



Local perceptions of socio-ecological drivers and effects of coastal armoring: the case of Moorea, French Polynesia

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Abstract

This paper presents a transdisciplinary study focusing on the socio-ecological mechanisms at play in the alteration of Moorea's (French Polynesia) coastline. Building on a previous study synthesizing the results from monitoring efforts of the island's coastline from 1977 to 2018, we offer a joint analysis of scientific and local perceptions of coastal changes and of the impacts of coastal armoring in Moorea. Drawing on ecological and ethnographic data (111 semi-structured interviews of Moorea residents and representatives from local authorities), we analyze the drivers invoked by near-shore residents to modify their coastline as well as the perceived effects of coastal artificialization on the near-shore marine biodiversity and topography. We also address the broader economic and political contexts under which the island's coastline is being increasingly transformed. Overall, our study highlights how the perceptions of increased erosion coupled to poorly enforced regulations drive the progressive armoring of the coastline through a diversity of private-based developments. We discuss how the latter have, both for scientists and residents, controversial community-wide economic, social, and ecological impacts.

Keywords Coastal erosion · Coastal armoring · Coral reefs · French Polynesia

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Introduction

Over the past decades, climate change and its predicted consequences (e.g., sea-level rise, increased temperatures, and multiplication of extreme climatic events) have been a growing source of concern, especially for the Small Pacific Island States (SPIS) due to their vulnerability to such events (Moritz et al., 2018; Nunn, 2013; Walshe & Stancioff, 2018). These islands have become iconic landmarks of the global environmental discourse raising awareness on the major threats climate change will present in the foreseeable future (Chambers & Chambers, 2007; Connell, 2015; Howes et al., 2018; Nicholls & Cazenave, 2010; Parry et al., 2007; Ratter, 2018). Pacific islanders will have to cope with such threats with apparently little means to mitigate them. While the Pacific region is often portrayed as one of the prime victims of global climate change, it is also acclaimed for its resilience to major stresses (Viviani et al., 2019; Kelman, 2018; Hughes et al., 2017). SPIS communities have a rich heritage, developed over centuries, of knowledge, practices, and adaptive strategies which have allowed them to overcome unexpected disruptions and catastrophes (Bambridge & Latouche, 2017; Ballard et al., 2020; Calandra, 2020). However, the intensity and rapidity of globally and locally induced environmental changes in these islands — combined with a lack of resources — may prevent communities from successfully adapting to novel and sudden challenges (Westoby et al., 2020; Lauer et al., 2013; Nunn, 2013).

Coastlines have been identified as particularly vulnerable environments to the rapid socio-ecological changes occurring in the South Pacific (Madi Moussa et al., 2019). Yet, they provide many essential ecosystem services for humans (e.g., fish nursery areas, marine food resources as well as beaches for various tourism-oriented and recreational activities) (Aouiche et al., 2016; Barth et al., 2015; Liqueste et al., 2013; Lecchini et al., 2009). The management of this crucial land-sea interface represents an environmental challenge as it is subject to multiple pressures, such as the following: growing beach and soil erosion, public or private coastal artificialization (e.g., landfills, construction of harbors and seawalls), as well as increased release of bio-chemical and non-degradable waste (Defeo et al., 2009). With various degrees of severity, each of these stressors has an impact on the coastal marine environment, and its biodiversity and bio-productivity (Madi Moussa et al., 2019; Lecchini et al., 2009; Dugan et al., 2008; Mimura & Nunn, 1998).

Our paper presents a case study from the island of Moorea (French Polynesia) in which we combine results from a longitudinal research program conducted by marine biologists on the dynamics of the local coastal environment and its vulnerability to multiple anthropogenic stressors alongside an ethnographic survey of residents' perceptions of coastal armoring. Based on the results of a longitudinal time-series monitoring, the ecological changes of Moorea's coastline from 1977 to 2018 (Madi Moussa et al., 2019), we assess, in this paper, the vulnerability of the island's different coastal habitats (defined according to their ecological and geomorphological attributes) to climatic risks, erosion, and flood. In addition, drawing on ethnographic material ($N = 111$ semi-structured interviews), it examines the perceptions Moorea residents have of vulnerability of their coastline, the drivers

that push landowners and local authorities to armor the coastline and the perceived effects of such coastal modifications. Finally, we underline the relevance for longitudinal monitoring programs of coastal environments to document, through an interdisciplinary approach, the socio-ecological dynamics of these ecologically and culturally important ecosystems. We also suggest that greater outreach from the scientific community may help not only to inform local authorities and residents of the potentially undesirable consequences of coastal infrastructure, but also to co-design successful conservation strategies targeting the rehabilitation of coral reef coastal socio-ecosystems.

