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# 1 Cumulative impact assessments can show the benefits of integrating 2 land-based management with marine spatial planning

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## 9 **Abstract**

10 Cumulative impact assessments can inform ecosystem-based management by mapping  
11 human pressures and assessing their intensity on ecosystem components. However, its use to  
12 inform local management is scarce, largely due to the need for fine-grained spatial data  
13 representing ecosystem threats that can assess impacts at a local scale. Here, we applied the  
14 cumulative impact assessment framework to Moorea's coral reef, French Polynesia to inform  
15 the ongoing revision of the island-wide marine spatial management plan. We combined high  
16 spatial resolution data on 11 local anthropogenic pressures and four ecological components  
17 with expert vulnerability assessments. Results revealed that the entire reef is impacted by at  
18 least four pressures: coral reef fisheries, agriculture, land use change and urbanization. These  
19 activities together contribute to 87% of the overall cumulative impact. Most importantly, land-  
20 based activities contribute to more than half (52%) of the overall impact. Other high-impact  
21 activities, such as reef-based tourism, remain very localized and contribute little to the overall  
22 human impact. These findings show that by focusing solely on reef-based activities, the  
23 current management plan misses critical sources of impact. Not considering land-based  
24 activities in the management may lead to decisions that could fail to significantly lower  
25 cumulative human impact on the reef. This study demonstrates how operationalizing the  
26 cumulative human impact framework at a local scale can help managers identify key leverage  
27 points likely to yield improved ecological outcomes.

28 **Keywords:** *Cumulative effect assessment - Threat maps - Human impacts - Land-based*  
29 *pressures - Coral reefs - French Polynesia*

## 30 1. Introduction

31

32 Biodiversity in coastal zones provides highly valuable ecosystems and at times vital services to  
33 communities worldwide (Barbier et al., 2011; de Groot et al., 2012). With about 40% of the  
34 world's population living near the coast (CIESIN, 2012), human activities on both land and  
35 water exacerbate pressures on coastal ecosystems (He and Silliman, 2019). Overfishing,  
36 pollution, and other human activities have already seriously depleted highly productive  
37 coastal ecosystems such as salt marshes (Deegan et al., 2012), seagrass meadows (Waycott et  
38 al., 2009), mangroves (Polidoro et al., 2010) and coral reefs (Pandolfi et al., 2003), to a point  
39 that goods, services and cultural benefits provided in these areas are critically endangered  
40 (Barbier, 2017; Cardinale et al., 2012). Moreover, human activities and their associated  
41 pressures are often overlapping in space and time, creating hotspots of cumulative impact  
42 with no trends of decrease (Halpern et al., 2019).

43

44 In this context, specific interventions for conserving biodiversity are a cornerstone of  
45 ecosystem services protection (Duarte et al., 2020). Integrating a wide range of  
46 environmental, ecological and human factors, Ecosystem-Based Management (EBM) has  
47 emerged as a holistic and consensual approach to secure ecosystems' capacity to provide  
48 ecosystem services against local as well as distant human pressures (Enright and Boteler,  
49 2020; Long et al., 2015; McLeod et al., 2005). Local management is key to both reducing  
50 exposure to local threats and improving resilience to global change (Harvey et al., 2018;  
51 Lefcheck et al., 2018; MacNeil et al., 2019; O'Leary et al., 2017; Roberts et al., 2017; Shaver et  
52 al., 2018; I. D. Williams et al., 2019; Wu et al., 2017). Local management is also essential to  
53 define tangible targets and empower local stakeholders.

54

55 In an EBM perspective, cumulative impact assessments can help practitioners set  
56 management priorities by weighing ecosystems' vulnerability against exposure to different  
57 human activities in a spatially explicit way (Kappel et al., 2012). Cumulative impact  
58 assessments remain one of the few comprehensive tools that allow quantifying how humans  
59 are affecting natural systems, and how actions targeting specific stressors may be expected to  
60 alter the overall impacts (Halpern et al., 2008a). While traditionally used in the marine  
61 environment to inform management and policy decisions on the global (Halpern et al., 2019,

62 2015, 2008b) and regional scales (Ban et al., 2010; Bevilacqua et al., 2018; Clarke Murray et  
63 al., 2015; Gissi et al., 2017; Halpern et al., 2009; Korpinen et al., 2012; Micheli et al., 2013),  
64 key challenges remain to apply the cumulative impact framework on the local scale. These  
65 include the availability of fine-scale resolution data on human activities and associated  
66 pressures, especially in a land-sea continuum perspective (Clark et al., 2016), the outputs'  
67 representation in a comprehensive way for local planners and managers (Lombard et al.,  
68 2019), and the integration of the inherent uncertainty into decision-support (Stock et al.,  
69 2018).

70

71 Coral reefs are among the most threatened marine ecosystems in the world and are affected  
72 by a broad range of activities and pressures (Halpern et al., 2019; Harborne et al., 2017;  
73 Williams et al., 2019), jeopardizing the provision of key ecosystem services such as coastal  
74 protection, food provisioning and cultural heritage (Cinner, 2014; Hicks and Cinner, 2014).  
75 While mitigating distal threats like climate change require global action (Morrison et al. 2020),  
76 local management of activities such as fishing, shipping, tourism and coastal development can  
77 help reduce impacts and support resilience to global stressors (Anthony et al., 2015). Here,  
78 we use and extend the cumulative impact model framework to characterize and explore the  
79 impact of human activities on scales relevant to most community-based decisions and  
80 management interventions, using the coral reef ecosystem of Moorea, in French Polynesia, as  
81 case-study. Specifically, we operationalized the linked cumulative impact model framework to  
82 produce a map of cumulative impact that would enable planners, resource managers, and  
83 communities to examine spatial variation in human pressures and explore different sources  
84 of impact at a fine spatial scale to inform local decision-making.

