Deep-Sea Research II ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at SciVerse ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Anthropogenic biogeochemical impacts on coral reefs in the Pacific Islands—An overview

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ARTICLE INFO

Keywords:
Biogeochemical impacts
Coral reefs
Pacific Islands
Human activities

ABSTRACT

Coral reefs dominate the coastal environment in many Pacific Islands, being present as atolls, coral platforms, barrier and fringing reefs. With ever increasing populations and migration of people to the coast, the anthropogenic impacts on these reefs have increased dramatically in the last 30 years. While research on these impacts has been limited, some important progress has been made. This paper reviews some of the completed studies, with outcomes from American Samoa, Fiji, French Polynesia, Guam, Saipan, New Caledonia and Tonga presented. These studies indicate that the most significant impacts have been found in locations close to major urban centres or industrial and mining activities. The extent of impact varies from place to place with minimal impacts in the more isolated and less industrialised communities. Common anthropogenic impacts are contamination caused by inadequate sewage treatment, erosion from adjacent agricultural and urban expansion activities, poor waste management, eutrophication, inefficient and/or inappropriate pesticide use and hydrocarbons use, storage and management. The outcomes include contaminated sediments (trace metals, pesticides, PCBs, hydrocarbons) with some impacts on resident biota. In some instances, the edible quality of local fisheries resources has been significantly compromised.

Even in locations with small populations, increasing populations and poor economic conditions have resulted in noticeable effects on the adjacent fringing reefs, including dramatic algal proliferation and declines in fish numbers resulting from increasing nutrient discharges and increased herbivore fish catches. Recovery measures including fishing bans and alternative fishing practices have been implemented to address these issues in some areas.

1. Introduction

1.1. South pacific region/coral reefs

Coral reefs are a dominant feature of the Pacific Islands. They are unique to tropical and certain subtropical oceans since the reef-building organisms require water temperatures in excess of 22 °C. Coral structures include atolls [essentially reefs of variable thickness built up by corals (and other organisms) resting on a volcanic base] and reef platforms having an elevation generally less than 5 m above mean sea level. In the central and south Pacific, some countries consist entirely of low elevation coral structures, e.g., Tuvalu, others contain atoll groups, e.g., the Cook Islands, and some countries consist of mainly volcanic islands with a few isolated atolls, e.g., Ontong Java in the Solomon Islands. Fringing and barrier reefs are common around 'high' islands (those having a volcanic or other non-calcareous features rising to elevations above 50 m (Cumberland, 1956).

Most major population centres in the Pacific Islands have evolved in coastal locations that afforded some form of protection against storms where shipping is the main mode of transport. Many of these centres are located in bays protected by barrier reefs, by islands or by riverine deltas. However, since these geomorphological features also have the effect of limiting, to some extent, mixing of near-shore and open ocean waters (Viles and Spenser, 1995), they tend also to facilitate contaminant accumulation in the near-shore waters with which most people commonly interact.

This paper reviews various studies that have been carried out on investigation of the impact of anthropogenic activities on coral reefs and related water bodies in the Pacific Islands (Fig. 1). It is not meant to be comprehensive, rather it uses case studies to

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0967-0645/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.dsr2.2013.02.014

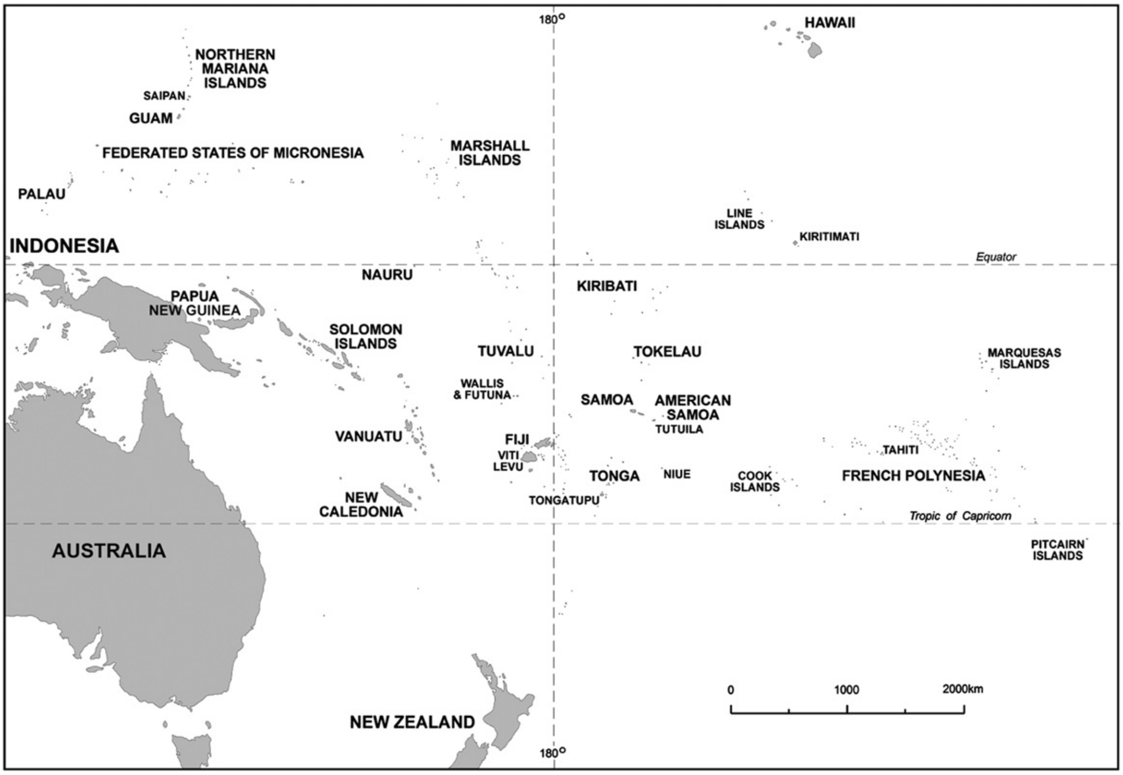

Fig. 1. The South Pacific Region.

illustrate the main issues that are currently of greatest concern. The sites referred to are, for the most part, major urban centres (Saipan, Guam, Suva, Fanga'uta), although one site (Coral Coast, Fiji) examines impacts of a growing population in a rural area, while another (Tutuila) compares urban and isolated rural areas around one island. Some important work completed in the French territories in the Pacific is also discussed.

2. Case studies

2.1. Western Coast, Saipan, CNMI

Saipan (15°12′N, 145°43′E)(Fig. 1) is the major population centre of the Commonwealth of the Northern Mariana Islands (CNMI). The resident population is nearing 60,000, and there is a substantial influx of tourists, mainly from SE Asia and Japan. Saipan has been a shipping centre in Micronesia for about 400 years, but major increases in shipping activity have taken place since the 1940s during and following World War II. Tanapag Lagoon is a typical high-island barrier reef lagoon bordering the western shore of central Saipan, and adjacent to the main port area on that island. It is about 9 km long and 3 km at its widest point, and covers an area of about 13 km^2. Large expanses of patch reef, interspersed among sand and rubble, provide for a diversity of shallow water habitats and harbour rich assemblages of flora and fauna (Amesbury et al., 1979; Doty and Marsh, 1977). In addition to its ecological significance, the Lagoon supports a variety of recreational activities, and local people traditionally harvest many fisheries resources for food.

