Results of the Territorial Monitoring Program of American Samoa for 2009, Benthic Section, including information on the tsunami effects.

By Douglas Fenner, Ph.D.

Coral Reef Monitoring Ecologist
Department of Marine & Wildlife Resources (DMWR)
American Samoa

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Contents

Acknowledgements

Thank you to boat captain Mika Letuane. Thanks also to Ekueta Schuster for filling tanks and other support, and for DMWR enforcement for the use of their giant pickup to pull the boat over the very steep pass to the boat ramp at Fagasa on the north side of Tutuila. Special thanks go to the Fagatele Bay National Marine Sanctuary, for the use of the Sanctuary boat when the DMWR boat was not available, which was most of the time.

Abstract

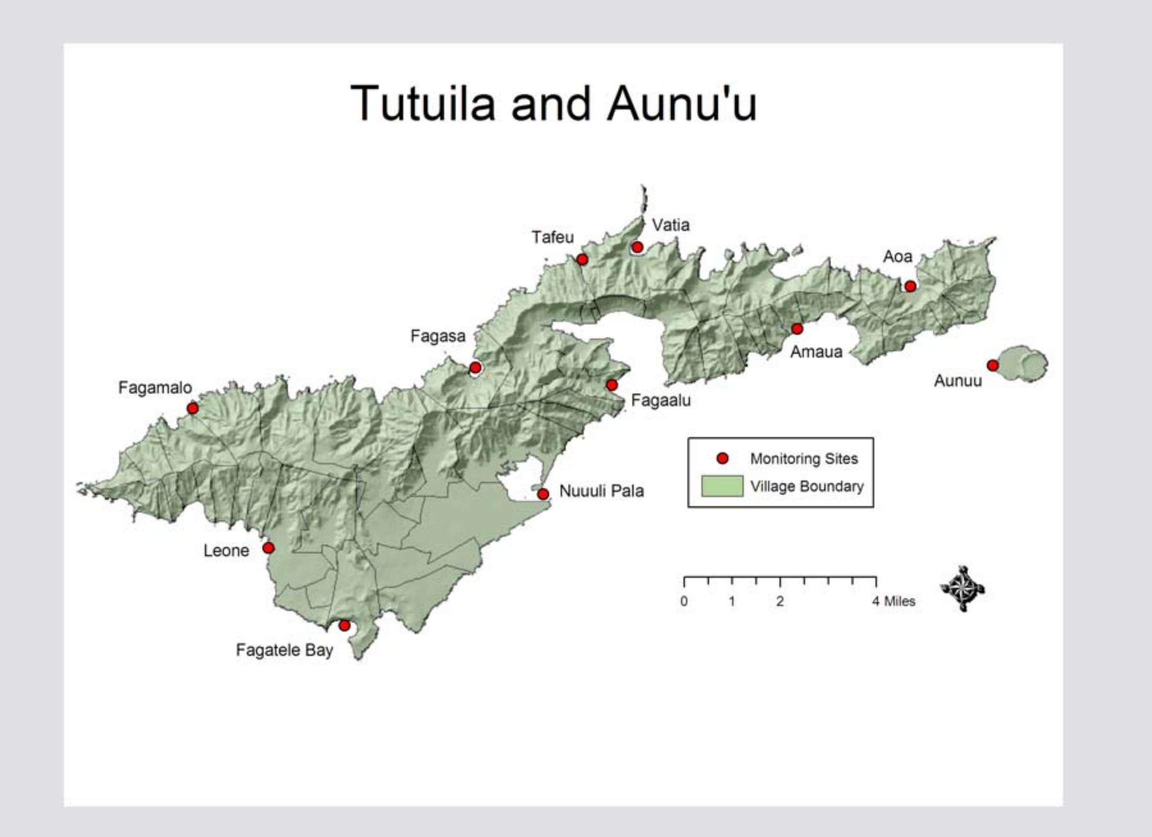
Because of the Sept. 29, 2009 tsunami and a variety of other delays, only 7 sites were monitored in 2009. Coral cover, which had risen slightly in 2008, remained at that level, with 28.6% cover in 2009. Coralline algae continues to dominate the reefs and macroalgae continues to be rare. The live coral index increased slightly from the 2008 value which was already over 90%, and there is no overall trend from 2005-2009. The value is much higher than the South Pacific average, indicating relatively healthy reefs. Coral lifeforms continue to be dominated by encrusting corals. *Porites* was the most common single genus of corals, followed by *Acropora* and *Montipora*. The most common coral species is *Porites rus*, followed by encrusting *Montipora*. While there was no overall trend in the number of lifeforms or genera per site, there was a small overall increase in the number of coral species recorded per site over the five years of monitoring. Fagasa shows a trend over five years of increasing coral cover and decreasing turf algae. Aunu’u shows no trends, nor does Amaua, Faga’alu, or Fagatele. Nu’uuli had an increase in branching coralline algae and decrease in crustose calcareous algae over the first four years, followed by a decrease in branching coralline algae and increase in crustose calcareous algae in 2009. Likely the branching algae just grew over

the crustose algae, which remained alive, and when the branching algae regressed the crustose algae could be seen again. Leone has an increasing trend in coral cover in 2008 and 2009, but the 2009 increase may be due to transect tape placement. Bleaching continues to appear each austral summer in the airport pool, and disappear in the austral winter, with the same pattern in the Alofau pool. Coral diseases remain minor, but a couple of diseases were noticed that had not been seen previously. The tsunami of Sept 29, 2009, was a major disturbance for the coral reefs of Tutuila. It struck hardest at villages in bays such as Pago Pago, Fagasa, and Leone, but also in some villages outside bays such as Poloa and Tula. It struck both the north and south sides of the island. Bays funnel the wave energy into a smaller area resulting in a much higher wave, with the maximum wave height over 10 m. Along most of the coastline, there was little or no damage. Under water, the pattern was similar, with most places having little or no damage, and a few places having major damage. A small patch of staghorn in the ava at Fagaitua was completely removed. The slope next to Matafau school at Faga'alu was heavily damaged, though coral cover was low there before the tsunami. Large amounts of rubble were moved on the reef slope in the inner bay at Vatia, though there was little damage at the outer bay. Areas in Fagatele Bay also had major movements of rubble. In Leone, delicate table corals and staghorns were undamaged in one area, and completely destroyed in another. So far 38 sites have been surveyed. Tsunamis are natural, there is nothing we can do to stop them, they have been going on as long as the island has been here, and will continue to happen. Coral reefs here have survived 1.5 million years of tsunamis, and are still healthy. The reefs will recover from this tsunami, unless they have been weakened by damage from humans. One of the most important things in monitoring is placing transects as close as possible to the same location year after year. Power analysis greatly underestimates the ability of such a program to detect change, since it assumes random transect placement.

The report is 71 pages long, and includes 53 figures.

Methods

The original 11 core sites are shown in the map below. All are on Tutuila and nearby Aunu'u.



The benthic methods were the same as in 2008, with a few minor changes. In the core monitoring, four 50-m tapes were laid on a depth contour between 8 and 10 m deep. A space between them of about 15 m was kept. Benthic categories were recorded under each 0.5 m point on the tape. Benthic categories included live coral, dead coral, dead coral with algae, crustose calcareous algae, branching coralline algae, fleshy macroalgae, turf algae, rock, sand, rubble, soft coral, and sponge. "Branching coralline algae" included a soft feathery species that was the most common in that category. That species is *Cheilosporum spectabile*. Any rock that is not colored white has turf on it, and was recorded as turf. Corals were identified to lifeform, genus, and species when possible, and if the macroalgae was *Halimeda* or *Dictyot*a, or something else that was identifiable, that was recorded. Soft corals were recorded to genus when possible. Lifeforms included encrusting, massive, foliose, branching, columnar, submassive, mushroom, *Millepora*, *Acropora* branching, *Acropora* table, *Acropora* digitate, and *Acropora* encrusting. Horizontal visibility was recorded using the tape. Two transect tapes were done on the first dive, and an additional two tapes were done on the second dive. Invertebrates were recorded on a return pass. Sites were re-located using the GPS and markers as indicated in the 2005 report. One day was required for each site. In 2008, a total of 12 sites were recorded, including the original 11 plus Masacre Bay. For 2009, however, weather, lack of working boats, and lack of willing boat captain meant that only seven sites had been recorded, all but one on the south side, when the tsunami struck on Sept. 29, 2009. The tsunami made the boat ramps inoperable at Pago Pago and Fagasa.

In addition, all three of the boats which the department has access to were inoperable until at least the middle of 2010. Thus, for 2009, only seven sites were recorded.

As in 2007 and 2008, the rugosity measurements which were omitted, because a third team member was not available and when included it lengthened dive times to the point where running out of air was a distinct possibility, thus reducing the margin of safety. Further, it appears that the measurement depends primarily on exactly where the chain falls, and that changes in rugosity caused by coral growth will take quite a few years before they would be detectable. A hurricane could make changes in rugosity quickly by removing corals, and if significant hurricane damage occurs, the rugosity measurements can be repeated. Until changes in coral cover or other rugosity changes are apparent, repeating the measurement of rugosity is not worth the increased risk of running out of air. In future years it is hoped that an additional team member can record the rugosity measure.

When laying the tape, the primary consideration is to keep the tape between 8 m and 9 m deep. The tape is passed along the sides of projections, including live corals such as *Pocillopora* and table corals, which usually have an overhanging side. If it is passed around first one side of one projection and then the other side of another, it is anchored securely from wave action moving it either way at that point. An attempt is made to anchor the tape in this fashion as often as possible, but in some areas there is little to anchor the tape on. A continuing problem is what to do about clefts in the reef. A cleft that is narrow and deep is crossed straight to an anchoring point on the other side. If it is large, then the tape may be laid along one side of it, going up toward shallower water but staying at 8-9 m depth, and then when the bottom rises to that depth, crossing to the other side and continuing on that side out of the canyon. The principle problem with that is finding an anchoring point near the head of the canyon that can hold the tape at the head. The tape is read at each point by reading the substrate under the point at the time at which the diver is directly above the point. A string and weight are not used, as surge and the movement of the tape in the surge makes that a much more difficult procedure. If the tape is stretched between two points far apart and the surge is heavy, the tape can move a meter or more in either direction with each wave. This opens up an opportunity for bias, as the point on the tape sweeps across a variety of benthic patches. If the point on the bottom is recorded that is first seen from a vertical viewpoint, then bias is minimized. An attempt is made to minimize bias in laying the tape by choosing a route based on depth and anchoring points for the tape, not the substrate.

The direct observation underwater of what is under points makes it easier to identify species, and so allows greater taxonomic resolution than video techniques.

Dates of collection of data are shown in Table 1.

Table 1. Dates of collection of benthic transect data for each site, reef slope.

Location	**Date**
Fagasa	8/5/09
Aunu'u	4/14/09
Amaua	3/27/09
Faga'alu	3/24/09
Nu'uuli	3/13/09
Fagatele	5/11/09
Leone	7/13/09

Monitoring of bleaching continues as before, with visual estimates of the amount of staghorn bleached in different areas of the airport and Alofau pools, about biweekly. The reef flat and slope are also recorded at Alofau each time data is taken.

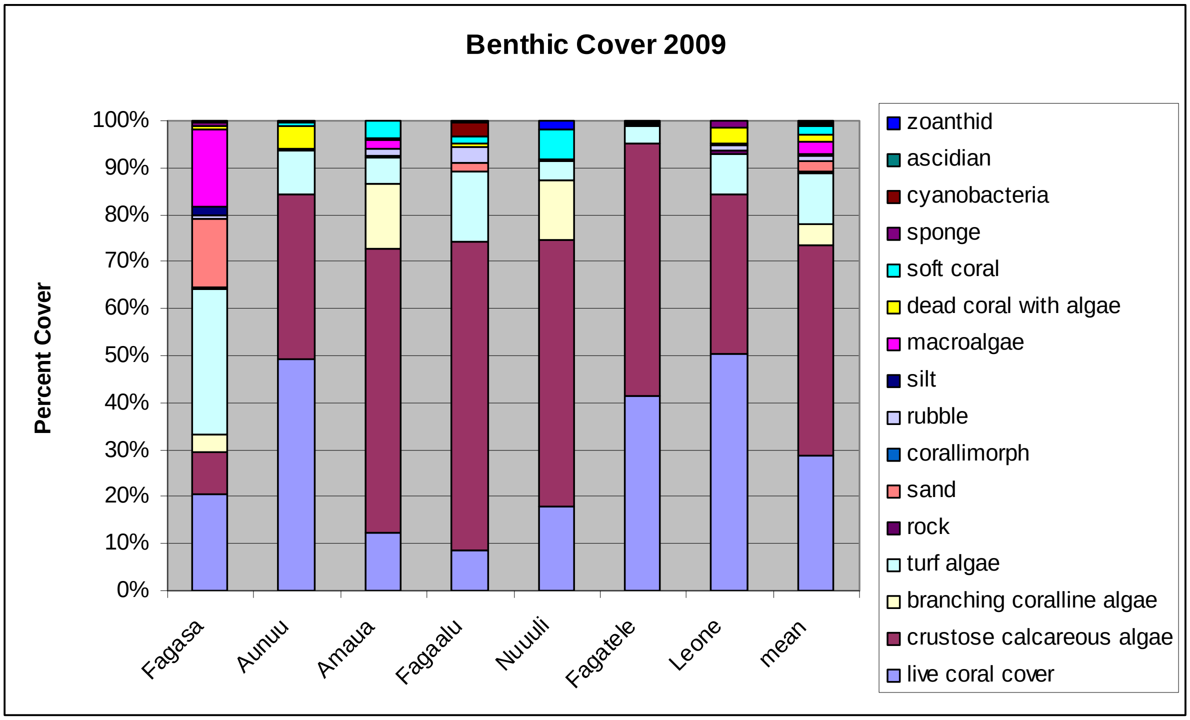
Results

For background information on the coral reefs of American Samoa, see Wells (1988), Craig et al. (2005), Sabater and Tofaeono (2006, 2007), Whaylen and Fenner (2006), Fenner (2008a,b), Fenner et al. (2008), Birkeland et al. (2008), and Brainard et al. (2008), Craig (2009) and Fenner (2009; 2010).

Reef Slopes

Data was only taken from seven sites, only one of which is on the north side (Fagasa). Figure 1 shows the results. Aunu'u and Leone had the highest coral cover, followed by Fagatele, and Amaua and Faga'alu had the lowest cover. Coralline algae continues to be abundant on south side sites, and turf continues to be abundant at Fagasa.

Figure 1.


Benthic Cover 2009
Percent Cover
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Fagasa
Aunuu
Amaua
Fagaalu
Nuuuli
Fagatele
Leone
mean
zoanthid
ascidian
cyanobacteria
sponge
soft coral
dead coral with algae
macroalgae
silt
rubble
corallimorph
sand
rock
turf algae
branching coralline algae
crustose calcareous algae
live coral cover

In order to detect trends, it is necessary to compare the mean cover for 2009 with the mean cover of the same seven sites in previous years, instead of comparing it to the mean cover of all the sites in previous years. Figure 2 shows a comparison of the mean for the seven sites for 2009, with means for the same seven sites in previous years. Most benthic categories are very stable in these seven sites over the five years of monitoring, but coral cover actually shows a slight increase, from 25.5% cover in 2005 to 28.6% cover in 2009.

Figure 2.

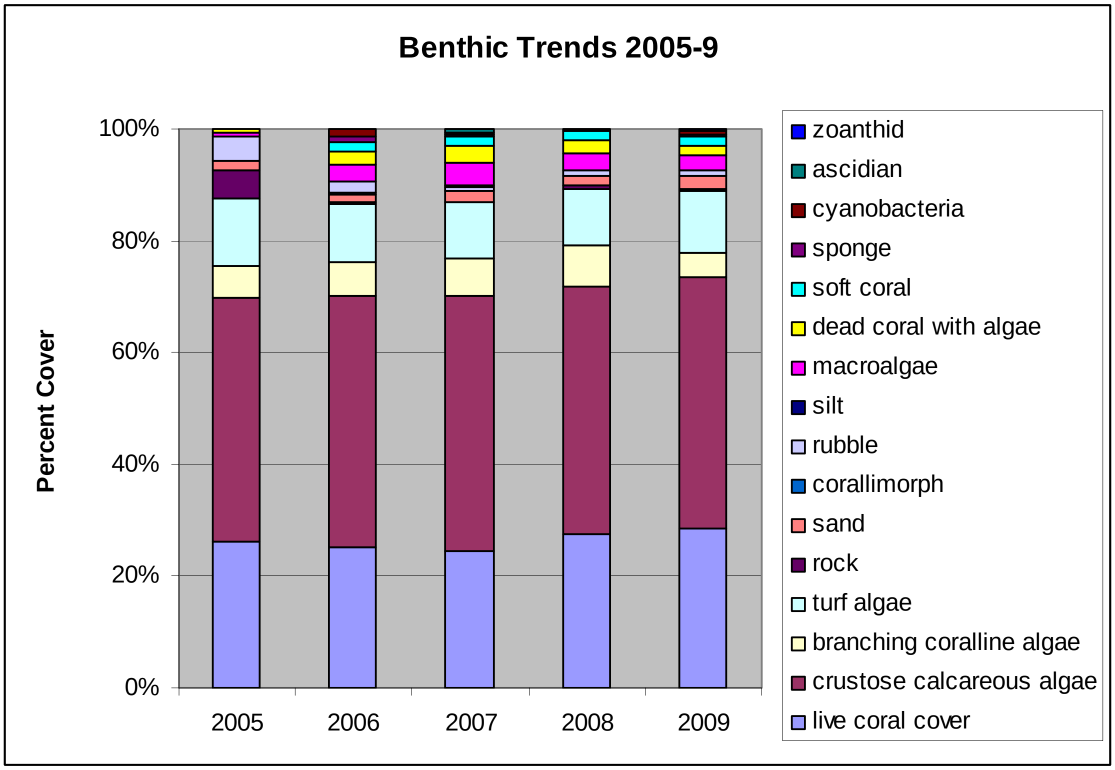
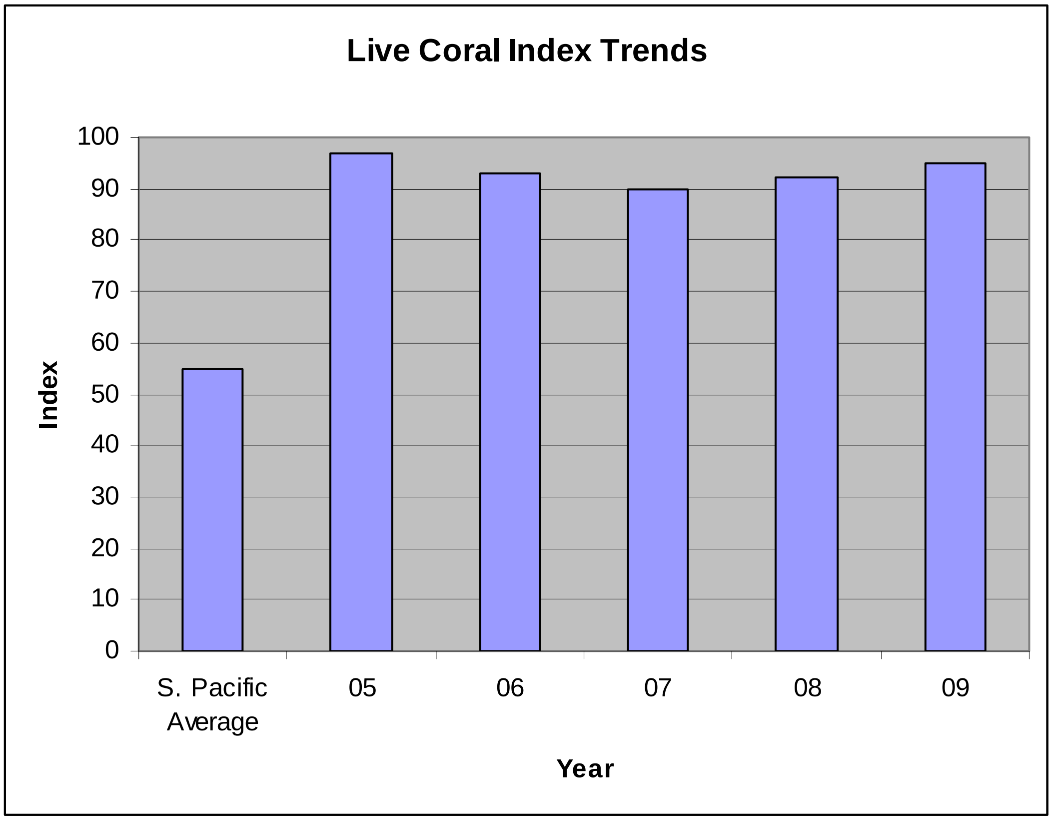


Figure 3 shows trends in the live coral index. The index = live cover / (live cover + dead coral), and is expressed in percent, so 100 = 100% live coral and 0 = 0% live coral. So high values are good and low values indicate a large amount of recently killed coral. Figure 3 shows the index for the seven sites recorded in 2009, but all sites in previous years. Also shown is the mean for South Pacific sites reported by ProcFISH at the Secretariat of the Pacific Community (SPC). Values in American Samoa are much higher than the mean for the South Pacific, and indicate healthy reefs. There appears to be no overall trend in the index over time.

