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Harnessing the potential of vulnerability assessments for managing social-ecological systems

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Abstract

The concept of vulnerability has broadened from initial applications in the fields of risk and hazards, human ecology and resilience to now being included into the management of social-ecological systems (SESs). We review how this concept has been operationalized in various contexts and identify opportunities and challenges to apply vulnerability assessments to SESs management in the face of social, environmental, and climatic changes. We propose a 12-step framework to help practitioners scope, design, operationalize, and implement vulnerability assessments that can effectively minimize exposure, reduce sensitivity, and build adaptive capacity. We describe the rationale, assumptions and implications that underlie each step and highlight future research directions that are critically needed to further enable vulnerability assessments to address real-world sustainability challenges. These include applying biocultural approaches, building knowledge about SES vulnerability to non-climate stressors, and anticipating potential trade-offs and maladaptation. The framework presented provides a roadmap for the development of integrated vulnerability assessments that are robust, context-specific and relevant to social-ecological management objectives.

Keywords: conservation planning; environmental management; risk; social-ecological systems; sustainability; vulnerability

Introduction

Vulnerability assessments can inform the development of adaptation and conservation policy and support the integration of socio-economic and ecological factors into decision-making (Metcalf *et al.* 2015; Gurney *et al.* 2019). They help identify weak points in a system in order to design appropriate interventions to sustain social-ecological systems (SESs) in the face of environmental change.

Research on vulnerability has traditionally been carried out within three linked fields of knowledge, with varying understanding and use of the concept: (1) anticipation of how environmental hazards, generally climate-related, are likely to impact human societies (risk and hazard research); (2) exploration of the social causes of differential susceptibility (political ecology); and (3) identification of underlying processes that determine the ability to cope and adapt to change (resilience research) (Turner *et al.* 2003a; Kasperson *et al.* 2005; Adger 2006; Eakin and Luers 2006; Brugère and De Young 2015). Building on the conceptual and practical foundations provided by these complementary approaches, the Intergovernmental Panel on Climate Change (IPCC) presented a definition that is now the foundation of many vulnerability assessments: “vulnerability [to climate change] is the degree to which systems are susceptible to, and unable to cope with, adverse impacts [of climate change]” (IPCC 2001, 2007). This formulation includes three key dimensions: exposure, sensitivity and adaptive capacity.

As management and conservation move towards more holistic and integrative approaches, and more quantitative datasets and model outputs from multidisciplinary projects become available (Guerrero *et al.* 2018), efforts to assess vulnerability have gained attention in relation to SES. Vulnerability assessments help identify vulnerable components or places within the SES (vulnerability ‘hotspots’) and better understand structural deficiencies (vulnerability ‘sources’), informing management prioritization and design, respectively (Cinner *et al.* 2013b, a; Foden *et al.* 2013; Maina *et al.* 2016; Smith *et al.* 2016; Johnson and Welch 2016; Thiault *et al.* 2018b). Vulnerability assessments are also increasingly used as a common objective or tool for resilience-based management and adaptation policy (Anthony *et al.* 2015; Mcleod *et al.* 2019). For example, various Pacific Island countries have implemented integrated vulnerability assessments with the aim to improve multi-sector coordination, strategically tailor interventions and prioritize management effort and resource

allocation (SPC-SPREP-GIZ 2016) and, in some cases, address specific issues such as food security (Bell and Taylor 2015; Bell *et al.* 2018).

Although originally centered around the impacts of climate-related stressors on human societies, vulnerability, as used today, overlaps with key themes of the contemporary sustainability narrative, including human-nature interactions, complex systems science, sustainable development goals, global change and ecological resilience and adaptation (Clark *et al.* 2003; Turner *et al.* 2003a; Folke *et al.* 2016). For example, vulnerability is increasingly used to encompass more complex processes such as cross-scalar influences, tele-coupling and multiple stressors (O'Brien and Leichenko 2000; Turner *et al.* 2003b; O'Brien *et al.* 2004; Belliveau *et al.* 2006; Tschakert 2007; Adger *et al.* 2009; McDowell and Hess 2012; Debortoli *et al.* 2018). Likewise, the emergent concept of social-ecological vulnerability (Marshall *et al.* 2009; Cinner *et al.* 2013b; Maina *et al.* 2016; Berrouet *et al.* 2018; Thiault *et al.* 2018a, b; Depietri 2019) echoes the increasingly mainstream recognition that people and nature are interdependent, because people are part of ecosystems and shape them, but are also fundamentally dependent on the capacity of these systems to support wellbeing and development (Fischer *et al.* 2015; Lebot and Siméoni 2015; Aswani *et al.* 2017; Ticktin *et al.* 2018; IPBES 2019).

Scholars exploring SES vulnerability have made great strides toward identifying key processes affecting system sustainability. But despite the potential of the vulnerability concept to tackle contemporary management problems, barriers continue to prevent uptake by policy-makers and managers (Table 1), and too few assessments lead to tangible outcomes or actions to reduce vulnerability in SESs. The lack of comprehensive, widely applicable and reliable guidance to accompany both analyses and programmatic efforts for vulnerability assessments has raised concerns about their suitability to fulfill strategic objectives, such as communicating risk, rationalizing policy decisions, and monitoring the effect of management interventions (Füssel 2007; Hinkel 2011).

Here, our aim is two-fold. First, we aim to channel vulnerability assessments in a way that fosters knowledge accumulation and sharing through synthesis and generalization. To this end, we suggest a 12-step framework that guides practitioners to easily understand and conduct a vulnerability assessment. This framework synthesizes the different practices that

107 have been used to evaluate vulnerability in SESs and highlights current best-practices. Second,
108 we propose new directions for research and application.

Table 1 | Challenges for considering vulnerability assessments in decision-making.

Concerns	Opportunities for addressing concerns
<ul style="list-style-type: none"> • Vulnerability research provides a static understanding of a likely dynamic problem. 	<ul style="list-style-type: none"> • Use a longitudinal study design by repeating vulnerability assessments over time. Employ visualization and analytics tools that can illustrate vulnerability and associated components across space and time.
<ul style="list-style-type: none"> • Indicators oversimplify complex processes leading to vulnerability. • Assumptions of simple linear relationships between indicators and vulnerability that do not reflect the dynamic processes driving vulnerability. 	<ul style="list-style-type: none"> • Use multiple indicators from various data sources and knowledge systems for triangulation and maximum accuracy. Adapt indicators to the assessment objectives. • Be explicit about the assumptions and limitations underpinning the indicators selected. • Clearly indicate the overall objective and perspective driving the assessment (socioeconomic, biocultural, ecological, etc.) and how interactions between the various system's components were considered. • Formulate algorithms that best represent the relationship among vulnerability dimensions and indicators
<ul style="list-style-type: none"> • Elements of vulnerability vary according to the context, scale and study perspective. 	<ul style="list-style-type: none"> • Lists of contributors to a system's vulnerability (e.g., dimensions of exposure, sensitivity and adaptive capacity and their sub-elements) have been identified in various contexts and scales, and can be used to guide the selection of locally-relevant indicators. • Large-scale vulnerability assessments provide a motivation for more detailed, contextual analyses of the place-based dynamics of vulnerability at smaller scales.
<ul style="list-style-type: none"> • Vulnerability assessments rely preferentially upon specialized, academic knowledge and insufficient consideration of key stakeholders. 	<ul style="list-style-type: none"> • Encourage stakeholder input and participation from diverse knowledge systems at appropriate stage(s) of the assessment. • Be consistent with local terminology and ontologies, use non-technical language where possible.
<ul style="list-style-type: none"> • Vulnerability terminology has a negative connotation and is disempowering to local people by labeling them as 'vulnerable'. 	<ul style="list-style-type: none"> • Careful use of vulnerability terminology. "Vulnerability" and other negatively balanced terms should be used within academic and government circles but not in actual research and communication with local people. • Highlight empowering elements such as experience, adaptive capacity or resilience when working and communicating with local people.
<ul style="list-style-type: none"> • Vulnerability gives too little attention to the underlying drivers that shape exposure-sensitivities and adaptations. 	<ul style="list-style-type: none"> • Draw greater attention to the socio-economic, political, governance and cultural contexts that shape how stressors are experienced and responded to, for example through participatory approaches.
<ul style="list-style-type: none"> • Elements of vulnerability do not carry equal weight between contexts. 	<ul style="list-style-type: none"> • Local expert judgement, multi-criteria decision techniques, and other approaches that are available enable quantification of the relative contribution of individual indicators when empirical weights are not available.