Over the last quarter century, the southern, nearshore fringing reef section of Tanapag Lagoon has become heavily impacted by human activities. Primary sources of anthropogenic disturbances between Muchot Point and Flores Point, a distance of approximately 3 km, include a commercial port (Saipan Harbour) and bulk fuel facility, a sewer outfall, a municipal waste dump, and two small-boat marinas. The area is also heavily inundated by stormwater runoff during prolonged periods of wet weather. Several studies have examined the impacts on these human activities on the sediments and biota in the Lagoon (e.g., Denton et al., 2006a, 2009).

Sediments have been sampled adjacent to the shoreline and further offshore, up to 2250 m. Analysis for a range of trace metals showed that offshore sediments were not significantly contaminated, but there was evidence of accumulation of anthropogenic metals, especially Cu, Pb, Zn, and to a lesser degree Cd, Ni, Cr, Hg, in nearshore waters around the old municipal dump and adjacent to boat marinas. In general, metal concentrations decreased on moving seaward and/or away from identified sources of metal contamination. PCB analyses showed all offshore sites were relatively free of contamination (concentrations < 1 ng/g); relatively high values were found adjacent to the old dump (16.6 ng/g) and in the area around the port (8–11 ng/g). Detailed studies of individual congener profiles indicated that Aroclor 1260 and possibly 1254 were the main PCB sources in Tanapag Lagoon, probably leaked from electrical transformers. PAH concentrations were also very low in offshore sites (< 0.5 µg/g), but nearshore sites showed higher values (e.g., 2.4 µg/g near the port, 3.2 µg/g near the old dump). The PAH profiles were dominated by higher molar mass compounds, but the actual source (e.g., combustion or aged petrochemical spills) could not be confirmed. Overall, the sediments in Tanapag Lagoon were considered relatively clean apart from problems around the main port, the old waste dump site and the small boat marina (Denton et al., 2006a).

In two related studies, dominant biotic representatives were sampled from various sites within the Lagoon (Denton et al., 2009, 2010) and analysed for trace metals. Preference was given to species traditionally harvested as food by local residents or considered to have bioindicator potential. Many organisms (e.g., algae, seagrass, bivalves) were found to be enriched in some trace

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metals (Cr, Cu, Pb, Zn) at one or more contaminated sites identified at the southern end of the lagoon (dry dock, old dump, boat marina). From a human health perspective only lead and copper were identified as elements of concern and only in bivalves from the old dump area (Denton et al., 2009). Mercury levels in axial muscle of over 300 popular table fish (65 species) from the Lagoon proper were all well below the current US Food and Drug Administration guideline of 1.0 μg/g wet weight (USFDA, 1998) with 84% of the overall catch yielding values below 0.01 μg/g wet weight (Denton et al., 2010). While Hg concentrations were somewhat elevated in representatives from around the port area and municipal dump, the highest levels encountered were generally found in specimens captured some distance from obvious sources of pollution known at the time.

A follow-up investigation traced the mercury back to an old incinerator site at the Commonwealth Health Center, Saipan's only public hospital (Denton et al., 2011). The incinerator was used for the destruction of medical wastes from the hospital and other medical clinics on island. It was eventually shut down for multiple violations of the Clean Air Act in 2006 (US EPA, 2005), just 18 months after the fish survey had been completed. Mercury levels in certain species from the impacted area were measured again in 2007 (Denton et al., 2011) and found to be substantially lower than those recorded during the earlier survey

2.2. Pago Gay, Guam

Guam (13°28′N, 144°45′E) has been dramatically impacted by human activities since World War II and has undergone considerable economic growth and urban expansion over the last 30 years. It also has a thriving tourist industry that currently attracts over one million visitors annually. Today, the island is poised on the brink of another economic boom associated with the relocation of 18,000 US marines and their dependants to Guam from Okinawa, Japan, in 2014. The population, which presently stands at around 185,000, is expected to approach 250,000 by 2020 as a direct result of this military build-up. Environmental problems currently experienced on the island are largely associated with solid and hazardous waste disposal, storm water runoff, and the treatment and disposal of domestic and industrial wastewaters.

Guam has been the major shipping centre in Micronesia for about 400 years. Trace metals, PCBs and PAHs in sediments and biota have been investigated in the island's major port and smaller boat harbours (Denton et al., 2005, 2006b,c,d,e). Relatively few studies, however, have examined the impacts of Guam's growth and development on the coastal environment. This is particularly so on the western side of central Guam where the greatest intensity of commercial and industrial activities exists. Pago Bay on the eastern side of the island has been subjected to far less direct human intervention, although the possible impact on its fisheries of a poorly managed landfill, in the nearby village of Ordot, has been of long-standing concern. The landfill is located in the catchment of the Lonfit/Pago River system that drains into the southern half of Pago Bay, and has been releasing heavy metal enriched leachate into the watershed for over 60 years

Recent studies have identified mild to moderate heavy metal contamination in Lonfit River surface waters and sediments immediately adjacent to the landfill but no measurable contamination in either water or bottom sediment matrices further downstream (Denton et al., 2007, 2008). Likewise, there were no abnormal metal levels in aquatic organisms anywhere within the watershed itself (Denton et al., 2007), or in the Bay (Denton and Morrison, 2009). It was concluded that soluble metals released from the landfill during dry weather (low flow conditions) are rapidly sequestered by aluminium and iron oxyhydroxides present in streams and subsequently deposited in the beds of tributaries and at the confluence of the Longfit River. In subsequent heavy rains, the contaminant laden sediments are scoured and carried away from the river to offshore deepwater beyond the reef front, via the Pago Bay channel, a flooded river valley. This natural cleansing process prevents metals discharged from the landfill from accumulating in the watershed and in the Bay. Any residual contamination from the landfill that accumulates in and around the river mouth is periodically flushed from the system by major storms (typhoons) that frequently impact the eastern side of the island. While these studies clearly demonstrated that the Lonfit/Pago River system and Pago Bay are not permanent sinks for metal contaminants leached from the landfill, they did reveal some mild Pb enrichment in sediments and bivalves near an old military firing range at the southern end of the Bay. Marginally elevated levels of Zn and Hg were also identified in both media near sources of ground water intrusion, septic-tank leachate and urban runoff at the northern end of the fringing reef (Denton and Morrison, 2009). Nevertheless, the impacts of these metal sources on the edible quality of aquatic resources in these areas were considered inconsequential.

2.3. Suva Lagoon, Fiji

Suva, the capital of the Fiji Islands, located on the southeast corner of Viti Levu at 18°06′S, 178°30′E (Fig. 1), is the major commercial, shipping and industrial centre in the South Pacific islands. The city has rapidly expanded in the last 50 years with significant population growth (50,000– > 200,000) in the catchment of the adjacent lagoon over the last 30 years. Suva Lagoon is located within a well-developed barrier reef system and is made up of two parts—Laucala Bay on the east and Suva Harbour on the west. Significant small industry development around the shoreline has occurred in recent years including ship-building and repair, metal manufacturing, food processing and packaging, oil storage and handling, in addition to activities associated with the operations of Suva port. Studies on pollution in Suva lagoon have been undertaken by various researchers over the past 30 years, and the major findings are summarised in Morrison et al. (2006).

