19 Aspects of Biology and Ecological Functioning of Coral Reefs in Guam and the Commonwealth of the Northern Mariana Islands

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19.1 Introduction

The Mariana Islands are a chain of 16 volcanic peaks stretching over a distance of approximately 2,500 km from 13° to 21° N latitude and centered at 145° E longitude (Fig. 19.1). Politically, the area is divided into two jurisdictions, Guam and the Commonwealth of the Northern Mariana Islands. Guam is a US territory located at 13°28′ N, 144°45′ E and is the southernmost island in the Mariana Archipelago. It is the largest island in Micronesia, with an area of 560 km^2 and a maximum elevation of approximately 405 m above sea level. The northern portion of the island is relatively flat and consists primarily of uplifted limestone. The southern half of the island is primarily volcanic, with more topographic relief, and large areas of highly erodible lateritic soils (Siegrist and Randall 1992; Chapter 18, Riegl et al.). The island possesses fringing reefs, patch reefs, submerged reefs, offshore banks, and a barrier reef surrounding the southern shores. The reef margin varies in width, from tens of meters along some of the windward areas, to well over 100 m. The combined area of coral reefs and lagoons is approximately 69 km^2 in nearshore waters between 0–3 nmi, and an additional 110 km^2 in federal waters greater than 3 nmi offshore (Hunter 1995).

Guam was ceded to the US in 1898 following the Spanish-American War, and was placed under the administration of the Department of the Navy, with a US appointed governor. It was occupied by the Japanese from 1941 to 1944, after which time it was retaken by US Forces. US President Truman signed the Organic Act in 1949 establishing Guam as an unincorporated territory of the United States and granting citizenship to the island's people. A territorial college was established in 1952, which later became the University of Guam, accredited by the Western Association of Schools and Colleges. The University of Guam Marine Laboratory was established in 1970, and became a center for regional research on coral reefs. The Marine Laboratory has been largely responsible for the wealth of information available on coral reef taxonomy, biology and ecology in the western Pacific, and maintains a database and taxonomic collection as well as access to many regional coral reef-related publications.

The Commonwealth of the Northern Mariana Islands (CNMI), like Guam, was part of the Trust Territory of the Pacific Islands under US administration following World War II. The island chain, named after the widow of Spain's King Phillip IV, Mariana of Austria, became a Commonwealth of the United States in the 1970s, following the approval of a covenant, followed by the ratification of a local constitution. This group of islands extends from the inhabited island of Rota (Luta), just to the north of Guam, to the uninhabited island of Farallon de Parajos. There are three active volcanoes between this northern most point and the main island of Saipan, which is the most populated and developed island in the CNMI.

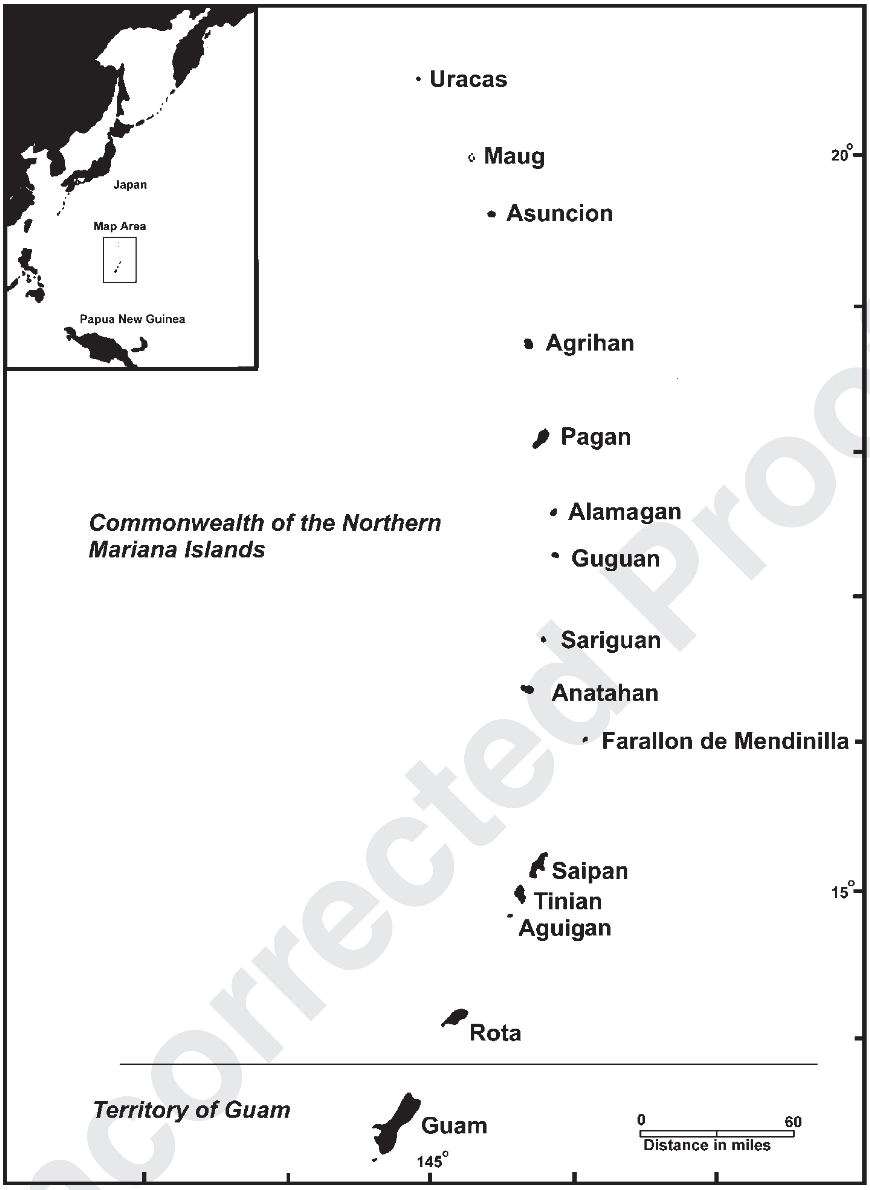

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Fig. 19.1. Location of Guam and the Commonwealth of the Northern Mariana Islands in the western Pacific

The entire Marianas chain is an island arc system which lies to the west of the Marianas Trench, an active subduction zone where the Pacific Plate is being subducted under the Philippine Plate. Geologically, the group can be divided into the older, inactive volcanic islands of Guam, Rota, Aguijan, Tinian, Saipan and Farallon de Medenilla, which have substantial limestone deposits, and the nine younger, volcanically active northern islands that are offset to the west, including Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug and Farallon de Parajos (Randall 2003; Chapter 18, Riegl et al.).

19.2 Climate and Oceanographic Conditions

Guam and the CNMI are truly tropical islands, with a typical air temperature of approximately 28°, with a range from 24°C to 30°C, and similar seawater temperatures affecting coastal coral reefs. There is a pronounced dry season from December through June, with a rainy season typically extending from July through November. These islands are regularly hit by typhoons and tropical storms that can occur throughout the year (more often June through November, but major storms have hit during the months of December and January). During these events, winds can exceed 180 miles/h (290 km/h), with associated heavy rains, and large oceanic waves hitting the reefs and shores. Normal rainfall is variable among years, with an average of 218 cm, with the documented record of over 400 cm for Guam in 1976, an El Niño year.

The Mariana Islands are affected by seasonal tradewinds, which normally come out of the northeast or east, averaging 15 knots. As such, the corals and reefs on the windward exposures exhibit signs of wave activity, including more robust forms and skeletal characteristics, wave-mediated orientations and spur-and-groove formations.

The islands are also affected by the near-surface North Pacific Equatorial current that generally flows westward with speeds 0.1–0.2 m s^{-1}, larger in the south than in the north (Fig. 19.2a). On meeting the land mass of Guam, a 35 km long, slab-shaped island, these currents are deflected and generate unsteady eddies in its lee and areas of convergence of smaller-scale, localized currents (Wolanski et al. 2003a). A number of transient eddies off the tips of the island were apparent, the smallest eddies were at the scale of local topographic features such as headlands and embayments, while other eddies were island-size (Fig. 19.2b). In addition, large (200 km in diameter) oceanic eddies occasionally also travel past Guam and can generate for periods

