Chapter 28

The Samoan Archipelago

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28.1 THE DEFINED REGION

28.1.1 Geography, Topography, Geological Description

The Samoan Archipelago consists of a nearly east–west chain of islands plus one small atoll to the north. It is located in the central South Pacific, about 14 degrees south of the equator. The western half of the chain is the Independent State of Samoa (previously called Western Samoa), and the eastern half is the US Territory of American Samoa (Fig. 28.1). Independent Samoa includes the western most island which is also the largest, Savai'i, and Upolu, the second largest island. American Samoa's largest island is Tutuila. Just south of that is Aunu'u, east of which is a group of three small islands called "Manu'a," two of which are connected by a bridge and surrounded by a single continuous reef. To the east of that lies a small atoll, Rose (Muliava), and to the north lies Swains Island which is a slightly raised atoll with a closed, brackish lagoon. The latter are all parts of American Samoa (see Fig. 28.1).

The archipelago rests on a hotspot on the Pacific Plate, which moves westward about 7 cm per year. The hotspot is presently located under an active submarine volcano named Vailulu'u located east of Ta'u. Ta'u is 70,000-years old, and the progression of islands westwards increase in age to 5 million years old at Savai'i (Koppers et al., 2008), consistent with the hotspot and plate motion hypothesis. Younger larva eruptions occur on some of the older islands. Savai'i is a broad island with gentle slopes, but the rest of the volcanic high islands are mostly quite steep, with relatively frequent small landslides and stream deltas composed of small basalt rocks on top of the carbonate reef flat. The south side of Ta'u is crescent shaped and was produced by a gigantic slide of rock that has been dated to 22,000 years ago (Williams et al., 2014). Ofu and Olosega are the remains of a single volcano from which the north and south sides slid off into deep water (Hart & Jackson, 2014).

Tutuila and Ofu-Olosega have submerged shelves around them, about 30–100 m deep, and up to 1–4 km wide. At the outer edge the shelf drops off steeply, in some areas as a vertical cliff extending from 100 to about 450 m deep. The shelf has an interrupted ring of banks inward from the edge which appears to be a drowned barrier reef. On southwestern Tutuila, there are lava flows on top of the shelf that are younger than the shelf (Fig. 28.2).

Some of the island shorelines in the archipelago have fringing reefs (Figs. 28.3 and 28.4A–C.). Swains Island also is surrounded by fringing reef, extending as reef flat from the shoreline. On Tutuila, reef flats (Fig. 28.4B) extend along about half the coast and average about 116 m wide (Gelfenbaum, Apotsos, Stevens, & Jaffe, 2011). Swains does not have coral on its reef flat, which appears mostly to be slightly higher than extreme low tide levels. Typically, the reef crest has a mixture of corals and coralline algae although those of Rose Atoll and Swains Island are composed of only coralline algae. In most areas, the upper forereef slope is gradual, with deep surge channels that run down the slope (Fig. 28.4C). The reef slope often has the highest coral cover on the reef, and ends at about 10–30 m deep where there is a nearly flat shelf, but extends further downward on Ta'u, Swains, and Rose (Vroom, Page, Kenyon, & Brainard, 2006; Fig. 28.3).

For more information on the geology of American Samoa and additional references, see Birkeland et al. (2008), Fenner (2016), and Hart et al. (2004) Hart and Jackson (2014).

28.2 PHYSICAL OCEANOGRAPHY

During the austral winter, trade winds blow the east, and more wave energy strikes the south coast than the north. American Samoa lies in the South Equatorial Current, which has warm water flowing westward, and a deep thermocline at about 120–200 m deep. Sea surface temperatures in the Samoan archipelago average about 29–30°C in the austral summer and 27–28°C in the austral winter. Conditions differ with latitude, so the sea surface temperature (SST) at Swains is warmest.

World Seas: An Environmental Evaluation. https://doi.org/10.1016/B978-0-08-100853-9.00052-X

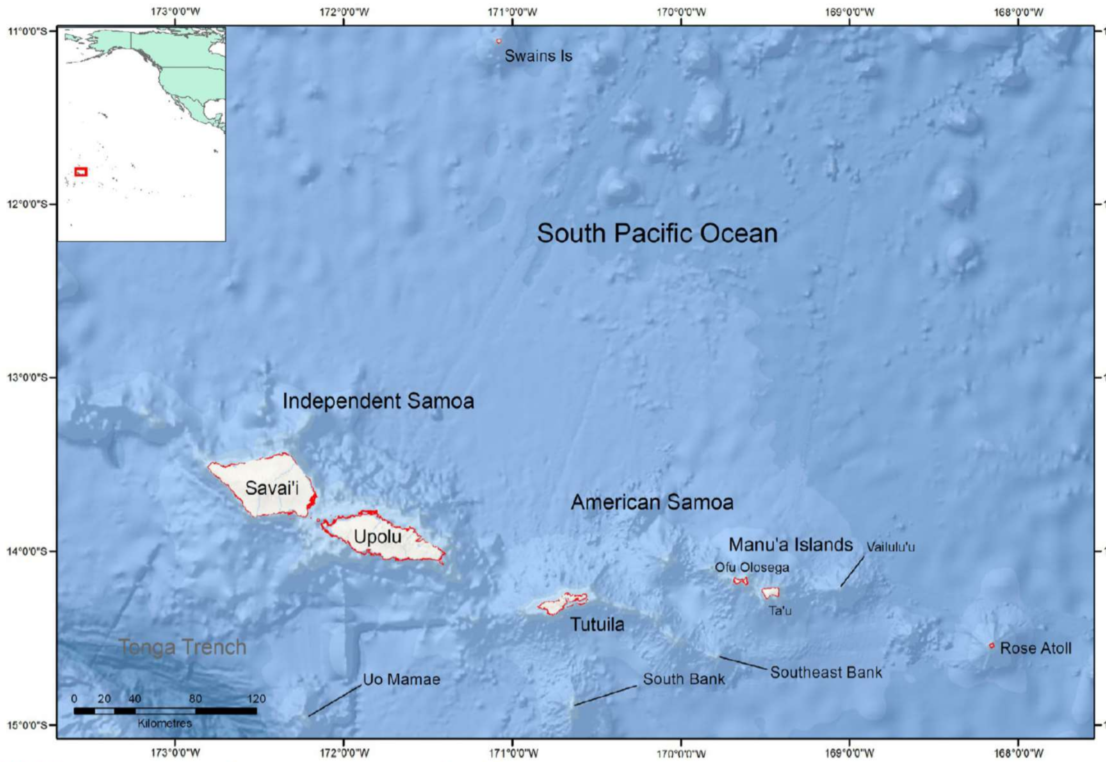


FIG. 28.1 The Samoan Archipelago. The Independent State of Samoa used to be called Western Samoa.

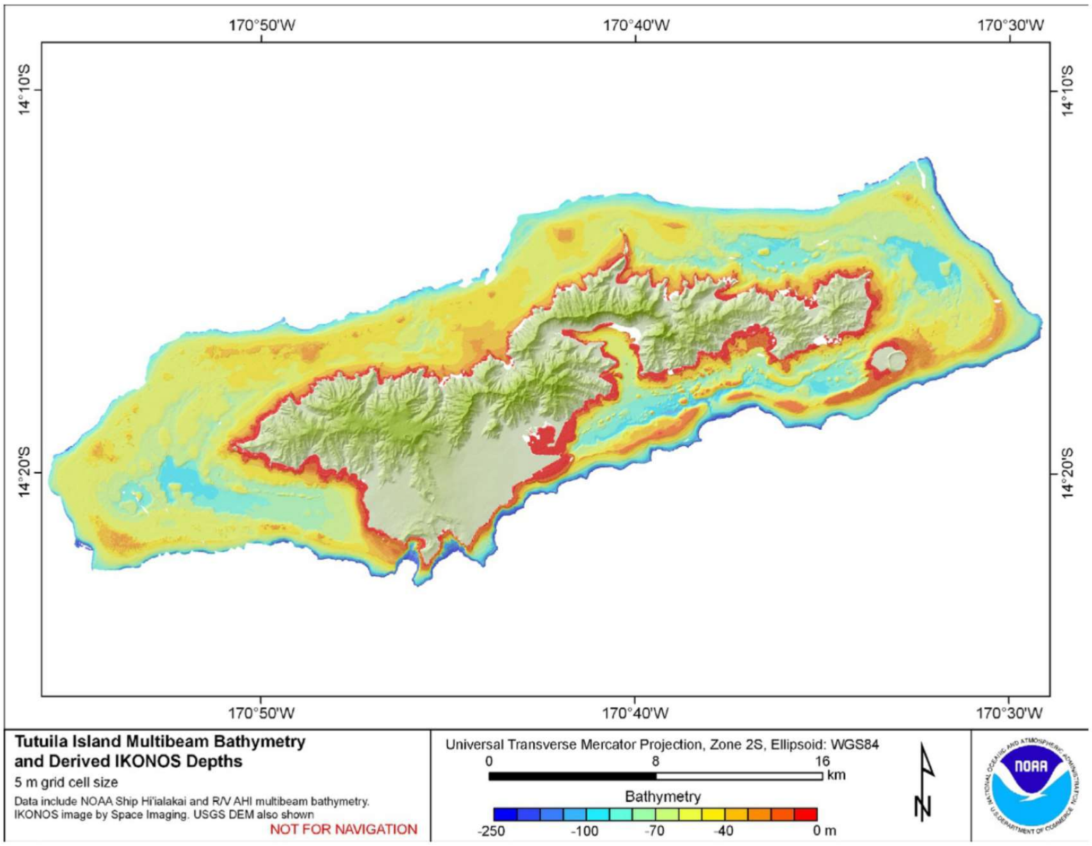


FIG. 28.2 The shelf and sunken barrier reef around Tutuila. Downloaded from ftp://ftp.soest.hawaii.edu/pibhmc/website/data/amsamoa/bathymetry/Tut_bathymetry_mb&IKONOS.jpg.

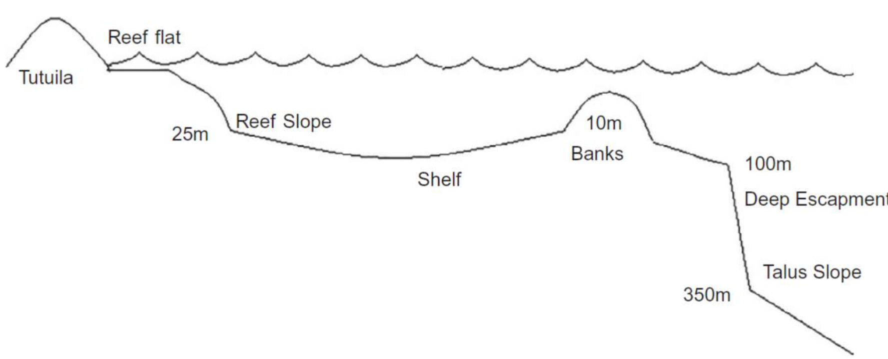


FIG. 28.3 Schematic reef profile for the south side of Tutuila. Vertical scale exaggerated. *From Fenner, D., et al. (2008). The state of coral reef ecosystems of American Samoa. In Waddell, J. E. and Clarke, A. M. (Eds.), The state of coral reef ecosystems of the United States and Pacific freely associated states: 2008. NOAA technical memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team, Silver Spring MD, pp. 307–351.*

FIG. 28.4 (A) A photograph of the reef in the National Park on the south side of Ofu Island showing the back-reef pools near shore, the reef flat, the crest (surf zone), and the upper reef slope with surge channels. Light green or blue areas are sand. (B) Reef flat on the south side of Tutuila at low tide. (C) A reef on the north side of Upolu, showing the wide but shallow lagoon, the reef flat, crest, and reef slope.