Nutrient data for Suva Lagoon span a period of about 25 years. The data sets are not consistent in terms of methods used and the parameters measured (total element versus reactive components). In some instances quality control procedures have also been questioned. Nevertheless, some valid conclusions can be drawn from the available data. For example, dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations are often high compared to open ocean values, with reported values ranging from 50 to 450 μmol/L for DIN and 8–12 μmol/L for DIP. Values for both parameters vary with tide, season, amount of runoff (wet weather) and source. Singh et al. (2009) considered sewage discharges to be a major source of nutrients in dry periods, while rivers were considered to be the dominant source during wet weather when high flows carry sewage material from small treatment plants and septic overflows as well as diffuse land-based source materials. At sites near the barrier reef, nutrient concentrations are about DIN < 1 μmol/L, DIP ~0.1 μmol/L, values close to those in the open ocean. There is evidence, however, that despite these low average concentrations near the barrier reef, algal growth has been increasing in recent years (including Sargassum that was not found in the 1970s and 1980s) (L.F. Zann, personal communication).

Sediment trace metal studies in Suva Lagoon have identified two major sources—riverine non-carbonate materials and reef derived carbonate materials (Fernandez et al., 2006; Morrison et al., 2001) with the carbonate influence increasing on moving towards the barrier reef. On top of these variations, concentrations of metals of concern for health are generally higher in nearshore waters (Morrison et al., 2001), especially around 'hot spot areas', such as, the Lami dump, closed in 2006 (Naidu and Morrison, 1994), Lami industrial area (Gangaiya et al., 2001), and the Walu Bay industrial area (Pb, Sb and Zn: Naidu and Morrison, 1994). Suva Lagoon sediments have been reported to have significant TBT contamination, including the highest reported TBT values in the world (92–360 μg/g, Maata and Koshy, 2001; Stewart and de Mora, 1992). However, monobutyl tin (MBT)/dibutyl tin (DBT) ratios are generally below 0.1, indicating that little or no additions of TBT in recent years (Maata and Koshy, 2001).

Some data exist for organic contaminant in Suva lagoon, with emphasis organochlorines and PCBs. The highest concentrations found in Suva lagoon sediments (up to 14 ng/g DDT and metabolites, 8 ng/g dieldrin and 30 ng/g total PCBs) are relatively low compared with other parts of the world (Morrison et al., 1996). Organochlorine pesticides were used until 1980, for mosquito control in the city and for agricultural purposes in adjacent farming areas. PCBs were components of transformers used in the old electricity generating facility adjacent to Nabukalou Creek in the centre of Suva city. There is no data for any organochlorinated compounds in shellfish or other biota from Suva lagoon.

The disposal and untreated sewage into Suva Lagoon presents a constant challenge to environmental managers from a human health perspective. Typically, the hygienic quality of recreational waters is monitored using faecal indicator bacteria. In Fiji, it is recommended that faecal coliform (FC) counts should be less that 400 colony forming units (CFUs) per 100 mL water and less that 2 FC/g flesh wet weight for shellfish comsumption. Data for Suva lagoon show faecal coliform (FC) densities ranging from 0 to $>$10,000 CFUs/100 mL with sites around Kinoya, Nubukalou Creek and Lami showing the highest values and minimal change over the period 1978–2005 (Morrison et al., 2006). FC contents in mangrove oysters (*Crassostrea mordax*) taken from Suva Lagoon range from 0.7 to 24,000 FC/g (Morrison et al., 2006). The potential health risks associated with eating raw shellfish from Suva lagoon can be high, although less so if shellfish are depurated, marinated or cooked appropriately.

Overall, the contaminant data from Suva lagoon is indicative of relatively low levels of contamination by trace metals, persistent organic pollutants, apart from a few localised hotspots. Identifying problem areas is unfortunately hampered by the absence of any management plan for the Lagoon or its catchment, due to the fact that while legislative/administrative powers for pollution control are distributed among several agencies, interagency interactions are often limited.

2.4. Coral Coast, Fiji

The Coral Coast region is located on the south coast of Viti Levu (Fig. 1), the main island of the Fiji group. It has a stretch of about 60 km of coastline where fringing reefs lie adjacent to a high island. Traditionally, its population consisted of a number of coastal villages with small populations and subsistence lifestyles. Since the 1960s, this has been one of the fastest developing regions in Fiji, mainly as a result of tourism activities. This has led to increases in village populations with more intensive fishing and reef gleaning and more intensive root crop farming, chicken and pig production. These changes have contributed to increased nutrient concentrations (up to $>$10 μmol/L average DIN, $>$1 μmol/L average DIP) in coastal waters (Tamata, 2007) sourced from sewage and animal sources particularly during wet weather (confirmed by stable isotope studies). For example, at a Valase site undergoing development, dry weather concentrations averaged relatively low values (nitrate 0.07 μmol/L, phosphate 0.10 μmol/L), while average wet weather concentrations were much higher (nitrate 6.06 μmol/L and phosphate 0.37 μmol/L). The herbivore fish population was decreased due to overfishing and this resulted in extensive growth of Sargassum and some filamentous algal species that led to corals in some parts of the reef system being overwhelmed (Tamata, 2007).

Alarmed by these changes in their reef systems in terms of food supply and tourism, local communities solicited assistance from local scientists. The scientists carried out investigations, including grazing exclusion trials that clearly revealed the impact of herbivory in Sargassum control. This finding led to the establishment of locally managed marine protected areas under local community control with *tabu* (bans) on fishing, in certain areas, especially for herbivorous species. The local community has also developed strategies for improved management of nutrient sources, including improved solid waste management practices, replanting of buffer strips of vegetation along river banks, relocating piggeries away from river banks, and the construction of wetlands for treatment of wastewater (Tamata, 2007)

Another important outcome is the active participation of local community members in monitoring fisheries stocks through the catch per unit effort (CPUE) information recording, which is then passed on to the scientists for analysis. Community-coordinated re-afforestation of catchment areas and mangrove replanting along the coastline have emerged along the Coral Coast. In these initiatives scientists play a facilitation and advisory role to the communities.

2.5. Fanga'uta Lagoon, Tonga

Fanga'uta Lagoon is the major coastal water body of Tongatapu (Fig. 1), the main island of the Tonga group located at 21°12′S, 175°12′W. The island of Tongatapu is a raised coral platform covered with soils derived from volcanic ash and corals. Fanga'uta Lagoon's catchment has a resident population of about 40,000 people, including a significant portion of the capital, Nuku'alofa. The lagoon has suffered many anthropogenic impacts including substantial coastal modification, vegetation and mangrove removal, surface runoff from roads and farmland, sedimentation, polluted groundwater inputs, overfishing, waste dumping, and a general lack of appreciation of ecological benefits of the system (Kaly and Morrison, 2005).

Anthropogenic impact investigations were carried out in 1983–1984, 1988–1989, 1992, and 1998–2001. Bottom sediments were mixtures of coralline and volcanic-soil derived materials (Morrison and Brown, 2003). There was no evidence of any trace metal contamination of sediments or shellfish (Morrison and Brown, 2003). Low levels of organochlorine pesticides and PCBs were found in 1992 in lagoon sediments (Harrison et al., 1996) close to a known illegal dumping site. In a complementary study in 2000, low concentrations of chlorfluazuron and flusilazole found in sediments, probably originating from use in nearby agricultural fields (Chen et al., 2000).

