along with its exposure sensitivities and adaptive capacities, means that it is capable of migrating across nodes to alter system structure, status quo, or dynamic function. Vulnerability is understood in this manner with the objective of highlighting, among other factors, deficits in adaptive capacity and priority areas for adaptation. More specifically, an understanding of the role of modulation and redundancy between components with time, underpinned by knowledge of *why* certain areas are vulnerable, also allows the pinpointing of areas that are priorities for adaptive learning, potentially maladaptive trajectories, or other areas, which could be potentially susceptible to positive and negative feedback.

The CAS vulnerability approach is an attempt to overcome critiques leveled at past vulnerability approaches. Not only does the framing address the issue of how exogenous and endogenous drivers in adaptive capacity and exposure sensitivity drive local manifestations of vulnerability, but its focus on vulnerability as a process also departs from previous constructions and framings of vulnerability as a static and constant state. The utility of our approach comes from its ability to be generalized. If the components and relative bounds of a system are known, it would be possible to reconstruct and reorder nodes within our approach to assess vulnerability for any system across any given timescale, so long as it is conceptualized as complex and adaptive. Although the approach is not explicitly tied to a set of methods, it has been designed with the application of a longitudinal methodology in mind. Longitudinal application of our typology would facilitate an improved understanding of the magnitudes of deficit and surplus relating to both adaptive capacity and exposure sensitivity with time. Such work is rare at present but is urgently needed if we are to better understand how societal systems will be affected by future climate change.

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AUTHOR CONTRIBUTIONS

A.N. and J.F. conceived and developed the approach with additional input from T.P. and J.V.A. A.N. produced the original draft of and diagrams. All authors edited and approved the manuscript.

REFERENCES

1. Intergovernmental Panel on Climate Change (2018). Global Warming of 1.5°C. An IPCC Special Report. https://www.ipcc.ch/sr15/download/.
2. Gunderson, L.H., and Holling, C.S. (2002). Panarchy: Understanding Transformations in Human and Natural Systems (Island Press).
3. Low, B., Costanza, R., Ostrom, E., Wilson, J., and Simon, C. (1999). Human-ecosystem interactions: a dynamic integrated model. Ecol. Econ. *31*, 227–242.
4. Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., et al. (2007). Complexity of coupled human and natural systems. Science *317*, 1513–1516.
5. Blaikie, P., Wisner, B.G., Cannon, T., and Davis, I. (1994). At Risk (Routledge).
6. Bohle, H.G., Downing, T.E., and Watts, M.J. (1994). Climate change and social vulnerability. Glob. Environ. Change *4*, 37–48.
7. Kelly, P.M., and Adger, W.N. (2000). Theory and practice in assessing vulnerability to climate change and facilitating adaptation. Clim. Change *47*, 325–352.
8. Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., et al. (2003). A framework for vulnerability analysis in sustainability science. Proc. Natl. Acad. Sci. USA *100*, 8074–8079.
9. Ford, J.D., Smit, B., and Wandel, J. (2006). Vulnerability to climate change in the Arctic: a case study from Arctic Bay, Canada. Glob. Environ. Change *16*, 145–160.
10. Füssel, H.-M. (2007). Vulnerability: a generally applicable conceptual framework for climate change research. Glob. Environ. Change *17*, 155–167.
11. Tschakert, P., van Oort, B., St. Clair, A.L., and LaMadrid, A. (2013). Inequality and transformation analyses: a complementary lens for addressing vulnerability to climate change. Clim. Dev. *5*, 340–350.
12. Bennett, N.J., Blythe, J., Tyler, S., and Ban, N.C. (2016). Communities and change in the anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures. Reg. Environ. Change *16*, 907–926.
13. Watts, M.J., and Bohle, H.G. (1993). Hunger, famine and the space of vulnerability. GeoJournal *30* (2), 117–125.
14. Adger, W.N., and Kelly, P.M. (1999). Social vulnerability to climate change and the architecture of entitlements. Mitig. Adapt. Strat. Glob. Change *4*, 253–266.
15. O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L., et al. (2004). Mapping vulnerability to multiple stressors: climate change and globalization in India. Glob. Environ. Change *14*, 303–313.
16. Eakin, H., Winkels, A., and Sendzimir, J. (2009). Nested vulnerability: exploring cross-scale linkages and vulnerability teleconnections in Mexican and Vietnamese coffee systems. Environ. Sci. Pol. *12*, 398–412.