Oceanic conditions are relatively stable, but more variable to the north and south of the archipelago. The archipelago is in oligotrophic oceanic conditions and shows the "Island Mass Effect" of having slightly higher nutrient levels around the islands. Sea level has been rising at a rate of 2 mm per year since 1948, and shows temporary lowering of about 20–25 cm during strong El Niño years (Pirhalla, Ransi, Kendall, & Fenner, 2011). The oceanography of the Samoan Archipelago is considered in more detail in Brainard et al. (2008), Pirhalla et al. (2011), and Gove et al. (2016, 2013).

A National Oceanic and Atmospheric Administration (NOAA) study with drifter buoys in 2002–2004 showed that in 45 days, most buoys drifted less than 550 km from their starting point, and did not reach any other archipelagoes. Most did not get close to land during their travel (Craig & Brainard, 2010).

Horizontal water clarity on Tutuila was about 25 m and showed no trend from 2005 to 2012 (Fenner, 2013b). Water clarity farther off shore increases, perhaps to ca. 40 m, but was not measured. In Pago Pago Harbor which is narrow and nearly cuts Tutuila in two, there is little flushing and the water is often green in the harbor indicating nutrient buildup. Water clarity is lowest at the head of the harbor, with Secchi Disk readings of 3 m, and increases toward the mouth of the harbor, where readings of 20 m were recorded (Fenner, 2008).

28.3 NATURAL ENVIRONMENTAL VARIABLES, SEASONALITY

28.3.1 Climate, Freshwater Discharges

Heavy rainfall often comes in short bursts with little seasonal variation. The size of streams and rivers are proportional to the size of the islands. Runoff with silt floats on the saltwater and, outside the reef, the silt-laden fresh water is mixed so that sediment is diluted and some settles to the bottom. Sedimentation inside bays is greater than outside bays.

28.4 MAJOR COASTAL AND SHALLOW HABITATS

28.4.1 Coral Reefs

Most of the coral reefs of the Samoan archipelago are fringing, but Rose Atoll (Muliava) is an atoll with a lagoon, Tutuila is surrounded by a drowned barrier reef in addition to the fringing reef, and Upolu and Savai'i have wider barrier reefs with very shallow lagoons. All are discontinuous. Ofu has natural back-reef pools with a high diversity of corals, dominated by massive *Porites* (Craig, Birkeland, & Belliveau, 2001). The coral communities of dredged back-reef pools on Tutuila are typically dominated by staghorn and finger corals (Fig. 28.5A), have low diversity, and sandy areas.

The forereef slopes in some areas are more gentle and encrusting *Montipora* is the most common coral (Fig. 28.5B). Slopes often have a diversity of corals and can reach high coral cover (Fig. 28.5C and D). The reef slopes of American Samoa have few vertical "walls."

The first transect ever taken on coral reefs in the Pacific (and second in the world) was taken by Alfred Mayor on reef flats in Pago Pago Harbor in 1917. At that time, it had abundant coral. It had less coral in 1974, which continued to decline until the 1990s, by which time there was a borrow pit near shore, most of the reef flat was covered with dead coral rubble, and only the crest area had live coral. It has remained that way since then (Birkeland, Green, Fenner, Squair, & Dahl, 2013). Another transect taken at the same time in the harbor by Cary originally had a high soft coral cover, but by the time that transect was repeated in 2003, there was no soft coral cover left (see Craig, DiDonato, Fenner, & Hawkins, 2005). All reefs in the inner half of the harbor have been dredged, built over, or are now degraded. More extensive monitoring by Charles

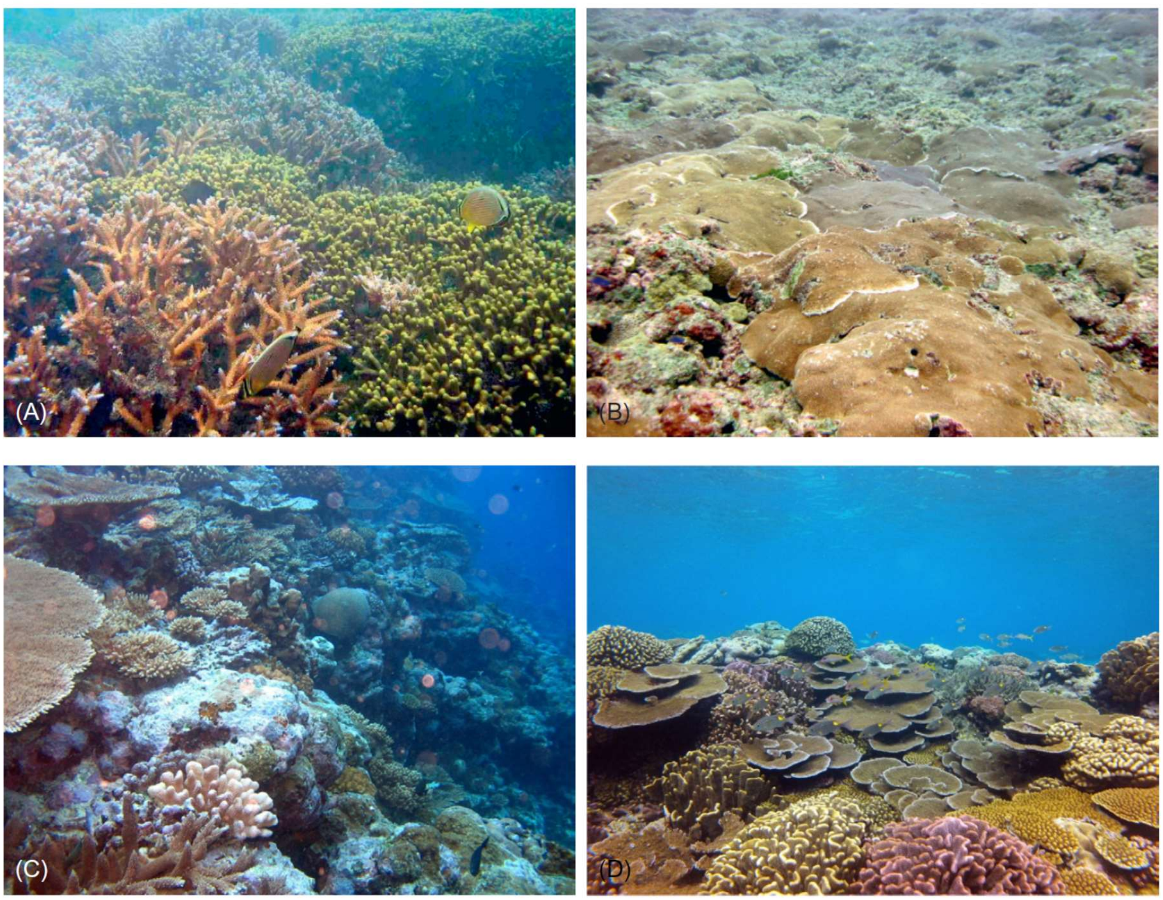


FIG. 28.5 (A) Staghorn and finger coral in a back-reef pool on Tutuila at Alofau. (B) Reef slope on Ta'u Island illustrating encrusting *Montipora grisea* colonies that are the most common coral on Tutuila. (C) A reef slope on Aunu'u Island with coralline algae and high coral diversity. Photos copyright Douglas Fenner. (D) An area of exceptionally high coral cover in Fagatele Bay, American Samoa National Marine Sanctuary, Tutuila. *Photo by Wendy Cover, copyright by NOAA.*

Birkeland and Alison Green was begun on Tutuila after the mass outbreak of crown-of-thorns starfish that peaked in 1978, and coral cover showed large fluctuations (Craig et al., 2005).

Collection of annual benthic cover data along with more continuous observations began with the Department of Marine and Wildlife Resource (DMWR)'s Territorial Coral Reef Monitoring Program in 2005, supported by the NOAA Coral Reef Conservation Program. Spatial variation was very high (Fig. 28.6A and B.). Coral cover averaged 28%, crustose calcareous algae (CCA) averaged 35%, turf algae averaged 16%, and macroalgae averaged 2% in 2005. Four other benthic surveys using transects but different methods and sets of sites in 2006 reported coral cover ranging from 24% to 35%, averaging 28% (graph shown in Fenner et al., 2008), and all reported high CCA cover. Other monitoring programs replicated these findings with different sites. Observation showed that coralline algae are present at some sites on the north side, above a depth of about 3 m, with a pattern driven by water motion. In Fagatele Bay, coralline algae cover is very high down to at least 18 m deep; wave surge which favors coralline algae is especially strong in the bay.

Changes with time over the period of 2005–2012 were small and gradual, with a gradual increase in coral cover from 29% to 36% (Fig. 28.6B). Coral cover increased (smoothly), particularly in the later years.

In the National Park, which includes about a third of the north coast of Tutuila, data showed a significant increase in coral cover from 2007 to 2015 (Brown et al., 2016).

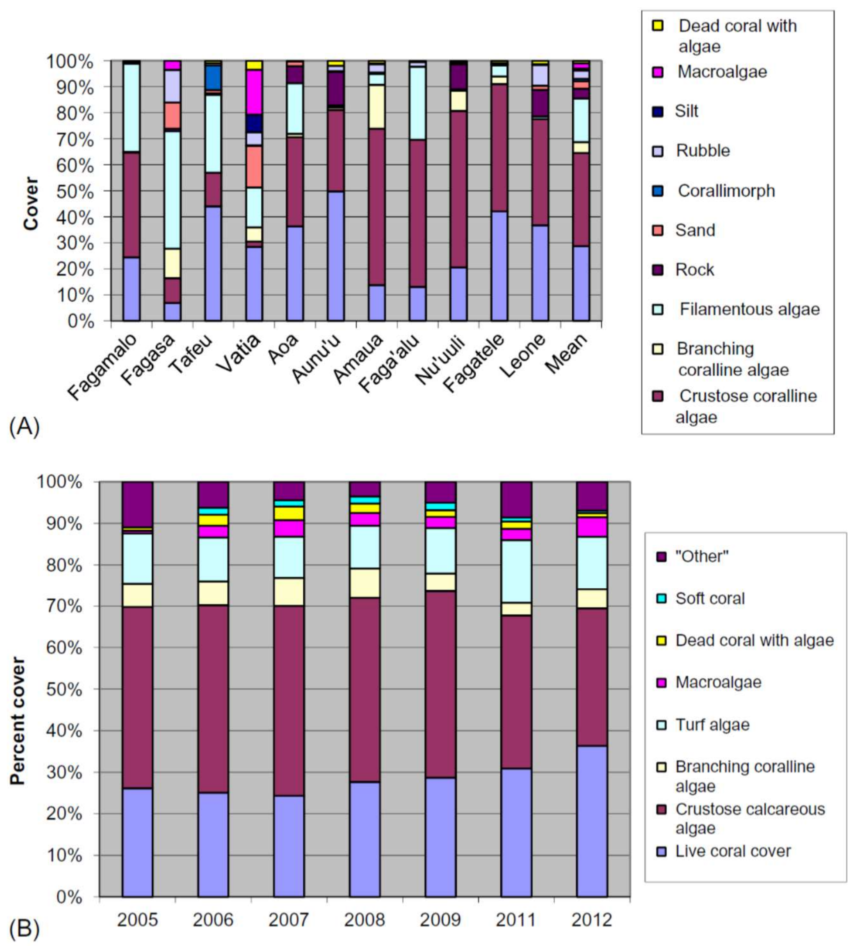


FIG. 28.6 (A) Benthic cover by site, Tutuila and Aunu'u, 2005. Sites are ordered starting on the left with the westernmost site on the north shore and going clockwise to Aoa on the northeast, Aunu'u Island to the southeast of the island and Leone to the southwest of the island. Data from point-intercept transects taken at 8.5 m depth, from Whaylen and Fenner (2006). (B) Trends in benthic cover on Tutuila reef slopes from 2005 to 2012, from Fenner (2013a). Insufficient data were taken in 2010 to be included.

