



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

Charles Loiseau, Lauric Thiault, Rodolphe Devillers, Joachim Claudet

► To cite this version:

Charles Loiseau, Lauric Thiault, Rodolphe Devillers, Joachim Claudet. Cumulative impact assessments can show the benefits of integrating land-based management with marine spatial planning. *Science of the Total Environment*, 2021, 787, pp.147339. <10.1016/j.scitotenv.2021.147339>. <hal-03228740>

HAL Id: hal-03228740

<https://hal.science/hal-03228740v1>

Submitted on 18 May 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

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

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

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

^bLaboratoire d'Excellence CORAIL, Moorea, French Polynesia

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

Abstract

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

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

1. Introduction

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

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

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

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

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

2. Materials and Methods

2.1. Study site

2.1.1. Coral reef ecosystem

Located in French Polynesia, Moorea is a volcanic island surrounded by a 49 km² semi-enclosed coral reef, shallow (less than 30 m deep) and relatively narrow (maximum 1500 m long) lagoon, connected to the Pacific Ocean by 12 passes (Figure 1). While the fore reef is directly exposed to oceanic conditions, the lagoon is more sheltered and includes a shallow

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

2.1.2. Socio-economical context

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

2.1.3. Marine Spatial Planning

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

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

2.2. Cumulative impact assessment

2.2.1. Human activities and associated pressures

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

2.2.1.1. Land-based activities

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

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

2.2.1.2. *Sea-based activities*

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

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

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

2.2.4. Cumulative impact framework

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

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

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

2.2.5. Uncertainty analyses

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

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

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

3. Results

3.1. Cumulative impact assessment overview

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

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

3.2. Spatial extent of human activities

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

3.3. Human activities contributions to cumulative impact

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

3.4. Uncertainty analysis

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

4. Discussion

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

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

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

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

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

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

Conclusion

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

Declaration of competing interest

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

411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442

Acknowledgements

This work was made possible through financial support of Agence Nationale de la Recherche (ANR-14-CE03-0001-01). We thank Lucas Aubouin, Camille Antoine and Fanny Robert-Triaud for their valuable comments that improved this manuscript, René Galzin for its helpful support during the beginning of this work and Peter Esteve for his technical support.

References

Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., von Wehrden, H., Abernethy, P., Ives, C.D., Jager, N.W., Lang, D.J., 2017. Leverage points for sustainability transformation. *Ambio* 46, 30–39. <https://doi.org/10.1007/s13280-016-0800-y>

Adjeroud, M., Kayal, M., Iborra-Cantonnet, C., Vercelloni, J., Bosserelle, P., Liao, V., Chancerelle, Y., Claudet, J., Penin, L., 2018. Recovery of coral assemblages despite acute and recurrent disturbances on a South Central Pacific reef. *Sci. Rep.* 8, 1–8. <https://doi.org/10.1038/s41598-018-27891-3>

Álvarez-Romero, J.G., Pressey, R.L., Ban, N.C., Vance-Borland, K., Willer, C., Klein, C.J., Gaines, S.D., 2011. Integrated land-sea conservation planning: The missing links. *Annu. Rev. Ecol. Evol. Syst.* 42, 381–409. <https://doi.org/10.1146/annurev-ecolsys-102209-144702>

Anthony, K.R.N., Marshall, P.A., Abdulla, A., Beeden, R., Bergh, C., Black, R., Eakin, C.M., Game, E.T., Gooch, M., Graham, N.A.J., Green, A., Heron, S.F., van Hooidonk, R., Knowland, C., Mangubhai, S., Marshall, N., Maynard, J.A., McGinnity, P., Mcleod, E., Mumby, P.J., Nyström, M., Obura, D., Oliver, J., Possingham, H.P., Pressey, R.L., Rowlands, G.P., Tamelander, J., Wachenfeld, D., Wear, S., 2015. Operationalizing resilience for adaptive coral reef management under global environmental change. *Glob. Chang. Biol.* 21, 48–61. <https://doi.org/10.1111/gcb.12700>

Ban, N.C., Alidina, H.M., Ardron, J.A., 2010. Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada’s Pacific waters as a case study. *Mar. Policy* 34, 876–886. <https://doi.org/10.1016/j.marpol.2010.01.010>

Barbier, E.B., 2017. Marine ecosystem services. *Curr. Biol.* 27, R507–R510. <https://doi.org/10.1016/j.cub.2017.03.020>

443 Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value
 444 of estuarine and coastal ecosystem services. *Ecol. Monogr.* 81, 169–193.
 445 <https://doi.org/10.1890/10-1510.1>

446 Bevilacqua, S., Guarnieri, G., Farella, G., Terlizzi, A., Frascchetti, S., 2018. A regional
 447 assessment of cumulative impact mapping on Mediterranean coralligenous Outcrops.
 448 *Sci. Rep.* 8, 2–12. <https://doi.org/10.1038/s41598-018-20297-1>

449 Brown, C.J., Jupiter, S.D., Albert, S., Anthony, K.R.N., Hamilton, R.J., Fredston-Hermann, A.,
 450 Halpern, B.S., Lin, H.Y., Maina, J., Mangubhai, S., Mumby, P.J., Possingham, H.P.,
 451 Saunders, M.I., Tulloch, V.J.D., Wenger, A., Klein, C.J., 2019. A guide to modelling
 452 priorities for managing land-based impacts on coastal ecosystems. *J. Appl. Ecol.* 56,
 453 1106–1116. <https://doi.org/10.1111/1365-2664.13331>

454 Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A.,
 455 MacE, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B.,
 456 Larigauderie, A., Srivastava, D.S., Naeem, S., 2012. Biodiversity loss and its impact on
 457 humanity. *Nature* 486, 59–67. <https://doi.org/10.1038/nature11148>

458 Carlson, R.R., Foo, S.A., Asner, G.P., 2019. Land Use Impacts on Coral Reef Health: A Ridge-
 459 to-Reef Perspective. *Front. Mar. Sci.* 6, 1–19.
 460 <https://doi.org/10.3389/fmars.2019.00562>

461 Cinner, J., 2014. Coral reef livelihoods. *Curr. Opin. Environ. Sustain.* 7, 65–71.
 462 <https://doi.org/10.1016/j.cosust.2013.11.025>

463 Clark, D., Goodwin, E., Sinner, J., Ellis, J., Singh, G., 2016. Validation and limitations of a
 464 cumulative impact model for an estuary. *Ocean Coast. Manag.* 120, 88–98.
 465 <https://doi.org/10.1016/j.ocecoaman.2015.11.013>

466 Clarke Murray, C., Agbayani, S., Alidina, H.M., Ban, N.C., 2015. Advancing marine cumulative
 467 effects mapping: An update in Canada's Pacific waters. *Mar. Policy* 58, 71–77.
 468 <https://doi.org/10.1016/j.marpol.2015.04.003>

469 Collin, A., Hench, J., 2015. Extracting shallow bathymetry from very high resolution satellite
 470 spectral bands and a machine learning algorithm. *International Council of the*
 471 *Exploration of the Sea (ICES)* CM/N:24.