Few studies have fully integrated ecological and social approaches in order to jointly document scientific and local perceptions of the ecological changes and impacts of coastal armoring. While many coral reef monitoring programs exist in the South Pacific (Mahabot et al., 2017; Moritz et al., 2018), only a handful of longitudinal monitoring programs have produced detailed and systematic time series documenting the evolution of the coastline and its armoring (Collen et al., 2009; Webb & Kench, 2010; Ford, 2012; Rankey, 2011). Studies tend to either minutely describe patterns of shoreline changes and coastal armoring (Duvat, 2013; Ford, 2012; Xue, 2001) or to document the local perceptions of coastal erosion as well as the drivers of coastal alterations (Betzold & Mohamed, 2017; Donner & Webber, 2014; Ratter et al., 2016). Documenting the socio-ecological dynamics of coastal environments — in the context of climate change — requires scientists to transcend disciplinary boundaries. Such collaborations alone may yield a comparative understanding of local perceptions of environmental changes and the way people seek to adapt to them. Multi-disciplinary research can, in turn, inform public policies to implement effective measures of coastal conservation and urge decision-makers to consider altogether the ecological, economic, and cultural importance of maintaining healthy coastal environments (Moritz et al., 2018; Nunn, 2013).

Study site

Moorea Island (17°30'S, 149°5'W), French Polynesia, is part of the Windward Islands of the Society Islands archipelago. Located roughly 15 km East of Tahiti, it is surrounded by a 61-km-long barrier reef forming a 0.5- to 1-km-wide lagoon communicating with the open ocean through 12 passes (Fig. 1). Over 80% of Moorea's population is concentrated barely a meter above sea level within a 100-m-wide corridor along the coast. The ever-increasing population — 4,000 inhabitants in 1962 to 17,000 inhabitants in 2017 (ISPF, 2017) — is key to understanding the numerous biophysical and socio-economic changes the island's coastline has been facing, namely due to increased urbanization. Tourism is a major component of Moorea's local economy. Near a quarter of all hotel rooms in French Polynesia are located in Moorea, and Moorea ranks as the 2nd most visited island of French Polynesia — 99,996 tourists visited the island in 2017 (IEOM, 2017). The coastal areas are the mainstay of the tourism industry (Madi Moussa et al., 2019; Walker, 2001; Walker et al., 2014).

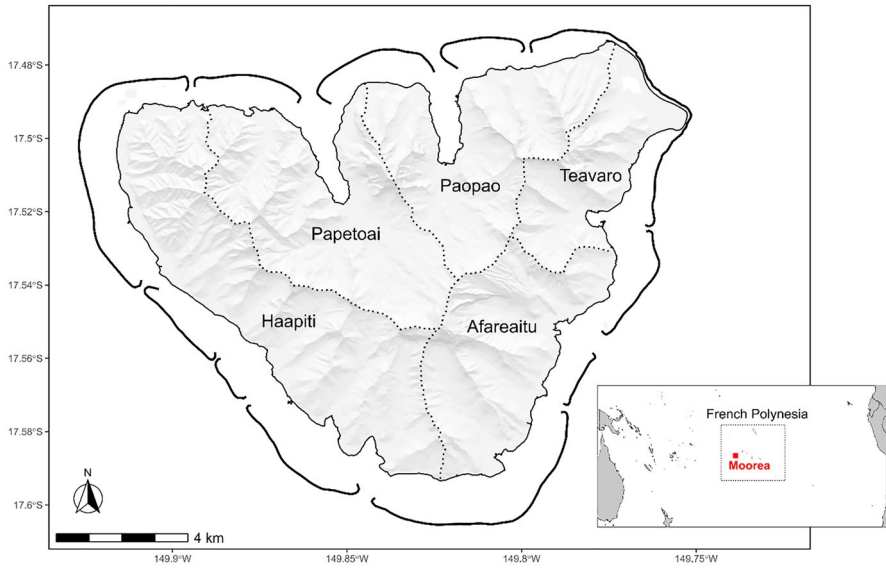


Fig. 1 Map of Moorea (French Polynesia)

The coastal environment, often presenting a shallow fringing reef, is referred to in Tahitian by the term *tahatai*. Another term often used by Tahitians to delimit the beach from the lagoon is *hiti*, which means side, frontier, or border. For residents, it is both a recreational area and a place where subsistence activities, notably fishing, are carried out. During weekends or holidays, an important number of people enjoy their day at the beach to swim, barbecue, and gather with friends and family. Access to shore is equally important for people to launch their boats and out-riggers either for recreational activities (e.g., *va'a* sport designed out-rigger) or subsistence activities (e.g., fishers swimming or paddling out to their fishing grounds). Some fishing (line, net, and more rarely harpoon fishing) as well as invertebrate harvesting activities are also carried out directly near shore or on the fringing reef.

Materials and methods

Coastal vulnerability to climate change — 1977 to 2018

The monitoring of Moorea's coastline has been conducted since 1977 to document the evolution of the relative proportion of seven main coastal habitat categories (Table 1) around the island. Results from this longitudinal program have been published by Madi Moussa et al. (2019) where authors have compared the extent of Moorea's coastal artificialization between 1977, 1993, 2001, 2009, and 2018 (Table 1). Unpublished data concerning the geomorphological, biological, and socio-economic characterization of coastal profiles are used here to assess the vulnerability of Moorea's coast to climate-change-induced stressors. Data were

Table 1 Range and limits of the different variables used to estimate the coastal vulnerability index (source of primary data: Madi Moussa et al., 2019). According to Hereher (2016), coastal vulnerability to climate change is considered low when CVI ranges from 0 to 1.8, moderate between 1.8 and 3.0, and high when the CVI value is over 3.1