The NOAA CRED (Coral Reef Ecosystem Division) visited each US Pacific archipelago to collect monitoring data every 2 years, and now every 3 years. Averages for the US Pacific archipelagos presented in Vroom (2010) based on towed-diver surveys were 22% coral cover for American Samoa, 17% for the Marianas, 29% for the US Pacific remote islands, 13% for Hawaii, and 19% for the uninhabited near-pristine islands of Hawaii, the Marianas Islands, and the remote US islands combined. Tutuila and American Samoa have relatively good coral cover in comparison to many places (Fenner, 2013b). Fig. 28.7A shows coral cover trends for each of the islands in American Samoa based on NOAA towed-diver surveys.

Another index of reef health is the ratio of live coral cover to live plus dead coral cover. American Samoa averages over 90% of the coral alive, with no trend over years. This is higher than figures for the world and Indo-Pacific (Reef Check), the Philippines, Indonesia, and the South Pacific (Bruno & Selig, 2007; Fenner, 2013b).

Vroom (2010) (Fig. 28.2c) shows that in towed-diver transects, Tutuila had 18% macroalgae cover, other islands in American Samoa had similar cover except Swains which had 30% macroalgae cover, as did the other US Pacific archipelagoes, although there was wide variation from island to island. Fenner (2013b) found that live coral plus CCA covered about 70% of Tutuila slope substrate at about 8.5 m depth, and showed no trend over time. The cover of calcifying organisms (coral, CCA, branching coralline algae, and calcareous macroalgae) was about 75% in Tutuila, non-calcifying cover filled the remaining 25%, and there was no trend.

Fig. 28.8A shows that the two uninhabited islands in American Samoa have more reef building cover than the mean for all of the 39 uninhabited US Pacific islands and reefs, and each of the three inhabited islands in American Samoa have more reef building cover than the mean for the 17 inhabited US Pacific Islands.

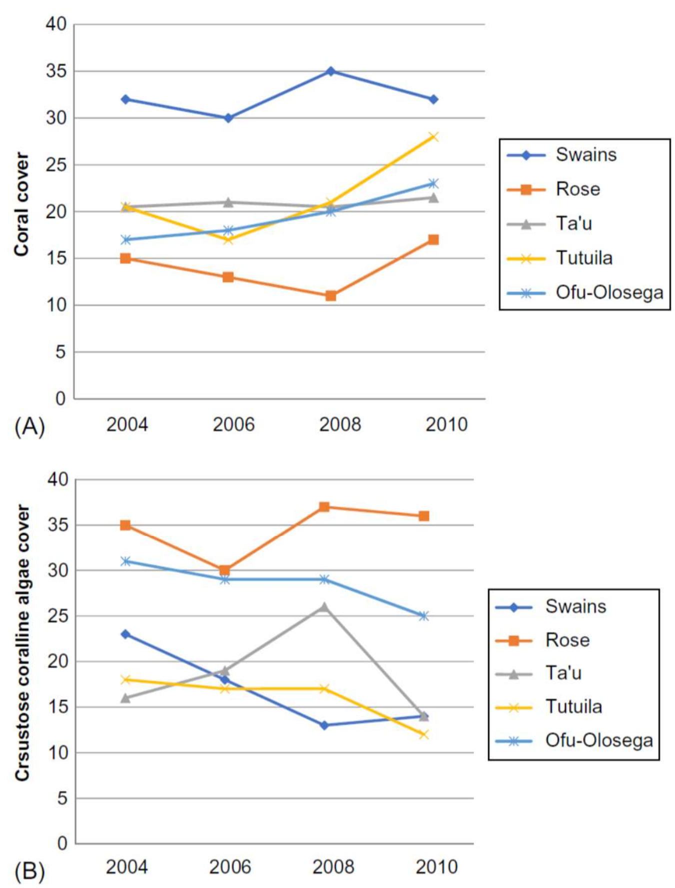


FIG. 28.7 (A) Coral cover trends for the islands of American Samoa, based on towed-diver estimates of benthic cover every 5 min. (B) Crustose coralline algae cover trends for the islands of American Samoa, based on towed-diver estimates of benthic cover every 5 min. *Redrawn from Pacific Islands Fisheries Science Center. (2011a). Coral reef ecosystems of American Samoa: A 2002-2010 overview. Honolulu: NOAA Fisheries Pacific Islands Fisheries Science Center, PIFSC Special Publication, SP-11-02, p. 48.*

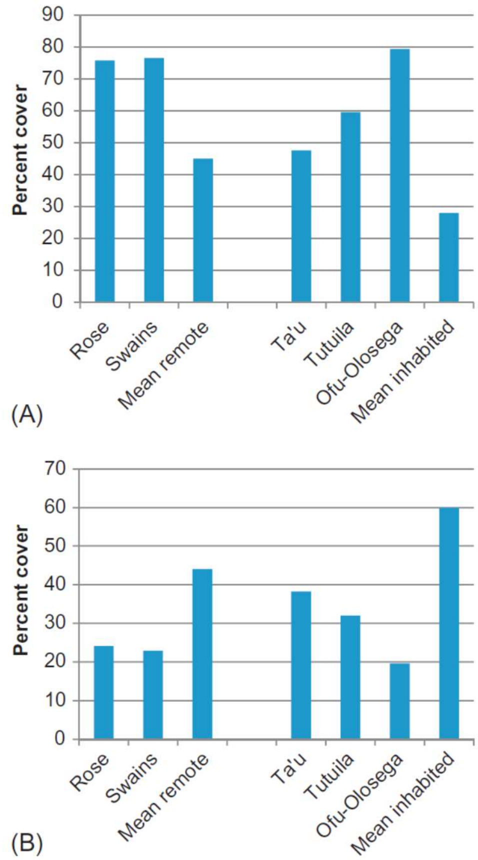


FIG. 28.8 (A) The cover of reef builders on American Samoa islands compared with the corresponding means for other US Pacific islands and reefs. (B) The cover of fleshy algae on American Samoa islands compared with the corresponding means for other US Pacific islands and reefs. *Redrawn from Smith, J. E., Brainard, R., Carter, A., Grillo, S., Edwards, C., Harris, J., Lewis, L., Obura, D., Rohwer, F. Sala, E., Vroom, P. S., & Sandin, S. (2016). Re-evaluating the health of coral-reef communities: Baselines and evidence for human impacts across the Central Pacific. Proceedings of the Royal Society B 283, 1–9, 20151985.*

Further, Fig. 28.8B shows that the fleshy algae cover (turf plus macroalgae) of each of the uninhabited American Samoa islands is less than that of the uninhabited island mean, and the fleshy algae cover of American Samoa inhabited islands is less than the inhabited island mean (Smith et al., 2016).

Benthic cover data were also taken at 4.5 and 18.5 m depth at five sites on the south side of Tutuila, one north side site, and the one site at Aunu'u. The average for these sites is shown in Fig. 28.9, combined with reef flat data separated into inner reef flat and outer reef flats. Coral cover increased from inner reef flat to outer reef flat but did not change with depth on the reef slope. Turf algae cover was much higher on the reef flats than slopes. Coralline algae cover was much greater on slopes than on reef flats, and decreased on the reef slopes with depth (Fenner, 2009) (Fig. 28.9).

Corals have also been found at mesophotic depths in American Samoa, from 30 to 110 m deep. Hard substrate covered most of the bottom in the shallow part of this depth range, while unconsolidated sediments (predominantly carbonate) covered the shelf. Coral cover was highest on the tops of patch reefs and banks at 30–50 m deep, and macroalgae cover highest near shore and on the slopes of banks at 50–60 m. Encrusting *Montipora* and massive coral such as *Porites* were more abundant in shallow parts of this depth range than deep. Table and plate corals were most abundant at 60–70 m depth. Branching coral cover was high in the 80–110 m depth range (Bare et al., 2010).

Rose Atoll has the only deep lagoon in the archipelago. Towed-diver data indicated the outer reef slopes of Rose Atoll (Muliava) averaged 22.6% coral cover, while the lagoon floor and perimeter had 0.4% coral cover. While the outer slopes were dominated by coralline algae with 55%–67% cover, lagoon pinnacles were dominated by turf algae. Coral communities were quite different in the lagoon from the reef slopes (Kenyon, Maragos, & Cooper, 2010).

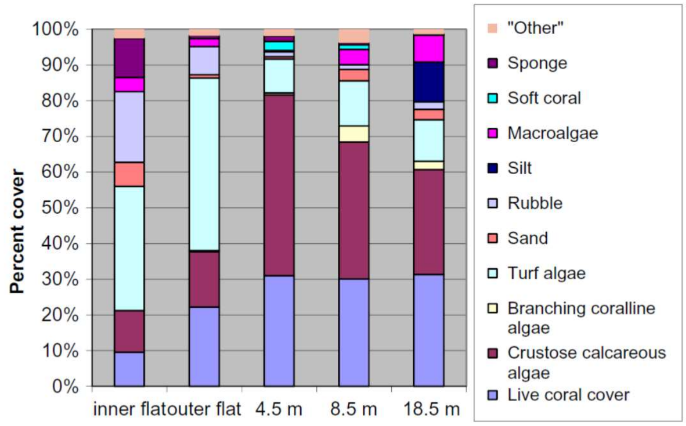


FIG. 28.9 Average cover by zone across the reefs on Tutuila.

The total number of coral genera per island recorded in 2004 and 2006 varied according to the total bank top area for each island. It was highest on Ofu-Olosega, slightly lower on Tutuila and Ta'u, clearly lower on Rose, and clearly lower still on Swains (Brainard et al., 2008). A *Porites lutea* colony on the southwest coast of Ta'u is about 7 m tall and 41 m in circumference (Brown et al., 2009). A 6 m core from the colony begins at the year 1470 CE, but based on the additional height of the colony, the colony is estimated to be about 800 years old total (R. Dunbar, personal communication).

28.4.1.1 Diversity

A total of about 2700 marine species have been reported in American Samoa so far (listed by group, in Fenner et al., 2008), but that figure is heavily dependent on the amount of effort expended on each group. About 1000 fish species have been reported (Wass, 1984; P. Brown personal communication) and with only few additional species being reported, the fish fauna is probably well known. A field guidebook illustrates common invertebrates on the reef flats (Madrigal, 1999). Fenner (2016) has verified only about 250 corals so far from skeletons, from the 400 names that have been claimed for the region. Brown (2011) reported 385 species of gastropods in 50 families; about 222 species of eukaryote algae and two species of seagrass are known and 360 species of eukaryote algae, while three species of seagrass are known from Independent Samoa (Skelton, 2003; Skelton & South, 2004, 2006, 2007; P. Skelton, personal communication). If blue-green algae (cyanobacteria) are added, the total for the archipelago is probably to be about 500 species (P. Skelton, personal communication). American Samoa has 45% of the coral species that the Coral Triangle has, 42% of the coral species on reef crests, and 23% of the coral species on reef flats (Karlson, Cornell, & Hughes, 2004).