85

## 86 **2. Materials and Methods**

### 87 **2.1. Study site**

#### 88 *2.1.1. Coral reef ecosystem*

89

90 Located in French Polynesia, Moorea is a volcanic island surrounded by a 49 km<sup>2</sup> semi-  
91 enclosed coral reef, shallow (less than 30 m deep) and relatively narrow (maximum 1500 m  
92 long) lagoon, connected to the Pacific Ocean by 12 passes (Figure 1). While the fore reef is  
93 directly exposed to oceanic conditions, the lagoon is more sheltered and includes a shallow

94 barrier reef (less than three meters deep), a fringing reef adjacent to land, and a channel (>  
95 10 m deep) that separates the two. In the three past decades, Moorea's fore reefs has been  
96 exposed to numerous acute disturbances including two cyclones, one crown-of-thorns starfish  
97 outbreak, and five bleaching events (Adjeroud et al., 2018; Vercelloni et al., 2019). Until now,  
98 coral cover always managed to reach the pre-disturbance levels following many of these  
99 events. However, coral assemblages have changed significantly (Adjeroud et al., 2018;  
100 Pratchett et al., 2011; Trapon et al., 2011), with cascading effects on fish assemblages (Lamy  
101 et al., 2016) leading to a deficit in biodiversity and ecosystem functioning, a phenomenon  
102 called "recovery debt" (Dubois et al., 2019).

103  
104  
105

### 2.1.2. *Socio-economical context*

106 Moorea's population increased from 7,059 people in 1983 to 17,463 in 2017, becoming the  
107 second most populated island of French Polynesia after Tahiti (INSEE-ISPF 2017). Human  
108 population and activities are mostly concentrated in a narrow land strip adjacent to the coast,  
109 due to the steep island topography. In the 90's, the "Progress Pact", an economic plan  
110 promoting local economic self-sufficiency based on tourism, agriculture, fishing and pearl  
111 farming, led to a shift from a subsistence economy (dominated by small-scale fisheries and  
112 farming) to a cash economy (relying mostly on tourism and services sector) (Leenhardt et al.,  
113 2016; Walker et al., 2014). Agriculture, which is now largely based on large pineapple  
114 plantations, has become more intensive and intended to the export market. As the third most  
115 visited island in French Polynesia after Tahiti and Bora-Bora (INSEE-ISPF 2019), tourism is an  
116 important economic sector of Moorea. It is supported by international resorts construction  
117 and relies largely on reef-based activities. However, while Moorea inhabitants exhibit a lower  
118 dependency to marine resources for food provisioning compared to other Pacific Islands  
119 (Rassweiler et al., 2020), between 35% and 50% of its population are still engaged in a fishing-  
120 related activity and feel strongly connected to the reef (Leenhardt et al., 2016; Thiault et al.,  
121 2017).

122  
123  
124

### 2.1.3. *Marine Spatial Planning*

125 Following tourism development around Moorea, a marine spatial plan (*Plan de Gestion de*  
126 *l'Espace Maritime*, PGEM) -the first in French Polynesia- was implemented in 2005 following

127 more than 10 years of consultation processes (Hunter et al., 2018). The PGEM encompasses  
128 the whole lagoon and the fore reef down to 70 m deep, and specifically regulates fishing  
129 activities through 8 marine protected areas (MPA) covering 17% of its waters, of which 5 are  
130 fully protected and 3 moderately protected (Thiault et al., 2019). Other regulations include  
131 delineation of areas for recreational activities including swimming, ray and shark provisioning  
132 and boating, while coral extraction and embankments are prohibited island-wide. However,  
133 no explicit connections were made between this marine spatial plan and the pre-existing land  
134 planning framework (*Plan Général d'Aménagement*, PGA) during the planning process, and  
135 issues such as land-based pollution and sedimentation largely overlooked.

136

## 137 **2.2. Cumulative impact assessment**

138

### 139 *2.2.1. Human activities and associated pressures*

140

141 We reviewed the primary and grey literature and identified 11 human activities that can have  
142 a direct impact on Moorea's marine ecosystem (Table S1). Activities were grouped into two  
143 broad categories: land-based activities and sea-based activities. For each activity, we used  
144 fine-scale data to model the spatial extent and intensity of their associated pressures.  
145 Supplementary materials provide a detailed explanation of each pressures' models and a  
146 review of impacts.

147

#### 148 *2.2.1.1. Land-based activities*

149

150 We considered three land-based activities: agriculture, land conversion, and urbanization.  
151 Pressures from agriculture and land conversion were considered as point-source pollutions  
152 originating from the watersheds and associated river mouths, whereas pollution from  
153 urbanization was considered as originating from individual houses all along the coast. These  
154 activities result in different pressures on the adjacent coral reef ecosystem, such as  
155 eutrophication due to fertilizers and increase in sedimentation rates, and pollution from  
156 pesticides and sewage (Fabricius, 2005; Magris and Ban, 2019). Point-sources pressures were  
157 modelled using data on land occupation inside each watershed. Values indicating the intensity  
158 of the pressure were computed, associated to the corresponding river mouth, and extended

159 spatially into the lagoon using a diffusion model. Sewage discharge from urbanization was  
160 based on houses density in the area (see Supplementary Material 2.1 for more details on land-  
161 based activities impacts and modeling). To model the diffusion of pressures from agriculture  
162 and land conversion, we adapted a linked land-sea modeling framework designed for local  
163 management, using a cost-path surface model built from three factors known to affect  
164 diffusion: depth, distance from the shore and wind speed (Delevaux et al., 2018).

165

#### 166 2.2.1.2. *Sea-based activities*

167

168 Eight activities take place directly into the lagoon and along the fore reef. Six are related to  
169 tourism (i.e., boat traffic, mooring, anchoring, beach attendance, diving, wildlife provisioning),  
170 and the two remaining are coral reef fisheries and shoreline modification. Moorea's shoreline  
171 evolution is monitored since 1977 (Madi Moussa et al., 2019), allowing the modeling of the  
172 resulting pressure on near-shore habitats (see Supplementary Material 1.2.1). Pressure  
173 coming from fishery in Moorea is acknowledged as very challenging to assess given the  
174 complexity of the artisanal coral-reef fishery and the absence of stock monitoring (Leenhardt  
175 et al., 2016). As a proxy for fishing pressure, we thus use a fishing effort model based on  
176 socioeconomic data (households' dependence on fishing) and participatory mapping of the  
177 fishermen's spatial preference for fishing grounds (Thiault et al., 2017). This model is the most  
178 recent attempt to describe the fishing pressure in Moorea in a spatially explicit way.