Coastal Vulnerability Index (CVI)			
	Weak (<1.8)	Moderate (1.8–3.1)	Strong (>3.1)
Topography in terms of the coastal slope (T)	> 24%	24–12%	< 12%
Coastal geomorphology (G)	Beach rock, Rocks and broken stones in original position	Walls and embankments	Black sand beaches, White sand beaches, muddy areas, herbaceous zones, mangroves
Biota is related to the fauna/flora of the coast (B)	Coastline without human construction	Coral reefs	Mangroves
Socioeconomic factor (S)	Inaccessible coastline	Beaches	City, village, tourism activities

collected through direct observation and surveys were systematically carried out at the same season in order to avoid accounting for natural seasonal changes along the coast when carrying out inter-annual comparisons. In this paper, we will focus on comparing the state of the coastline between 1977 and 2018 and will not account for variations between each monitoring campaign (i.e., 1993, 2001, 2009).

The Coastal Vulnerability Index (CVI) is one of the most commonly used and simple methods to assess coastal vulnerability to erosion, flooding, or sea level rise (Gornitz, 1991). The first methodological step for calculating the CVI implies identifying key variables representing potentially significant drivers influencing coastal change and vulnerability. Although widely used, the original CVI formulation did not include socio-economic aspects (e.g., number of people affected, infrastructural damage, or economic costs) within the assessment of coastal vulnerability (Gornitz, 1991; Cooper & McLaughlin, 1998). Here, we used the original CVI in association with variables able to more properly represent the complexity of the coastal system in relation to socio-economic aspects (for similar approaches see Szlafsztein & Sterr, 2007; McLaughlin & Cooper, 2010). Parameters we have used include geological variables (e.g., coastal geomorphology, slope and erosion/accretion profile), biological variables (e.g., presence of coral or mangrove ecosystems), and socio-economic variables (e.g., presence of public or tourist-oriented infrastructures, businesses, cities). As a second step, key variables for each coastal habitat category (cf. Table 1) were estimated according to a three-level qualitative score ranging from 1 (low) to 3 (strong) indicating each variable's contribution to coastal vulnerability. Estimates were made based on direct observations and measurements carried out in the field during each monitoring campaign (1977 and 2018) — see Madi Moussa et al. (2019) for more details. Final step consists in aggregating all variables into a single index using the formula defined by Hereher (2016).

$$CVI = [(T \times G \times B \times S) / 4]^{1/2}$$

T: topography in terms of the coastal slope

G: coastal Geomorphology

B: biota is related to coastal fauna/flora

S: socioeconomic factor (coastal land use)

CVI values for each coastal habitat category are provided in Table 2. We have also computed for 1977 and 2018 the island CVI average by weighing CVI values according to coastal habitats' relative distribution around the island.

Residents' perceptions of coastal changes

In 2018/2019, anthropological fieldwork was carried out in Moorea to document residents' perceptions of coastal changes. First author conducted a set of semi-structured interviews ($N=37$) targeting, all around the island, female and male residents living along the coast. During the interviews, particular attention was brought to the perceived consequences of coastal armoring. Stakeholders involved in the tourism industry ($N=13$ — owners of family managed *pensions de famille* (i.e., bed and breakfasts) as well as hotel managers) were also interviewed. When residents were interviewed

Table 2 Summary for each coastal habitat categories of their relative proportion around Moorea's coast and of their estimated vulnerability index (1977 and 2018)

	Prop		CVI	
	1977	2018	1977	2018
Rocks and broken stones in original position	1.6	2	2.1	2.3
Beach rock	4.3	5	2.1	2.5
Walls and embankments	12.1	56.5	3.3	3.4
Muddy areas or herbaceous zone, possibly with mangroves	1.5	4	3.7	3.9
White sand beaches with coarse mud and detrital substrate at less than 50 cm at high tide	34.5	22	3.9	4
Black sand beaches	0.6	0.5	3.7	4.3
White sand beaches without high vegetation or at more than 50 cm to high tide	45.4	10	4	4.3
Island weighted average			3.77	3.58

at their home, we described and discussed — in situ — how and why they had or had not modified the coast along their lagoon-adjacent land plots. Finally, representatives from local authorities ($N = 2$, Moorea Municipality and French Polynesian Urban planning service) were also interviewed to better document existing regulations, their applicability, and their limits.

In a broader perspective, second author carried out another set of semi-structured interviews which were not destined to focus on coastal alterations alone. Interviews were designed to document people's perceptions of the evolution and state of the lagoon and its resources as well as the perceived causes of such changes ($N=59$). Results from these interviews allow us to examine the extent to which discourses about environmental change focus particularly on the coastal environment and the degree to which such evolutions are perceived to be related to the increasing artificialization of the coastline or not. Moreover, we conducted ethnographic fieldwork and participant observation focusing particularly on lagoon fisheries for over 29 months (April 2018 to September 2020).