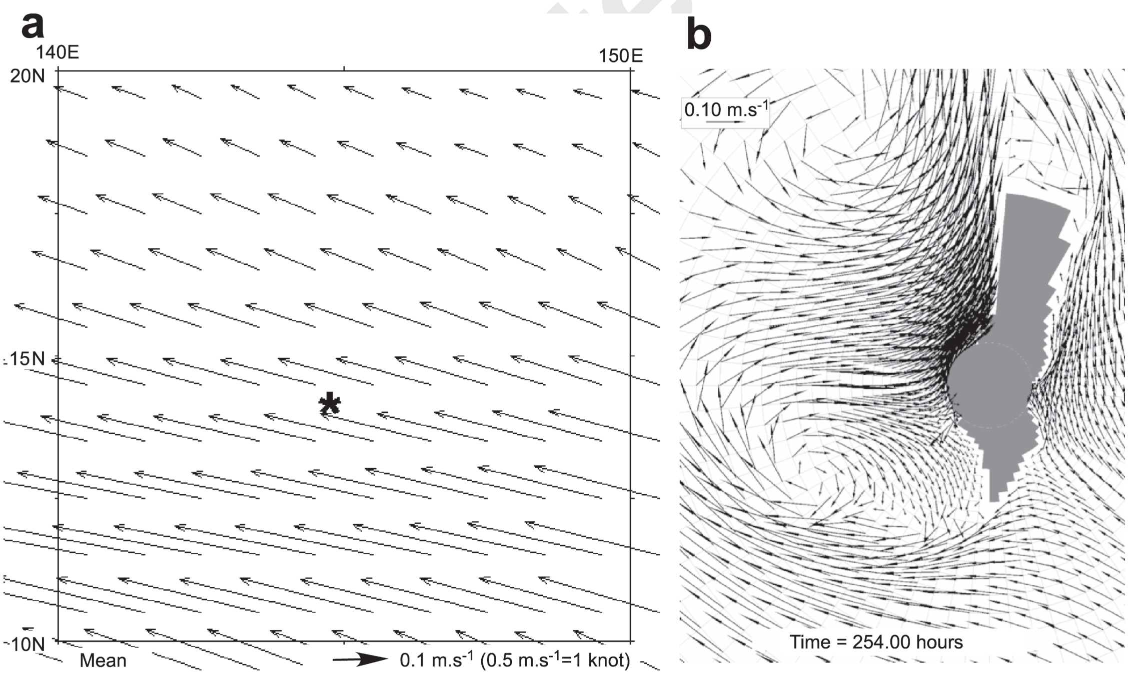


FIG. 19.2. (**a**) Long-term (1993–2206) averaged near-surface, currents, in the Mariana Islands area, predicted from NOAA's OSCAR satellite data. The area shown is 10–30° N and 140–140° E. The horizontal resolution of the data is 1°. * = Guam Island. (**b**) An example of the predicted synoptic distribution of the predicted near-surface currents around Guam for a northwestward far-field current impinging on Guam (Reproduced from Wolanski et al. 2003a by permission of Elsevier)

typically 1–2 weeks in duration currents in the opposite direction to those generated by the North Pacific Equatorial Current. Eddies around Guam are sufficiently energetic to return fish and coral eggs and larvae to their natal reefs in Guam, thereby enabling self-seeding of coral reefs in Guam, while recruitment from far-away reefs is also possible and would vary enormously from year to year dependent on the oceanic currents at the time of spawning. Numerical models also predict that large (up to 30 m amplitude) island-generated internal waves may occur around Guam, however, no observations are presently available to support this prediction.

19.3 Biogeographical Setting of the Area

Guam and the CNMI are oceanic islands, far removed from any continental landmasses. The nearest neighbors are the islands of the Republic of Palau, 1,295 km to the southwest and the Federated States of Micronesia to the southwest (841 km) through the southeast (2,204 km). The Philippines lie to the west (2,300 km), and Japan, ca. 2,500 km to the north.

These islands are located in an area of high marine biodiversity, just to the east of the "Coral Triangle" of highest marine biodiversity (New Guinea, Indonesia and the Philippines). The Marianas fauna includes over 375 species of scleractinian corals, 195 species of echinoderms, 650 crustaceans and 1,000 species of reef and shorefishes (see review issue of Micronesica, Vol. 35–36, 2003; Randall and Myers 1983; Randall 2003; Porter et al. 2005).

The marine flora and fauna are relatively well-studied and documented through a variety of peer-reviewed publications, technical reports, environmental impacts statements and surveys (see the University of Guam Marine Laboratory web site, http://www.uog.edu/marinelab, for a list of contributions).

19.4 Biodiversity of Major Organismal Groups

19.4.1 Corals and Invertebrates

Randall (2003) reported a total of 377 scleractinian corals covering 20 families from the Marianas Islands (Fig. 19.3). Guam's reefs contain all of the major genera of reef-building corals, notably species of *Acropora*, *Porites*, *Pocillopora*, *Favia*, *Favites*, *Montipora*, *Fungia*, *Pavona*, *Montastrea*, *Leptoria*, *Leptastrea*, *Psammacora*, and *Galaxea*. Apra Harbor, protected from most oceanic swells a majority of the time, has well-developed shallow patch and fringing reefs, dominated by *Porites* spp., with a degree of vertical zonation from the surface to a depth of 20–30 m. Large anemones hosting different species of clown fish are also found in the Harbor. Within this bay, a few deeper mounds (20–25 m) exist with a good diversity and abundance of large sponges. Sclerosponges have been found in caves just to the south of the harbor. There is a steep drop off to the west of Apra Harbor, over 1,000 ft, which was identified as a possible OTEC (ocean thermal energy conversion) site. There is a pronounced vertical zonation of corals and other species along this slope.

Piti Bay, to the north of Apra Harbor, contains a unique and expansive rubble zone that is home to a number of new invertebrate records and previously undescribed species. There are rich benthic epifauna and infauna that includes a variety of holothurians (*Thelenota ananas*, *Bohadschia marmorata*, *B. argus*, *Holothuria atra*, *H. edulis*, *Actinopyga mauritiana*, and *Holothuria nobilis)*, mollusks and crustaceans. Several "bomb holes" that are actually karst caves with collapsed ceilings, are present within the bay, one of which contains an underwater observatory built in the late 1980s. This controversial project was opposed by many within the research and local communities. Corals (mostly *Porites* spp.) and soft corals (dominated by *Sinularia* and *Sarcophyton* spp.) line the edges of the "bomb holes".

Several outbreaks of *Acanthaster plancii,* the crown-of-thorns starfish occurred the 1970s and 1980s (Colgan 1987; Bonito 2002; Quinn and Kojis 2003). Additionally, the corallivorous starfish *Culcita novaeguinea* and the coral eating mollusk *Drupella* sp. are also found on the reefs of the Mariana Islands.

The molluscan fauna of Guam and the CNMI is rich, with approximately 800 species of prosobranch gastropods identified from shallow water reef habitats (Smith 2003). Giant clams are found on the reefs of Guam and the CNMI, with evidence that populations of *Tridacna gigas* and possibly

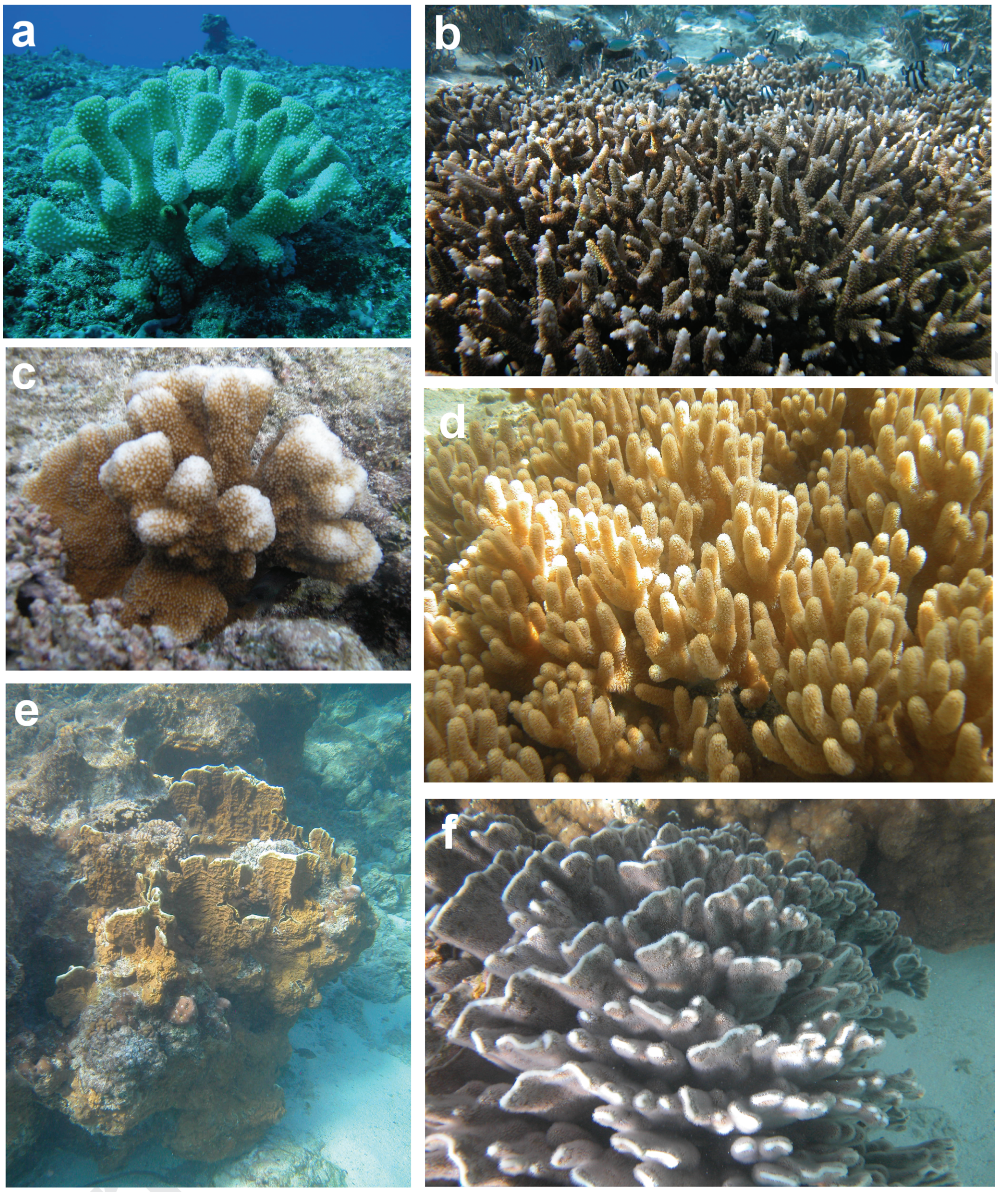
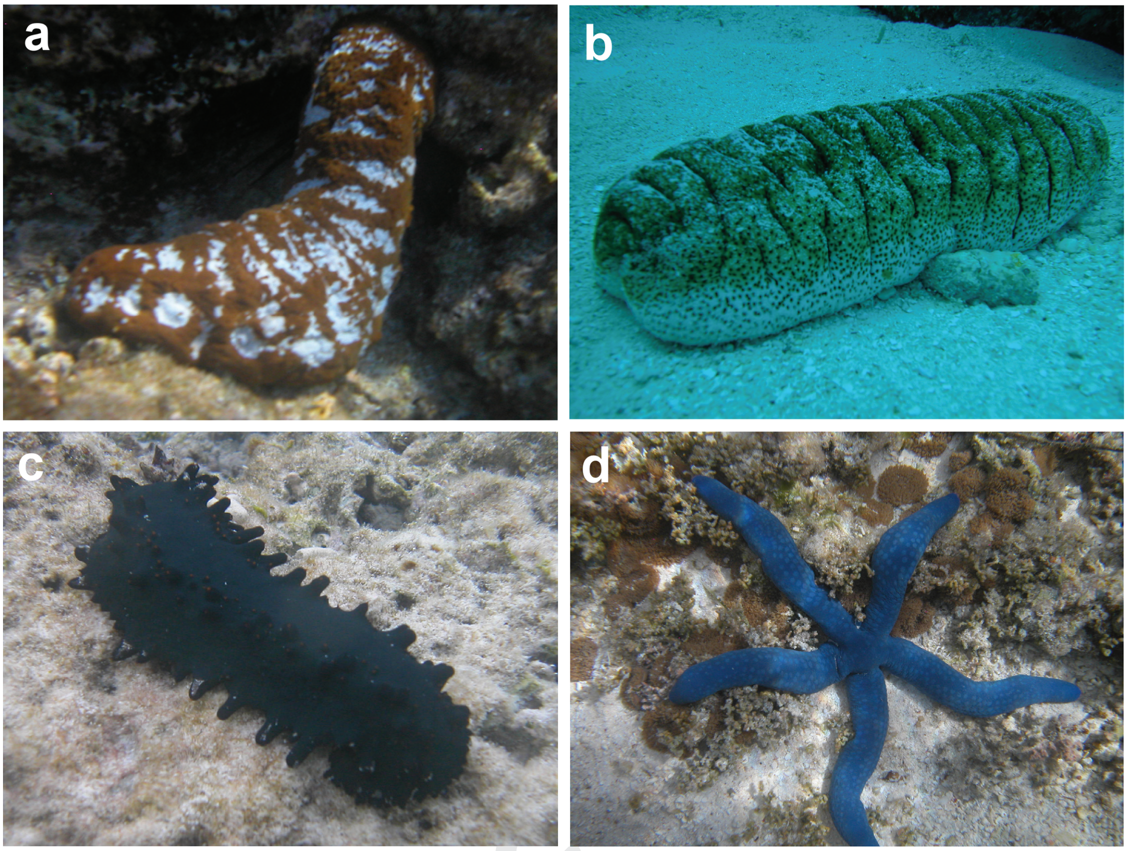


