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29 **Abstract**

30 Sustaining human well-being is intimately linked to maintaining productive and healthy
31 ecosystems. Avoiding trade-offs and fostering synergies is however challenging. Here, we
32 present an operational approach that integrates biodiversity conservation, human
33 development and natural resource management by (1) accounting for/modelling resource
34 and resource user interactions through the lens of social-ecological vulnerability (i.e.
35 encompassing exposure, sensitivity and adaptive capacity), (2) identifying “eco-centric” and
36 “socio-centric” interventions that address the social or ecological sources of vulnerability, (3)
37 prioritizing those expected to yield co-benefits and minimize trade-offs, and (4) selecting
38 interventions that are best suited to the local context. Application of this approach to a coral
39 reef fishery in French Polynesia suggested a portfolio of development-, livelihood- and
40 ecosystem-based interventions, thus proposing a shift from the current ecosystem-focused
41 approach towards a more social-ecological perspective. Our approach is intended to help
42 managers and decision-makers better integrate conservation and natural resource
43 management in such a flexible, transparent way that it can be the support for stakeholder’s
44 engagement processes and adaptive management.

45 **Introduction**

46 Achieving sustainability on our overexploited planet is one of the grand challenges of our
47 time (Rockström et al. 2009). This global challenge has local expressions that are both social
48 and ecological in form, because people and nature are linked and interdependent (Fischer et
49 al. 2015). Such strong social-ecological relationships are especially apparent in resource-
50 dependent settings such as forestry communities or coastal fisheries, where unsustainable
51 use of natural resources can lead to serious and tangible impacts on both ecosystems and
52 the people that depend on them (Ostrom 2009; IPBES 2019).

53 Many governmental agencies and NGOs are beginning to embrace a more nuanced view of
54 sustainability that sits at the nexus between social and ecological perspectives (Bakker et al.
55 2010; Díaz et al. 2015). As a result, strategies aiming to improve conservation and social
56 outcomes increasingly incorporate both elements in design and implementation (Mace
57 2014). Indeed, through initiatives such as multiple-use protected areas and ecosystem-based
58 management, social considerations are now embedded in the design of many “eco-centric”
59 measures, hence broadening a predominantly ecological view of conservation and natural
60 resource management (Ban et al. 2013; Kittinger et al. 2014). Correspondingly, the
61 sustainable livelihood approach illustrates how the human development community, whose
62 “socio-centric” entry-point has been predominantly centered around reducing poverty or
63 fostering development opportunities, increasingly recognizes good environmental status as
64 part of the conditions affecting the success of interventions (Krantz 2001; Roe et al. 2015;
65 Wicander & Coad 2018).

66 Integration of a social-ecological science perspective into human development, conservation
67 and natural resource management has enhanced the long-term equitability and

68 effectiveness of the initiatives of each. Moreover, decades of applications of eco- and socio-
69 centric strategies in various settings have offered important insights and experience that
70 provide valuable foundations upon which more integrated, cross-disciplinary approaches can
71 be built. Although still imperfect, we now have a better understanding of what can work and
72 what cannot, in what contexts, why, and how to avoid potentially undesirable outcomes
73 (Barrett et al. 2005; Cox et al. 2010; Wright et al. 2016; Barnes et al. 2017; Wicander & Coad
74 2018). Despite these positive developments, responses to sustainability problems continue
75 to be dominated by strategies focusing mostly on either the human or environmental
76 elements of the social-ecological systems.

77 Successfully dealing with conservation and sustainability requires a diverse portfolio of
78 interventions. Therefore, the challenge now is to stop striving for eco-centric *or* socio-centric
79 strategies, and instead seek synergies of the two. Indeed, and although they may diverge in
80 many ways, eco-centric and socio-centric approaches are often complementary: when well
81 designed, eco-centric interventions can enhance elements of human well-being, and socio-
82 centric interventions can improve ecological condition (McClanahan et al. 2008; Roe et al.
83 2015; Ban et al. 2019; Naidoo et al. 2019). Yet, neither intervention is likely to provide a
84 “silver bullet” (Ostrom et al. 2007). Instead, we should be looking for a “silver buckshot”,
85 where several tools in the box are used.

86 Insights offered by social-ecological systems thinking, and the extensive and mature
87 knowledge supporting human development, natural resource management, and
88 conservation together provide momentum for developing and institutionalizing a new
89 generation of management practices that positions the links between people and nature at
90 its core. Here we aim to address the narrower, but still difficult challenge of improving

91 integration across independent but complementary sustainability-seeking strategies while
92 ensuring relevance to decision-makers and practitioners. To do so, we have developed an
93 approach based on “vulnerability profiles”, which represent the system’s social and
94 ecological elements that are favoring or undermining sustainability, thus revealing the
95 internal features that can most effectively be targeted by sustainability interventions. This
96 approach ultimately makes apparent a portfolio of interventions that can help realize co-
97 benefits across goals relating to conservation, food security and human well-being. We
98 illustrate our approach using the case of a small-scale coral reef fishery in French Polynesia,
99 where fishing activity represents both an invaluable source of benefits for local communities
100 and an important pressure on the ecosystem.

101 **A vulnerability-based approach for integrated management of** 102 **social-ecological systems**

103 The approach we present here draws on recent developments in vulnerability and social-
104 ecological system thinking (Cinner et al. 2013; Thiault et al. 2018a; Appendix A). It involves a
105 four-step procedure that leads to the identification of practical interventions that most
106 appropriately echoes the needs and opportunities of a particular social-ecological system
107 (Fig. 1). It is intended to serve as an operational guide for the place-based management of
108 resource and resource user interactions, where ecological vulnerability refers to the
109 vulnerability of the resource (e.g. water, wild food, landscape) to use by the resource users
110 (e.g. farmers, fishers) and social vulnerability refers to the vulnerability of the resource users
111 to use-induced resource degradation. Therefore, it does not necessarily aim to address all
112 drivers of change in the social-ecological system of interest. It assumes that the system's
113 boundaries have been identified and that analysts aspire to achieve social *and* ecological
114 outcomes.