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- Vulnerability lacks clarity on the relative importance of each indicator.
 - Apply sensitivity and uncertainty analyses.
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Assessing vulnerability in social-ecological systems

In our opinion, practitioners attempting to assess vulnerability of SESs should apply four phases: scoping, design, operationalization and implementation (Fig. 1). Each phase is composed of multiple steps for which we describe the overall rationale and review relevant approaches employed to date, their assumptions, and potential shortcomings. The framework we present is not meant to be prescriptive but rather to highlight important steps and challenges, based on an extensive review of the literature and our experiences in applying vulnerability assessments in different settings. Vulnerability assessments encompass a broad range of approaches, scales and objectives, but here, we only refer to indicator-based assessments that are relevant to local and regional management and policies.

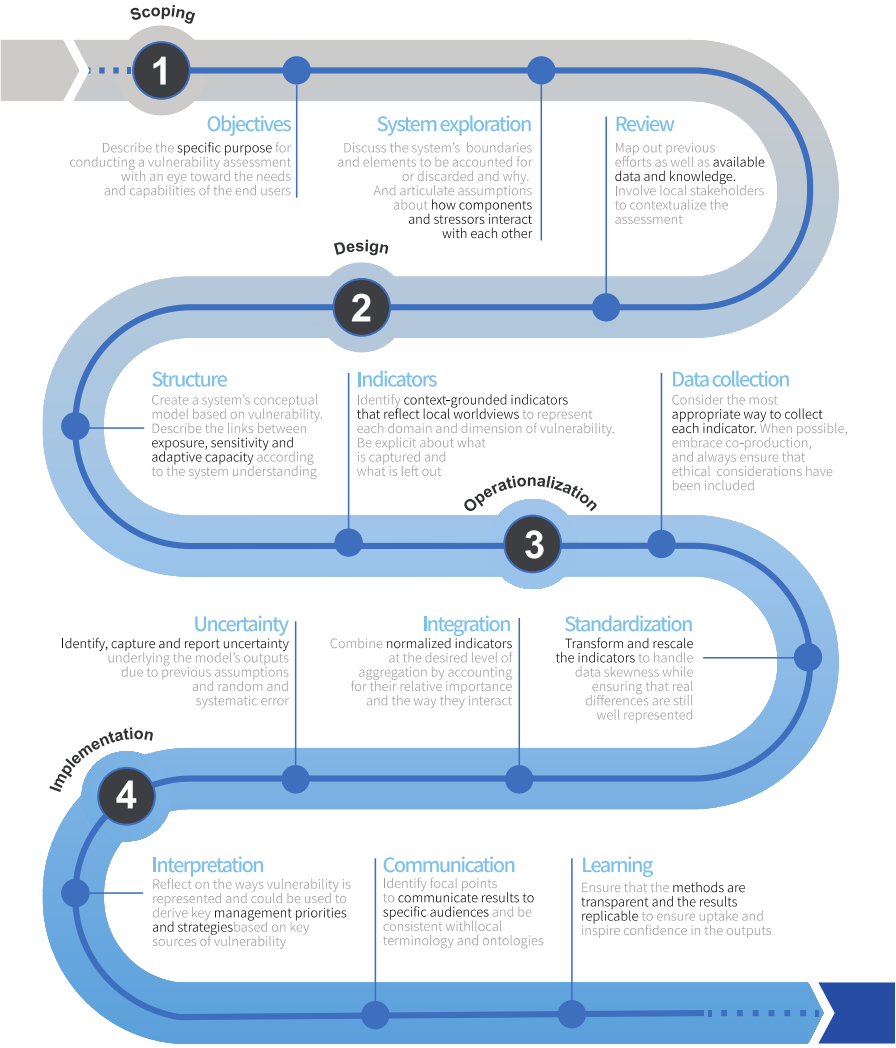


Figure 1: Flowchart of the four phases and 12 steps for conducting robust, context-specific and policy-relevant vulnerability assessments of social-ecological systems.

1. Scoping

The point of entry to every vulnerability assessment begins by clearly articulating the objectives, the spatial and temporal boundaries, the system components being assessed, and the available data and resources. This first phase lays the foundation for the rest of the vulnerability assessment.

1.1. Objectives and engagement with end-users

For vulnerability assessments to be more than an academic exercise and effectively support decision-making, they should be designed with a focus on the needs of the end-users, whether they be local managers, policy-makers or other stakeholders. Engaging with practitioners from the start is a critical first step to clearly articulate the specific purpose of the assessment, and identify the general decision context and specific trigger points for action within existing regulatory frameworks. This step thus involves examining the specific needs of the end-users and identifying the main questions to be answered, but also determining the timeframe for the assessment (e.g. are the results going to inform short-term decisions and actions, or medium- to long-term planning?) as well as the agency and opportunity context in which it will be imbedded.

Vulnerability assessments have application in a variety of contexts. They can, for instance, help establish management and planning priorities (Aretano *et al.* 2015; Mora *et al.* 2015; Thiault *et al.* 2018b; Lapola *et al.* 2019; Bourgoignie *et al.* 2020), assist in informing and designing management strategies and interventions (Cinner *et al.* 2012; Johnson and Welch 2016; Humphries *et al.* 2019; Thiault *et al.* 2019a), set a baseline and assess change (Fawcett *et al.* 2017; Thiault *et al.* 2018a), inform sectorial programming (Ayers and Huq 2009; Cinner *et al.* 2012), or conduct scenario planning for building management alternatives (Hallegatte *et al.* 2011). Importantly, each assessment varies not only in the type of output, but also in input requirements. Therefore, the right approach for any particular assessment will depend on the end-user's goals, and on the level of resources (data, expertise, time, funding) available.

Discussions to set assessment objectives can also be good fora to develop common principles for “good practice” in carrying out vulnerability assessments. These should include assurances for: stakeholder participation (steps 1.3 and 3.1); ensuring free, prior and informed consent in data collection (step 3.1); consideration of gender and social inclusion and human rights

approaches in identified interventions (step 4.1); and maintaining confidentiality of data from affected populations (step 4.2).

Since vulnerability involves a particular terminology, and the assessment is a collaborative endeavor, developing system literacy may be warranted to discuss and reflect collectively on the key concepts. To help in this process, we provide definitions and examples of key terms and concepts (Table 2).

Table 2 | Glossary of terms with definitions adapted from the primary literature and illustrative examples from social (S) and ecological (E) systems.