472 Davenport, J., Davenport, J.L., 2006. The impact of tourism and personal leisure transport on
 473 coastal environments: A review. *Estuar. Coast. Shelf Sci.* 67, 280–292.
 474 <https://doi.org/10.1016/j.ecss.2005.11.026>

475 de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M.,
 476 Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R.,
 477 Rodriguez, L.C., ten Brink, P., van Beukering, P., 2012. Global estimates of the value of
 478 ecosystems and their services in monetary units. *Ecosyst. Serv.* 1, 50–61.
 479 <https://doi.org/10.1016/j.ecoser.2012.07.005>

480 Deegan, L.A., Johnson, D.S., Warren, R.S., Peterson, B.J., Fleeger, J.W., Fagherazzi, S.,
 481 Wollheim, W.M., 2012. Coastal eutrophication as a driver of salt marsh loss. *Nature*
 482 490, 388–392. <https://doi.org/10.1038/nature11533>

483 Delevaux, J.M.S., Whittier, R., Stamoulis, K.A., Bremer, L.L., Jupiter, S., Friedlander, A.M.,
 484 Poti, M., Guannel, G., Kurashima, N., Winter, K.B., Toonen, R., Conklin, E., Wiggins, C.,
 485 Knudby, A., Goodell, W., Burnett, K., Yee, S., Htun, H., Oleson, K.L.L., Wiegner, T.,
 486 Ticktin, T., 2018. A linked land-sea modeling framework to inform ridge-to-reef
 487 management in high oceanic islands. *PLoS One* 13, e0193230.
 488 <https://doi.org/10.1371/journal.pone.0193230>

489 Duarte, C.M., Agusti, S., Barbier, E., Britten, G.L., Castilla, J.C., Gattuso, J.P., Fulweiler, R.W.,
 490 Hughes, T.P., Knowlton, N., Lovelock, C.E., Lotze, H.K., Predragovic, M., Poloczanska, E.,
 491 Roberts, C., Worm, B., 2020. Rebuilding marine life. *Nature* 580, 39–51.
 492 <https://doi.org/10.1038/s41586-020-2146-7>

493 Dubois, M., Gascuel, D., Coll, M., Claudet, J., 2019. Recovery Debts Can Be Revealed by
 494 Ecosystem Network-Based Approaches. *Ecosystems* 22, 658–676.
 495 <https://doi.org/10.1007/s10021-018-0294-5>

496 Center for International Earth Science Information Network - CIESIN - Columbia University.
 497 2012. National Aggregates of Geospatial Data Collection: Population, Landscape, And
 498 Climate Estimates, Version 3 (PLACE III). Palisades, NY: NASA Socioeconomic Data and
 499 Applications Center (SEDAC). <https://doi.org/10.7927/H4F769GP>.

500 Enright, S.R., Boteler, B., 2020. The Ecosystem Approach in International Marine
 501 Environmental Law and Governance, in: O’Higgins, T.G., Lago, M., DeWitt, T.H. (Eds.),
 502 Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity. Springer
 503 International Publishing, Cham, pp. 333–352. [https://doi.org/10.1007/978-3-030-](https://doi.org/10.1007/978-3-030-45843-0_17)
 504 [45843-0_17](https://doi.org/10.1007/978-3-030-45843-0_17)

505 Evans, J.S., 2020. *spatialEco* R package version 1.3-
 506 4, <https://github.com/jeffrejevans/spatialEco>.

507 Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs:
 508 Review and synthesis. *Mar. Pollut. Bull.* 50, 125–146.
 509 <https://doi.org/10.1016/j.marpolbul.2004.11.028>

510 Fischer, J., Riechers, M., 2019. A leverage points perspective on sustainability. *People Nat.* 1,
 511 115–120. <https://doi.org/10.1002/pan3.13>

512 Gaspar, C., Bambridge, T., 2008. Territorialités et aires marines protégées à Moorea
 513 (Polynésie française). *J. Soc. Ocean.* 231–246. <https://doi.org/10.4000/jso.2462>

514 Gissi, E., Menegon, S., Sarretta, A., Appiotti, F., Maragno, D., Vianello, A., Depellegrin, D.,
 515 Venier, C., Barbanti, A., 2017. Addressing uncertainty in modelling cumulative impacts
 516 within maritime spatial planning in the Adriatic and Ionian region. *PLoS One* 12, 1–30.
 517 <https://doi.org/10.1371/journal.pone.0180501>

518 Halpern, B.S., Frazier, M., Afflerbach, J., Lowndes, J.S., Micheli, F., O’Hara, C., Scarborough,
 519 C., Selkoe, K.A., 2019. Recent pace of change in human impact on the world’s ocean.
 520 *Sci. Rep.* 9, 11609. <https://doi.org/10.1038/s41598-019-47201-9>

521 Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., Lowndes, J.S.,
 522 Rockwood, R.C., Selig, E.R., Selkoe, K.A., Walbridge, S., 2015. Spatial and temporal
 523 changes in cumulative human impacts on the world’s ocean. *Nat. Commun.* 6, 1–7.
 524 <https://doi.org/10.1038/ncomms8615>

525 Halpern, B.S., Fujita, R., 2013. Assumptions, challenges, and future directions in cumulative
 526 impact analysis. *Ecosphere* 4, 1–11. <https://doi.org/10.1890/ES13-00181.1>

527 Halpern, B.S., Kappel, C. V., Selkoe, K.A., Micheli, F., Ebert, C.M., Kontgis, C., Crain, C.M.,
 528 Martone, R.G., Shearer, C., Teck, S.J., 2009. Mapping cumulative human impacts to
 529 California Current marine ecosystems. *Conserv. Lett.* 2, 138–148.
 530 <https://doi.org/10.1111/j.1755-263x.2009.00058.x>