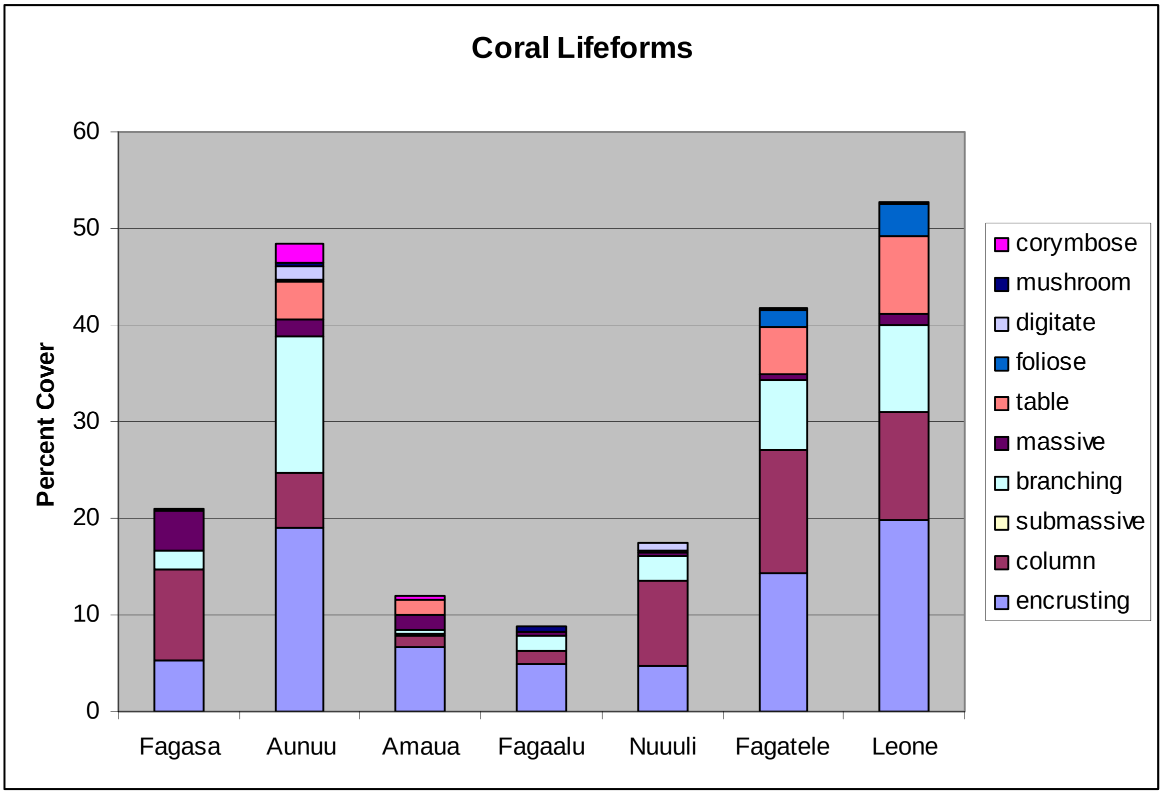
Figure 3.



Coral Lifeforms

The lifeforms of corals are their shapes. Figure 4 shows the coral lifeforms at the seven sites. Encrusting continues to be the most common lifeform at most sites, with column and branching following.

Figure 4.



The mean cover of the different coral lifeforms is shown in Figure 5. Encrusting continues to be the most common lifeform, followed by column, branching, and table.

Figure 5.

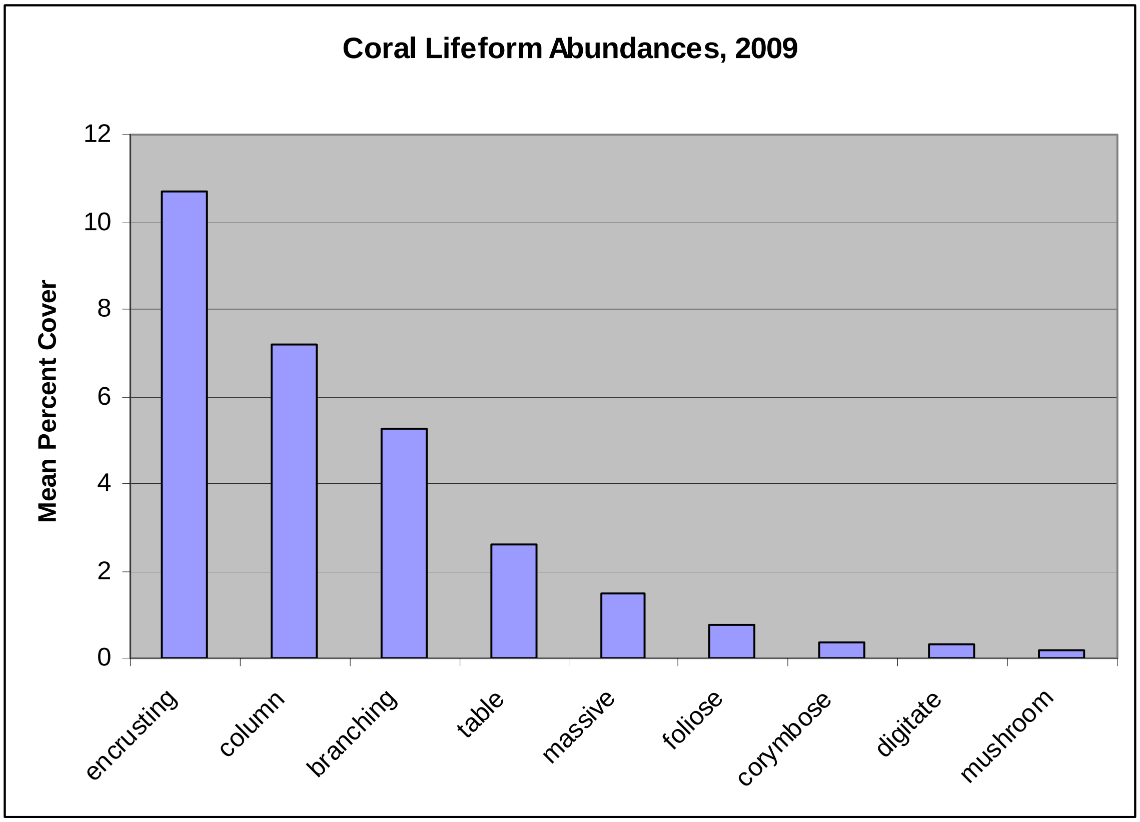


Figure 6 shows the number of coral lifeforms per site. Aunu'u had the most, followed by Amaua, Fagatele, and Leone.

Figure 6.

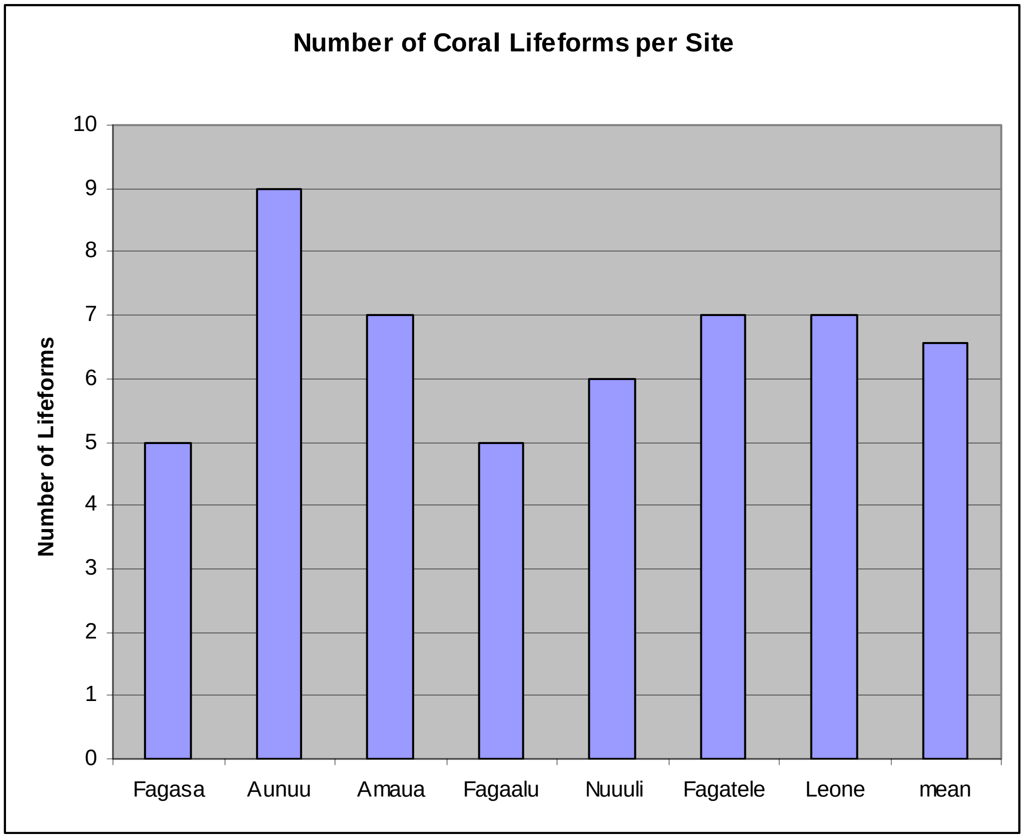
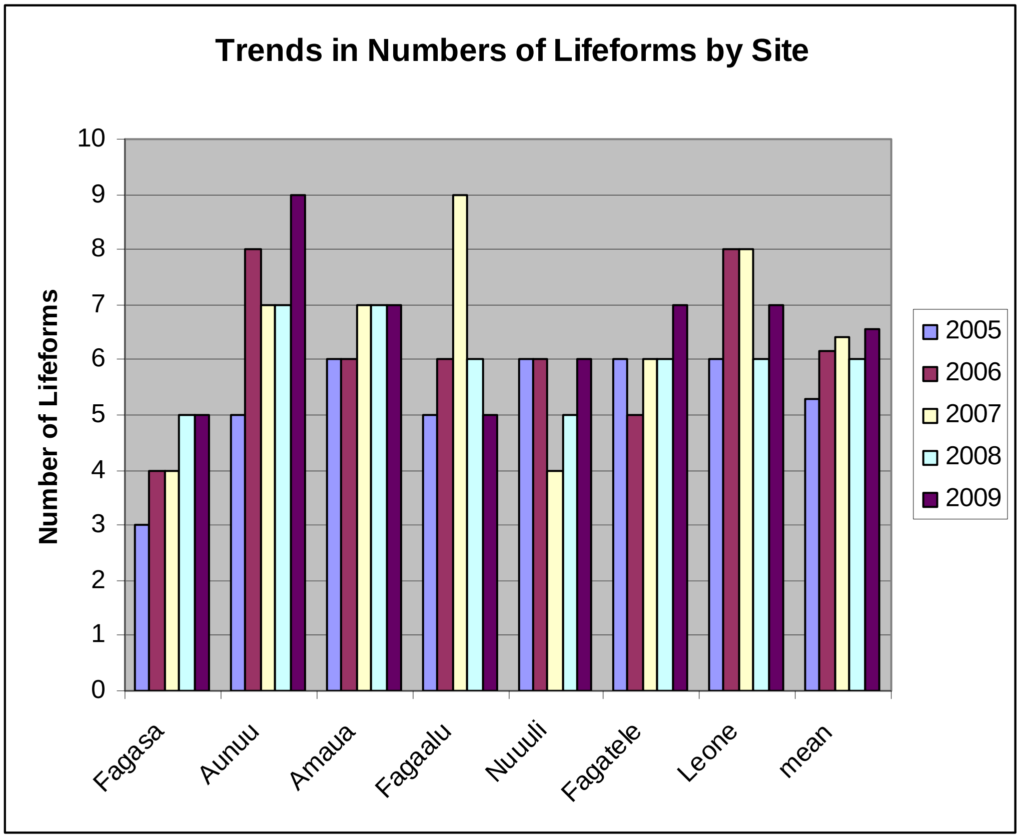


Figure 7 shows the trends in the number of lifeforms by site.

Figure 7.



Genera

Figure 8 shows the coral genera by site. *Porites*, *Acropora*, and *Montipora* were the most common genera.

Figure 8.

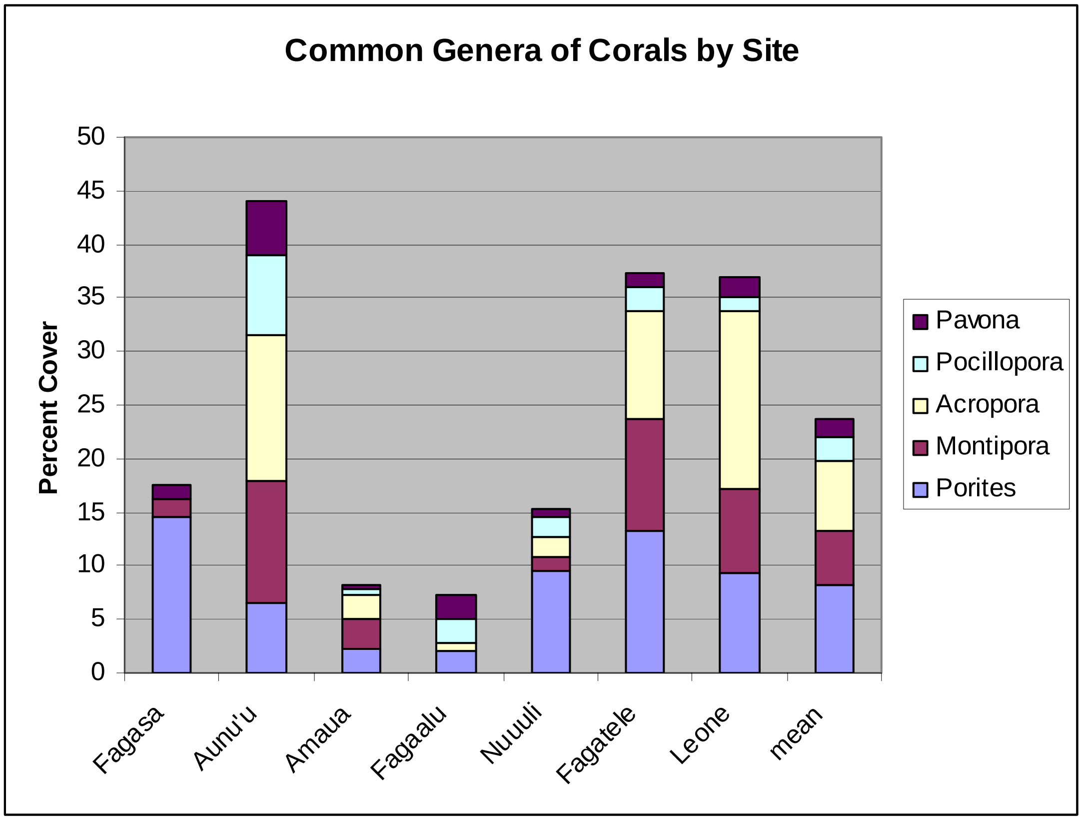


Figure 9 shows the mean cover of the most common genera.

Figure 9.

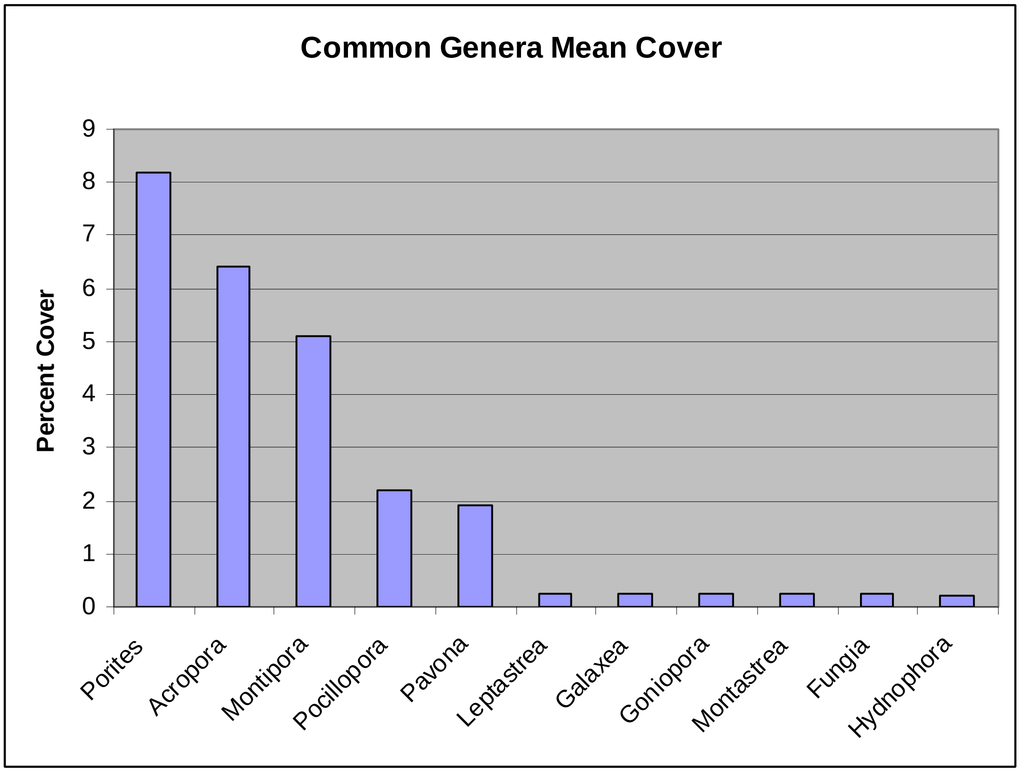


Figure 10 shows the number of genera by site.

Figure 10.