179

180 Moorea's tourism sector has rapidly grown in the last decades. It relies on a variety of activities  
181 such as diving, wildlife provisioning, and an increase in boat traffic and beaches attendance.  
182 The increase in boats and people use of the lagoon for touristic activities can be detrimental  
183 to coral reef ecosystem, through direct pressures (e.g, boat anchors, divers fins, trampling)  
184 causing physical damages to the reef, and through different types of pollution (e.g, noise  
185 production, release of pollutants, sewage) generated by the use of engines (Davenport and  
186 Davenport, 2006). Outside boat traffic and beach use, activities are restricted to specific places  
187 for different reasons: for example, wildlife provisioning is partially regulated by the PGEM,  
188 allowing the activity to only take place in six sites, even if one supplementary site has been  
189 observed. Similarly, mooring and the related anchoring are only allowed inside the lagoon at  
190 five specific sites. Diving tends to also take place at specific sites around Moorea, some of

191 them being included in the PGEM, while others appearing on websites of diving operators,  
192 confirmed by face-to-face interviews.

193

194 To assess beach attendance, we combined data on household density along the coast, tourism  
195 infrastructures and presence of public beaches which allow to model the intensity of this  
196 pressure inside the lagoon, taking into account the distance to the shore and depth. Finally,  
197 our boat traffic intensity model was based on least-cost distance between boats' departure  
198 and arrival sites, which can be specific sites in the lagoon (wildlife provisioning sites, diving  
199 sites) or sites used for regular trips (from cruise ship parking to harbor, ferries to Tahiti, jet-ski  
200 tour, and dolphin and whale watching). The intensity of each of these six sub-activities was  
201 calculated based on the frequency of their trip. Supplementary Materials 2.2 provides a  
202 detailed explanation of each pressure modeling.

203

#### 204 *2.2.2. Habitats*

205

206 We considered four reef habitats, each characterized by a unique geomorphology , and  
207 specific benthic and fish assemblages: (1) the fringing reef, directly adjacent to the shore and  
208 less than two meters deep; (2) sandy bottoms, which include mainly the channel that  
209 separates the fringing and the barrier reefs, but also some sand banks and areas inside the  
210 lagoon; (3) the barrier reef, less than three meters deep and intersected by the passes,  
211 exhibiting similar coral cover compared to fringing reef but a greater specific richness; and (4)  
212 the fore reef, outside the lagoon, separated by the reef crest, from 0 to 65 m deep and directly  
213 influenced by the open ocean. It exhibits the greatest coral cover and species richness.

214

215 We derived a spatial layer of these habitats substrate map from very-high resolution satellite  
216 imagery (Collin and Hench, 2015). Cells for which substrate was dominated by sediments were  
217 classified as sandy bottom. We used the channel to discriminate spatially coral reef patches  
218 belonging to the fringing reef from those belonging to the barrier reef, while the reef crest  
219 discriminates the barrier reef from the fore reef (Figure S1).

220

221

#### 222 *2.2.3. Vulnerability coefficients*



223

224 Vulnerability coefficients, used to translate pressure intensities on habitats into impacts, were  
225 obtained using an expert judgement process. We interviewed 15 experts on French Polynesia  
226 coral reef ecosystems and management to discriminate how each activity impacts each  
227 habitats, based on five criteria: the spatial scale of the pressure, its frequency, its functional  
228 impact, the ecosystem resistance and the recovery time (Halpern et al., 2007). For example,  
229 the criteria about the scale of a pressure is evaluated against 7 categories (no occurrence of  
230 the pressure, occurrence in less than 1 kilometer, between 1 and 10 kilometers, between 10  
231 and 100, between 100 and 1000, 1000 and 10000 and finally in more than 10 000 kilometers),  
232 and the certainty is evaluated against 4 categories (none, low, medium, high). Each category  
233 was then ranked (in this case from 0 to 6 for the scale, and from 0 to 4 for the certainty), and  
234 experts assigned a rank in each criteria, for each pressure, and on each ecological habitats  
235 along with the certainty rank. Mean values for these five criteria weighted by the certainty  
236 were then used to assign a single weighted vulnerability coefficient for each habitat facing  
237 each pressure (Table S4).

238

#### 239 2.2.4. Cumulative impact framework

240

241 To assess the cumulative impact of human activities on Moorea's lagoon and fore reef, we  
242 used an additive model combining the location and intensities of human pressures on  
243 different habitats (Halpern et al., 2008b). We weighted these pressures based on vulnerability  
244 coefficients derived from experts' assessment as:

245

$$246 I_c = \sum_{i=1}^n \sum_{j=1}^m P_i E_j \mu_{i,j} \quad (1)$$

247

248 where  $I_c$  is the cumulative impact score for a given pixel  $c$ ,  $P_i$  is the log-transformed and  
249 normalized value of anthropogenic pressures  $i$  ( $n = 11$ ),  $E_j$  is the presence or absence of  
250 habitat  $j$  ( $m = 4$ ), and  $\mu_{i,j}$  is the vulnerability coefficients of habitat  $j$  to pressure  $i$  (Figure 2).

251

#### 252 2.2.5. Uncertainty analyses

253

254 Uncertainty in the model's outputs was estimated using a method adapted from Stock and  
255 Micheli (2016). In this study, the authors identified nine model assumptions or data quality  
256 issues (referred to as "factor" hereafter) that could generate uncertainty, five of which were  
257 potentially present in our model: (1) missing pressure data, (2) type of transformation for  
258 pressure layers, (3) errors in vulnerability coefficients, (4) nonlinear responses, and (5)  
259 multiple pressure effects.

260

261 We quantified our model's uncertainty by bootstrapping these five factors using Monte-Carlo  
262 simulations (1000 runs). In each simulation run, factors were set to values randomly assigned  
263 from their ranges and cumulative impact was calculated. We then recorded how often pixels  
264 was in the first (low-impact area) or the last quartiles (high-impact area) of cumulative impact  
265 distribution to compare the robustness of low and high impacted areas with our original  
266 model. We assumed a low- or high-impact pixel is robust when it is confirmed by more than  
267 75% of simulations (*i.e.* a pixel belonging to the first or last quartiles of original cumulative  
268 impact and belongs as well in the first of last quartiles of cumulative impact score in more  
269 than 75% of simulations).