In the late 1990s, a significant decline in seagrass cover, with increased epiphyte growth relative to the 1980s, was observed (e.g., see Kaly, 1998). In 1992, the lagoon water was transparent with coral and seagrass communities visible to depths of at least 2 m. In 1993, after a period of occasional algal blooms, the lagoon suddenly and permanently turned green, and has stayed that way until the present time. *Caulerpa* and *Halimeda* algal species increased in abundance and increased turbidity was measured. Fish and shellfish catches, in terms of both total mass and sizes of individuals declined, with the continuing (often illegal) removal of mangroves for housing believed to be contributing to major habitat loss for juvenile fish. Increasing urbanisation, some of which occurred in cleared mangrove areas, along with poor

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building standards control were considered contributing problems, e.g., inappropriate septic tank location was contributing to nutrient runoff and eutrophication in the lagoon.

Based on the outcomes of scientific studies and community consultations, a full management plan for the lagoon was prepared (Prescott et al., 2001), but this has not yet been implemented to any extent due to financial constraints.

2.6. Tutuila, American Samoa

Tutuila, located at 14°17′S, 170°41′W (Fig. 1), is the main island of the American Samoa group and is the site of Pago Pago, the capital and main port. Tutuila is globally a remote location, distanced from any major global sources of pollution, unless pollutants have been transported atmospherically over long distances (Peshut, 2009). At this remote location, trace elements in sediments would be expected to reflect naturally occurring background conditions for volcanic high island sites not influenced by anthropogenic impacts. Tutuila is a rugged volcanic island dominated by olivine basalts (Stearns, 1944; Staudigel et al., 2006). The coastline (200 km long) is extremely irregular with numerous small open bays, which lack bars or barrier reefs, and are subject to the sea conditions of exposed coasts. Pago Pago Harbour is one of the few protected areas and maintains most of its natural shoreline, except for some filled areas near the main port, which have been developed for commercial shipping activities and two fish canneries. Tutuila has no estuaries and most of the coastline is rocky with abrupt elevation changes immediately above breaking waves. Surface waters are limited to a few dozen perennial streams, most of which have short, steep reaches, and typically low base flows. Coral reefs are the dominant marine habitat for Tutuila near-shore waters, with 60% of the coastline occupied by narrow fringing reefs.

As part of a larger ecological investigation (Peshut, 2009), levels of sedimentary trace metals (As, Cd, Cu, Fe, Hg, Mn, Ni, P, Sr, Zn) were examined at six study sites on Tutuila. Five of these sites were located in near pristine coastal areas while one (Loa) was located in Pago Pago Harbour, the most human-impacted zone in Tutuila. Sediment samples from all sites were dominated with carbonates (aragonite and calcite) with minor contributions of quartz, kaolinite, illite and chlorite). There was no evidence of trace element contamination at any sites (Morrison et al., 2010). Indeed, the observed variations could all be explained by assuming the sediments were predominantly of coralline origin, mixed with varying amounts of basalt-derived material. Strong correlations (coefficients >0.8) were found between the main basaltic elements (Al, Fe, Mn, K, Ti, Si, P) all of which showed strong negative correlations with Ca. Two notable features among the basalt derived elements were: (1) Cu showed effectively no strong correlations with any other element examined (not even Zn, as has been found at other similar Pacific locations—Denton et al., 2005; Morrison et al., 1997); (2) As showed strong correlations with nine other elements (positive with Al, Fe, K, Mn, Ti, Zn, P, Si and negative with Ca) which again is different from some other Pacific sites, where As usually shows few correlations.

Surprisingly, the elemental data for the Loa samples taken in Pago Pago Harbour showed no clear differences from the other sites, with the exception of Hg (total) which were 3–9 times higher than elsewhere in the study area. Inter-site differences for MeHg were smaller, however, with variation factors of 1–3 (Peshut, 2009). While there are limited sources of pollution in Tutuila, some activities in the harbour are potential sources of contamination (ship repair and maintenance, cargo and fuel spillage, fish cannery effluents, illegal dumping). The absence of any metal pollution indication (at Loa) is inconsistent with results from Suva, Fiji (Naidu and Morrison, 1994), Apra Harbour, Guam (Denton et al., 2005) and Tanapag Lagoon, Saipan, CNMI (Denton et al., 2009), where significant metal pollution of harbour sediments has been observed. The lack of metal contamination at Loa may simply relate to the lack of industrial activity, as compared to other small Pacific Island harbour sites where economic development is significantly greater relative to Tutuila.

2.7. French Territories in the South Pacific

The French Pacific territories exhibit a wide diversity of island types including continental islands (New Caledonia), archipelagos (French Polynesia) and isolated atolls (Gardes and Salvat, 2008). The majority of reefs in these territories are considered healthy (Salvat et al., 2008), but increasing anthropogenic activity, e.g., mining, fisheries, tourism, is leading to significant impacts in some areas, especially near urban centres. Nuclear experiments carried out in French Polynesia from 1966 to 1996 are also of interest in terms of environmental impacts.

2.7.1. New Caledonia

Nickel mining and the related metal-processing industry constitute both a threat to coastal and marine biodiversity in New Caledonia (22°15′S, 166°26′E), and the driving force supporting the economy of the country (David et al., 2010; Pascal et al., 2007). Economic development and environmental preservation remain two contradictory processes and significant efforts have been made to identify the unique diversity present in New Caledonia for the addition of a large part of its reefs to the UNESCO World Heritage List (Andrefouet and Wantiez, 2010). This is particularly important on the eve of major anthropogenic perturbation linked to the development of a new nickel mine on the island's north-western coast (Chabanet et al., 2010).

In New Caledonia, the major studies on anthropogenic biogeochemical impacts have recently emerged from a large interdisciplinary group funded by the 'Programme National Environment Cotier' (PNEC) from 2000 to 2008. This program aimed to continue the study of the impact of anthropogenic activities on the functioning of the southwest lagoon of New Caledonia initiated by the 'ECOTROPE' program in 1996. Recent studies have extended the preliminary research on the indicators of human-induced physical disturbance (Chabanet et al., 2005) and particle inputs on coral reefs (Fishez et al., 2005) by developing a framework and the tools for anthropogenic biogeochemical impact studies. Physical processes studied include coastal erosion (Dumas et al., 2010), the circulation and transport of suspended sediment (Ouillon et al., 2010), and the biogeochemical typology and temporal variability of the lagoon waters of New Caledonia (Fishez et al., 2010).

Trace metal contamination and bioaccumulation mechanisms have been studied for the brown alga *Lobophora variegata* (Metian et al., 2008a), the tropical scallop *Comptopallium radula* (Metian et al., 2008b), the tropical oysters *Isognomon isognomon* and *Malleus regula* (Hedoin et al., 2010a, 2010b), the clam *Gafrarium tumidum* (Hedoin et al., 2010b), and the butterfly fish *Chaetodon speculum* (Labonne et al., 2008). With the exception of the butterfly fish, all species were useful bioindicator species for surveying metal contamination. Transplantation studies revealed, however, that due to the very efficient metal retention capacity of the shellfish, particular attention to the origin of bioindicators was required if used in low contamination areas (Hedoin et al., 2011).

