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

3 Charles Loiseau^{a,b}, Lauric Thiault^{a,b}, Rodolphe Devillers^c, Joachim Claudet^{a,b}

4 ^aNational Center for Scientific Research, PSL Université Paris, CRIOBE, USR 3278 CNRS-EPHE-UPVD,
5 Maison des Océans, 195 rue Saint-Jacques 75005 Paris, France

6 ^bLaboratoire d'Excellence CORAIL, Moorea, French Polynesia

7 ^c ESPACE-DEV, Institut de Recherche pour le Développement (IRD), Univ Antilles, Univ Guyane, Univ
8 Montpellier, Univ Réunion, Montpellier, France

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 km² 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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417

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Map of the study area - Moorea, in French Polynesia

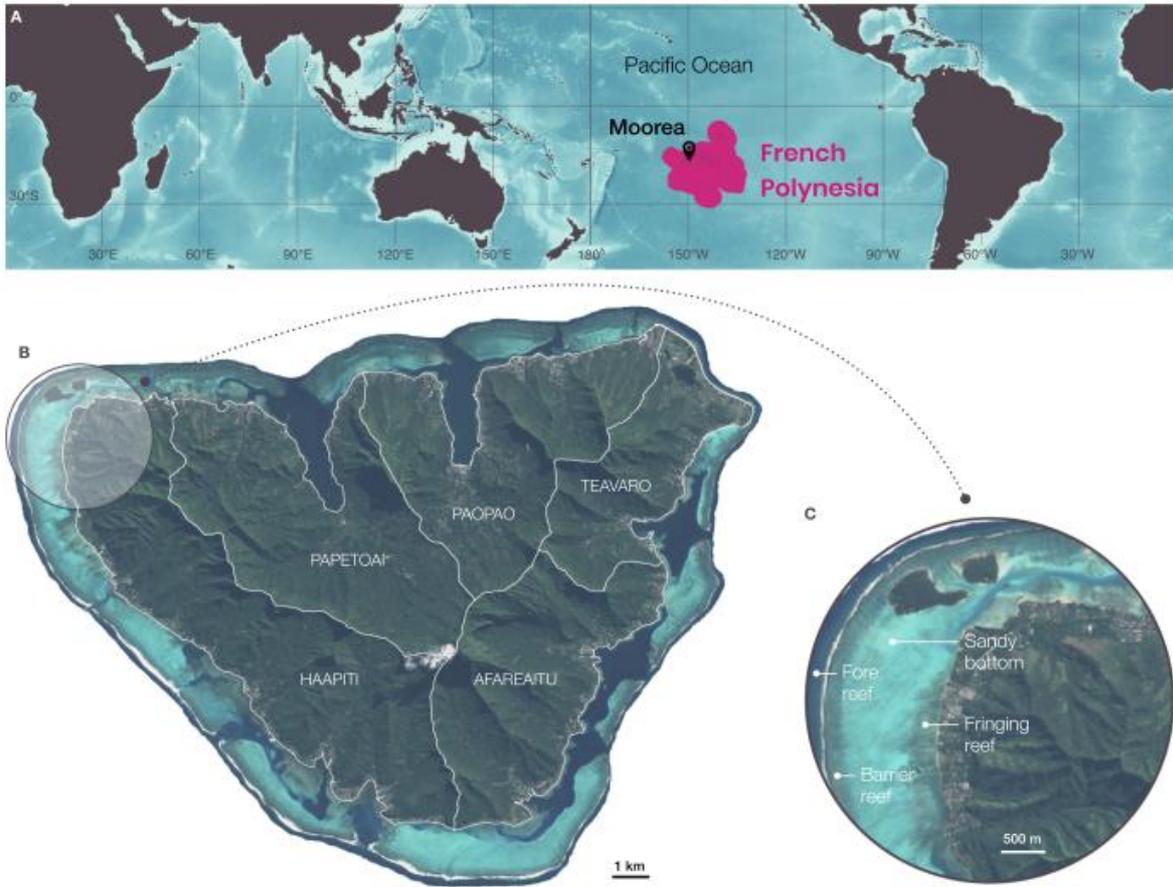
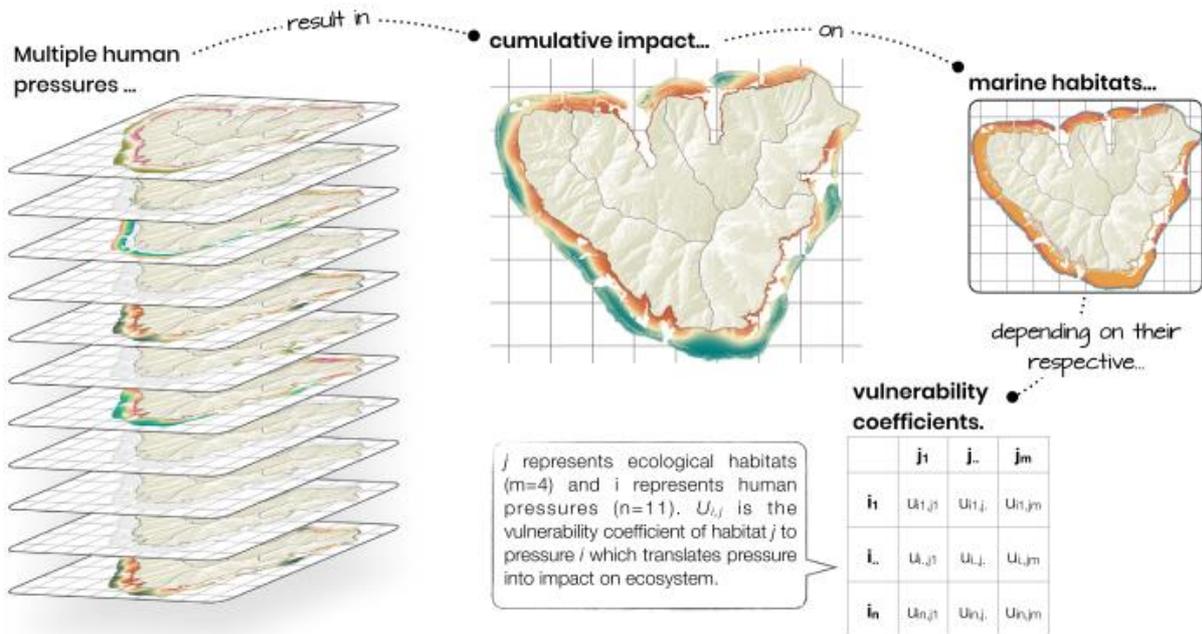