270

271 All analyses were conducted in QGIS software v.3.4.8 (QGIS Development Team, 2020) and R  
272 software v.4.0.3 (R Core Team, 2020) using the raster (Hijmans, 2020), sf (Pebesma, 2018),  
273 gdistance (Van Etten, 2017), and SpatialEco (Evans, 2020) packages for spatial analyses, as well  
274 as ggplot2 (Wickham, 2016) and tmap (Tennekes, 2018) for figures and maps production.

275

### 276 **3. Results**

#### 277 **3.1. Cumulative impact assessment overview**

278

279 The entire system studied is impacted by human activities, although the reef system is  
280 heterogeneously affected around Moorea (mean  $I_c = 2.6$ ; Figure 3A-B). Impacts are generally  
281 larger close to shore, with fringing reefs displaying the highest levels of impact overall (mean  
282  $I_c = 5.7$ ). The barrier reef and sandy bottoms both exhibit lower cumulative impact scores,  
283 while the fore reef is the least impacted (Figure 3C). Cumulative human impact is particularly

284 high off the municipalities of Papetoai and Paopao (mean  $I_c = 3.6$  and  $3.4$ , respectively), while  
285 it remains close to average for Teavaro and Haapiti. Afareaitu has the lowest impact score  
286 with a mean  $I_c$  of  $1.9$  (Figure 3D).

287

### 288 **3.2. Spatial extent of human activities**

289

290 Agriculture, fisheries, land conversion and urbanization impact the entire reef ecosystem  
291 across all five municipalities (Figure 4). Two other activities impacting a large portion of the  
292 reef are boat traffic (84% of the study area), and wildlife provisioning (31%), located mainly in  
293 the north municipalities of Papetoai and Teavaro, and on the fore reef. The five other activities  
294 (i.e., beaches attendance, mooring, shoreline modification, diving and anchoring) are  
295 distributed around the island in very specific locations, hence impacting a much smaller  
296 proportion of the different habitats (Figure 4A). Papetoai and Teavaro are the most concerned  
297 by impacts extent, especially for wildlife provisioning and mooring (Figure 4B). Boat traffic and  
298 wildlife provisioning have a higher impact on offshore habitats. However, the fringing reef is  
299 impacted by all activities, except for diving and anchoring.

300

### 301 **3.3. Human activities contributions to cumulative impact**

302

303 Fisheries are consistently the largest contributor to the overall cumulative human impact and,  
304 when added with land-conversion and urbanization, contribute to more than 80% of the  
305 overall cumulative impact (Figure 5A). There is only one habitat where fisheries are outpaced  
306 precisely by land conversion and urbanization, the fringing reef (Figure 5B). However, land-  
307 based activities contribute together to more than half of the cumulative impact around  
308 Moorea. In the barrier reef and the fore reef, impact is largely driven by fisheries and boat  
309 traffic. While heterogeneity between contributors is observed for habitats, municipalities  
310 have the same three activities as those observed at the island scale (Figure 5C). The fourth  
311 most impacting activity is agriculture in Afareaitu and Haapiti, while it is boat traffic in Paopao,  
312 Papetoai and Teavaro.

313

### 314 **3.4. Uncertainty analysis**

315

316 Comparison between low- and high-impact area in the 1000 Monte-Carlo simulations (*i.e.*  
317 pixels being in first or last quartiles of cumulative impact score in more than 75% of  
318 simulations) and our original model indicates that 35% of original low-impact area and 23%  
319 of high-impact area are robust to factor variations (Figure 6A,B). High-impacted habitat  
320 fringing reef (43% of this habitat is highly impacted) exhibits 45% of robust high-impact area,  
321 while other habitats high-impact area are poorly robust. Low-impact areas, mostly on sandy  
322 bottoms, are robust at 15% (Figure 6C). Municipalities located in the north of Moorea display  
323 between 7% and 12% of robust high-impact areas, while municipalities in the south (mainly  
324 Haapiti and Afareaitu) host robust low-impact areas (both 12%). Results are similar to those  
325 observed in global studies on cumulative impact uncertainty (Stock et al., 2018; Stock and  
326 Micheli, 2016).

327

#### 328 **4. Discussion**

329

330 Our cumulative impact assessment provides, to our knowledge, the most comprehensive fine-  
331 scale mapping of cumulative human impact in a marine environment to date. We found that  
332 over half of the overall cumulative impact on Moorea's reef is due to land-based activities:  
333 agriculture, land conversion and urbanization. In addition to having large impacts in intensity,  
334 the footprint of land-based activities is widely distributed throughout the reef and across all  
335 municipalities. These findings underline the critical role that integrated "ridge-to-reef  
336 management" should play (Álvarez-Romero et al., 2011; Brown et al., 2019; Carlson et al.,  
337 2019; Wenger et al., 2020). However, the current marine spatial plan does not address land-  
338 based pressures, focusing instead exclusively on regulating marine activities, hence failing to  
339 protect its waters from its key pressures. Our results highlight the large benefits that can be  
340 derived from focusing management attention towards more transformative, deeper leverage  
341 points (*sensu* Abson et al., 2017; Fischer and Riechers, 2019) that might be more difficult to  
342 attain but potentially yielding more ecological benefits. These may require, among others, a  
343 greater collaboration between relevant agencies to better integrate both terrestrial and  
344 marine systems and threats, and effectively mitigate land-based pressures on the reef (Thiault  
345 et al., 2020). In addition, putting land-sea interactions at the core of the management plan is  
346 also critical to avoid the current management mismatches between the land-sea continuum  
347 as perceived by traditional Polynesian management styles (Leenhardt et al., 2017). Moreover,

348 mitigation of land-based pressures is likely to have the greatest positive impact on the intrinsic  
349 ecological resilience of the reef, especially inside the lagoon, and avoid a focus on restricting  
350 fishing activities, which can be detrimental when associated with high social vulnerability  
351 (Thiault et al., 2020).

