Organic and metallic contaminants in reef fish from the South Pacific region, with emphasis on New Caledonia

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Abstract

Approximately 1000 coral reef fish were collected from 27 sites across 8 island countries and territories in the Pacific: Fiji, French Polynesia, Kiribati, New Caledonia, Samoa, Vanuatu, Wallis and Futuna, and Rapa Nui. Around 400 of the fish were obtained in New Caledonia, making it the most extensively sampled. Fish were analysed for their concentrations of 36 pesticides and metallic trace elements. Through measuring contaminant concentrations at the individual fish level and integrating these results at the fish community level, our study identifies potential factors explaining their prevalence in fish communities at the New Caledonian and South Pacific regional scales. Spatial patterns varied significantly, depending on the compound, with concentrations in fish flesh generally higher in the central and southwest Pacific than in the eastern part of the Pacific basin. These patterns were influenced by biological, environmental, anthropogenic and biogeographical factors such as fish size, sea surface temperature, gross domestic product per capita, and land area. In New Caledonia, fish size also emerged as the most important correlate of contaminant concentrations. Monthly rainfall was the second most important variable for pesticides, whereas the reef surface area was the second variable explaining metallic element concentrations. Our results enhance our understanding of the extent of contamination in the South Pacific, while underscoring the urgent need for long-term and large-scale spatial monitoring of diverse contaminants in this region.

Introduction

Most South Pacific islands are geographically isolated from continental margins, and have limited industrial and agricultural production, and relatively small human populations (Fey et al. 2019; Nalley et al. 2023). In these islands, human communities have traditionally relied on harvesting marine resources, mainly for the consumption of coastal and pelagic fish (Pratchett et al. 2011; Johnson et al. 2017; Bell et al. 2018). Per capita fish consumption in the Pacific is among the highest in the world, ranging from 50 kg to 110 kg per person per year (Bell et al. 2009). Coral reef and other coastal fish are often favoured in subsistence fishing practices over pelagic species due to the accessibility of their stocks. Moreover, coral reef fish represent a major source of protein, essential vitamins and minerals, as well as essential omega-3 and omega-6 polyunsaturated fatty acids (Wang et al. 2018; Hicks et al. 2019; Byrd et al. 2021). Despite their high nutritional value, however, coral reef fish may also represent a major vector of several chemical contaminants, which raises concerns due to their high consumption in the Pacific (Marti-Cid et al. 2007; Storelli 2008; Sabino et al. 2022). Among the most critical environmental disturbances is pollution driven by human activities, particularly urban and industrial expansion, which has led to widespread contamination of coastal ecosystems through runoff (e.g. rivers, coastal erosion, waste discharge), posing a significant risk to both ecosystems and human health. Three major classes of contaminants that are of particular concern include polychlorobiphenyls (PCBs), pesticides (which are classified as persistent organic pollutants, or POPs), and metallic trace elements (MTEs) (Fey et al. 2019). These ubiquitous contaminants can be toxic even at low concentrations; are resistant to degradation; and may be dispersed over long distances (Phillips 1995). Furthermore, they have the potential to bioaccumulate over the course of an individual organism's life and/or to bioamplify along trophic networks, posing potential health risks to consumers (e.g. De Gieter and Baeyens 2005; Baeyens et al. 2005).

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Pollutants and contaminants in New Caledonia

The coral reefs of New Caledonia are particularly interesting because the archipelago is a major global biodiversity hotspot (Myers et al. 2000). Listed as a UNESCO World Heritage site in 2008, New Caledonia hosts the world's largest lagoon and the second-largest coral barrier reef after Australia's Great Barrier Reef. Moreover, the lagoon contains one-third of the world's most remote reefs, largely untouched by human activity or pollution (Januchowski-Hartley et al. 2020). Despite their importance as a major natural and fishery resource, however, the coral reefs of New Caledonia are under increasing anthropogenic pressure, primarily due to mining activities, agricultural development, industrialisation, and recent and rapid urbanisation. New Caledonian soils are naturally rich in cobalt (Co), chromium (Cr), iron (Fe), manganese (Mn), and mostly nickel (Ni). New Caledonia possesses 10% of the world's nickel resources (Losfeld et al. 2015), and numerous open-pit mines have been in operation since the late 19th century. Intensive mining activities, combined with natural soil erosion caused by tropical rainfall, has resulted in significant sediment deposition in, (Ouillon et al. 2010; Garcin et al. 2013) and contamination of, coastal waters (Hédouin et al. 2009). In addition, the expansion of industrial infrastructure and urban development, and the use of phytosanitary products in agriculture, exacerbate the contamination of terrestrial and coastal marine ecosystems. Thus, New Caledonia represents an interesting case for understanding the impact of urban, agricultural and industrial contamination on coral reef ecosystems.