17. Adger, W.N., Eakin, H., and Winkels, A. (2009). Nested and teleconnected vulnerabilities to environmental change. Front. Ecol. Environ. *7*, 150–157.
18. Fazey, I., Kesby, M., Evely, A., Latham, I., Wagatora, D., Hagasua, J.-E., Reed, M.S., and Christie, M. (2010). A three-tiered approach to participatory vulnerability assessment in the Solomon Islands. Glob. Environ. Change *20*, 713–728.
19. Flynn, M., Ford, J.D., Pearce, T., and Harper, S.L.; IHACC Research Team (2018). Participatory scenario planning and climate change

impacts, adaptation and vulnerability research in the Arctic. Environ. Sci. Pol. *79*, 45–53.

20. Marino, E.K., and Faas, A.J. (2020). Is vulnerability an outdated concept? After subjects and spaces. Ann. Anthropol. Pract. https://doi.org/10.1111/napa.12132.
21. Bankoff, G. (2001). Rendering the world unsafe: 'vulnerability' as Western discourse. Disasters *25*, 19–35.
22. Ford, J.D., Pearce, T.D., McDowell, G., Berrang-Ford, L., Sayles, J.S., and Belfer, E. (2018). Vulnerability and its discontents: the past, present, and future of climate change vulnerability research. Clim.Change *151*, 189–203.
23. Räsänen, A., Juhola, S., Nygren, A., Käkönen, M., Kallio, M., Monge, A., and Kanninen, M. (2016). Climate change, multiple stressors and human vulnerability: a systematic review. Reg. Environ. Change *16*, 2291–2302.
24. Ford, J.D., and Pearce, T. (2012). Climate change vulnerability and adaptation research focusing on the Inuit subsistence sector in Canada: directions for future research. Can. Geogr. *56*, 275–287.
25. Hewitson, B.C., Janetos, T.R., Carter, F., Georgi, R.G., Gones, W.-T., Kwon, L.O., Mearns, E.L.F., and van Aalst, M.K. (2014). Regional Context. Climate Change 2014: Impacts, Adaptation and Vulnerability Part B: Regional Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press).
26. Jurgilevich, A., Räsänen, A., Groundstroem, F., and Juhola, S. (2017). A systematic review of dynamics in climate risk and vulnerability assessments. Environ. Res. Lett. *12*, 013002.
27. Comfort, L., Wisner, B., Cutter, S., Pulwarty, R., Hewitt, K., Oliver-Smith, A., Weiner, J., Fordham, M., Peacock, W., and Krimgold, F. (1999). Reframing disaster policy: the global evolution of vulnerable communities. Glob. Env. Change B Environ. Haz. *1*, 39–44.
28. Oliver-Smith, A. (1994). Peru's five-hundred year earthquake: vulnerability in historical context. In Disasters, Development and Environment, A. Varley, ed. (Wiley), pp. 3–48.
29. Kelman, I., Gaillard, J.C., Lewis, J., and Mercer, J. (2016). Learning from the history of disaster vulnerability and resilience research and practice for climate change. Nat. Hazards *82*, 129–143.
30. Lewis, J., and Kelman, I. (2010). Places, people and perpetuity: community capacities in ecologies of catastrophe. ACME *9*, 191–220.
31. Lewis, J. (1999). Development in Disaster-Prone Place: Studies of Vulnerability (Intermediate Technology Publications).
32. Intergovernmental Panel on Climate Change (2001). Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press).
33. Intergovernmental Panel on Climate Change (2007). AR4 Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press).
34. Costa, L., and Kropp, J.P. (2012). Linking components of vulnerability in theoretic frameworks and case studies. Sustain. Sci. *8*, 1–9.
35. Wisner, B. (2016). Vulnerability as a concept, model, metric and tool. In Oxford Research Encyclopaedia of Natural Hazards Science, S. Cutter, ed. (Oxford University Press). https://doi.org/10.1093/acrefore/9780199389407.013.25.
36. Ribot, J. (2017). Vulnerability does not just fall from the sky: addressing the vulnerability conundrum. In Risk Conundrums, R.E. Kasperson, ed. (Routledge), pp. 224–242.
37. Timmerman, P. (1981). Vulnerability, Resilience and the Collapse of Society. Environmental Monograph No. 1 (University of Toronto).
38. Gaillard, J.C. (2010). Vulnerability, capacity and resilience: perspectives for climate and development policy. J. Int. Dev. *22*, 218–232.