Kendall et al. (2011) distinguished 30 distinct biogeographic regions within the archipelago, and 51 hotspots within it. They reported that the sparsely populated islands of Manu'a (Ofu-Olosega and Ta'u) and Savai'i generally had higher values of several variables than the more densely populated islands of Tutuila and Upolu, and within Upolu and Tutuila the densely populated areas around Apia (the only city in the archipelago) and Pago Pago Harbor have many of the sites with the lowest values of the measured variables. Fish showed generally smaller biogeographic differences among sites than corals. The relatively isolated Swains Island had very different fish and coral communities. Rose Atoll, a small island isolated from upstream larval sources had relatively low coral and fish richness. There were general trends in the archipelago of increasing coral cover, richness, and fish biomass toward the west, consistent with islands to the west being downstream from those to the east (Kendall, Poti, Wynne, Kinian, & Bauer, 2011), and being larger.

Giant clams are uncommon to rare on outer reef slopes of all of the islands of American Samoa, but are common on pinnacles in the lagoon at Rose Atoll (Muliava) (Green & Craig, 1999). Giant clams continue to be rare outside Rose Atoll lagoon (Brainard et al., 2008). They are least common on the most densely populated islands of Upolu and Tutuila, which supports the view that they are overfished there (Green & Craig, 1999). Fishermen have reported a decline in giant clam stocks, and fishing statistics show a decline in catch over two decades (references in Green & Craig, 1999).

The shelled cephalopod, *Nautilus pompilius*, is found in the Samoas. Shells found are slightly different from those in other areas (Saunders, Bond, & Itano, 1989). Surveys found that American Samoa had 1.48 Nautilus per km, which was not significantly different from Fiji and Australia (Barord et al., 2014).

A green colonial ascidian (sea squirt), *Diplosoma similis*, was recorded to have covered large areas of the reef at Swains in 2006 and 2008, growing over living coral (Vargas-Ángel, Godwin, Asher, & Brainard, 2009). The average ascidian cover increased from near zero in 2004 to over 15% in 2006, then over 20% in 2008, and returned to near zero in 2010. However, live coral cover remained steady from 2004 to 2010 (Pacific Islands Fisheries Science Center, 2011a).

Filter feeders are uncommon and/or small in American Samoa, outside of the harbor. Filter feeding bioeroders such as boring sponges and burrowing clams are also uncommon, as are large urchins. There appears to be low levels of bioerosion. In the harbor, there are filter feeding oysters along the water line and a sponge community in deep water, feeding on water green with plankton.

Green sea turtles nest on Rose Atoll, with a very small number nesting on the other islands of American Samoa. Most of those adults spend most of the year feeding in Fiji, where seagrass beds are much larger and denser than in American Samoa. Immature hawksbill turtles can be seen in shallow water, but adults are rarely seen.

Eleven species of marine mammals have been found in American Samoa, such as resident porpoises. Humpback whales which feed off Antarctica in the austral summer–winter in the Samoan Archipelago where they calve and mate (citations in Fenner et al., 2008; Craig, 2009).

28.4.1.2 Disease

Coral diseases are widespread in American Samoa and present at most sites (Work & Rameyer, 2005), but only a very small proportion of colonies are affected (0.14%). So far, a total of 15 coral diseases have been reported. White syndrome (which is often fatal to the coral) and growth anomalies are the most common diseases on Tutuila. Disease prevalence (percentage of colonies infected) varies among coral genera, with *Acropora* having the highest prevalence, and among islands, with growth anomalies most common on Ta'u and Tutuila and least common at Rose (Aeby, Work, Fenner, & DiDonato, 2009; Fenner et al., 2008).

On all islands of American Samoa disease was found at an average of 63% of all sites, with Rose, Ta'u, and Swains having 81%, 88%, and 100% of sites affected, respectively. Only 55% of sites on Tutuila, Ofu, and Olosega had disease. The mean prevalence was 0.34% which is at least an order of magnitude lower than in the Caribbean and Great Barrier Reef. Four groups of disease state were found: bleaching, growth anomalies, band disease, and "other lesions." Growth anomalies were most common around Ofu-Olosega and affected *Acropora abrotanoides* and *Acropora cytherea* the most. Bleaching was most common around Ofu-Olosega and all lesions were small and focal. Only six instances of tissue loss were recorded, and one of black band. Of the 45 coral genera recorded in the study, 15 showed disease and/or predation. *Acropora*, *Astreopora,* and *Montastrea* were the most commonly affected genera. *Acanthaster* (starfish) and *Drupella* (snail) predation was most common on Rose followed by Swains, with lower frequencies around Tutuila and Ofu-Olosega (Brainard et al., 2008). The most recent survey of diseases, in 2015, also found a low percentage of colonies with disease (NOAA PIFSC, 2015).

Acropora white syndrome was less prevalent in Tutuila, where coral diversity is high, than in the Northwestern Hawaiian Islands, where coral diversity is low. The severity of this disease and mortality rates were higher in Hawaii than American Samoa (Aeby, Bourne, Wilson, & Work, 2011), which is consistent with the more general finding that disease prevalence is reduced in more diverse ecosystems. One disease in American Samoa, a dark color patch on some species of *Pavona*, was found to be associated with fungal filaments growing up from the skeleton into the coral tissue (Work, Aeby, & Coles, 2008; Work, Aeby, Stanton, & Fenner, 2008). The distribution, morphological variety, and prevalence of growth anomalies on *Acropora* colonies in American Samoa are greater than in Hawaii and Johnston Atoll (Work, Aeby, & Coles, 2008; Work, Aeby, Stanton, & Fenner, 2008).

During coral bleaching events in 2002 and 2003, formerly rare coral diseases such as white syndrome were observed to be even more common (Craig et al., 2005). A few small outbreaks of disease have been recorded on Tutuila in recent years. An outbreak of a disease that produced white and yellow areas on a group of about 100 *Porites rus* colonies in the back-reef pool in front of Vaoto Lodge on Ofu was observed in November 2011. A few years later, there were only a few little patches of living tissue remaining on a few colonies. Disease is common on *Pocillopora* colonies on reef slopes, as are dead colonies. It appears that this disease is endemic and continuous (Fenner, 2011).

Coralline algae are also subject to diseases, with five such diseases known in American Samoa. Coralline lethal orange disease (CLOD) is by far (97%) the most common disease recorded. It is by far the most abundant on Ofu-Olosega, followed by Tutuila, with much less at Ta'u, less still at Rose, and none at Swains. CLOD cases were found in clusters (Brainard et al., 2008). American Samoa has the most coralline algae disease of any of the US Pacific Island areas, and more than 70% of all lesions observed in a study of the 42 US Pacific Islands were found in American Samoa. However, coralline algae cover in American Samoa is so high that the amount of disease per unit of coralline algae cover is not as high as in the southern Marianas. Within American Samoa, the highest amount of disease per unit of coralline algae was on

Tutuila, Ofu-Olosega, and Ta'u, and the lowest at Rose Atoll. Coralline algae disease increased on Rose Atoll from 2006 to 2008, but changes were not statistically significant on other islands. Thus, American Samoa has both a large number of coralline algae disease cases and a relatively high diversity of these diseases, yet it does not affect the abundance of the coralline algae (Vargas-Ángel, 2010).

28.4.2 Crown-of-Thorns Starfish

Fishermen remember an outbreak of crown-of-thorns starfish on Tutuila around 1938. There was another on the south side of Upolu in 1969. Another outbreak on Tutuila in 1977–81 was particularly severe, and at one point, a population estimated at 83,000 was found on Taema Banks, where coral mortality was estimated at about 95%. Over 384,477 animals were estimated to be in just the Aoa to Oneonoa area of northeastern Tutuila in May 1978. A bounty was paid for starfish removal, and 486,933 were removed before funding ran out, but they were still abundant in April 1979, and did not decline until the following year. Most of western Tutuila was not affected, except in Fagatele Bay, where mortality was estimated to be 95%. Manu'a, Swains, and Rose were not affected (Green, 2002), but the outbreak occurred in Upolu, with a few reports in Savai'i as well. Outbreaks on Upolu continued for most of the 1980s, and appeared to increase in the mid-1980s on Savai'i (Zann & Bell, 1991). In 2002, there was a chronic population on the slopes of Ofu (Fisk & Birkeland, 2002; Green, 2002).

In November 2011, about 80 starfish were found on the south side of Tutuila near the airport, and populations slowly but steadily increased after that. Several agencies, led by the National Park, killed them with an auto-filling injection gun, removing 15,537 between March 2013 and October 2014. By about mid-2015, the park area on the north side of Tutuila was largely clear of them. The south side has not been surveyed (Clark, 2014). The culling campaign may have averted a major outbreak and coral damage.

In Independent Samoa, an outbreak of crown-of-thorns was reported from several villages after the 2009 tsunami. In 2005, the Marine Conservation Division of the Division of Environment and Conservation of the Ministry of Natural Resources and the Environment conducted surveys around selected areas of Upolu, Savai'i, and Manono Islands, and found crown of thorns at about 39 sites around Upolu, seven sites around Manono, and seven sites around Savai'i. A total of 1530 starfish were injected, 1174 being on the eastern side of Nu'utele Island (Marine Conservation Division of the Division of Environment and Conservation, 2015).

28.4.3 Physical Disturbances

The Samoan archipelago is periodically hit by hurricanes. Hurricane Tusi struck Swains Island in February 1987 and badly damaged the reefs, reducing coral cover to 0%–12% coral cover, except on the eastern side where a small area escaped damage. Nine years later (March 1996) coral had recovered to 45%–65% cover (Green, 1996). Houk, Musberger, and Wiles (2010) recorded a 5%–45% drop in coral cover from 2003 to 2005 on Tutuila, which they attributed to hurricane Heta which struck in early January 2004. The eye of Heta passed about 220 km west of Tutuila (Fenner et al., 2008) but was a category 5 storm and did significant damage on land. At Swains Island, wave heights during Heta were reported to reach 8 m. Damage to coral was greatest at the NW and SW points of the island, with live coral cover decreased as much as 52%, while damage on the northeast corner was lowest, as low as 0%. Average coral cover for the island decreased from 60% to 30%, and then 2 years later had increased to 45% (Brainard et al., 2008; Hoeke et al., 2009). Coral cover recorded by visual estimate from towboards decreased at all of the islands from 2002 to 2004 (after Heta), but towboard estimates in 2004 were substantially less than transect visual estimates for Tutuila, Ta'u, and Swains, raising questions about accuracy. The path of Heta, from northwest to southeast, took it closer to Tutuila than any other islands, and it was twice as far from Swains and Rose as from Tutuila (Fenner et al., 2008) suggesting that the data be viewed with some skepticism. When the author first viewed the reefs of Tutuila in 2005, no damage was apparent at monitoring sites.