Methodology

Combining a large-scale approach in the South Pacific with a more detailed approach in New Caledonia appears particularly appropriate for highlighting general and local trends in coral reef fish contamination. In New Caledonia, more fish dorsal muscle samples were collected, spanning from coastal areas to the barrier reef, and across an isolation gradient, from urbanised and industrialised zones to geographically remote locations with minimal to no human influence.

Detailed information on sampling, analytical procedures and data modelling are found in Wejieme et al. (2025a, b), and readers are encouraged to look at these works for further technical details. In brief, two kinds of data were combined for the modelling: concentration of contaminants in individual fish on sampled sites, and underwater surveys of fish communities at the Pacific regional scale. Machine learning models[8] were used to combine both datasets to derive contamination estimated at the regional level (see Wejieme et al. 2025a for details). In the two following sections, we have chosen to present only some of our results, both at the regional scale for the case of pesticides with a focus on glyphosate (Wejieme et al. 2025a), and at the local New Caledonian scale for the case of MTEs, with a focus on nickel (Wejieme et al. 2025b).

Contamination at the Pacific scale

At all sites and among both herbivorous and carnivorous fish, glyphosate was by far the most abundant pesticide, reaching 85% of all pesticides, with an average concentration slightly less than 90 nanograms per gram (ng/g, dry weight). Other pesticides showed very low concentrations (e.g. pp-DDT, isodrin; elements often under the detection limit) to intermediate values (e.g. pp-DDD, β-endosulfan). The most significant drivers of glyphosate concentrations in coral reef fish were individual fish size (explaining ~42% of variation) and the nearby human population size (~17% of variation). If the importance of these drivers is also evidenced for several other pesticides, as well as for some metallic elements, the overall pesticide concentrations (i.e. glyphosate and 20 other measured pesticides combined) also depend, in decreasing dependence, on sea surface temperature, land area within 3 km, and anthropogenic drivers such as areas dedicated to agriculture, pesticide trade and/or GDP.

For the observed glyphosate concentrations, which were not modelled, there are significant interspecific variations, but also inter-individual variations, without a clear link to the biological characteristics of the species. For example, the minimal observed value of glyphosate was 8.2 ± 2.7 ng/g (n=5) for *Acanthurus nigrofuscus* (an herbivorous surgeonfish) (Fig.1) in New Caledonia, and the maximum was 670 ± 240 ng/g (n=19) for *Stegastes nigricans* (a territorial, omnivorous damselfish) (Fig.1) also in New Caledonia.

Accounting for both elements' concentrations in fish and species distributions across the region, modelled (i.e. extrapolation at the fish communities' level to unsampled species and sites) concentrations of contaminants, whether for MTEs or pesticides, were generally higher in the central and southwest Pacific, and lower in the eastern part of the Pacific basin, which encompasses regions such as French Polynesia, Cook Islands and Rapa Nui (Wejieme et al. 2025a). For example, among MTEs, the highest mercury (Hg) concentrations were found in New Caledonia (4.4 µg/g), and the lowest in the Tuamotu Islands in French

8 Machine learning models are computer programs that are trained using data sets to find patterns in, provide estimations or make predictions based on new data.

Figure 1. *Acanthurus nigrofuscus* (top) and *Stegastes nigricans* (bottom).
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Polynesia (0.7 µg/g), Solomon Islands (0.8 µg/g) and Tuvalu (0.9 µg/g). Moderately low concentrations were found in Cook Islands (1.2 µg/g), Niue (1.3 µg/g) and the Marshall Islands (1.7 µg/g). Despite these large differences across the Pacific, the concentration of Hg in coral reef fish in Pacific islands was generally low. Thus, despite its known toxicity, our results for Hg do not appear to pose a serious threat in Pacific islands from a human consumption and health perspective.