531 Halpern, B.S., McLeod, K.L., Rosenberg, A.A., Crowder, L.B., 2008a. Managing for cumulative
 532 impacts in ecosystem-based management through ocean zoning. *Ocean Coast. Manag.*
 533 51, 203–211. <https://doi.org/10.1016/j.ocecoaman.2007.08.002>

534 Halpern, B.S., Selkoe, K.A., Micheli, F., Kappel, C. V., 2007. Evaluating and ranking the
 535 vulnerability of global marine ecosystems to anthropogenic threats. *Conserv. Biol.* 21,
 536 1301–1315. <https://doi.org/10.1111/j.1523-1739.2007.00752.x>

537 Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C. V., Micheli, F., D’Agrosa, C., Bruno, J.F.,
 538 Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P.,

539 Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008b. A global map of
 540 human impact on marine ecosystems. *Science* (80-.). 319, 948–952.
 541 <https://doi.org/10.1126/science.1149345>

542 Harborne, A.R., Rogers, A., Bozec, Y.M., Mumby, P.J., 2017. Multiple Stressors and the
 543 Functioning of Coral Reefs. *Ann. Rev. Mar. Sci.* 9, 445–468.
 544 <https://doi.org/10.1146/annurev-marine-010816-060551>

545 Harvey, B.J., Nash, K.L., Blanchard, J.L., Edwards, D.P., 2018. Ecosystem-based management
 546 of coral reefs under climate change. *Ecol. Evol.* 8, 6354–6368.
 547 <https://doi.org/10.1002/ece3.4146>

548 He, Q., Silliman, B.R., 2019. Climate Change, Human Impacts, and Coastal Ecosystems in the
 549 Anthropocene. *Curr. Biol.* 29, R1021–R1035. <https://doi.org/10.1016/j.cub.2019.08.042>

550 Hicks, C.C., Cinner, J.E., 2014. Social, institutional, and knowledge mechanisms mediate
 551 diverse Ecosystem service benefits from coral reefs. *Proc. Natl. Acad. Sci. U. S. A.* 111,
 552 17791–17796. <https://doi.org/10.1073/pnas.1413473111>

553 Hijmans, R.J., 2020. raster: Geographic Data Analysis and Modeling. R package version
 554 3.0-12. <https://CRAN.R-project.org/package=raster>

555 Hunter, C.E., Lauer, M., Levine, A., Holbrook, S., Rassweiler, A., 2018. Maneuvering towards
 556 adaptive co-management in a coral reef fishery. *Mar. Policy* 98, 77–84.
 557 <https://doi.org/10.1016/j.marpol.2018.09.016>

558 Insee-ISPF, Recensement de la population, 2017

559 Insee-ISPF, 2019. Points conjoncture de la Polynésie française, Tableau de bord du tourisme
 560 – Année 2019, [http://www.ispf.pf/docs/default-source/tb-tourisme/tbd-annuel-](http://www.ispf.pf/docs/default-source/tb-tourisme/tbd-annuel-2019.pdf?sfvrsn=6)
 561 [2019.pdf?sfvrsn=6](http://www.ispf.pf/docs/default-source/tb-tourisme/tbd-annuel-2019.pdf?sfvrsn=6)

562 Kappel, C. V., Halpern, B.S., Selkoe, K.A., Cooke, R.M., 2012. Eliciting expert knowledge of
 563 ecosystem vulnerability to human stressors to support comprehensive ocean
 564 management, in: Perera, A.H., Drew, C.A., Johnson, C.J. (Eds.), *Expert Knowledge and Its*
 565 *Application in Landscape Ecology*. Springer New York, New York, NY, pp. 253–277.
 566 https://doi.org/10.1007/978-1-4614-1034-8_13

567 Korpinen, S., Meski, L., Andersen, J.H., Laamanen, M., 2012. Human pressures and their
 568 potential impact on the Baltic Sea ecosystem. *Ecol. Indic.* 15, 105–114.
 569 <https://doi.org/10.1016/j.ecolind.2011.09.023>

570 Lamy, T., Galzin, R., Kulbicki, M., Lison de Loma, T., Claudet, J., 2016. Three decades of

571 recurrent declines and recoveries in corals belie ongoing change in fish assemblages.
 572 Coral Reefs 35, 293–302. <https://doi.org/10.1007/s00338-015-1371-2>
 573 Leenhardt, P., Lauer, M., Moussa, R.M., Holbrook, S.J., Rassweiler, A., Schmitt, R.J., Claudet,
 574 J., 2016. Complexities and uncertainties in transitioning small-scale coral reef fisheries.
 575 Front. Mar. Sci. 3, 1–9. <https://doi.org/10.3389/fmars.2016.00070>
 576 Leenhardt, P., Stelzenmüller, V., Pascal, N., Probst, W.N., Aubanel, A., Bambridge, T., Charles,
 577 M., Clua, E., Féral, F., Quinquis, B., Salvat, B., Claudet, J., 2017. Exploring social-
 578 ecological dynamics of a coral reef resource system using participatory modeling and
 579 empirical data. Mar. Policy 78, 90–97. <https://doi.org/10.1016/j.marpol.2017.01.014>
 580 Lefcheck, J.S., Orth, R.J., Dennison, W.C., Wilcox, D.J., Murphy, R.R., Keisman, J., Gurbisz, C.,
 581 Hannam, M., Brooke Landry, J., Moore, K.A., Patrick, C.J., Testa, J., Weller, D.E., Batiuk,
 582 R.A., 2018. Long-term nutrient reductions lead to the unprecedented recovery of a
 583 temperate coastal region. Proc. Natl. Acad. Sci. U. S. A. 115, 3658–3662.
 584 <https://doi.org/10.1073/pnas.1715798115>
 585 Lombard, A.T., Ban, N.C., Smith, J.L., Lester, S.E., Sink, K.J., Wood, S.A., Jacob, A.L., Kyriazi, Z.,
 586 Tingey, R., Sims, H.E., 2019. Practical approaches and advances in spatial tools to
 587 achieve multi-objective marine spatial planning. Front. Mar. Sci. 6, 1–9.
 588 <https://doi.org/10.3389/fmars.2019.00166>
 589 Long, R.D., Charles, A., Stephenson, R.L., 2015. Key principles of marine ecosystem-based
 590 management. Mar. Policy 57, 53–60. <https://doi.org/10.1016/j.marpol.2015.01.013>
 591 MacNeil, M.A., Mellin, C., Matthews, S., Wolff, N.H., McClanahan, T.R., Devlin, M., Drovandi,
 592 C., Mengersen, K., Graham, N.A.J., 2019. Water quality mediates resilience on the Great
 593 Barrier Reef. Nat. Ecol. Evol. 3, 620–627. <https://doi.org/10.1038/s41559-019-0832-3>
 594 Madi Moussa, R., Fogg, L., Bertucci, F., Calandra, M., Collin, A., Aubanel, A., Polti, S., Benet,
 595 A., Salvat, B., Galzin, R., Planes, S., Lecchini, D., 2019. Long-term coastline monitoring on
 596 a coral reef island (Moorea, French Polynesia). Ocean Coast. Manag. 180, 104928.
 597 <https://doi.org/10.1016/j.ocecoaman.2019.104928>
 598 Magris, R.A., Ban, N.C., 2019. A meta-analysis reveals global patterns of sediment effects on
 599 marine biodiversity. Glob. Ecol. Biogeogr. 28, 1879–1898.
 600 <https://doi.org/10.1111/geb.12990>
 601 McLeod, K.L., Lubchenco, J., Palumbi, S., Rosenberg, A.A., 2005. Scientific Consensus
 602 Statement on Marine Ecosystem-Based Management (Communication Partnership for