Fig. 19.3. Some representative members of the Mariana Islands coral reef fauna (photos by Megan Berkle) (**a**) *Pocillopora eydouxi* (scleractinia) (**b**) *Acropora* cf. *abrolhosensis* (scleractinia) (**c**) *Acropora (Isopora) palifera* (scleractinia) (**d**) *Sinularia* cf. *leptoclada* (alcyonacea) (**e**) *Millepora platyphylla* (milleporina) (**f**) *Heliopora coerulaea* (helioporacea)

T. crocea were collected to the point of local extinction (Smith 2003), while the smaller species including *T. maxima*, and *T. squamosa* are still found. Bailey-Brock (1999) reports 101 polychaete species from coral reefs on Guam and 15 from Saipan. It can be assumed that these marked differences are more related to sampling than true faunistic differences between the islands. The polychaete fauna on Marianas reef flats is similar to that in comparable habitats of Hawaii, Eniwetok, and Indonesia.



[Au1] Fig. 19.4. Some members of the echinoderm fauna of the Mariana Islands (photos by Megan Berkle) (**a**) *Actinopyga mauritiana*, the surf redfish (**b**) *Holothuria fuscopunctata* (**c**) *Stichopus chloronotus* (**d**) *Linckia laevigata*

19.4.2 Zonation and Community Patterns

There are a variety of coral reef types in the Mariana Islands, including barrier reefs, fringing reefs, patch reefs, and submerged reefs associated with offshore banks (Chapter 18, Riegl et al.). Well developed carbonate platforms are found extending from shore on most of the islands, although these are less pronounced on the northern and geologically younger islands. The Mariana Islands have three species of seagrasses, *Enhalus acoroides*, *Halophila minor*, and *Halodule univervis*, which can be found in well-developed seagrass beds (Tsuda et al. 1977). Also coastal mangroves occur (*Avicennia marina*, *Bruguiera gymnorrhiza*, *Heritiera littoralis*, *Hibiscus tiliaceus*, *Lumnitzera littorea*, *Nypa fruticans*, *Rhizophora mucronata*, and *Xylocarpus moluccensis*) in the Marianas, but many areas have been impacted throughout the island chain by dredging and coastal development (Mueller-Dombois and Fosberg 1998).

Within the Mariana Archipelago the most notable, broad-scale, reef-community zonation pattern exists between the northern, volcanically active islands and the southern, raised limestone islands (Fig. 19.5). [Au2] A recent survey of 40 fringing reefs throughout the northern islands found that while coral diversity and colony surface area are significantly lower on the northern islands compared with the southern (mean of 62 species per site and 206 cm^2, mean of 82 species, 312 cm^2, respectively; Houk, unpublished data), population density is similar (mean of 144 and 139 colonies per site, respectively). This suggests that recruitment is not limiting, rather that harsh environmental conditions select against species settlement and growth (Randall 1985; Houk and van Woesik 2006). In support of this hypothesis, Randall

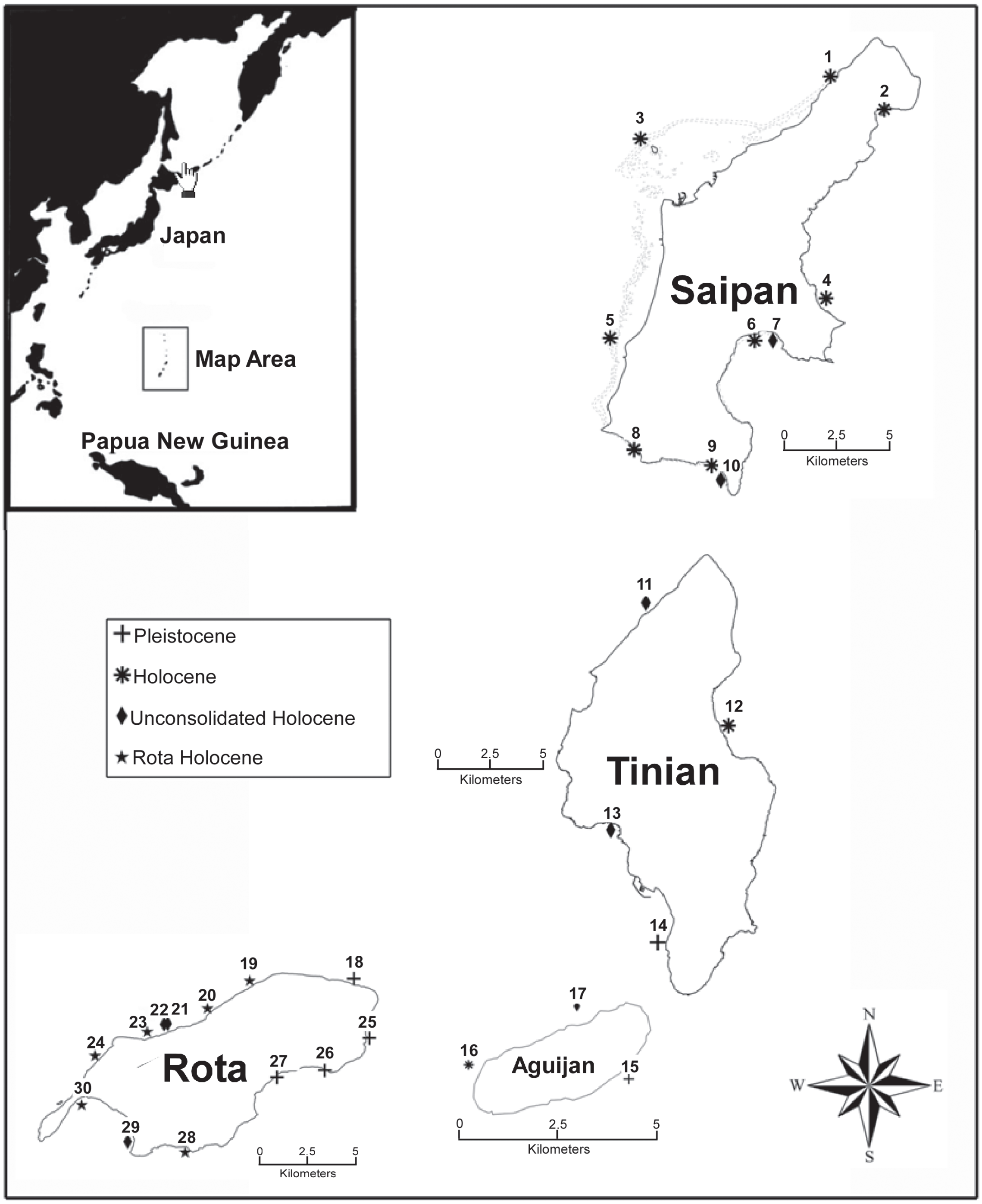


FIG. 19.5. A map of CNMI's southern islands showing long-term monitoring locations and geomorphological settings. The distance between islands is not drawn to scale

(1985) found a significant relationship between percent coral coverage and geomorphological habitat complexity. The failure of fringing reefs to form on much of the coastline around the northern islands is attributed to: (1) unfavorable bathymetry, (2) a lack of favorable substrate on which corals can settle and grow, (3) a high exposure to wave energy, (4) the re-suspension of volcanic ash, and (5) volcanic eruptions. While it is clear that the failure of reefs to form is ultimately a consequence of the environment (Sheppard 1982; van Woesik and Done 1997; Montaggioni 2005), the proposed mechanism halting growth in the northern islands is a combination of natural disturbances acting against coral colony growth.