Damage to reefs following a hurricane was also observed In American Samoa after Hurricane Wilma struck Tutuila in 2011. Wilma was category 1 strength and the only places damage was found were at Vatia Bay and Pola Island, on the north shore. The outer part of the bay sustained moderate damage (Fenner, unpublished observations), while the east side of Pola Island, just outside the bay, sustained heavy damage. Recovery in coral cover was recorded in subsequent years (Clark, Halperin, & Fuiava, 2015).

There are records of 59 tsunamis striking American Samoa before 2009, with the first in 1837 and the greatest runup height just 2.4 m (Dunbar & Weaver, 2015). On September 29, 2009 in American Samoa, an 8.1 magnitude earthquake occurred east of the Tonga Trench, about 200 km south of the Samoan archipelago. About 20 min later, a large tsunami struck Tutuila and Upolu. On land, there was massive damage in some restricted locations. On Tutuila, Pago Pago Harbor, Leone, Tula, Poloa, and Fagasa were among the villages hardest hit, while on Upolu the east coast and the central south coast of the island were hardest hit. The runup of the tsunami was over 12 m on Tutuila at Fagasa and Paloa and 7 m at Tula and the head of Pago Pago Harbor, while it was only about 2–3 m along much of the coast. Water went as far as 600 m inland (Jaffe et al., 2010). A different source reports the maximum runup was 18 m at Paloa, with 5.9 m on Olosega, and 12 m on western Ta'u (Dunbar & Weaver, 2015). A significant amount of debris from on land was deposited in some areas on the reef. Damage to reefs was concentrated to some restricted locations but mostly was not damaged. The tsunami had no detectable effect in the National Park Tutuila unit, which is on the north shore (Clark et al., 2015). In Fagatele Bay, there were a few large swaths of old coral rubble which were mobilized by the tsunami, with no corals on them after the tsunami. Within 6 months, the flows of rubble had 100% coralline algae cover (Fenner, 2011), presumably the first stage of recovery. Fagasa and Vatia could not be surveyed on the north owing of weather and boat ramp damage. The most debris was found in the southwest section of Tutuila, from Poloa to Leone.

A study of the effects of the tsunami on the eastern end and south-central coast of Upolu reported that damage ranged from severe where piles of dead corals were left to areas of little impact. At Vailoa on the east coast, the area covered by algae increased over time, but the live coral cover, which was high, did not change in the transects. Estimated fish catch did not change after the tsunami, but fish sales did show a brief reduction and then rapid recovery (McAdoo et al., 2011).

28.5 INTRODUCED AND ENDANGERED SPECIES

A study of introduced marine species found 28 nonindigenous or cryptogenic marine species in American Samoa, mostly in Pago Pago Harbor (Coles et al., 2003). None have been reported to be invasive, although the snowflake soft coral (*Carijoa riisei*) that is reported to be invasive in Hawaii is common on the docks in Apia Harbor, Upolu (P. Skelton, personal communication) and one colony has been found near the canneries in Pago Pago Harbor (Fenner, 2013b).

28.5.1 Species Extinction Risks

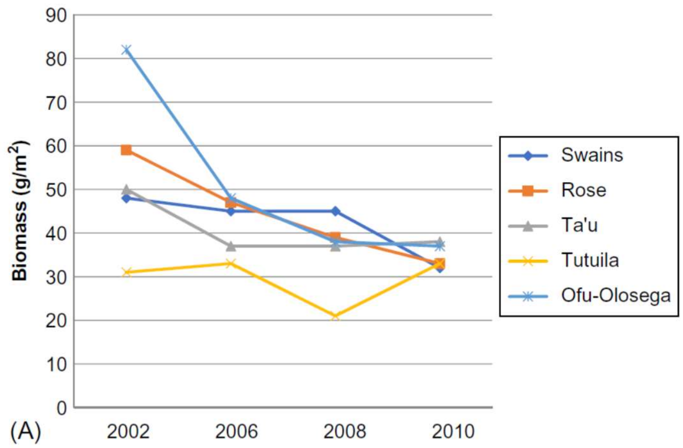
A study of the extinction risk of reef corals worldwide (Carpenter et al., 2008) reported that 75 coral species in the US Pacific waters were threatened to some degree. About 54 of the 75 species occur in American Samoa (Brainard et al., 2011). Kenyon, Maragos, and Fenner (2010) compiled records of which species were found in federally protected waters in American Samoa. Subsequently, NOAA listed 15 species as Threatened under the US Endangered Species Act, of which six have been found in American Samoa. Zgliczynski et al. (2013) reported 21 species of reef fish on Tutuila which have been listed as endangered or vulnerable on the IUCN Red List. American Samoa had the lowest abundance of large-bodied species listed as endangered or vulnerable of any US Pacific region, with 2 individuals km^{-2}. Among the small-bodied species listed, 5 of the 22 grouper species recorded in American Samoa were significantly more abundant on the uninhabited islands than the inhabited islands. The coral hind and blacktip grouper were rare or not recorded on the inhabited islands.

28.5.2 Fish

About 1000 fish species are known from American Samoa. The total fish biomass on each is less than the median for all the 39 islands and reefs in the US Pacific surveyed, and less than one-sixth that at the highest biomass reefs (NOAA Pacific Islands Fisheries Science Center, 2011a, Fig. 28.6). This contrasts with coral cover (see earlier).

The total reef-fish biomass at mid-depths on the reef slope decreased markedly at Rose Atoll and Ofu-Olosega from 2002 to 2010, and was relatively steady throughout the monitoring period for the other islands (Fig. 28.10A). By biomass, over half were primary consumers on the high islands of Tutuila, Ofu-Olosega, and Ta'u, mainly composed of parrotfish and surgeonfish, with primarily small- and medium-size species in those families. The detritus-eating striped bristletooth (surgeonfish, *Ctenochaetus striatus*) has the largest biomass of any species. Primary consumers have a lower proportion of the biomass at Swains than at the other islands, with only 12%–25% of total biomass at Swains compared with 34%–67% at all other islands. Parrotfish composed only 2% of the biomass at Swains, compared with 11%–21% of the biomass at other islands (NOAA PIFSC, 2011a). Less than half of the total biomass of these fish communities was composed of secondary consumers (omnivores and invertivores), planktivores, and picivores, combined. This contrasts with many remote, near-pristine reefs, where apex predators alone are the largest group by biomass, sometimes composing half or more of all the biomass.

The NOAA CRED program fish data have been divided into browsers, grazer/detritivores (bristletooth surgeonfish, *Ctenochaetus*), scrapers/small excavators (small bodied parrotfish), and large excavators/bioeroders (large-bodied parrotfish). The biomass of browsers is low, and the biomass of grazers/detritivores is much larger. Swains has low biomass of all herbivores. Macroalgae and turf cover decreased with increasing biomass of grazer/detritivores. Encrusting algae increased with increasing biomass of grazer/detritivores and browsers. Hard coral increased with increasing biomass of large



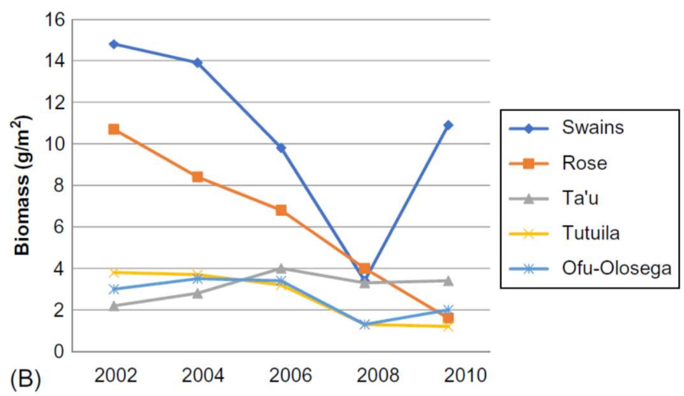


FIG. 28.10 (A) Trends in reef fish total biomass, by island, based on belt transects and stationary point counts at mid-depths on reef slopes. In the period from 2002 to 2008, the data were taken in belt transects, and from 2008 to 2016 were taken by stationary point counts. Anomalous data from 2004 and 2012 were excluded. (B) Trends in the biomass of large fishes, over 50cm length, by island, based on data from towed-diver surveys of large fish. *Redrawn from Pacific Islands Fisheries Science Center. (2011a). Coral reef ecosystems of American Samoa: A 2002-2010 overview. Honolulu: NOAA Fisheries Pacific Islands Fisheries Science Center, PIFSC Special Publication, SP-11-02, p. 48.*

excavators/bioeroders (Heenan & Williams, 2013). This illustrates the importance of maintaining these fish communities. In a subsequent study, grazers and detritivores were separated, and the data show that American Samoa islands have substantial biomass of both of those groups.

The biomass of large fishes (over 50cm length) decreased markedly from 2002 to 2010 at Rose Atoll, but was relatively steady for the other islands except Swains where it was high and highly variable (Fig. 28.10B). Large-bodied fish families composed a small portion of the fish community at Tutuila compared with other islands. Groupers, snappers, jacks, and emperors composed only 11% of the total fish biomass at Tutuila compared with 20%–35% at other islands (NOAA PIFSC, 2011a), with the absolute biomass at Tutuila of 4.3 $g\,m^{-2}$ compared with 11.3 and 19.6 $g\,m^{-2}$ at Ta'u and Swains. This is consistent with the typical effects of fishing, as human populations are highest at Tutuila, less at the smaller high islands, and no humans live on the two atolls (Swains and Rose). The steep decline of large fish at Rose suggests that unrecorded, illegal fishing has been occurring there. There is no effective monitoring or enforcement of fishing at Rose because it is remote and has no human residents.

Models of the effects of humans predict that the biomass of reef fish has been reduced by 21%, 42%, and 56% at Ofu-Olosega, Ta'u, and Tutuila, respectively. The effect of humans on piscivores is such that at about 10 people per ha of reef, which is the value for Tutuila, piscivores are at about 20% of the value found on a remote-uninhabited reef (Williams et al., 2015). Maximum sustainable yield is at about 33% of the unfished biomass, thus piscivores at Tutuila are predicted to be overfished.

The reef fish biomass is higher on the south side of Tutuila than on the north side, probably because some of the north side substrate is colonized basalt, while the south side is all coral reef. Points also have higher fish biomass than other areas (Sabater & Tofaeono, 2007).

In Independent Samoa, monitoring in lagoons at Marine Protected Areas (MPAs) found that most fish recorded were juveniles, and medium-size fish such as snappers, emperors, and groupers were only observed in low numbers and had an average size of about 30cm. Abundances are higher on more exposed outer slopes (Chin et al., 2011; Sapatu & Hjorleifsson, 2008).

In a study of the reef fish of 17 Pacific Island nations and territories, Independent Samoa was reported to have abundances that were among the highest found in all 17 jurisdictions (American Samoa was not studied), and the fish biomass in Independent Samoa was mid-range for the 17 jurisdictions. This pattern implies that Independent Samoa had a smaller proportion of large fish than the areas with high biomass. Since fishing differentially removes larger fish, the moderate biomass suggests moderate fishing pressure in the range of fishing pressure found in this study (Pinca et al., 2012).

28.5.2.1 *Larvae and Connectivity*

Simulations based on current patterns have led to the conclusion that the overall westward currents in the archipelago mean that connectivity among islands consists mainly of islands providing larvae to islands to the west of the origin. The archipelago is so distant from other archipelagoes that it is heavily dependent on internal sources of larvae to sustain coral reef populations. Each island tends to be self-seeding, particularly for species with shorter larval lives. The much larger islands of Independent Samoa contribute over twice as many larvae as the smaller islands of American Samoa (Kendall, Poti, Wynne, et al., 2011).