39. Hinkel, J. (2011). Indicators of vulnerability and adaptive capacity: towards a clarification of the science–policy interface. Glob. Environ. Change *21*, 198–208.
40. O'Brien, K., Eriksen, S., Nygaard, L.P., and Schjolden, A. (2007). Why different interpretations of vulnerability matter in climate change discourses. Clim. Pol. *7*, 73–88.
41. Joakim, E.P., Mortsch, L., and Oulahen, G. (2015). Using vulnerability and resilience concepts to advance climate change adaptation. Environ. Hazards *14*, 137–155.
42. Ribot, J. (2014). Cause and response: vulnerability and climate in the Anthropocene. J. Peasant Stud. *41*, 667–705.
43. Kelman, I., Gaillard, J.C., and Mercer, J. (2015). Climate change's role in disaster risk reduction's future: beyond vulnerability and resilience. Int. J. Disast. Risk Sc. *6*, 21–27.
44. O'Keefe, P., Westgate, K., and Wisner, B. (1976). Taking the naturalness out of natural disasters. Nature *260*, 566–567.
45. Oliver-Smith, A. (1977). Disaster rehabilitation and social change in yungay, Peru. Hum. Organ. *36*, 5–13.
46. Hewitt, K. (1983). The idea of calamity in a technocratic age. In Interpretations of Calamity: From the Viewpoint of Human Ecology, K. Hewitt, ed. (Allen & Unwin, Inc)), pp. 3–30.
47. Liverman, D.M. (1990). Vulnerability to global environmental change. In Understanding Global Environmental Change: The Contributions of Risk Analysis and Management, R.E. Kasperson, ed. (Centre for Technology, Environment and Development, Clark University), pp. 27–44.
48. McLaughlin, P., and Dietz, T. (2008). Structure, agency and environment: toward an integrated perspective on vulnerability. Glob. Environ. Change *18*, 99–111.
49. Sen, A. (1981). Poverty and Famines: An Essay on Entitlement and Deprivation (Clarendon Press).
50. Chambers, R. (1989). Editorial introduction: vulnerability, coping and policy. IDS Bull. *20*, 1–7.
51. Brooks, N. (2003). Vulnerability, Risk and Adaptation: A Conceptual Framework (University of East Anglia, Tyndall Centre for Climate Change Research).
52. Ford, J.D., and Smit, B. (2004). A framework for assessing the vulnerability of communities in the Canadian Arctic to risks associated with climate change. Arctic *57*, 389–400.
53. Füssel, H.-M., and Klein, R.J.T. (2006). Climate change vulnerability assessments: an evolution of conceptual thinking. Clim. Change *75*, 301–329.
54. van den Berg, H.J., and Keenan, J.M. (2019). Dynamic vulnerability in the pursuit of just adaptation processes: a Boston case study. Environ. Sci. Pol. *94*, 90–100.
55. Tschakert, P. (2007). Views from the vulnerable: understanding climatic and other stressors in the Sahel. Glob. Environ. Change *17*, 381–396.
56. Tuler, S., Agyeman, J., da Silva, P.P., LoRusso, K.R., and Kay, R. (2008). Assessing vulnerabilities: integrating information about driving forces that affect risks and resilience in fishing communities. Hum. Ecol. Rev. *15* (2), 171–184.
57. McDowell, J.Z., and Hess, J.J. (2012). Accessing adaptation: multiple stressors on livelihoods in the Bolivian highlands under a changing climate. Glob. Environ. Change *22*, 342–352.
58. McCubbin, S., Smit, B., and Pearce, T. (2015). Where does climate fit? Vulnerability to climate change in the context of multiple stressors in Funafuti, Tuvalu. Glob. Environ. Change *30*, 43–55.
59. Gautam, Y., and Andersen, P. (2017). Multiple stressors, food system vulnerability and food insecurity in Humla, Nepal. Reg. Environ. Change *17*, 1493–1504.
60. Zavaleta, C., Berrang-Ford, L., Ford, J., Llanos-Cuentas, A., Cárcamo, C., Ross, N.A., Lancha, G., Sherman, M., and Harper, S.L.; the Indigenous Health and Adaptation to Climate Change Research Group (2018). Multiple non-climatic drivers of food insecurity reinforce climate change maladaptation trajectories among Peruvian Indigenous Shawi in the Amazon. PLoS One *13*, e0205714.