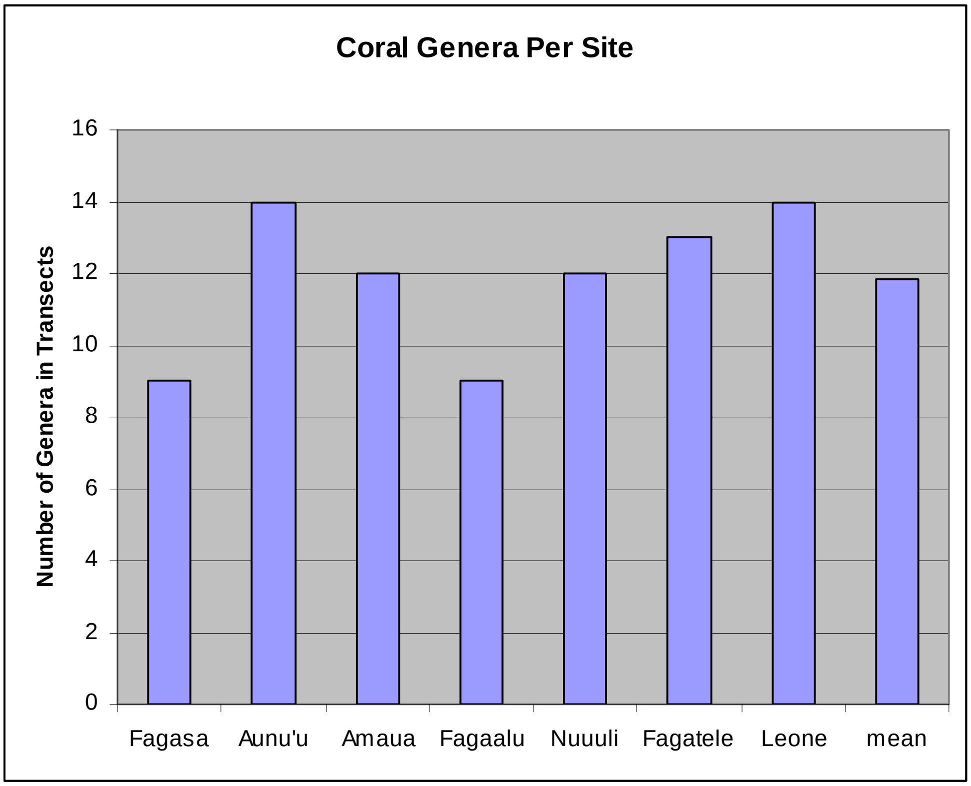
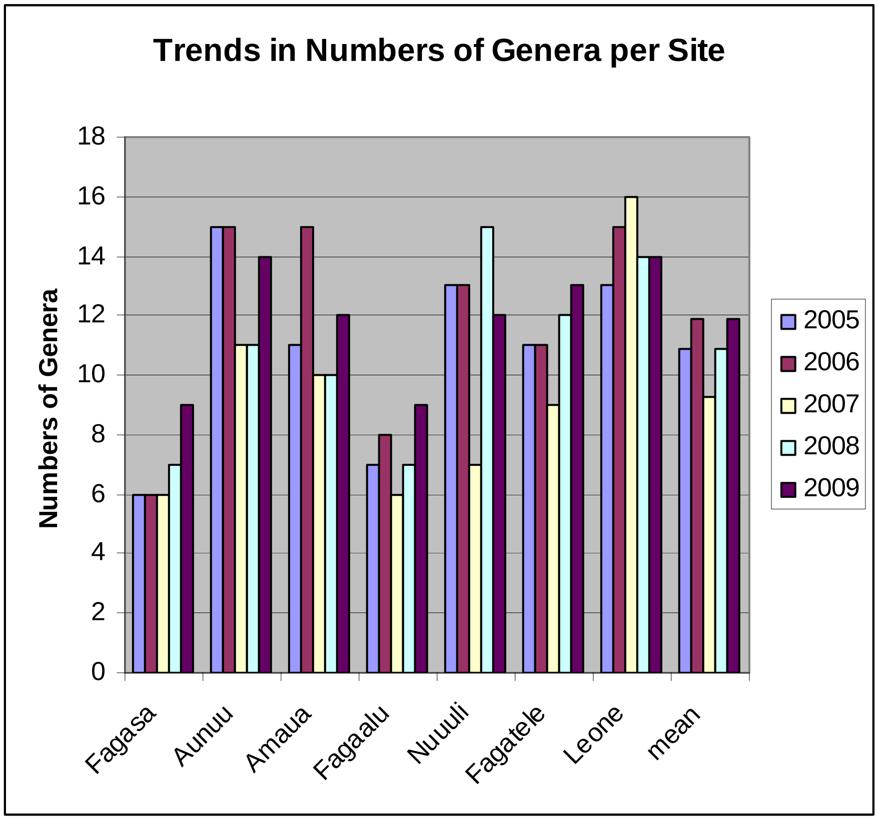


Figure 11 shows trends in the numbers of coral genera per site. There is no trend in the mean number of genera.

Figure 11.



Coral Species

Figure 12 shows the most common coral species by site. *Porites rus* is the most common coral followed by encrusting *Montipora*.

Figure 12.

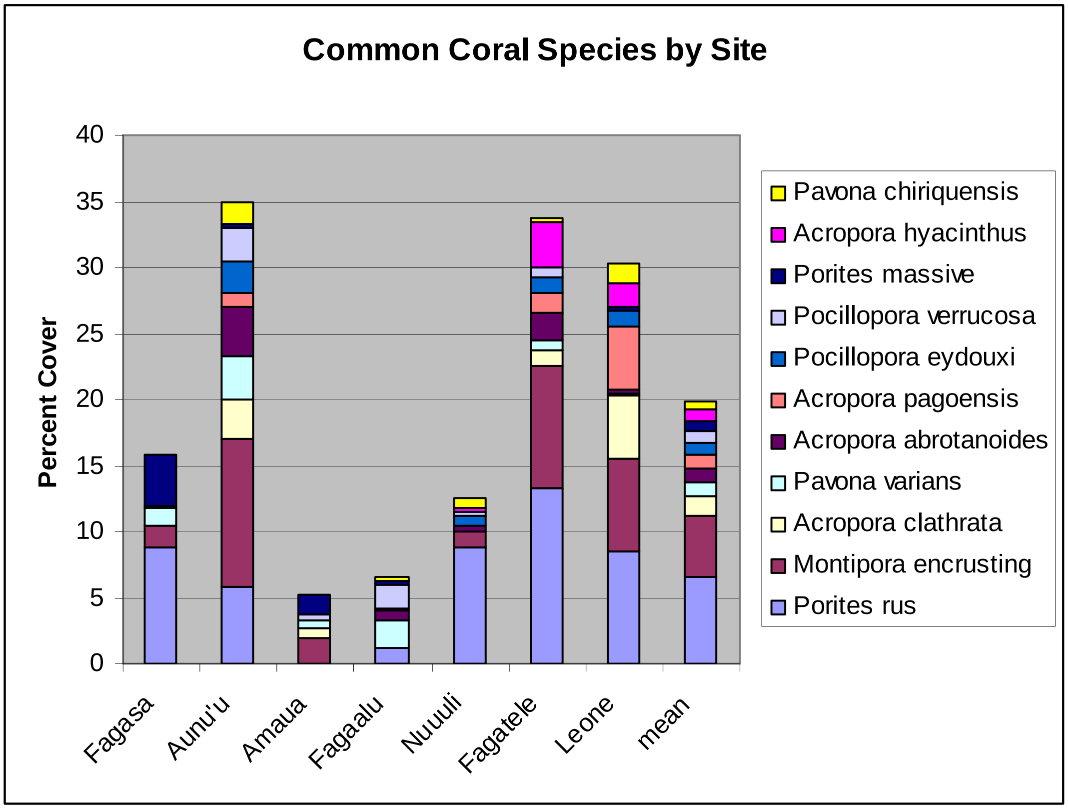


Figure13 presents the mean cover of the most common coral species. *Porites rus* was the most common, followed by encrusting *Montipora*, *Acropora clathrata*, and *Pavona varians*.

Figure 13.

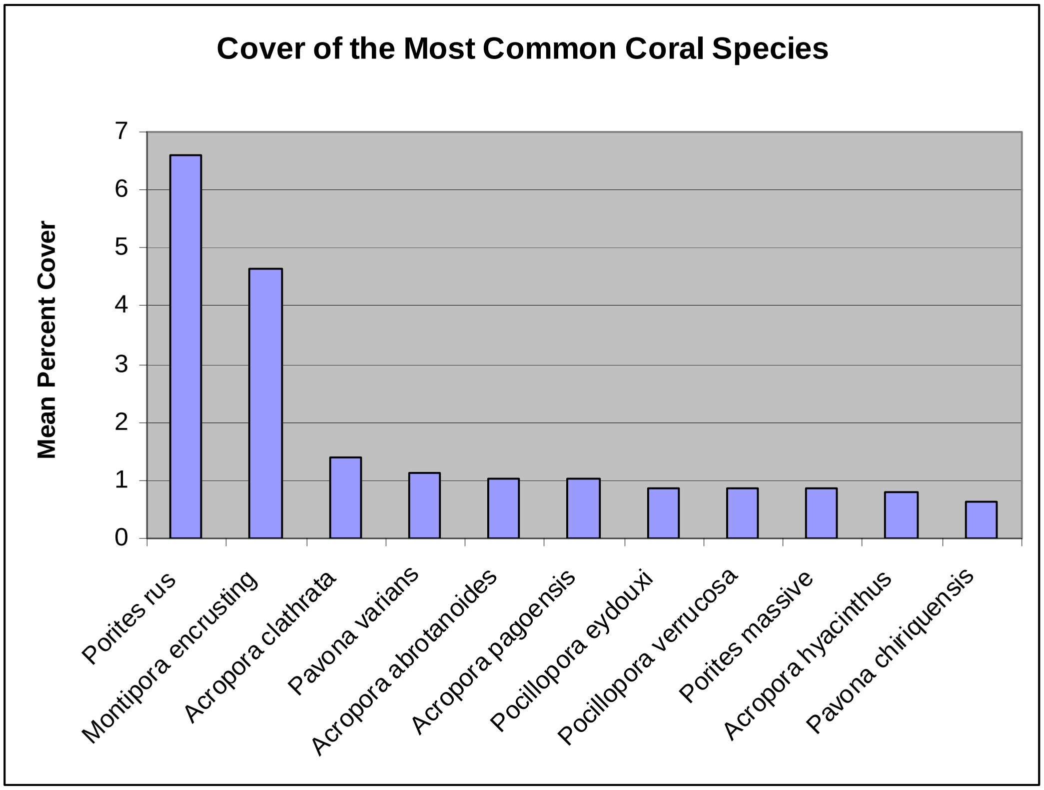


Figure 14 shows the number of species per site. Aunu'u has the highest number of species, followed by Leone and Fagatele Bay.

Figure 14

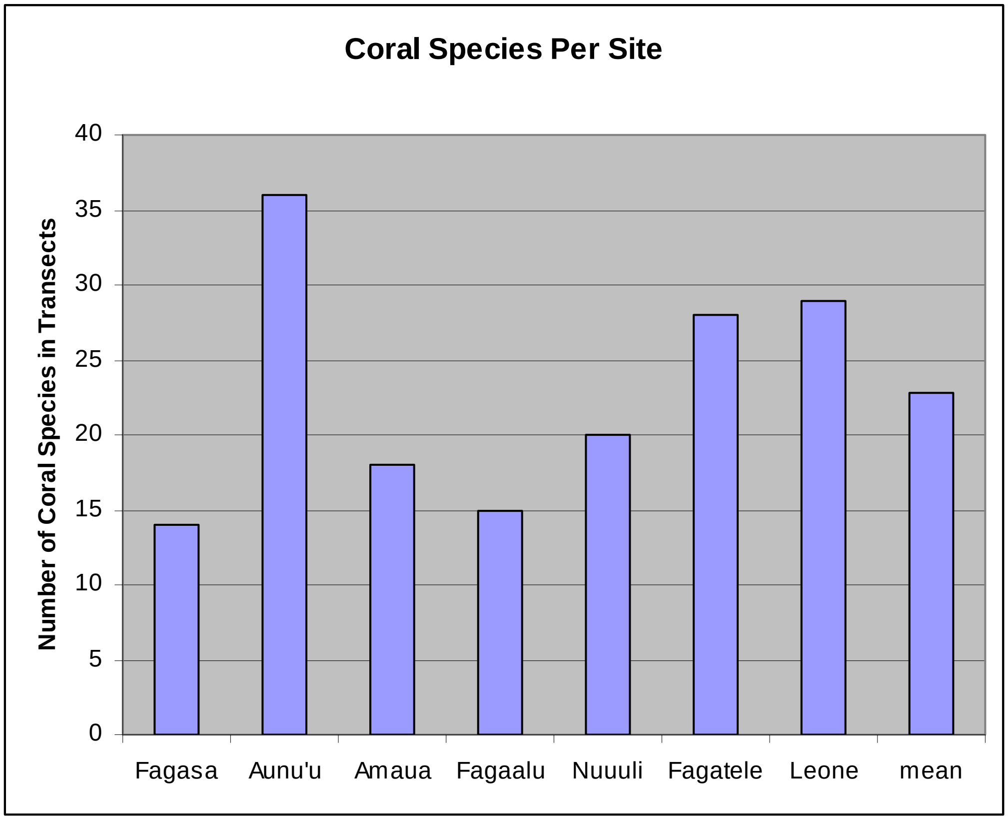
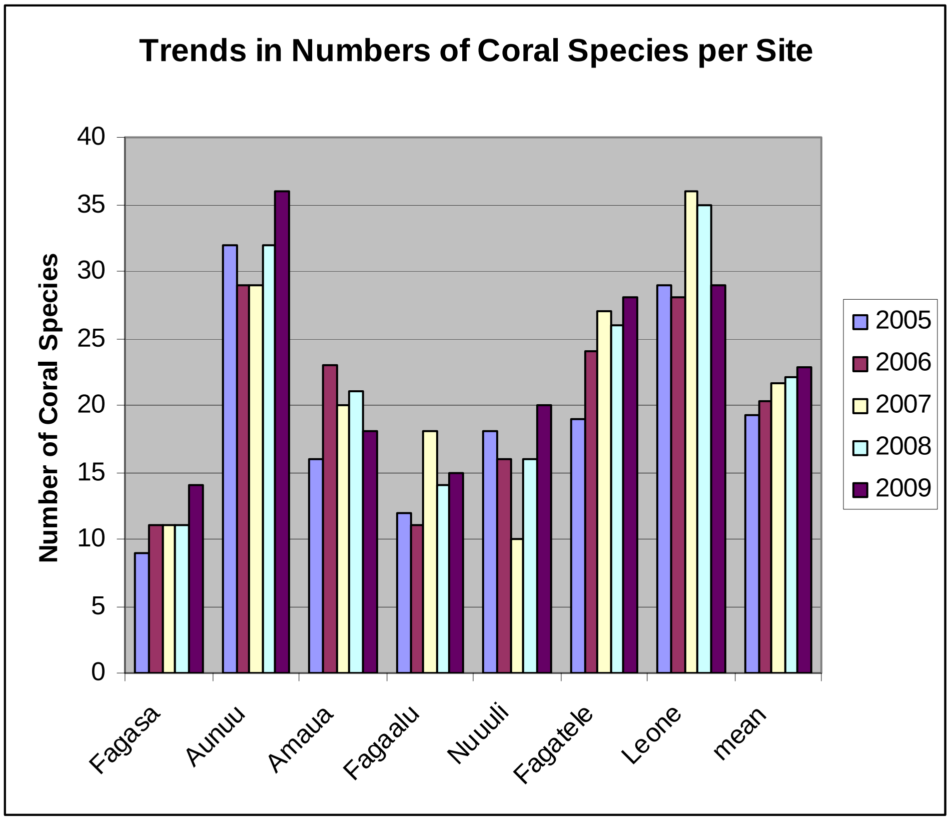


Figure 15 shows trends in the number of species at each site. The differences between sites in the number of coral species is fairly stable. The mean number of species shows a slight but steady upward trend over years.

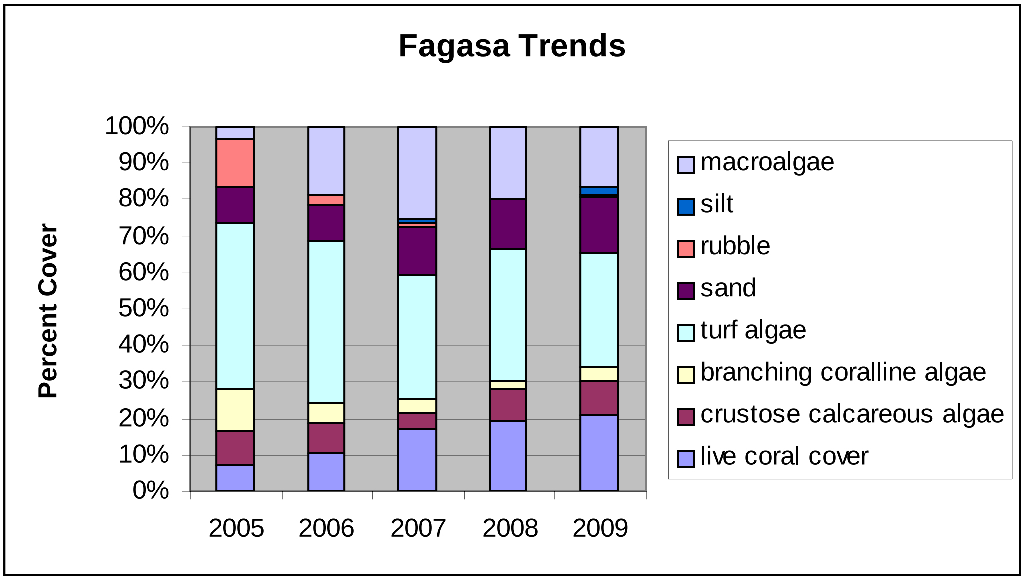
Figure 15.



Trends at Individual Sites

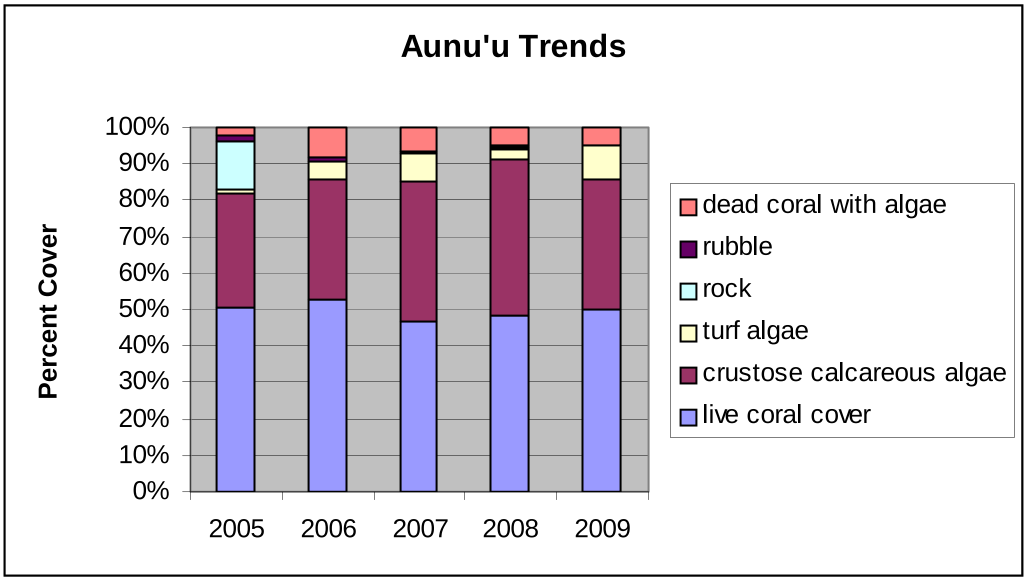
Data in Fagasa was taken before the Sept. 29 tsunami. In Fagasa, benthic data for 2009 was little changed from 2008 (Figure 16). Coral cover continued to be about 20%, following four years of increases ending in 2008. Turf algae decreased slightly, sand increased, and macroalgae decreased. The longer-term trend has been that macroalgae increased up to 2007 and then decreased slightly thereafter. Increases in sand seem particularly unlikely to be real, most likely that reflects the location of the tape, either going over larger parts of the sandy-bottomed cracks between the large reef lumps, or smaller amounts.

