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ORIGINAL ARTICLE

Multi-decadal coastal evolution of remote Pacific islands: armouring of Taha'a, Raiatea, Maupiti, and Rangiroa (French Polynesia)

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Abstract

Coastal urbanisation is not constrained only to heavily industrialised cities. It has reached the coastlines of French Polynesia islands (South Pacific). In the context of climate change–induced cyclones and storms, sea level rise, and ecosystem damage, characterising the evolution and current extent of man-made structures along coastlines is of key importance for managers. In French Polynesia, three high volcanic islands (Taha'a, Raiatea, Maupiti) and one atoll (Rangiroa) were selected as case studies to highlight the increasing extent of artificial coastal structures in a tropical setting. Using high-resolution aerial imagery from the mid-twentieth century and from recent years, changes in coastal typology were assessed. The proportion of natural coastlines decreased from over 90% to under 40% within seven decades on the volcanic islands, mostly due to a boom in private embankments. This decrease was more limited in Rangiroa (93 to 89%), possibly due to its different morphological characteristics and coastal protection requirements. Based on these changes, for more sustainable management of island coasts, we recommend adopting case-by-case policies to rectify past and current management and urban planning strategies, especially relating to private embankments.

Keywords Coast · Erosion · Urbanisation · Airborne imagery · Spaceborne imagery

Introduction

Coastal zones are coveted worldwide for urban development, leisure activities, and transportation hubs (Cooper and Jackson 2019). They have been modified in response to demographic and economic growth since the end of the nineteenth century (Dafforn et al. 2015). In French Polynesia (tropical South Pacific), studies have highlighted a shift in coastal typology on numerous islands. On Moorea and Bora-Bora, two islands with over 10,000 inhabitants and which are major tourism destinationsm natural coastlines — beaches, vegetated zones, mangroves — have given place to man-made structures — embankments (more or less cemented pile of rocks and rubble) and quays — (Madi Moussa et al. 2019; Gairin et al. 2021), which embody major touristic destinations with over 10,000 inhabitants. These constructions allow to reclaim land over the sea and protect coastlines against erosional processes. They however have extensive impacts on the landscapes, coastline stability, and shallow marine ecosystems. Coastal modifications are not constrained to highly frequented islands such as Moorea and Bora-Bora; islands relatively spared from mass tourism and heavy urban development, and that for some promote

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green and niche tourism, also have coastlines exposed to armouring. In the Tuamotu archipelago, even on isolated and sparsely-populated islands, man-made structures and sand mining induce coastline destabilization (Duvat et al. 2017).

To inform stakeholders, the present study aims at quantifying coastline evolution on four French Polynesian islands: Taha'a, Raiatea, and Maupiti, three high volcanic Leeward Islands, and Rangiroa, a Tuamotu atoll. Very high spatial resolution imagery available since the mid-twentieth century enabled the characterisation and comparison of coastal changes on each island. The study's purpose is to quantify the extent of coastal modifications in French Polynesia, a remote territory of the South Pacific which has not been spared from the global drive for urbanisation.

Materials and methods

Study sites

Four islands were selected based on the availability of very high spatial resolution imagery obtained in the 1950s and 1960s and due to their socio-ecological characteristics. They are remote and rural but face issues linked to increasing population and economical activities. They have contrasting topographies: three volcanic Leeward islands (Taha'a, Raiatea, and Maupiti) and a low-lying Tuamotu atoll (Rangiroa). These islands can shed light on general processes occurring in similar Polynesian islands and help to decipher the drivers of coastal hardening.

Taha'a (16°′S, 151°30′W, land surface: ~ 88km^2, summit: 590 m) is a volcanic island surrounded by a barrier reef that it shares with Raiatea. Its population increased from 3751 to 5234 inhabitants from 1983 to 2017 (ISPF 2021). Taha'a has multiple long and narrow bays, bordered on the land-side by mangroves. The island's belt road goes over bridges crossing the bays and restricting water flow.

Raiatea (16°44′S, 151°27′W, land surface: ~ 175km^2, summit: 1017 m) is a volcanic island in the same lagoon as Taha'a. Its population increased from 7445 in 1983 to 12,249 in 2017 (ISPF 2021). Its coastline has been modified over the years with the construction of embankments and quays, notably for the airport located on its northern coast.