Corals reef growth in the southern islands of Saipan, Tinian, Aguijan, Rota, and Guam has not been uniform throughout the Holocene, which has resulted in further community zonation patterns. Typical reef growth, whereby a reef first aggrades to sea-level which is then followed by progradation, is rare throughout these islands. Overall relatively few late Holocene reefs are found throughout the Marianas, a trend common to high latitude reefs (above 15°) (Harriott and Banks 2002; Nozawa et al. 2006). Most modern reef flats represent flooded and abraded surfaces of early Holocene reefs formed on planed Pleistocene planation. In many locations late Holocene reef growth is absent, which creates a diverse assemblage of shallow-water habitats (Randall and Siegrist 1988). The largest shallow water system is Tanapag Lagoon in Saipan, which is a good example of this heterogeneous reef-building process insofar as its morphology is determined by pre-existing morphology, rather than modern reef building processes alone (Cloud 1959; Chapter 18, Riegl et al.). In some localities, modern coral communities have formed well-developed spur-and-groove reefs, while others remain entirely devoid of coral-mediated carbonate deposition. The 52 km coastline of Tinian Island only exhibits reef growth on 21%, while the 147 km coastline of Guam is 59% reef-fringed.

[Au3] Houk and van Woesik (personal communication) identified four distinct geomorphological settings in the CNMI with widely differing modern coral assemblages, and linked coral community persistence through time to geomorphology. They defined settings as: (1) typical Holocene, (2) unconsolidated Holocene, (3) Rota Holocene, and (4) Pleistocene reefs (Fig. 19.6). The community setting of typical Holocene reefs is distinct due to the diverse assemblage of framework building corals, dominated by encrusting *Montipora*, massive *Porites*, and large *Acropora* and *Pocillopora*. Unpublished data from in situ conductivity and temperature sensors suggest that freshwater discharge through the reef matrix on the unconsolidated Holocene reefs after storms causes the notable difference between typical versus unconsolidated Holocene reefs. Thus, the magnitude and nature of freshwater input may be an influential driver of coral communities (Umezawa et al. 2002). In the unconsolidated reef setting more columnar and fewer encrusting corals were found, likely due to a lack of suitable reef substrate and in protected localities, such unconsolidated reefs can be dominated by mono-specific stands of *Porites rus*, *Coscinaraea columna*, or *Pavona* spp.

Rota's and some of Guam's present-day reefs are super-imposed over the remains of early Holocene reef growth exposed by eustatic sea-level drop coupled with geological uplift ~2,000 years ago (Dickinson 2000; Kayanne et al. 1993; Chapter 18, Riegl et al.). Rota's modern spur-and-groove reef slopes contain small to medium-sized massive colonies, with the exception of *Astreopora* corals that attain larger sizes. The fossilized, raised reef-flats along the coast of Rota are a visual reminder that typical Holocene reefs dominated by branching *Acropora* and *Pocillopora* corals once prevailed (see also Chapter 18, Riegl et al.).

In some areas, substantial modern deposition is absent and small massive corals occur directly on the Pleistocene surface. Juvenile, framework building corals are commonly found but the environment limits their size (Harriott and Banks 2002; van Woesik and Done 1997; Nozawa et al. 2006; Houk 2006).

Interestingly, among the common macroinvertebrates that are annually surveyed at 30 sites throughout the CNMI, only the sea-cucumbers show a positive response to modern reef deposits (Fig. 19.7). The genera *Stichopus* and *Actinopyga* are more abundant on Holocene reef crests, where they are commonly harvested, than in other environments. Sea-urchins and sea-stars showed an opposite trend, increasing in abundance in low-relief reef settings (Fig. 19.6). While sea-cucumbers are in many places in the Pacific critically over-exploited, some good populations remain in the Mariana Islands (Kerr et al. 1993; Trianni and Bryan 2004).

A physiographic zonation pattern common to coral reefs also exists in the Marianas (Darwin 1892; Sheppard 1982; Done 1983), and is best [Au4,5]

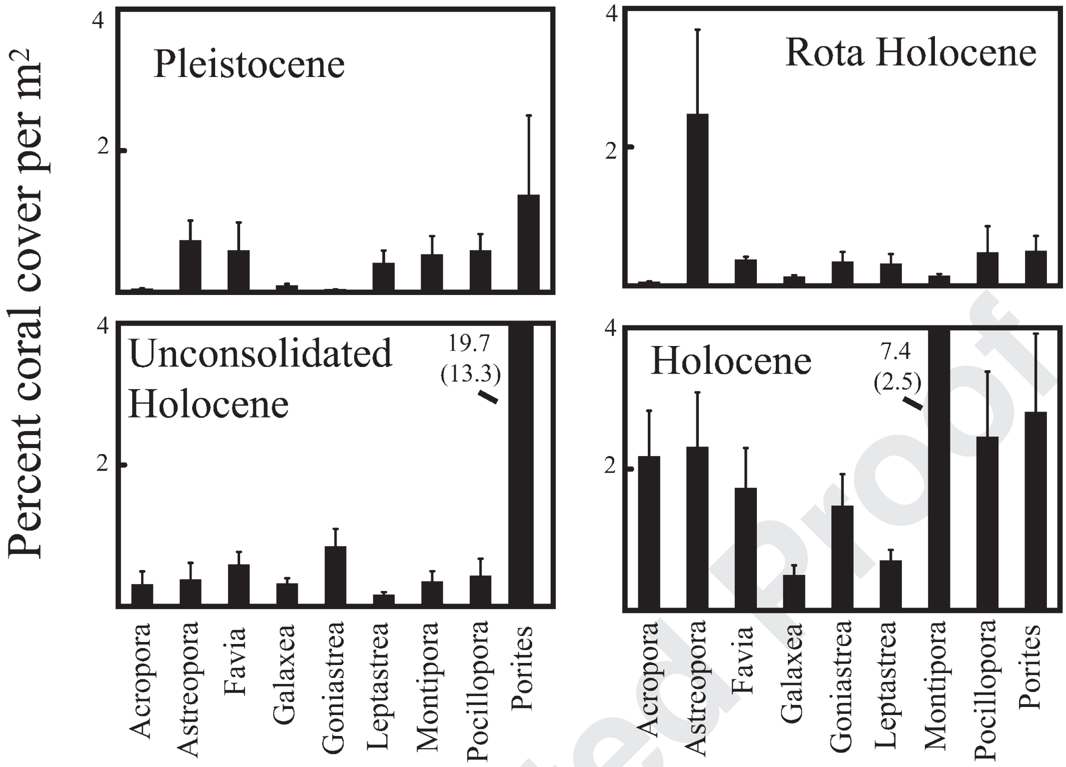


FIG. 19.6. Coral abundance in each geological setting

delineated into three habitats: (1) the back-reef/lagoon, (2) the high-energy reef-crest, and (3) the reef slope. Obvious differences in modern growth occur between these habitats, as dictated by the abiotic environment (light, wave energy, and oxygen levels).

19.5 Fisheries

The harvest of fisheries resources from nearshore coral reefs in the present day CNMI had been occurring since the Prehistoric Phase over 3,000 years before present (Amesbury et al. 1989). Various occurrences of fishing were documented from the logs of different early European explorers, with archaeological and historical evidence and accounts having been summarized by Amesbury and Hunter-Anderson (2003).

No documented information of commercialized harvest from the Spanish Period exists, and prior to the Japanese occupation coral reef resource harvest was primarily conducted for subsistence purposes. During the German occupancy of the Marianas from 1899 to 1914, it was noted by a German district officer of Guam that Carolinians from Saipan dove for trepang at Aguigan, selling them to Japanese merchants (Amesbury et al. 1989). This activity marks the first documented directed commercial fishing effort by indigenous peoples in the CNMI.