Term	Definition	Social and ecological examples
Vulnerability	Degree to which a system's components are susceptible to, or unable to cope with, adverse effects of a stressor (modified from IPCC 2001, 2007). Vulnerability has three dimensions: exposure, sensitivity, and adaptive capacity.	Vulnerability of [component]'s [attribute] to [stressor].
Vulnerability assessment	Analytical exercise whose goal is to assess vulnerability of a valued attribute of one or more system's component(s) to one or more stressor(s) (Tonmoy <i>et al.</i> 2014), often with the aim to inform management and decision-making.	Multi-dimensional models (Pacifi <i>et al.</i> 2015), fuzzy cognitive mapping (Singh and Nair 2014), paleo-ecological reconstructions or scenarios as proxies (Beaugrand <i>et al.</i> 2015), criteria-based assessments (Cinner <i>et al.</i> 2013a; Johnson <i>et al.</i> 2016).
Component	Sub-system entity that is contained within the system of interest.	S: Individuals, households, communities, countries. E: Species, stocks, habitats, ecosystems, eco-regions.
Attribute	Quality or feature inherent to the system's component likely to be affected by a stressor. Change in a component's attribute following exposure may provide a measure of vulnerability outcome.	S: Household wellbeing, community health. E: Species biomass, stock productivity, ecosystem condition.
Stressor	Threat to a component. Either a major spike in pressure (pulse) beyond the normal range of variability in which the system operates, or a continuous or slow onset pressure (press), commonly within the range of normal variability (adapted from Turner <i>et al.</i> 2003a).	S: Economic/market shocks (pulse), population growth (press or pulse), coup d'état (pulse) E: Tropical cyclone (pulse), sea level rise (press), changing water quality (pulse or press).
Exposure	Nature and degree to which a component is in contact with, or subject to, a stressor (IPCC 2001; Kasperson <i>et al.</i> 2005; Adger 2006; Gallopín 2006).	Magnitude, frequency, duration and/or extent of [stressor] experienced by [component].
Sensitivity	Conditions determining the degree to which a component is directly or indirectly altered or modified in the short-term by stressor exposure (modified from IPCC 2001, 2007 and Bousquet <i>et al.</i> 2015).	S: Economic, demographic, psychological and cultural dependency (Marshall <i>et al.</i> 2017) E: Specialization, dependence on environmental triggers, dependence on interspecific interactions [likely to be disrupted by stressor], rarity (Foden <i>et al.</i> 2013).
Adaptive Capacity	Latent ability to implement effective and responses to changes by minimizing, coping with, or recovering from the potential impacts of a stressor (Whitney <i>et al.</i> 2017; Cinner <i>et al.</i> 2018).	S: Assets, flexibility, organization, learning, agency (Cinner <i>et al.</i> 2018). E: Life-history traits, genetic variation and evolvability, phenotypic plasticity, (Nicotra <i>et al.</i> 2015).

1.2 System exploration

This step is about framing the vulnerability assessment. It requires describing explicitly the key elements of the SES to be accounted for, and articulating assumptions about how SES components and stressors interact. Through this step, analysts focus on what is important, provisionally deciding what should be included and what should be left out, eventually arriving at a shared conceptual understanding of the identity of the system (Binder *et al.* 2013). Specifically, this step includes identifying key component(s) (*vulnerability of what?*), the stressor(s) (*vulnerability to what?*) and the pathways through which system components are affected by the stressor(s). For example, in the vulnerability framework developed by Cinner *et al.* (2012), the authors decided to explicitly focus on vulnerability of coupled coral reef SES to climate change impacts at the community-level. While the authors acknowledged that multiple factors can affect coral reef SES, they explicitly focused their analysis on pathways to direct ecological impact from temperature-induced bleaching and mortality of reef-building corals (ecological vulnerability) and associated loss of ecosystem services (social vulnerability).

Another key issue to consider during this initial system exploration is the temporal and spatial scale of the assessment, which needs to correspond to the scales of underlying processes that affect the outcome and the time horizons of the management decisions in order to be compatible with the objectives (step 1.1). In defining a systems boundary, the scope of the study is explicitly set based on a number of factors including budget, data needs and other resources necessary for vulnerability assessments. For example, if the objective is to prioritize national implementation of a certain policy (e.g. protected areas) based on current vulnerability, then the assessment could be static and remain constrained to national boundaries (REF). On the other hand, if the objective is about assessing system response to a policy, then repeated assessments involving two or more snapshots will be warranted to capture dynamic feedback (REF).

1.3 Review

Once the objectives are defined and the key components and stressor(s) have been clearly articulated, it is important to map out previous efforts and projects that have had similar objectives. This process will: assist in planning for data collection (e.g. prioritizing resource allocation for new primary data sources) and analysis (e.g. identifying technical capacities

needed); create an evidence-base for evaluating system component responses to changed conditions; assist in aggregating indicators; and may lead to re-evaluation of assessment objectives and scope. Beyond the people directing the assessment, a variety of stakeholders may be involved to assist in this step. Decision-makers, managers, resource users, opinion leaders, scientists and holders of traditional knowledge can, among others, provide important data and sociocultural and political context (Reed 2008; Skroblin *et al.* 2019). The degree of engagement with these stakeholders will depend on the specific circumstances and needs.

2. Design

Reflecting on the objectives, system model, and available resources enables a strategic approach to designing the vulnerability assessment. Practitioners can build on the knowledge generated in the Scoping phase to identify the most appropriate assessment structure and design indicators. The choices made at all these steps should be justified and documented for transparency and replicability.

2.1 Model structure

We propose that quantitative vulnerability assessments should include at least three nested layers of increasing detail: *dimensions*, *domains* and *indicators*, which comprehensively incorporate relevant theories and context-grounded information (Box 1). The model structure describes high-level interactions, generally among social and/or ecological *dimensions*, and helps translate the system understanding (from step 1.2) into a causal model of vulnerability. The model structure is the backbone of the vulnerability assessment. Its choice is therefore important because it shapes the outputs that will be derived from the assessment.

Box 1: Dimensions, domains and indicators of vulnerability

A vulnerability assessment should be capable of determining what makes each case unique and what makes each case generalized and comparable across settings. Here we propose that vulnerability assessments incorporate three nested layers that vary in the specificity of their definition: dimensions (generic), domains (moving from generic to specific) and indicators (context-specific).

Vulnerability is comprised of three broad *dimensions*: exposure, sensitivity and adaptive capacity (Table 1): (1) Exposure is the magnitude, frequency, duration and/or extent in which a component is in contact with, or subject to, a stressor; (2) sensitivity defines the degree to which a component is directly or indirectly altered or modified in the short-term by the stressor; and (3) adaptive capacity captures current ability to minimize, cope with, or recover from the potential impact of a stressor through effective and long-term responses to changes (Table 1). All three *dimensions* influence vulnerability but, especially in social-ecological vulnerability assessments, the division between these dimensions is not always clear. Since *dimensions* provide the higher-level (first tier) underpinnings for implementing vulnerability-based management (i.e., reducing exposure, decreasing sensitivity and/or building adaptive capacity), it is crucial that the meaning of each dimension within the particular context of the analysis is clearly stated.

Domains break down each dimension into the features that moderate, or contribute to vulnerability. The domains are the features of the systems' component(s) that are most critical to influencing vulnerability in the general context of the study (described during the 'Scoping' phase). They enable practitioners to identify parts of the dimensions that are contributing the most to overall vulnerability, or which could benefit from efforts to reduce vulnerability. We consider *domains* to be heuristics that help scientists and practitioners organize their inquiries of vulnerability. While there are no 'incorrect' domains, it is crucial that they fit the context of the study system and location, and are anchored in relevant theories.

Building on decades of empirical and theoretical work, authors have indeed proposed a variety of *domains* to characterize dimensions of vulnerability. For example, in the context of climate change, exposure can be based on environmental variables/stressors likely to impact system components (Mora *et al.* 2018). These stressors typically fall into either press (chronic) or pulse (acute) *domains* (Anthony *et al.* 2015). Example of climate stressors used to describe indicators may include precipitation change (press) and extreme marine heat events (pulse) (Day *et al.* 2019; Fig 2). In addition to climate stressors, exposure *domains* may derive from environment, economic or other external pressures. Recently, Marshall *et al.* (2017) proposed that social sensitivity to environmental change be disaggregated into four *domains* (economic dependency, demographic dependency, physiological dependency and cultural dependency),

and Cinner et al. (2018) that social adaptive capacity relied on five *domains* (assets, flexibility, social organization, learning and agency). Likewise, a number of studies have developed *domains* for ecological components (Weißhuhn et al. 2018; Foden et al. 2019). For example, still in the context of climate change, Foden et al. (2013) proposed four *domains* of sensitivity (specialization, dependence on environmental triggers, dependence on interspecific interactions likely to be disrupted by stressor, and rarity), and Nicotra et al. (2015) identified three key *domains* of species adaptive capacity (life-history traits, genetic variation and evolvability, and phenotypic plasticity).