115 **Step 1: Assessing resource and resource user interactions through the lens of vulnerability**

116 The approach first guides analysts to independently assess each key dimension of social-
117 ecological vulnerability (Cinner et al. 2013; Thiault et al. 2018a), namely resource exposure,
118 sensitivity and adaptive capacity to exploitation (ecological vulnerability), and users'
119 exposure, sensitivity and adaptive capacity to resource decline (social vulnerability). Social
120 exposure is determined by ecological vulnerability (Appendix A; Fig. S1) and thus does not
121 need to be assessed explicitly. Ecological sensitivity and adaptive capacity can be difficult to
122 untangle because they are determined by similar processes. Here, we refer to their
123 combination as "intrinsic resilience" but acknowledge that resilience entails far more
124 complex processes that are not captured by this model. The four remaining dimensions can

125 then be combined to allocate ecological and social components to one of four quadrants,
126 hereafter referred to as vulnerability profiles (Fig. 2). Profiles are labelled as “lower
127 concern”, “potential adapter”, “high latent risk” and “greater concern” and characterize the
128 main elements that best determine social and ecological vulnerabilities, highlighting what
129 needs to be targeted to reduce vulnerability. Analysts can characterize vulnerability
130 profiles in the way that it best suited to social-ecological context (Appendix B).

131 **Step 2: Selecting interventions that can reduce source(s) of vulnerability**

132 Step 2 involves identifying relevant interventions that target the features identified in the
133 previous step. They could include interventions focusing on the resource (“eco-centric”
134 interventions such as ecological engineering, permanent closures, or output controls), on
135 resource users (“socio-centric” such as livelihood-focused interventions, market-based
136 approaches, or assets enhancement), or a combination of those depending on the elements
137 that need addressing. Analysts may be interested in implementing participatory mechanisms
138 to develop this initial list of interventions. All options should be explored carefully for holistic
139 management. To help in the screening process, we propose a typology of interventions
140 commonly used by development, natural resource management and conservation
141 communities, and describe their expected impacts on ecological and social vulnerability
142 profiles (Table 1). Analysts might look to this template as a starting point, adapting and
143 rearranging as necessary.

144 **Step 3: Prioritizing interventions that can advance social-ecological co-benefits**

145 Step 3 entails being critical of negative collateral impacts that some interventions might
146 have, as well as employing those initiatives that benefit each system (Sayer et al. 2013;
147 Howe et al. 2014). Indeed, in order to be successful and balanced, management

148 interventions identified in step 2 must be appropriately positioned in the social and
149 ecological context in such a way that they do not further undermine any component of the
150 system. Instead, they should be employed to reduce negative impacts and/or induce positive
151 change. In Table 1, we summarize how various types of commonly used interventions
152 implemented on one component may have indirect effects on others, and how this can be
153 interpreted using the ecological and social vulnerability profiles from step 1. Like in the
154 previous step, this template can be further tweaked to local contexts.

155 **Step 4: Developing an interventions portfolio that suits the broader social-ecological**
156 **landscape**

157 The last step captures the wider context in which the local interactions between resource
158 and resource users are embedded to ensure the feasibility and viability of previously
159 identified interventions. This step includes documenting the social norms, values, cultural
160 practices, aspirations, place attachment and historical and environmental features that can
161 facilitate or hinder specific interventions (Ostrom 2009; Armitage et al. 2012). To ensure the
162 sustainability and legitimacy of selected interventions, traits of the governance structure
163 need to be accounted for (Leenhardt et al 2015). Mixed methods approaches and
164 triangulation of qualitative and quantitative data from various sources (Appendix B; Game et
165 al. 2018) can create a cohesive picture that will help analysts assess whether each candidate
166 intervention is appropriate, equitable and legitimate (Kittinger et al. 2014).

167 Our vulnerability-based approach thus consists of four steps eventually leading to the
168 selection of one or more interventions that are important and actionable to reduce social
169 *and* ecological vulnerabilities (Fig. 3). By effectively considering the linkages between key
170 social and ecological components, it enables to identify management strategies that are

171 more likely to meet both ecological and social goals than if one criterion only was
172 considered. As such, it offers practical insights that can inform integrated management
173 strategies and planning in a broad range of contexts.

174 **Illustrating the approach: a coral reef fishery case study**

175 We use the coral reefs and the associated small-scale fishery of Moorea, French Polynesia,
176 to illustrate the application of the approach described above. Overall, the Moorea fishery is
177 highly challenging to manage due to inextricable yet diffuse links between people and the
178 reef (Leenhardt et al. 2016). The marine spatial plan in which fisheries management is
179 embedded was under revision at the time this study was conducted (Hunter et al. 2018), and
180 our pilot assessment was conducted in parallel of the revision process.

181 In order to consider linked social-ecological vulnerabilities in the specific context of fish (the
182 resource) and fishing households (the resource users), we compiled data on marine resource
183 dependency (i.e. social sensitivity) and adaptive capacity from 6,698 households, and
184 combined it with reef-wide models of target fish assemblages, characterized by their
185 intrinsic resilience and exposure to fishing. The combination of each dimension of social and
186 ecological vulnerabilities was represented spatially to visualize the vulnerability profiles (step
187 1; Fig. 4). We then applied the general typology of eco- and socio-centric management
188 interventions (Table 1) into the context of small-scale fisheries (steps 2-3; Table 2). Finally,
189 we used a combination of archival research, semi-structured interviews from key
190 informants, and participant observations to gain insights into the broader context, thus
191 allowing us to better capture elements that could facilitate or hinder each potential
192 intervention (step 4; Table 2). See Appendix B for a full description of the methods.