19.5.1 Reef Fisheries Landings

In the Japanese Period (1914–1944) the commercial harvest of fisheries resources was high, as evidenced by over 2,000 t landed in 1941 (Smith 1947). Of the 1941 total, about 318 t were listed as "other fish", and about 28 t as "sea cucumber" and "other shells". Additionally, about 12 t of "sharks" were landed. If one-half of the "other fish" and "sharks" categories are considered coral reef species, then about 165 t of nearshore reef fish and sharks were also harvested, bringing the total 1,941

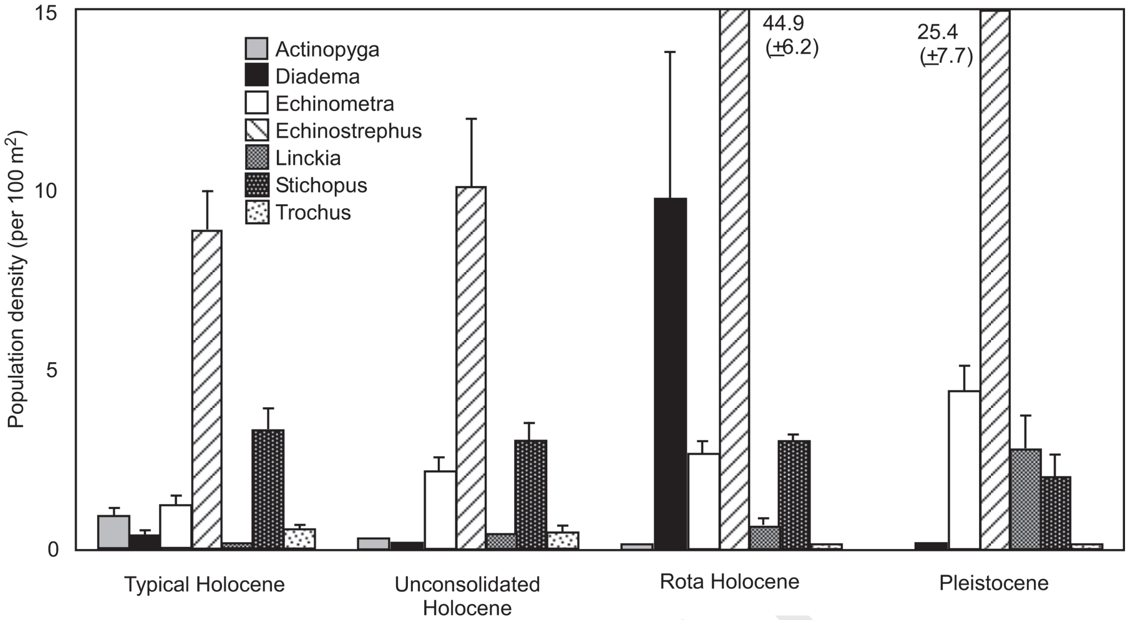


FIG. 19.7. Macroinvertebrate abundance in each geological settings

nearshore coral reef harvest to about 193 t. The lack of available data from the Japanese Period remains a quandary, as it is not known whether the 1,941 landings represent a high, low or mean level. The degree of fishing effort during the Japanese Period could have been influential in molding the current nearshore coral reef community structure.

Amesbury and Hunter-Anderson (2003) reviewed archaeological and anthropological data concerning reef fishing in Guam and the Northern Mariana Islands and summarized contemporary landings. They provide a summary of landings from the Trust Territory Administrative Period (1947–1976) in the Northern Mariana Islands from 1948 through 1977, excepting the years 1950–1956 and 1973–1975 when no statistics were available. Although the accuracy of landings is not definable, there appears to be significant variation in landings during this period, and in most years both pelagic and nearshore landings are aggregated. Unlike during the Japanese Period, the majority of fish landed during the Trust Territory Administrative Period (TTAP) were probably nearshore fish, and for non- or small-scale commercial purposes. In the years 1957–1960, the percentage of "tuna" that comprised the total fisheries landings were recorded separately, and ranged from 4% to 33%, averaging about 17%. As tuna are the primary constituent of contemporary pelagic fisheries landings, it can be assumed that the majority of the total landings consisted of bottom-associated fish and of reef fish since hydraulic and electric reels used in contemporary deeper bottom fisheries were in an incipient stage of development. The long-term average of fisheries landings from this period was about 39 t, and using the 1957–1960 average this figure can be amended to about 33 t.

The primary contemporary fisheries data acquisition method employed in the CNMI is through the collection of commercial sales receipts from fishermen and vendors. The Commercial Purchase Database System (CPDS) is a product of collaboration between the Western Pacific Fishery Information Network (WesPacFIN) and the CNMI Division of Fish and Wildlife (DFW). The CPDS is presumed to capture about 80% of all commercial landings in the CNMI. The documented commercial landings of reef fish indicate a sudden increase from 1981 through 1990, followed by stabilized landings from 1991 through 2002, with a decline from 2003 to 2004 and a rise in 2005–2006 (Fig. 19.8). The CPDS long-term average for commercial landings of reef fish and invertebrates in the CNMI from 1981 to 2006 is about 77 t. Raising this average by the 20% provides a long-term average of about 93 t.

The landings from the three referenced data sources are depicted in Fig. 19.9.

19.5.2 Management of Coral Reef Fisheries Resources in the CNMI

Although historical landings provide some information regarding coral reef fisheries resources, they are insufficient for use as a practical management tool. In addition to the CPDS both shore-based and boat-based creel surveys have been inconsistently implemented since the early 1990s, yielding inadequate trend data for coral reef fisheries. Although creel surveys have been successfully implemented in many jurisdictions and are essential for general data monitoring and collection, the protocols of data collection as well as the limitations of the data are not always adequate to manage fisheries. All data collection activities in the CNMI are voluntary, as no law exists that requires fishermen to provide the DFW with catch and effort data. As a result, many reef fisheries in the CNMI have been directly monitored and assessed, oftentimes by attaching data reporting conditions to export permits or relying on the goodwill of the fishermen to cooperate. In some cases, management measures have been enacted in agreement with survey and assessment results. Some case examples follow.

19.5.2.1 Scuba Spear Fishery in the CNMI

During the mid 1990s the scuba-spear reef fishery based out of Saipan was monitored and assessed

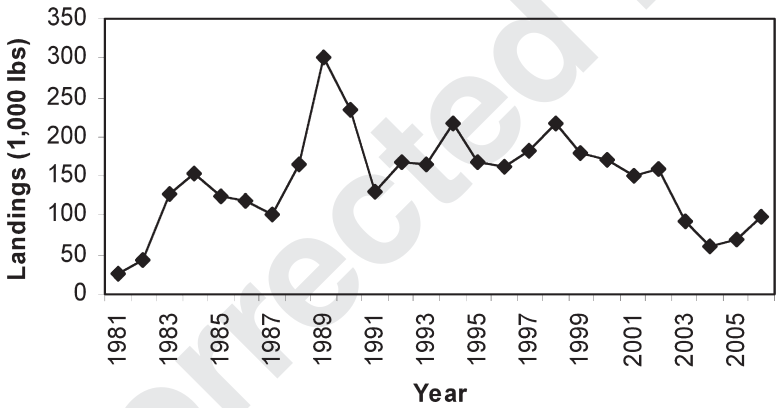


Fig. 19.8. CNMI Division of Fish and Wildlife Commercial Purchase Database Landings, 1981–2006

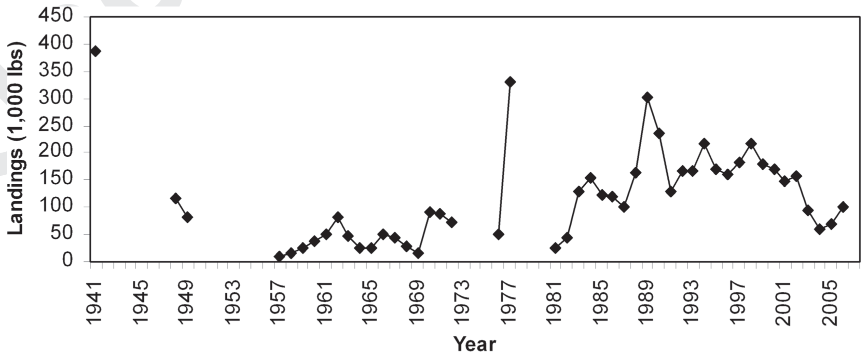


Fig. 19.9. Documented landings of coral reef resources. Japanese Period 1941; Trust Territory Period 1948–1977; CNMI Period 1981–2006

by the Division of Fish and Wildlife (Graham 1994; Trianni 1998). This fishery harvested reef fish from nearshore coral reefs around Saipan and Tinian, but also from coral reefs at islands north of Saipan. A number of species harvested in this fishery that represented primary food fish groups were evaluated by comparison of mean fork length (FL) per location (Trianni 1998). Significant differences were observed with mean FL being typically larger for specimens from the Northern Islands, followed by Tinian and Saipan. These results are summarized in Table 19.1. Catch per unit of effort data (CPUE) collected from Saipan and Tinian during two sampling periods, Period 1 (1993–1994) and Period 2 (1995–1996), showed a significant decline from Period 1 to Period 2. CPUE was also found to be lower for Saipan than Tinian, with the lowest CPUE values for each island obtained from leeward aspects. Conclusions drawn from Graham (1994) and Trianni (1998) suggested the ban on the use of scuba-spear fishing as well as indiscriminate methods such as gill nets. The proposed ban on the use of gill nets was supported by independent reef fish survey in 1979 focusing on fish resources in the Saipan Lagoon (Amesbury et al. 1979), which was repeated in 1997 (Duenas and Associates 1997). Results indicated that primary groups of food fish had decreased in number between surveys (Fig. 19.10).

Fishing effort utilizing scuba-spear fishing eventually became more prevalent on Tinian and Rota, as Saipan-based companies began fishing at those islands when nearshore resources in Saipan became increasingly difficult to harvest. This led to local concerns for reef fish resources on Tinian and Rota, as well as on Saipan. The use of scuba-spear fishing was perceived as being a non-traditional method in direct conflict with the free-diving spear fishermen community. As a result of local community concerns and pressure, the passing

Table 19.1. List of species evaluated for mean fork length by location from the scuba-spear fishery. 1 = largest, 3 = smallest.