The areas with the highest predicted concentrations of glyphosate in coral reef fish were mainly from high islands from the central Pacific (Fig. 2), such as Fiji (198 ng/g) and Tonga (178 ng/g). Elevated concentrations were also found in the western part of the Pacific basin, including Solomon Islands (~160 ng/g), Papua New Guinea (~140 ng/g), New Caledonia (~130 ng/g), and even in some eastern parts, such as Tahiti in French Polynesia (~120 ng/g). Conversely, areas with the lowest glyphosate concentrations did not show a clear spatial pattern, for example Niue (~55 ng/g), Nauru and Cook Islands (~30 ng/g in both cases). Pesticides are used to hinder the development of various pests such as insects and weeds, and can enter water bodies through various pathways, including runoff from non-irrigated agricultural land and the drainage system (Stehle and

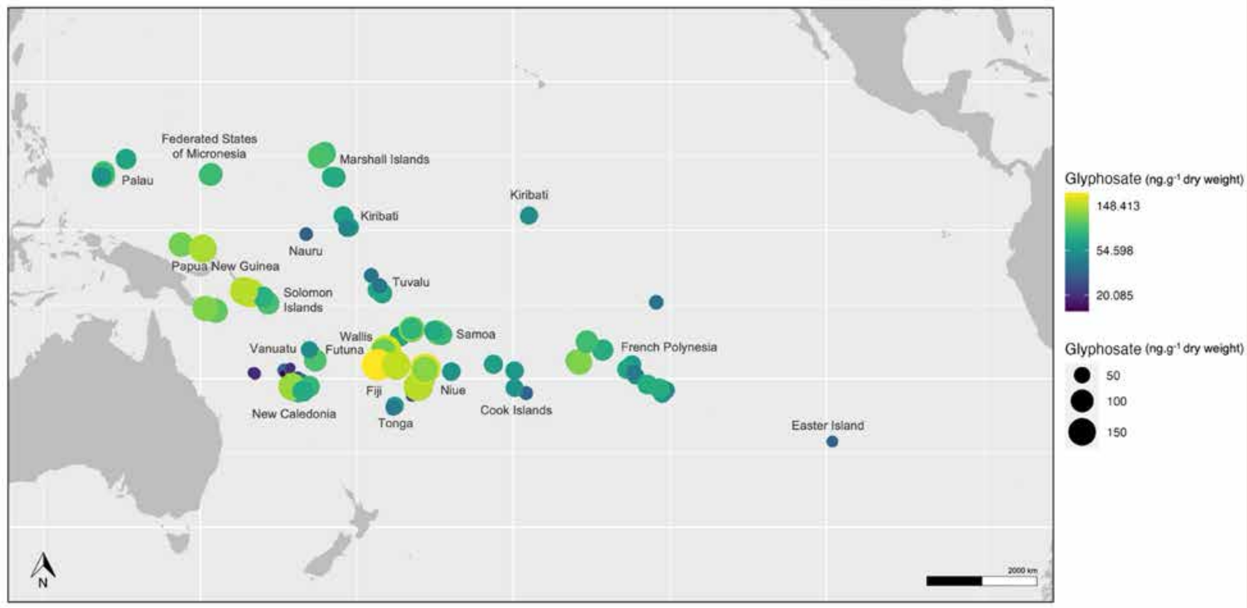

Figure 2. Predicted (i.e. modelled) glyphosate concentrations (in ng/g dry weight) in Pacific coral reef fish using environmental, biological, biogeographical and anthropogenic variables as drivers.

Schulz 2015). In the case of glyphosate, fish size was the most important variable explaining its concentration. This is one of the most controversial pesticides to date, suggesting a bioaccumulation process and perhaps even biomagnification. Anthropogenic drivers also played significant roles in explaining glyphosate concentrations, suggesting both a general and possibly illegal use of glyphosate and not just for agricultural purposes (e.g. also for public and private gardens), as well as its ability to disperse over such a spatial scale. The use of agricultural pesticides in Oceania has seen significant growth, more than tripling between 1990 and 2021 (FAO 2023a, b). Although the quantity of pesticides used per hectare of cultivated land (1.66 kg/ha) in relation to the value of agricultural production (0.83 kg/USD 1000) is relatively low, the quantity per capita is notably high, reaching 1.30 kg/person. Although the values of contaminant concentrations that we found were below health risk thresholds, the fact remains that we have observed and modelled the distribution of various MTEs and pesticides over a large part of the Pacific, which is concerning and clearly needs further investigation.