603 Science and the Sea). Prep. by Sci. policy Expert. to Provid. Inf. about coasts Ocean. to
 604 U.S. policy- makers 1–21.

605 Micheli, F., Halpern, B.S., Walbridge, S., Ciriaco, S., Ferretti, F., Frascchetti, S., Lewison, R.,
 606 Nykjaer, L., Rosenberg, A.A., 2013. Cumulative human impacts on Mediterranean and
 607 Black Sea marine ecosystems: Assessing current pressures and opportunities. PLoS One
 608 8. <https://doi.org/10.1371/journal.pone.0079889>

609 Noble, M.M., Harasti, D., Pittock, J., Doran, B., 2019. Understanding the spatial diversity of
 610 social uses, dynamics, and conflicts in marine spatial planning. J. Environ. Manage. 246,
 611 929–940. <https://doi.org/10.1016/j.jenvman.2019.06.048>

612 O’Leary, J.K., Micheli, F., Airoidi, L., Boch, C., De Leo, G., Elahi, R., Ferretti, F., Graham, N.A.J.,
 613 Litvin, S.Y., Low, N.H., Lummis, S., Nickols, K.J., Wong, J., 2017. The resilience of marine
 614 ecosystems to climatic disturbances. Bioscience 67, 208–220.
 615 <https://doi.org/10.1093/biosci/biw161>

616 Pandolfi, J.M., Bradbury, R.H., Sala, E., Hughes, T.P., Bjorndal, K.A., Cooke, R.G., McArdle, D.,
 617 McClenachan, L., Newman, M.J.H., Paredes, G., Warner, R.R., Jackson, J.B.C., 2003.
 618 Global trajectories of the long-term decline of coral reef ecosystems. Science (80-.).
 619 301, 955–958. <https://doi.org/10.1126/science.1085706>

620 Pebesma, E., 2018. Simple Features for R: Standardized Support for Spatial Vector Data. The
 621 R Journal 10 (1), 439–446, <https://doi.org/10.32614/RJ-2018-009>

622 Polidoro, B.A., Carpenter, K.E., Collins, L., Duke, N.C., Ellison, A.M., Ellison, J.C., Farnsworth,
 623 E.J., Fernando, E.S., Kathiresan, K., Koedam, N.E., Livingstone, S.R., Miyagi, T., Moore,
 624 G.E., Nam, V.N., Ong, J.E., Primavera, J.H., Salmo, S.G., Sanciangco, J.C., Sukardjo, S.,
 625 Wang, Y., Yong, J.W.H., 2010. The loss of species: Mangrove extinction risk and
 626 geographic areas of global concern. PLoS One 5, e10095.
 627 <https://doi.org/10.1371/journal.pone.0010095>

628 Pratchett, M.S., Trapon, M., Berumen, M.L., Chong-Seng, K., 2011. Recent disturbances
 629 augment community shifts in coral assemblages in Moorea, French Polynesia. Coral
 630 Reefs 30, 183–193. <https://doi.org/10.1007/s00338-010-0678-2>

631 QGIS Development Team, 2020. QGIS Geographic Information System. Open Source
 632 Geospatial Foundation. URL <http://qgis.org>

633 R Core Team. R: A language and environment for statistical computing. R Foundation for
 634 Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing; 2020.