Fig. 1. Study area; Moorea, French Polynesia. French Polynesia is located in the South Pacific (A). Moorea is the second largest island after Tahiti (B). For the cumulative impact assessment we focus here on four marine habitats (C): fringing reef, barrier reef, fore reef and sandy bottom.

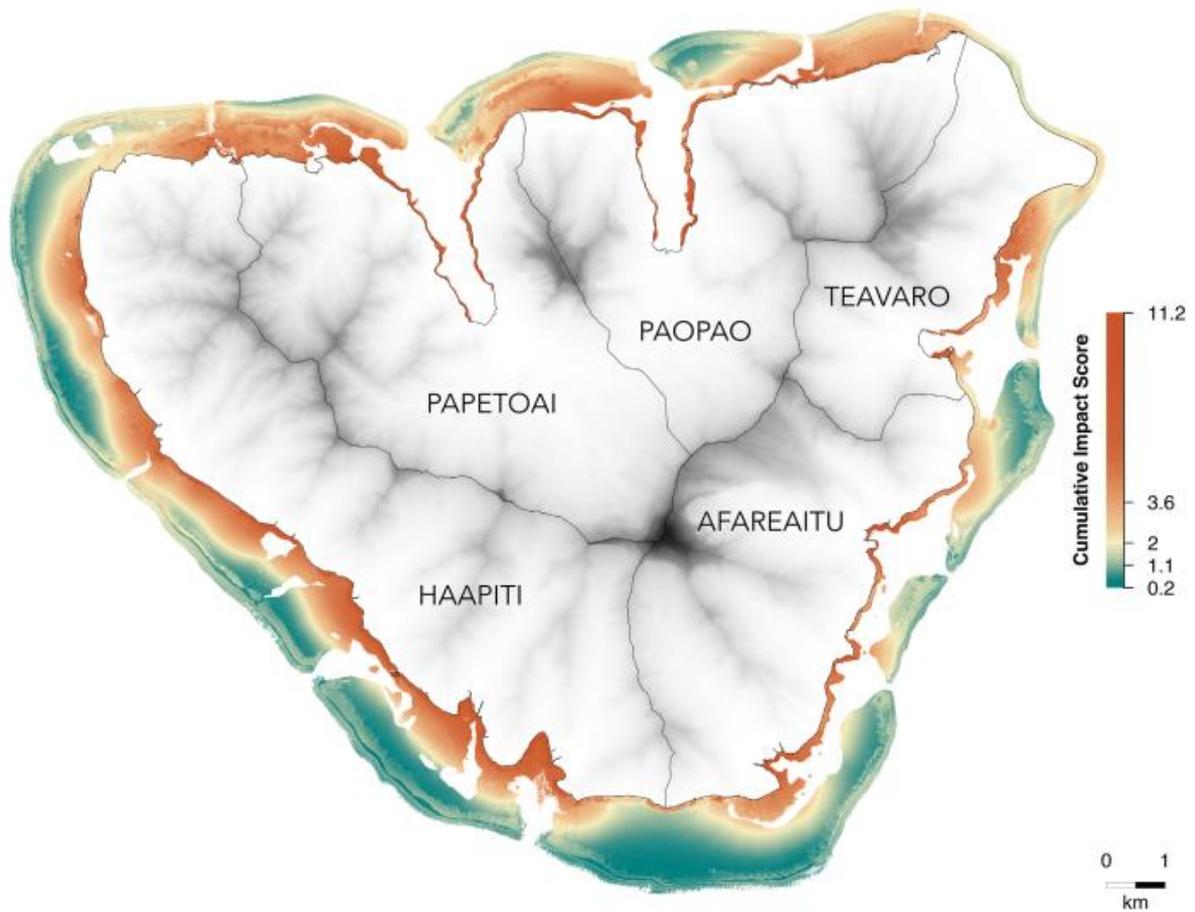
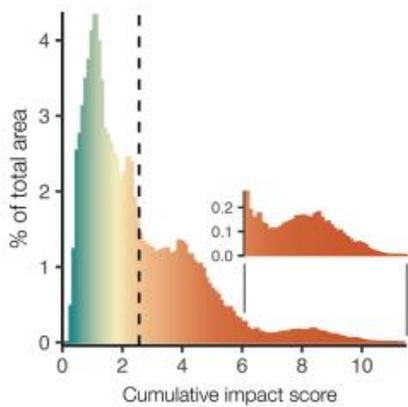
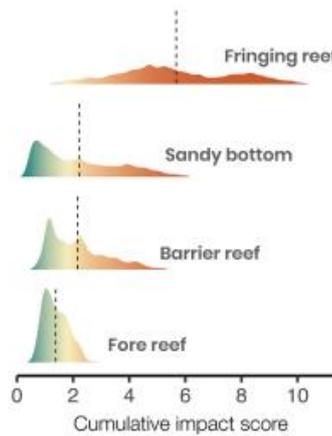
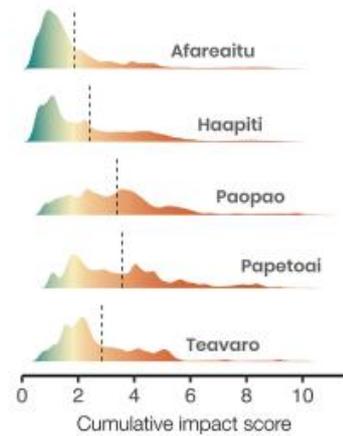