A rapidly changing coastline: local practices and legislation

Trends and profiles of coastal armoring

Over the past four decades, Moorea's coastline has been significantly altered. Results from the coastal monitoring program are revealing: the coast has shifted from a beach-dominated profile in 1977 (around 70% of the entire coast) to one dominated by artificial embankments and walls (56.5% of the coast in 2018 — cf. Table 2). The sharp increase of coastal infrastructure results from public as well as private initiatives. The former have played a relatively minor role in the coastal developments covered by this study as they have been quite rare and — apart from

the ring-road — cover relatively small portions of the coast¹. Even though the island's asphalt ring-road was completed in the 1980s, its development has had little impact on the 1977 profile of the coast we have documented as it was built over a pre-existing coral rubble road. The booming population combined with the galloping tourism industry has contributed to increasing demand for lagoon-adjacent land plots and to their progressive armoring.

The armoring and protection of the coast has resulted from the progressive development of a wide array of infrastructures which vary in terms of their size, shape, and orientation along the coast as well as the type of materials they are made out of. We have observed vertical concrete seawalls; ripraps made out of piled stones, tires, and even seashells; stone groynes built perpendicularly to the coast; and softer vegetation-based coastal engineering. One of the main sources of variation in the type of observed infrastructure is families' or businesses' level of income. The wealthiest families we have met had the means to undertake significant developments by back-filling their land with earth dug out from the mountains and by reshaping the border of their plots along the coast through the construction of vertical seawalls or ripraps. Often plot limits are extended into the sea in order to reclaim portions of land considered to have, overtime, been progressively “nibbled” by the sea (see Fig. 2a, c). Such heavy developments are usually undertaken by professional contractors. Conversely, families with more limited means opt for alternative and cheaper solutions. A family we have encountered in Haapiti built a seawall along their plot using old tires piled up one on top of the other (see Fig. 2d), another family erected a seawall made out of piled-up sand bags (recycling old cement or rice bags) and yet other families we have met made similar home-made infrastructures using stones collected from the rivers or large seashells harvested in the lagoon. As a 50-year-old resident of Papetoai mentioned, such infrastructures have the benefit of being inexpensive but, due to their limited longevity, have the inconvenience of requiring extensive maintenance efforts. This highlights significant socio-economic disparities between seafront owners. Less affluent families who lack the means to cope with coastal erosion may sometimes suffer the additional adverse effects of increased erosion due to the development of coastal infrastructure by wealthier neighbors. This may cause disparities to widen as land value may fluctuate according to owners' abilities to mitigate the effects of coastal degradation and land loss.

Most families living on lagoon-front plots had made the decision to alter their coastline using one of the above mentioned types of infrastructure ($N = 29$ out of 37). More rarely, other residents ($N = 8$ out of 37) said they preferred either to “let nature do its course” or to use softer coastal engineering methods in “much the same way as older generations did.” In this regard, a man living in Tiahura (North coast) near a river mouth chose to maintain the existing row of trees planted along the beach by his ancestors despite the fact that it blocked the view of the beach and lagoon. He mentioned that several tree species — such as the *aito* (*Casuarina equisetifolia*), the *miro* (*Thespesia populnea*), the *tianina* (*Hernandia nymphaeifolia*), and the *purao* (*Hibiscus tiliaceus*) — were chosen, planted, and maintained along

¹ There is one large ferry wharf and 7 public cement boat ramps around the island.



Fig. 2 Illustration of coastal armoring and erosion. **a** Beach rock exposure along the West coast of Moorea (Haapiti); **b** vertical concrete seawall in Moorea protecting a previously eroded plot of land; **c** level of income as source of varying coastal infrastructures; **d** home-made seawall made from old tires to prevent coastal erosion. © Maëlle Calandra and Jean Wencélius

the coast based on their capacity to mitigate the effects of erosion thanks to their rapid growth rate as well as the density of their far-reaching roots.

Regulations over the public coastal and marine domain

From our experience and the comments of our informants, the diversity of coastal infrastructures and the multiplicity of stakeholders progressively armoring the coastline is a direct result of a relatively inefficient regulatory framework which, in addition to being poorly enforced, does not regulate the type or nature of coastal infrastructures. As a French Overseas Territory, different areas of administrative and political competence are defined between the French State and the local French Polynesian government. While jurisdiction over the ocean and its resources is a shared competence involving both governments, lagoons and coastlines fall into the marine public domain, which came under the sole jurisdiction of French Polynesian Government in 1986. Consequently, the highly restrictive French law prohibiting any new developments within 100 m of the coastline does not apply in French Polynesia. Landfills, seawalls, or any other type of construction within the defined

marine public domain — which extends 3 m inland from sea level at its highest tide — require prior authorization from the Urban Planning Service of French Polynesia. These authorizations that are coined “*concessions maritimes*” in French (we will hereafter refer to them as “marine concessions”) are not a title of private ownership but a form of lease; land owners who have been granted a marine concession to build a seawall or to undertake a backfilling extension of their plot must pay a flat monthly rent to the French Polynesian Government (USD2 per square meter). In some cases, owners may buy back from the Government their land extensions at the realty market value.

However, very few people who armor the coastline actually go through the legal process of asking for a “marine concession” (Aubanel, 2016). Several reasons can explain this general lack of compliance. First, respondents who undertook coastal developments without filing an official demand, justified their action as they regretted the slowness of an administrative process whose outcome is uncertain. They perceive their land to be gradually disappearing, and they are eager to act. Moreover, a feeling of injustice from residents comes into play. Some consider that tourist operators — supported by the Territorial government as members of a key economic sector — may find it easier than residents to be granted marine concession leases to the marine public domain and the right to develop infrastructure on the lagoon front.