193 The current management approaches implemented in Moorea to manage local fisheries are
194 not aligned with the approaches suggested by our approach. For example, the fore reef
195 generally shows high intrinsic resilience and relatively low exposure to fishing (Fig.1;
196 Appendix C, Fig. S2). Our results suggest that such configurations may support the
197 development of fully protected areas because these ecologically efficient but socially
198 restrictive measures are easier to implement and represent lower opportunity costs for local
199 households. Yet, despite the large permanent fisheries closure system (20% of the total reef
200 area), the fore reef only represents 7.7% of the total area protected (Appendix C, Fig. S3). In
201 contrast, lagoon areas closed to fishing are in some cases located in front of poorly adaptive,
202 and sometimes highly sensitive households (Fig. 3; Appendix C, Fig. S3), creating a policy
203 setting that could exacerbate social vulnerability and certainly lead to challenges for
204 compliance. Given the criticisms against the current network of fully protected areas and
205 their lack of ecological effectiveness (likely due to, in part, to poaching; Thiault et al. 2019),
206 such conservation measures should be prioritized on the fore reef or in lagoon areas where
207 associated people are weakly sensitive can adapt to the loss of fishing grounds (Fig. 4).
208 Where households are most vulnerable (e.g. Fig. 4b; Appendix C, Fig. S2), less restrictive
209 interventions such as size and species regulations, or temporal closures, could be used to
210 reduce fishing effort (i.e. ecological exposure) at a lower opportunity cost for users.
211 Although these types of interventions can be more difficult to enforce, and the perceptions
212 on which are the best modalities can differ among stakeholders, they are generally
213 supported by users and can be underpinned by preexisting legislation (Table 2). In parallel to
214 addressing ecological exposure, ecological intrinsic resilience needs to be enhanced,
215 particularly within the lagoon (Fig. 4). Although managers may for instance replicate
216 previous stock enhancement interventions of targeted herbivores (Taiarui et al. 2019),

217 improving the management of land-based activities are likely to have the greatest positive
218 impact on ecological intrinsic resilience (Leenhardt et al. 2017). This type of approach is in
219 line with principles from traditional 'ridge-to-reef' management, but its implementation
220 would require greater collaboration among relevant agencies (Table 2).

221 In various locations around Moorea (e.g. Fig 4b-c), it is particularly relevant to couple the
222 above eco-centric interventions with socio-centric ones focusing on the root cause of social
223 vulnerability. This implies moving beyond stakeholder consultation processes to also
224 investing in strategies that directly tackle social adaptive capacity and/or sensitivity. This
225 may entail livelihood-focused measures such as incentives to diversify occupations (e.g.
226 agriculture, tourism, aquaculture) and catch, although challenges regarding socio-cultural
227 barriers need to be anticipated to avoid discrepancies between expectations and actual
228 outcomes (Table 2). Community buy-in may for instance be leveraged via churches and other
229 stakeholder groups, while land tenure issues can for example be overcome through enabling
230 local community members to lease land cheaply for agricultural purposes. If well designed,
231 and if new livelihoods are effectively created as alternatives rather than supplementary
232 sources of outcome (Wright et al. 2016), such interventions have the potential to reduce
233 both social (reduced dependency, enhanced flexibility) and ecological vulnerability (released
234 pressure on the resource). Enhancing adaptive capacity through social capital building, and
235 encouraging learning and cooperation may, in Moorea, build on established stakeholder
236 groups like cultural associations, while the recently created decentralized management
237 committees provide an obvious forum for discussion on reef-related issues and solutions
238 within the community (Table 2). Investments in market-based interventions and insurance
239 schemes do not seem applicable for Moorea due to the absence of markets and the

240 difficulty of identifying individual fishers (Table 2). Island-wide, and in particular in high
241 socially sensitive areas (Fig. 4b-c), it is essential to develop strategies that do not make local
242 communities more dependent on reef-based resources that are already highly vulnerable.
243 This is why island-scale incentives for motorized boats or new fishing gear should be
244 avoided.

245 Instead of constraining decision-makers to a single strategy-focused approach defined *a*
246 *priori* (i.e. eco- *or* socio-centric), our results compel decision-makers to consider multiple
247 entry points. Although many challenges remain to ensure the success of Moorea's
248 management (Hunter et al. 2018), our results suggest that the current strategy could be
249 upgraded by shifting from a focus exclusively on the resource to account more specifically
250 for social-ecological linkages in each location, and embracing a broader range of
251 management options that include eco- *and* socio-centric interventions.

252 **Reflections on the vulnerability-based approach**

253 Our four-step process represents a significant departure from more mainstream approaches
254 to vulnerability conceptualization and practice. First, the framing is new. At its core, it builds
255 on, and brings together insights from social-ecological science and vulnerability, moving the
256 latter from its original perspective (natural hazards and climate) towards a sustainability one
257 that includes people, both as a factor affecting environmental outcomes, and as a recipient
258 of environmental benefits that require human well-being to be improved (Thiault et al.
259 2018a). Second, it builds on previous applications and uses of the vulnerability construct,
260 providing guidance not only for prioritization, but also for real, pragmatic, and balanced
261 interventions. Third, our framework effectively bridges independent, yet complementary

262 approaches such as ecosystem-based management (Levin et al. 2009), resilience-based
263 management (Mcleod et al. 2019), and the sustainable livelihood approach (Krantz 2001).

264 Based on our experience we believe that this approach is likely to infuse a more
265 comprehensive vision into conservation and natural resource management (Guerrero et al.
266 2018), and empower practitioners to develop more integrated management strategies.