The New Caledonian case

Overall, the average concentrations of MTEs ranged from very low (e.g. silver [Ag], cadmium [Cd]; often below the detection limit) to high concentrations (e.g. arsenic [As], iron [Fe], and zinc [Zn]) up to ~140 mg/g (dry weight) for Fe in the isolated Entrecasteaux atolls in the far north.

Regarding pesticides, glyphosate was by far the most abundant, accounting for ~90% of all detected pesticides, with an average concentration of ~140 ng/g. However, this dominance should be interpreted with caution, as glyphosate was analysed only in a small subset of fish.

As for the large-scale (i.e. Pacific-wide) approach, individual fish size was the most influential driver influencing MTE (all elements combined) concentrations, explaining ~27% of variation in New Caledonia. The reef area within a 3 km buffer zone ranked second (~15%), followed by soil lithology (~11%). But for some 'mining elements' such as Cr and Ni, the mining registry[9] was the most important factor explaining concentrations in fish, more so than the role of individual size for both Cr and Ni.

For the Ni concentrations observed (i.e. not modelled), and similarly to the glyphosate at the Pacific scale, there are significant interspecific variations, but also inter-individual variations, without a clear link to the biological characteristics of the species (e.g. diet) or local environment (evidence for a source of pollution). For example, the minimum measured amount of Ni was 0.07 ± 0.04 mg/g (n=4) for *Plectropomus laevis* (a carnivorous grouper) (Fig. 3) in La Foa, on the west coast of New Caledonia's Grande Terre, and the maximum was 31.6 ± 39.5 mg/g (n=3) for *Zanclus cornutus* (an omnivore) (Fig. 3) in the far north of Entrecasteaux atolls.

Modelled (i.e. extrapolation at the fish communities' level to unsampled species and sites) concentrations of

9 The mining registry aggregates data from the active mining concessions, exploration permits, and technical reserves, and provides detailed information on mining titles, owners, concession boundaries, surface and location, as well as other aspects related to mining activity.