Secondly, some informants mentioned how illegitimate they found existing regulations. Many believe them to be an imposition from the French State oblivious to the local cultural and social context. While this is a subject of misunderstanding — the regulation has been voted and enacted by the French Polynesian Parliament composed of locally elected representatives — the general framework instituting land as a purely private domain and the lagoon as a public domain is an obvious heritage of French colonial rule (Gaspar & Bambridge, 2008). Indeed, in the pre-contact period, land and sea were managed and appropriated as a unique entity. Even though slices of land and sea (ranging from mountain top to the reef) were appropriated by relatively large political, social, and kin groups rather than individuals as is the case today for land (Bambridge, 2016; Oliver, 1975), the coastline and the lagoon formed nonetheless part of an estate. Human-made modifications to the coastline or the lagoon are not an entirely new phenomenon as infrastructures such as fish *weirs* (Blanchet et al., 1985) or political-religious temples known as *marae* (Saura, 2019) were built in the lagoon or directly on the coast. Such forms of appropriation and management no longer exist today in Moorea, but the idea that landowners may shape as they see fit the coastline of their estate does linger on.

Finally, the lack of enforcement of existing regulations does not provide any incentive for people to actually play by the book. When interviewing local and territorial authorities, we were told that, to date, no landowner had ever been sanctioned and asked to destroy or remove the illegal coastal infrastructure he or she had undertaken. Other informants, who were planning to build seawalls or embankments, mentioned that municipal councilmen had — off the record and informally — told them to go along and not bother with filing an official authorization demand. Realtors as well as officials from Moorea’s Municipality and French Polynesian Urban planning service we have interviewed stressed that illegal embankments and coastal developments are most often legally recognized post hoc by the French Polynesian

Government who either grants a marine concession or asks owners to buy back land extensions.

Yet, at the local scale, there is growing concern for the ever increasing artificialization of Moorea's coastline. Several dynamic community groups have been opposing over the past two decades new coastal development projects such as extensions of hotels' over-water bungalows or the design of new seaside residential areas. The municipal government is currently implementing a new Management Plan for the Marine Environment (PGEM), which sets the protection of coastal environments as one of its priorities. According to this management scheme, the municipality has de facto prohibited the construction of any new coastal infrastructures. It, however, allows for case-specific exemptions: public services, landowners, or businesses who wish to file a demand for a government-level marine concession should present their project for prior approval to the municipal-level PGEM steering committee. With greater local oversight, the municipality hopes to limit the number of illegal coastal infrastructures, by acting as a buffer between, on the one hand, residents as well as private investors, and on the other, the French Polynesian Government considered to be too lenient in granting post hoc marine concessions.

Socio-ecological drivers of coastal armoring

Vulnerability of the different coastal habitats

We have estimated, for the years 1977 and 2018, the vulnerability index of seven coastal habitat categories (cf. Table 1). One of the goals was to assess whether the main changes Moorea's coast has been undergoing — i.e., notably increased artificialization — have overall strengthened or weakened the coast's exposure to climatic risks such as floods, erosion, or cyclones. All but two of the coastal habitats we have identified (i.e., beach rock as well as rocks and broken stones in their original position — cf. Table 2) can be considered highly vulnerable. Indeed, for both years they score — and so does the island average — above the 3.1 threshold above which coasts are considered to be highly vulnerable to the effects of climatic risks (Hereher, 2016). However, results indicate that the overall weighted CVI value, while remaining at a high level in 2018 (3.58), has slightly decreased since 1977 (3.77). The high value recorded for 1977 can be explained by several factors. Moorea Island is surrounded mostly by coral reef ecosystems as well as some mangroves which are both considered very vulnerable. Furthermore, in 1977 the island's coast was dominated by sand beaches among which we have discriminated 3 categories (cf. Table 2) which CVI values for both years rank the highest compared to the other coastal habitats, thus driving the island average towards a high value.

Because the vulnerability index includes socio-economic variables (such as potential cost of climatic hazards to coastal infrastructure), the CVI value for portions of armored coast is relatively high (3.3 in 1977 and 3.4 in 2018) but scores significantly lower than sand beaches do. The steady increase of artificial embankments and seawalls at the expense of sand beaches drives the slight decrease of the island's average CVI value over time. While we could draw the conclusion that the armoring of Moorea coastline has participated in decreasing its coastal vulnerability

to climatic risks, we should also notice that overtime each coastal habitat has seen its vulnerability index increase (cf. Table 2). It could be argued that armoring a portion of the coast reduces its exposure to erosion and extreme climatic events while increasing the vulnerability of adjacent non-armored portions of the coast.