267 The spatial representation of the vulnerability profiles revealed potential interventions best
268 suited to each location around the island, thus allowing local managers to examine
269 previously unexplored, yet locally-relevant management possibilities. The approach leading
270 to the selection of the interventions portfolio is transparent and can be replicated through
271 time, providing a structure for implementing an adaptive management process that supports
272 responsive strategies (Kaplan-Hallam & Bennett 2018).

273 The use of vulnerability in a resource management context is relatively recent (REF), and its
274 use as practical tool is still controversial (Appendix A, Table S1). Most commonly, critiques
275 relate to the potential ‘top-down’ process of vulnerability assessments, where local
276 communities’ input into the process can be left aside(Cameron 2012). In our approach, each
277 step can rely on a community-based, participatory process, for instance by engaging
278 stakeholders into the design and collection of indicators (step 1), the identification of
279 candidate interventions (steps 2-3), or analysis of the overall context (step 4). This would not
280 only be critical for improving the quality of the assessment, but may also promote
281 opportunities to reflecting a richer knowledge that aligns with local people’s perspectives
282 and insights (Reed 2008; Dacks et al. 2019). In addition, this process –like any vulnerability
283 assessment– underplays other elements such as design considerations and complex
284 interactions between and among social and ecological components that also shape the

285 success of a particular intervention (Agrawal & Redford 2006; Wright et al. 2016; Selig et al.
286 2017). Our approach is not meant to be prescriptive and should rather be the support of
287 discussions within a planning process.

288 **Conclusions**

289 Achieving social and ecological objectives are intimately linked goals. Therefore, they should
290 be integrated within the same framework. Our proposed approach illustrates that there is
291 much scope for improved integration of data, ideas and management practices across
292 various fields and disciplines. Although this will not solve all the challenges facing
293 conservation and natural resource management, it broadens the range of options, offering
294 more transparency in decision-support tools.

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300 **Supporting Information.**

301 Appendix A. Additional conceptual information on vulnerability.

302 Appendix B. Case study methods.

303 Appendix C. Additional results.

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- 442

443 **Table legends**

444 **Table 1** | Typology of interventions to manage resource-user dependencies, and implications for
 445 social and ecological vulnerability profiles. Symbols indicate the effect of interventions (◻ positive; ⊗
 446 negative; ○ no effect) on each vulnerability profile (Step 1: greater concern: purple; potential
 447 adapter: yellow; high latent risk: blue; lower concern: grey; see Fig. 2). Intervention types a-e: “eco-
 448 centric” interventions. Intervention types 1-8: “socio-centric” interventions. Clear boxes indicate
 449 direct effects on the component (e.g. effect of eco-centric interventions on the resource; Step 2) and
 450 shaded boxes indicate indirect effects (e.g. effect of eco-centric interventions on the resource users;
 451 Step 3).

		Ecological Component (resource)				Social Component (resource users)				Rationale
Type of intervention	Vulnerability profile	Greater concern	Potential adapter	High latent risk	Lower concern	Greater concern	Potential adapter	High latent risk	Lower concern	
Eco-centric interventions	a - Mitigate other pressures	◻	◻	◻	◻	◻	◻	◻	◻	Reducing exposure of the resource to other pressures without affecting the use of concern may improve ecological intrinsic resilience to human use through better ecosystem functioning without negatively impacting social component.
	b - Ecological engineering	◻	◻	◻	◻	◻	◻	◻	◻	Ecological engineering can help mitigate damage to, or improve, natural habitats while also increasing ecosystem services supply. Does not represent an opportunity cost to users but requires high economic investments.
	c - Permanent closure	◻	◻	◻	◻	⊗	◻	⊗	◻	Permanent closures are an extreme type of input control (d) that has different implications for both the ecological component and its associated social component. By preventing impact from direct use, permanent closures enhance intrinsic resilience of the resource unit. However, this can involve significant social costs and thus requires high social adaptive capacity to avoid negative social outcomes or poor compliance from resource users (and therefore reduced effectiveness of strategy).
	d - Input control	◻	◻	◻	◻	◻	◻	◻	◻	Input controls are limits on the amount or type of effort users put into their activities. They indirectly control the amount of resource extracted, allowing resource recovery by reducing resource use or access by resource users (temporarily, in space, etc.), which reduces resource exposure but does not necessarily improve its intrinsic resilience. Opportunity cost depends on the design, regulations and other parameters, but are generally lower than permanent closures.
	e - Output control	◻	◻	◻	◻	⊗	◻	⊗	◻	Output controls directly limit the amount of resource that can be extracted. They generally require a high level of social adaptive capacity (organization, good access to information, assets, collective action, etc.) to be implemented effectively as well as strong leadership and administrative investments.
Socio-centric interventions	1 - Alternative occupations	◻	◻	◻	◻	◻	◻	◻	◻	Alternative occupations the risk of livelihood failure by spreading it across more than one income source. Reduces resource dependency and enhances the ability to exit the sector, but depends on community aspirations and must satisfy the same range of benefits (job satisfaction, prestige, nutrition) singular of the original activity.
	2 - Alternative resources	◻	◻	◻	◻	◻	◻	◻	◻	Incentivizing a culturally appropriate shift in uses and consumption toward more nutritive or more resilient or diverse resources and can reduce demand volume and/or improve the stability of benefits derived from resource use. In some rare cases, incentives for targeting invasive species can enhance ecological intrinsic resilience in the case of wildlife harvesting.
	3 - Insurance scheme	◻	◻	◻	◻	◻	◻	◻	◻	Insurance schemes provide a safety-net in case of environmental perturbation that may cause a loss of resource supply, avoiding escalation of unsustainable resource use.
	4 - Social capital building	◻	◻	◻	◻	◻	◻	◻	◻	Building social capital increases the adaptive capacity of users, enhances bargaining power in relation to traders/market, improves logistics and access to information, manage risk through collective action and facilitates the use and adoption of new (potentially more sustainable) practices. May help removing critical barriers to social adaptation.
	5 - Assets strengthening	◻	◻	◻	◻	◻	◻	◻	◻	Direct improvement of adaptive capacity components. May help removing critical barriers to social adaptation.
	6 - Market system improvement	⊗	◻	◻	◻	◻	◻	◻	◻	Improved value chains, marketing, eco-labeling and supply chain simplification with middleman can create higher and/or more stable income for resource users. May induce a shift in use practices that may displace use effort leading to new areas being exposed to use. May help removing critical barriers to social adaptation.
	7 - Within-sector diversification	⊗	◻	⊗	◻	◻	⊗	◻	◻	Flexibility to move across different resource use strategies is important for adaptive capacity but may push part-time users into full-time operations to repay loans and to earn an adequate return on the increased investment (i.e., increase social sensitivity). May also increase pressure on resource (i.e., ecological exposure).
	8 - Capacity enhancement	⊗	⊗	⊗	◻	◻	⊗	◻	◻	Improves use efficiency, increases incomes across users only if the resource remains relatively under-exposed and highly resilient. May increase resource dependency due to economic investment. May induce distal impacts on adjacent resources.