Maupiti (16°25′S, 152°15′W, land surface: ~ 10km^2, summit: 380 m) is a volcanic island surrounded by a barrier reef. Its population increased from 794 in 1983 to 1286 in 2017 (ISPF 2021). Since the mid-twentieth century, its coastline has become increasingly urbanised, with the construction of embankments along public land, roads, and private properties to preserve them from strong swells.

Rangiroa contrasts with the other islands. It is the world's second largest atoll and has an elliptical shape with a length of 80 km and maximum width of 35 km (15°07,S, 147°38,W, land surface: ~ 79km^2, lagoon surface: ~ 1446km^2; Kumar et al. 2013). Its population increased from 1169 in 1983 to 2709 in 2017 (ISPF 2021). The towns of Tiputa (971 inhabitants) and Avatoru (817) are located on the most populated *motu* (sandy islands on the barrier reef with sufficient shingle to render them more or less permanent; Nunn 1994) in the north of the atoll. These towns were selected as study sites (Fig. 1).

Data acquisition

The oldest available high-resolution vertical aerial imagery was obtained from the French Geographic Institute (IGN 2022) and the most recent satellite imagery was extracted from Google Earth (cf. method from Collin et al. 2014) for each island (cf. Table 1 in Appendix for imagery dates, sources, and specificities). A ground-based coastal typology survey was performed in 2021 on Maupiti and Taha'a and was used to confirm the image interpretation for all islands.

Data processing

Orthomosaics created by assembling the aerial images with Agisoft Metashape 1.7.1 were georeferenced using ArcGIS 10.8.1 through adjust or 2nd polynomial transformations. Fixed features such as lagoon pinnacles and buildings were used as ground control points (similar to Duvat and Pillet 2017). Using the sea-side edge of vegetation, the coastline was traced manually with the ArcGIS Editor tool.

The coastline was classified into the eight main categories identifiable on the images: sandy beaches, mangroves, high vegetation (tall trees), low vegetation (or reeds), natural rocky shores, road embankments, embankments along private and public land (difference determined through the type of construction visible on the satellite images near the embankment, and ground truthing for the most recent images) land, and quays (method similar to Madi Moussa et al. 2019 and Gairin et al. 2021; ground-view and aerial appearance of the categories depicted in Figs. 2, 3 and 4 of Gairin et al. 2021, and in Fig. 2). The coastal classifications of the most recent images of Maupiti and Taha'a were based on ground surveys to confirm the bird-eye appearance of each category and enable the manual classification of previous images through photointerpretation (Mury et al. 2019; Gairin et al. 2021). Coastal classification was performed by splitting the coastline into segments with the ArcGIS Editor tool. The percentage of the coastline corresponding to each category was calculated with the length of each segment.

Lastly, to complement the results, long-term inhabitants were informally interviewed on Maupiti, Taha'a, and Rangiroa to provide more background as to why coastal armouring was put in place over time.