635 Rassweiler, A., Lauer, M., Lester, S.E., Holbrook, S.J., Schmitt, R.J., Madi Moussa, R.,
 636 Munsterman, K.S., Lenihan, H.S., Brooks, A.J., Wencélius, J., Claudet, J., 2020.
 637 Perceptions and responses of Pacific Island fishers to changing coral reefs. *Ambio* 49,
 638 130–143. <https://doi.org/10.1007/s13280-019-01154-5>
 639 Roberts, C.M., O’Leary, B.C., Mccauley, D.J., Cury, P.M., Duarte, C.M., Lubchenco, J., Pauly,
 640 D., Sáenz-Arroyo, A., Sumaila, U.R., Wilson, R.W., Worm, B., Castilla, J.C., 2017. Marine
 641 reserves can mitigate and promote adaptation to climate change. *Proc. Natl. Acad. Sci.*
 642 U. S. A. 114, 6167–6175. <https://doi.org/10.1073/pnas.1701262114>
 643 Shaver, E.C., Burkepile, D.E., Silliman, B.R., 2018. Local management actions can increase
 644 coral resilience to thermally-induced bleaching. *Nat. Ecol. Evol.* 2, 1075–1079.
 645 <https://doi.org/10.1038/s41559-018-0589-0>
 646 Stock, A., Crowder, L.B., Halpern, B.S., Micheli, F., 2018. Uncertainty analysis and robust
 647 areas of high and low modeled human impact on the global oceans. *Conserv. Biol.* 32,
 648 1368–1379. <https://doi.org/10.1111/cobi.13141>
 649 Stock, A., Micheli, F., 2016. Effects of model assumptions and data quality on spatial
 650 cumulative human impact assessments. *Glob. Ecol. Biogeogr.* 25, 1321–1332.
 651 <https://doi.org/10.1111/geb.12493>
 652 Tennekkes, M., 2018. tmap: Thematic Maps in R. *Journal of Statistical Software*, **84**(6), 1–39.
 653 <https://doi.org/10.18637/jss.v084.i06>
 654 Thiault, L., Collin, A., Chlous, F., Gelcich, S., Claudet, J., 2017. Combining participatory and
 655 socioeconomic approaches to map fishing effort in smallscale fisheries. *PLoS One* 12, 1–
 656 18. <https://doi.org/10.1371/journal.pone.0176862>
 657 Thiault, L., Gelcich, S., Marshall, N., Marshall, P., Chlous, F., Claudet, J., 2020.
 658 Operationalizing vulnerability for social–ecological integration in conservation and
 659 natural resource management. *Conserv. Lett.* 13, 1–13.
 660 <https://doi.org/10.1111/conl.12677>
 661 Thiault, L., Kernaléguen, L., Osenberg, C.W., Lison de Loma, T., Chancerelle, Y., Siu, G.,
 662 Claudet, J., 2019. Ecological evaluation of a marine protected area network: a
 663 progressive-change BACIPS approach. *Ecosphere* 10, 1–12.
 664 <https://doi.org/10.1002/ecs2.2576>
 665 Traçon, M.L., Pratchett, M.S., Penin, L., 2011. Comparative Effects of Different Disturbances
 666 in Coral Reef Habitats in Moorea, French Polynesia. *J. Mar. Biol.* 2011, 1–11.

<https://doi.org/10.1155/2011/807625>

Van Etten, J., 2017. R Package gdistance: Distances and Routes on Geographical Grids.

Journal of Statistical Software, 76(13), 1–21. [doi:10.18637/jss.v076.i13](https://doi.org/10.18637/jss.v076.i13)

Vercelloni, J., Kayal, M., Chancerelle, Y., Planes, S., 2019. Exposure, vulnerability, and resiliency of French Polynesian coral reefs to environmental disturbances. Sci. Rep. 9, 1–11. <https://doi.org/10.1038/s41598-018-38228-5>

Walker, B.L.E., 2001. Mapping Moorea's lagoons: Conflicts over marine protected areas in French Polynesia. Inaug. Pacific Reg. Meet. Int. Assoc. Study Common Prop. 1–23.

Walker, B.L.E., López-Carr, D., Chen, C., Currier, K., 2014. Perceptions of environmental change in Moorea, French Polynesia: the importance of temporal, spatial, and scalar contexts. GeoJournal 79, 705–719. <https://doi.org/10.1007/s10708-014-9548-8>

Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., Calladine, A., Fourqurean, J.W., Heck, K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Short, F.T., Williams, S.L., 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc. Natl. Acad. Sci. 106, 12377–12381. <https://doi.org/10.1073/pnas.0905620106>

Wenger, A.S., Harris, D., Weber, S., Vaghi, F., Nand, Y., Naisilisili, W., Hughes, A., Delevaux, J., Klein, C.J., Watson, J., Mumby, P.J., Jupiter, S.D., 2020. Best-practice forestry management delivers diminishing returns for coral reefs with increased land-clearing. J. Appl. Ecol. 57, 2381–2392. <https://doi.org/10.1111/1365-2664.13743>

Wickham, H., 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. ISBN 978-3-319-24277-4, <https://ggplot2.tidyverse.org>.

Williams, G.J., Graham, N.A.J., Jouffray, J.B., Norström, A. V., Nyström, M., Gove, J.M., Heenan, A., Wedding, L.M., 2019. Coral reef ecology in the Anthropocene. Funct. Ecol. 33, 1014–1022. <https://doi.org/10.1111/1365-2435.13290>

Williams, I.D., Kindinger, T.L., Couch, C.S., Walsh, W.J., Minton, D., Oliver, T.A., 2019. Can Herbivore Management Increase the Persistence of Indo-Pacific Coral Reefs? Front. Mar. Sci. 6, 1–15. <https://doi.org/10.3389/fmars.2019.00557>

Wu, P.P.Y., Mengersen, K., McMahon, K., Kendrick, G.A., Chartrand, K., York, P.H., Rasheed, M.A., Caley, M.J., 2017. Timing anthropogenic stressors to mitigate their impact on marine ecosystem resilience. Nat. Commun. 8, 1263. <https://doi.org/10.1038/s41467-017-01306-9>