A study of coral assemblages from fringing reefs to oceanic barrier reefs in the southwestern lagoon of New Caledonia addressed the specific relationships between the spatial patterns and recruitment processes of coral and water and sediment quality, in particular, the presence of nutrients and trace metals (Adjeroud et al., 2010). Surprisingly, results revealed no clear cross-shelf gradient in richness, abundance, and percent cover for all coral genera from most to least disturbed areas. Instead, the composition and abundance of coral assemblages appeared correlated to the substrate type rather than water quality or the metal concentrations in sediments. The relationship between the distribution of juveniles and adults predicted relatively limited replenishment capacities in these reefs. Consequently, the results of this study illustrated the importance of management and conservation efforts along fringing reefs within bays, where anthropogenic activities and subsequent pollution are important.

The southwest lagoon of New Caledonia was also the site of a study of the spatial and temporal distribution of zooplanktonic prey of fish larvae, i.e., small crustaceans and small copepods, in relation to environmental conditions. Results indicated that the volume and total density of zooplankton were correlated to increasing chlorophyll *a* and particulate organic matter (POM) concentration along a gradient from the lagoon to the bays (Carassou et al., 2010). Differences in assemblage composition between the lagoon and the bays were influenced by wind speed, surface temperature, chlorophyll *a* and POM. The high abundance of zooplanktonic prey in bays suggested that sheltered bays, most influenced by terrigenous inputs, were likely to provide the best feeding conditions and therefore should receive more attention in management and conservation efforts.

2.7.2. French Polynesia

Studies on pesticide impacts on the coral reefs of Tahiti (see Fig. 1) and Moorea have been summarised by Roche et al. (2011). As pesticide contamination has been identified as one of the main stressors of coral reefs and is a potential major threat to coral reef ecosystems (Fabricius et al., 2005; Ramade and Roche, 2006), the French section of the International Coral Reef Initiative (ICRI), the IFRECOR, launched a survey on pesticide residues in key organisms from the coral reef trophic webs in several French Territories, including Tahiti and Moorea.

On each island, surveys were carried out on two inshore coral reef sites using control (traditional agriculture) versus impacted (intensive agriculture) sites in the wet and dry seasons. Key species included the green coralline alga *Halimeda crassata*, the clam *Tridacna maxima*, scleractinian coral species *Fungia spp*., the holothurian *Halodeima atra*, and fishes *Chlorurus sordidus* and *Epinephelus merra*. Organochlorine pesticides including chlordecone and herbicides from chloracetic acid, triazine and substituted urea families were studied.

The results first demonstrated the presence of chlordecone in all key organisms at all sites, despite this material never having been officially used in French Polynesia (Roche et al., 2011). Additionally, chlordecone average concentrations were higher in organisms from reef sites located off the rural traditional agriculture areas than the ones from intensive agriculture areas, suggesting unregulated widespread use of pesticides in traditional subsistence agriculture (Roche et al., 2011). Second, herbicides such as atrazine, simazine, alachlor, metoalchlore, and terbutylazine were also detected in reef organisms from most sites. In some instances, recorded concentrations were sufficient to induce significant photosynthesis inhibition in Symbodinium (Jones and Kerswell, 2003). Finally, while average organochlorine insecticide levels were generally low, a few samples showed $\sum$DDT concentrations as high as 1080 ng/g in the liver of grouper and parrotfish from Tahiti and $\sum$DDT 393 ng/g in holothuria from Moorea (Roche et al., 2011).

Overall, the contamination of coral reef communities by organochlorine pesticides, insecticides and some herbicides, although widespread, did not correlate with the agriculture intensity in the cultivated coastal areas of Tahiti and Moorea. Some insecticide concentrations observed were among the highest recorded in coral reef communities to date (Deichmann et al., 1972; Glynn et al., 1995; Von Westerhagen and Klumpp, 1995). One of the major results of this study was the unexpected ubiquitous detection of chlordecone in all sites and all organisms sampled. Due to the extreme persistence of this pesticide, the contamination of coral reef communities raises concern for public health as some of the organisms sampled are currently used for consumption by local populations and the risks of long-term exposures are unknown.

2.7.3. Mururoa atoll

Between 1966 and 1996, France conducted 193 nuclear experiments on Mururoa (21°53′S, 138°52′W) and Fangataufa (22°16′S, 138°47′W) atolls in French Polynesia, including 41 in the atmosphere, 137 underground and 15 security tests without nuclear detonation. Since 1966, comprehensive monitoring of radiological conditions has been carried out in order to assess environmental impacts and radiation exposure rates of local populations in the five archipelagos of French Polynesia. This was completed in 1996 by an independent study by the International Atomic Energy Agency (IAEA) following the end of the nuclear experiments. The radiation levels detected in 1996 are now used as a benchmark for the radioactive contamination of the local environment.

Large landslides occurred in Mururoa atoll as a result of nuclear tests in 1979 (Flouzat, 2011). While limited to the south-west of Mururoa atoll, these events were responsible for generating large swells that submerged part of the neighbouring island of Tureia, located 105 km northeast of Mururoa at 20°50′S, 138°32′W. As a result of concerns raised by Tureia residents, a numeric model was used in 2011 to determine the hydrologic effects of collapses of portions of the coral structure (volume <50–670 million m^3) of the northern part of Mururoa atoll (Flouzat, 2011). Simulation results indicated that the predicted hydrologic effects from the collapse of small portions of the coral structure would remain localised to Mururoa atoll without any consequences for neighbouring islands. The collapse of a large portion of the northern part of Mururoa atoll, however, was predicted to generate a wave 20 m high within a 500 m radius, travelling at 600 km/h and with a swell length of several kilometers. At Mururoa, the sea water level would reach 2–5 m in populated areas of the island. Furthermore, the wave induced by the collapse of Mururoa atoll would be expected to reach the south of Tureia atoll in approximately 10 min and the north of that island in 13 min (Flouzat, 2011). The south and western parts of Tureia atoll would be expected to be submerged and face destruction equivalent to cyclonic waves. In the northern part of the Tureia, areas less than 3 m above sea level would be partially to totally submerged. The majority of the population lives more than 3 m above sea level in the northern part of the atoll, but for people living less than 3 m above sea level, this potential event would pose a severe threat.

To put the risks from atoll collapse into perspective, coral reefs in French Polynesia, as in most places in Pacific, are subjected to major natural disturbances responsible for damaging the physical and biological structure of coral reefs and their communities. Between 1980 and 2005, French Polynesia has been affected by 15 cyclones, seven bleaching events, several *Acanthaster planci* outbreaks and dystrophic crises (Salvat et al., 2008). Out of the 13 islands monitored between 1992 and 2002, only two were unaffected by these natural disturbances and the impact of coral bleaching and cyclones varied greatly at local and regional scales

Please cite this article as: Morrison, R.J., et al., Anthropogenic biogeochemical impacts on coral reefs in the Pacific Islands—An overview. Deep-Sea Res. II (2013), http://dx.doi.org/10.1016/j.dsr2.2013.02.014

(Adjeroud et al., 2005). Cyclones are usually the most destructive and were directly responsible for the destruction of 80% and 40% of coral reefs on the outer-slope of Tikehau and Takapoto islands, respectively (Harmelin-Vivien and Laboute, 1983; Laboute, 1985; Salvat and Wilkinson, 2011). Similarly, historical records and seismic monitoring activities show that French Polynesia is also frequently affected by tsunamis of various amplitudes, the Marquesas Islands and Rurutu Island being the most at risk (Schindele et al., 2006; Sladen et al., 2007). The 1946 Aleutian and 1960 Chilean events were the last two ocean-wide tsunamis that generated significant damage in most archipelagos and no earthquake of magnitude higher than 8.4 occurred since 1965. Only one tsunami was generated by a local source, in 1999, due to a cliff landslide on Fatu Hiva Island and caused serious damage in adjacent Omoa Bay (Hebert et al., 2002).