61. Li, A., and Ford, J. (2019). Understanding socio-ecological vulnerability to climatic change through a trajectories of change approach: a case study from an indigenous community in Panama. Weather Clim. Soc. *11*, 577–593.
62. Whitfield, S., Beauchamp, E., Boyd, D.S., Burslem, D., Byg, A., Colledge, F., Cutler, M.E.J., Didena, M., Dougill, A., Foody, G., et al. (2019). Exploring temporality in socio-ecological resilience through experiences of the 2015-16 El Niño across the Tropics. Glob. Environ. Change *55*, 1–14.
63. Smit, B., and Pilifosova, O. (2003). From adaptation to adaptive capacity and vulnerability reduction. In Climate Change, Adaptive Capacity and Development, J.B. Smith, R.J.T. Klein, and S. Huq, eds. (Imperial College Press), pp. 9–28.
64. Luers, A.L. (2005). The surface of vulnerability: an analytical framework for examining environmental change. Glob. Environ. Change *15*, 214–223.
65. Debortoli, N.S., Sayles, J.S., Clark, D.G., and Ford, J.D. (2018). A systems network approach for climate change vulnerability assessment. Environ. Res. Lett. *13*, 104019.
66. Windfeld, E.J., Ford, J.D., Berrang-Ford, L., and McDowell, G. (2019). How do community-level climate change vulnerability assessments treat

future vulnerability and integrate diverse datasets? A review of the literature. Environ. Rev. *27*, 427–434.
67. Fawcett, D., Pearce, T., Ford, J.D., and Archer, L. (2017). Operationalizing longitudinal approaches to climate change vulnerability assessment. Glob. Environ. Change *45*, 79–88.
68. Ray, A.J., and Webb, R.S. (2016). Understanding the use context: decision calendars as frameworks for linking climate to policy, planning an decision-making. In Climate in Context: Science and Society Partnering for Adaptation, A.S. Parris, G.M. Garfin, K. Dow, R. Meyer, and S.L. Close, eds. (John Wiley & Sons), pp. 27–50.
69. Duvat, V.K.E., Magnan, A.K., Wise, R.M., Hay, J.E., Fazey, I., Hinkel, J., Stojanovic, T., Yamano, H., and Ballu, V. (2017). Trajectories of exposure and vulnerability of small islands to climate change. Wires Clim. Change *8*, https://doi.org/10.1002/wcc.478.
70. Penn, H.J.F., Gerlach, S.C., and Loring, P.A. (2016). Seasons of stress: understanding the dynamic nature of people's ability to respond to change and surprise. Weather Clim. Soc. *8*, 435–446.
71. Chapin, F.S., Folke, C., and Kofinas, G.P. (2009). A framework for understanding change, in principles of ecosystem stewardship. In Principles of Ecosystems Stewardship: Resilience-Based Natural Resource Management in a Changing World, C. Folke, G.P. Kofinas, and F.S. Chapin, eds. (Springer), pp. 3–28.
72. Ericksen, P.J. (2008). What is the vulnerability of a food system to global environmental change? Ecol. Soc. *13*, 14.
73. Ford, J.D., McDowell, G., Shirley, J., Pitre, M., Siewierski, R., Gough, W., Duerden, F., Pearce, T., Adams, P., and Statham, S. (2013). The dynamic multiscale nature of climate change vulnerability: an Inuit harvesting example. Ann. Am. Assoc. Geog. *103*, 1193–1211.
74. McDowell, G., Ford, J., and Jones, J. (2016). Community-level climate change vulnerability research: trends, progress, and future directions. Environ. Res. Lett. *11*, 033001.
75. Levin, S.A., and Lubchenco, J. (2008). Resilience, robustness, and marine ecosystem-based management. BioScience *58*, 27–32.
76. Timmermans, W., Ónega López, F., and Roggema, R. (2012). Complexity theory, spatial planning and adaptation to climate change. In Swarming Landscapes: The Art of Designing for Climate Adaptation, R. Rogemma, ed. (Springer), pp. 43–65.
77. Norberg, J., and Cumming, G. (2008). Complexity Theory for a Sustainable Future (Columbia University Press).
78. Manson, S.M. (2001). Simplifying complexity: a review of complexity theory. Geoforum *32*, 405–414.
79. Preiser, R., Biggs, R., De Vos, A., and Folke, C. (2018). Social-ecological systems as complex adaptive systems: organizing principles for advancing research methods and approaches. Ecol. Soc. *23*, 46.