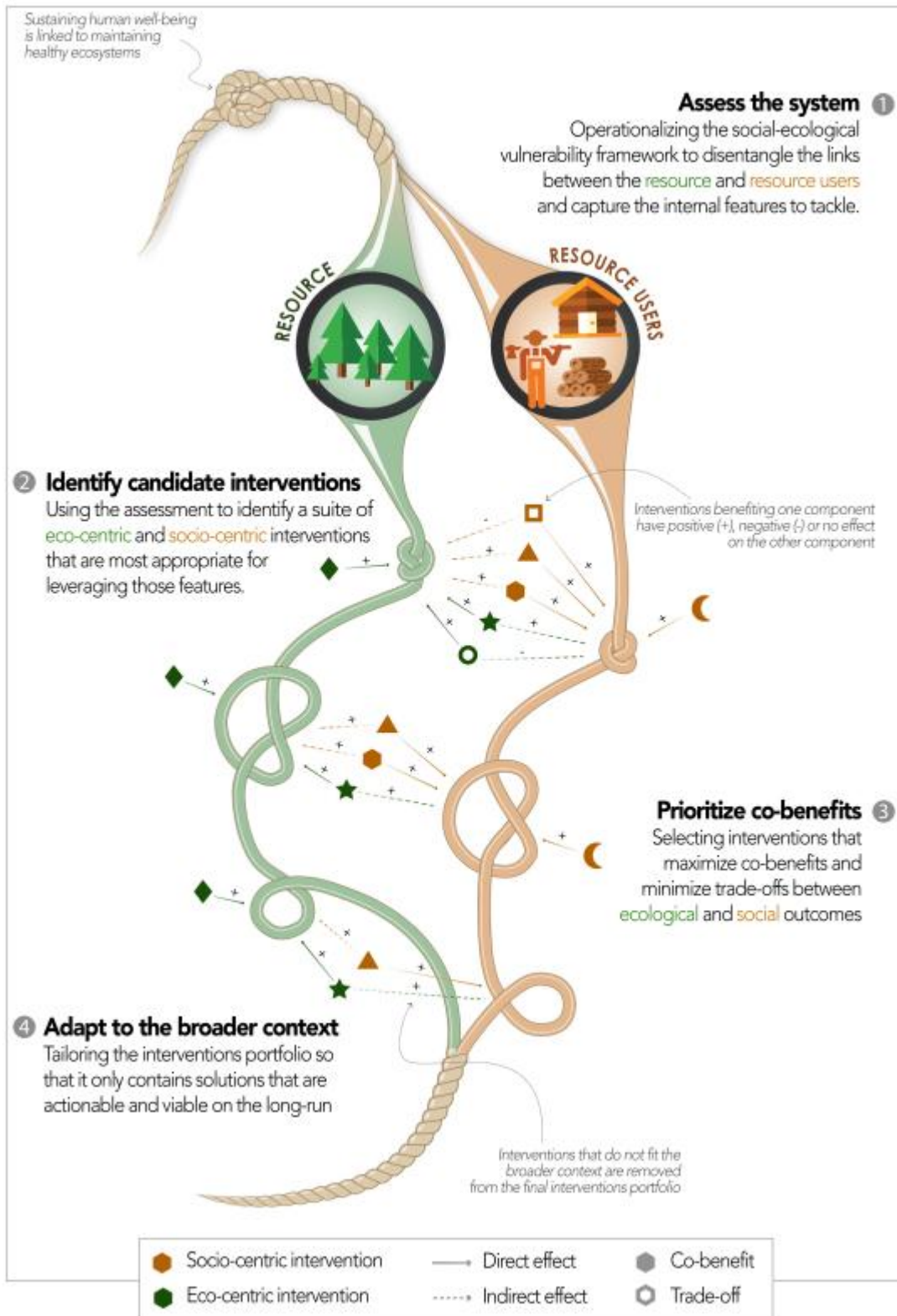
Note. Symbols indicate the effect of interventions (● positive; ⊗ negative; ○ no effect) on each vulnerability profile (Step 1: greater concern: purple; potential adapter: yellow; high latent risk: blue; lower concern: grey; see Figure 2). Intervention types a-e: “ecocentric” interventions. Intervention types 1-8: “sociocentric” interventions. Clear boxes indicate direct effects on the component (e.g., effect of ecocentric interventions on the resource; Step 2) and shaded boxes indicate indirect effects (e.g., effect of ecocentric interventions on the resource users; Step 3). See Supporting Information Appendix B for details on the typology.