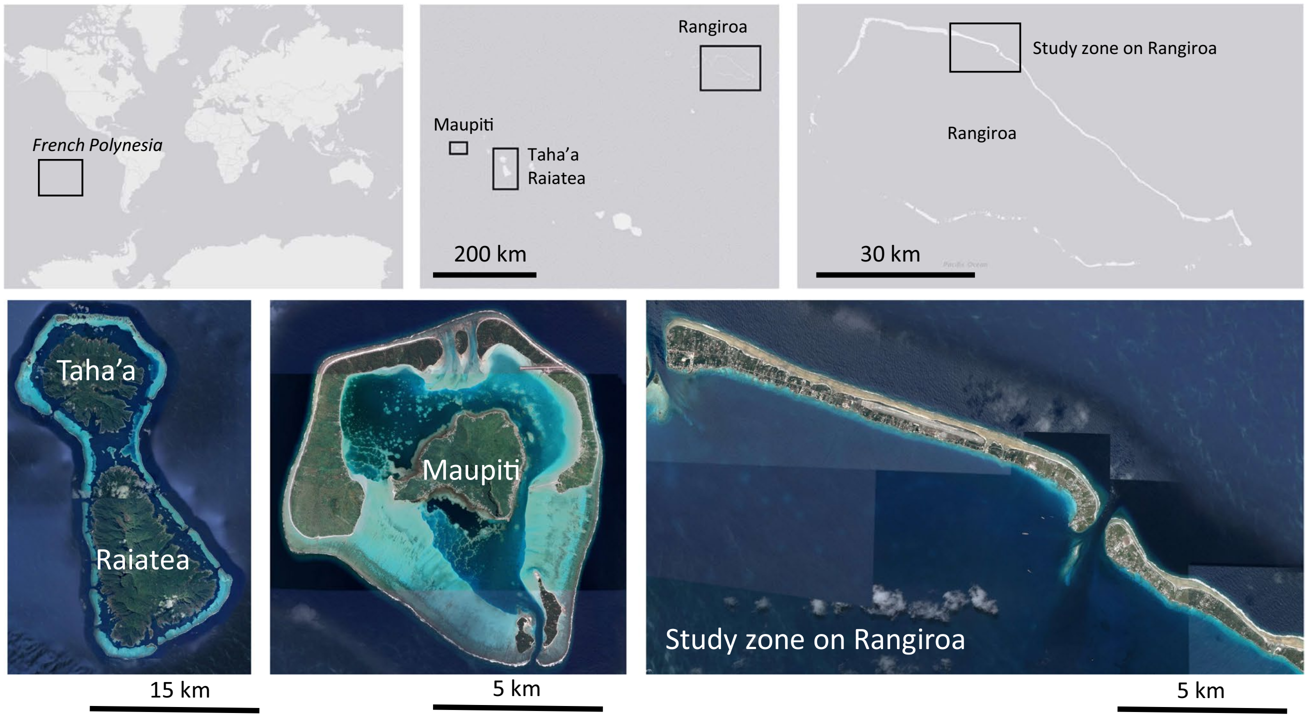

Fig. 1 Location of French Polynesia, of Raiatea, Taha'a, Maupiti, and Rangiroa, and of the study zone on Rangiroa, and satellite imagery of the different islands (Google Earth 2022). The top of all images is oriented towards the north

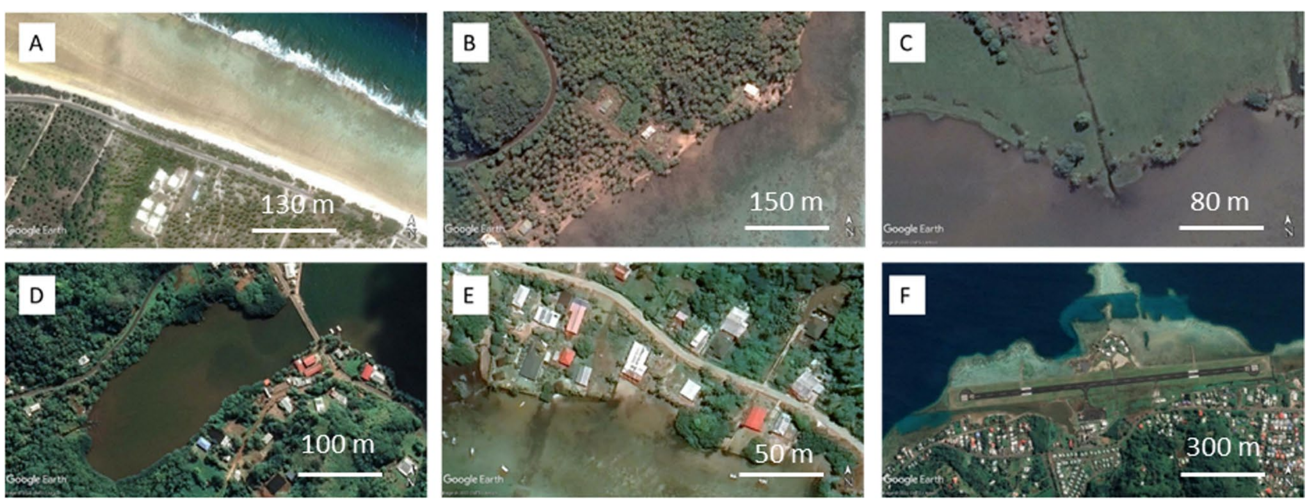

Fig. 2 Aerial views of **A** a sandy beach on the outer part of the atoll of Rangiroa, **B** high vegetation on Raiatea along a fringing reef, **C** low vegetation on Raiatea near a shallow fringing reef, **D** narrow bay cut off by a belt road, with a shoreline bordered by mangroves on Taha'a, **E** private embankments on Maupiti allowing for land reclamation for private gardens, and **F** public embankments on Raiatea protecting the lagoon side of the airport runway. Images from Google Earth (2022)