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Cumulative impact assessment framework



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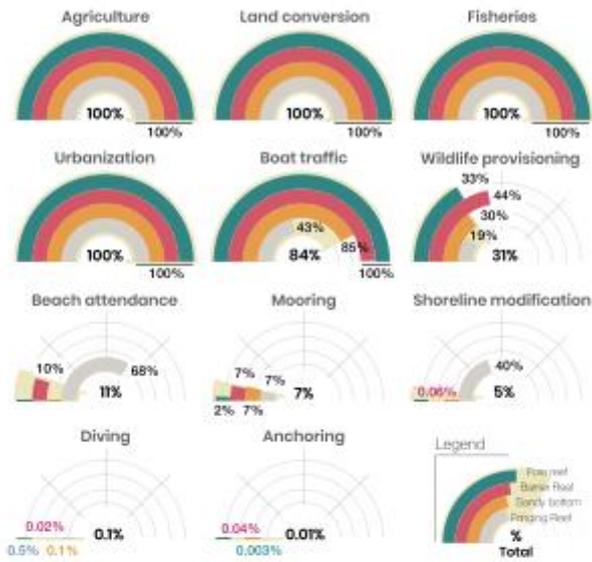
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Fig. 3. Cumulative impact in Moorea. Map of the cumulative impact on marine habitats around Moorea (A) and overall cumulative impact score (B) distributed per habitat (C) and municipality (D). The dashed vertical lines in B, C and D indicate the average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