The larvae of a few species of coral reef fish are numerous enough that they can be observed to settle out of the plankton onto the reefs in pulses, usually around January–April. Several species are relatively large when they settle, and can form noticeable schools in shallow water. Striped bristletooth (surgeons) are about 3–4cm in length when they settle, as are rabbitfish, and goatfish are about 10cm long. In 2002, vast numbers of striped bristletooth (surgeons) settled and many appeared to be starving (Green, 2002).

Many reef fish lead relatively long lives. Striped bristletooths and striped surgeons can live about 20–40years. They were found elsewhere to grow rapidly for their first 2years, and then remain the same size for the rest of their lives. This is true for striped bristletooths in American Samoa as well. Size, age, and sexual maturity were used to distinguish recruits, juveniles, and adults in American Samoa. Recruits had uniform densities around Tutuila, spatially and over time. Densities of recruits were higher in rubble and the density of adults correlated with the presence of coralline algae. Adults are more common outside bays than inside bays. Recruit and adult local abundances were negatively correlated, indicating ontogenetic shifts in habitat use with increases in size and age (Ochavillo, Tofaeono, Sabater, & Trip, 2011).

A few new species of fish have been discovered in American Samoa, such as Leslie's Cardinalfish, *Apogon leslei* (named after Leslie Whaylen) discovered at Rose Atoll (Craig, 2009). Whaylen and the author simultaneously discovered a new species of clownfish on Tutuila, also found on Fiji, Tonga, and Wallis Island, named the Pacific anemonefish, *Amphiprion pacificus* (Allen, Drew, & Fenner, 2010).

28.5.2.2 *Summary of Reef Health*

A summary of 17 different indicators of reef health found that most indicated that coral reef health in American Samoa is relatively good, although not perfect or pristine. The greatest damage to the reefs was done by the 1978 crown-of-thorns starfish outbreak, by dredging of reef flats to obtain material to build airport runways or add to village land or to create small harbors, by filling in and building on top of reef flats, and by fishing (Fenner, 2013b). The coral recovered well after the 1978 starfish outbreak, suggesting resilient reefs, although coral cover may not have returned to values seen before the outbreak, or to the same coral community. An impact score based on the National Center for Ecological Analysis and Synthesis scoring system has been generated for the marine environment for each of the islands. Tutuila scored 12.4, Ofu-Olosega 8.4, Ta'u and Swains 8.6, and Rose 8.2. For comparison, Oahu scored 15.6 and Jarvis (Line Islands) scored 4. On a microbilization score based on the metabolism of all microbes divided by the metabolism of microbes plus fish, which correlated well ($r^2=0.68$) with the impact score, Tutuila scored 65%, Ta'u scored 57%, Swains score 47%, Ofu-Olosega 39%, and Rose 26%. For comparison, Oahu scored 98% and Wake Atoll 8% (McDole et al., 2012).

28.5.3 Soft Substrates

Pago Pago Harbor on Tutuila has a soft bottom, which in the shallow areas near the head of the harbor has some *Halimeda* algae on sandy mounds. Much of the harbor is about 70m deep. Portions of the shelf around Tutuila which is about 30–100m deep are indicated to be soft at the surface by multibeam backscatter (Brainard et al., 2008). Between Taema Banks outside the harbor on the south side and the shelf edge at about 60–80m depths, the sandy bottom was dominated by *Halimeda* algae. Sandy areas at the deeper end of this range which do not have *Halimeda* had large populations of the world's largest discoid foraminiferan, *Cycloclypeus carpenteri*, which reaches a maximum of 10 cm diameter (Song, Black, & Lipps, 1994) although more commonly reaches about 3 cm diameter. The Pala Lagoon on the south side of Tutuila is now nearly enclosed by the Pago Pago Airport runway. The bottom is covered with soft terrestrial mud. This appears to be a pupping area for reef sharks. Mangrove crabs are taken from the fringing mangroves and some burrowing clams are taken from the lagoon.

28.5.3.1 Mangroves

American Samoa and Independent Samoa have the same three species of mangroves (Ellison, 2009). All mangrove stands in American Samoa are in estuaries and all are small. The largest is at the Pala Lagoon in Nu'uuli on the south coast of Tutuila, the next largest is at Leone on the southwest coast, there is also a very small grove at Alofau on the southeast coast, and there is a grove on Aunu'u Island. American Samoa has 51 ha. Independent Samoa has 700–725 ha of mangroves.

28.5.4 Seagrass Beds

American Samoa has only two species of seagrass, which are in the same genus (*Halophila*). They produce very sparse beds from near the shoreline to at least 30 m deep (at Fatagele Bay, Tutuila). They do not appear to be habitat for any organisms other than filamentous algae. Independent Samoa has three to five species of seagrass (Ellison, 2009; Skelton & South, 2006) such as one species of much larger seagrass that grows at least 30 cm tall and forms dense beds (*Syringodium isoetifolium*), and thus is probably habitat and food for other organisms.

28.6 OFFSHORE SYSTEMS

28.6.1 Pelagic and Benthic, Seamounts

The seamount about 65 km south of Tutuila known as "South Bank" is a guyote, with a nearly flat top and a slight raised rim, suggesting it was an atoll at one time. The top is 25–30 m deep and almost entirely covered with coralline algae rhodoliths and sand on a very smooth, flat, solid, hard carbonate surface. Coral cover and diversity is very low and very few fish were seen. Both gray reef sharks and humphead wrasse were seen (Pacific Islands Fisheries Science Center, 2011b).

28.7 CLIMATE CHANGE IMPACTS

Sea surface temperatures have been rising in American Samoa (US EPA, 2007; Pirhalla et al., 2011, Fig. 28.6) as they are elsewhere. Mass coral bleaching events at Tutuila in American Samoa were documented in 1994, 2002, 2003, 2015, and 2017. Significant but not catastrophic mortality was documented in 1994 (Goreau & Hayes, 1994) and observed in 2003, and to a lesser extent, in 2002 (P. Craig, personal communication). In March 2002, 2.3% of colonies at 10 m depth were bleached on Tutuila, with an average of 11.8% on Manu'a and 18% on Ofu, 7% on Olosega, and 9% on Ta'u (Fisk & Birkeland, 2002). Coral bleaching was also recorded from Rose Atoll and the Ofu back-reef pools in 1994 (Craig et al., 2001; Kenyon, Maragos, & Cooper, 2010; Kenyon, Maragos, & Fenner, 2010), indicating that the bleaching was not restricted to Tutuila. Corals again bleached in 2015, beginning early in the year and ending about June, and then again in 2017.

Bleaching on all islands was assessed in February 15–March 30, 2015 on reef slopes. The mean percentage of colonies that were bleached ranged from 1.0% for Ta'u, to 10.6% for Swains (Table 1 in NOAA, 2015). Bleaching on Tutuila in 2015 was most intense on some of the reef flats and was generally less on reef slopes, where it decreased with depth. At two locations (airport pool and Lauli'i reef flat), up to 90% of staghorn corals were killed in 2015 and at another (Coconut Point pool) about 50% were killed. In 2017, bleaching patterns appeared similar to 2015, although perhaps with less mortality.

Of the staghorn corals (*Acropora* sp.) and finger corals (*Porites cylindrica*) in back-reef pools on American Samoa, staghorn corals but not finger corals were observed bleached each summer starting in 2004 (Fig. 28.11A and B). Few if any staghorn corals died by 2015. The percentage of corals that were bleached correlated well with sea surface temperatures (Fenner & Heron, 2009). The experience of 12 or more years of bleaching and recovery each year did not protect many of these staghorn corals from dying in the mass coral bleaching event in 2015.

The back-reef pools of Tutuila are artificial, having been dredged out to provide material for building land, perhaps around the 1940s. They host a low diversity of corals. In contrast, the natural pools on the south side of Ofu Island host a high diversity of coral species (at least 100 species). On sunny summer days, the water in these pools can heat up during low tide to as high as 34.5°C for short periods (Craig et al., 2001), well above the local bleaching threshold on reef slopes, yet

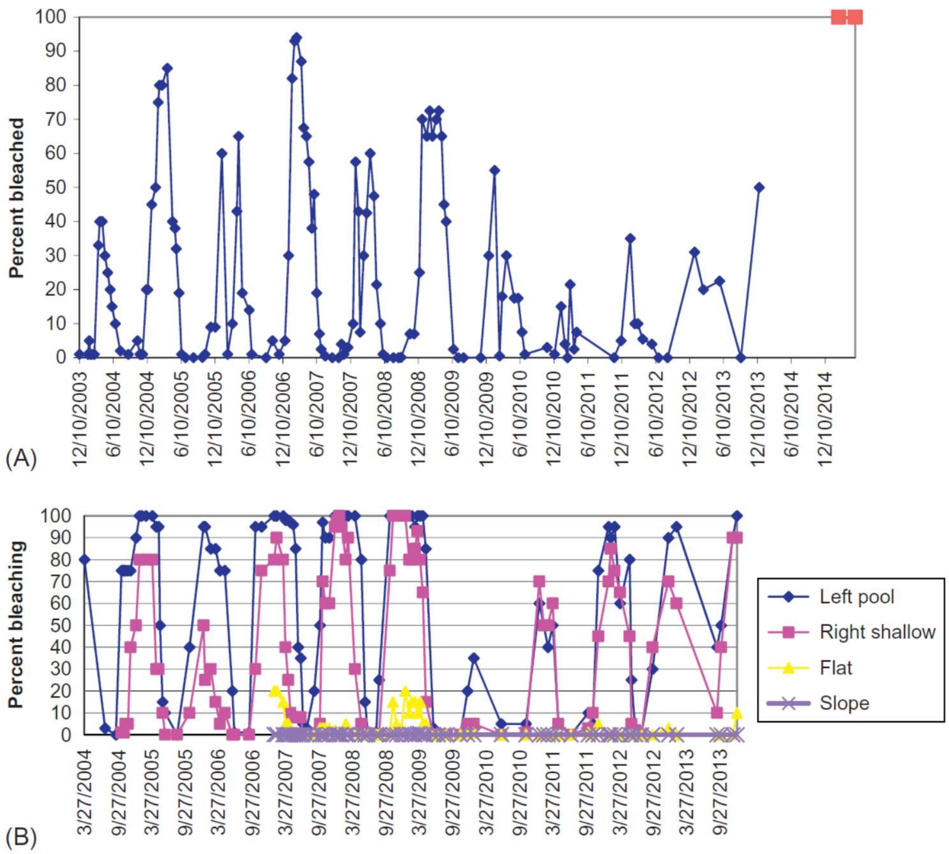


FIG. 28.11 (A) Bleaching of staghorn corals at the airport back-reef pool, Tutuila. The two red squares were during the 2015 mass coral bleaching event. (B) Bleaching levels at Alofau in two areas of the pool, on the reef flat, and on the slope, from 2004 to 2013. *Modified from Fenner, D. (2013a). Results of the territorial monitoring program of American Samoa for 2011, benthic section. Dept. of Marine & Wildlife Resources, American Samoa, p. 151 and Fenner, D. (2013b). Results of the territorial monitoring program of American Samoa for 2012, benthic section. Dept. of Marine & Wildlife Resources, American Samoa, p. 112.*

in most years, there is little if any summer bleaching. These pools also vary extensively in pH and oxygen with time of day (Birkeland et al., 2008; Craig et al., 2001). This was investigated in more detail in a more recent study (Koweek et al., 2015).