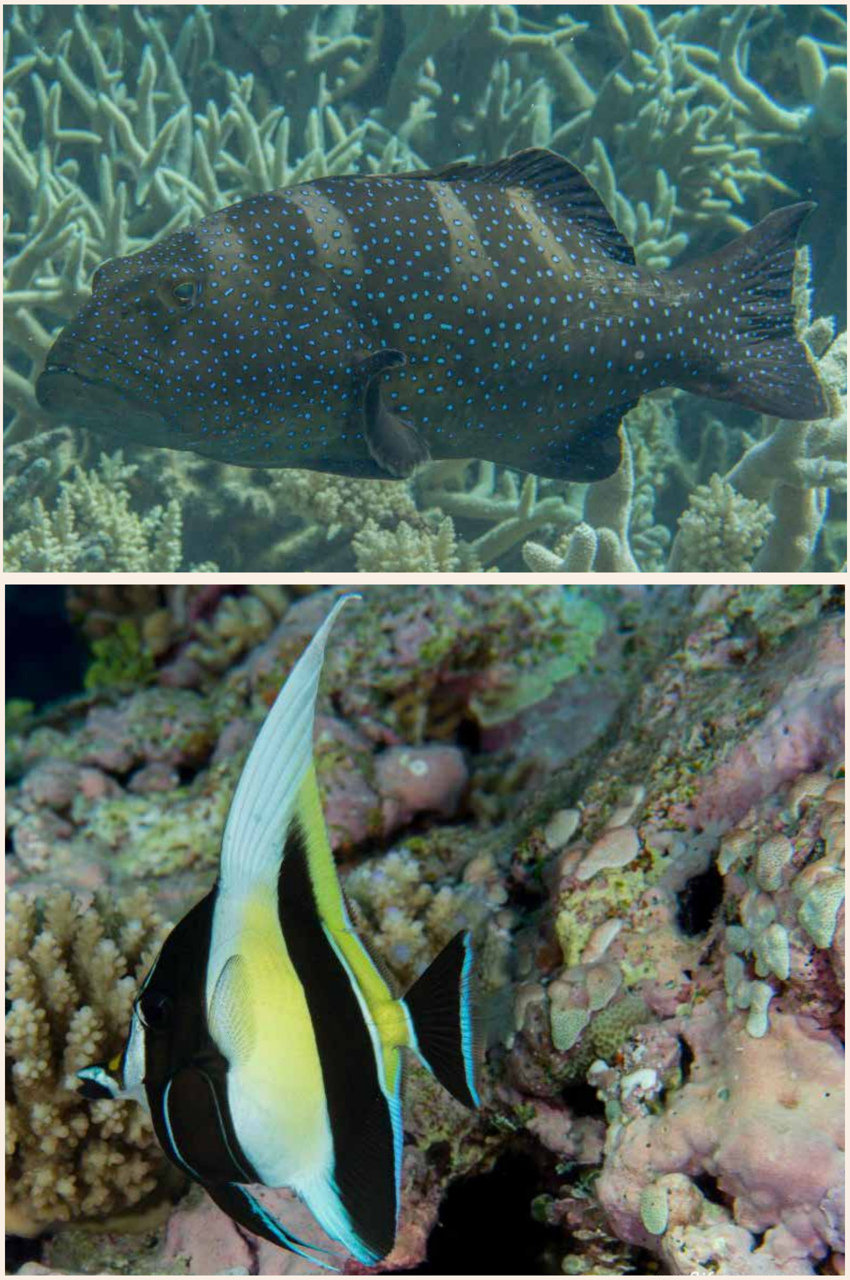

Figure 3. *Plectropomus laevis* (top) and *Zanclus cornutus* (bottom).
Images: © Rick Stuart-Smith, Reef Life Survey

contaminants, whether for MTEs or POPs, were generally higher in the southwest lagoon, and lower in the other zones. However, some local exceptions were found. For instance, the modelled distribution of Ni contamination reveals maximum concentrations at Pouebo on the northeast coast (Fig. 4) (11.3 µg/g), Noumea in the south (9.6 µg/g), Thio on the east coast (9.4 µg/g) and Moindou on the central west coast (7.9 µg/g). The lowest concentrations were assessed in the remote Petrie Reef (1.9 µg/g) and "Récif des Français" northwest of New Caledonia (0.8 µg/g). For most contaminants, a gradient from the coast to the barrier reef was found, with higher average modelled concentrations on coastal reefs than on barrier reefs, such as for Ni (Fig. 2).

While contaminants' concentrations were generally low, our results reveal consistent anthropogenic influences, particularly for mining-associated elements such as Cr and Ni, with some areas exhibiting higher concentrations linked to local environmental, biological, biogeographical and anthropomorphic variables. Modelled concentrations of most contaminants tend to be higher in the southwestern part of New Caledonia's lagoon, while they are generally lower in areas farther away from urbanised