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A Spatial extent of human activities impact per habitat



B Spatial extent of human activities impact per municipality

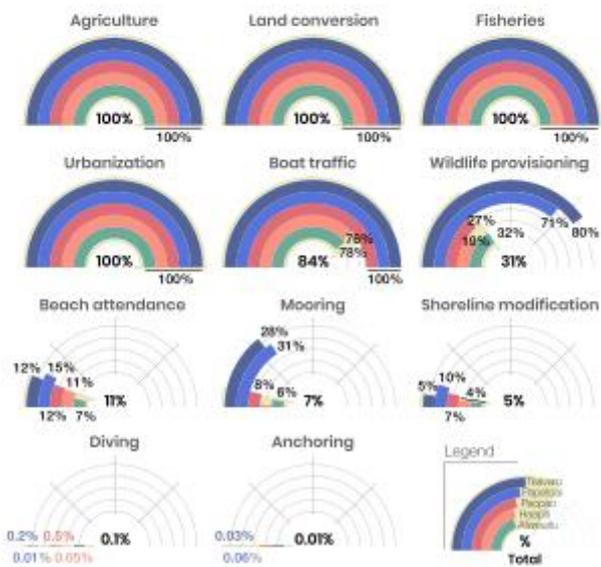


Fig. 4. Spatial extent of human activities in Moorea, per habitat (A) and per municipality (B). Percentages in the middle of semi-circles indicate the spatial extent of each activities in the entire study area (related to the brown colored large bar). (For interpretation of the references to color in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