452

453 **Table 2** | Application of the generic typology of eco- and socio-centric interventions (Table 1) to a
 454 small-scale coral reef fishery. Examples of interventions are presented, together with how they
 455 would be filtered in Moorea according the island’s broader context (Step 4), which may facilitate or
 456 prevent successful implementation of particular interventions.

		Examples of interventions in the context of small-scale coral reef fisheries		Elements of broader context in Moorea (Step 4)	
Type of intervention				Enablers	Challenges
Eco-centric interventions	(a) Mitigate other sources of impact	<ul style="list-style-type: none"> - Integrated coastal zone management (ICZM) - Marine Spatial Planning (MSP) - Ridge-to-reef management 	<ul style="list-style-type: none"> - Aligns with principles from traditional ridge-to-reef management - Main sources of impact identified 	<ul style="list-style-type: none"> - Lack of political will to enforce law regulating embankments - Lack of funding sources for integrated management - Lack of effective collaboration among administrative agencies working on land and at sea 	
	(b) Ecological engineering	<ul style="list-style-type: none"> - Artificial reefs - Active habitat restoration - Restocking and stock enhancement 	<ul style="list-style-type: none"> - Aquaculture and related technologies available locally for key target species - Similar initiative successfully implemented in analogous context - Several local associations actively involved in restoration programs 	<ul style="list-style-type: none"> - Economic cost of engineered solutions - Focus on too few species - Environmental impact still uncertain 	
	(c) Permanent closures	<ul style="list-style-type: none"> - Marine reserves, no-take zones, fully protected areas 	<ul style="list-style-type: none"> - Aligns with methods from traditional management (<i>rūhu</i>) - Suitable legislative framework - Relatively easy to monitor - Some groups already actively enforced previous fully protected areas 	<ul style="list-style-type: none"> - Previous experiences created a sense of distrust - Lack of surveillance capacity (most fishing occurs at night) 	
	(d) Input control	<ul style="list-style-type: none"> - Temporal closures/closed seasons (fishing taboos) - Restriction on target species - Size restrictions (protect young, protect breeders) - Licenses & exclusive access rights - Gear regulations (minimum mesh size, gear restriction) 	<ul style="list-style-type: none"> - Aligns with methods from traditional management (<i>rūhu</i>) - Suitable legislative framework - Extensive local ecological knowledge - Strong social pressure within community encourages self-enforcement 	<ul style="list-style-type: none"> - Overlap with other national-level regulations may create confusion and complexity - Top-down enforcement difficult due to the diffuse nature of the fisheries - Intractable disagreements among stakeholders - Reef area too small to grant exclusive rights that would not create inequities among fishers 	
	(e) Output control	<ul style="list-style-type: none"> - Total Allowable Catches (TACs) and quotas - Output rights 	<ul style="list-style-type: none"> - Fishers have recently self-organized into management committees that operate at the municipality level - Ongoing marine ecological monitoring to estimate quotas 	<ul style="list-style-type: none"> - Most catch for self-consumption rather than for economic purposes - Risk creating inequities among fishers - Estimating quota remains challenging in coral reefs settings - No centralized selling point (catch sold on roadside) 	
Socio-centric interventions	1. Alternative occupations	<ul style="list-style-type: none"> - Provide land for agriculture or aquaculture - Develop sustainable tourism 	<ul style="list-style-type: none"> - Many alternative occupations align with some community members' aspirations and needs - Relevant local agencies and legal framework already in place - High level of unemployment - High tourism potential - Municipality-owned land available 	<ul style="list-style-type: none"> - Aspirations are highly heterogeneous within the community - Land tenure system disrupted by colonialism and globalization - Alternative occupations are typically used to increase income rather than reducing resource use - Powerful external interests associated with the tourism industry - Lack of effective collaboration among administrative agencies working on land and at sea 	

Type of intervention	Examples of interventions in the context of small-scale coral reef fisheries	Elements of broader context in Moorea (Step 4)	
		Enablers	Challenges
2. Alternative resources	<ul style="list-style-type: none"> - Incentivize diet shifts (new target species) - Promote imported animal protein 	<ul style="list-style-type: none"> - Variety of alternative species available - Moorea's population is not food insecure - Fishers regularly adapt target species in response to ecological changes 	<ul style="list-style-type: none"> - Cultural barriers to resource change (tradition, taste) - Lack of capacity to induce behavioral change - External sources of protein generally more expensive (e.g., imported meat) or unsustainable (e.g., high nutrient loadings from pig farms)
3. Insurance schemes	<ul style="list-style-type: none"> - Corporate insurer - Government or informal insurances 	<ul style="list-style-type: none"> - Strong centralized government in Tahiti 	<ul style="list-style-type: none"> - Targeting fishers difficult due to the diffuse nature of the fisheries
4. Social capital building	<ul style="list-style-type: none"> - Knowledge-sharing and learning platforms - Fisheries cooperatives - Associations and other organizational forms 	<ul style="list-style-type: none"> - Fishers have recently self-organized into management committees that operate at the municipality level - Many groups already in place to support knowledge sharing, community cohesion, and/or environmental stewardship 	<ul style="list-style-type: none"> - Intractable political positioning - Lack of funding sources for learning platforms
5. Assets strengthening	<ul style="list-style-type: none"> - Access to health services - Education (formal education) - Infrastructure (fish freezer) - Information (mobile phone) 	<ul style="list-style-type: none"> - Developed country with subsidies from Metropolitan France 	<ul style="list-style-type: none"> - No wish for a centralized market (past experiences failed)
6. Market system improvement	<ul style="list-style-type: none"> - Strengthen relations among actors - Upgrade value chains - Simplify supply chains 		<ul style="list-style-type: none"> - No centralized selling point (catch sold on roadside) - No export to external market (all catch consumed locally)
7. Within-sector diversification	<ul style="list-style-type: none"> - New gear - Alternative fishing methods 	<ul style="list-style-type: none"> - Highly selective local fishing practices - Highly versatile - Economic incentives already in place for registered fishers 	<ul style="list-style-type: none"> - Certain net fishing practices perceived as overly effective and unfair/unsustainable
8. Capacity enhancement	<ul style="list-style-type: none"> - Improved boats - Subsidizing motorization 	<ul style="list-style-type: none"> - Attractiveness of fore reef 	<ul style="list-style-type: none"> - May disrupt spatial organization of fishing activities (informal ownership/access) - Will dramatically increase pressure on the resource