In some cases, *domains* can include multiple elements that are deemed locally relevant. For example, various elements of education have been identified as being important for Pacific Island communities: quality of education; access to and use of formal educational pathways; role of local knowledge/language in formal education; diverse learning opportunities; access to and use of technical and scientific information (Dacks et al. 2019).

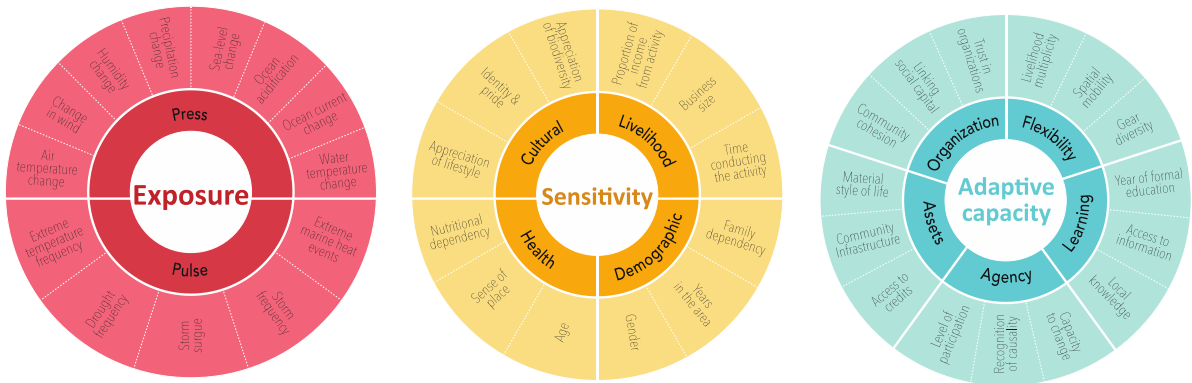


Figure 2: Conceptual diagram illustrating the three proposed nested layers for theoretically and contextually-grounded vulnerability assessments: *dimensions* (inner circle), *domains* (middle circle) and *indicators* (outer circle). Examples of domains and indicators are modified from (Marshall et al. 2017; Cinner et al. 2018; Day et al. 2019) and describe social vulnerability of resource-dependent communities to climate change.

Various model structures linking exposure, sensitivity and adaptive capacity have been proposed over the past few decades that reflect the way the system was conceptualized initially (step 1.2). In its simplest form, a vulnerability assessment focuses on one single type of component (e.g. communities, countries, species, habitats, ecosystems) in relation to a single stressor (e.g. economic shock, population growth, tropical cyclone, climate change). In this case, exposure and sensitivity determine the potential impact, and vulnerability then results from the potential impact combined with (or tempered by) adaptive capacity (Fig 3a).

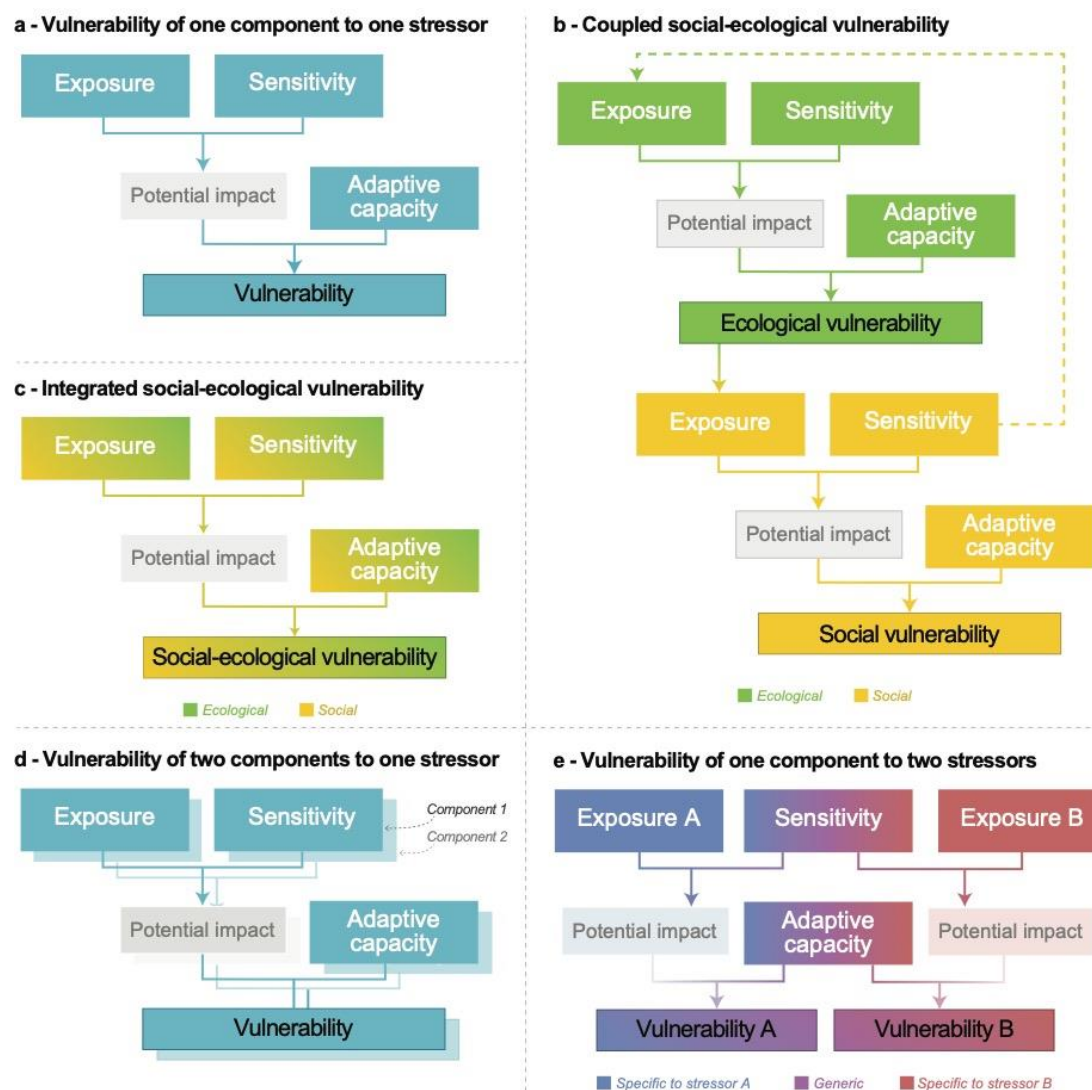


Figure 3 | Examples of possible structures for the vulnerability assessments, depending on how the system was conceptualized.