352

353 The second largest contributor to the overall cumulative impact is fishing. It is the activity that  
354 alone has the most profound and widespread impact, affecting the entire reef and  
355 contributing to more than a third to the overall impact. These findings may appear surprising  
356 given the low impact on habitats the highly selective gears (mostly spearguns, lines and nets)  
357 used in Moorea has (Rassweiler et al., 2020). However, this may reflect the ubiquitous nature  
358 of fishing within the community (high livelihood dependency on fishing leading to high fishing  
359 capacity) (Leenhardt et al., 2016; Thiault et al., 2017), as showed by the fact that it ranked first  
360 in all municipalities. In addition, the relatively small lagoon width, the twelve passes and the  
361 convenience to fish on the outer slope under good weather conditions allow fishermen to  
362 access all reef components, although distance to the shore remains a key driver of fishing  
363 pressure (Thiault et al., 2017). Currently, the marine spatial plan around Moorea combines  
364 spatial (e.g., marine protected areas) and gear-based restrictions. While the existing Moorea  
365 MPA network appears effective, ecological benefits are weaker than expected (Thiault et al.,  
366 2019). Weak compliance and enforcement have previously been put forward to explain their  
367 lower effectiveness, but the above-mentioned widespread impacts of land-based activities  
368 may also play a role.

369

370 Tourism-based activities, which were a major concern for stakeholders during and after the  
371 implementation of the marine spatial plan (Gaspar and Bambridge, 2008; Walker, 2001), were  
372 found to contribute very little to the overall impact. Nevertheless, when such activities do  
373 occur, the mean impact is high, highlighting that managing tourism activities remains key to  
374 reduce human impact on the reef . This is even more critical given that jet-skiing and other  
375 new activities such as flyboard are becoming increasingly popular. Boat traffic, which here  
376 reflects the daily operations of tourism operators, was the only tourism-related activity whose  
377 impact remained relatively widespread. Improving the management of this activity may  
378 require strategically channeling boat traffic away from vulnerable habitats (i.e. barrier reef

379 and fore reef) to lower its contribution to cumulative impact or other sea-based activities (i.e.,  
380 fishing) to reduce conflicts between stakeholders (Noble et al., 2019).

381

382 Our study advances the application of cumulative impact assessments to local contexts, based  
383 on empirical spatial data. By design, the cumulative impact model focuses on simple  
384 interactions between pressures and ecological components. However, such interactions are  
385 often complex, and relatively simple representations of relationships and feedbacks between  
386 ecological components and threats may obscure information that is important to understand  
387 system dynamics, key drivers, and opportunities for effective intervention (Halpern and Fujita,  
388 2013). Future work building on new data and models could expand the set of activities and  
389 incorporate more complexity. This would further improve the ability of stakeholders and  
390 decision-makers to identify sources of impact on ecosystems and discover a wider range of  
391 options for managing coral reefs for the benefit of the people who depend on them.

392

### 393 **Conclusion**

394

395 Cumulative human impact assessments offer an approach for planners and decision makers  
396 to identify which areas are the most and least impacted, which activities are responsible for  
397 these impacts, and can thus help target and prioritize management actions. More generally,  
398 it can underpin improved and balanced consideration of the human dimension in place-based  
399 environmental management initiatives. Because of the standardized nature of the cumulative  
400 impact model, this approach enables direct and fine-scale comparisons that allow decision  
401 makers and stakeholders to measure and map change through time (see Halpern et al., 2015  
402 for an application of this at a global scale). Such information may provide additional  
403 indications on the nature of changes (key sources of impact affected), and its direction  
404 (positive or negative) in specific locations. This approach is likely to be applicable in a variety  
405 of other places where human activity represents both an important threat to the ecosystem  
406 and an invaluable source of benefits for local communities.

407

### 408 **Declaration of competing interest**

409 The authors declare that they have no known competing financial interests or personal  
410 relationships that could have appeared to influence the work reported in this paper.

411

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Map of the study area - Moorea, in French Polynesia