Figure 16.



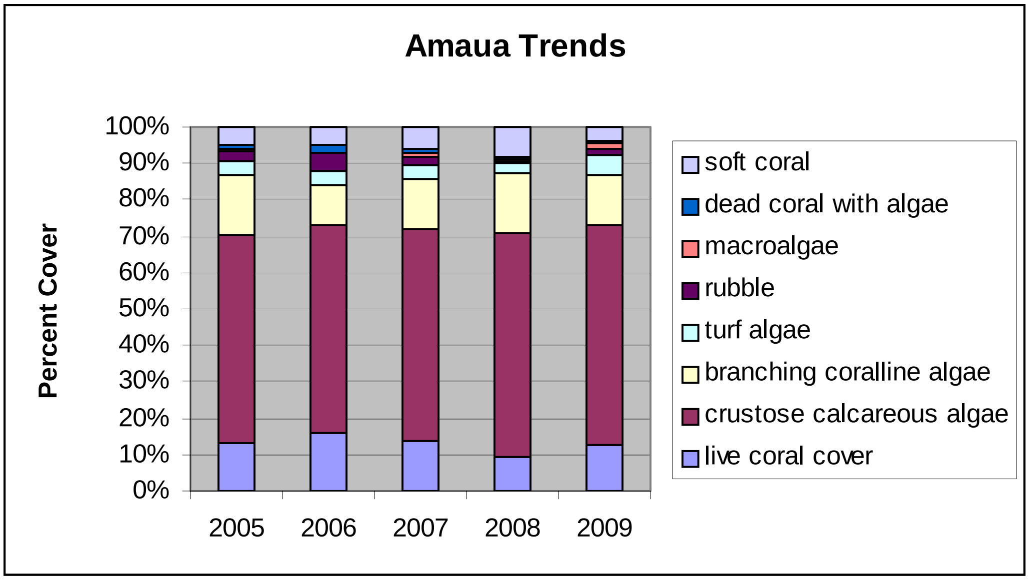
Data was gathered from Aunu'u before the Sept 29 tsunami. There was only minor change from 2008, and the long-term trend is very steady (Figure 17). Coral cover continues to be 50%, but there was a small decrease in crustose calcareous algae back to levels more typical of 2005-2006. Turf increased slightly, back to closer to 2007 levels. All these changes are minor and may reflect tape placement. It appears that this site at Aunu'u is very stable.

Figure 17.



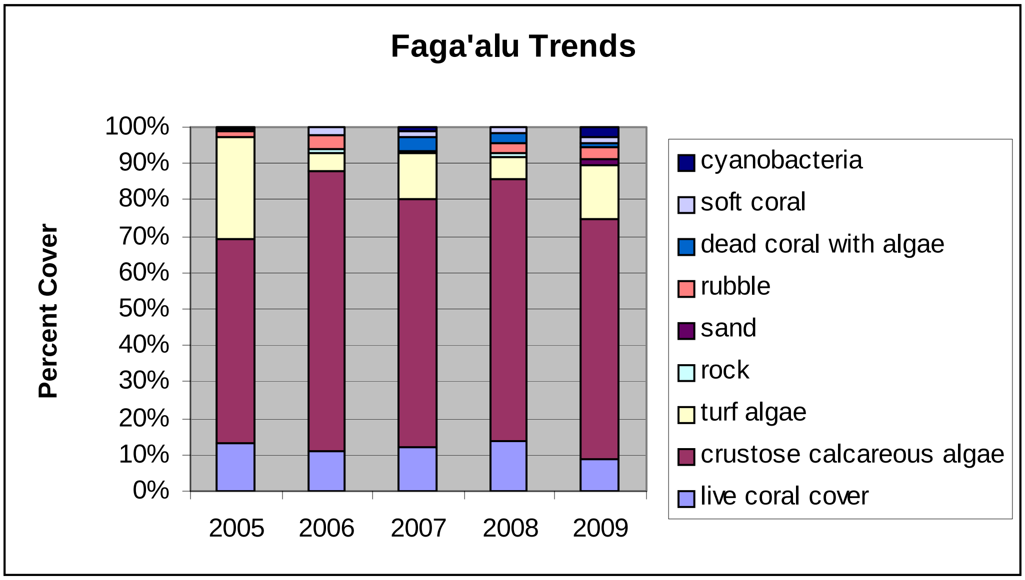
Data was recorded from Amaua before the Sept. 29 tsunami. The reef cover in 2009 was very similar to that in previous years, with coral cover around 12%, crustose calcareous algae about 60%, and branching coralline algae at a bit over 10% (Figure 18). There appear to be no trends over the five years that data have been recorded.

Figure 18.



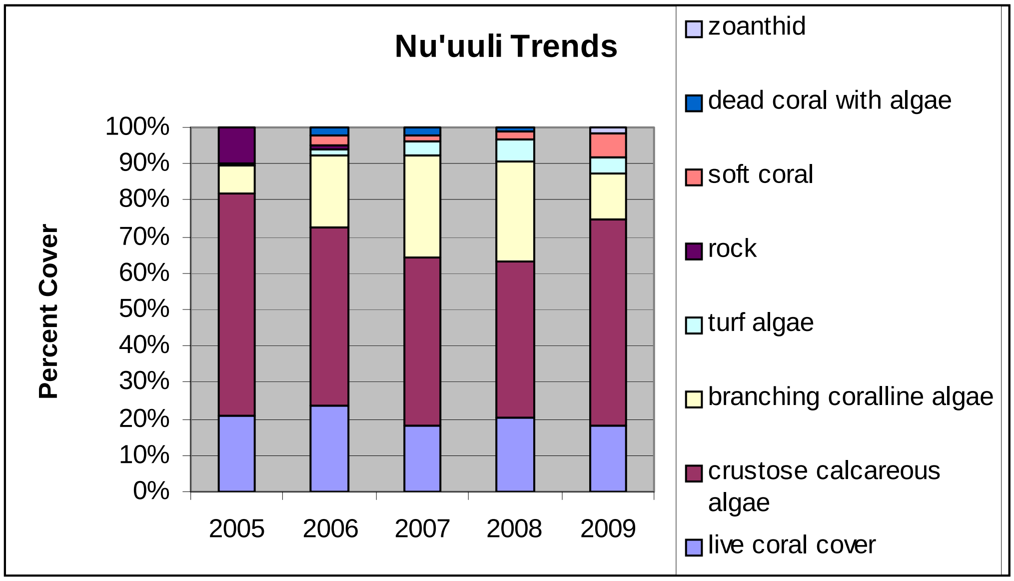
Data was collected from Faga'alu before the Sept. 29 tsunami. Coral cover was down slightly, but remains close to the 10% cover average over the five years of monitoring (Figure 19). Crustose calcareous algae was lower than in 2008, and turf increased. However, these values were within the range seen in previous years, and there appears to be no systematic trends.

Figure 19.



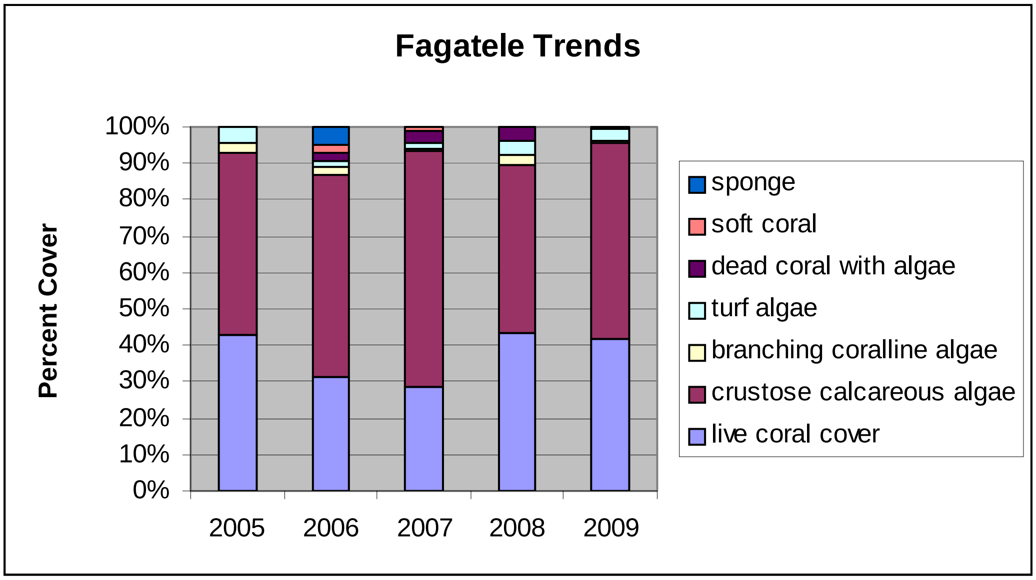
The data for Nu'uuli was recorded before the Sept. 29 tsunami. Live coral cover continues to be about 20% (Figure 20). Crustose calcareous algae increased from 2008 at the expense of branching coralline algae, which decreased. It appears that over the five years of monitoring, first branching coralline algae increased at the expense of crustose calcareous algae, and now this trend has reversed. It appears that the branching coralline algae grows over the crustose algae covering it, but it is still there and alive and likely healthy, so if the branching coralline algae recedes, it is revealed again. Although it is possible that transect placement caused this, the fact that coral cover is so steady suggests it is real. Why these changes occurred is not clear.

Figure 20.



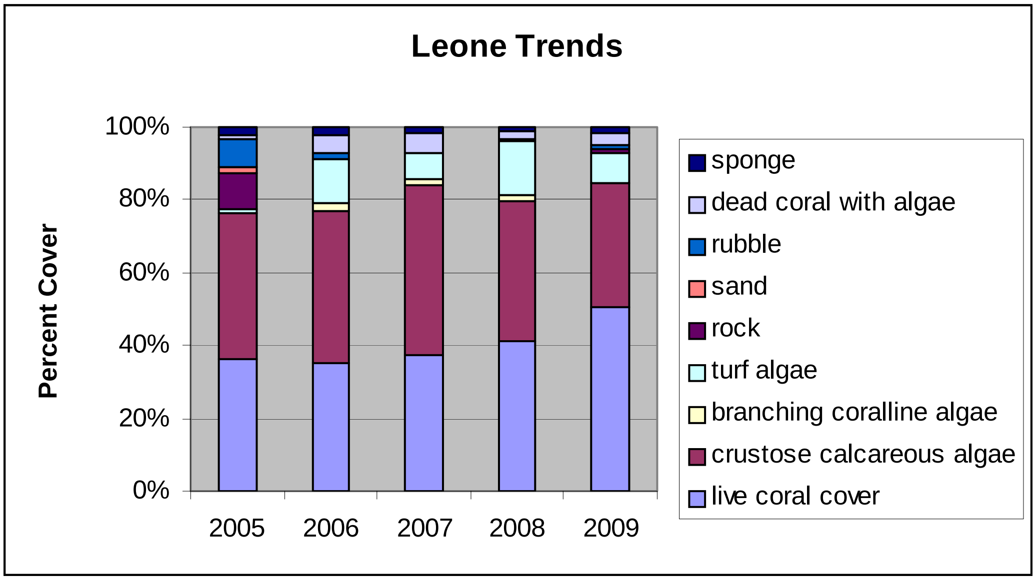
Data was gathered from Fagatele Bay before the Sept. 29 tsunami. Coral cover was just slightly less than in 2008, but very similar to 2005 as well as 2008 (Figure 21). As noted in the report for 2008, it appears likely that the tape was in a slightly different location in 2006 and 2007. The amount of crustose calcareous algae increased slightly in 2009. But it appears that there are no overall trends in the Fagatele Bay data.

Figure 21.



Data for Leone were taken before the Sept. 29 tsunami. There was an increase in coral cover from 40 to 50%, at the expense of crustose calcareous algae (Figure 22). The cause of this may well have been a change in the location of the second two tapes. After the first two tapes had been taken, the weather had changed and become rough and the skipper felt it wise to return to port. We returned another day, but did not have the buoy to mark the end of the first two transects precisely. Near the end of the fourth transect, it became clear that the third and fourth tapes were located to the east of their normal location. Thus, while it is possible that Leone had an increase in coral cover, it is more likely that the changed tape location accounts for the apparent increase. The reef appeared to be just as in previous years.

Figure 22.



Invertebrates

Figure 23 shows the number of invertebrates at each site.

Figure 23.

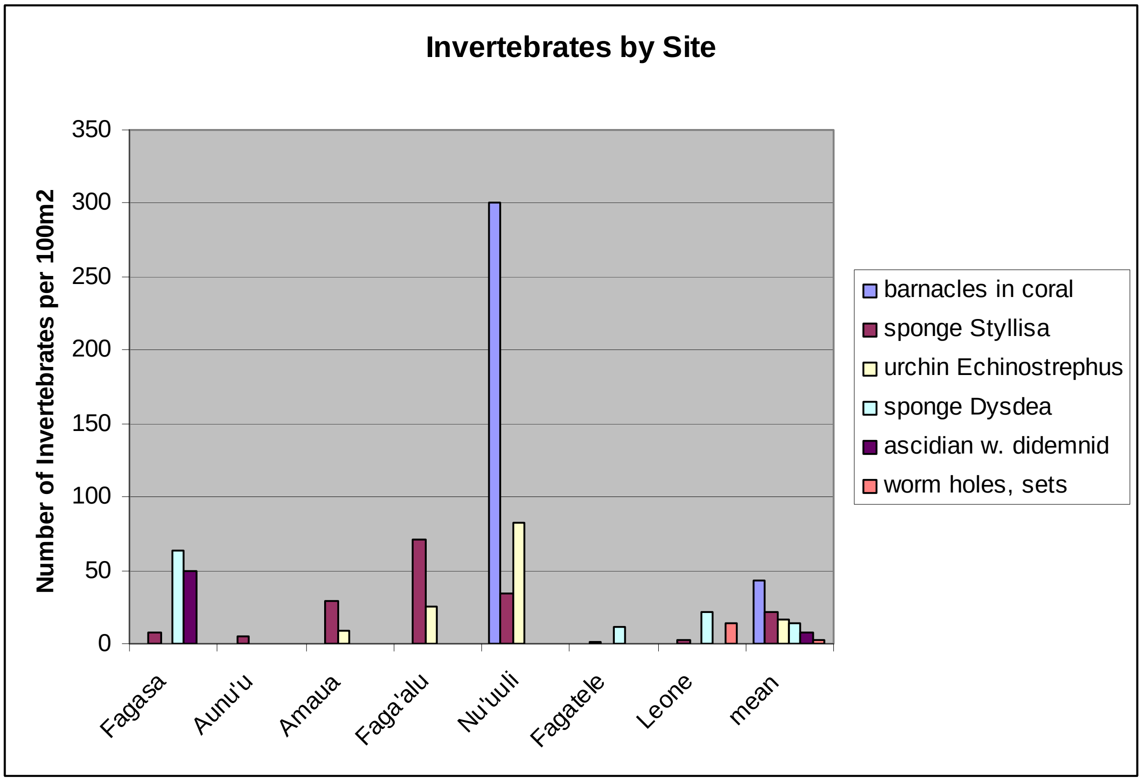


Figure 24 shows the mean number of invertebrates at each site.

Figure 24.

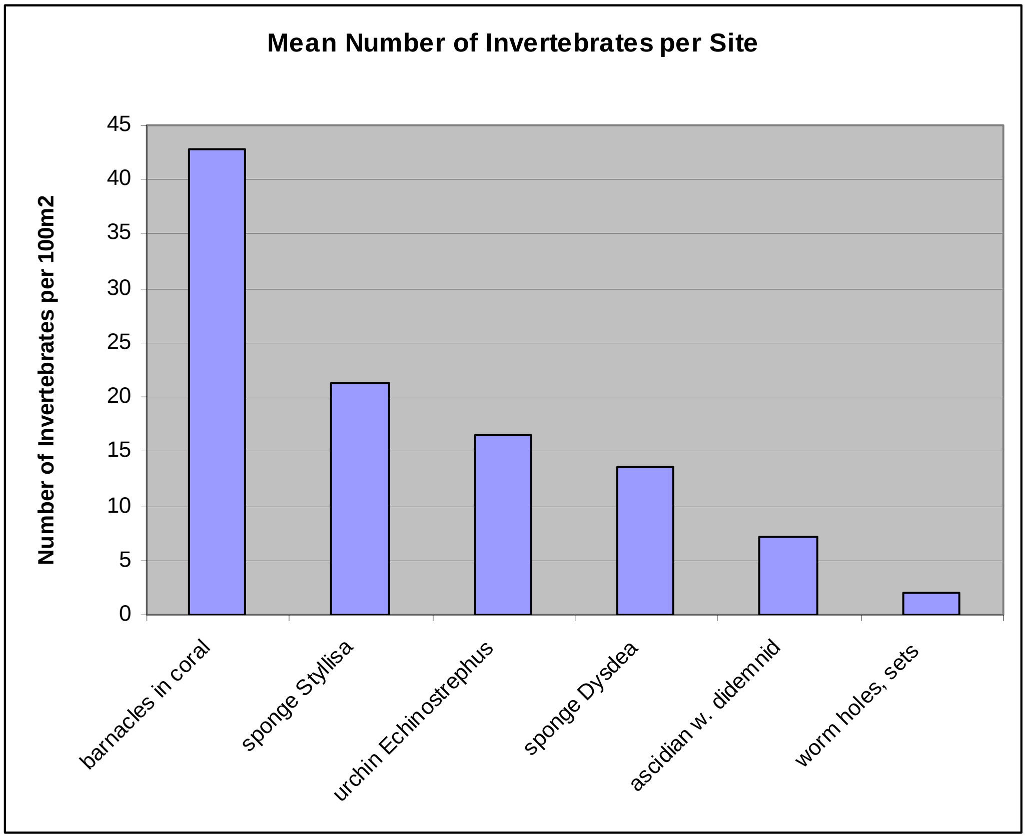


Figure 25 shows trends in the numbers of different kinds of invertebrates at each site.

Figure 25.