In more complex instances, social and ecological components may be considered as linked and interdependent, for example through ecosystem services delivery (e.g. vulnerability of a social component to vulnerability of the ecological component), use (e.g. vulnerability of ecological component to use by a social component), or both. In such cases, social and ecological vulnerabilities are “coupled” and influence each other: the ecological vulnerability assessment is used as input data to the exposure of social vulnerability assessment (Marshall *et al.* 2009; Cinner *et al.* 2013a), and social sensitivity potentially affects ecological exposure (Thiault *et al.* 2018a, b) (Fig. 3b). Alternatively, an “integrated” assessment dove-tails both ecological and social indicators in a single assessment step to deliver semi-quantitative results that identify the main sources of vulnerability and determine which actions will be the most

effective (Johnson and Welch 2016; Johnson *et al.* 2016; Bell *et al.* 2018) (Fig. 3c). Selecting between a “coupled” or “integrated” approach depends on the understanding of the linkages between social and biophysical systems. If the objective of the assessment is to examine the vulnerability of two or more types of components to the same stressor, dimensions are likely to be specific to each component (Fig. 3d), unless shared pathways and processes are involved across components. For instance, in their global assessment of the vulnerability of agriculture and fisheries (the components), Blanchard *et al.* 2017 used sector-specific exposure (projected changes in sectorial productivity) and sensitivity (dependency on each sector) but adopted a generic view of adaptive capacity because they considered that their indicator (level of economic development) enabled a country to mobilize resources and adjust any type of food production sector to potential climate-induced impacts. Alternatively, an assessment of one component to two (or more) stressors (O’Brien and Leichenko 2000; Leichenko and O’Brien 2002; Bennett *et al.* 2014; Thiault *et al.* 2019b) may require a parallel assessment where some *domains* and indicators are generic to all stressors while others are specific to a stressor (Fig. 3e).

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2.2. Indicators

Indicators are characteristics or processes that can be measured or estimated to track the state or trend of a particular *domain*. Indicators, more so than *dimensions* or *domains*, can be customized (Box 1) to each specific context, availability of information, and the overall resources available. The best indicators are those that are specific, measurable, attainable, relevant and time-bound (SMART).

Analysts use indicators as quantifiable representations of system components and attributes. In doing so, they place value on what they believe to be important representations of exposure, sensitivity and adaptive capacity and their underlying *domains*. Co-creation of indicators with decision-makers and end-users helps to ensure that they are context grounded and reflect local worldviews.

Any evaluation of vulnerability based on indicators will always comprise a subset of all possible sources of vulnerability and so will capture only a fraction of ‘true’ vulnerability (Brenkert and

Malone 2005). For example, some cultural values and knowledge are characteristically aspatial (Ban *et al.* 2013) and may be impractical to incorporate in a spatial vulnerability model. Bias toward easily quantifiable indicators can miss critical elements driving system vulnerability, while indicators that are not relevant to local viewpoints, aspirations, and cultural settings can misdirect the assessment outputs and result in the implementation of programs that do not fit local contexts (Sterling *et al.* 2017b). It is therefore critical to define what the subset of indicators represents and what it omits. Co-creation of indicators with the end-users of the assessment as well as with affected stakeholders (e.g. resource users) is critical so that they are both context grounded and also reflect local worldviews (Tengö *et al.* 2014). However, it is important to note that this type co-production of indicators can create trade-offs with generalizability, as the indicators developed may lack meaning and applicability in other locations.

Because individual indicators generally do not perfectly characterize each vulnerability *domain*, and because indicators are subject to measurement uncertainty, it is desirable to consider several indicators concurrently for each *domain*. Indicators also need to reflect what can be addressed by management interventions in order to avoid a mismatch between what is assessed and what is addressed.

3. Operationalization

Once the assessment design is established, methodological issues need to be considered. This phase includes reflecting on how data are collected and analyzed, and estimating underlying uncertainties so that the outputs can be adequately represented and interpreted by the end-users.

3.1. Data collection

How the data are collected, why, and by whom are all important considerations, as the data included in the vulnerability assessment will inform the outcomes, relevance, applicability, and use. It is therefore important to consider the most appropriate method and methodology for each indicator, and how this may influence the outcomes of the vulnerability assessment. Since each vulnerability assessment is context-specific, the most appropriate data may vary depending on scope, circumstances and resource availability.

Possible data sources include data from primary research (ecological surveys, interviews, perceptions, model projections), secondary data sets (official databases, censuses, expert elicitation, spatial data), and grey literature (Kittinger *et al.* 2014). It is of great value to incorporate local actors, decision-makers, and other stakeholders in the research. To achieve this, existing empirical data could be considered along with information derived from expert elicitation, local surveys, participatory mapping, workshops and focus groups (Cochrane *et al.* 2019).

Local and cultural knowledge can play a key role in developing a holistic understanding of the system, integrating locally-grounded sources of data, and identifying locally-relevant indicators. This step can be an opportunity to embrace co-design and co-production (Lemos *et al.* 2018; Wyborn *et al.* 2019) and engage with approaches that build upon local cultural perspectives, values, knowledge, and needs (Sterling *et al.* 2017a). For example, resource-dependent communities, which are at the frontline of vulnerability to change, have experiences that can provide local expertise on suitable indicators (McMillen *et al.* 2014). Therefore, their participation is also instrumental to identifying relevant adaptation actions (step 4.1). By contrast with the above “objective” approaches that are independent of the subject's judgment, a “subjective” analysis relying on people's self-assessments of their own exposure, sensitivity or adaptive capacity may be employed (Jones 2018).

Importantly, the vulnerability assessment and associated data collection must be ethical, and ethics applications should be sought wherever is necessary and appropriate. Ibbett and Brittain (2019) recently found that nearly half of the conservation journal articles that should have included ethics information did not, which means important ethical safeguards were not in place for human participants or collaborators in this research. Ethics will be an especially important consideration for vulnerability assessments, as these assessments will typically be carried out in areas where people may already be vulnerable or at risk.

Climate forecasts and greenhouse gas emission scenarios

Central to vulnerability analyses is the role of climate change in influencing the system. Often climate change as represented by General Circulation models (GCMs) derived projections, is presented as exposure component of vulnerability. An understanding of the different climate scenarios is paramount, given that climate forecasts are based on future scenarios of

greenhouse gas (GHG) emissions (IPCC, 2014). It is essential that CCVA explicitly states and describes the assumptions pertaining to GHG emission (i.e. climate change scenarios) considered in the assessment. For example, the IPCC climate change assessment reports explicitly describe the scenarios considered (i.e. AR4 scenario in the 4th generation models (commonly referred to as SRES); AR5 scenario in the 5th (current) generation models; and AR6 in the 6th generation (expected in 2021) models). Climate projections from the fourth IPCC assessment report (AR4) are based on a previous set of socio-economic based scenarios termed the *Special Report on Emissions Scenarios* (SRES; Nakicenovic & Swart, 2000). These SRES scenarios were the basis for the Coupled Model Inter-comparison Project (CMIP4) suite of Ocean and Atmosphere General Circulation Models (i.e. future climate data). Projections for the IPCC fifth assessment report (AR5) are based on the radiation-based scenarios of *Representative Concentration Pathways* (RCP; Moss et al. 2010; van Vuuren et al. 2011) and simulations from the Coupled Model Inter-comparison Project Phase 5 (CMIP5). Understanding the assumptions underpinning each of the emission scenarios is necessary for comparing and matching future climate predictions across different generations of IPCC climate change scenarios (i.e. SERS, AR5, AR6) to allow the use of data from the diverse set of models and scenarios (e.g. Table 1).

3.2. Standardization

Unless using an inductive approach (step 3.3), indicators generally have to be standardized through transformation and rescaling so that indicators of different units (e.g. number of person-job in households, degrees heating from climate change, contribution of an activity to livelihood) and scales (e.g. individual vs. community vs. country level) can be integrated (step 3.3). Decisions about if and how to standardize data can have important consequences on the outcomes of vulnerability assessments and require careful consideration.

Data transformation deals with handling skewness and distribution. While there is no single right answer for how best to transform data, there is reasonable justification for preserving some or all of the skew when deciding if and how to transform the data because the original variability generally represents real differences, and usually has relevance for understanding how vulnerability differs among components. Transformation may nevertheless be necessary to improve the interpretability of data or eliminate the effects of certain outliers that

otherwise would compress the variation. Common data transformation methods include Min-Max normalization and Z score normalization or, when the distribution is skewed towards one side, root-, cube root-, and log-transformation. Winsorization can also be applied when extreme values are present. This transformation sets outliers to a specified percentile of the data and has been applied in vulnerability assessments (Ekstrom *et al.* 2015). With knowledge of threshold responses in systems, outliers value could be Winsorized to the tipping point value, but these are currently assumptions unknown in the majority of cases, especially for social entities, and in turn would require more assumptions. Fuzzy logic technique can also be used to standardize and synthesize indicators especially in cases with complex response behavior pattern.