80. Cairney, P. (2012). Complexity theory in political science and public policy. Polit. Stud. Rev. *10*, 346–358.
81. Levin, S.A. (1998). Ecosystems and the biosphere as complex adaptive systems. Ecosystems *1*, 431–436.
82. Rammel, C., Stagl, S., and Wilfing, H. (2007). Managing complex adaptive systems—a co-evolutionary perspective on natural resource management. Ecol. Econ. *63*, 9–21.
83. May, R.M., Levin, S.A., and Sugihara, G. (2008). Complex systems: ecology for bankers. Nature *451*, 893–894.
84. Allen, C.R., and Holling, C.S. (2010). Novelty, adaptive capacity, and resilience. Ecol. Soc. *15*, 24.
85. Berkes, F., and Ross, H. (2013). Community resilience: toward an integrated approach. Soc. Nat. Resour. *26*, 5–20.
86. Kalaugher, E., Bornman, J.F., Clark, A., and Beukes, P. (2013). An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: the case of a New Zealand dairy farming system. Environ. Model. Softw. *39*, 176–187.
87. Schoon, M., and Van der Leeuw, S. (2015). The shift toward social-ecological systems perspectives: insights into the human-nature relationship. Nat. Sci. Soc. *23*, 166–174.
88. Walker, B., Holling, C.S., Carpenter, S.R., and Kinzig, A. (2004). Resilience, adaptability and transformability in social-ecological systems. Ecol. Soc. *9*, 5.
89. Smit, B., and Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. Glob. Environ. Change *16*, 282–292.
90. Kates, R.W., Travis, W.R., and Wilbanks, T.J. (2012). Transformational adaptation when incremental adaptations to climate change are insufficient. Proc. Natl. Acad. Sci. USA *109*, 7156–7161.
91. Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Zieryogel, G., Walker, B., Birkmann, J.,, van der Leeuw, S., Rockström, J., et al. (2010). Resilience and vulnerability: complementary or conflicting concepts? Ecol. Soc. *15*, 1–25.
92. Davidson-Hunt, I., and Berkes, F. (2003). Learning as you journey: Anishinaabe perception of social-ecological environments and adaptive learning. Ecol. Soc. *8*, 5.
93. Wise, R.M., Fazey, I., Stafford Smith, M., Park, S.E., Eakin, H.C., Archer van Garderen, E.R.M., and Campbell, B. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. Glob. Environ. Change *28*, 325–336.
94. Engle, N.L. (2011). Adaptive capacity and its assessment. Glob. Environ. Change *21*, 647–656.
95. Eakin, H., and Luers, A.L. (2006). Assessing the vulnerability of social-environmental systems. Annu. Rev. Environ. Resour. *31*, 365–394.
96. de Andrade, M.M.N., and Szlafsztein, C.F. (2018). Vulnerability assessment including tangible and intangible components in the index composition: an Amazon case study of flooding and flash flooding. Sci. Total Environ. *630*, 903–912.
97. Ericksen, P.J. (2008). Conceptualizing food systems for global environmental change research. Glob. Environ. Change *18*, 234–245.
98. Kuhnlein, H.V., Erasmus, B., and Spigelski, D. (2009). Indigenous Peoples' Food Systems: The Many Dimensions of Culture, Diversity and Environment for Nutrition and Health (Food and Agriculture Organization of the United Nations, Centre for Indigenous Peoples' Nutrition and Environment)).
99. Prno, J., Bradshaw, B., Wandel, J., Pearce, T., Smit, B., and Tozer, L. (2011). Community vulnerability to climate change in the context of other exposure-sensitivities in Kugluktuk, Nunavut. Polar Res. *30*, https://doi.org/10.3402/polar.v30i0.7363.
100. Ford, J.D. (2009). Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik. Nunavut. Reg. Environ. Change *9*, 83–100.
101. Statham, S., Ford, J., Berrang-Ford, L., Lardeau, M.-P., Gough, W., and Siewierski, R. (2014). Anomalous climatic conditions during winter 2010-2011 and vulnerability of the traditional Inuit food system in Iqaluit, Nunavut. Polar Rec. *51*, 301–317.
102. Ribot, J. (2011). Vulnerability before adaptation: toward transformative climate action. Glob. Environ. Change *21*, 1160–1162.
103. Tol, R.S.J., and Yohe, G.W. (2007). The weakest link hypothesis for adaptive capacity: an empirical test. Glob. Environ. Change *17*, 218–227.