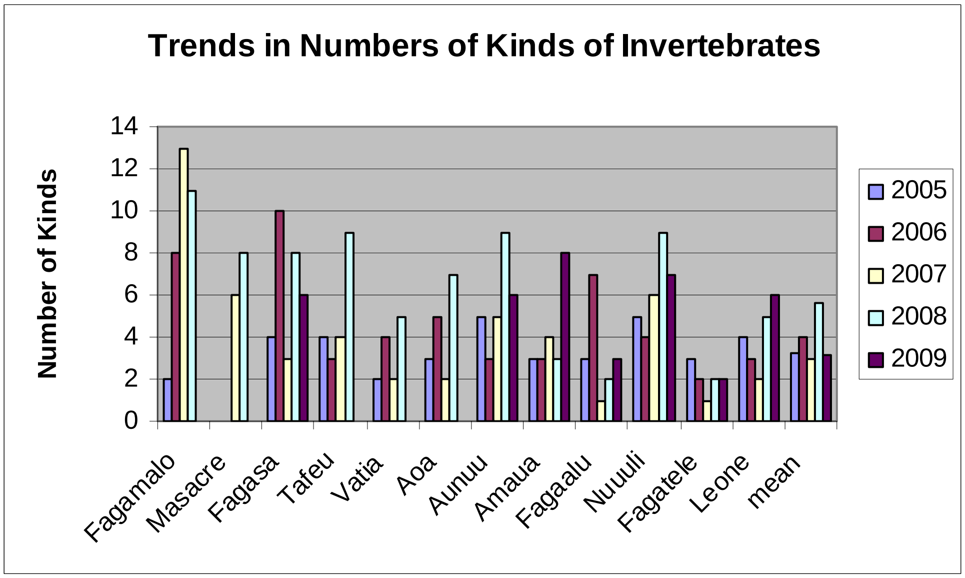
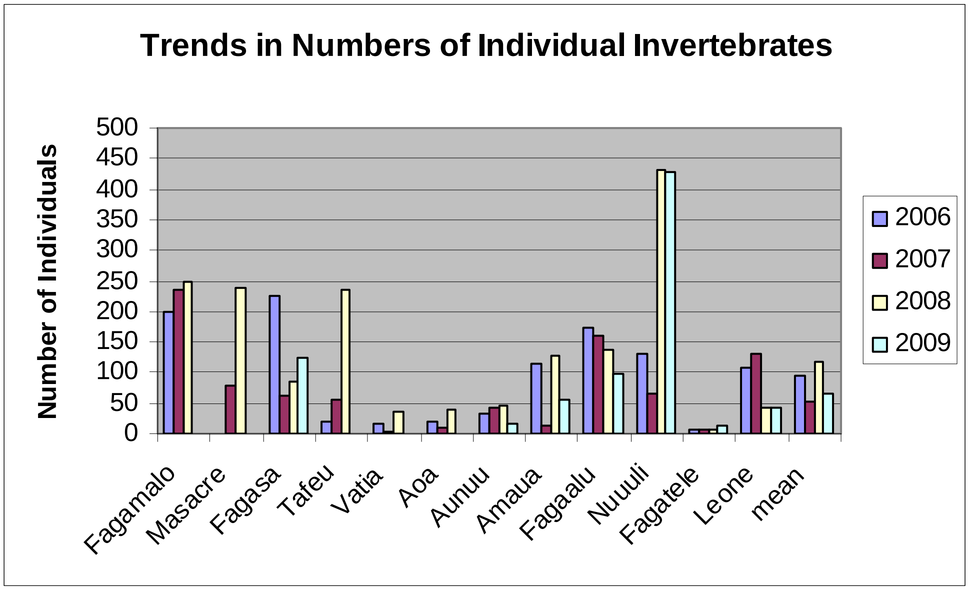


Figure 26 shows trends in the numbers of individual invertebrates at each site.

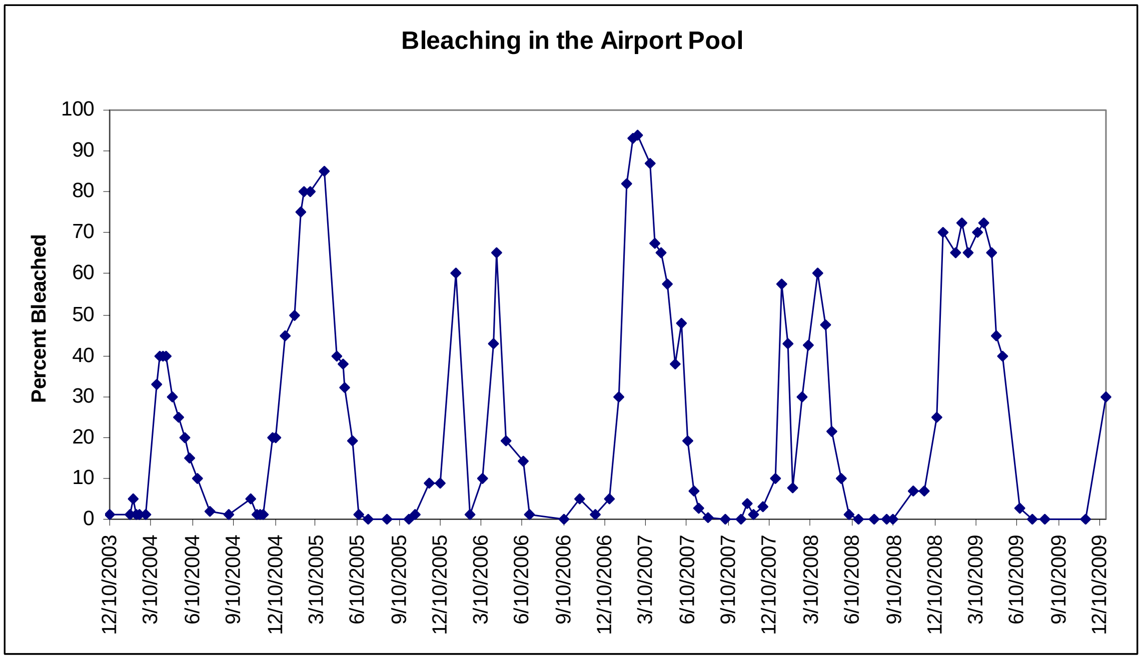


Neither of the graphs of trends shows any overall trend in the means, so invertebrate populations appear to be steady.

Bleaching

Bleaching monitoring continued in the airport backreef pool, and the Alofau pool. The annual austral summer bleaching of the staghorns continues, with the graph for the airport through 2009 shown below in Figure 27. The bleaching for 2009 was substantial,

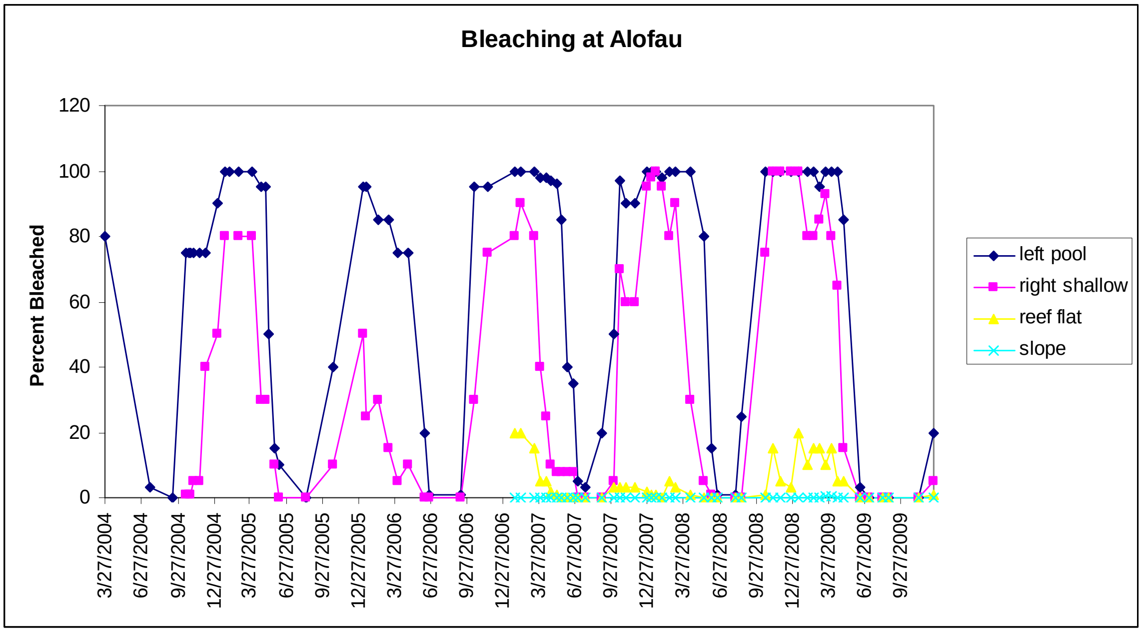
Figure 27.



not quite reaching as high a level as 2007, but not having a notch due to cloudy, rainy weather as in 2008 and 2006. The duration was typical. The next bleaching began at the end of 2009, right on time.

Figure 28 shows the bleaching record at Alofau. Bleaching was intense in 2009, with near 100% bleaching throughout the pool, and some bleaching on the reef flat. At the end of the year, the next bleaching cycle began, but the unbleached period late in 2009 was longer than in previous years.

Figure 28.



Coral Disease

Coral disease continues to appear to be relatively uncommon, but interesting diseases are noticed from time to time. There were a few large patches of the thin plate coral, *Echinopora lamellosa*, in Fagatele Bay, at about 20-30 feet deep. Some of the patches had dead areas in the shape of circular discs. The dead areas were covered with a variety of algae such as filamentous and coralline algae. Some had a thin dark ring in the living coral at the edge of the dead area. The tsunami seems to have completely removed the large patches before samples could be taken. The CRED team reported large patches with the same disease at other locations. Additional infected colonies were found at Fagafue Bay, on the north shore, and photos (Figures 29-33) and samples taken. The disease does not appear to move quickly as there is no white band between the live tissue and the area where algae covers the dead skeleton. Analyses of samples by Dr. Thierry Work did not reveal the cause.

Figure 29. A small field of *Echinopora lamellosa* near the mouth of Fagafue Bay, north shore of Tutuila, after the tsunami. Some greenish patches of disease can be seen on the nearest plates. In Fagatele Bay, large mounds of this thin delicate plating species shallower than about 8 m could not be found after the Sept. 29 tsunami, apparently they were completely removed. In deeper water, smaller patches like this one had remnants left after the tsunami.

Figure 30. Disease on *Echinopora lamellosa*. Taken at Fagafue Bay, north shore Tutuila, after the tsunami.

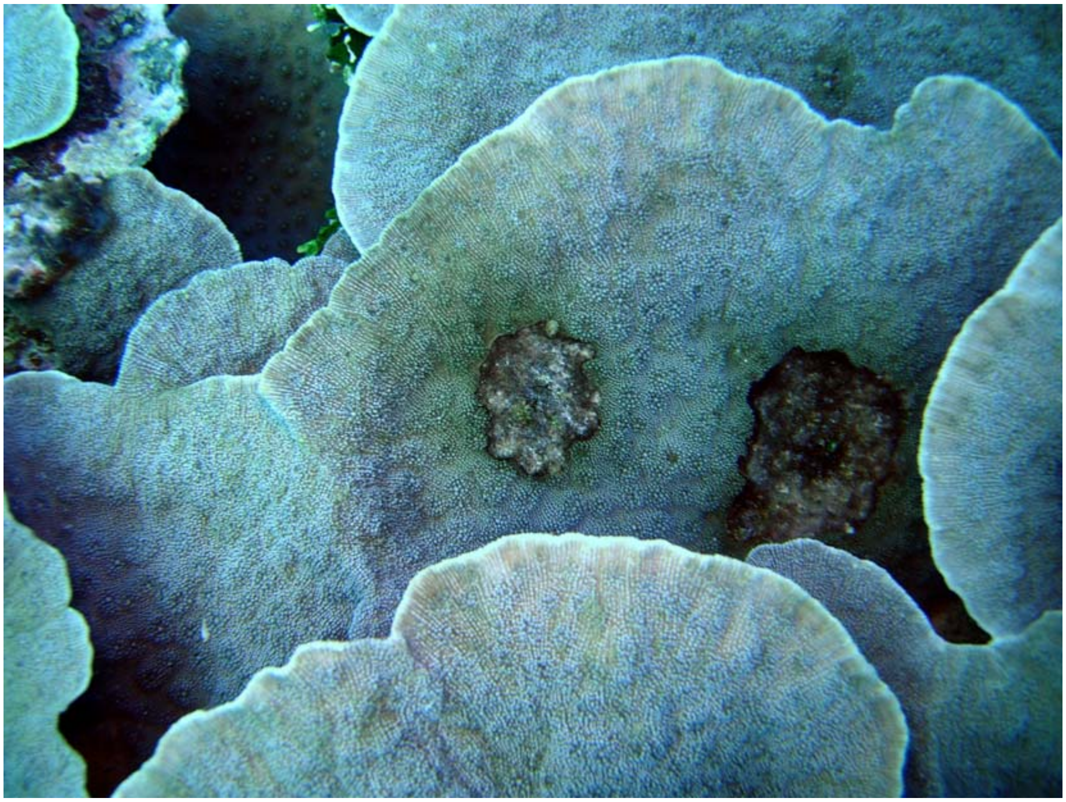


Figure 31. Disease on *Echinopora lamellosa*. Taken at Fagafue Bay, north shore Tutuila, after the tsunami.

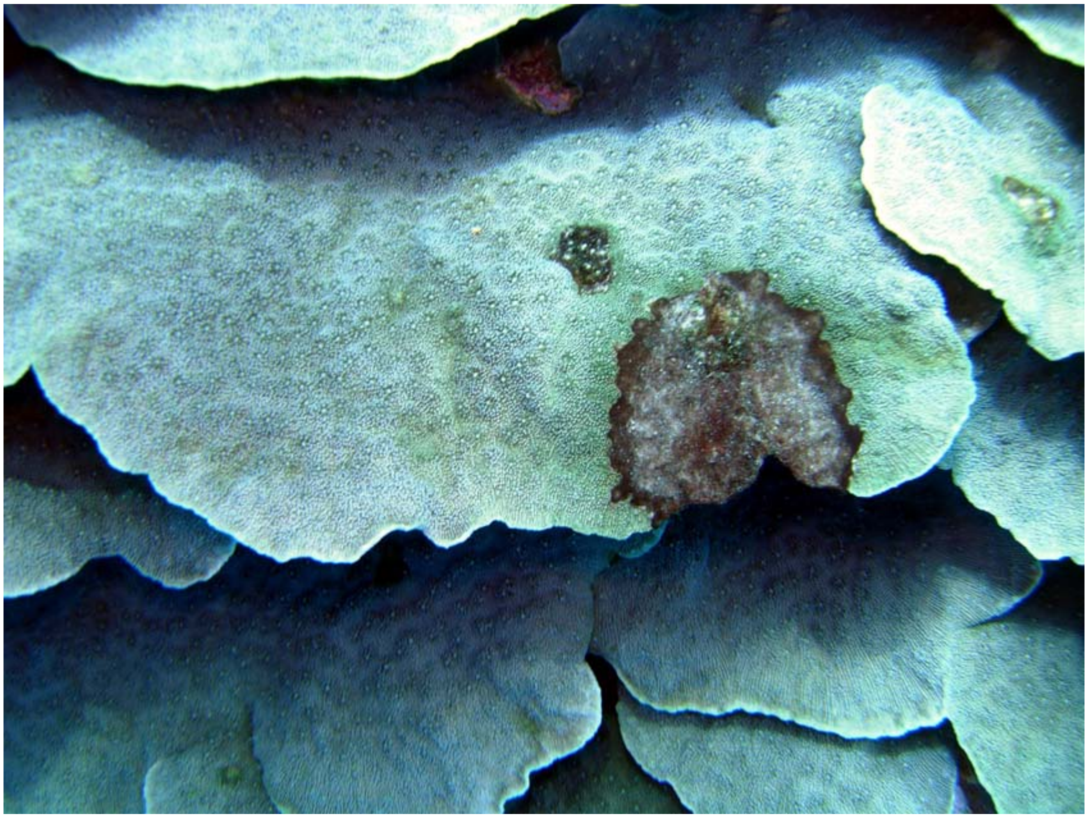


Figure 32. Disease on *Echinopora lamellosa*. Taken at Fagafue Bay, north shore Tutuila.

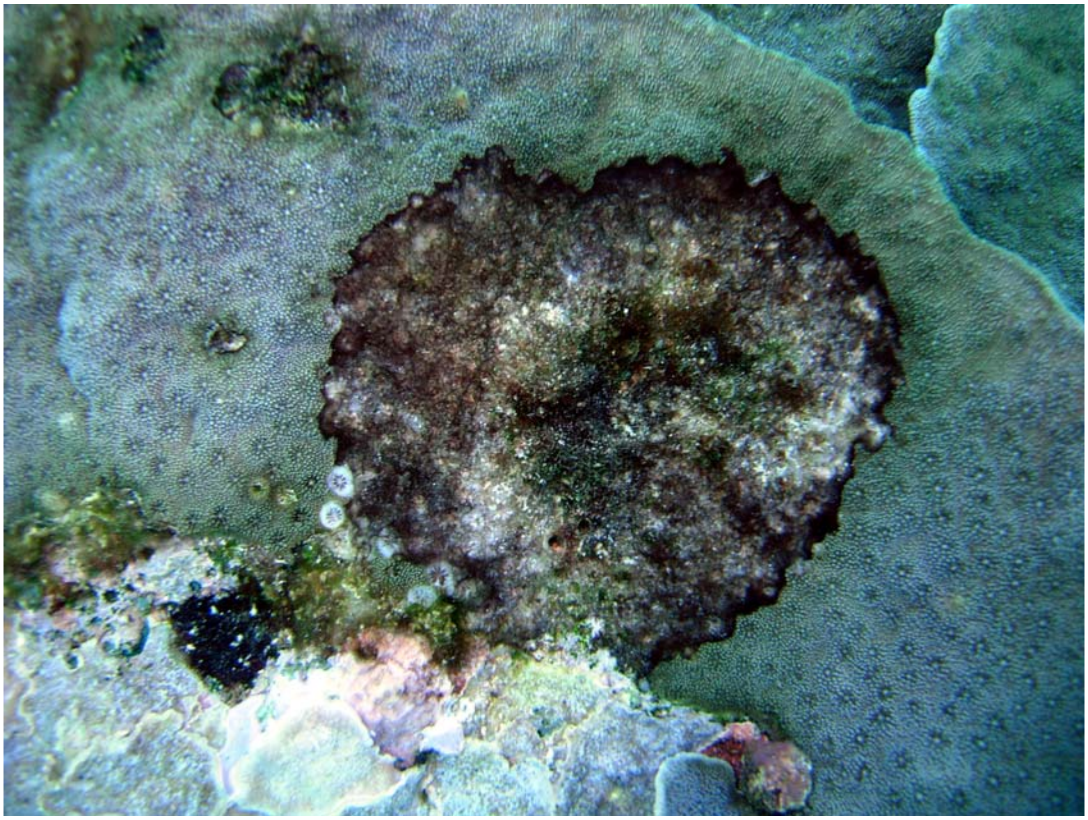
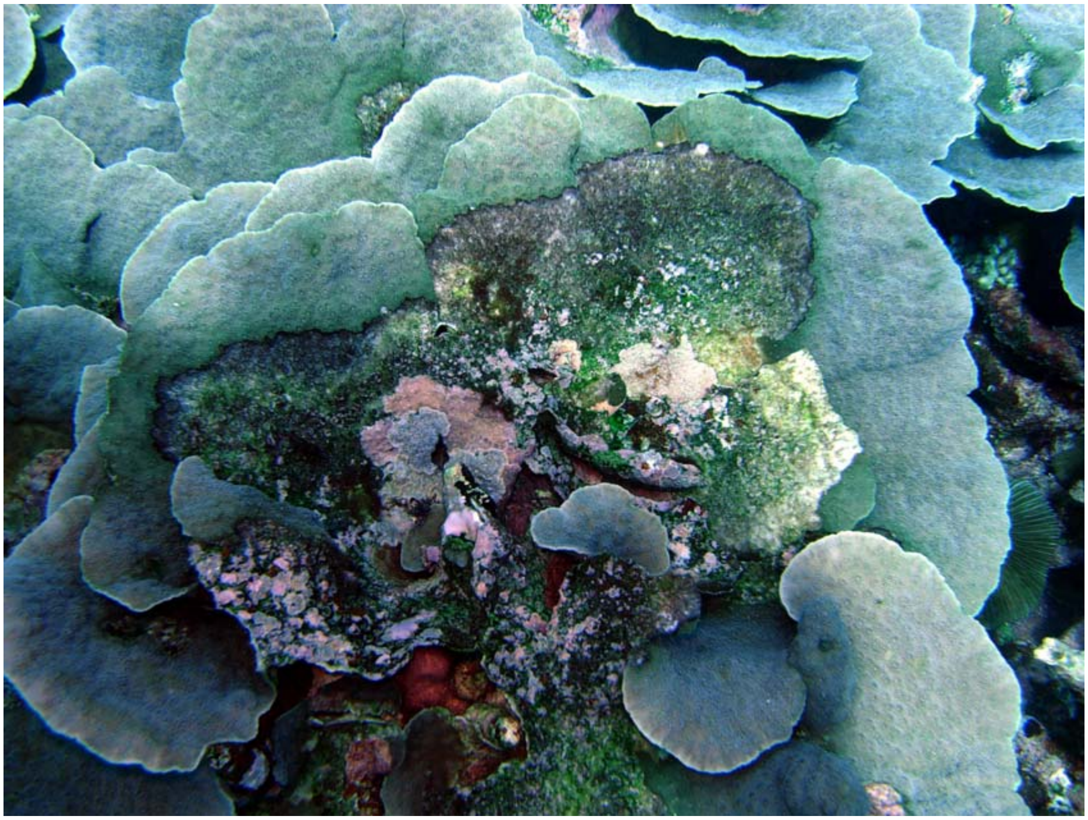


Figure 33. Disease on *Echinopora lamellosa*. Taken at Fagafue Bay, north shore Tutuila.