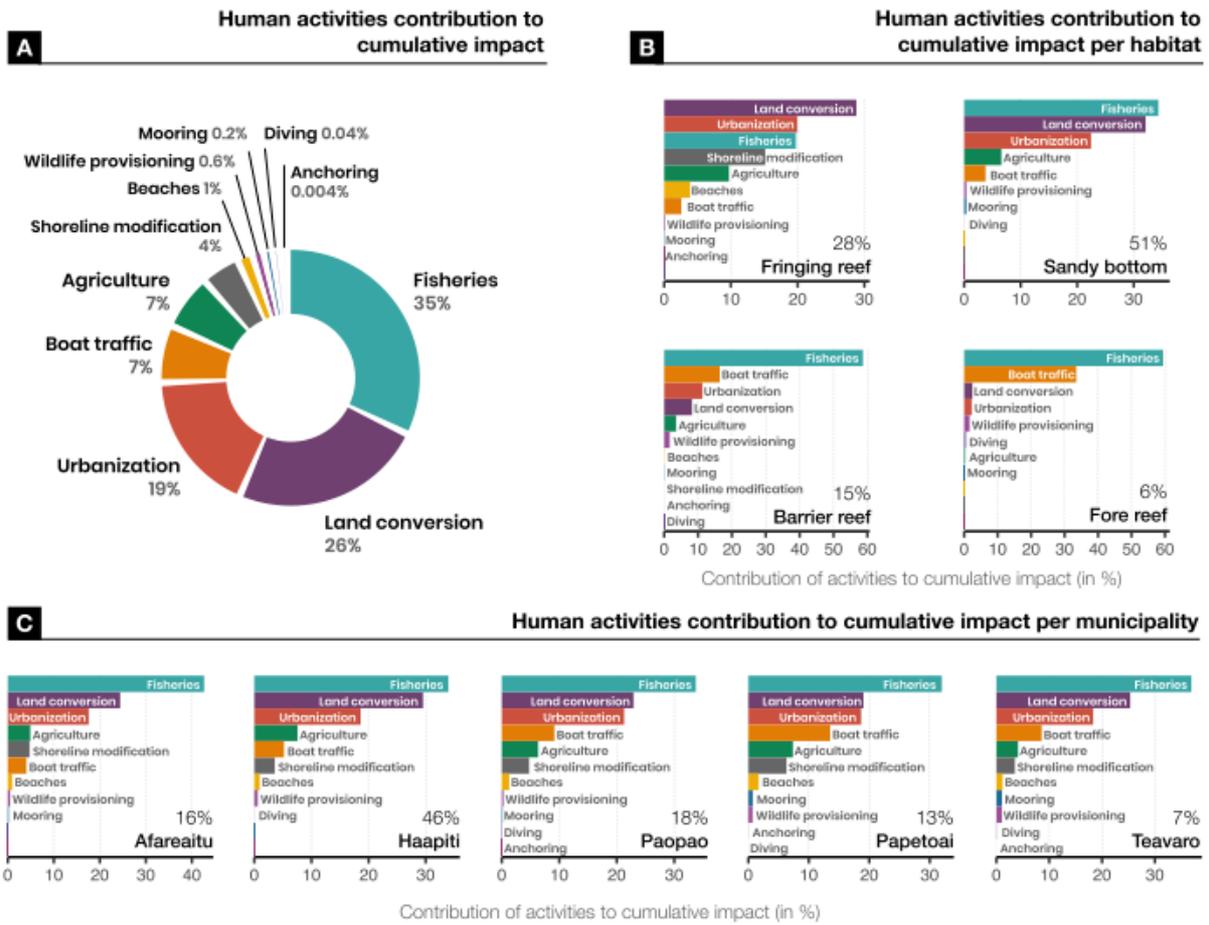


Fig. 5. Contribution of individual human activities to cumulative impact in Moorea, at the whole island scale (A), per habitat (B) and per municipality (C). Percentages above habitats and municipalities represent the proportion of overall cumulative impact in those habitats or municipalities.

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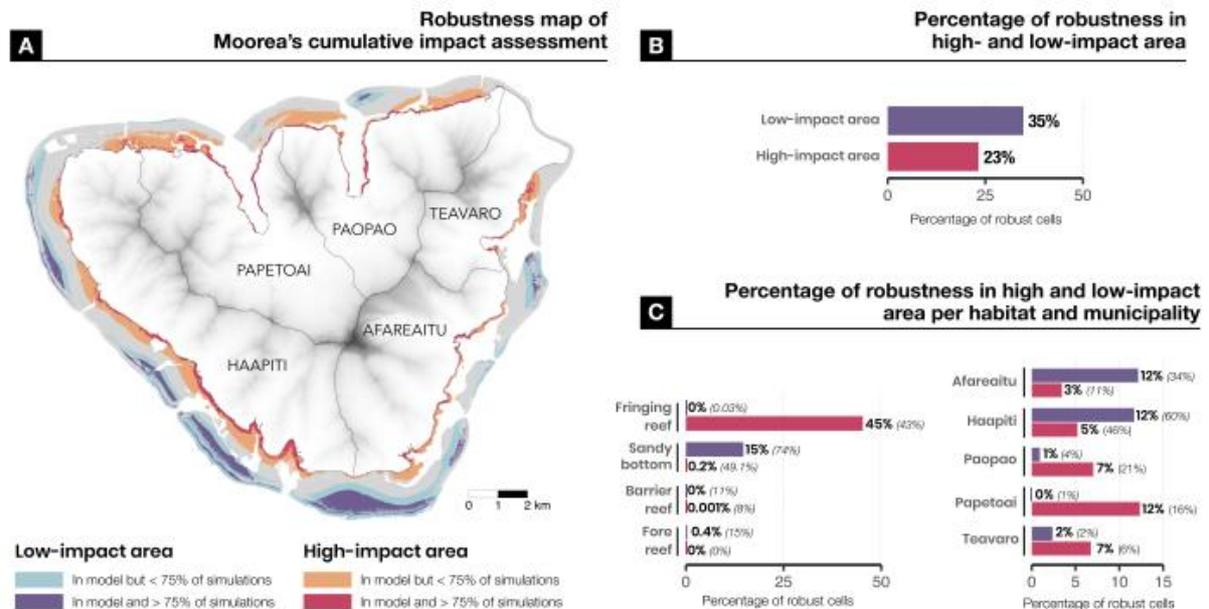


Fig. 6. Robustness of Moorea's cumulative impact assessment. Robustness mapped around Moorea (A), robustness expressed as proportion of robust pixels in low- and high-impact areas (B), and robustness per habitat and municipality (C). Percentages inside brackets in C indicate the proportion of original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

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