Results

From the mid-twentieth century to 2016–2017, natural coastline extents (sandy beaches, high and low vegetation, mangroves) decreased across all Leeward islands: from 94 to 31% between 1955 and 2016 on Maupiti, 97 to 38% between 1955 and 2017 on Taha'a, 91 to 35% between 1955 and 2017 on Raiatea (Fig. 3A and B). In detail, high vegetation was largely replaced by artificial structures: from 70 to 18% in Maupiti, 84 to 29% in Taha'a, 80 to 23% in Raiatea. The percentage of the other natural categories

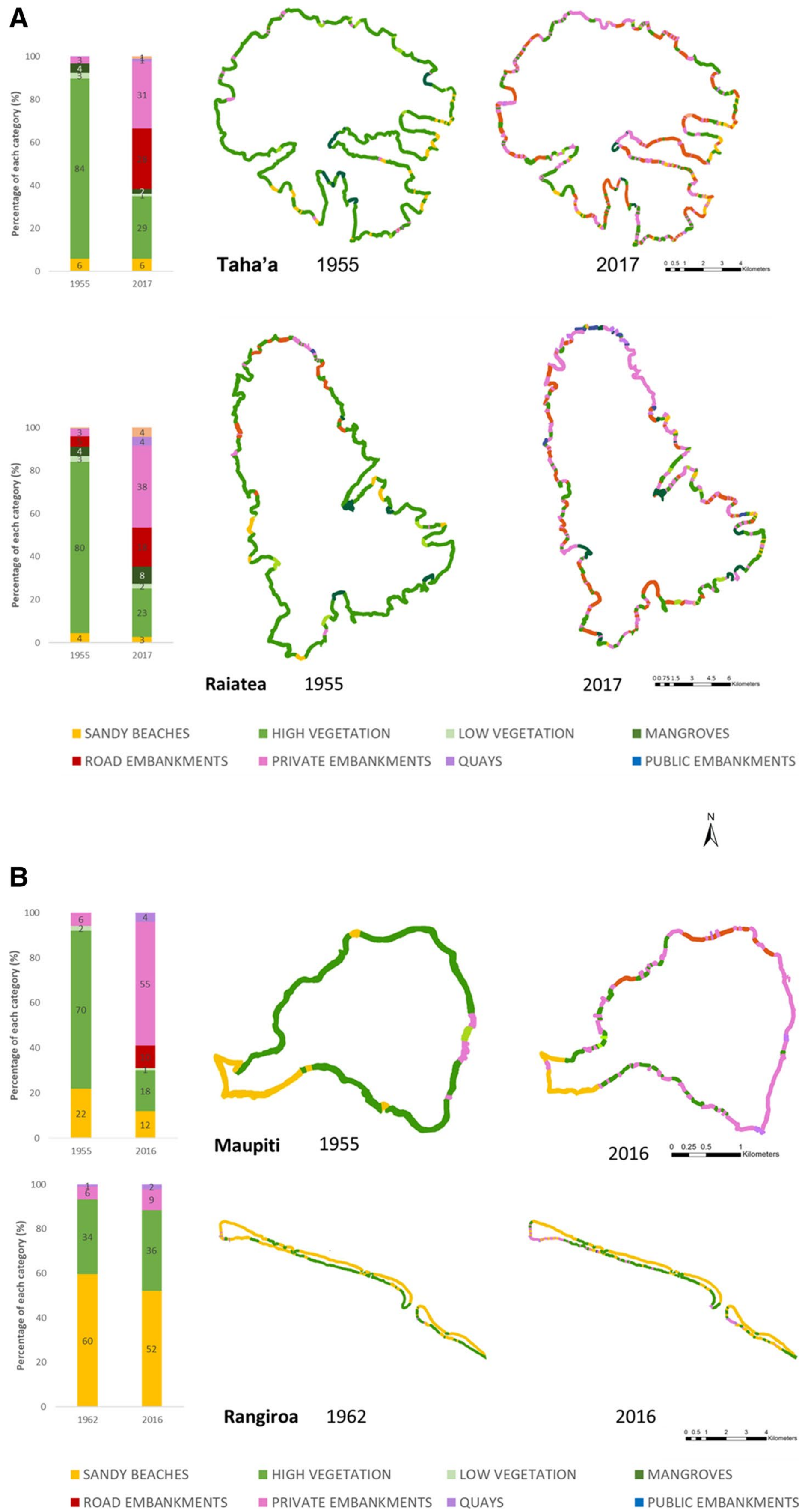

Fig. 3 Coastline classification of **A** Raiatea and Taha'a, **B** Maupiti and the selected study zone of Rangiroa (two northern *motu,* Avatoru and Tiputa), for the earliest and latest available imagery and percentage of the coastline as sandy beaches, rocks, vegetation zones, grass zones, mangroves, road embankments, private embankments, and quays, based on the earliest and latest imagery of each island. The error of these percentages can be estimated as 10% of the value (38 ± 4% of the coastline is a private embankment in Raiatea in 2017), due to coastline tracing and classification uncertainty

remained relatively stable (mangroves even expanded in Taha'a, from 4 to 8%).

The study zone on Rangiroa underwent a lesser change, with a transition from 93 to 89% of natural coastline between 1962 and 2016; the changes in coastline type occurred only on the lagoon-facing side (southern coastline), while the ocean-facing side remained natural.

The man-made category that mostly increased in extent across all islands is private embankments (6 to 55% in Maupiti, 3 to 31% in Taha'a, 3 to 38% in Raiatea, 6 to 9% in Rangiroa). These private embankments were often associated with land reclamation over the fringing reef. Road embankments also markedly increased in the volcanic islands (0 to 10% in Maupiti, 0 to 28% in Taha'a, 5 to 18% in Raiatea) but remain absent in Rangiroa. Other public constructions such as quays and other coastal infrastructures (airport, schools) requiring embankments also play an important role in the shift from natural to artificial coastal types in Raiatea, which is the most populated island studied here and has more public infrastructure (4% of the coastline is a quay and 4% a public embankment in 2017).