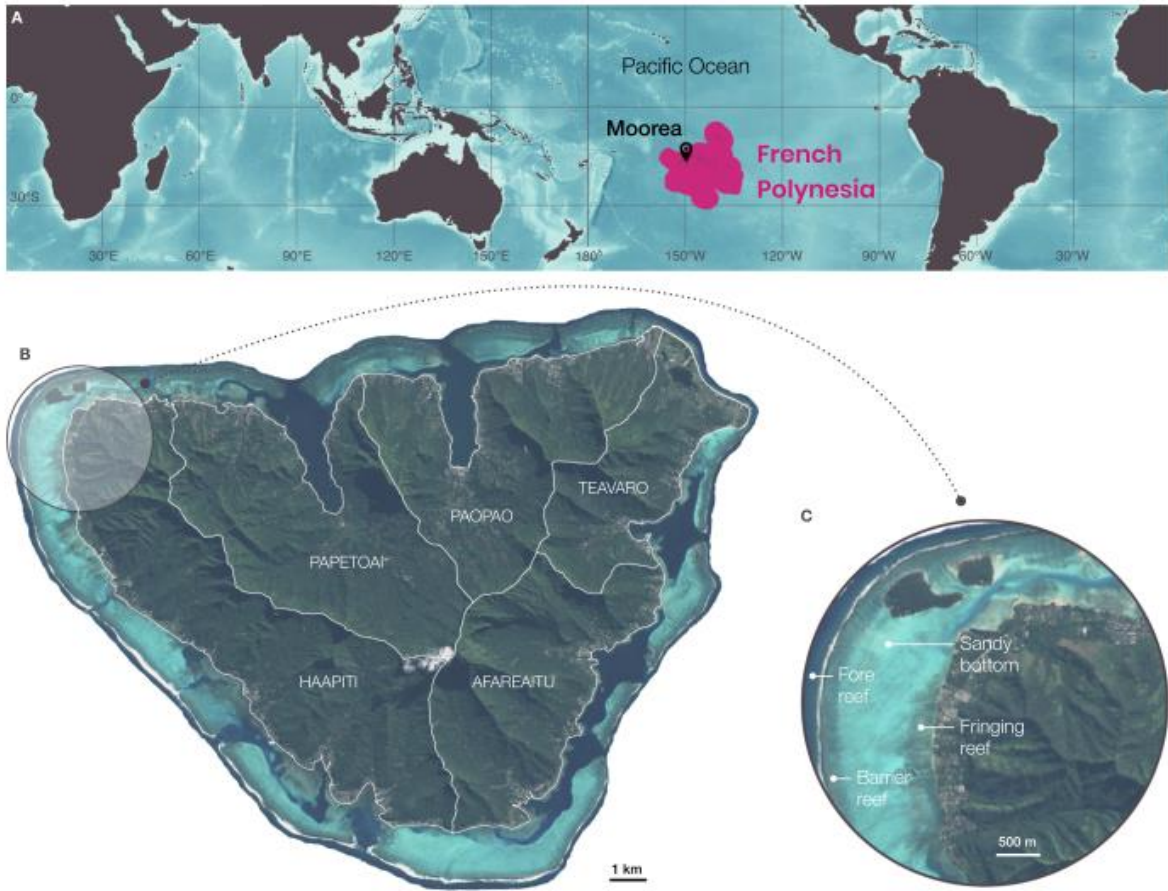
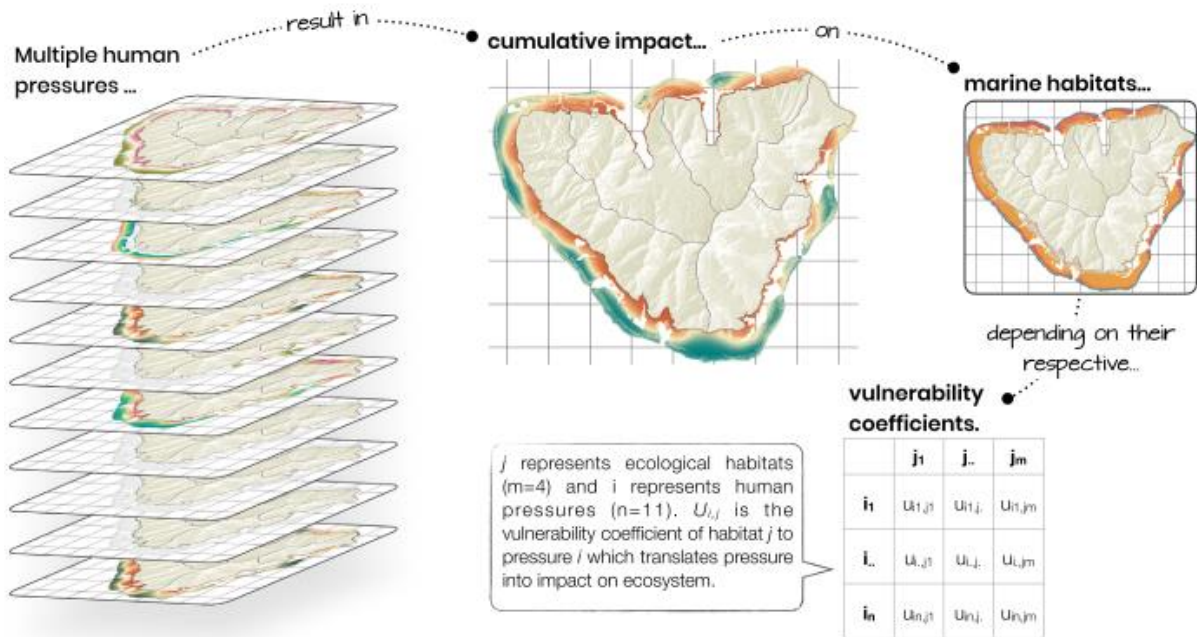


Fig. 1. Study area; Moorea, French Polynesia. French Polynesia is located in the South Pacific (A). Moorea is the second largest island after Tahiti (B). For the cumulative impact assessment we focus here on four marine habitats (C): fringing reef, barrier reef, fore reef and sandy bottom.