Rescaling involves adjusting values measured on different scales to a notionally common scale, say 0-100. In certain cases, indicators may already be scaled in this manner and can be used as is. In other cases, the indicator can be defined as a percentage (e.g. contribution of fishing to household income, proportion of climate-sensitive species) and can be readily converted to a 0-100 scale. Other indicators may have a finite range of possible values (e.g. level of trust on a Likert scale or Shannon diversity), and could be scaled by simply applying a constant multiplicative factor. Some, more challenging, indicators do not have a bounded range of possible values (e.g. household size, species biomass). In such cases, the lowest and highest values are generally used to define the bounds and rescale the other values proportionately, assuming that they represent the true range of all possible values. Whatever the decision about selecting these methods, it is important to be explicit and transparent about the decision.

For semi-quantitative assessments where secondary data or grey literature are used, scores are generally assigned for each indicator using criteria on a 3-point (or 5-point Likert) scale and the scores for each *dimension* are standardized and normalized to account for score variability.

3.3. Integration

Once standardized, it can be useful to combine indicators to provide a composite measure of vulnerability. When integrating, care should be taken to ensure complementarity of

indicators, their relative values (which standardization provides) and their relative importance to the system analyzed (see discussion on weighting below)

There are different ways that data can be integrated in a vulnerability assessment. Depending on the level of analysis required, indicators may be aggregated at the *domain-*, *dimension-* or overall vulnerability-level. This requires accounting for the relative importance of indicators (weights) and the way they interact to reflect the desired level of analysis. Aggregation and weighting methods are strong determinants of the outcomes of the vulnerability assessment (Monnereau *et al.* 2017) and this is why it is important to reflect on the appropriate approach.

There are three broad categories of weighting approaches. The first one relies on empirical weights derived from statistical models (e.g. regressions, tree-based, or structural equation models) to explain vulnerability outcomes (i.e. a measured change in a component's attribute) as a function of indicators describing exposure, sensitivity and adaptive capacity (Eakin and Bojórquez-Tapia 2008; Hinkel 2011; Morel *et al.* 2019). The rationale behind this "inductive approach" is that the means by which indicators determine vulnerability in one context can be translated to predict vulnerability in other broadly similar contexts. While results depend strongly on the inputs and available data being modelled, inductive approaches remain useful to refine theory and assess which particular indicators and interactions are more closely associated with vulnerability in a given context. Although very powerful, such kind of approaches have rarely been applied in practice so far (but see XXXX for +/- successful examples) as they typically require the model to be built prior to the vulnerability assessment and require large amounts of data.

Another less robust, but more operational method when empirical data are lacking, builds on available theory and knowledge to identify how indicators combine to form vulnerability. Because such information is generally qualitative by nature, "deductive arguments" rely on metrics such as the number of scientific papers attributing a causal effect of an indicator on an attribute to estimate the "amount of scientific evidence", and thus the weight, supporting a given indicators or domain (Cinner *et al.* 2013a). Alternatively, weights can be assigned by a pool of experts (i.e. academics, decision-makers, managers, stakeholders), either directly, or (preferably) indirectly using ranks to elicit scores through mathematical formulas multiple-criteria decision analysis (e.g. Analytic Hierarchy Process, Measuring Attractiveness by a

Categorical Based Evaluation Technique) (see for example McClanahan *et al.* 2008). Of course, expert judgements are not immune from potential biases (differences in experts' values, risk tolerance, and other subjective influences), but these can be minimized using a large number of experts to survey if the expert pool is large enough. They also have the added advantage of improving participation.

Third, approaches that cannot rely on inductive or deductive arguments have estimated weights based on the variability of the data for a given indicator (e.g. principal component analysis; Abson *et al.* 2012). Such data-driven "descriptive approach" is based on the structure (co-occurrence) of the indicators. Highly correlated indicators (e.g. wealth and education, or functional and taxonomic diversity) will tend to group together, and different principal components could be used to assess *domains*. Another type of deductive approach, include the use of equal weightings schemes (Tonmoy *et al.* 2014) under the assumption that all indicators contribute equally to a particular *domain* nested in a particular *dimension*. Choosing between a deductive and a descriptive approach is a decision based on the available data and whether it is known that some indicators are more important than others in influencing (negatively or positively) vulnerability. While it is likely that the influence of indicators is not equal, if the value and interactions among indicators are not well understood a decision should be made to treat them equally (Allison *et al.* 2009).

Despite being a defining feature of SES (Parrott and Meyer 2012) that has been highlighted in the vulnerability literature (Luers 2005), non-linear relationships are difficult to incorporate in practice due to the lack of information on how indicators, *domains* and *dimensions* of vulnerability generally interact to determine vulnerability. This is particularly true for deductive and descriptive approaches, which only provide weight estimates. Without clear evidence to include complex interactions, additive and multiplicative vulnerability remain default models. Both models require more assumptions. Additive models assume that the indicators are perfect substitutes, meaning that low value in one is compensated by high value in another one. Multiplicative models imply that vulnerability, dimensions or domains are limited by the lowest variable of the underlying determinants (but see Tol and Yohe (2007) for an empirical disproof of this assumption in a hazard/risk context). Other approaches based

on ranks (Parravicini *et al.* 2014) or network-based methods (Debortoli *et al.* 2018) have also been used in order to minimize the effect of data transformation on the final output.

3.4. Uncertainties

Uncertainty is a ubiquitous problem in vulnerability assessments, yet, few studies have explicitly engaged with it (Tonmoy *et al.* 2014). Uncertainty can emanate from four main sources. First, some processes generating vulnerability may not be known or quantifiable. Second, while individual indicators hold a relationship to a process generating vulnerability, the nature of this relationship is often undetermined (see step 3.3). Third, random (i.e. caused by natural fluctuations of indicators) and systematic errors (i.e. caused by the measurement method) can generate a high level of imprecision, especially if they are averaged over spatial or temporal scales and/or projected into the future. Fourth, indicators and the weights attached to them are sometimes evaluated by interviewing stakeholders or experts and the process inevitably carries a level of subjectivity, as well as possible variances between the opinions of different informants.

Various methods have been used to capture these different sources of uncertainty. The use of multiple indicators to depict individual *domains* (step 2.2), for instance, is a simple method to reduce random and measurement errors. Fuzzy-set theory has been used to incorporate uncertainty stemming from vague definitions and lack of knowledge about vulnerability and its *dimensions* (Eierdanz *et al.* 2008; Eakin and Bojórquez-Tapia 2008; Jones and Cheung 2017). Common multiple-criteria decision analysis methods often provide an estimation of judgement consistency, and can be used to adjust scores when during expert elicitation exercises aiming at estimating indicator weights (Eakin and Bojórquez-Tapia 2008; McClanahan *et al.* 2008; Thiault *et al.* 2018b). Computational experiments such as Monte Carlo simulations also help distinguishing robust from less reliable modelling results by modelling vulnerability under various combinations of data sources, transformation, aggregation and/or weightings methods where various data are randomly selected and used to investigate the range of possible vulnerability outcomes (Thiault *et al.* 2018b, 2019b; Bourgoin *et al.* 2020). Sensitivity analyses enable estimates of the overall influence of such factors and provide important knowledge for reviewing their reliability and potentially directing monitoring effort to increase robustness of the assessments. Issues of uncertainty

are not confined to vulnerability assessments, and lessons on how to deal with uncertainties can be learned from more mature strains of applied research such as cumulative impact assessments (Halpern and Fujita 2013; Stock and Micheli 2016; Stelzenmüller *et al.* 2018).