Discussion

Changes in coastal typology since the mid-twentieth century in French Polynesia

Countless coastal zones worldwide have undergone important changes in typology over the last decades (Cooper and Jackson 2019). These changes are often linked to demographic growth and economic development, requiring new infrastructures such as roads, harbours, airports, and schools. In French Polynesia, private land extensions over the fringing reefs, consolidated by private embankments, are common. They are put in place based on traditional rules that families own the land going from the top of the mountain to the barrier reef (Tetiarahi 1987). These private lands are a major driver of coastal changes in the islands. Taha'a, Raiatea, and Maupiti have undergone economic growth since the twentieth century, but to a lesser extent than other Polynesian islands such as Moorea, Tahiti, or Bora-Bora (French Polynesia's main tourism hubs). However, their coastal armouring (69% on Maupiti, 62% on Taha'a, 65% on Raiatea) is similar or even more extensive than on those islands. On Moorea, 57% of the coastline consisted of embankments in 2018 (Madi Moussa et al. 2019), and on Bora-Bora, 61% was artificial (Gairin et al. 2021). All these islands that have been studied so far, regardless of the extent of economic development and tourism pressure, have drastically changed in terms of coastal typology within a few decades. Despite the remoteness of French Polynesia, these figures are akin to those observed in Europe, Asia, and the USA, where up to 50% of the coastlines have been modified (Dafforn et al. 2015). These results echo other studies (Duvat et al. 2017), highlighting human impacts on coastlines and sedimentary budgets in rural, remote, and sparsely populated Tuamotu atolls. As French Polynesia is a French territory, with subsidies provided from Europe that can be used by local councils to put in place coastal armouring, such as a large publicly funded embankment along the southern beach of Matira on Bora-Bora (Gairin et al. 2021), it would be interesting to conduct similar studies on other South Pacific Islands without such subsidies (e.g., Tonga, Samoa, or Easter island).

