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

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30 **Abstract**

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

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

47 **Introduction**

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

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

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

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

79 Although originally centered around the impacts of climate-related stressors on human
80 societies, vulnerability, as used today, overlaps with key themes of the contemporary
81 sustainability narrative, including human-nature interactions, complex systems science,
82 sustainable development goals, global change and ecological resilience and adaptation (Clark
83 *et al.* 2003; Turner *et al.* 2003a; Folke *et al.* 2016). For example, vulnerability is increasingly
84 used to encompass more complex processes such as cross-scalar influences, tele-coupling and
85 multiple stressors (O'Brien and Leichenko 2000; Turner *et al.* 2003b; O'Brien *et al.* 2004;
86 Belliveau *et al.* 2006; Tschakert 2007; Adger *et al.* 2009; McDowell and Hess 2012; Debortoli
87 *et al.* 2018). Likewise, the emergent concept of social-ecological vulnerability (Marshall *et al.*
88 2009; Cinner *et al.* 2013b; Maina *et al.* 2016; Berrouet *et al.* 2018; Thiault *et al.* 2018a, b;
89 Depietri 2019) echoes the increasingly mainstream recognition that people and nature are
90 interdependent, because people are part of ecosystems and shape them, but are also
91 fundamentally dependent on the capacity of these systems to support wellbeing and
92 development (Fischer *et al.* 2015; Lebot and Siméoni 2015; Aswani *et al.* 2017; Ticktin *et al.*
93 2018; IPBES 2019).

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

103 Here, our aim is two-fold. First, we aim to channel vulnerability assessments in a way that
104 fosters knowledge accumulation and sharing through synthesis and generalization. To this
105 end, we suggest a 12-step framework that guides practitioners to easily understand and
106 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.

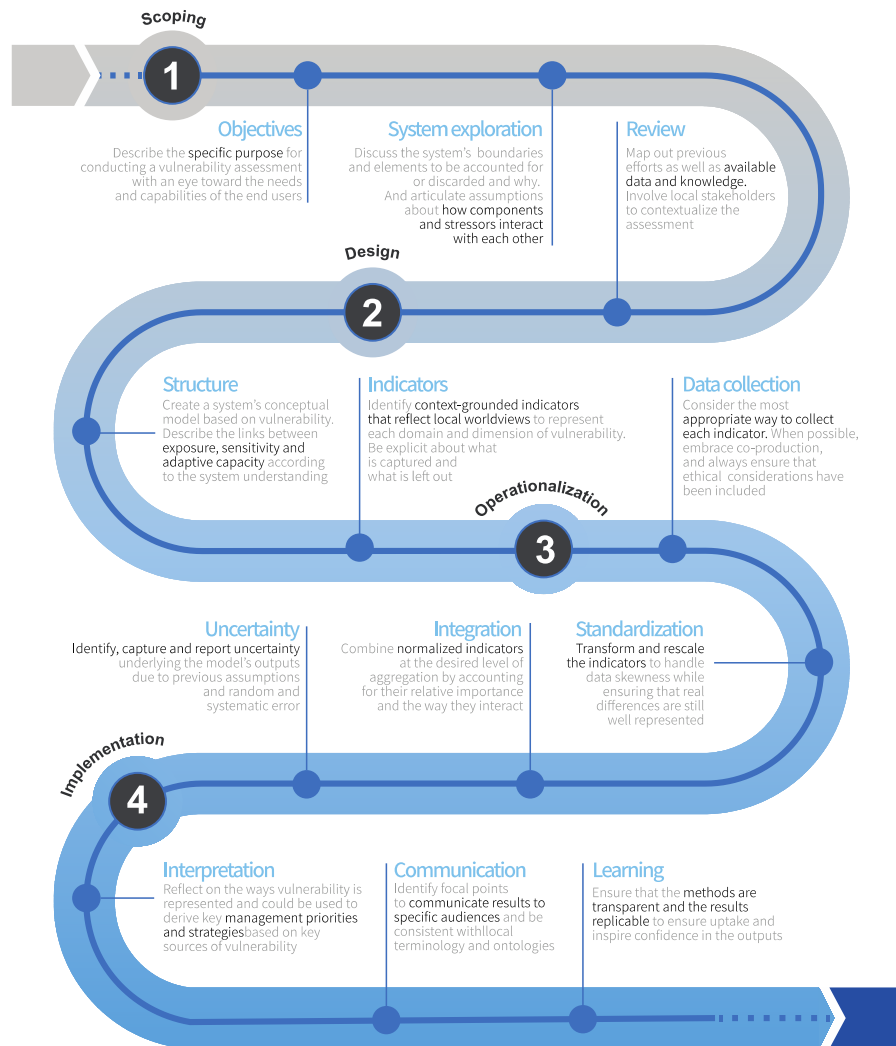
Table 1 | Challenges for considering vulnerability assessments in decision-making.