The branching coral, *Pocillopora*, is present on many of our reef slopes, though not one of the most common corals. *Pocillopora verrucosa* and *Pocillopora eydouxi* are two of the most common species there. In addition to living colonies, there are also a significant number of dead colonies, in fact those dead colonies are a significant proportion of all the dead colonies. The dead colonies are covered with coralline algae and/or filamentous algae. There are also colonies that are partly alive and partly dead, and they often have a few branches between the live and dead areas that appear to have a disease (Figure 34). On some colonies, a thin light line can be seen between the living and dead portions.

Figure 34. Typical view of diseased *Pocillopora* colonies, with some dead branches, some diseased branches, and other healthy branches.

The cause of the dead colonies is not hurricanes, since none of the branches are broken (they are in fact very strong). It is unlikely that they were eaten by Crown-of-Thorns starfish, since they are rare and have never been seen eating *Pocillopora* on the slope by the author. It is unlikely to be due to bleaching, since there aren't a lot of dead *Acropora* on the reef slopes. *Acropora* is at least as sensitive to high temperatures as *Pocillopora*. Some years there has been scattered bleaching on the upper surfaces of corals, which is almost exclusively on the *Pocillopora* and a small massive coral, *Montastrea curta*. However, none of the *M. curta* are dead. So it is unlikely to be due to bleaching.

The cause of the dead *Pocillopora* colonies is almost certainly disease, which appears to be a chronic problem. In spite of the disease, a significant number of living *Pocillopora* colonies remain.

Low tides

Observation in late October, 2009 of the reef flat in Fagasa revealed areas in which all or most all young table corals had been killed (Figure 35). Tables were typically around 30 cm diameter, with some possibly about 40 cm. All were completely heavily covered with turf which appeared to have been there for some time, more than just a few weeks, but not many years as the branchlets of the table were still distinct. Few tables near the edge of the reef were dead (Figure 36). Virtually none of the dead tables had any debris from the tsunami attached. At the edge of the reef many smaller juvenile tables had partial mortality, especially around the edge of the table, but few had complete mortality. It appeared that the fields of young tables that were all dead were killed by something that affected all tables and killed them completely, and that it was some time ago but not several years. All the information is consistent with their having been killed by low tides. Low tides were lowest in 2009 in July and August, particularly July 20-23, and August 18-20. This was a relatively cloudy, cool, and rainy period, and coral mortality on the reef flat was not noticed elsewhere. January and February had tides that were not quite as low, but likely the weather was sunnier and hotter. The pattern of mortality only being back from the edge of the reef is consistent with low tide, since wave splash could keep corals on the crest wet enough for them to survive.

Figure 35. Dead table corals on the reef flat back from the edge at Fagasa.

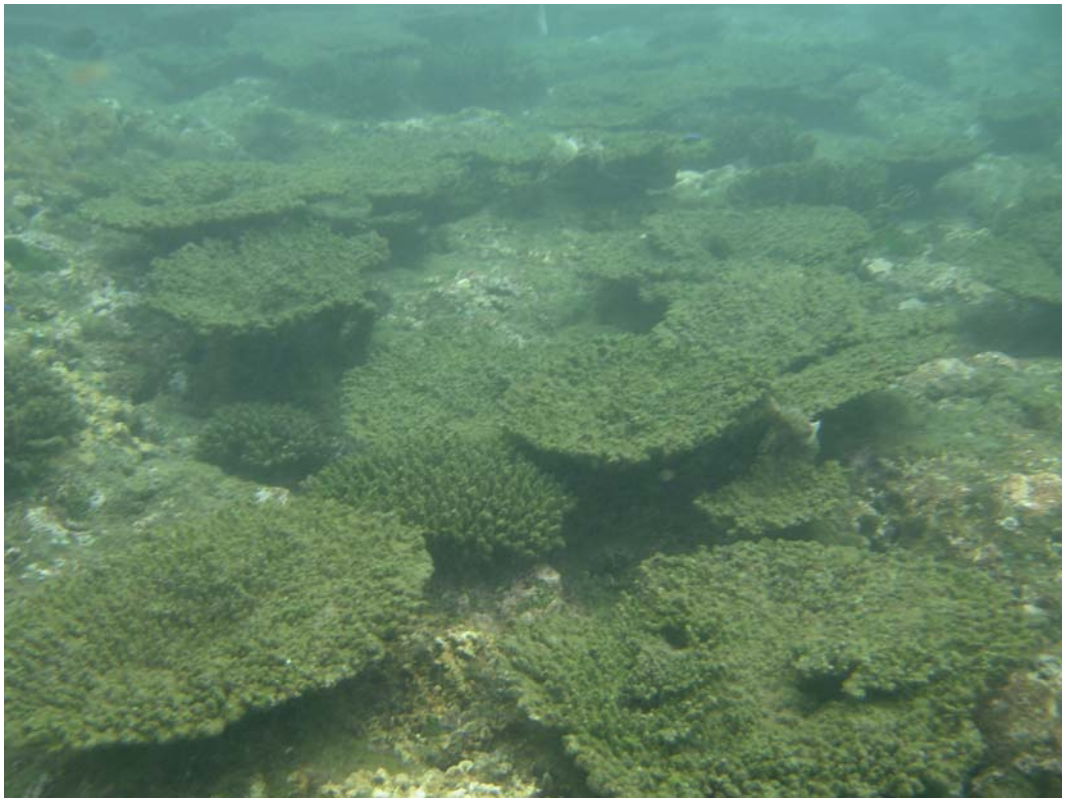
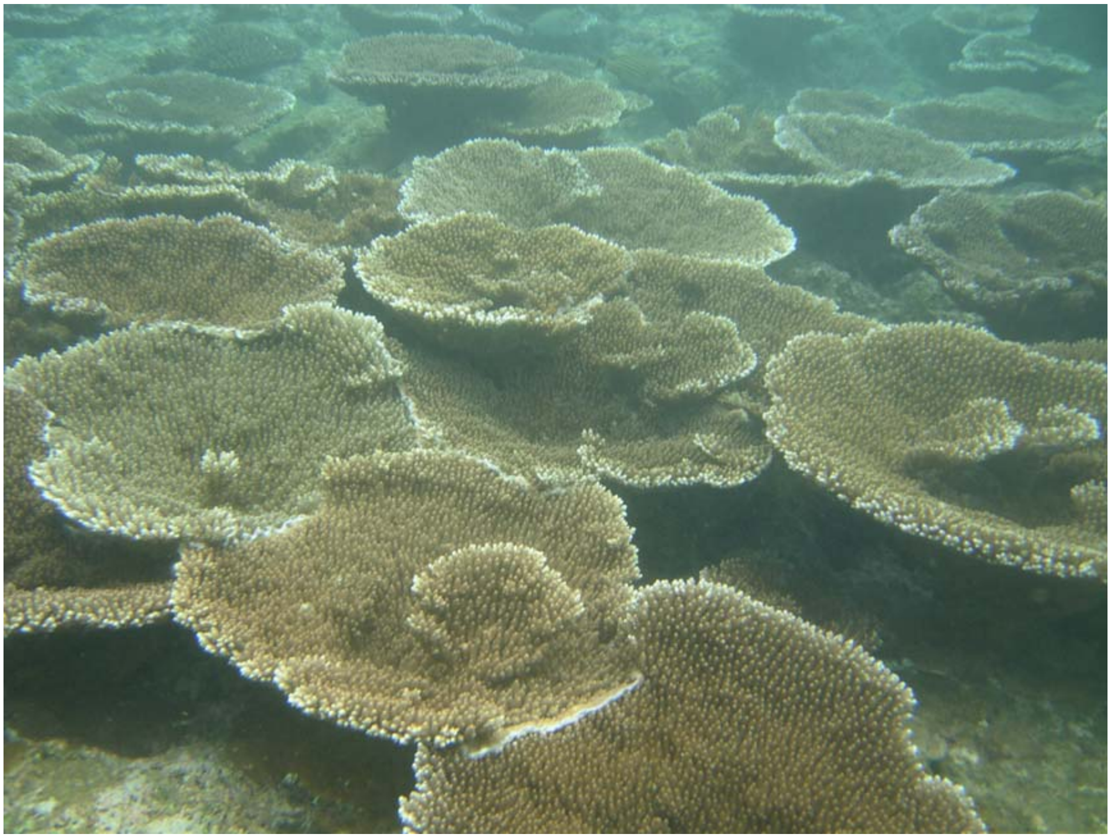


Figure 36. Live table corals on the reef flat near the edge at Fagasa. This is one of the best areas.

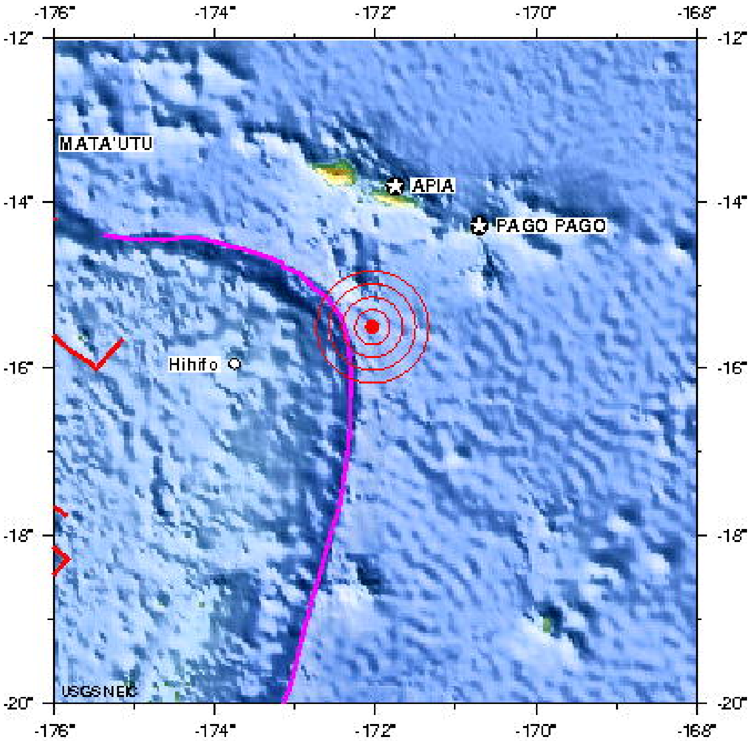


Tsunami of Sept 29, 2009

The tsunami of 2009 was the first major disturbance on the reefs of American Samoa since the beginning of the monitoring program in 2005. The author began surveying reef damage the day after the tsunami, and will continue into 2011.

At 6:48 am local time, Sept. 29, 2009, an 8.1 magnitude earthquake occurred just east of the northern end of the Tongan Trench, about 120 miles southwest of Tutuila. The earthquake was produced by a normal fault, in the area east of the Tongan Trench, where the Pacific Plate is being bent to go down into the Tongan Trench and be subducted (Figure 37). It was not a megathrust earthquake, such as those produced by subduction in trenches, such as the 9.3 magnitude earthquake in Ache, Indonesia, that produced tsunamis that killed about 230,000 people on Dec. 26, 2004. In a normal fault, rock on one side of a fault rises, and on the other side of the fault falls (Figure 38). When this happens on the sea floor, a large area of rock suddenly rises on one side, and falls on the other. This lifts or lowers the sea water, setting in motion the tsunami waves.

Figure 37.



SAMOA ISLANDS REGION

2009 09 29 17:48:10 UTC 15.51S 172.03W Depth: 18 km, Magnitude: 8.1

Earthquake Location

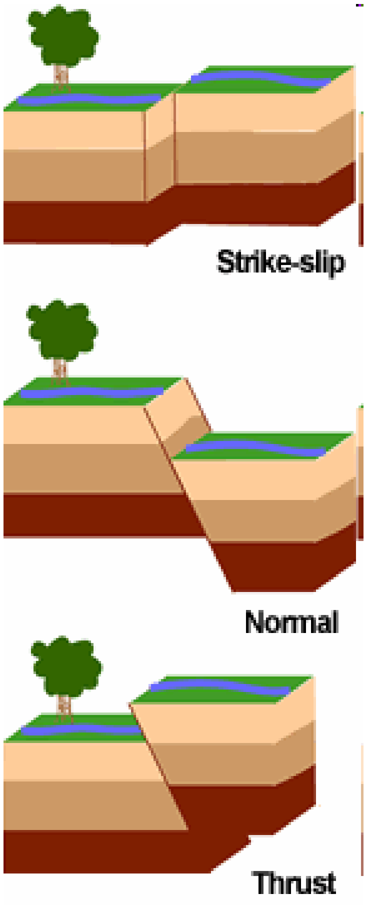


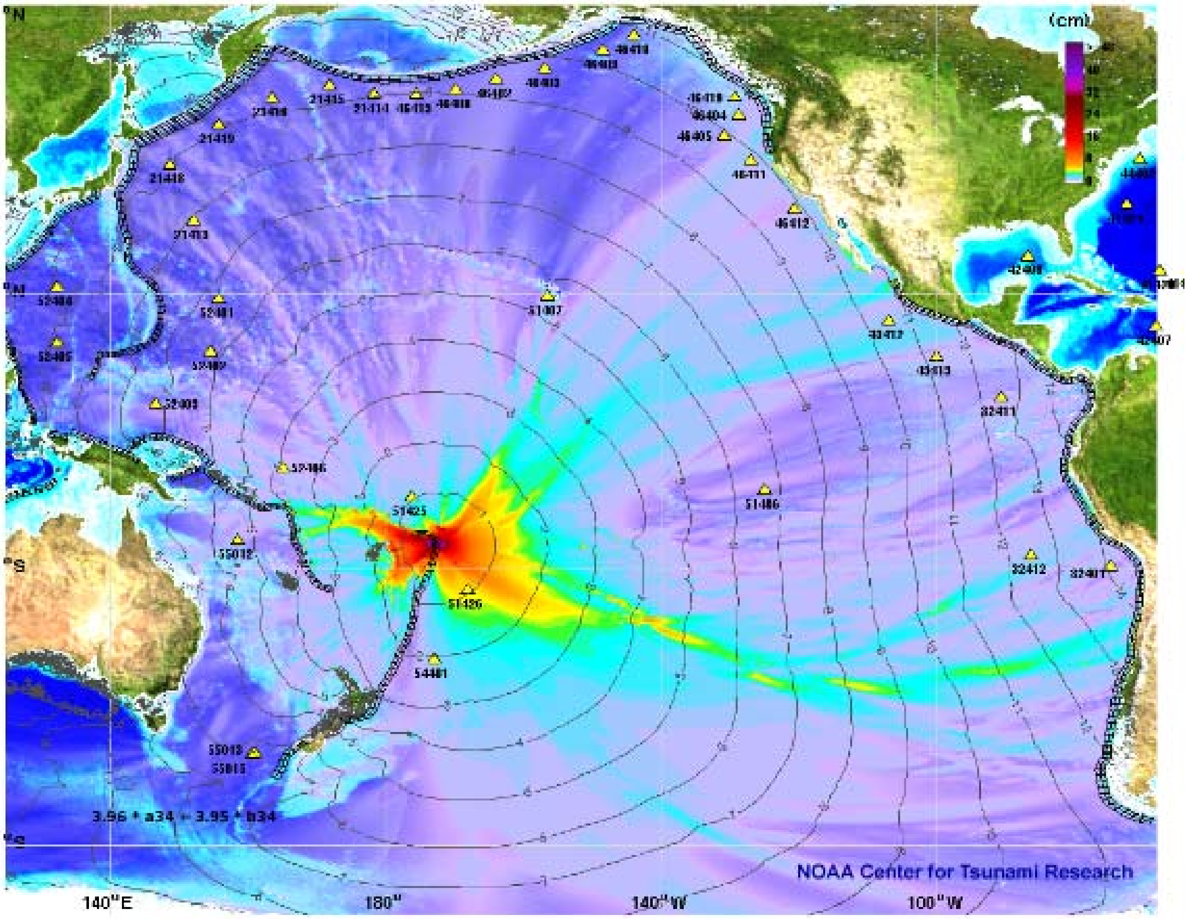
Figure 38.

Tsunami waves are quite different from wind waves (waves produced by wind). In the deep ocean, tsunami waves are about one foot (30 cm) high, and travel over 500 miles (800 km) per hour . Water moves in the entire water column from surface to sea floor, no matter how deep the water is, unlike wind waves, which have water movement that decreases quickly with depth from the surface. Wind waves also can be much taller (up to around 60 feet or 20 m tall in the eye of the largest hurricanes), move much more slowly, and are much shorter, and hence easily visible. A tsunami wave is on the order of 100 miles (160 km) long, so it cannot be seen visually by observers on a boat. A boat would rise or fall about a foot, but over a period of several minutes, so it would be undetectable in most instances. Because the wave moves so fast and the distance to Tutuila was not great, the wave arrives very quickly indeed. As a tsunami moves into shallower water, it moves slower and slower, so that by the time it reaches a shoreline, it often is moving “only” about 50 miles (80 km) an hour. Part of the delay until the wave comes ashore is the time taken by moving slower in shallower water. Tsunamis are not single waves, but rather a wave train, a series of many waves, in general largest near the beginning and tapering off with time. There may be around a half dozen of the largest waves, but then the waves taper off gradually, with a total of many waves. The wave height increases as the wave passes into shallower and shallower water, and becomes more and more noticeable. The slope of the bottom concentrates the movement of water and energy into an ever smaller space between the bottom and the surface as the wave comes ashore.

The word “tsunami” is a Japanese wave, and means “harbor wave.” Japanese fishermen long ago would return to port not having seen anything unusual, to find the harbor devastated by a giant wave. The shape of a harbor or bay can act like a funnel, funneling the wave energy into the inner harbor where the wave can be much larger and thus more destructive than along an open coastline. The height and power of the wave depend on the shape of the bay and the bottom in the bay, and mathematical models run on computers can be used to try to predict the size and power of the waves in different places.

This general understanding of tsunamis can help make sense of what happened in Tutuila on Sept. 29. The earthquake was close enough to Tutuila that the island experienced a strong and relatively long-lasting earthquake, lasting a minute or more. Computer modeling based on what was known about the earthquake movements, was used to model the spread of waves from the earthquake epicenter. As shown in the map below (Figure 39), the model predicts that the greatest wave energy went toward the northeast from the center. Because Tutuila and Manu’a are located to the northeast of the earthquake center, they were exposed to some of the strongest waves. Upolu was also far enough east to be exposed to the powerful waves, but Savai’i is to the north or even northwest of the epicenter, and so was spared the strong waves. Savai’i was not reported to have damage, while Upolu and Tutuila were. Damage in Manu’a was light. Keep in mind that the map below is a prediction of a mathematical model on a computer, not actual data that was recorded. The actual pattern may have been different from that predicted by the model, we don’t know at this point.