The proportion of embankments is markedly lower in Rangiroa than on the Leeward islands (Fig. 3). The steep topography of the volcanic islands leads the population to concentrate near the coast, and many constructions are built directly on the coastline, thus requiring embankments to consolidate the lands. The coastlines of these volcanic islands are also relatively exposed to waves and storm surges, leading to the need to protect coastal zones through artificial structures. In contrast, Rangiroa has a flat topography, allowing a larger fraction of constructions to be built more than a few metres away from the sea (the inhabited *motu* are 300 to 500 m wide). In addition, the ocean-facing side of the Rangiroa atoll is mostly uninhabited (only forested areas, fields, and beaches) and hence does not require embankments. The lagoon-facing side, although more densely populated, does not require many embankments — the coastline remained stable between 1966 and 2013 on the Avatoru and Tiputa motu studied here (Duvat et al. 2017). Although Rangiroa is the capital island of the Tuamotu Archipelago, with an airport, harbour, and numerous public infrastructures, its coastal typology has remained relatively natural. However, other local issues may affect its coastline, notably sand mining on nearby motu and coastline protection structures (Duvat et al. 2017, 2020).

Drivers of coastal artificialisation and armouring

The reasons underlying coastal armouring differ from island to island and were identified through conversations with islanders on Taha'a, Maupiti, and Rangiroa (no fieldwork was performed on Raiatea for logistical reasons). Firstly, armouring the coastal zones with embankments can be done to prevent flooding during storms (model of the flood caused by 1983 cyclone Orama-Nisha on Rangiroa by Collin et al. (2020)). Indeed, on Maupiti, most walls were implemented to elevate lands after a flood caused by storms at the end of the 1990s (notably during the 1997–1998 cyclone season, with category 2 cyclone Osea; Larrue and Chiron 2010). On Taha'a, there are more diverse reasons for coastal armouring. In some exposed zones, walls have been put in place recently in response to erosional processes attributed to boat traffic by the islanders. In other areas, walls are put in place to counter the landward growth of mangroves.

Rhizophora stylosa mangrove trees were first introduced in the 1930s in French Polynesia to promote crab and oyster farming (Cavaloc 1988). The mangroves on Taha'a are located within calm and shallow bays where erosional forces may be limited (contrarily to cases elsewhere where mangroves actively play a role against coastal erosion; Gracia et al. 2018); interviewed residents perceived them as invasive and often actively removed them. On all islands, another main driver of embankment construction is land reclamation over shallow fringing reefs for private house construction, public infrastructure development (e.g., the airport in Raiatea), and roads. Reclamation is a driver of coastal change in many other tropical Pacific islands (e.g., Majuro in the Marshall Islands; Ford 2012; Kiribati; Biribo and Woodroffe 2013; multi-island study across the Central Pacific; Webb and Kench 2010). This also echoes the results of other studies in French Polynesia: in Bora-Bora, Moorea, and the Tuamotu, embankments were put in place mostly to reclaim shallow reefs (and, often without building permits, extend private land) as well as to counter coastal erosion in more recent years (Duvat et al. 2017; Madi Moussa et al. 2019; Gairin et al. 2021). The large extent of coastal armouring on all islands is partially due to weak or absent enforcement of building regulations for the private embankment portion (Duvat et al. 2020). It is also linked to urban planning directly designed at exploiting the flat and easily constructible coastal zones in the steep and mountainous volcanic islands where population density is booming. In French Polynesia, the sea level has increased by ~ 2.5 to 2.7 ± 0.5 mm/y since the mid-twentieth century in northern Tuamotu and Tahiti respectively (Becker et al. 2012). Sea level rise was not mentioned as a reason for coastal armouring by the interviewed islanders, although it is perceived as an existential threat in many other atolls of the Pacific (Donner and Webber 2014; Teaiwa 2019). However, the sea level is predicted to rise by 0.43 to 0.84 cm by 2100 (Oppenheimer et al. 2019). Most constructions, notably on the Rangiroa atoll but also in all the coastal zones of the volcanic islands, are not sufficiently high relative to the sea to avoid submersion during storms in the short term (about half of the houses are located in zones that have been submersed at least once since the 1980s on Rangiroa; Magnan et al. 2019) and due to sea level rise in the longer term.