The shorelines of Tutuila are being actively eroded, and many shorelines have been or are being hardened to combat erosion. Sea-level rise probably contributes to this erosion. At this point, there does not appear to be direct evidence yet of the effects of ocean acidification on corals here or of changes in hurricane intensity or frequency.

28.8 HUMAN POPULATIONS AFFECTING THE AREA

The Independent State of Samoa has about 194,000 people, three quarters of which live on Upolu. American Samoa had 55,519 people in the 2010 census, and has probably not changed much since then. In 1900, American Samoa had only 5679 people, and the population grew exponentially until reaching 57,000 in the year 2000 (Craig et al., 2005). The 2010 census results surprised many, and some still believe the 2010 figures were incorrect. Swains Island, the smallest populated island in American Samoa, had 164 people in 1950 working on a coconut plantation that covered the whole island, then coconut prices dropped, and now no people live there. The populations of Ofu, Olosega, and Ta'u have been decreasing in recent decades, they now have about half the population as previously (Brainard et al., 2008). All of the chiefs of Ofu, Olosega, and Ta'u now live on Tutuila, which has 96% of the population (Craig, Green, & Tuilangi, 2008). The population of Independent Samoa is also stable, with people leaving to go to New Zealand or Australia. These patterns are consistent with a phenomenon called "the depopulating of the Pacific" where people leave small islands to move to larger population centers. This is part of the broader, worldwide, movement of populations from rural to urban areas and poor countries to rich countries, driven by more jobs and services in urban areas and in rich countries. Twice as many American Samoans live outside the territory as in the territory. Completed family sizes have decreased from about six to four children in American Samoa.

28.9 CITIES AND PEOPLE, DEVELOPMENT, ECONOMICS, AND CHANGE

The economy of American Samoa has been about 1/3 tuna canneries, 1/3 local government, and 1/3 local businesses selling to those who work in the other sectors. Almost the entire economy is subsidized by the US government (mainly by programs all states receive), 70% of local government is financed by the United States. In Independent Samoa, the industrial sector represents 58% of the economy, services 30%, and agriculture 11%. Agriculture employs two-thirds of the labor force (https://en.wikipedia.org/wiki/Samoa). Much of the eastern portion of Upolu is covered with coconut groves, but the coconut industry collapsed about the time of World War I. Independent Samoa receives less financial assistance from New Zealand and international agencies than American Samoa receives from the United States. As a result, significant numbers of people from Samoa have gone to American Samoa, where most of the workers in the canneries are from Independent Samoa (and some are from Tonga), and nearly 40% of the population are from Independent Samoa. Many people have relatives on the other side, everyone speaks the same language and has the same traditional culture. The economies of both American Samoa and Independent Samoa do not appear to be growing rapidly. Apia is the only (small) city in Independent Samoa, and American Samoa only has villages, but population is centered around the harbor and Tafuna Plains.

A study of the economic value of coral reefs and mangroves in American Samoa found that coral reefs had recreational benefits of $73,000 per year, fisheries benefits of $759,000, coastal protection benefits of $447,000 a year, and a total economic value which includes resident and visitor nonuse values, of $5.1 million a year. Mangroves had $46,000 annual fisheries benefits, $135,000 annual coastal protection benefits, and a total economic value of $750,000 per year. When potential nonuse benefits accruing to the US general public are included, the overall benefits could be in the order of at least US$10 million/year for coral reefs and US$1.5 million/year for mangroves. The study reported that continued business as usual practices would lead to a decline in use benefits, while an optimal sustainable management would see a considerable increase in both use and nonuse benefits (Spurgeon et al., 2004).

28.9.1 Land-Based Pollution

High phosphate detergents sold in American Samoa produced high phosphates in stream water until 2012, when they were banned by the governor's executive order.

A study of the effects of nonpoint pollution at 16 reef slope sites around Tutuila found negative correlations among watershed variables and three biological measures (coral species richness, community evenness, and the percentage of benthic substrate favorable for coral growth) (Houk, Didonato, Iguel, & Van Woesik, 2005). However, an attempt to find a correlation among the human population of districts and coral cover and coral richness on reef slopes did not find significant correlations (Fenner, 2008, 2009), but correlations among visibility in the water and coral cover and coral richness were significant (Fenner, 2013b).

28.9.2 Marine-Based Pollution

28.9.2.1 Coastal Erosion, Landfill, Mining

Some of the coastline of Tutuila shows signs of rapid erosion, and shoreline armoring with basalt rocks or concrete revetments continues. There are several gravel quarries, one of which at Faga'alu (at the mouth of the harbor) released large amounts of silt in storm water (about three times natural), which killed many of the corals in a small area on the north side of Faga'alu Bay. The quarry has been modified to reduce sediment discharge. Bay sediments have relatively low, probably natural, levels of chemical contaminants (Holst Rice, Messina, Biggs, Vargas-Angel, & Whitall, 2016).

28.9.2.2 Forest Clearance

In American Samoa, most of the native trees are too small and not straight enough to be commercially valuable, the slopes too steep to log, and islands too small and remote for logging to be profitable. The slopes are also too steep for coconut groves, so most of the territory retains uncut forest, which holds water and soil from runoff. Relatively small areas near the base of slopes have been cleared in a few places for taro patches. The steep slopes of eastern Upolu are also forested, as is much of Savai'i. The gentle slopes of western Upolu were cleared long ago for coconut groves, which remain.

28.9.2.3 Pollutants: Pesticides, Industrial, Nutrients, Radioactivity

There is probably chemical contamination of sediments below the shipyard in Pago Pago Harbor due to hull cleaning and other activities. Heavy metal contamination has been found in fish and shellfish within the harbor and at some sites outside the harbor (Craig, Saucerman, & Wiegman, 2000). The two canneries in the harbor used to release all their effluent into the harbor, which is not well flushed and so nutrient buildup was significant. In 1991, a pipeline was built to 47 m depth at the mouth of Pago Pago Harbor to carry liquid effluent, and sludge was carried by ship to a location 8 km offshore (Craig et al., 2000, 2005). Nutrient levels in the harbor dropped significantly within 2 years. In April 2007, new turf on a soccer field at the head of Pago Pago Harbor was heavily fertilized to promote grass growth. Soon red tide blooms appeared in the harbor. The soccer field was not used in 2008. Fertilizer application resumed in 2009, and severe red tide blooms in the harbor appeared periodically, caused by the dinoflagellate, *Ceratium furca*. The blooms were not toxic. There were no more blooms following a program of reduced soccer field fertilizer application (Morton, Shuler, Paternoster, Fanolua, & Vargo, 2011). Black algae have been periodically reported in front of Olosega Village. A filamentous algae bloom in Olosega back-reef pool was observed in January 2005, 9 days after Hurricane Olaf struck the island. Eighteen months later a study of nitrogen isotopes algae in Olosega and Ofu lagoons did not find any blooms, the isotopes did not point to human nitrogen sources, and the lagoons were deemed healthy (Garrison, Kroeger, Fenner, & Craig, 2008).

Piggeries and septic systems are major contributors to nutrient runoff, particularly on Tutuila, where about 96% of the human population of American Samoa live. Many isolated villages are not connected to the central sewage system. Most have septic tanks, but some houses have cesspools which probably contribute nutrients to nearshore waters. There are about 1000 piggeries in American Samoa with about 9000 pigs. The American Samoa Environmental Protection Agency initiated a program to move piggeries away from streams and promote dry litter systems. Nutrient inputs to streams from pigs have been reduced by 10s of thousands of pounds per year.

Waters near beaches frequently exceed national standards for bacterial contamination, about 40% of the time in 2006 (Craig et al., 2005).

28.9.2.4 Shipping, Accidents

A large Navy ship, the Chehalis, sank in Pago Pago Harbor in 1948 near the main docks, in about 60 m of water. It remains there today, where it is not a navigation hazard owing of the depth, but some fuel remains on board. Nine longliner tuna boats were driven onto the reef flat in Pago Pago Harbor by Hurricane Val in 1991. All have been removed (Fenner et al., 2008). Another longliner went aground at the shore near the village of Amouli and remains there. A longliner went aground on Rose Atoll in 1993, and the surrounding reef became dominated by black cyanobacteria algae. The ship was cut up and mostly removed over the years, and the black cyanobacteria has slowly declined since then (Craig et al., 2005; Kelly et al., 2012; Maragos & Burgett, 2003; Schroeder, Green, DeMartini, & Kenyon, 2008). A longliner ran aground on the reef at Coconut Point on Tutuila in 2016 and remains there. There are many other shipwrecks in American Samoa as well (Tilberg, 2007).

28.10 RESOURCES

28.10.1 Fisheries, Artisanal, and Industrial

American Samoa has the world's largest and third largest tuna canneries, although the smaller cannery is not operational at this point. The tuna comes from purse seiners and long liners from all over the South Pacific. The purse seiners are mostly US flagged, and the long liners are mostly from the Republic of China (Taiwan). The number of longliners has decreased greatly in recent years, they now go to Independent Samoa and transfer their catch to vessels that take the tuna to canneries in other countries. About $20 million per year worth of tuna has been caught in recent years by smaller ships (roughly 50 ft. long) in a locally based longliner fleet. All fishing in the American Samoa exclusive economic zone (EEZ) is by US vessels. The United States now imposes annual catch limits for each species of tuna.

American Samoa has four locally based fisheries: the shoreline subsistence (coral reef plus scad) fishery is the largest, followed by an artisanal pelagic fishery, an artisanal "bottomfish" fishery, and a very small recreational (pelagic) tournament fishery. Between 1979 and 1991, when the human population increased by 46%, the coral reef fishery effort decreased by 8%, and the coral reef catch decreased by 54% (Craig, Bonwith, Aitaoto, & Hamm, 1993). The decreased effort was caused by a shift toward store-bought food (Sabater & Carroll, 2009), while the decrease in catch more than effort indicates decreasing reef fish stocks. The bottomfish fishery targets a handful of snapper and grouper species which live below the depths of coral reefs. It uses small, double hull, aluminum boats constructed in Independent Samoa, and small outboard engines. Several hooks are attached on the ends of nylon lines which are lowered vertically from the boat. By 1991, the bottomfish catch had decreased to only 14% of its peak (Craig et al., 2005). Since then, the price of fuel has risen while the local price of fish has not risen, and as a result the artisinal bottomfish and pelagic fleets and catches have dwindled and nearly disappeared.

Craig et al. (1993) report 69 species in the subsistence fisheries of American Samoa. The Western Pacific Regional Fisheries Management Council has a list of coral reef fisheries management unit species for American Samoa that consists of 102 species (and at least a half dozen important invertebrate fishery species), and lists a similar number of 'candidate species' which are caught less often (Fisheries Council, 2011).

The composition of organisms found in middens dated 1000–3000 years ago was similar to that currently harvested (Craig et al., 2008). Traditional fishing during this period employed fish hooks carved from shells, lines woven from coconut husk fibers, wooden spears, woven basket traps for goatfish larvae, and wooden canoes made from hollowed out logs, powered by paddling or sails.