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.

-
- Vulnerability lacks clarity on the relative importance of each indicator.
 - Apply sensitivity and uncertainty analyses.
-

111 Assessing vulnerability in social-ecological systems

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



121

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

124 **1. Scoping**

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

129 *1.1. Objectives and engagement with end-users*

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

140 Vulnerability assessments have application in a variety of contexts. They can, for instance,
141 help establish management and planning priorities (Aretano *et al.* 2015; Mora *et al.* 2015;
142 Thiault *et al.* 2018b; Lapola *et al.* 2019; Bourgoin *et al.* 2020), assist in informing and designing
143 management strategies and interventions (Cinner *et al.* 2012; Johnson and Welch 2016;
144 Humphries *et al.* 2019; Thiault *et al.* 2019a), set a baseline and assess change (Fawcett *et al.*
145 2017; Thiault *et al.* 2018a), inform sectorial programming (Ayers and Huq 2009; Cinner *et al.*
146 2012), or conduct scenario planning for building management alternatives (Hallegatte *et al.*
147 2011). Importantly, each assessment varies not only in the type of output, but also in input
148 requirements. Therefore, the right approach for any particular assessment will depend on the
149 end-user's goals, and on the level of resources (data, expertise, time, funding) available.

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

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

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

160 **Table 2** | Glossary of terms with definitions adapted from the primary literature and illustrative examples from
 161 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).

162 *1.2 System exploration*

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

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

187 *1.3 Review*

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

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

199 **2. Design**

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

205 *2.1 Model structure*

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

213 **Box 1:** Dimensions, domains and indicators of vulnerability

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

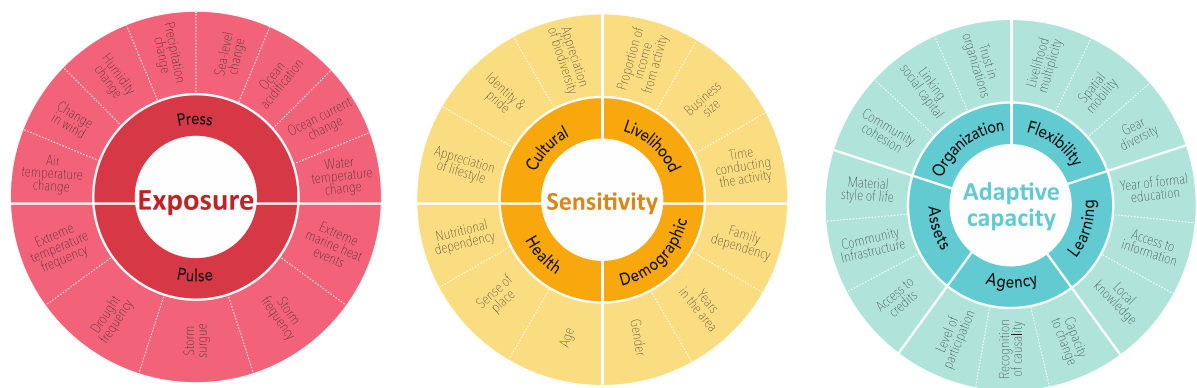
219 Vulnerability is comprised of three broad *dimensions*: exposure, sensitivity and adaptive
220 capacity (Table 1): (1) Exposure is the magnitude, frequency, duration and/or extent in which
221 a component is in contact with, or subject to, a stressor; (2) sensitivity defines the degree to
222 which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