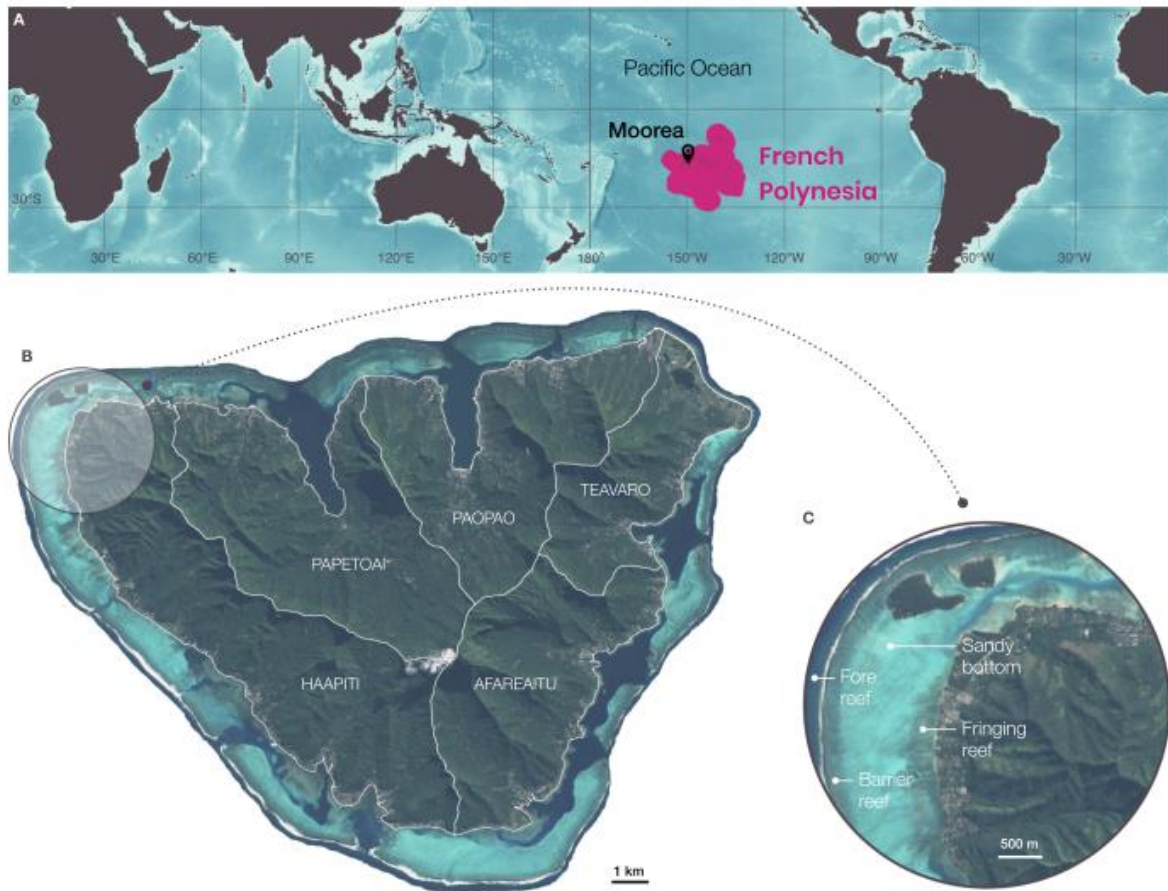


Fig. 1. Study area; Moorea, French Polynesia. French Polynesia is located in the South Pacific (A). Moorea is the second largest island after Tahiti (B). For the cumulative impact assessment we focus here on four marine habitats (C): fringing reef, barrier reef, fore reef and sandy bottom.

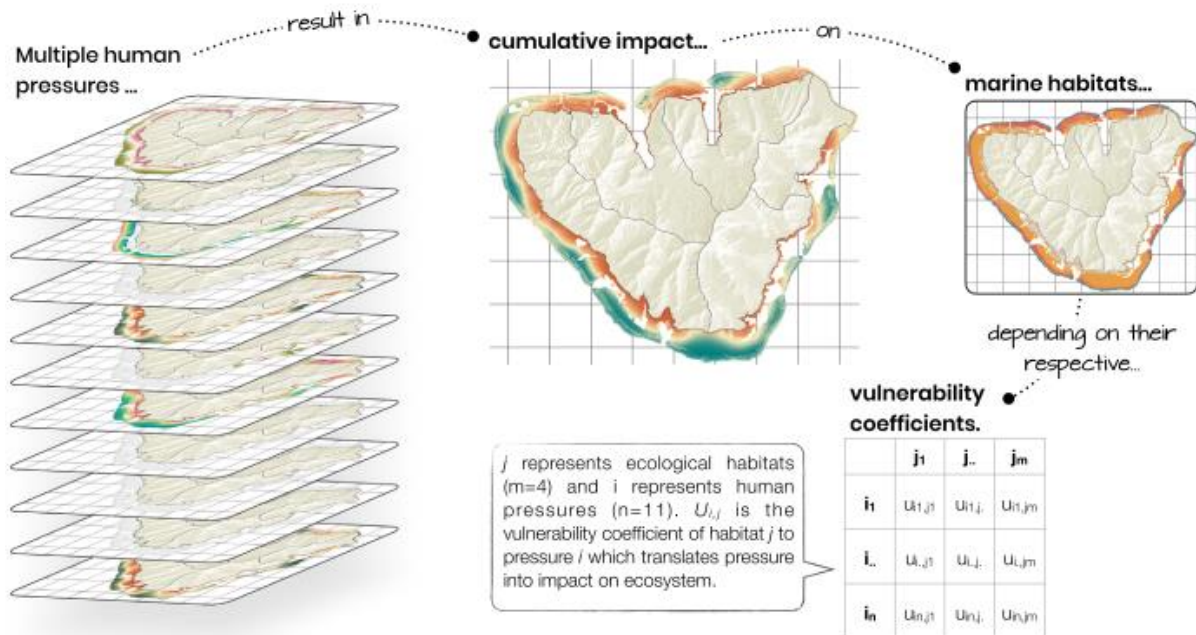


Fig. 2. Schematic representation of the cumulative impact assessment framework used.