Family	Species	Location		
		Saipan	Tinian	Northern Islands
Holocentridae	*Myripristis berndti*	3	2	1
Serranidae	*Epinelophelus fasciatus*	2	2	1
Lutjanidae	*Lutjanus kasmira*	2	2	1
Lethrinidae	*Gnathodentex aurolineatus*	3	2	1
Caesionidae	*Pterocaesio tile*	3	1	2
Scaridae	*Scarus rubrioviolaceus*	2	2	1
	Scarus forsteni	2	3	1
Acanthuridae	*Acanthurus blochii*	2	1	1
	Acanthurus lineatus	2	2	1
	Naso lituratus	3	2	1
	Naso unicornis	2	1	2

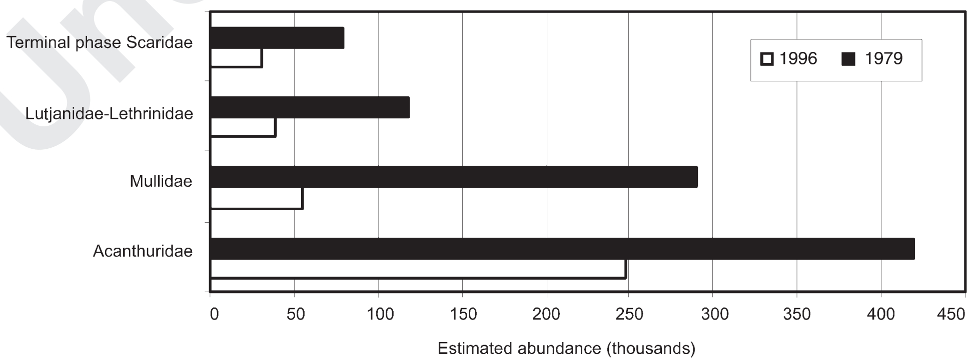


Fig. 19.10. Comparison of primary food fish group abundance from fisheries independent surveys in 1979 and 1997

of local laws to prohibit the use of scuba-spear fishing began in 2000 when Rota local law 12–2 was enacted. Tinian enacted local law 13–01 in 2002, and Saipan and the Northern Islands enacted Saipan and the Northern Islands local law 13–13 in 2003. These laws remain in effect.

19.5.2.2 Sea Cucumber Fishery in the CNMI

In October 1995 a sea cucumber fishery that targeted the surf redfish, *Actinopyga mauritiana*, began on the island of Rota (Trianni 2002). The CNMI DFW became aware of the fishery in December 1995 and instituted management measures in January 1996. One problem with the fishery was the lack of baseline abundance data from which to manage harvest levels. As the economic abundance of surf redfish declined on Rota, the fishing company planned to switch harvest to Saipan in mid-1996. Planned preharvest surveys on Saipan were not allowed to commence, and harvest began without baseline data to mange from. The DFW created export permit conditions and successfully enforced them, managing the fishery by evaluating CPUE over time (Trianni 2003). As the Saipan CPUE declined with time the fishery was halted and a survey of the resource in harvested areas was commenced in April 1997. The results of that survey, along with results from depletion modeling, indicated from 78% to 90% of initial population sizes in the harvested areas were removed (Trianni 2003). Based on these results, the Saipan sea cucumber fishery was subsequently terminated in May 1997. Although management of sea cucumber fisheries in the CNMI had proven challenging, political pressures in 1997 sought to allow harvest on the island of Tinian. The DFW successfully conducted a pre-harvest survey in fall 1997 and determined that harvest of the surf redfish in Tinian was not sustainable either biologically or economically. Subsequently, no harvest was allowed on Tinian (Trianni and Bryan 2004). It was eventually accepted that sea cucumber fisheries in the CNMI were not sustainable at a commercial level, and any subsequent inquiries for resource harvest be viewed with extreme caution.

During the progression of the sea cucumber fishery from Rota to Saipan, public concerns mounted as to the sustainability of the sea cucumber resource to harvest as well as the impact on the coral reef ecosystem. The CNMI Government eventually recognized the public concern over the harvest of sea cucumbers, an industry that served primarily to satisfy markets in Hong Kong and Taiwan, to the detriment of local coral reef resources. In 1998 House Bill No. 11–144 was introduced, becoming Public Law 11–63 in 1999. This law established a 10-year moratorium on the harvest of sea cucumbers (as well as seaweeds and seagrasses) throughout the CNMI.

19.6 Environmental Factors Influencing Reef Biology

The Mariana Islands are regularly affected by strong typhoons and oceanic swells, with associated high energy waves that can break branching corals, overturn large massive colonies and scour encrusting forms through the abrasive nature of moving sand and rubble. Additionally, the island chain is situated in an area of high tectonic activity, with frequent earthquakes of relatively high magnitudes (in 1993, Guam experienced an event measuring 8.4 on the Richter scale). Faults and slumping have affected reefs throughout the island chain.

Many of the corals studied to date (ca. 40 species) including Acroporids, Poritids, Favids and Pocilloporids, participate in synchronous mass spawning events, 7–10 days following the June and July full moons (Richmond and Hunter 1990; Richmond 1997). Peak reproductive activity corresponds with the rainy season, and periods of reproductive failure due to runoff and coastal pollution have been documented for reefs in the area (Richmond 1996, 1997).

The crown-of-thorns starfish, *Acanthaster planci*, has been responsible for declines in live coral cover resulting from several documented outbreaks during the 1960s, 1970s, 1980s and 1990s. The first documented outbreak occurred in 1967 (Chesher 1969) and Randall (1973) reported a resulting substantial effect on coral cover from approximately 50–60% over a 30 m depth range to less than 20% on the reef front and approximately 1% at deeper depths. Bonito (2002) studied coral community structure at Tanguisson Reef on the leeward side of the island, and demonstrated a significant correlation with outbreaks of *Acanthaster* (Fig. 19.11).

Coral diseases, increases in cyanobacteria, and outbreaks of the encrusting sponge *Terpios* have also affected coral reef community structure on Guam.

19.6.1 Water Quality

Guam underwent a development boom in the late 1980s and early 1990s. Increased stormwater runoff from an airport expansion project, new roads, hotels, shopping centers and golf courses resulted in reduced coastal water quality, especially in bays and areas of restricted water circulation (Richmond and Davis 2002). The salinity of waters over coastal reefs was found to drop below 28 ppt after periods of rainfall during summer coral spawning events, which was documented to result in reproductive failure (Richmond 1996). Stormwater collection passes into sewer lines and during periods of heavy rain, water is diverted around the sewage treatment plants and discharged directly into the ocean outfall pipes with treatment at best at the primary level. Three of the Island's outfall pipes discharge within 200 m of the shoreline, in depths of 20–25 m and in areas where corals are found. Extension

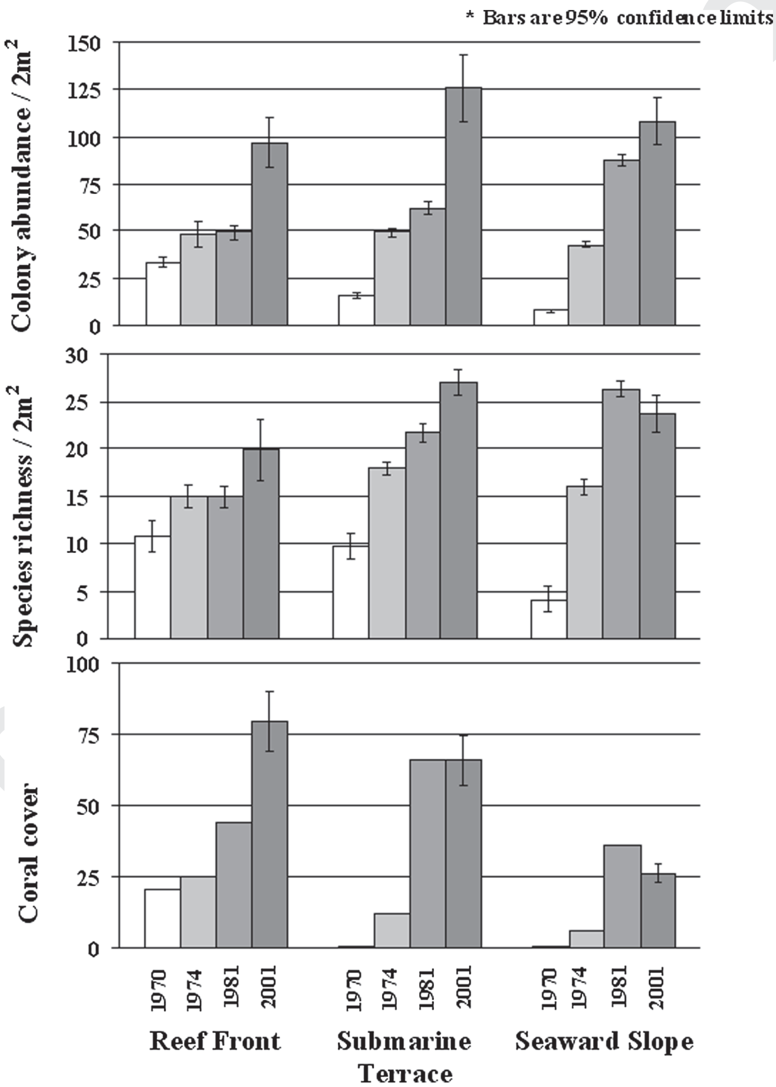


FIG. 19.11. Coral community structure as influenced by *Acanthaster* outbreaks

of the Northern and Central District outfalls into deeper waters further offshore is planned.

A variety of pollutants have been found in the sediments and a variety of marine organisms from Apra Harbor, including PCBs, heavy metals (arsenic, copper, lead, mercury and tin) and PAHs (Denton et al. 1999), which is not surprising based on the high level of military, shipping and related activities occurring within the enclosed bay. The levels reported were considered "mild to moderate," when compared to other harbors around the world, yet are a cause for concern considering re-suspension that could occur as a result of a proposed harbor dredging project. Agrochemicals, both pesticides and fertilizers are also a concern for Guam's coastal waters, resulting from agriculture, golf courses and turf maintenance on the grounds of ocean front hotels.