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

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

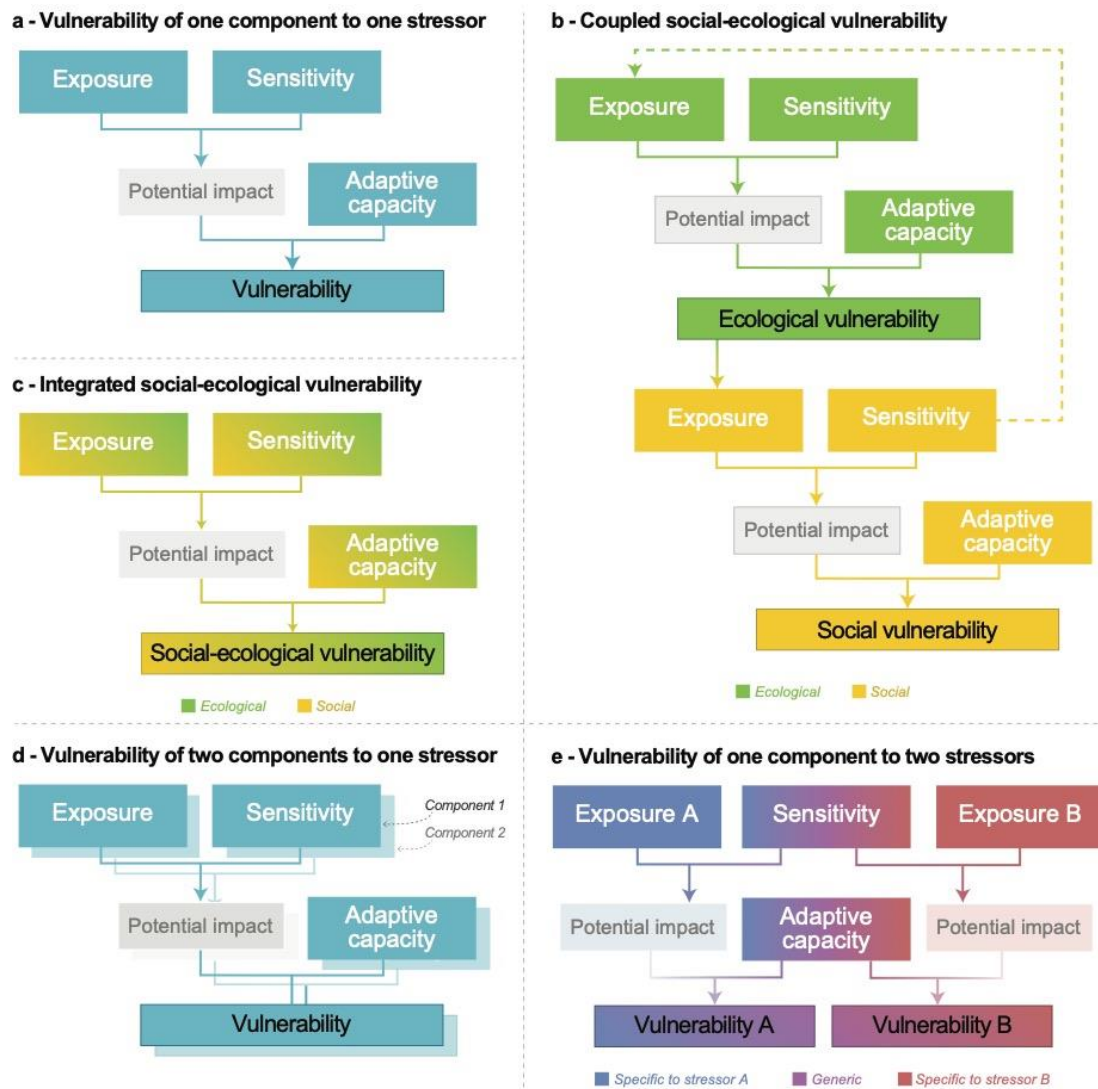
249 and Cinner et al. (2018) that social adaptive capacity relied on five *domains* (assets, flexibility,
 250 social organization, learning and agency). Likewise, a number of studies have developed
 251 *domains* for ecological components (Weißhuhn et al. 2018; Foden et al. 2019). For example,
 252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

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



262
 263 **Figure 2:** Conceptual diagram illustrating the three proposed nested layers for theoretically and contextually-
 264 grounded vulnerability assessments: *dimensions* (inner circle), *domains* (middle circle) and *indicators* (outer circle).
 265 Examples of domains and indicators are modified from (Marshall et al. 2017; Cinner et al. 2018; Day et al.
 266 2019) and describe social vulnerability of resource-dependent communities to climate change.

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



274

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

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

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

302 .