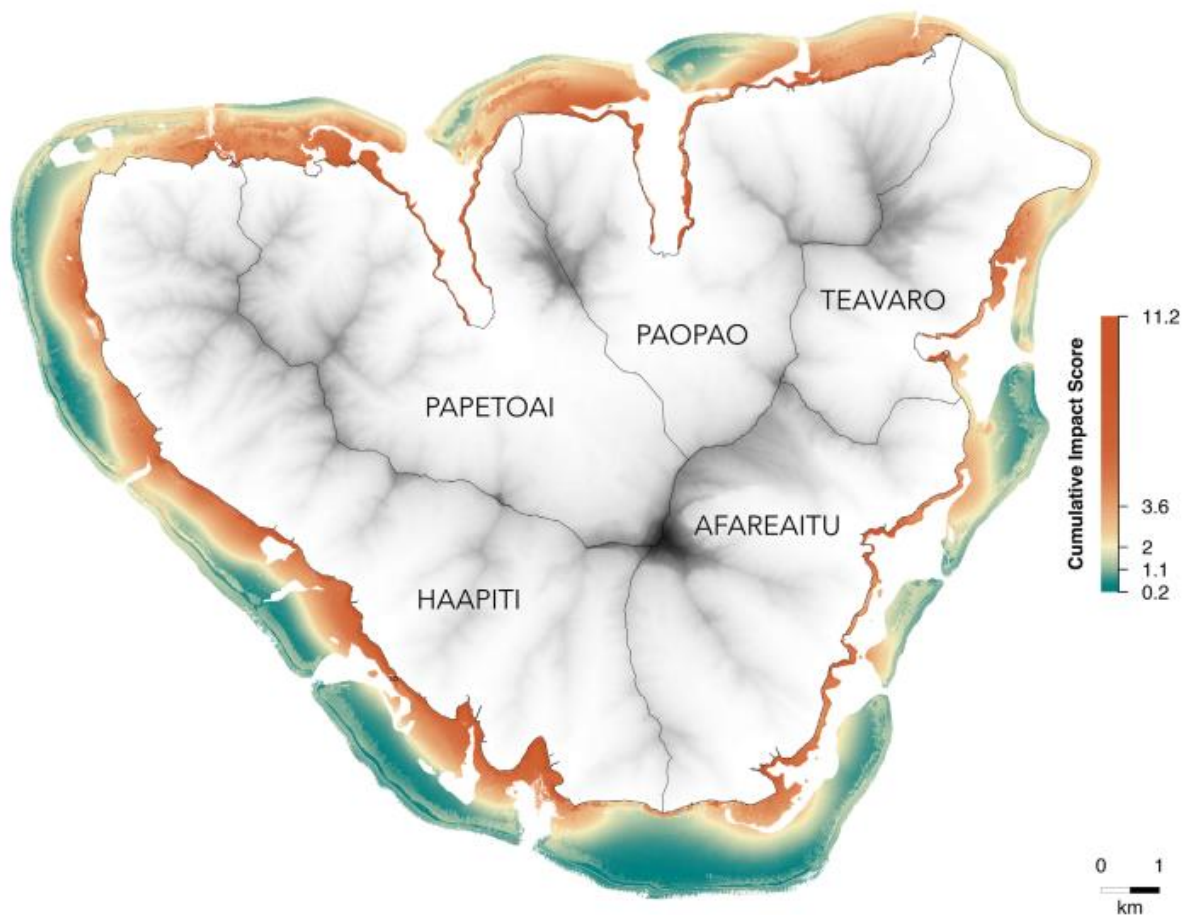
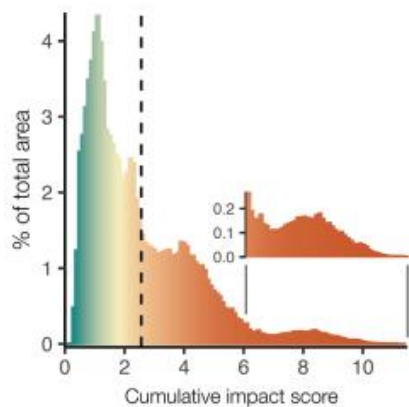
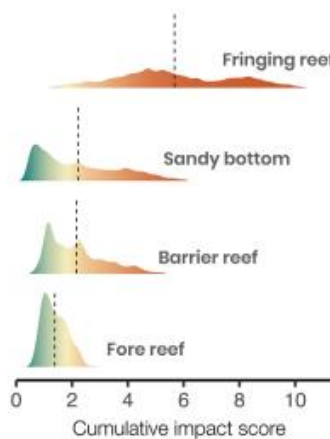
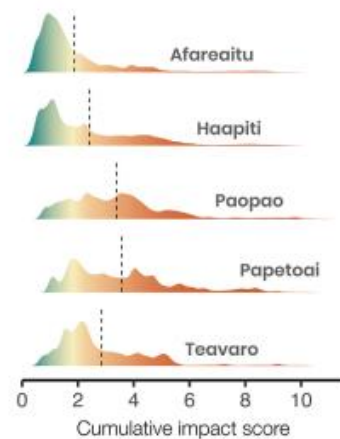
A**Moorea's cumulative impact map****B** Island-wide cumulative impact distribution**C** Cumulative impact distribution per habitat**D** Cumulative impact distribution per municipality

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.

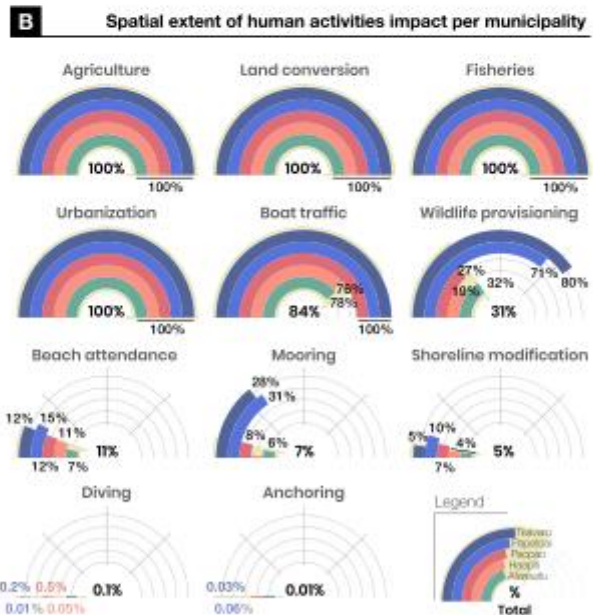
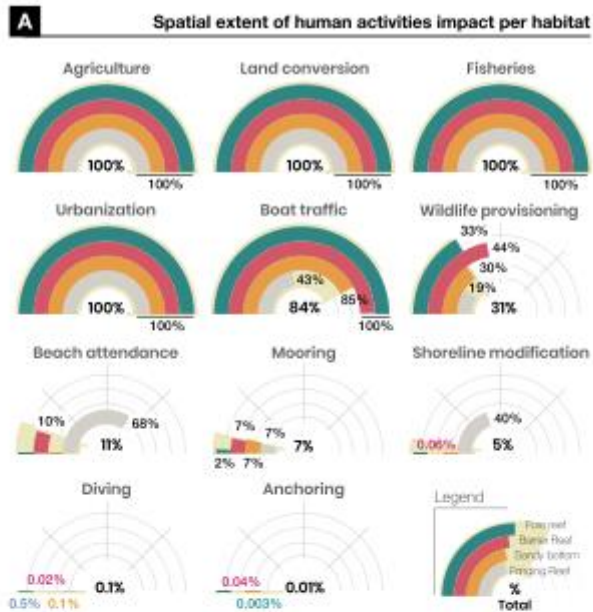


Fig. 4. Spatial extent of human activities in Moorea, per habitat (A) and per municipality (B). Percentages in the middle of semi-circles indicate the spatial extent of each activities in the entire study area (related to the brown colored large bar). (For interpretation of the references to color in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