Why do people modify the coastline? Local perceptions of coastal erosion

As evidenced by our estimation of coastal habitats' vulnerability index, sand beaches constitute the coastal category which are the most vulnerable to climatic risks and erosion. This assessment is corroborated by the results of our ethnographic survey. Indeed interview analyses have highlighted that most of our respondents have witnessed important changes on their beach front or along the coastline they are most familiar with and have also noticed unusual and extreme events (e.g., the highest tide, highest swell). When talking about shifts in the coastal environment, all of the respondents focused their discourses on the progressive and constant erosion of beaches and land along the coast. Soil erosion is, by far, the main concern and people describe how plots along the coast have been gradually "nibbled" and "scratched" by the sea. The process is evidenced, according to interviewees, by the increasing exhumation of tree roots, the gradual tipping of trees over the beach, and the uncovering of the beach rock dugout by the swell (see Fig. 2a). They fear that the progressive erosion of the coastline will inevitably result in reducing the size of their plots and that is how they justify the undertaking of coastal infrastructure designed to protect their land. It is worth mentioning that soil and beach erosion is equally a source of concern for local authorities. The French Polynesian and municipal governments have recently undertaken the construction of a large cement artificial reef in front of one of the island's three public beaches in order to mitigate the gradual disappearance and erosion of the sand beach (Guillet et al., 2016).

Comments about coastal change greatly vary around the island according to each coast's exposure to different types of natural hazards. Extreme climatic events, such as cyclones, are the main factor people mention on the West coast. The last cyclone in Moorea dates to February 4th, 2010 (cyclone Oli — category 4). Damages on the coastline were generated both by wind and wave. People living on the West coast mentioned how the damages caused by Oli pushed them to build walls or embankments in order to protect their plots from future erosion and floods. The decrease, noted by Madi Moussa et al. (2019), of white-sand beaches on that part of the island and the matching increase of seawalls or embankments support this point. On the South coast, Cyclone Oli was rarely mentioned. Residents considered that the changes observed overtime on the Southern coastline mainly resulted from the exposure to the strong south-eastern trade wind named *maraamu* in Tahitian (which blows during the austral winter, from June to September) and its associated strong oceanic swell. Both wind and swell are considered to cause significant damages to their beaches as well as coastal infrastructures and to increase risks of flood. Lastly, on the Northern coast, human activities rather than climatic causes were invoked as a factor of soil erosion. Respondents interviewed in that area of the island pointed out how the waves

generated by an ever-increasing sea-traffic (e.g., lagoon boat tours, jet skis, etc.) have participated in sand displacement and beach disappearance. Other inhabitants declared they had lost part of their coastline because of the changes caused by neighboring artificial embankments, overwater bungalows, and cement retaining walls built by hotels along the coast.

For residents, coastline erosion is a reality — whether it is perceived to result from the constant process of waves battering the shore or through more exceptional climatic events such as cyclones or high swells. All of our informants agreed to consider that the processes of coastal erosion and degradation will escalate in the years to come, some mentioning rising sea levels or extreme climatic events as aggravating factors. Relatively few informants ($N = 3$ out of 37) mentioned climate change as an overarching or ultimate cause, and those who did stress their fondness for environmental documentaries and their exposure to global media. One respondent mentioned how frightened she was of spectacular events such as tsunamis which, however, have been rare in the Society islands archipelago² (Sladen et al., 2007; Schindelé et al., 2006; Okal et al., 2002). Studies in the Pacific have shown how global media and scientific discourse shape people's perceptions of the local environmental dynamics and changes — notably Rudiak-Gould (2014) — and such a process is evidently at play in Moorea and may constitute an essential motive for people to armor the coastline.

Perception of the socio-ecological effects of coastal armoring

While addressing sea-front owners' need to mitigate the effects of perceived increased erosion, coastal armoring is controversial as it has both social and ecological side-effects which have community-wide impacts. We have stressed in the first section of this paper the social and economic importance of the coastline for residents and how it provides important ecosystem services some of which are considered to be threatened by coastal infrastructure. The increasing artificialization of the shoreline raises several topics of controversy among residents; we outline the main three in the sections below.

Artificial embankments impede access to the coast

Across interviews carried out with residents who do not live immediately on the coast, informants regretted that access to shore has become more difficult and have expressed feelings of deprivation from what is considered a public right. Indeed, open land plots by the sea are increasingly rare as people build their houses upon them and fence them off. Roads leading to shore are often privately owned and owners may sometimes refuse passage as they mention being frustrated by the disrespectful behavior of some pedestrians or beach users. For instance, a sea-side land

² In French Polynesia, since 1837, 15 tsunamis have been recorded and 11 of them have caused damages. The most exposed archipelago is Marquesas (Schindelé et al., 2006).

tenant who was seeking to close out the passage to the beach in front of his house expressed the following: “People and especially youngsters come all the time. They stay late and play their music loud. And you should see the rubbish they leave and then it’s up to me to clean up.” Furthermore, landowners and people who have acquired a marine concession enabling them to build along the coastline rarely respect the regulation to free a 3-m-wide corridor along the shore to allow passage for pedestrians (Aubanel, 2016). A 20-year-old woman we have met related how she could no longer access a beach she used to go to frequently with family and friends. The adjacent plot belonged to a church community which backfilled the plot right into the sea and built an imposing stone riprap all the while closing access to the site from the ring-road. As the developments had been carried out without prior authorization from the French Polynesian or municipal governments, complaints had been filed by residents but, at the time of the interview, no legal action or sanction had been undertaken. This example provides a good illustration of how the parallel decrease of sand beaches and increase of artificial embankments reduce residents’ ability to access the shore leading to tension among community members.