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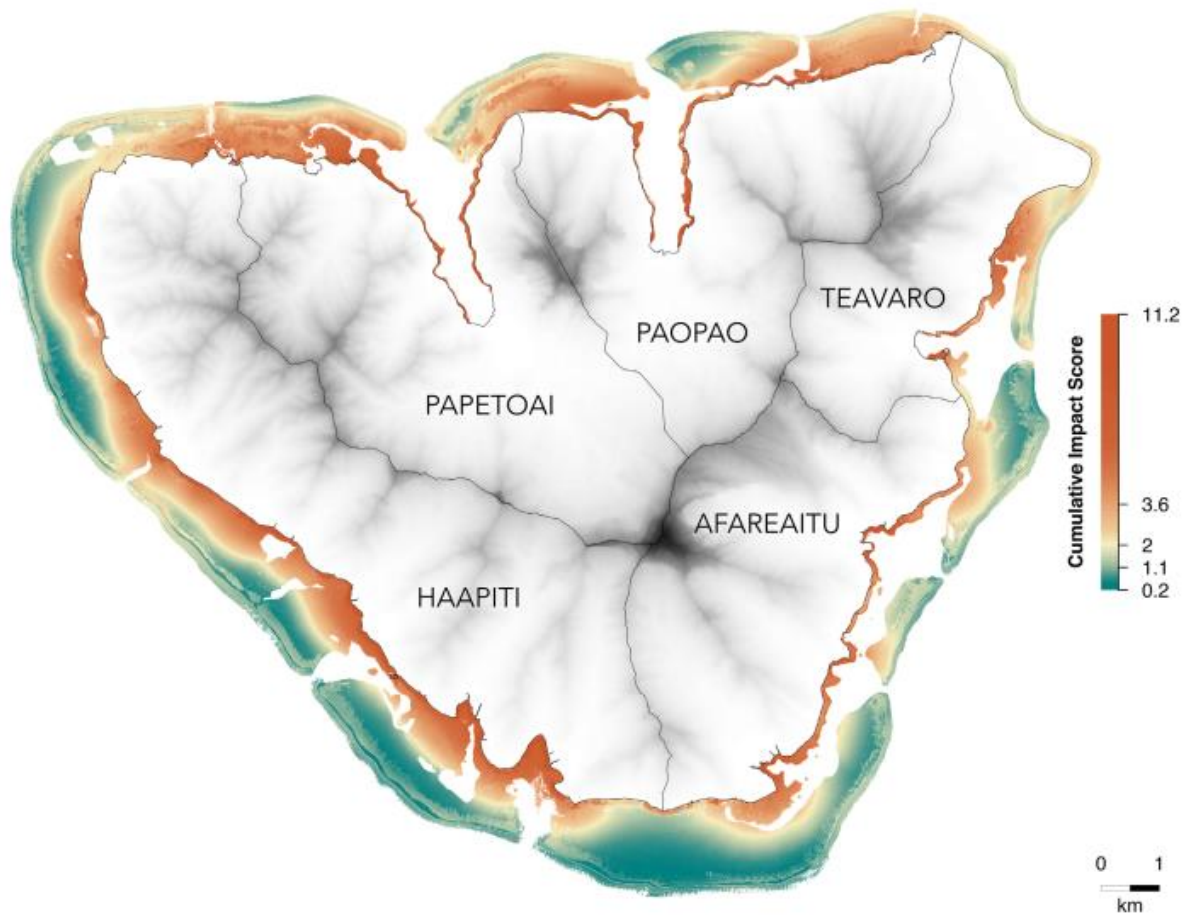
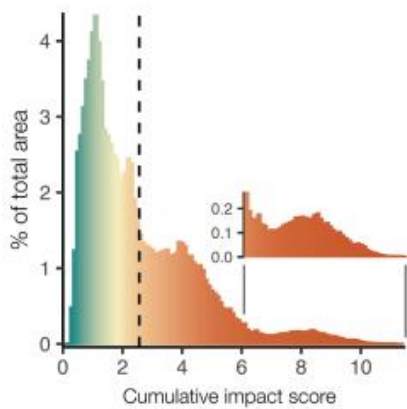
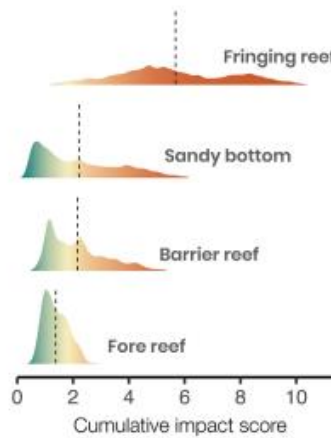
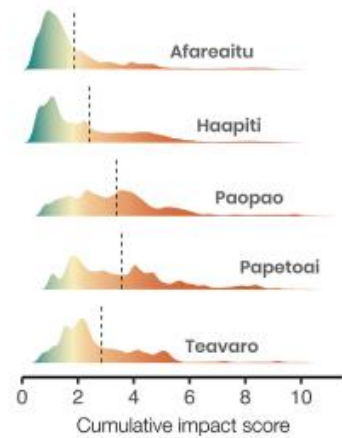
Cumulative impact assessment framework



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Fig. 2. Schematic representation of the cumulative impact assessment framework used.



**A****Moorea's cumulative impact map****B** Island-wide cumulative impact distribution**C** Cumulative impact distribution per habitat**D** Cumulative impact distribution per municipality

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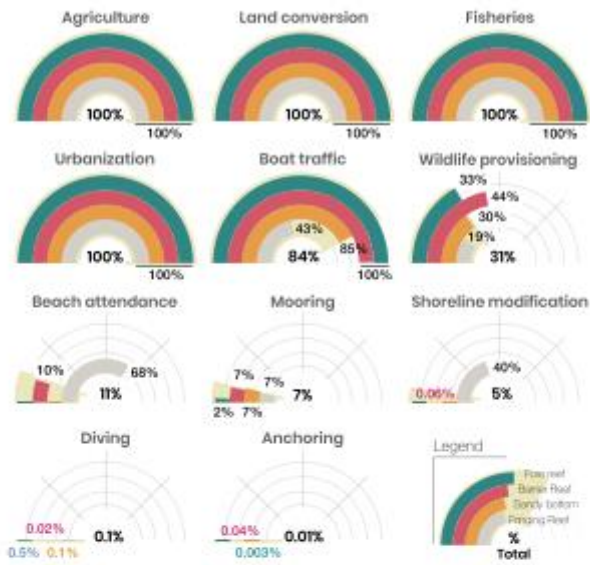
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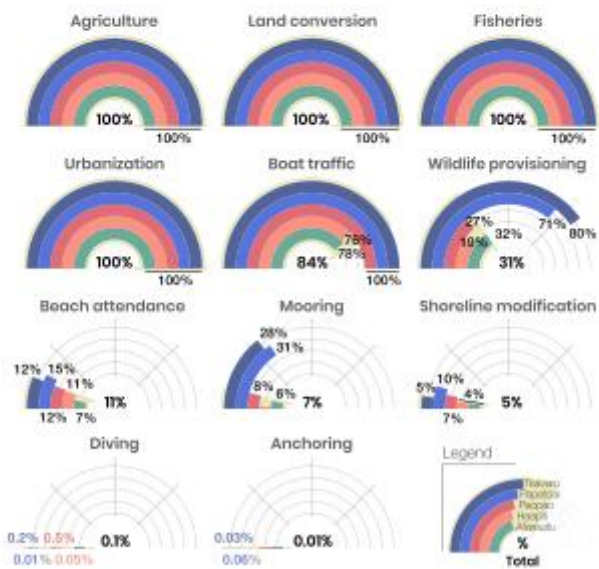
**Fig. 3.** Cumulative impact in Moorea. Map of the cumulative impact on marine habitats around Moorea (A) and overall cumulative impact score (B) distributed per habitat (C) and municipality (D). The dashed vertical lines in B, C and D indicate the average cumulative impact score.