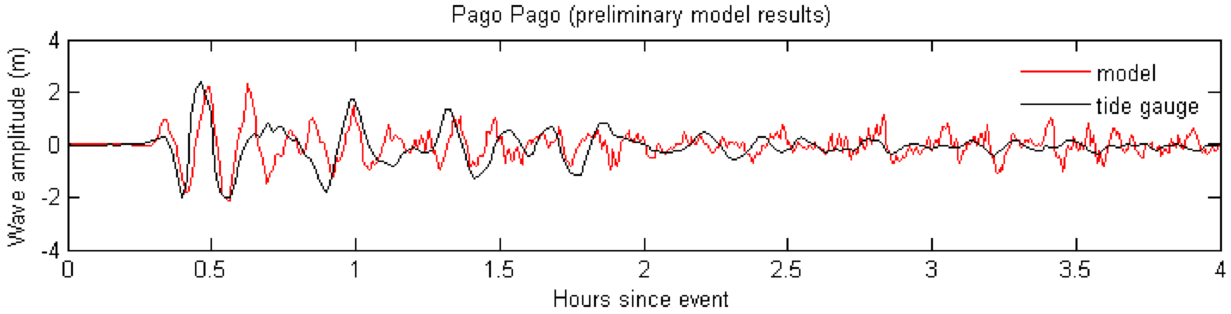
Figure 39.



The actual tsunami wave train was recorded at the DMWR dock in the harbor with a NOAA tide gauge installed there, and is shown in the figure below. Notice that the tsunami is not a single wave, rather it is a whole series of waves or a wave train. The largest waves are at the beginning, and the size of the waves decreases over time after the first wave. Tsunamis experienced along a shoreline can begin with the water

Figure 40. The black line is the actual water level recorded by the NOAA tide gauge at DMWR, while the red line is the prediction produced by a computer model based on characteristics of the earthquake and the shape of the sea floor near and in the harbor.

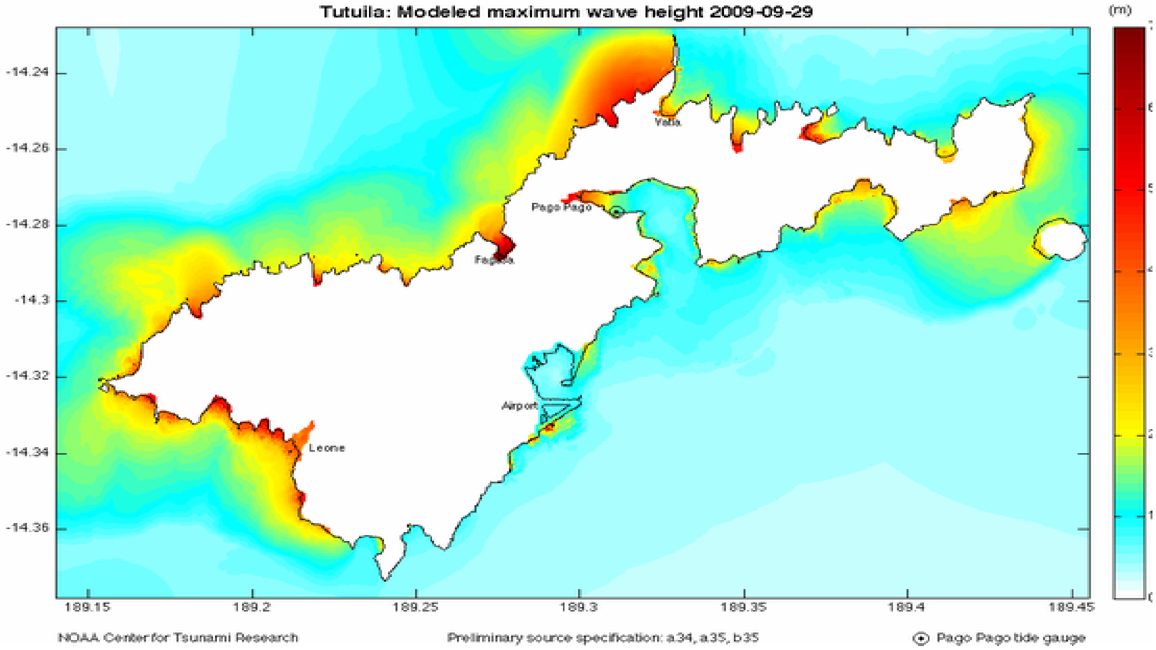
Figure 40.



withdrawing, which was the case in Ache, Indonesia, in 2004. The first noticeable water movement at Tutuila was also a lowering of the water level, as shown in the tide gauge graph above. However, it is reported that this is not always the case, and the first thing can be a water rise. The water level rises slower than water can move horizontally in the ocean, so it may resemble a tide more than anything, leading to the common English name, "tidal wave," which is misleading in the sense that it has nothing to do with tides. But like tides, the water lowers or rises relatively slowly, in this case over the course of several minutes (which is still much faster than tides, which require hours). But it does not form a visible wave on the ocean surface like wind waves. Once the water has risen, though, if it has risen higher than a horizontal surface like a reef flat or low lying land, then the water in the ocean will rush onto that horizontal surface with a great deal of force. The higher the water rises above the flat surface, the greater the force of the water rushing onto that flat surface. Tutuila was studied by experts from the US Geological Survey soon after the tsunami to record evidence of how high the tsunami waves were in different places, and how far they went. "Run-up" is how high the wave reaches at its greatest distance reached inland, and the maximum run-up on Tutuila was around 14 m above sea level, or 46 feet. When the ocean rises 46 feet above normal sea level, the water rushing ashore can do enormous damage, as happened on Tutuila and Upolu. The tsunami striking the coast of Ache province at the western end of Sumatra Island, Indonesia, on Dec. 26, 2004, was a similar height (10-15 m high, Baird et al. 2005) and killed over 120,000 people (additional people were killed elsewhere). True to the Japanese name, the tsunami here had some of its most destructive effects in villages in bays such as Pago Pago, Fagasa, and Leone. In the harbor, the damage was greatest at the head of the harbor at Pago Pago, with damage beginning in Fagatogo and getting stronger toward the head of the bay. This clearly illustrates how the funnel shape of the bay concentrates the water movement and energy at the head of the bay. There were also some heavily damaged villages that were in less deeply indented bays, such as Amenave, Poloa, and Tula. The unseen underwater topography in those bays probably contributed to the damage. Damage also appears to have been severe along open coasts of Upolu where the role of underwater topography is not yet clear. Upolu has much wider reef flats than Tutuila, which may have provided a shallow flat surface that accentuated the rushing of water. An additional factor that plays a role in the process is the roughness of the ocean bottom and the land surface. Coral reefs usually have lots of corals growing up from them, which form a rough surface that provides drag on water movement, both wind waves from hurricanes and tsunamis. Thus, the reefs and their corals absorb part of the tsunami energy. On land, forests such as mangroves can reduce the force of a tsunami wave (Dahdough-Guebas, 2005; Danielson et al. 2005; Kathiresan and Rajendran, 2005; Wilkinson et al. 2006), although if the tsunami is large enough, the tsunami can literally rip out an entire forest (Kerr et al. 2006; Kerr and Baird, 2007). Plus, a tsunami consists of a wave train, so even if the forest reduces the power of the first wave, if the first wave rips the forest out, the forest cannot reduce the power of the second wave. So mangroves and other forests can provide protection for small and medium size tsunamis, but not for the largest tsunamis.

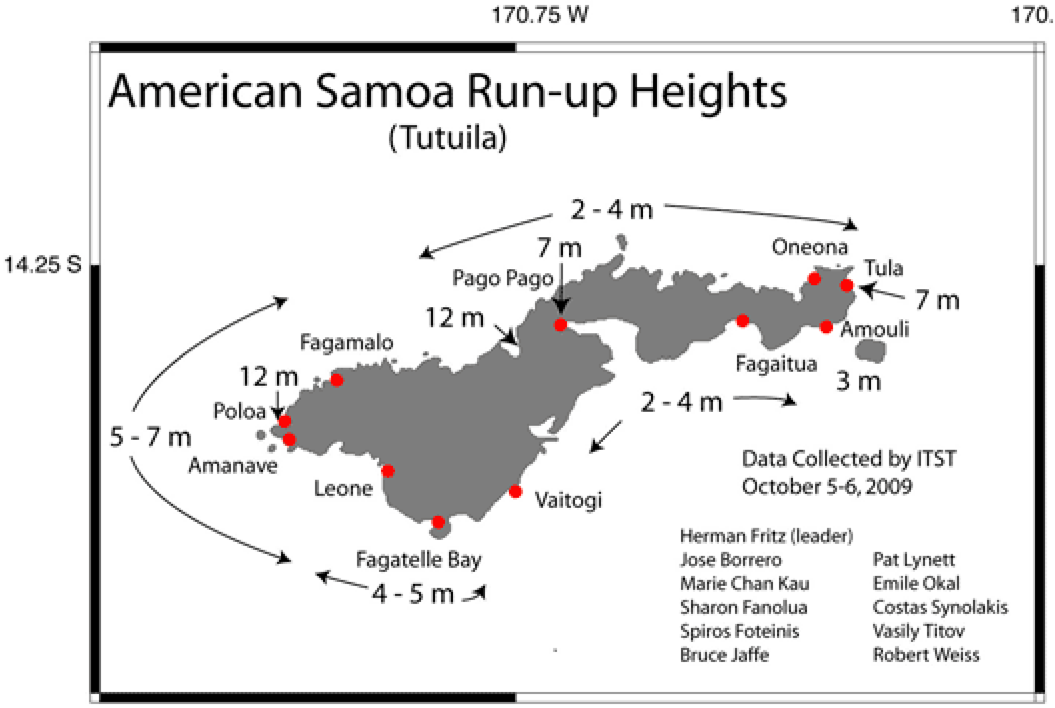
In Tutuila, the tsunami damaged both the north and south sides of the island. Pago Pago Harbor, Leone, and Amanave, which were all heavily damaged, are all on the south side of the island. Fagasa is on the north side of the island, and Tula is on the east end of the island. Thus, all sides of the island were damaged. If the tsunami came from the south, one might think that while the south side would be damaged the north would be protected by the island, since the island would stop the wave from reaching the north side. That exact type of thing happens with wind waves; if wind waves are only coming from the south, then they will strike the south side but not the north, where it will be calm. Two things probably acted such that the north was not spared. First, the island is oriented in a southwest to northeast angle, such that a tsunami generated southwest of the island should strike the two shores almost equally. Perhaps the southwest coast which faces the southwest should be hit hardest, and the northeast coast which faces the northwest, should be best protected. There were no villages that were heavily damaged on the northeast quarter of the island, but several of the most damaged villages, such as Leone, Asili, and Amanave, are on the southwest, and Tula is on the east end of the island. The other thing that may have kept the north from being spared, is the fact that the wave length is so long that it would take a large island to provide much protection. Tsunami waves are on the order of 100 miles (160 km) long. For waves of any type, if an object is much larger than the wavelength, it will produce a strong shadow or protected area on the side away from the direction the waves come. If the wave length is much larger than the object, then the object will provide no protection from the waves, which will wrap around the object and strike all sides of the object with similar power. Tutuila is only about 17 miles (27 km) long, far too small to protect the side away from the waves. Upolu, on the other hand, is larger and might be able to provide some protection to its north shore. Indeed, the reports are that the south and east sides of Upolu were heavily damaged, but the north side was not. The pattern of wave height and damage around a real island is likely to be a complex pattern resulting from the tsunami direction, shape of the island (bays, points, etc.) and the shape of the underwater topography. Mathematical models run on computers have been used to try to predict where the waves would be strong and weak. A map of predicted wave height produced by such a model is shown in Figure 41 below. Notice that bays such as the harbor and Fagasa were indeed predicted to have large tsunamis, as was Leone. Tula was not predicted to have a large tsunami, yet considerable damage occurred there. The predictions of such models depend on the accuracy of the map of submarine topography. Such models are never perfect, and most likely they will be improved based on more accurate data on submarine topography, and possibly changes in the model itself. One of the US Geological Survey teams used a sonar system to map bottom topography in Fagafue Bay east of Masacre Bay, in order to try to better predict the wave heights they recorded on land.

Figure 41.



Teams from USGS (U.S. Geological Survey) and Japan arrived soon after the tsunami, to map where the tsunami waters went in selected locations. They walked, looking for evidence for how high the tsunami waters went, and the horizontal spatial limits of the water. Evidence included things like plants that turned brown from the saltwater immersion, broken plants, water lines, sand or gravel accumulation. Much of this kind of evidence is ephemeral and disappears quickly after a tsunami. The team used GPS to accurately map the height and the horizontal extend of the tsunami "run-up," or how far the water went. Figure 42 shows a preliminary map of their results.

Fig. 42.



Tsunamis may have at least a couple of different types of damaging effects on coral reefs. The first is the direct damaging effects of the water movement itself, breaking corals and moving corals and rubble. The second is the washing of debris from on land, primarily from humans, onto the reef. The debris can cause damage to the reef in at least a couple ways. First, the debris can act as a battering ram to break coral as the tsunami moves it over the reef. Once the tsunami is over, most of the debris is likely to still be loose and available to act as a battering ram in the next storm or especially hurricane. The fact that the debris is not causing damage at the moment does not mean it will not in the future. The second way the debris can cause damage is by covering or smothering corals. The debris on Tutuila reefs seems to have three major components: corrugated iron roofing sheets, tires, and cloth. The cloth is particularly destructive to corals, by getting wrapped around the corals and cutting off both light and water movement to the corals. Debris densities were correlated with the presence of villages that were heavily damaged. It is likely that debris was most abundant in the village, next most abundant on the reef flat, and next most abundant after that on the reef slope. In a project in late November and early December, a NOAA debris removal team removed about 4.5 tons of heavy debris, mostly tires and roofing. A team lead by Alice Lawrence in DMWR removed large amounts of cloth and other small debris from reef flats and nearshore reefs during the last months of 2009.

Figure 43. Cloth wrapped around a coral at Fagasa. A small amount of coral can be seen along the upper edge in the center.

Figure 44. A juvenile table coral with a smaller amount of cloth wrapped on it. Notice the broken branch bases on the lower edge of the coral.

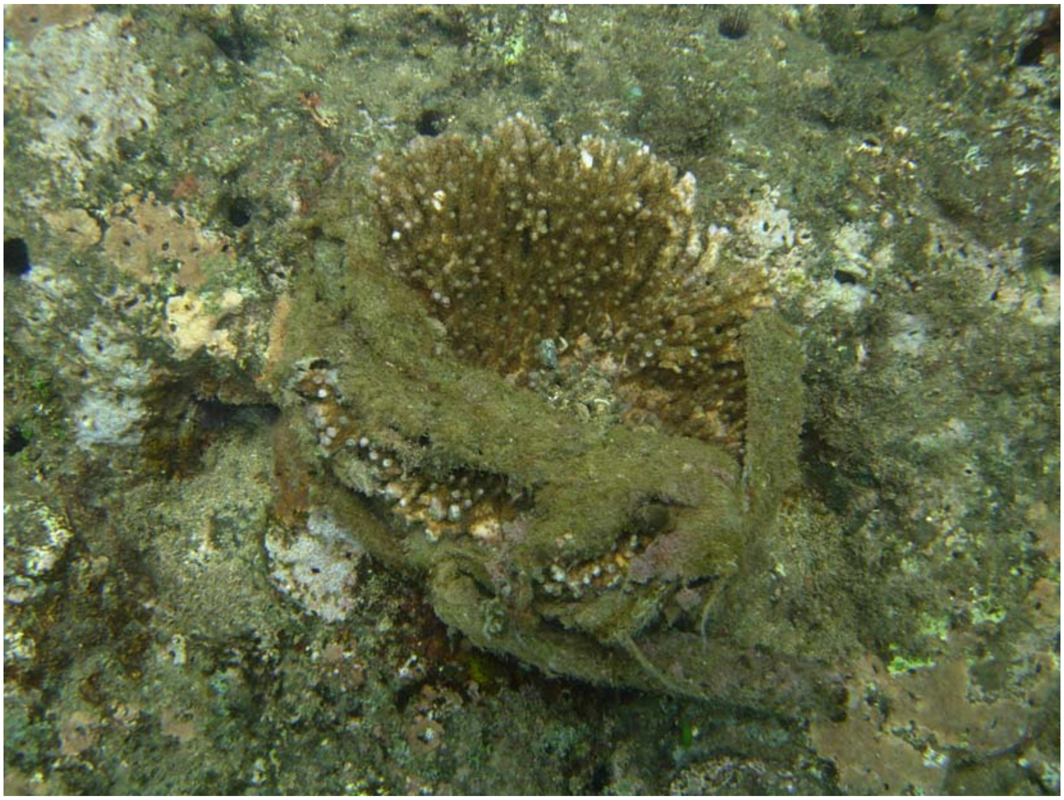
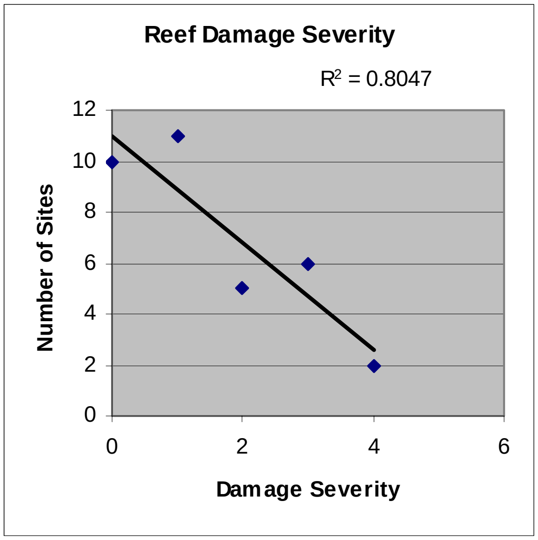


Figure 45. Coral damaged during the tsunami, possibly by cloth or hard objects striking it.

Beginning the day after the tsunami, the author began surveying damage to the coral reefs of Tutuila, and was soon joined by others. Surveys concentrated on areas in bays and in front of villages with heavy damage, but other locations were examined as well. Some surveys were conducted by SCUBA from boat, and others were conduced by snorkel from shore. Descriptions of damage to individual sites are presented in Appendix 1.

There are a few general things that may be concluded from the information in the descriptions of Appendix 1. One thing is that lightly damaged sites were much more common than heavily damaged sites. There were only two sites with catastrophic damage, while there were 10 sites with no damage and 12 sites with light damage. The number of sites decreased with increasing severity of damage, as seen in Figure 46 below.

Figure 46.



On the other hand, reef damage did not correlate with village damage. Poloa and Fagasa had heavy village damage, but little damage to their reefs. Leone had very heavy village damage, but only moderate reef damage. Reef and village damage were not correlated, as Figure 47 below shows. Reef damage was estimated from rapid visual assessment, and categorized on a 0 to 4 scale, no damage to catastrophic. Village damage was assessed in a CRAG survey, and the damage estimates of that report were used in this figure. It appears likely that different processes are involved in producing village and reef damage. The amount of debris was positively correlated with the amount of damage to villages, as shown in Figure 48 below. The amount of debris on the reefs was estimated in the same rapid surveys that recorded reef damage. The NOAA debris team

Figure 47.