3. Conclusions

The studies described above illustrate that anthropogenic biogeochemical impacts in the Pacific Islands are significant, but most of the problems occur near major population centres or industrial zones. Other issues have been identified but not discussed here—microbial contamination, sedimentation, dynamite fishing and reef blasting for boat passages, cyanide and other toxic chemical fishing. While a large proportion of the early investigations were completed by outsiders/visitors, there is now a body of well-trained local scientists to carry on this work. Unfortunately, many of these professionals remain limited by inadequacies of funding and facilities. The development of sound coastal management and resource protection policies lags behind the more developed countries of the world despite improved interactions between scientists and community leaders, regulators and environmental managers.

Acknowledgments

The authors would like to acknowledge the assistance of Dominique Ponton, Bernard Salvat and Rene Galzin with the provision of recent materials on the French Territories in the Pacific.

References

Adjeroud, M., Chancerelle, Y., Schrimm, M., Perez, T., Lecchini, D., Galzin, R., Salvat, B., 2005. Detecting the effects of natural disturbances on coral assemblages in French Polynesia: a decade survey at multiple scales. Aquat. Living Resour. 18, 111–123.

Adjeroud, M., Fernandez, J.M., Carroll, A.G., Harrison, P.L., Penin, L., 2010. Spatial patterns and recruitment processes of coral assemblages among contrasting environmental conditions in the southwestern lagoon of New Caledonia. Mar. Pollut. Bull. 61, 375–386.

Amesbury, S.S., Lassuy, D.R., Myers, R.F., Vaughan Tyndzik, 1979. A Survey of the Fish Resources of Saipan Lagoon. University of Guam Marine Laboratory Technical Report No. 52, Mangilao, Guam, 58 pp.

Andrefouet, S., Wantiez, L., 2010. Characterizing the diversity of coral reef habitats and fish communities found in a UNESCO World Heritage Site: the strategy developed for lagoons of New Caledonia. Mar. Pollut. Bull 61, 612–620.

Carassou, L., Le Borgne, R., Rolland, E., Ponton, D., 2010. Spatial and temporal distribution of zooplankton related to the environmental conditions in the coral reef lagoon of New Caledonia, Southwest Pacific. Mar. Pollut. Bull. 61, 367–374.

Chabanet, P., Adjeroud, M., Andrefouet, S., Bozec, Y.-M., Ferraris, J., Garcìa-Charton, J.-A., Schrimm, M., 2005. Human-induced physical disturbances and their indicators on coral reef habitats: a multi-scale approach. Aquat. Living Resour. 18, 215–230.

Chabanet, P., Guillemot, N., Kulbicki, M., Vigliola, L., Sarramegna, S., 2010. Baseline study of the spatio-temporal patterns of reef fish assemblages prior to a major mining project in New Caledonia (South Pacific). Mar. Pollut. Bull. 61, 598–611.

Chen, Z., Kookana, R., Naidu, R., Morrison, R.J. 2000. Pesticide Residues in Sediment and Soil Samples form the Kingdom of Tonga: A Preliminary Study. Report from CSIRO Land and Water, Glen Osmond, South Australia, to the Department of Environment, Nuku'alofa, Tonga.

Cumberland, K.B., 1956. Southwest Pacific: A Geography of Australia, New Zealand and their Pacific Island Neighbours. McGraw-Hill, New York, pp. 8–12.

David, G., Leopold, M., Dumas, P.S., Ferraris, J., Herrenschmidt, J.B., Fontenelle, G., 2010. Integrated coastal zone management perspectives to ensure the sustainability of coral reefs in New Caledonia. Mar. Pollut. Bull. 61, 323–334.

Deichmann, W.B., Cubit, D.A., MacDonald, W.E., Beasley, A.G., 1972. Organochlorine pesticides in the tissue of the Great barracuda (*Sphyraena barracuda*). Arch. Toxikol. 29, 287–309.

Denton, G.R.W., Concepcion, L.P., Wood, H.R., Morrison, R.J., 2005. Trace metals in sediments of four harbours in Guam. Mar. Pollut. Bull. 50, 1133–1141.

Denton, G.R.W., Bearden, B.G., Concepcion, P., Wood, H.R., Morrison, R.J., 2006a. Contaminant assessment of surface sediments from Tanapag Lagoon, Saipan, Commonwealth of the Northern Marianas Islands. Mar. Pollut. Bull. 52, 703–710.

Denton, G.R.W., Concepcion, L.P., Wood, H.R., Morrison, R.J., 2006b. Polychlorinated biphenyls (PCBs) in marine organisms from four harbours in Guam. Mar. Pollut. Bull. 52, 214–225.

Denton, G.R.W., Concepcion, L.P., Wood, H.R., Morrison, R.J., 2006c. Polychlorinated biphenyls (PCBs) in sediments from four harbours in Guam. Mar. Pollut. Bull. 52, 710–718.

Denton, G.R.W., Concepcion, L.P., Wood, H.R., Morrison, R.J., 2006d. Polycyclic aromatic hydrocarbons (PAHs) in small island coastal environments: a case study from harbours in Guam, Micronesia. Mar. Pollut. Bull. 52, 1090–1117.

Denton, G.R.W., Concepcion, L.P., Wood, H.R., Morrison, R.J., 2006e. Trace metals in marine organisms from four harbours in Guam. Mar. Pollut. Bull. 52, 1786–1804.

Denton, G.R.W., M.C. Olsen, Y. Wen, 2007. Solid waste disposal on Guam: impact of an unsanitary landfill on the heavy metal status of adjacent community representatives. In: Wang, Y., Li, S., Huang, P., Yuzhong, Y., Ying, A., Sun, X. (Eds.) *Progress in Environmental Science and Technology*, vol. 1, pp. 1169–1176. Proceedings of the 2007 International Symposium on Environmental Science and Technology, Beijing, China, November 13–16, 2007, Science Press, USA. Available at: 〈http://www.weriguam.org/pdf/pollution-monitoring-and-assessment-program/recent-publications/8.pdf〉.

Denton, G.R.W., Golabi, M.H., Iyekar, C., Wood, H.R., Conception, L.P., Wen, Y. 2008. Impact of Ordot dump on water quality of the Lonfit River Basin in Central Guam. 2. Aqueous chemical and biological contaminants. *Micronesica* 40: 149–167. Available at: 〈http://www.weriguam.org/pdf/pollution-monitoring-and-assessment-program/recent-publications/7.pdf〉.