703

**A** Spatial extent of human activities impact per habitat



**B** Spatial extent of human activities impact per municipality



**Fig. 4.** Spatial extent of human activities in Moorea, per habitat (A) and per municipality (B). Percentages in the middle of semi-circles indicate the spatial extent of each activities in the entire study area (related to the brown colored large bar). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

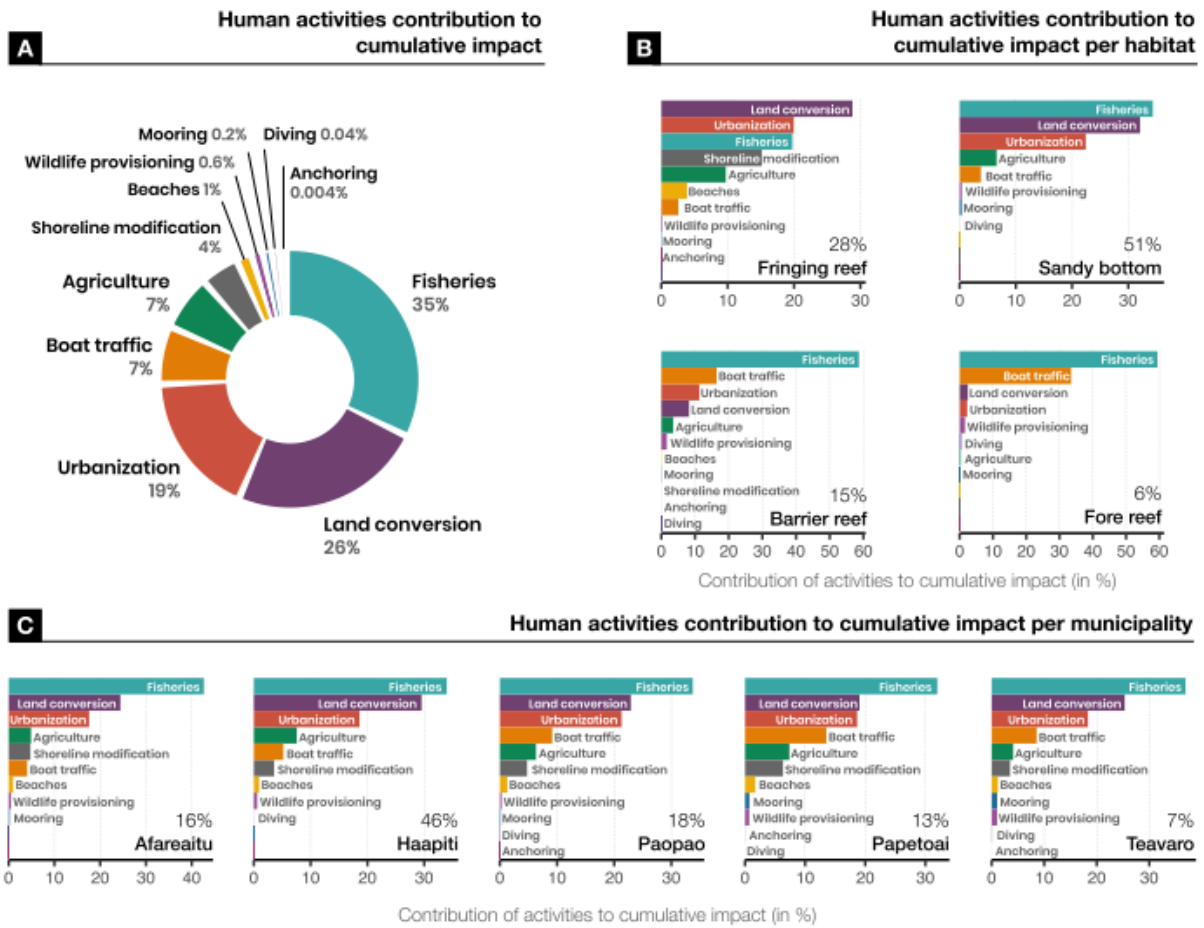


Fig. 5. Contribution of individual human activities to cumulative impact in Moorea, at the whole island scale (A), per habitat (B) and per municipality (C). Percentages above habitats and municipalities represent the proportion of overall cumulative impact in those habitats or municipalities.

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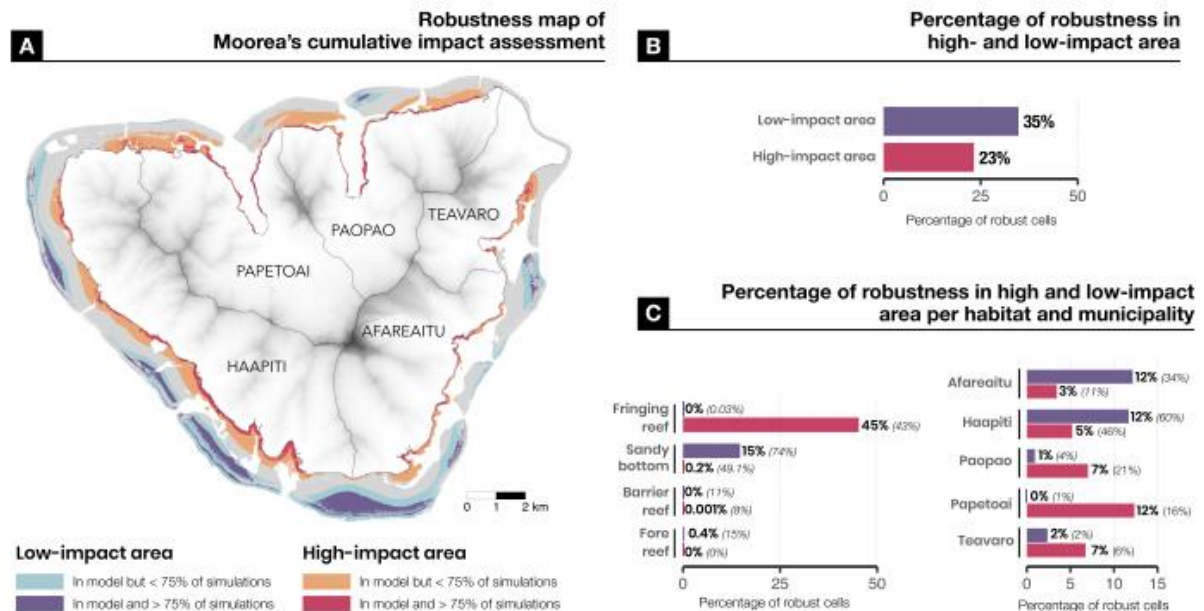


Fig. 6. Robustness of Moorea's cumulative impact assessment. Robustness mapped around Moorea (A), robustness expressed as proportion of robust pixels in low- and high-impact areas (B), and robustness per habitat and municipality (C). Percentages inside brackets in C indicate the proportion of original low- or high-impact area per habitat or municipality.

706