460

461 **Figure 1** | Integrating social and ecological perspectives when designing sustainability interventions.
 462 (1) Step 1: the social-ecological system is assessed by analyzing the linked vulnerabilities of the
 463 resource (green) and associated resource users (orange). (2) Step 2: this assessment enables to
 464 identify social (users' sensitivity and/or adaptive capacity to resource depletion) and ecological

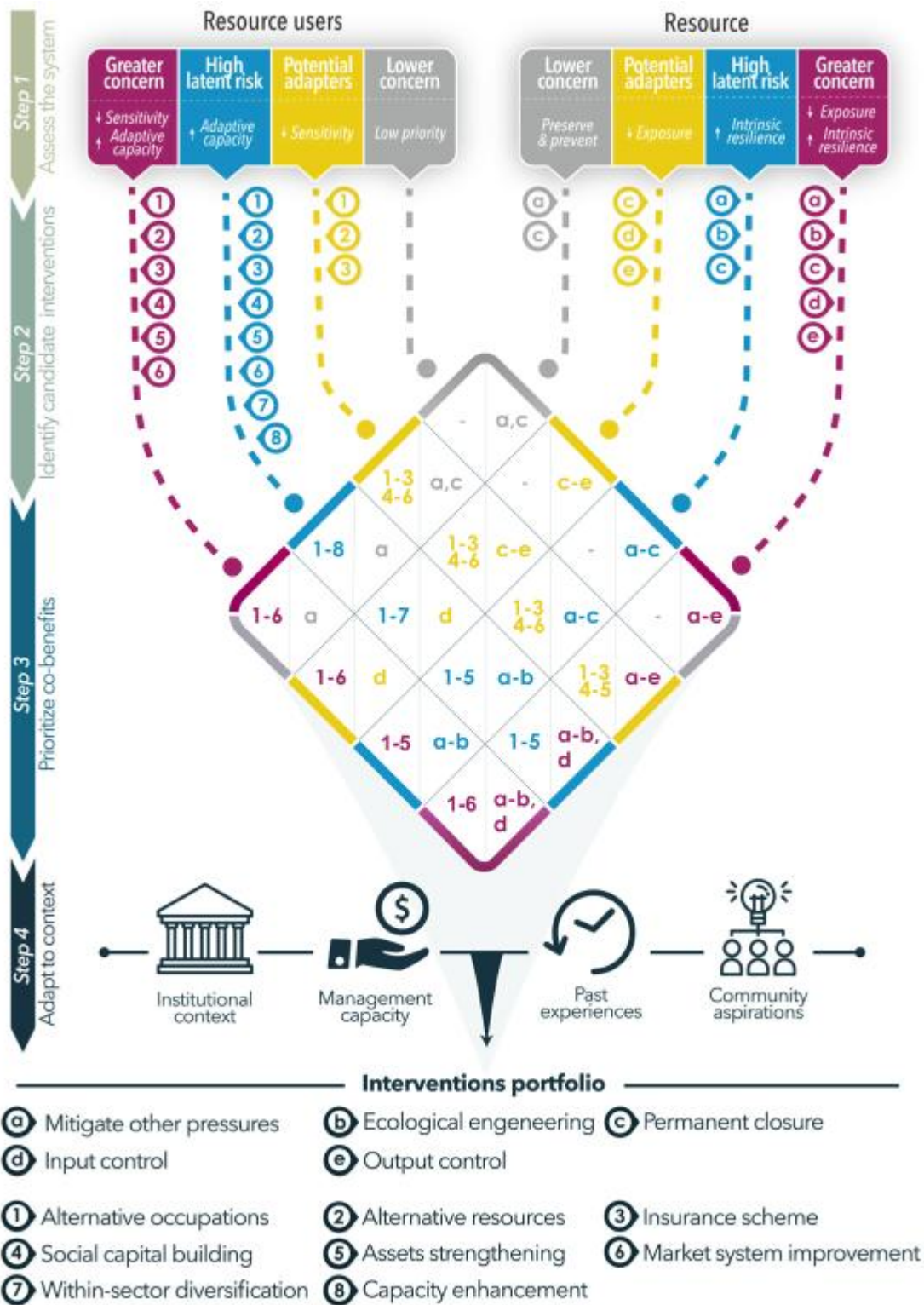
465 (resource' exposure and intrinsic resilience to exploitation) elements that are favoring or
 466 undermining sustainability and derive a set of candidate interventions (represented by shapes;
 467 green=eco-centric; orange=socio-centric) that can be leveraged to address them. (3) Step 3:
 468 interventions that are expected to have negative indirect effects (open shapes) are withdrawn to
 469 retain only those who can foster co-benefits (i.e. solid shapes). (4) Step 4: to be locally viable and
 470 actionable, the final portfolio must only include interventions that fit the broader context.