Spiraling effects of coastal armoring

The development of artificial embankments may also create tension among lagoon-front owners themselves. While coastal infrastructure enables those who undertake them to maintain or extend their land plots, it may have adverse effects for immediate neighboring plots and beaches. Indeed, seawalls created along a part of the coast will accelerate the erosion of adjacent sections of the coast encouraging neighbors to themselves build more infrastructure triggering a downward spiral effect where armoring calls for ever more armoring. Results from our CVI assessment point to such a process if we consider how the CVI value of each coastal habitat we have documented has increased over time. This domino effect has been reported by our respondents as well. In Maatea (South coast), a man in his fifties explained how he had observed the sea level move inward over his land several tens of centimeters and cause extensive erosion after his uncle had back-filled the parcel next to his. In response, he in turn built a concrete-block seawall in front of his own property and has filled-in the lost ground (see Fig 2b).

Coastal embankments parallel to the coast also affect sand displacement and cause sand beaches immediately in front of the embankments to progressively recede. Respondents who had constructed such embankments did notice the phenomenon but consider it negligible as limiting land erosion is the primary desired outcome rather than sand retention. Those who do create outward stone groynes for sand retention purposes — as often do hotels, resorts, and *pensions de famille* — may achieve their goal while affecting sand availability for neighboring plots (Donner & Webber, 2014; Mimura & Nunn, 1998) and participate in pushing neighbors to themselves create infrastructures in order to maintain a sand-beach shore. This may also deepen existing socio-economic inequalities as owners affected by the developments undertaken by neighbors might not have the financial means to adjust and may consequently expose their plot to greater erosion, land loss, and market-value drop (see Fig. 2c).

Scientists' and residents' perceptions of the ecological impacts of coastal armoring

Ecologists working in Moorea have highlighted the ecologically detrimental effects of coastal armoring even though there is debate concerning the varying effects different types of infrastructure may have, some showing apparently beneficial impacts on biodiversity. Lecchini et al. (2009) showed that coastal embankments in Moorea deteriorated adjacent fringing reefs through habitat loss and decrease of proportion of living corals which, in turn, has led to a decrease of juvenile fish along the coastline. For example, more commercially prized fish (e.g., *Mullidae*, *Mugilidae*, *Carangidae*) were observed near non-armored sandy beaches than in areas located in front of coastal infrastructure. Similarly, Gittman et al. (2016), in their meta-analysis of the effects of artificial embankments on biodiversity and coastal ecosystem services (i.e., habitat provisioning), have shown that biodiversity documented along seawalls was 23% less abundant (in terms of biomass) and 45% less species-rich (in terms of number of different species) than unarmored shorelines. Likewise, several other studies have indicated that coastal infrastructures negatively impact fish recruitment patterns, foraging behavior, and community structure and dynamics of marine fish and sessile invertebrates (e.g., Oricchio et al., 2016; Connell, 2001; Connell & Glasby, 1999; Wright et al., 2020). However, the provision of shelter and somewhat complex habitat provided by artificial embankments may have created, in some cases, an artificial reef-type habitat along the shoreline in Moorea. Similarly, Folpp et al. (2020) showed that artificial reefs can increase the carrying capacity in estuaries by providing refuge that would otherwise be unavailable.

While noticing a rapid degradation of the coastal environment, residents do not identify artificial embankments as the main driver of observed changes. During interviews in which coastal armoring was not the main topic of discussion, we asked informants to express their feelings about the changes they may have observed in their marine environment. Few informants spontaneously declared having perceived any significant changes. However, when prompting them more specifically about the coastal environment, they have almost all indicated ($N = 57$ out of 59) its rapid deterioration over the past decades. Several indicators have been used by our informants to justify their statements. The most recurring observations concerned the apparent high mortality of corals on the fringing reefs as well as an increasing near-shore sedimentation (93% of informants). Relatedly, some informants mentioned observing fewer large fish on the fringing reefs and notably Jacks (*Carangidae* family) who hunt down juvenile fish seeking refuge near the coastline. A few others have insisted on the disappearance, near-shore, of food-prized invertebrates such as giant clams (*pahua* — *Tridacna maxima*) and sea urchins (*hava'e* — *Araesoma thetidis*).

Consensus concerning the causes of such trends is much weaker. Some informants invoked “climate change” or increasing water temperatures as a driving factor for coral mortality. Other informants admittedly blamed themselves for coastal degradation. A woman from Papetoai stated: “It’s because of us that it’s dead all over tahatai (coastline). Because of the pollution and the litter. There’s no longer any fa’atura (respect).” Indeed, many informants invoked the increase of material and chemical pollution of coral reefs (e.g., plastics, litter, agricultural pesticides, and herbicides)

and the sewage run-off from tourist resorts, sailboats, purification stations, and individual houses as drivers of the deteriorating coastal environment. Among other drivers, respondents mentioned the creation of private boat channels for steering boats to shore or the dredging of the lagoon to collect sand or coral rubble — which has been strictly prohibited for over 15 years ($N = 6$ out of 59). Lastly, in this set of interviews, none of the respondents has spontaneously indicated the effects of coastal artificialization (e.g., construction of seawalls or embankments) on marine biodiversity loss. It is worth mentioning, however, that T. Bambridge in 2015 and 2017 had interviewed elders and experienced fishers who did consider coastal armoring as an important factor affecting the decrease in fish biodiversity and abundance. Interestingly, some informants mentioned the artificial channeling of rivers, their embankments and dredging as a cause of increased sedimentation in the lagoon which in turn is considered to degrade habitat and impact coral mortality ($N=11$ out of 59).