Denton, G.R.W., Morrison, R.J., 2009. The impact of a landfill on the trace metal status of Pago Bay, Guam. Mar. Pollut. Bull. 58, 150–162.

Denton, G.R.W., Morrison, R.J., Bearden, B.G., Houk, P., Starmer, J.A., Wood, H.R., 2009. Impact of a coastal landfill in a tropical lagoon on trace metal concentrations in surrounding marine biota: a case study from Saipan, Commonwealth of the Northern Mariana Islands (CNMI). Mar. Pollut. Bull. 58, 424–431.

Denton, G.R.W., M.S. Trianni. M.C. Tenorio, 2010. Impact of Land-Based Sources of Pollution on Coastal Water Quality of Saipan, Commonwealth of the Northern Mariana Islands (CNMI): Arsenic, Mercury and PCBs in Popular Table Fish from Saipan Lagoon. Technical Report No. 130. Water and Environmental Research Institute, University of Guam, 98 pp. Available at: 〈http://www.weriguam.org/reports/item/impact-of-land-based-sources-of-pollution-on-coastal-water-quality-of-saipan-commonwealth-of-the-northern-mariana〉.

Denton, G.R.W., Trianni, M.S., Bearden, B.G., Houk, P.C., Starmer, J.A., 2011. Impact of a medical waste incinerator on mercury levels in lagoon fish from a small tropical island in the Western Pacific. J. Toxicol. Environ. Health: Part A 74, 1–5.

Doty, J.E., Marsh, J.A. Jr. 1977. Marine Survey of Tanapag, Saipan: The Power Barge "Impedance". University of Guam Marine Laboratory Technical Report No. 33, Mangilao, Guam, 147 pp.

Dumas, P., Printemps, J., Mangeas, M., Luneau, G., 2010. Developing erosion models for integrated coastal zone management: a case study of The New Caledonia west coast. Mar. Pollut. Bull. 61, 519–529.

U.S. EPA, 2005. EPA Orders Medical Waste Incinerator in Saipan to Close. U.S. Environmental Protection Agency. Available at: 〈http://yosemite.epa.gov/opa/admpress.nsf/665323ad33bb55ee852572a000657b63/78d76fafe47b8823852570d8005e178d!OpenDocument〉.

Fabricius, K., De'ath, G., McCook, L., Turak, E., Williams, D.L., 2005. Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef. Mar. Pollut. Bull. 51, 384–398.

Fernandez, J.-M., Cadiou, G., Moreton, B., Legendre, R., Fishez, R., Badie, C., 2006. Overview of the metal distribution in surface deposits and sedimentary records in Suva Lagoon. In: Morrison, R.J., Aalbersberg, W.G.L. (Eds.), At the Crossroads—Science and Management of Suva Lagoon. University of the South Pacific, Suva, Fiji, pp. 106–119.

Fishez, R., Adjeroud, M., Bozec, Y.-M., Breau, L., Chancerelle, Y., Chevillon, C., Douillet, P., Fernandez, J.-M., Frouin, P., Kulbicki, M., Moreton, B., Ouillon, S., Payri, C., Perez, T., Sasal, P., Thébault, J., 2005. A review of selected indicators of particle, nutrient and metal inputs in coral reef lagoon systems. Aquat. Living Resour. 18, 125–147.

Fishez, R., Chifflet, S., Douillet, P., Gerard, P., Gutierrez, F., Jouon, A., Ouillon, S., Grenz, C., 2010. Biogeochemical typology and temporal variability of lagoon