Consequences of coastal armouring

Coastal modifications are not without consequences. In French Polynesia, they are commonly put in place on private lands without permits, prior studies, or sound engineering design, similarly to other islands worldwide, which can lead to unintended consequences (Kench 2012). Firstly, it leads to the destruction of natural habitats directly — with impacts on biodiversity (Mercader et al. 2017) and through the disruption of currents, water renewal processes, and nutrient filtration (e.g., by mangroves and seagrasses). On Taha'a, a belt road interrupts numerous bays (example in Fig. 2D) and leads to water stagnation, making the inner bays unhospitable to marine life and possibly leading to a proliferation of mosquitoes (a common issue in French Polynesia; Marris 2017). Furthermore, artificial coastal structures in French Polynesia have been found to directly impact coastline stability by causing heightened erosion in natural stretches near artificial structures (e.g., Matira beach in Bora-Bora, Gairin et al. 2021); coastline destabilization through land reclamation and engineering projects in the Tuamotu, Duvat et al. 2017). This enhanced erosion, coupled with climate change — increase in storm frequency, sea level rise — may make armouring efforts insufficient in the long term. However, building even more structures to seek to maintain current coastline positions may disrupt of natural sedimentary regimes that can enhance erosion in neighbouring natural stretches of coastline (Gairin et al. 2021; Nunn et al. 2021). Studies of the coastline evolution positioning based on historical aerial imagery, as were performed on Bora-Bora (Gairin et al. 2021) and in the Tuamotu (Duvat et al. 2017), could provide further insights into the consequences of man-made structures on each island and inform future management.

Perspectives and future steps for stakeholders

Lastly, as evidenced by the contrasting evolution in coastal typology between the volcanic islands and an atoll — Rangiroa — and highlighted by discussions with islanders about the historical causes of embankment construction, case-by-case policies are required to rectify past (and current) coastal management and urban planning strategies. Residents near harbours in Taha'a that did not possess private embankments noted erosion caused by boat traffic and requested speed reductions and modifications in navigation routes as short-term solutions; restricting new constructions in areas at risk of erosion and flooding while promoting relocation to higher ground could be envisaged in the long term (Nunn et al. 2021). Coastal restoration can have multiple facets. The current artificial structures can either be modified to be more welcoming for marine life (by adding frames or other substrate-complexifying objects (Mercader et al. 2017); this would however not solve erosion issues. More efficiently, man-made structures should be replaced by natural alternatives, such as planting deep-rooted Polynesian trees that can retain sediments (Calandra et al. 2021; Nunn et al. 2021). Such solutions need to garner funding and public support, as they mostly concern private embankments.

Overall, this study contributes to a growing pool of knowledge about human disturbances of the coastline in French Polynesia. It constitutes a baseline to communicate with the public and promote sustainable coastal management so that decision-makers on French Polynesian islands can make informed decisions in the face of climate change-induced cyclones and storms, sea level rise (with drastic implications for lifestyles within a few decades), and loss of biodiversity (Oppenheimer et al. 2019; IPCC 2021).

Appendix

Table 1

Table 1 Year of acquisition and spatial resolution of the aerial imagery used for each study island (Taha'a, Raiatea, Maupiti, and Rangiroa)

Island	Year of acquisition	Source	Image type	Spatial resolution (m)
Taha'a	1955	Aerial photograph	Single band grey	0.67
	2017	Satellite imagery	Multiband colour	1.00
Raiatea	1955	Aerial photograph	Single band grey	0.67
	2017	Satellite imagery	Multiband colour	1.00
Maupiti	1955	Aerial photograph	Single band grey	0.63
	2016	Satellite imagery	Multiband colour	0.5
Rangiroa	1962	Aerial photograph	Single band grey	0.58
	2016	Satellite imagery	Multiband colour	1.00

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Declarations

Conflict of interest The authors declare no competing interests.

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