303 2.2. Indicators

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

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

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

316 Malone 2005). For example, some cultural values and knowledge are characteristically
317 aspatial (Ban *et al.* 2013) and may be impractical to incorporate in a spatial vulnerability
318 model. Bias toward easily quantifiable indicators can miss critical elements driving system
319 vulnerability, while indicators that are not relevant to local viewpoints, aspirations, and
320 cultural settings can misdirect the assessment outputs and result in the implementation of
321 programs that do not fit local contexts (Sterling *et al.* 2017b). It is therefore critical to define
322 what the subset of indicators represents and what it omits. Co-creation of indicators with the
323 end-users of the assessment as well as with affected stakeholders (e.g. resource users) is
324 critical so that they are both context grounded and also reflect local worldviews (Tengö *et al.*
325 2014). However, it is important to note that this type co-production of indicators can create
326 trade-offs with generalizability, as the indicators developed may lack meaning and
327 applicability in other locations.

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

333 **3. Operationalization**

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

338 *3.1. Data collection*

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

345 Possible data sources include data from primary research (ecological surveys, interviews,
346 perceptions, model projections), secondary data sets (official databases, censuses, expert
347 elicitation, spatial data), and grey literature (Kittinger *et al.* 2014). It is of great value to
348 incorporate local actors, decision-makers, and other stakeholders in the research. To achieve
349 this, existing empirical data could be considered along with information derived from expert
350 elicitation, local surveys, participatory mapping, workshops and focus groups (Cochrane *et al.*
351 2019).

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

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

370 **Climate forecasts and greenhouse gas emission scenarios**

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

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

392 3.2. Standardization

393 Unless using an inductive approach (step 3.3), indicators generally have to be standardized
394 through transformation and rescaling so that indicators of different units (e.g. number of
395 person-job in households, degrees heating from climate change, contribution of an activity to
396 livelihood) and scales (e.g. individual vs. community vs. country level) can be integrated (step
397 3.3). Decisions about if and how to standardize data can have important consequences on the
398 outcomes of vulnerability assessments and require careful consideration.

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

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

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

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

431 3.3. Integration

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

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

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

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

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

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

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

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

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

495 3.4. Uncertainties

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

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

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

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

532 **4. Implementation**

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

537 *4.1. Interpretation*

538 Interpreting the outputs of vulnerability assessments is essential for decision-making. This
539 step entails reflecting on how vulnerability can be portrayed in two, complementary ways:
540 aggregated or disaggregated. First, assessments that describe vulnerability at the highest
541 aggregation level, produce a vulnerability score and/or ranking. This information can in turn
542 help decision-makers select targets and set identify priorities (e.g. protecting the 15 most
543 vulnerable species, investing in capacity building for the 10% most vulnerable areas assessed,
544 or spreading effort across the range of vulnerability scores). Aggregated vulnerability
545 portrayals are especially suited in a spatial context, where vulnerability ‘hotspots’ can be
546 priorities or discarded, depending on the overall strategy (Parravicini *et al.* 2014; Smith *et al.*
547 2016; Thiault *et al.* 2018b). This type of information can potentially be incorporated within a
548 framework for systematic prioritization, for instance via *Marxan* or *prioritizer*. Fully
549 aggregated vulnerability outputs are also useful for temporal comparisons, where the
550 vulnerability of a system is expected to change over time following a particular event or
551 intervention or external stressors (Thiault *et al.* 2018a).

552 While aggregated assessments of vulnerability are useful, they can lack the specific
553 recommendations (and resolution of these) needed by decision-makers to understand and
554 effectively manage SESs. The second, disaggregated representation typically considers the
555 multiple *dimensions* of vulnerability (Sietz *et al.* 2011; Foden *et al.* 2013; Kok *et al.* 2016). By
556 looking at the interactions between exposure, sensitivity and adaptive capacity, leverage
557 points can be identified (Fischer and Riechers 2019) and option space for management and
558 policy explored. Indeed, if low vulnerability is the fundamental objective, then it can be
559 achieved via actions to reduce exposure, decrease sensitivity, build adaptive capacity, or a
560 combination of those, depending on the main sources of vulnerability. An array of strategies
561 to address each *dimension* contributing to vulnerability has been identified. These are
562 generally derived from the applied research literature and “translated” in the language of
563 vulnerability (Thiault *et al.* 2019a). For example, in their vulnerability assessment of fishing
564 communities to the impacts of climate change, Cinner *et al.* (2012) have proposed
565 interventions focusing on strengthening community groups and investing in strong local
566 institutions to build social adaptive capacity, both of which are directly derived from Ostrom’s
567 and colleagues’ work on commons and fisheries applications (Ostrom 2009; Basurto *et al.*
568 2013). Other recommendations based on this assessment include the development of social
569 safety nets, adaptive management approaches or poverty reduction, and diversifying
570 livelihoods which are core principles of the Sustainable Livelihood Approach (Allison and Ellis
571 2001; Allison and Horemans 2006). Many examples of vulnerability assessments in the
572 ecological realm have emerged over the recent years and identify avenues for management
573 and policy using the same rationale (Johnson and Marshall 2007; Foden *et al.* 2013; Parravicini
574 *et al.* 2014; Anthony *et al.* 2015; Okey *et al.* 2015; Bell *et al.* 2011, 2015; Johnson and Welch
575 2016; Johnson *et al.* 2016), illustrating the ability of this framework to foster multi-disciplinary
576 assessments that inform targeted policy and management.