Discharges into the coastal zone occur via surface runoff on the southern portion of Guam, and from both surface runoff and aquifer discharge on the northern, limestone areas. Due to urbanization, more non-permeable surfaces associated with roads, parking lots and other types of watershed modifications have increased over the past several decades, and are expected to become more of an issue, requiring efforts at integrated watershed management (Wolanski et al. 2004).

19.6.2 Present Status of Reef Health

Guam's reefs range from those in excellent condition to others that have been degraded by anthropogenic stressors. Runoff and sedimentation impacts differ substantially between the northern part of the island which consists of uplifted limestone and the southern part which is primarily volcanic with high topographic relief (see also Chapter 18, Riegl et al.). Assessment and monitoring programs have been ongoing on many of the reefs and associated communities since the 1970s and reveal a variety of human impacts, natural cycles of disturbance, and synergisms between the two.

The studies of Tanguisson Reef show periods of *Acanthaster* predation followed by periods of recovery. The reef front, reef slope and submarine terrace areas are a distance from the Northern District sewer outfall, and have demonstrated repeated periods of coral recruitment and recovery following acute periods of predation. Studies of the reefs adjacent to the outfall found chronic effects and the sustained loss of species. In contrast to the outer Tanguisson Reef sites, coral communities off Fouha Bay on southern Guam have shown continued losses tied to runoff and sedimentation (Table 19.2; Wolanski et al. 2004).

19.7 Human Impacts and Conservation Issues

Sedimentation is the major anthropogenic problem for the central and southern reefs. For the Ugum River Watershed, soil erosion was estimated at 176,500 t/km^2/year (DeMeo 1995). Forty six percent of this was attributed to roads on slopes, while 34% was contributed from badlands. Ugum Watershed erosion rates doubled from 1975 to 1993 (from 1,547,250 to 3,039,750 t/km^2/year), which was attributed to road construction and development projects. Sediment accumulation on reefs has been documented to substantially reduce both coral diversity and abundance (Randall and Birkeland 1978).

With over one million tourists visiting Guam each year, many from countries where a coral reef conservation ethic is not fully developed, damage to reefs is inevitable. In addition to impacts of SCUBA divers and snorkellers, underwater walking tours using surface-supplied equipment and a large number of personal watercraft (jet skis) have affected reefs and water quality. A coastal use zoning law called the Recreational Water Use Master Plan was passed into law to address these problems but needs enforcement support and to be updated to cover new activities and areas.

Groundings of fishing vessels, recreational watercraft and ships carrying cargo and illegal immigrants have resulted in localized damage to reefs. Guam's main power generation facilities are located on Cabras Island, in the northern portion of Apra Harbor. Elevated temperatures from the dis-

Table 19.2. Coral diversity versus distance from shore in Fouha Bay, Guam in 1978 and in 2003.

	1978	2003
Coral diversity vs distance from shore (cumulative)	0–25 m 3 spp. 0–75 m 40 spp. 0–125 89 spp. 0–200 104 spp.	0–40 m 0 spp. 45–90 m 5 spp. 100–275 m 41 spp.

charge of seawater used to cool the generators has resulted in coral mortality. The discharge of cleaning chemicals has also occurred, with subsequent impacts on local coral populations.

19.7.1 Fisheries Issues in the CNMI

The nearshore management of coral reef fisheries resources in the CNMI involves long-term low resolution monitoring through the CPDS and both boat-based and shore-based creel surveys, as well as directed monitoring of fisheries on an as-needed basis. These approaches have proved challenging, especially without the legal requirement of fishermen to provide data to the DFW. The result has been the institution of regulations banning the use of certain methods, such as the scuba-spear ban, and legislation that creates harvest moratoria, as with sea cucumbers. Additionally, the CNMI has four no-take Marine Sanctuaries, three on Saipan (Managaha Marine Conservation Area, Bird Island and Forbidden Island Marine Sanctuaries) and one on Rota (Sasanhaya Bay Fish Reserve), with plans to institute a limited take Marine Sanctuary on Tinian. These Marine Sanctuaries are relatively new, and the two oldest no-take reserves, the Managaha Marine Conservation Area (MMCA) and the Sasanhaya Bay Fish Reserve (SBFR) both have demonstrated positive changes over the course of annual assessments from 2000 through 2005/06, with examples provided in Fig. 19.12. In addition to monitoring and assessment of fisheries and Marine Sanctuaries, the Fisheries Research Section (FRS) of the DFW also conducts life history studies of select near shore reef fish. These life history studies provide age and growth parameters required for reliable stock assessments.

The coral reef fisheries resources of the CNMI have become better managed over time, and as research and monitoring activities continue to provide information for use in evaluating resource sustainability, it can be anticipated that coral reef fish resources will approach levels that effectively balance ecological necessities with sustenance needs.

19.7.2 Fisheries Issues on Local Coral Reefs in Guam

Fish populations and catch per unit effort (CPUE) have measurably declined in Guam since data collection began in 1985. Fishing practices, including the use of unattended gill nets, bleach, SCUBA spearfishing and fish traps have contributed to the problem. However, habitat loss due to sedimentation, pollution and physical damage has also been responsible for reduced fish populations.

Guam's Division of Aquatic and Wildlife Resources performed creel censuses that documented a 70% reduction (Fig. 19.13) in coastal fisheries catch from 1985 through 1996 (DAWR Annual Reports), and a comparable drop in catch per unit effort, that led to the passing of Public Law 24-21 in 1997 which established five no-take MPAs around the island and updated the local fishing regulation. These permanent no-take areas cover approximately 18% of Guam's coastal coral reef area and took 14 years to establish legally. This effort was made possible through one of the best coral reef shoreline creel surveys that annually estimates fisheries effort and harvest by method for the entire island. Additionally, the legal changes made through Public Law 24-21 served two primary purposes: to establish management measures to restore sustainable use and to improve enforceability.

A rapid shift in the health of the fisheries was marked by a dramatic move toward commercialization of the reef fisheries in the mid-1980s to support a rapidly growing tourism economy and significant development. Because of the increased demand for fish and a relatively small area of reef, this pressure did not take long to significantly reduce stocks. The rate of decline and the Government's inexperience with sharing fishery information with the public made the installation of effective management approaches publicly contentious. The earliest attempts did not include public input into the development of a strategy and after considerable exchange between government agencies, a series of public hearings were held. While public reactions were negative to the proposed no-take areas and to a number of regulatory changes the positive side was that at least public involvement had begun. Criteria were established to evaluate 60 proposed sites for fisheries management before selecting 9 after significant governmental and public input. A revised package was developed and taken back to public hearing which gained strong support for the changes and the overall need for establishing fisheries management measures. The revised package was then submitted to the legislature and again went through a hearing process after which the regulation package 19-2 was passed.

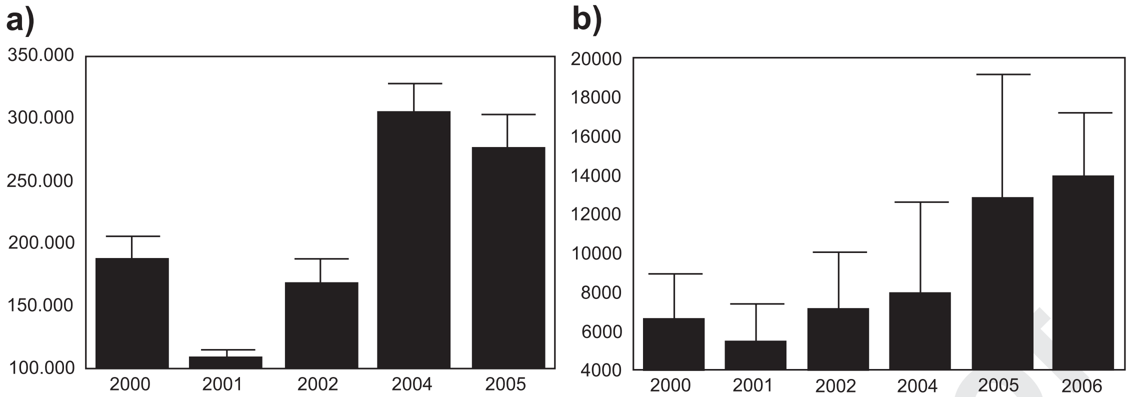


FIG. 19.12. Population estimates of (**a**) sedentary Acanthuridae from the Managaha Marine Conservation Area, and (**b**) terminal phase Scaridae from the Sasanhaya Bay Fish Reserve

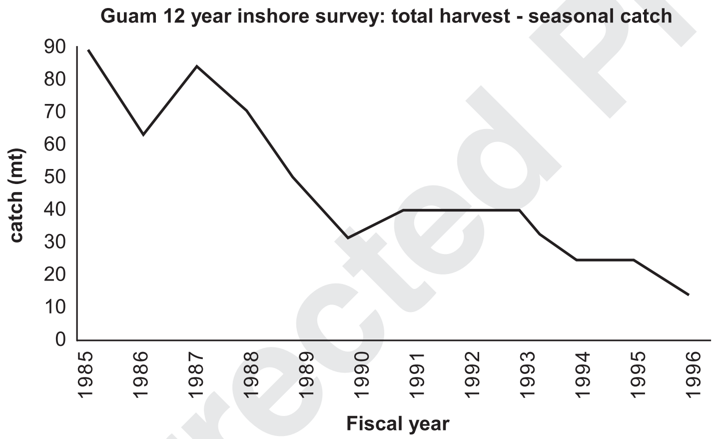


FIG. 19.13. Catch per unit effort (CPUE) for coastal fisheries on Guam from 1985 through 1996

No-take areas were established in 1997 but it was not until January of 2000 that the new regulations were fully enforced and proper signage was installed to inform the public and visitors of those areas that were protected. In total, there are two federal (i.e., War in the Pacific National Historical Park and Guam National Wildlife Refuge) and 11 territorial MPAs, with five of the territorial MPAs no-take marine reserves.