Even though neither ecologists nor residents share a consensual view about the effects of coastal infrastructures, a gap appears around their mutual perceptions and bodies of knowledge. Such divergences between scientific and local-based knowledge have been documented in the Pacific (Rudiak-Gould, 2014; Connell, 2003) and some have argued that they result from people's need to deal with day-to-day concerns rather than long-term or global changes which are harder to grasp and experience (Connell, 2013; Gaillard, 2012). In our case the gap stems from scientists and residents highlighting diverging effects and outcomes of such constructions. While residents consider that the main desired outcome is for seawalls and embankments to protect their land from erosion, ecologists stress their harmful effects on the near-shore underwater topography and coastal biodiversity (Mahabot et al., 2017; Lecchini et al., 2009).

Conclusion

This case study, at the crossroads of social and life-sciences, expands our understanding of the drivers that push landowners and local authorities to armor the coastline as well as of the perceived effects of coastal alterations. We have shown that Moorea's coastline is — as are those of most tropical coral reef islands — highly vulnerable and exposed to erosion and climatic hazards. Coastal erosion and its potential acceleration whether due to increasing local anthropogenic pressures or to global climate change is a major source of concern for local residents and authorities and a powerful driver for coastal armoring. In a context where regulation of coastal armoring is poorly enforced and respected, the development of private-based and uncoordinated coastal infrastructure has been over the past decades the most common solution to mitigate the effects of coastal erosion and has participated in a sharp decrease of sand beaches.

This coastal armoring “reflex” has been well documented across the Pacific (Betzold & Mohamed, 2017; Donner & Webber, 2014; Duvat, 2013; Nunn, 2012; Xue, 2001). Coastal armoring, however, has resulted in controversial community-wide consequences. First, it has limited people's ability to access the coast for

recreational or economic purposes which is source of tension among community members, notably between the wealthiest who have developed significant coastal infrastructures and less affluent families living further away from the seafront who feel deprived from easy accesses to the beaches and shoreline. Second, it may trigger, through sand displacement and increased erosion of neighboring non-armored coast, a spiraling effect calling for greater armoring and causing widening socio-economic disparities between those who have and those who do not have the means to undertake efficient measures against coastal erosion and degradation. Finally, its potential harmful consequences on coastal biodiversity and related ecosystem services (such as fish nurseries provided by healthy coastal environment) impact the community as a whole. Developing a more efficient legal framework regulating the nature of infrastructures and promoting, as suggested by Morris et al. (2018), ecologically engineered solutions in order to design infrastructures that may answer the need of landowners to protect their sea-front plots all the while benefiting coastal biodiversity may be an avenue to limit the impact of coastal armoring.

Even though there is growing awareness as to the necessity to protect the near-shore environment, the adverse effects of coastal armoring — and particularly their ecological impact — are poorly understood and subject of debate, both among residents and scientists. Lack of awareness of the potential negative impacts of seawalls and embankments on coastal ecosystems seems to be a common trend in the Pacific (Betzold & Mohamed, 2017; Nunn, 2013; Cooper & Pilkey, 2012). This calls for greater outreach from the scientific community towards local authorities and residents so as to inform of the potentially undesirable consequences of coastal infrastructure and to co-design successful conservation strategies targeting the rehabilitation of coral reef coastal socio-ecosystems (Westoby et al., 2020; Moritz et al., 2018; McNamara, 2013). Science communication, however, goes both ways and scientists could benefit from the input of local communities in order to take into account the multiple processes residents mention as playing a significant role in the deterioration of coastal biodiversity (e.g., sedimentation, nutrient-enriched run-offs, pollution, increase of marine traffic) so as to consider the effects of multiple and confounding factors rather than seeking to isolate a single factor (e.g., coastal armoring alone) to model the evolution of coastal environments and biodiversity (Connell, 2015). Furthermore, as residents acutely observed the effects of increasing near-shore sedimentation caused by river bed and embankment alterations, engaging issues of coastal erosion and degradation within a broader perspective to include inland streams and rivers in monitoring and management efforts could better address local preoccupations (Kay & Alder, 2017). This is particularly true in the case of small tropical coral reef islands in which terrestrial run-off has a significant impact on the marine ecological and biochemical dynamics (Adam et al., 2021; Fabricius, 2005).

It is imperative to keep conducting and to network across the South Pacific longitudinal monitoring programs of coastal environments documenting, through an interdisciplinary approach, the socio-ecological dynamics of this ecologically and culturally important ecosystem in order to fill-in the lack of reliable data which is often pointed out in the literature (Nunn, 2013).

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Declarations

Conflict of interest The authors declare no competing interests.

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