FIGURE 2 Social and ecological vulnerability profiles and associated management targets (Step 1). Each profile is identified through the combinations of exposure and intrinsic resilience gradients (ecological vulnerability), or sensitivity and adaptive capacity gradients (social vulnerability), and thus reveals the internal elements that can most effectively be targeted by sustainability interventions. Note that “intrinsic resilience” refer to the combination of ecological sensitivity and adaptive capacity. See Supporting Information Appendix A for full description of vulnerability profiles

471

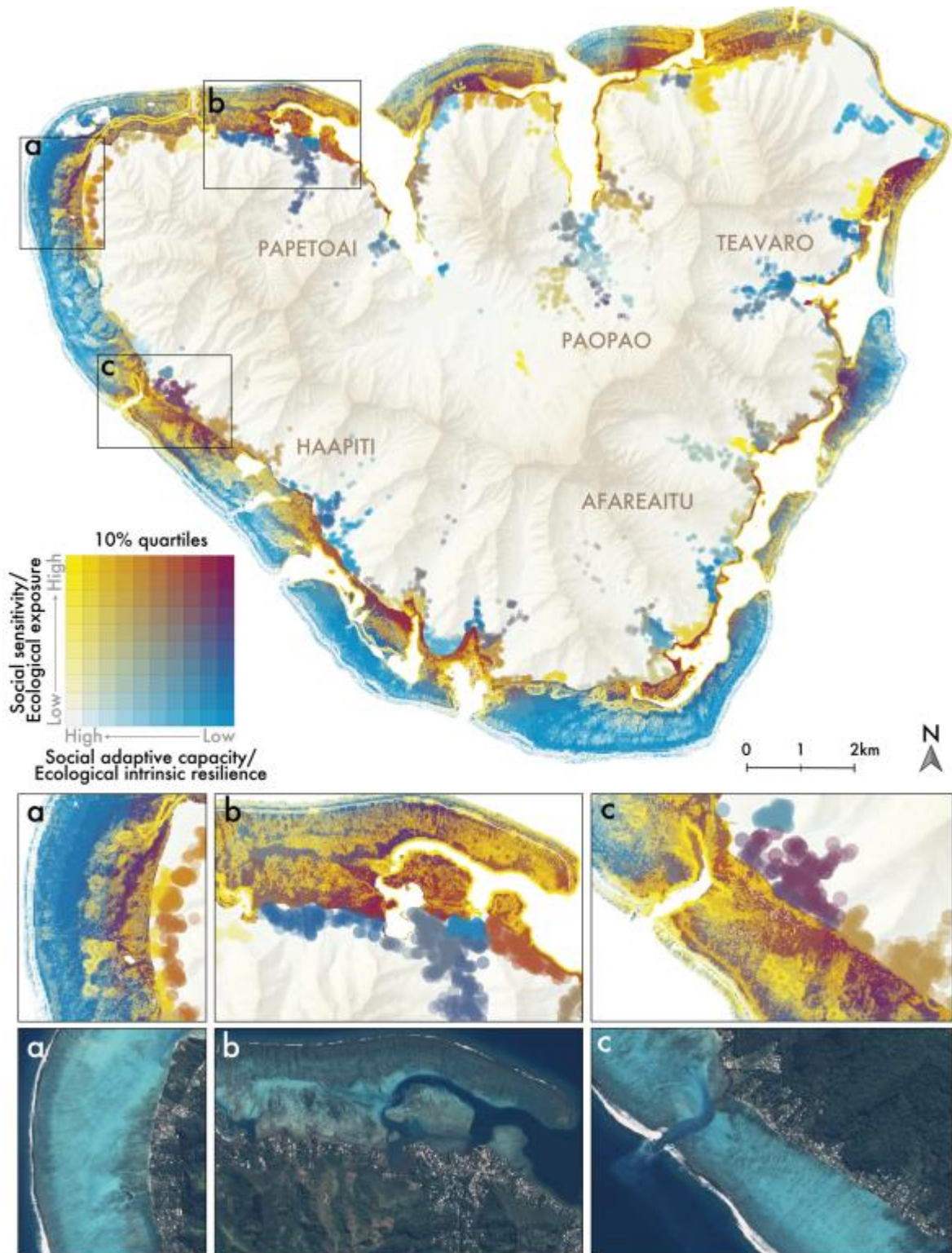
472 **Figure 2** | Social and ecological vulnerability profiles and associated management targets (Step 1).
 473 Each profile is identified through the combinations of exposure and intrinsic resilience gradients
 474 (ecological vulnerability), or sensitivity and adaptive capacity gradients (social vulnerability), and thus
 475 reveals the internal elements that can most effectively be targeted by sustainability interventions.
 476 See Appendix A for full description of vulnerability profiles.



477

478 **Figure 3** | Flowchart illustrating the key steps of the approach proposed. Step 1: identify the key
 479 vulnerability driver(s) to address through social and ecological vulnerability profiles. Step 2: for each
 480 component, determine a set of potential interventions to reduce each component’s driver(s) of
 481 vulnerability. Step 3: consider the vulnerability profile of the associated component and determine a
 482 portfolio of potential interventions that minimizes trade-offs and promotes co-benefits. Step 4:
 483 ensure the viability of the interventions portfolio by reviewing identified interventions in the local
 484 context (e.g. institutional, management capacity, past experience, community aspirations). This
 485 generic framework can be adapted to each context by identifying specific interventions falling into

486 each generic typology (see Table 2 and Appendix C, Fig. S1 for a fishery-specific application of the
487 generic approach).



488

489 **Figure 4** | Assessment of the coral reef fishery of Moorea, French Polynesia, using spatially-explicit
490 profiles of social and ecological vulnerability (Step 1). Since households mostly depended on resource
491 located on adjacent reefs for provision and cultural services associated with fishing, combinations of
492 social and ecological vulnerability profiles were spatially linked. Insets highlight different

493 combinations of profiles requiring specific portfolio of intervention (Fig. 3; see Appendix C, Fig. S1 for
494 a fishery-specific application of the general approach).