Assessing uncertainties is a valuable component of vulnerability assessments. Not only does an integrated measure of uncertainty in the final result inform the measure of confidence in applying the outcomes, it can also inform potential revision to how indicators may have been integrated (step 3.3). Perhaps of greatest value, quantified (including categorized) uncertainty can identify opportunities for future efforts to reduce the determined uncertainty (e.g., through additional research efforts).

4. Implementation

The results of a vulnerability assessment are not an endpoint, but a source of information to incorporate into decision-making and planning. This phase is about moving from assessment results to real-world application. The success of this phase determines the extent to which vulnerability will be practically managed and the concept made useful.

4.1. Interpretation

Interpreting the outputs of vulnerability assessments is essential for decision-making. This step entails reflecting on how vulnerability can be portrayed in two, complementary ways: aggregated or disaggregated. First, assessments that describe vulnerability at the highest aggregation level, produce a vulnerability score and/or ranking. This information can in turn help decision-makers select targets and set identify priorities (e.g. protecting the 15 most vulnerable species, investing in capacity building for the 10% most vulnerable areas assessed, or spreading effort across the range of vulnerability scores). Aggregated vulnerability portrayals are especially suited in a spatial context, where vulnerability ‘hotspots’ can be priorities or discarded, depending on the overall strategy (Parravicini *et al.* 2014; Smith *et al.* 2016; Thiault *et al.* 2018b). This type of information can potentially be incorporated within a framework for systematic prioritization, for instance via *Marxan* or *prioritizer*. Fully aggregated vulnerability outputs are also useful for temporal comparisons, where the vulnerability of a system is expected to change over time following a particular event or intervention or external stressors (Thiault *et al.* 2018a).

While aggregated assessments of vulnerability are useful, they can lack the specific recommendations (and resolution of these) needed by decision-makers to understand and effectively manage SESs. The second, disaggregated representation typically considers the multiple *dimensions* of vulnerability (Sietz *et al.* 2011; Foden *et al.* 2013; Kok *et al.* 2016). By looking at the interactions between exposure, sensitivity and adaptive capacity, leverage points can be identified (Fischer and Riechers 2019) and option space for management and policy explored. Indeed, if low vulnerability is the fundamental objective, then it can be achieved via actions to reduce exposure, decrease sensitivity, build adaptive capacity, or a combination of those, depending on the main sources of vulnerability. An array of strategies to address each *dimension* contributing to vulnerability has been identified. These are generally derived from the applied research literature and “translated” in the language of vulnerability (Thiault *et al.* 2019a). For example, in their vulnerability assessment of fishing communities to the impacts of climate change, Cinner *et al.* (2012) have proposed interventions focusing on strengthening community groups and investing in strong local institutions to build social adaptive capacity, both of which are directly derived from Ostrom’s and colleagues’ work on commons and fisheries applications (Ostrom 2009; Basurto *et al.* 2013). Other recommendations based on this assessment include the development of social safety nets, adaptive management approaches or poverty reduction, and diversifying livelihoods which are core principles of the Sustainable Livelihood Approach (Allison and Ellis 2001; Allison and Horemans 2006). Many examples of vulnerability assessments in the ecological realm have emerged over the recent years and identify avenues for management and policy using the same rationale (Johnson and Marshall 2007; Foden *et al.* 2013; Parravicini *et al.* 2014; Anthony *et al.* 2015; Okey *et al.* 2015; Bell *et al.* 2011, 2015; Johnson and Welch 2016; Johnson *et al.* 2016), illustrating the ability of this framework to foster multi-disciplinary assessments that inform targeted policy and management.

Of course, aggregated and disaggregated approaches are not mutually exclusive and can be taken sequentially, thus providing a richer understanding of management priorities and potential strategies. Cluster analyses that group a set of components according to the similarity of their indicators or *domains* are an example of hybrid approach to identify both management priorities (high vulnerable clusters) and options (cluster-specific sources of vulnerability potentially leading to cluster-specific interventions) (Sietz *et al.* 2011, 2017).

Each intervention should be evaluated against other broader social, economic, and cultural considerations as well as the agency and opportunity contexts defined in step 1.1. For example, the ‘sweet spot’ for management in terms of an ideal intervention can be to target a component assessed as highly vulnerable where importance (value) and amenability to management (cost effectiveness) are also high (Johnson *et al.* 2016). Outside this ‘sweet spot’ there will be trade-offs among the three and managers can select the trade-offs that best align with the management objectives, stakeholder values and budget.

4.2. Communication

Once the outputs are obtained, care should be given to the way the results are communicated to the intended audience. Being vulnerable can be seen as a negative concept and emphasis should be given to the resilience and adaptive capacity concepts. One should pay attention to clear articulation of terms and avoidance of undefined acronyms or obscure technical jargon. This is also where most of the cost-effective policy levers for transformation can be found. Furthermore, it can be useful to place any proposed response activities in the context of maintaining the status quo (which may include undertaking no action). For effective communication, VA producers would need employ available media and visual aids (e.g., graphs, tables, maps and figures) for dissemination. Use of color in graphics to indicate relative vulnerability of the species assessed and error bars to indicate the limits of uncertainty can be powerful means of communication (Dubois et al., 2011). Media such as brief reports, graphs and summary tables can quickly convey complexities that are hard to explain in other ways. Furthermore, present technology has made it possible for the establishment of platforms that allow illustration of vulnerability and its components across temporal and spatial dimensions.

Recently, social media has become increasingly useful for disseminating results to broad audiences. For example, Twitter, Facebook, and Instagram posts that include striking images, graphs and videos can direct audiences toward more in-depth reports, briefing notes and media reports about vulnerability assessment results, while enabling the popularization of ideas that might otherwise be overlooked in decision-making processes.

It is important to be aware of the problems inherent in communicating CCVA results. Two kinds of content that need special attention are those of uncertainty and vulnerability. Scientific uncertainty is vastly different to the common use of the term, and this point needs to be clearly refreshed for certain audiences. Where possible it is important to quantify uncertainty and

provide descriptions of what is known and what is uncertain. For example, it is certain that sea level will rise but less certain about the magnitude of the rise.

When communicating VA results, being transparent on uncertainty levels (step 3.4), as in any risk or cumulative impact assessment (Stelzenmüller *et al.* 2018) is of primary importance. An appropriate way of communicating such VA results would include scenarios that encompass the species' known (or likely) responses to favor wet habitats, likelihoods of how those habitats might be affected, and the uncertainties surrounding how a species will respond to new conditions where its preferred habitat(s) cannot be found. The uncertainty is not in the species' preferences, but in how the habitats will change and how the species will respond to a new climate. It may be helpful to emphasize what we know based on applied principles of ecology, physics and/or chemistry, with very little uncertainty, first and foremost.

4.3. Learning

XXXXX

The transfer of data and knowledge is a neglected key step in vulnerability assessments. Transparent and replicable assessments are needed to ensure trust, uptake into decision-making and actions, and improve SESs understanding as a whole.

Being transparent and able to replicate the results will give researchers, decision-makers, and stakeholders confidence in the assessment in its use as a tool to inform policy and practice.

Replicability is necessary to identify lags in the system's responses to environmental change and management interventions, to assess for the impact on new stressors on vulnerability, or to account for new relevant data as it becomes available. Replicated assessments can also indicate if management priorities, resource allocations and applied interventions have been fit and appropriate for reducing vulnerability. Guidance now exists on how to make science more open and replicable (Lowndes *et al.* 2017)

Vulnerability assessments need to be transparent. Failure to do so precludes a full understanding of what has been done for non-specialists. Decisions are often not taken directly based on vulnerability assessment outcomes, but the outputs of the assessments are the basis for discussions in arenas where multiple knowledge sources compete in supporting a decision (Claudet *et al.* 2020). In such arenas, the uptake of vulnerability assessments is

643 facilitated for assessments where all the steps are evidenced and where all the decisions that
644 have been taken (e.g. boundaries of the system, type of data, choice of indicators, ...) are
645 documented.. Developing a repository of vulnerability assessments, where all the above
646 choices are explicitly documented, as it exists for other fields (e.g. EcoBase for EwE models;
647 systematic planning (Álvarez-Romero *et al.* 2018)) would help in this respect.