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

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

590 4.2. Communication

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

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

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

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

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

625 *4.3. Learning*

626 XXXXX

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

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

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

638 Vulnerability assessments need to be transparent. Failure to do so precludes a full
639 understanding of what has been done for non-specialists. Decisions are often not taken
640 directly based on vulnerability assessment outcomes, but the outputs of the assessments are
641 the basis for discussions in arenas where multiple knowledge sources compete in supporting
642 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.

648 **Future research avenues**

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

654 *Biocultural approaches*

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

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

664 *Vulnerability to non-climatic stressors:*

665 So far, most applications of the vulnerability concept have focused on the socioeconomic
666 impacts caused by hazards- and climate-related stressors, and most knowledge on
667 vulnerability relates to these schools of thought. However, SES are exposed and potentially
668 vulnerable to a broad range of socioeconomic and biophysical stressors beyond climate and
669 the subsequent environmental change (Bennett *et al.* 2016). As a consequence, vulnerability
670 has gained traction in other areas, with applications ranging from social vulnerability to
671 management (Chen *et al.* 2014; Chen and Lopez-Carr 2014; Tilley and López-Angarita 2016),
672 socioeconomic changes (O'Brien and Leichenko 2000; O'Brien *et al.* 2004; Belliveau *et al.*
673 2006; Thompson *et al.* 2016), poaching (Thiault *et al.* 2019b), fire (Aretano *et al.* 2015), and
674 other human uses of ecosystems (Jones and Cheung 2017; Thiault *et al.* 2018b; Bourgoin *et*
675 *al.* 2020). However, such assessments tend to lack theoretical and/or empirical underpinnings,

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

678 One possibility to improve the robustness and relevance of the vulnerability concept outside
679 of its original field may be to draw on other, linked strains of research more explicitly.
680 Ecological vulnerability assessments, for instance, are largely based on work from the
681 resilience and ecotoxicology literatures (Ippolito *et al.* 2010; Mumby *et al.* 2014; Beroya-Eitner
682 2016), which use similar languages and concepts (e.g. sensitivity/resistance,
683 adaptation/recovery) and enable inference from empirical evidence. In regards to social
684 vulnerability in a management and natural resource management context, lessons can be
685 learned from diagnostic and archetype approaches when looked at through the lens of
686 vulnerability (Oberlack *et al.* 2016; Fader and Rulli 2017; Eisenack *et al.* 2019). For instance,
687 Ostrom's SES framework (Ostrom 2009) can serve as a knowledge base for identifying the key
688 attributes that foster or hinder SES sustainability and relevant interventions to reduce
689 vulnerability.

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

699 *Trade-offs and maladaptation:*

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

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

708 One of the key aspects of social-ecological vulnerability may be the potential for high social
709 adaptive capacity (generally considered desirable) to enable exploitation and degradation of
710 an ecological component (generally considered undesirable) (Cinner *et al.* 2011). This
711 phenomenon has been termed amplifying adaptive capacity because of the propensity for
712 adaptive capacity to amplify environmental change (Cinner *et al.* 2011). However, we know
713 little about how to avoid amplifying adaptive capacity and how to foster adaptive capacity
714 associated with responses likely to reduce ecological degradation (dampening adaptive
715 capacity. Unrecognized trade-offs inherent in vulnerability-based management may also
716 occur across vulnerability *domains* and across spatial and temporal scales (Cinner *et al.* 2018).
717 Other forms of trade-offs occur when stressor-specific capacity building programs
718 inadvertently increase vulnerability to other stressors. This may occur, for instance, when high
719 adaptive capacity exposes people to new stressors, increase their sensitivity to those new
720 stressors, or crowds-out the means available for other specific adaptation (Belliveau *et al.*
721 2006; McDowell and Hess 2012; Bacon *et al.* 2017; Finkbeiner *et al.* 2017).

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

731 **Conclusions**

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

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

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1051

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.

1055