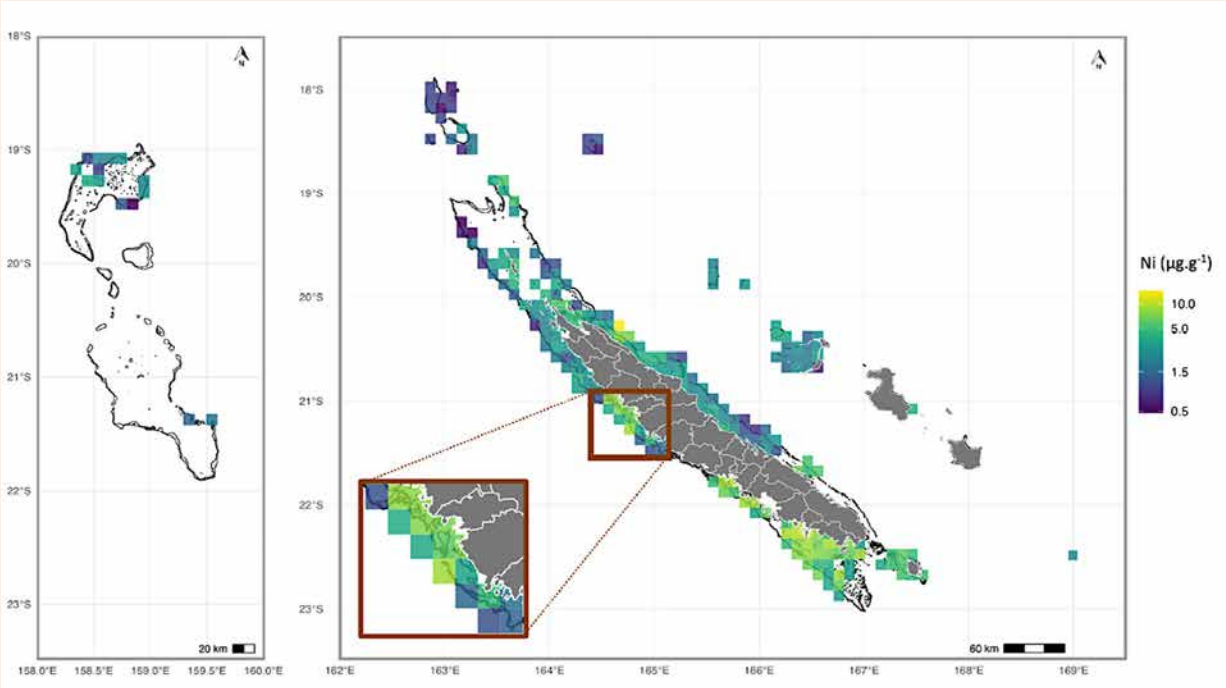

Figure 4. Predicted (i.e. modelled) nickel concentration (in mg/g dry weight) in New Caledonian coral reef fish using environmental, biological, biogeographical and anthropogenic variables as drivers. The left inset map shows the Chesterfield reefs, within New Caledonia's exclusive economic zone. The small inset map below the map of New Caledonia shows an example of coast to barrier reef differences.

zones, including geographically isolated areas without any significant human influence. This finding unsurprisingly underscores and reinforces the impact of human activities on marine ecosystem contamination. The case of Ni needs particular attention due to its crucial importance for the New Caledonian economy. The soils of New Caledonia are naturally rich in Ni but mining exploitation of this element has long been recognised as a major cause of environmental degradation on the island (Bird et al. 1984). Mining activities, initiated in 1880, intensified with the mechanisation of extractive industries in the 1950s, and have since led to the significant expansion of denuded areas, including mining sites, exploration zones, and mining roads, as well as an increase in mining waste (Iltis 1992). Mining activities currently represent the second-largest source of soil contamination by MTEs worldwide (Younger 2001). Soils undergo significant leaching of MTEs due to their high concentration, erosion sensitivity, and low water retention capacity, leading to prolonged persistence of these elements in the aquatic environment (Singh et al. 2005; Nouri et al. 2008; Ashraf et al. 2011). This contamination is particularly significant in New Caledonia with Ni resources concentrated in rocky formations that cover ~30% of the subsoil (Isnard et al. 2016). Mining activities, combined with natural soil erosion due to rainfall, contribute to high concentrations of Ni but also Co, Cr and Mn in New Caledonian coastal waters (Wejieme et al. 2025b).

Concluding remarks

Despite the necessary precautions that must be taken when extrapolating our results to areas and species not investigated here (see Wejieme et al. 2025a), this work represents the first robust study on coral reef fish contamination at the regional scale, with a more detailed focus on New Caledonia, both for MTEs and POPs. The works of Wejieme et al. (2025a, b) thus represent major steps forward by providing an unprecedented assessment of coral reef fish community contamination at the regional and local (New Caledonia) scales, allowing us to identify the most exposed areas and the key factors influencing contaminant distribution. Our study reveals the widespread presence of MTEs and POPs in coral reef fish in the Pacific Islands region, with concentrations generally ranging from low to moderate. However, even if contaminants were at relatively low concentrations in fish, thereby limiting the current health risk for humans, their interaction can potentially increase their hazardous effects (Fey et al. 2019). This aspect should be further explored in the future. Notably, even remote and uninhabited areas showed contamination, highlighting the potential role of atmospheric and oceanic transport. Our results underscore the need for targeted management strategies to mitigate pollution impacts and safeguard marine ecosystems. Integrating these insights into conservation efforts presents a promising pathway for more effective environmental management of Pacific coral reefs in the face of increasing anthropogenic pressures.

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