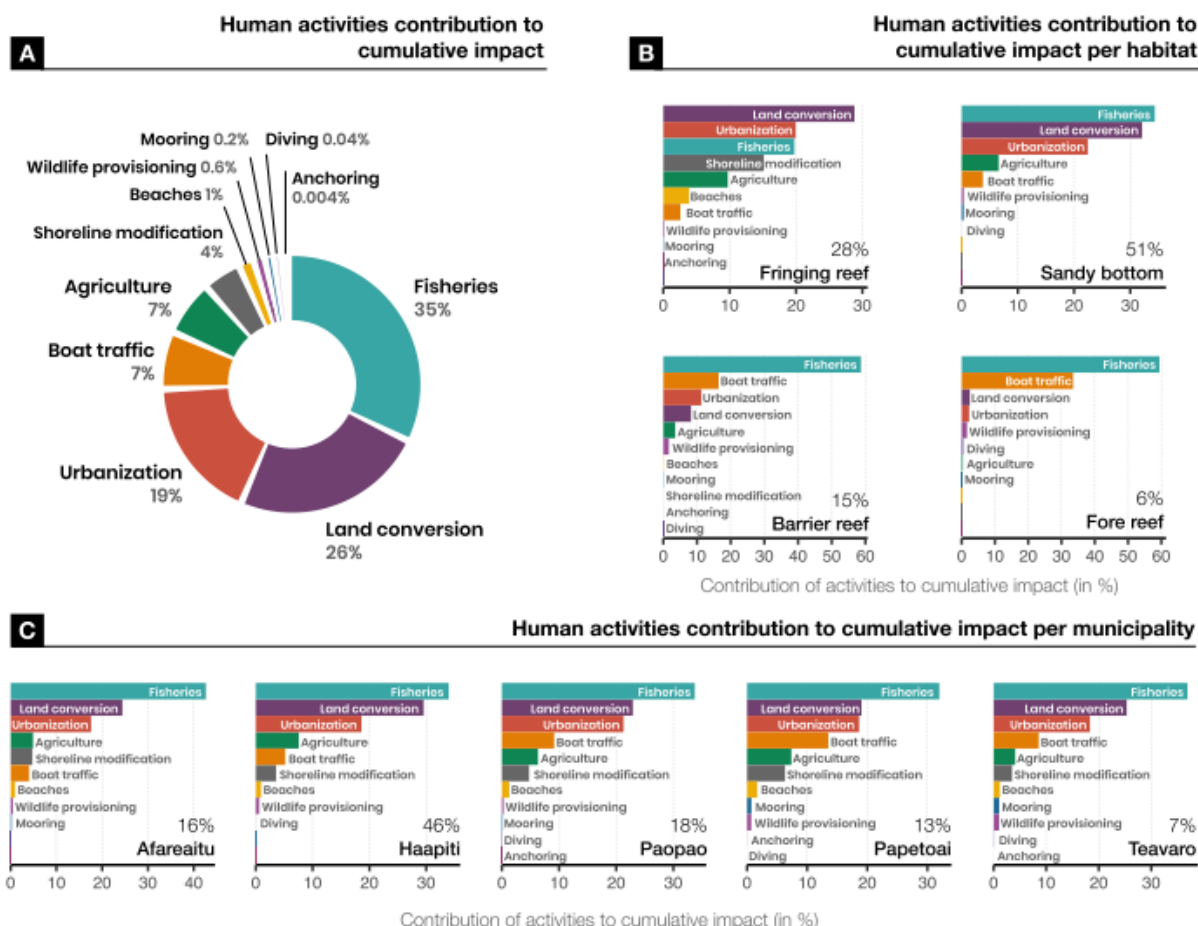


Fig. 5. Contribution of individual human activities to cumulative impact in Moorea, at the whole island scale (A), per habitat (B) and per municipality (C). Percentages above habitats and municipalities represent the proportion of overall cumulative impact in those habitats or municipalities.

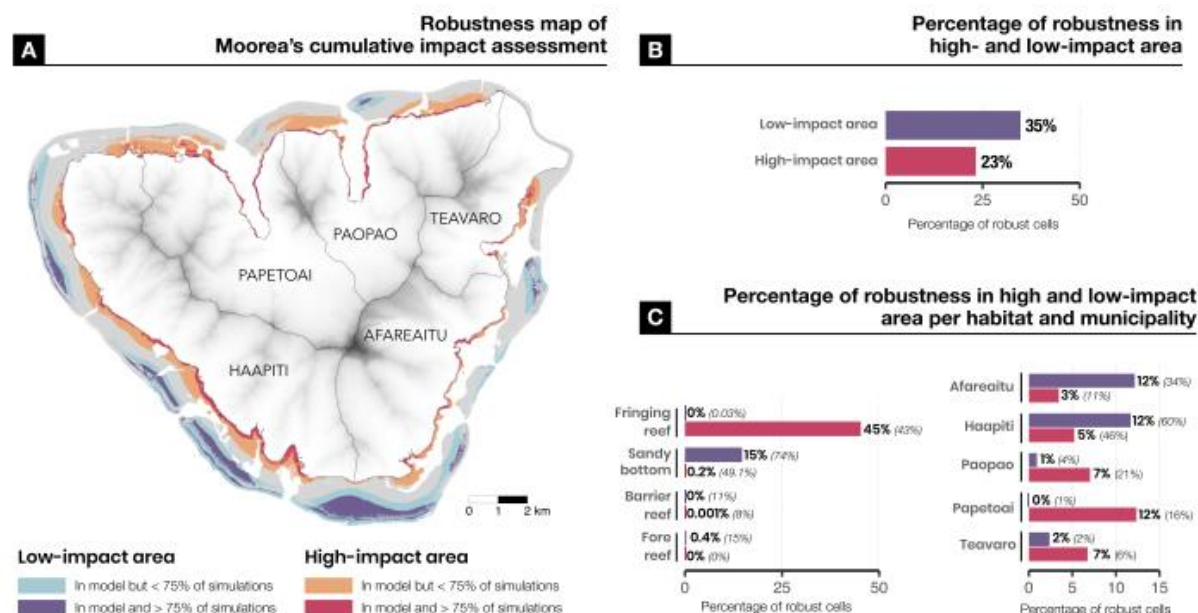


Fig. 6. Robustness of Moorea's cumulative impact assessment. Robustness mapped around Moorea (A), robustness expressed as proportion of robust pixels in low- and high-impact areas (B), and robustness per habitat and municipality (C). Percentages inside brackets in C indicate the proportion of original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