Coral reef fishery data taken in 1978 by Wass showed American Samoa to have the largest coral reef fish catch by weight per unit of reef area of any place known in the Pacific (Dalzell, Adams, & Polunin, 1996). However, this was largely an artifact of Wass using a small reef area, to a depth of just 8 m, instead of the reef area to 30 m as is commonly done (Craig et al., 2008). Reef fish catches have decreased substantially since then, and were declared "collapsed" by Newton, Côté, Pilling, Jennings, and Dulvy (2007) based on increasing human populations in American Samoa and very large catches followed by small catches. However, increasing financial support from the United States has allowed people in American Samoa to purchase more packaged food in local grocery stores, which has reduced fishing (Craig et al., 2008; Sabater & Carroll, 2009). *Re*-estimation of reef fish catches from 1950 to 2002 based on all available data shown that actual catches have been about 17 times larger than reported, and that catches have declined by 79% over that time period (Zeller, Booth, Davis, & Pauly, 2007). Fishing on reefs does continue at low levels, using a variety of methods. Traps are not used, except for small basket traps in the Manu'a Islands for newly settled goatfish. There is no cyanide fishing, and blast fishing is rare if it occurs at all. Even the lower levels of current fishing, however, produce substantial catches that probably have impacts (Craig et al., 2008).

Historically, Samoans free dove at night to spear fish (the method called Lama). About 1994, nighttime scuba spearfishing using waterproof flashlights increased. This greatly increased the power of fishing, particularly for catching parrotfish and surgeonfish. Page (1998) found that night scuba spearfishing had a catch of 2.2 kg per h per fisherman, while free divers caught 0.64 kg per h per fisherman. The total reef fish catch increased dramatically to over 10 times that previously. Page (1998) found that populations of the two largest species of parrotfish in the study were declining. The size of parrotfish caught declined over the period of the study (1996–98). The total estimated catch of parrotfish was close to maximum sustainable yield for the entire parrotfish stock, and scuba spearfishing caught 89% of the total annual catch. Scuba spearfishing was banned in 2001 by executive order (Green, 2003), but night snorkel spearfishing with flashlights remains legal. Additional information supporting the view that reef fish are overfished in American Samoa was presented in Birkeland et al. (2008).

Of the 1000 species of coral reef fish in American Samoa, only about 10% are large enough and common enough to be regularly caught. Large fish are much less common on populated islands but small fish are not (Williams et al., 2011), and this is a fingerprint of fishing. With sharks especially, there are larger populations of reef sharks on the uninhabited islands than on all the islands that are inhabited (Fenner, 2014). A study of shark populations found that the populated islands of American Samoa have about 4%–8% of the number of sharks they would have if people were not present (Nadon et al., 2012). As anything below about 33% is overfished for most species, reef sharks are overfished in American Samoa. Blacktip reef sharks and whitetip reef sharks are the most common, with all other shark species rare near shore. Gray reef sharks are probably the most overfished, since they are the most abundant on remote unfished reefs, and less common on Tutuila than blacktips and whitetips.

Bumphead parrotfish are the largest species of parrotfish, and sleep in schools on the bottom, and thus are particularly vulnerable to nighttime spearfishing. In American Samoa, interviews with fishermen and scientists indicated that there were schools of bumphead parrotfish in the past, sleeping in schools usually of 2–6 individuals but one being 30–50 individuals (Fenner, 2014). Now, only seven individuals of the species have been seen in the last 17 years, the last being seen about 2012. This species is commercially and ecologically extinct, and if not biologically extinct it is certainly critically endangered. Yet in 2012, the Western Regional Fisheries Management Council estimated the biomass of this species in American Samoa as 4699 pounds and set an annual catch limit of 235 pounds for it.

A study of the potential of coral reef fish communities to recover from fishing found that the time for a fish community to recover to its unfished biomass was estimated at about 40 years for areas open to fishing in Ofu-Olosega, 42 years for Rose (which is closed to fishing), 42 years for restricted areas of Tutuila, 43 years for restricted areas of Swains, 50 years for open areas of Ta'u, and 54 years for open areas of Tutuila (MacNeil et al., 2015). This is based on the biomass of all the species together, and individual species can be in far worse condition.

On Ofu, a small, remote island with a declining human population, elder fishers felt that fishing is as good as it was when they were young, unlike elder fishers on Tutuila. In Ofu, the modern fish catches are broadly similar in composition to those seen in middens deposited from 3000 to 1000 years ago. The fish catch on Ofu is estimated to be only about 1%–3% of the standing stock of reef fish there. However, the standing stock of reef fish is still lower than on remote, lightly fished reefs and perhaps is even below that of fished mid-Pacific reefs, the total amount of fish taken from the reefs per kilometer of shore is substantial, and large fish are rare (an indicator of fishing pressure). Groupers, triggerfish, puffers, and butterflyfish were caught in large excess to their proportion in the fish community, while parrotfish, surgeonfish, emperors, and damselfish are caught much less (Craig et al., 2008). Fish in the first group are more probably to be overfished than in the second group.

There are large traditional fisheries for Akule (big eye scad), Palolo (polychaete worms), and octopus. Palolo famously spawn on one or two nights a year and are a traditional delicacy (Craig, 2009). Octopus, giant clams, lobsters, some sea cucumbers, sea urchins, and snails are taken all year round. Octopuses are very fast growing and so can resist heavy fishing, but giant clams and sea cucumbers are quite vulnerable. Additional species of invertebrates taken in fisheries have been reported from Independent Samoa (Andrews & Holthus, 1989).

Independent Samoa is more dependent on local fisheries than American Samoa because of less outside financial support. In four communities studied, the average consumption of fresh fish was 61 kg per person per year, and invertebrate consumption 9.6 kg per person per year. No differences were detected in fish stocks in MPAs and outside MPAs probably due to poor policing of the MPAs (Vunisea et al., 2008). Independent Samoa exports small amounts of aquarium fish and live rock, but American Samoa does not.

28.10.2 Aquaculture

Tilapia are grown in some very small freshwater operations on Tutuila, for local consumption.

28.10.3 Oil and Gas, Minerals

There are no oil, gas, or minerals in the archipelago.

28.10.4 Tourism

Tourists that visit Independent Samoa are primarily from New Zealand and Australia. It had 100,000 tourist arrivals in 2005, and tourism has been growing. Independent Samoa has the capacity and space for more tourists and welcomes them. By the year 1997, tourism brought in SAT102 million per year (Skelton, Bell, Mulipola, & Trevor, 2000).

There is little tourism in American Samoa, with only 7027 tourists in 2005. Cruise ships make several stops per year. There are few other tourists; most visitors are family members, government workers, or business people.

28.11 THREATS TO SUSTAINABLE USE OF RESOURCES

28.11.1 Fishing, Construction

Village elders in Ofu said that blast fishing and fish poisons (futu, made from a plant, *Barringtonia asiatica*, and commonly used for this traditionally in the South Pacific) were common 30–40 years ago, but are no longer used. They are banned by the village councils (Craig et al., 2008). Little if any destructive fishing appears to occur in Tutuila now. For poisons and other traditional Samoan fishing methods, see Herdrich and Armstrong (2008).

Reef flats were dredged at the airport, Coconut Point, Faga'alu, Gataivai-Utulei in the harbor, and Alofau for airport and village material. Dredged fill probably from the same area was put on top of reef flat in the 1960s to build land where a hotel was built (the Rainmaker) (D. Herdrich, personal communication). The US Navy built storage buildings on top of the reef flat on the north side of the inner harbor during or before World War II, and subsequently the tuna canneries and shipyard were built on that land. The sports field and natural gas facility on the outer part of the north shore of the harbor at Onososopo were built on top of the reef flat. A large mangrove area at the head of the harbor was cleared and filled in. Dredging was used to build one small boat harbor on Tutuila, two on Ta'u, and one on Ofu.

28.12 MANAGEMENT REGIMES

28.12.1 Protection and Conservation Measures, Legal Protective Instruments

The US Marine Mammal Protection Act covers all marine mammals in the US waters, such as American Samoan waters and its EEZ. The US Endangered Species Act protects sea turtles and 15 species of corals in the Pacific, at least 6 of standing stock of reef fish there. However, the standing stock of reef fish is still lower than on remote, lightly fished reefs and perhaps is even below that of fished mid-Pacific reefs, the total amount of fish taken from the reefs per kilometer of shore is substantial, and large fish are rare (an indicator of fishing pressure). Groupers, triggerfish, puffers, and butterflyfish were caught in large excess to their proportion in the fish community, while parrotfish, surgeonfish, emperors, and damselfish are caught much less (Craig et al., 2008). Fish in the first group are more probably to be overfished than in the second group.

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The National Park agreement with landowners prohibits commercial fishing within its boundaries, but not subsistence fishing. The National Marine Sanctuary prohibits fishing in parts of its (expanded) area, but not in other parts. Commercial fishing is prohibited in the 50-mile square of the National Marine Monument and National Marine Sanctuary around Rose Atoll, but subsistence fishing is allowed except within 12 miles of Rose Atoll. Rose Atoll from the high-water line inward is protected as a National Wildlife Refuge, this area is also a part of the National Monument but not a part of the National Marine Sanctuary.

The effectiveness of regulations in American Samoa is difficult to gauge. The ban on scuba spearfishing appears to be successful, the businesses that filled scuba tanks for spearfishing have ceased that activity, and there are few if any reports of scuba spearfishing. Female lobsters in berry and undersize lobsters are often found in markets, in spite of being illegal (Coutures, 2003). About 35% of giant clams harvested on Ofu are below legal size (Craig et al., 2008).

Green sea turtles that nest on Rose Atoll mainly go to Fiji to feed, where they can be legally taken.

Independent Samoa has a large community-based MPA program with 35 reserves on Upolu, 15 on Savai'i, and 4 on Manono. The American Samoa MPA program was modeled after the Samoa program. Independent Samoa allows the take of turtles, with a minimum size limit. As of 2005, there was a ban on the take of sea cucumbers, but they were still being taken (Vunisea et al., 2008). Skelton et al. (2000) provide an extensive overview of coral reef management programs in Independent Samoa.

28.12.2 Deficiencies and Missing Measures

Independent Samoa needs to consider protecting all sea turtles and marine mammals, the large reef fish species, and enforcing protection of sea cucumbers from commercial export. The international donor community needs to support monitoring, research, and management of coral reefs in Independent Samoa to a greater degree. American Samoa requires more no-take MPAs and perhaps more management of giant clams, and needs to evaluate the effectiveness of MPAs at increasing fish stocks.

Major disturbances such as hurricanes need to be documented better with direct observations and measurements of damage. The fish fauna of the archipelago is very well documented, but the coral fauna needs to be even more completely documented, such as taxonomic level study of skeletons. Even more needs to be known of the population trends and over-fishing status of rays and skates and of moderately large reef fishes.

28.13 SUMMARY, PROGNOSES, OR NEEDS

The coral reefs of American Samoa are relatively healthy compared with many reefs around the world by a variety of criteria, but are not pristine. Large reef fish species are overfished, reef flats have been dredged or built on, and crown-of-thorns starfish outbreaks have killed large amounts of coral. Hurricanes, a tsunami, and the lowest tides each year have also damaged the reefs, but reefs are well adapted to recover from these natural, brief events. Exactly why the reefs of the South Pacific and American Samoa have remained relatively healthy is not obvious. Perhaps, the banning of scuba spearfishing and culling of crown-of-thorns starfish have been among the most helpful regulations and actions. Possibly, the relatively low level of human impacts has allowed the reefs to remain relatively healthy and resilient. Mass coral bleaching is predicted to end coral reef ecosystems as we know them unless vigorous action is taken around the world to reduce the emission of greenhouse gases.

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