Future research avenues

We identified future research avenues to make vulnerability assessments more robust and useful. The ideas below are not the only way forward for improving vulnerability assessments (Eakin and Luers 2006), but they represent potential pathways for evaluating vulnerability in a way that is cognizant of the contemporary challenges facing SES and more in line with the present discourse on environmental policy.

Biocultural approaches

- to (1) better capture social-ecological interdependencies and (2) bridge global and local policy and management.

Vulnerability assessments are a powerful tool that can be applied at various scales, from local to global. However, it is important to not lose sight of one of their main objectives, guiding communities towards sustainability transformations. To be successful in doing so, engagement of both decision-makers and local communities is key. Using a biocultural approach (Sterling et al. 2017) to the co-development of the research question, assessment objectives and model structure, and to the co-creation of indicators can ensure VAs are both context grounded and reflect local worldviews (Sterling et al. 2017).

Vulnerability to non-climatic stressors:

So far, most applications of the vulnerability concept have focused on the socioeconomic impacts caused by hazards- and climate-related stressors, and most knowledge on vulnerability relates to these schools of thought. However, SES are exposed and potentially vulnerable to a broad range of socioeconomic and biophysical stressors beyond climate and the subsequent environmental change (Bennett *et al.* 2016). As a consequence, vulnerability has gained traction in other areas, with applications ranging from social vulnerability to management (Chen *et al.* 2014; Chen and Lopez-Carr 2014; Tilley and López-Angarita 2016), socioeconomic changes (O'Brien and Leichenko 2000; O'Brien *et al.* 2004; Belliveau *et al.* 2006; Thompson *et al.* 2016), poaching (Thiault *et al.* 2019b), fire (Aretano *et al.* 2015), and other human uses of ecosystems (Jones and Cheung 2017; Thiault *et al.* 2018b; Bourgoin *et al.* 2020). However, such assessments tend to lack theoretical and/or empirical underpinnings,

and are consequently undertaken without a good understanding of the determinants and processes affecting vulnerability in that particular context.

One possibility to improve the robustness and relevance of the vulnerability concept outside of its original field may be to draw on other, linked strains of research more explicitly. Ecological vulnerability assessments, for instance, are largely based on work from the resilience and ecotoxicology literatures (Ippolito *et al.* 2010; Mumby *et al.* 2014; Beroya-Eitner 2016), which use similar languages and concepts (e.g. sensitivity/resistance, adaptation/recovery) and enable inference from empirical evidence. In regards to social vulnerability in a management and natural resource management context, lessons can be learned from diagnostic and archetype approaches when looked at through the lens of vulnerability (Oberlack *et al.* 2016; Fader and Rulli 2017; Eisenack *et al.* 2019). For instance, Ostrom's SES framework (Ostrom 2009) can serve as a knowledge base for identifying the key attributes that foster or hinder SES sustainability and relevant interventions to reduce vulnerability.

When it is not possible to link vulnerability to findings from other fields, inductive approaches (step 3.3) could be employed. Before-After/Control-Impact types assessments can be implemented to test, for example, the sources of adaptive capacity that fishers draw upon when a new marine reserve is implemented in their fishing grounds (vulnerability to management), or how exposure to new market conditions is experienced by resource-dependent communities depending on their levels of sensitivity and adaptive capacity. While application of such powerful approaches to non-climatic stressors remain relatively rare to date, there is much scope for progress given the increasing availability of long-term monitoring data and the growing capacity of statistical models at handling complex processes.

Trade-offs and maladaptation:

A critical gap in vulnerability practice is insufficient consideration of the potential unintended or perverse side-effects that vulnerability reduction interventions may have due to feedbacks and linkages throughout the broader SES. It is often assumed that reducing vulnerability through targeted actions addressing the source(s) of vulnerability (e.g. enhancing adaptive capacity, reducing sensitivity) will benefit the SES as a whole. Yet, the relationships between the various components of a SES are complex, unlikely to be fully captured by a vulnerability

assessment, and therefore feedbacks and linkages may lead to unexpected outcomes at the SES level.

One of the key aspects of social-ecological vulnerability may be the potential for high social adaptive capacity (generally considered desirable) to enable exploitation and degradation of an ecological component (generally considered undesirable) (Cinner *et al.* 2011). This phenomenon has been termed amplifying adaptive capacity because of the propensity for adaptive capacity to amplify environmental change (Cinner *et al.* 2011). However, we know little about how to avoid amplifying adaptive capacity and how to foster adaptive capacity associated with responses likely to reduce ecological degradation (dampening adaptive capacity). Unrecognized trade-offs inherent in vulnerability-based management may also occur across vulnerability *domains* and across spatial and temporal scales (Cinner *et al.* 2018). Other forms of trade-offs occur when stressor-specific capacity building programs inadvertently increase vulnerability to other stressors. This may occur, for instance, when high adaptive capacity exposes people to new stressors, increase their sensitivity to those new stressors, or crowds-out the means available for other specific adaptation (Belliveau *et al.* 2006; McDowell and Hess 2012; Bacon *et al.* 2017; Finkbeiner *et al.* 2017).

Maladaptation can occur when for example, capacity building (e.g. improved infrastructure) may lead people to be overly reliant on these safety nets and become complacent or fail to perceive the need to invest in risk planning (Næss *et al.* 2005; Saldaña-Zorrilla 2008; Eakin and Bojórquez-Tapia 2008; Adger and Barnett 2009; Lemos *et al.* 2013; Barnett *et al.* 2015; Pomeroy *et al.* 2017). Failure to anticipate trade-offs and maladaptation can jeopardize sustainability (Barnett and O'Neill 2010). More research is needed to understand the likely positive or negative outcomes interventions might have across *dimensions, domains, components, and stressors*, and reduce uncertainty in vulnerability-based decisions (Heltberg *et al.* 2009).

Conclusions

The structure that is presented here addresses many of the short-comings of past approaches (Table 1) and thus represents the best available science. The intention is for this work to encourage practitioners to applying the best possible practices and stimulate much needed

discussion and experimentation. With careful consideration of the issues raised here, vulnerability assessments will become well grounded, thus giving them the potential to provide important insights to support decision-making. The structure presented in this paper represents a library of actions that can each be drawn upon as part of a vulnerability assessment. Implementing all of the steps may not always be possible given available resources and the planning and effort required. Nevertheless, increased awareness of the issues covered here will help to prevent inappropriate conclusions from being drawn from vulnerability studies. Improving the reliability of vulnerability assessments is not a small challenge, but a worthwhile one, given their great potential to provide balanced insights into management in a time when practical solutions to navigate new sustainability problems are needed.

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1052 Table 1: Comparison and matching of two generations of IPCC climate change experiments,
1053 commonly referred to as SRES and RCP scenarios described in greater detail by Moss et al.,
1054 (2010) & van Vuuren et al., (2011).

Climate change experiments		Description
RCP	SRES	Particular difference
RCP 2.6	None	
RCP 4.5	SRES B1	Median temperatures in RCP4.5 rise faster than in SRES B1 until mid-century, and slower afterwards.
RCP 6	SRES B2	Median temperatures in RCP6 rise faster than in SRES B2 during the three decades between 2060 and 2090, and slower during other periods of the twenty-first century.
RCP 8.5	SRES A1FI	Median temperatures in RCP 8.5 rise slower than in SRES A1FI during the period between 2035 and 2080, and faster during other periods of the twenty-first century.

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