19.8 Case Studies

The Reefs of Guam and the CNMI are affected by a combination of anthropogenic and natural stressors acting synergistically, and there are several case histories worth mentioning.

19.8.1 Typhoons and Tropical Storms

In December 1997, Supertyphoon Paka passed through the Mariana Islands, causing substantial damage to structures, vegetation and the infrastructure of Guam and Rota, with the eyewall passing over both islands. Winds gusting to over 200 mph were recorded, but the record or 236 mph could not be confirmed due to damage to the airfield's recording anemometer. While acute wave damage was observed on coastal reefs, with overturned and fragmented coral colonies, runoff and associated debris became a further confounding issue. Coastal surveys following the storm found a diverse assortment of deposited materials, from sheets of roofing tin causing abrasion to surviving corals to clothing wrapped around coral colonies and causing additional physical damage. Divers recovered and disposed of 40,000 lb of debris during reef clean-ups. Six tons were taken from the shallow reef areas and 14 t were recovered in waters from 3 to 20 m in depth. The rapid response was organized and supported through the cooperation and collaboration of local agencies, institutions, dive clubs and community members along with funding and logistical support from NOAA and the Department of the Interior. This effort has been used as a model for developing a rapid response protocol to address reef health following future events and disturbances.

19.8.2 Development and Poor Land Use Practices

Guam and the CNMI, particularly the island of Saipan, underwent a period of rapid economic growth and development during the 1990s, tied to what has been described as the Asian Bubble Economy. Due to the geographic location of the Mariana Islands, the tourism which served to fuel economic activity was primarily from Asia (Japan), and hence the "flavor" of development was also culturally tied to the funding source. Hotels, golf courses and tourist attractions were developed rapidly while the regulatory agencies and infrastructure struggled to keep up. The agency guidance and public testimony presented at public hearings were largely ignored, the environmental impact and assessment process was routinely violated and regulatory enforcement was insufficient to prevent substantial increases in erosion and sedimentation from poor land use practices. Foreign laborers brought in under the H-2 visa program, many of whom did not speak any English, were unaware of local fishing and collecting regulations, and often used destructive fishing practices. The results of these problems included user conflicts, failed infrastructure (power, water and sewer), extensive runoff and sedimentation from land clearing, and substantial impacts to coastal coral reefs and associated resources. While numerous damaging projects and examples of governmental failures to require and enforce adequate mitigation measures abound, the key outcome of value is the lesson learned that these islands need to address carrying capacity issues, develop and implement a more effective planning and review process, and communities need to have the political will to manage the next episode if there are to be robust coral reefs left as a legacy for future generations. Promises of economic sustainability were made that never occurred and environmental losses were substantial. As these islands prepare for a major increase in military activity due to base closures in Asia, adequate environmental precautions are critical to limit future losses.

19.8.3 Fouha Bay, Guam

Fouha Bay in southern Guam is an excellent example to illustrate the plight of coastal coral reefs throughout the world that are impacted by runoff and sedimentation. Runoff often contains a variety of toxicants, including hydrocarbons, pesticides and heavy metals. Freshwater alone can reduced the success of coral spawning events by osmotically stressing coral gametes and larvae, and the addition of pollutants can affect corals and other coral reef organisms at all life history stages (Richmond et al. 2007). Sediment can affect coral reefs through direct physical abrasion and burial, attenuation of light necessary for zooxanthellae to photosynthesize, through the burial of infaunal bioturbating organisms leading to localized anoxic conditions, and as a carrier of toxicants from land. Development has continued to be a concern in the absence of adequate efforts at integrated watershed management. Fouha Bay, on the southern shore of Guam, was studied in the 1970s and again from 2002 to 2005, and the results provide clear documentation of the impacts of runoff and sedimentation on coastal coral reef ecosystems (Table 19.2).

Fouha Bay receives inputs via a small river from a watershed of approximately 5 km^2. Suspended sediment concentration exceeded 500 mg l^{-1} for a few hours following rain events and can even reach more than 1,000 mg l^{-1}(Wolanski et al. 2003b). River floods are usually very short, typically lasting only a few hours. A near-surface river plume is formed that spreads throughout Fouha Bay (Fig. 19.8). As the tidal currents are weak, the main flushing process for the river plume is the baroclinic current driven by the river discharge. Also this current is weak, typically only a few centimeters per second and only exists during the river flood. Thereafter, the river plume floats passively over the oceanic waters in Fouha Bay. The residence time of the river plume in Fouha Bay – which is only 400 m in size – is large (>1 day). During that time over

75% of the fine riverine sediment flocculates and settles out from the near surface plume, in the process smothering corals and forming a near-bottom nepheloid layer. This sediment is resuspended by swell waves that occur during the passage of a hurricane (typhoon) in the surrounding ocean. During such events the suspended sediment concentration reached 2,000 mg l^{-1} for several days (Fig. 19.14). Coral reef ecohydrology models suggest that such events are harmful to corals and prevent coral regeneration (Wolanski et al. 2004).

19.9 Conclusions

The southern Mariana Islands have well-developed coral reefs that are presently subjected to a variety of stresses of natural and anthropogenic nature.

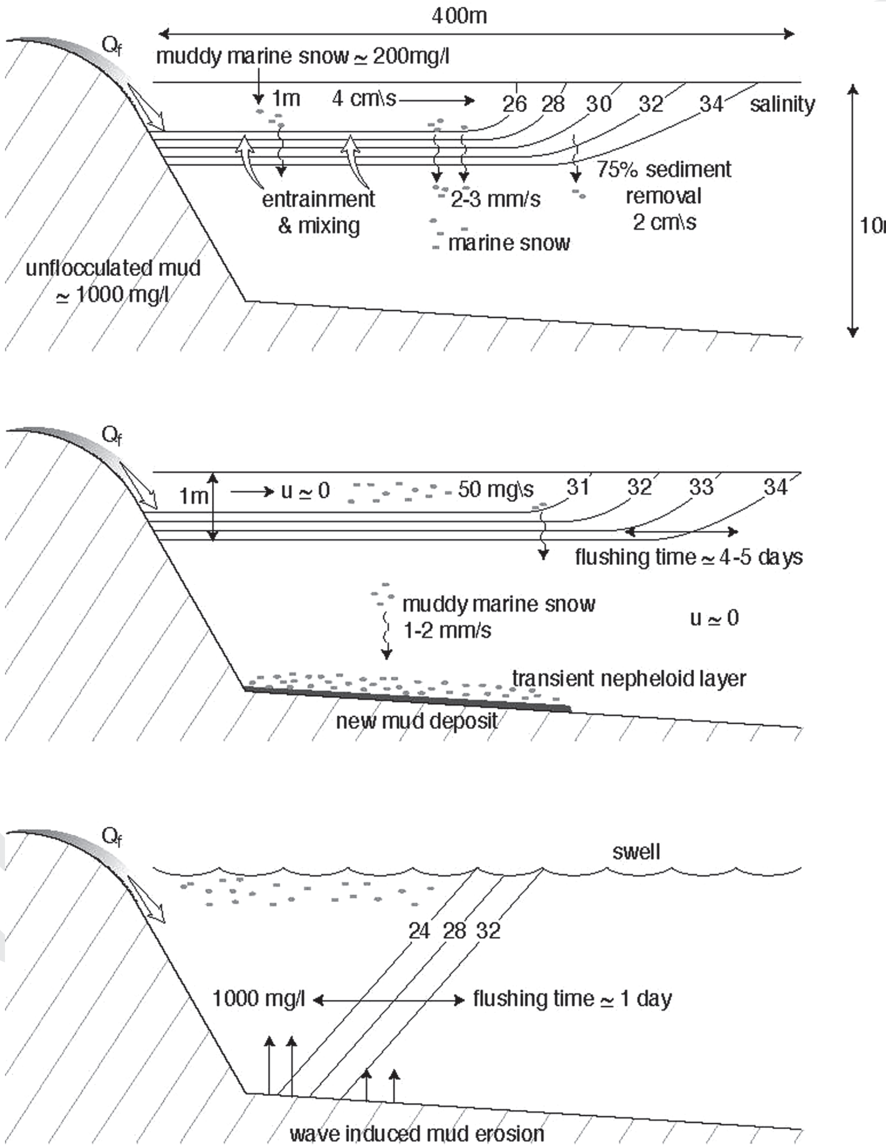


FIG. 19.14. Sketch of the dynamics of river and fine sediment in the transient river plume in Fouha Bay (top) during the river flood in calm weather, (middle) after the river flood in calm weather, and (bottom) during the river flood under a typhoon-driven swell (Reproduced from Wolanski et al. 2003b by permission of Elsevier)

They harbor one of the richest coral reef faunas in the USA. Coral reefs respond in their development to structural constraints by antecedent topography formed by early Holocene and Pleistocene reefs. Nature of bedrock is an important determinant of sedimentation stress, which is higher in areas of igneous rocks that weathers to lateritic soils and is vulnerable to erosion after deforeststaion. Fouha Bay in southern Guam is a case study for reefs under sedimentation stress. Natural impacts that have led to degradation of coral reef resources were outbreaks of crown-of-thorn starfish in the 1970s and 1980s as ell as the passage of typhoons. Increased development pressure has created significant decline of coral reefs and associated resources and forced the regulatory agencies to learn many valuable lessons. Efficiency of coral reef governance has improved but many challenges remain.

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