waters in a coral reef ecosystem subject to terrigeneous and anthropogenic inputs (New Caledonia). Mar. Pollut. Bull. 61, 309–322.
Flouzat, M., 2011. Surveillance geomechanique de l'atoll de Mururoa: conséquences pour l'atoll de Tureia d'un glissement de terrain de grande ampleur a Mururoa. Rapport du Commissariat a l'Énergie Atomique et aux Energies Alternatives, Arpajon cedex, 13 p.
Gangaiya, P., Tabudravu, J., South, R., Sotheeswaran, S., 2001. Heavy metal contamination of the Lami coastal environment, Fiji. S. Pac. J. Natural Sci. 19, 24–29.
Gardes, L., Salvat, B., 2008. Coral reefs in French Overseas Territories: a retrospective study of changes in health conditions of these diversified and vulnerable ecosystems recorded by monitoring networks. Rev. Ecol. (Terre Vie) 63, 23–32.
Glynn, P.W., Rumbold, D.G., Snedaker, S.C., 1995. Organochlorine pesticides residues in marine sediments and biota from the northern Florida reef tract. Mar. Pollut. Bull. 30, 384–398.
Harmelin-Vivien, M., Laboute, P., 1983. Preliminary data on underwater effects of cyclones on the outer slopes of Tikehau Island (Tuamotu, French Polynesia) and its fish fauna. Int. Soc. Reef Studies, Nice (Abstracts), 27.
Harrison, N.L., Gangaiya, P., Morrison, R.J., 1996. Organochlorines in the coastal marine environment of Vanuatu and Tonga. Mar. Pollut. Bull. 32, 575–579.
Hebert, H., Piatanesi, A., Heinrich, P., Schindele, F., Okal, E.A., 2002. Numerical modeling of the September 13, 1999 landslide and tsunami on Fatu Hiva Island (French Polynesia). Geophys. Res. Lett. 29 (10), 1484, http://dx.doi.org/10.1029/2001GL013774.
Hedoin, L., Metian, M., Teyssie, J.L., Fichez, R., Warnau, M., 2010a. Delineation of heavy metal contamination pathways (seawater, food and sediment) in tropical oysters from New Caledonia using radiotracer techniques. Mar. Pollut. Bull. 61, 542–553.
Hedoin, L., Metian, M., Lacoue-Labarthe, T., Fichez, R., Teyssie, J.L., Bustamante, P., Warnau, M., 2010b. Influence of food on the assimilation of selected metals in tropical bivalves from the New Caledonia lagoon: qualitative and quantitative aspects. Mar. Pollut. Bull. 61, 568–575.
Hedoin., L., Pringault, O., Bustamante, P., Fichez, R., Warnau, M., 2011. Validation of two tropical marine bivalves as bioindicators of mining contamination in the New Caledonia lagoon: field transplantation experiments. Water. Res 45, 483–496.
Jones, R.J., Kerswell, A.P., 2003. Phytotoxicity of photosystem II (PSII) herbicides to coral. Mar. Ecol. Prog. Ser. 261, 149–151.
Kaly, U.L., 1998. Monitoring Training and Lagoon Baseline Survey using the Fanga'uta Lagoon as a Case Study. Working Paper 16. Tonga Environmental Management and Planning Project, Department of Environment, Tonga, 77 p.
Kaly, U., Morrison, R.J., 2005. Four years in the life of Fanga'uta Lagoon, Tonga. In: Kay, R., Alder, J. (Eds.), Coastal Planning and Management, 2nd ed. Taylor & Francis Group, Oxford, pp. 317–318.
Labonne, M., Morize, E., Kulbicki, M., Ponton, D., Marec, L., 2008. Otolith chemical signature and growth of *Chaetodon speculum* in coastal areas of New Caledonia. Est. Coast. Shelf Sci. 78, 493–504.
Laboute, P. 1985. Evaluation of damage done by cyclones of 1982–1983 to the outer slopes of the Tikehau and Takapoto atolls (*Tuamotu Archipelago*). In: Proceedings of the Fifth International Coral Reef Congress, Tahiti, vol. 3, pp. 323–329.
Maata, M., Koshy, K., 2001. A study on tributyltin contamination of marine sediments in the major ports of Fiji. S. Pacific J. Natural Sci. 19, 1–4.
Metian, M., Giron, E., Borne, V., Hedouin, L., Teyssie, J.L., Warnau, M., 2008a. The brown alga *Lobophora variegata*, a bioindicator species for surveying metal contamination in tropical marine environments. J. Exp. Mar. Biol. Ecol. 362, 49–54.
Metian, M., Bustamante, P., Hedouin, L., Warnau, M., 2008b. Accumulation of nine metals and one metalloid in the tropical scallop *Comptopallium radula* from coral reefs in New Caledonia. Env. Pollut. 152, 543–552.
Morrison, R.J., Harrison, N.L., Gangaiya, P., 1996. Organochlorines in the estuarine and coastal marine environment of the Fiji Islands. Environ. Pollut. 93, 159–167.
Morrison, R.J., Gangaiya, P., Naqasima, M.R., Naidu, R., 1997. Trace metal studies in the Great Astrolabe Lagoon, Fiji, a pristine marine environment. Mar. Pollut. Bull 34, 353–356.
Morrison, R.J., Narayan, S.P., Gangaiya, P., 2001. Trace metal studies in Laucala Bay, Suva, Fiji. Mar. Pollut. Bull. 42, 397–404.
Morrison, R.J., Brown, P.L., 2003. Trace metals in Fanga'uta Lagoon, Kingdom of Tonga. Mar. Pollut. Bull. 46, 139–152.
Morrison, R.J., Gangaiya, P., Garimella, S., Singh, S.K., Maata, M., Chandra, A., 2006. Contamination of Suva Lagoon. In: Morrison, R.J., Aalbersberg, W.G.L. (Eds.), At the Crossroads—Science and Management of Suva Lagoon. University of the South Pacific, Suva, Fiji, pp. 146–155.
Morrison, R.J., Peshut, P.J., Lasorsa, B.K., 2010. Elemental composition and mineralogical characteristics of coastal marine sediments of Tutuila, American Samoa. Mar. Pollut. Bull. 60, 925–930.
Naidu, S.D., Morrison, R.J., 1994. Contamination of Suva Harbour, Fiji. Mar. Poll. Bull. 29, 126–130.
Ouillon, S., Douillet, P., Lefebvre, J.P., Le Gendre, R., Jouon, A., Bonneton, P., Fernandez, J.-M., Chevillon, C., Magand, O., Lefèvre, J., Le Hir, P., Laganier, R., Dumas, F., Marchesiello, P., Bel Madani, A., Andréfouët, S., Panché, J.-Y., Fichez, R., 2010. Circulation and suspended sediment transport in a coral reef lagoon: the south-west lagoon of New Caledonia. Mar. Pollut. Bull. 61, 269–296.
Pascal, M., Richer de Forges, B., Le Guyader, H., Simberloff, D., 2007. Mining and other threats to the New Caledonia biodiversity hotspot. Cons. Biol. 22, 498–499.
Peshut, P.J., 2009. Mercury Investigations in Remote Oceania: Wet Deposition and Bio-accumulation on Tutuila Island. PhD Thesis, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, Australia, 246 p.
Prescott, N., Kaly, U.L., Taufa, P., Matoto, L., Lepa, S.T., Niu, L., Faletau, T., Hibberd, J.K., Palaki, A., 2001. Environmental Management Plan for the Fanga'uta Lagoon System. Department of Environment, Tonga 50 p.
Ramade, F., Roche, H., 2006. Effets des polluants sur les écosystèmes récifaux. Rev. Ecol. (Terre Vie) 61, 3–33.
Roche, H., Salvat, B., Ramade, F., 2011. Assessment of the pesticides pollution of coral reefs communities from French Polynesia. Rev. Ecol. (Terre Vie) **66**, 3–10.
Salvat, B., Wilkinson, C., 2011. Cyclones and climate change in the South Pacific. Rev. Ecol. (Terre Vie) 66, 105–115.
Salvat, B., Aubanel, A., Adjeroud, M., Bouisset, P., Calmet, D., Chancerelle, Y., Cochennec, N., Davies, N., Fougerousse, A., Galzin, R., Lagouy, E., Lo, C., Monier, C., Ponsonnet, C., Remoissenet, G., Schneider, D., Stein, A., Tatarata, M., Villiers., L., 2008. Le suivi de l'etat des recifs coralliens de Polynesie Francaise et leur recente evolution. Rev. Ecol. (Terre Vie) 63, 103–135.
Schindele, F., Hebert, H., Reymond, D., Sladen, A., 2006. L'aléa tsunami en Polynésie française: synthese des observations et des mesures. C. R. Geosci. 338, 1133–1140.
Singh, S., Aalbersberg, W.G.L., Morrison, R.J., 2009. Nutrient pollution in Laucala Bay, Fiji. Water Air Soil Pollut. 204, 363–372.
Sladen, A., Hebert, H., Schindele, F., Reymond, D., 2007. L'alea tsunami en Polynésie française: apports de la simulation numerique. C. R. Geosci. 339, 303–316.
Staudigel, H., Hart, S.R., Pile, A., Bailey, B.E., Baker, E.T., Brooke, S., Connelly, D.P., Haucke, L., German, C.R., Hudson, I., Jones, D., Koppers, A.A.P., Konter, J., Lee, R., Pietsh, T.W., Tebo, B.M., Templeton, A.S., Zierenberg, R., Young, C.M., 2006. Vailulu'u seamount, Samoa: life and death on an active submarine volcano. Proc. Natl. Acad. Sci. U.S.A. 103, 6448–6453.
Stearns, H.T., 1944. Geology of the Samoan Islands. Bull. Geol. Soc. Am. 55, 1279–1332.
Stewart, C., de Mora, S.J., 1992. Elevated tri(n-butyl)tin concentrations in shellfish and sediments from Suva Harbour, Fiji. Appl. Organometal. Chem. 6, 507–512.
Tamata, U.B., 2007. Studies of Nutrient Variability and the Consequences for Benthic Communities on the Coral Coast Fringing Reefs, Fiji. PhD Thesis, University of Wollongong, Wollongong, Australia, 277 p +appendices.
USFDA, 1998. Appendix 5: FDA and EPA guidance levels. In: Fish and Fisheries Products Hazards and Controls Guide: Environmental Chemical Contaminants and Pesticides (A Chemical Hazard). U.S. Food & Drug Administration, Center for Food Safety and Applied Nutrition, Washington, D.C.. (Chapter 9).
Viles, H., Spenser, T., 1995. Coastal Problems. Edward Arnold, London 350 p.
Von Westerhagen, H., Klumpp, D.W., 1995. Xenobiotics in fish from Australian tropical coastal waters, including Great Barrier Reef. Mar. Pollut. Bull. 51, 876–881.

Please cite this article as: Morrison, R.J., et al., Anthropogenic biogeochemical impacts on coral reefs in the Pacific Islands—An overview. Deep-Sea Res. II (2013), http://dx.doi.org/10.1016/j.dsr2.2013.02.014