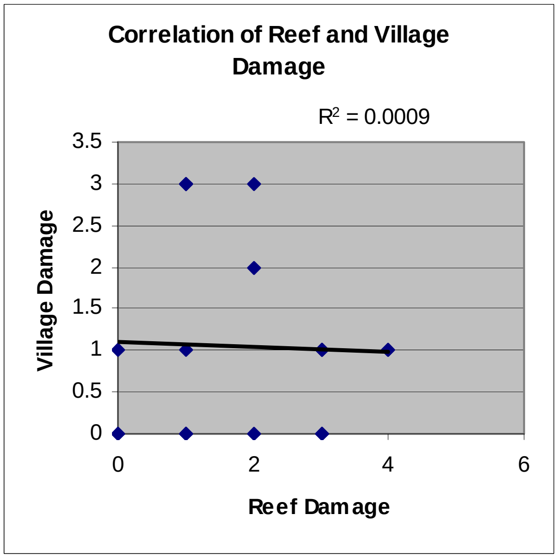
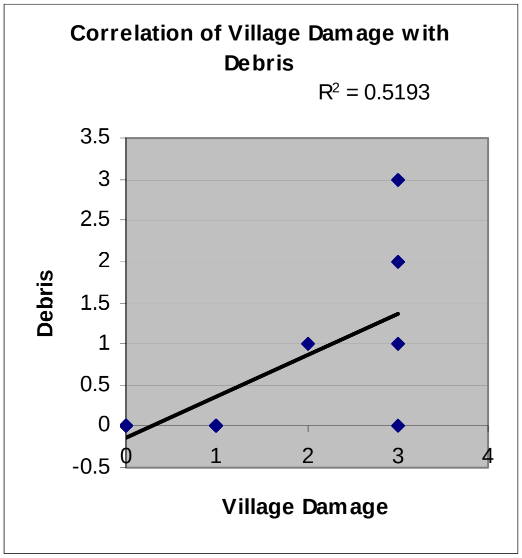


Figure 48.



found the same kind of effect, and were able to predict reef debris densities by just observing the number of FEMA tents for temporary village housing in a village.

A number of patterns were noticed in the damage to coral reefs. The most severe damage occurred at two sites in the avas or passes through the reef serving bays. The most severe was in the ava of Fagaitua Bay, a bay on the southeast. Before the tsunami, there was a patch of staghorn corals in the ava, within the bay. Afterwards, the entire patch was totally gone. There were large amounts of dead coral rubble that had clearly been moved by powerful currents, and places where rubble beds many feet thick had been moved away from hard structures. The staghorn bed was likely growing on a rubble bed, and got moved, tumbled, broken, mixed, and buried in the rubble beds. All this indicates that powerful currents ripped through that ava in the tsunami. The second most damaged site known was at the Matafau school near Faga'alu. The slope there is on one side of a large ava that connects the bay with the ocean. Corals were fairly sparse on the slope before the tsunami, but were greatly reduced by the tsunami. Much of the rubble was moved, indicating powerful currents swept the area.

Surely, the amount of damage is related to both the speed of water movement in different areas on the reef, and the strength or weakness of living corals or rubble beds or reef structures, as compared to their size and shape (which would determine the amount of force the water movement applied to them). The examples of severe damage in avas related above are examples of where high water velocities caused destruction. Another example of a place where water velocity caused damage was in Vatia Bay on the east side. Vatia village had little damage as apparently the tsunami wave did not go far up into the village. The bay has reef flat on both sides. On the west side, the reef flat slopes very gradually down to the reef slope. On the east, however, much of the reef flat has a very sharp dropoff from a horizontal surface to a vertical escarpment a few meters deep. The edge of the reef flat is also not straight, rather, it has rounded prominences separated by relatively narrow notches going into the edge of the reef flat, in some cases as much as around 30 feet (10 m) or so. The dropoff in such notches is probably closer to vertical than on the rounded prominences, where it may slope fairly steeply but not vertically.

After the tsunami, the notches had been gouged or scoured out at the base of the escarpment, with the sides of the scoured area being white, and a sharp horizontal demarcation above which the sides had color from coralline algae, etc (Figure 49). Thus, the white area, which could be as much as 2-3 m deep or more, had previously been filled with material. That material now forms a rubble debris fan on the slope below the scoured area. It appears the material removed was mostly rubble, though it may have had some sand and/or living corals on top of it. There was no sign of damage on top of the adjacent reef flat. The outer reef flat has coralline algae and corals on it. What happened almost surely was that when the tsunami wave was high, water poured onto the reef flat (farther in where there were rubble beds there was evidence of movement of rubble). Then when the ocean level went down between waves, the water level in the bay was meters below that of the reef flat, but the reef flat which may be around 100 m wide, would still have several meters of water on it, perhaps 5 m or so. The result would have been a cascade or waterfall of water off the edge of the reef flat. Where there was some slope and hard bottom below the edge of the rounded prominences, the waterfall would have done relatively little damage. But in a notch, where the dropoff was vertical, water would have been pouring in from both sides, and falling directly several meters onto rubble which it would scour out and transport down slope. The cascade may have been very large for a few minutes, with 10-12 feet (3-4 m) of water falling as much as 10-12 feet (3-4 meters) applying great force to scour out the rubble.

Figure 49. Channel at the foot of a groove in the reef crest at Vatia. The channel was scoured out by a waterfall coming off the reef flat.

Vatia could be contrasted with Alofau. The reef flat at Alofau ends in a sharp dropoff, in the section where waves usually don't break. However, there was no damage at the base of the escarpment. At the base of the escarpment the reef appears solid with corals growing on reef rock. Alofau shows plenty of signs of the power of the tsunami there, so the lack of damage at the reef flat drop-off was not because the tsunami was minor there. So the scouring that occurred in Vatia likely happened because of the rubble at the base of the dropoff which could be relatively easily moved by the cascade of water off the reef flat.

Vatia could also be contrasted to Larson's Bay. At the shore at Larson's, there is a vertical cliff that extends perhaps 30 feet (10 m) above wate. That cliff extends about 10 feet (3 m) under the sea level, below which is a slope with corals on it. The corals are all fine, there is just one or two overturned tables. Any place where there is a vertical cliff at the shoreline which extends well below the sea surface, when the tsunami wave arrives, the water level rises on the cliff over about 5 minutes, then it lowers for a similar amount of time. Little water motion happens in this process and nothing destructive happens. However, think of what happens when there is a large horizontal surface close to the sea level (such as a low lying coastal plain or a reef flat. If the sea level rises 15 feet (5 meters) in 5 minutes, the sea level is then about 5 m above the horizontal surface. Water will pour onto that horizontal surface and rush rapidly inward with great force. Unleashing a 5 m (16.5 feet) tall wall of water from a limitless ocean will cause a great deal of energy to be expended on that horizontal surface with great destructive possibilities. Once the sea level drops to about 15 feet (5 m) below normal sea level, and there is still 15 feet (5 m) of water on that horizontal surface, it will begin rushing off that surface and cascading into the ocean. The larger the horizontal surface the more water will rush on and off of it (at very large sizes it will not fill to sea level in 5 minutes, nor drain in 5 minutes). The higher the tsunami wave, the more water will rush onto the horizontal surface and the more power it will have. If the horizontal surface is above sea level, then the difference between its height and the height of the tsunami will determine how much water will rush onto it and how much energy will be available for destruction. If the horizontal surface is above the height of the tsunami wave, no water will rush onto it. For a horizontal surface below sea level, water will move on and off of it, but the greater the depth of the water, the less movement of the whole water column is required to produce the increase of 15 feet (5 m) in sea surface (and similar for decrease). The rate of rise and fall of the water also has the effect that the faster the rise and fall, the more force, since the water does not have time to slowly move onto the horizontal surface or off it, rather the faster the rise and fall the more like it is a wall of water rushing onto or off of the surface. Likely the rate of rise and fall interacts with the width of the horizontal surface, for a very narrow surface the rise and fall must be very fast indeed to have water rush on and off. Wind waves rise and fall fast enough to cause water to rush off and on very narrow shelves. For a tsunami the shelf needs to be much wider. Tsunamis differ to some degree in the wave period, how fast the water rises and falls, so a tsunami with a 20 minute period would need a shelf twice as wide to have the same rate of water rushing as a tsunami with a 10 minute period. The fact that there was great destruction on Upolu even where there was no bay, may have been due in part to having a wider reef flat than around Tutuila. The fact that there appears to have been little damage in Manu’a may be in part because the reef flats are much narrower there.

Another consideration is the roughness of surfaces. The rougher surfaces are, the more drag the surface will place on the moving water, which reduces the rate of water flow. In the water, the roughness of the reef is often called “rugosity.” Corals greatly increase the rugosity or roughness of the sea floor, and thus the amount of drag placed on water movement, whether from tsunamis or wind waves such as hurricanes. A rule of thumb for hurricanes is halving the rugosity of the reef will double the force of hurricane waves on the shoreline (Alvarez et al. 2009). On land, trees and buildings and other structures produce drag on the passing water. Mangroves often grow along shorelines, and they can reduce the force of tsunami waves and protect houses and people behind them, as it did in places like Sri Lanka and India for the Ache tsunami. If the tsunami is too large, however, as it was near the earthquake center in Ache, the tsunami is so powerful it can rip out or break off all trees as well as houses and the trees are ineffective at protecting anything behind them.

Baird et al. (2005) noted that in the Ache tsunami, large massive corals were often rolled. They speculated that corals with weak attachments or not attached, as many large massive corals are, are often moved by tsunamis. The same thing was observed on the beach at Leone where there were several small coral heads thrown up on the beach, and at Masacre and Fagafue bay on the northeast shore, where around 35 massive *Porites* colonies were deposited on the beaches, some fairly large (Brian Peck, personal comm.). Although a large massive coral like *Porites* is very heavy, it also has a large cross section for the water to exert force on, and clearly water motion was strong enough to roll them uphill onto the beach. Few rolled massive *Porites* were seen underwater, but those two bays have not been visually examined underwater yet. At Alofau, on the inner reef flat, there are a number of massive *Porites* colonies, and water movement with the tsunami was strong enough to move lots of rubble and do quite a lot of damage in the pool just inward from the reef flat. However, most of the massive *Porites* there must have been well attached, since very few (only a couple) had been turned over, even though some had had as much as about a foot (30 cm) of rubble dug out from around them. So whether they are rolled are not likely depends heavily on how well attached they are. Madin (2005) concludes that the strength of attachment of most coral colonies is likely less than the strength of the colony skeleton itself, and so weak attachment is likely to be the most vulnerable spot for mechanical breakage for many coral colonies. The attachment is often a hard thing for the living colony to control, as the substrate underneath the colony can be bioeroded. In some places, massive colonies can look like toadstools, with a thin column underneath the much larger living colony.

Staghorn corals are generally not attached, most are sitting on rubble or sand beds or growing on top of dead skeletons that may or may not be attached, but are easily broken if they aren’t already broken. Thus they are particularly vulnerable, and indeed they were seen to be tumbled and mixed with the underlying rubble in places like Faga’alu Bay, Faga’itua Bay, and to a lesser extent in the airport pool. Damage was nearly uniform in Faga’itua Bay, which has little topographical variation, but it was much more patchy in Faga’alu Bay, which had much greater topographic variation. In spots nothing but dead rubble was left, while in others the living staghorn was tumbled and mixed with the underlying rubble, and in other spots the staghorn was not damaged.

Another, quite different illustration of the vulnerability of loosely attached corals comes from the slope at Faga’alu. At the base of the outer reef slope, at about 15 m depth and greater, there is a community of plate corals, primarily *Mycedium* sp. but also *Astreopora randalli*, *Oxypora lacera*, and a few other rarer species. *Mycedium* forms whorls and series of tiers of plates like shingles. Such groups of plates can be a few meters across, and are comprised of thin plates that could act like sails in rapidly moving water. It appears that many were weakly attached or unattached, as most below a particular depth were overturned or moved. This also illustrates that the water moves at all depths, so damage can occur at any depth.

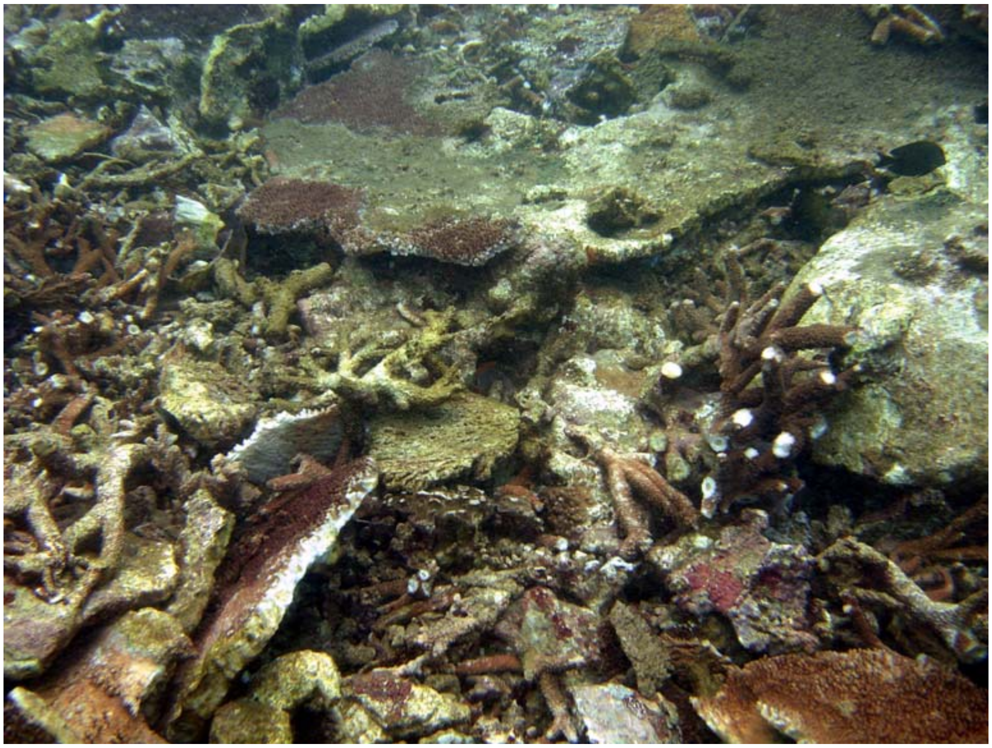
Another place where loosely attached corals got rolled was the mounds of *Porites cylindrica* (finger coral) in Alofau pool. Many but not all, of the mounds there got rolled and are now lying on their sides. Apparently most were weakly attached or not attached. Some of the colonies were fractured or smashed, with many broken branches forming a rubble bed on the bottom. For some of the mounds, the colony base may have been the weak point. Only the last 10 inches (20 cm) or so of the ends of branches are alive in most finger coral colonies, which leaves most of the mound as dead branches underneath the living tips. Dead coral is open to bioerosion by many organisms. All the indicators point to bioerosion being lower in American Samoa than elsewhere (see Fenner, 2011), but still over time the dead skeletons will weaken. This in addition to the relatively thin and weak branches may have led to the breakage and rolling of large finger coral mounds at Alofau.

Table corals are colonies of *Acropora* which as young colonies first form a base attached to the substrate, then a column, and then spread out in a nearly flat circular plate that resembles a table. The table shape makes it vulnerable to strong water motion, and indeed many tables (but not all by any means, not even most of them at most locations) were seen overturned on the reefs after the tsunami. Most tables seem to be strongly attached, and that attachment is not broken very often in normal circumstances. But the area of attachment is relatively small (about 20-30 cm diameter) for the size of the table top, which can reach several meters in diameter.

In a dense community of corals, once one coral is broken it can act as a battering ram to break neighboring corals. In surveying coral damage to a hurricane in the Caribbean, Fenner (1991) found that in patches of finger coral, typically either all branches were intact after the hurricane, or all were broken, and broken patches could be right next to unbroken patches. Just this effect may have occurred in an area of table corals on the slope at Leone. In one area, dense growths of table corals and staghorns were all intact and undamaged at Leone after the tsunami (Figure 50). In a nearby area, all tables and staghorns were destroyed, most being broken into fragments (Figure 51). Once some corals were loose, they likely acted as battering rams breaking others, until the entire community was nothing but rubble.

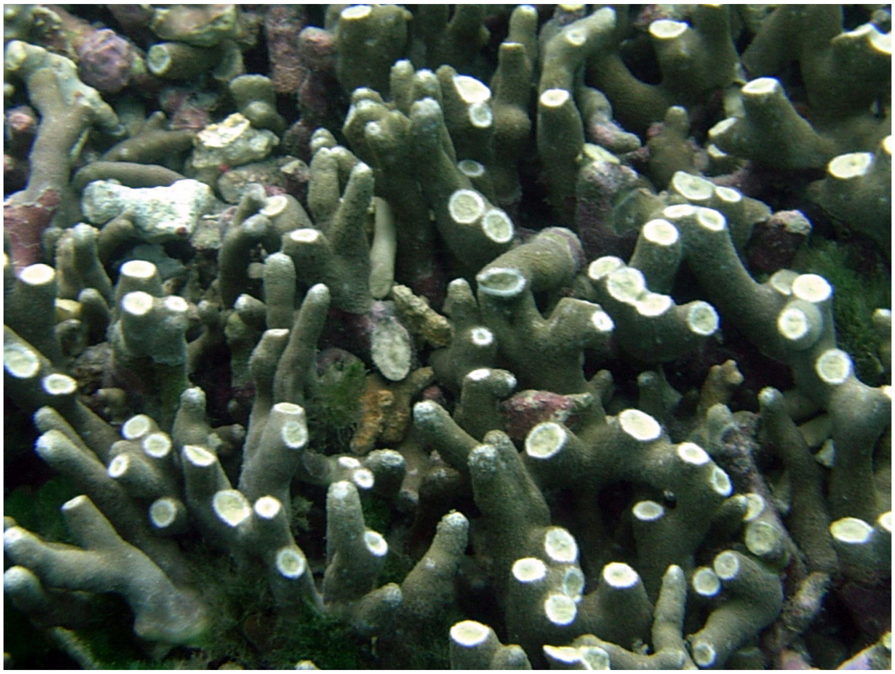
Figure 50. Undamaged area in Leone after the tsunami.

Figure 51. Damaged area in Leone after the tsunami.



The same projectile or battering ram principle may have also been involved in Fagatele Bay. Fagatele Bay has a fairly small reef flat, and then a large shelf of reef that starts at about 10 feet (3 m) deep and ends at about 40 feet (12 m) deep or so, ending in a steeper slope down to about 100 feet (30 m) depth. The shelf is large enough for the slope to be nearly imperceptible. On the shelf there are undulations that could be described as relatively low spur and groove formation. However, the bottom of most of the grooves have coral as well as the tops and sides. The ridges and grooves are perpendicular to the shoreline. After the tsunami, the lower surfaces of the grooves were completely covered with dead rubble. This is true in the more eastward part of the bay, and as you move westward there is less rubble and more live coral in the grooves. The ridges' tops and sides still have living coral and little rubble. Some of the coral colonies on the ridges have broken off branches, which are generally in patches on the coral, indicating they were likely broken off by passing debris. The rubble in the lower areas is rounded and has all the appearance of old rubble that was mobilized by the water movements in the tsunami. It may be that once some of the rubble was mobilized, it acted as a battering ram to loosen the rest. The rubble may be left from the crown-of-thorns starfish outbreak in 1978, when the starfish ate the tissue off nearly all the corals. Before the tsunami, areas could be seen where it appeared that coralline algae had covered rubble, some of which was from tables. Likely the coralline algae bound the rubble together to some degree, but there is a limit to the strength of that binding.

Figure 52. A colony of *Porites* in Vatia Bay with many branches broken off by the tsunami, showing the white of the skeleton.



Among the finger corals (*P. cylindrica*) of Alofau, there were colonies where all branches on most or all of the colony were broken off. Maybe part or all of another colony struck the colony to break the branches off. However, no sign of paths of breakage indicating where a projectile passed were seen. Another possibility may be that if a large mound was rolled, when it was rolling with the living branches down, they were broken off by collision with the substrate.

The violent water motion during the tsunami surely suspended a large fraction of the sediments in areas where strong motion occurred, including on land. The author and others examined the reef slope at Leone on Oct. 9, 10 days after the tsunami, and the water there was still very turbid from the tsunami. Several sites showed signs of damage from sediment, primarily reef sand. Some table corals (but certainly not all) at sites such as Vatia, Amalau and Afono had dead areas in the center and living coral on the outer edges (Figure 53). When examined soon after the tsunami, the dead areas still had sand on them, with black anoxic conditions in contact with the skeleton, where the tissue had died and rotted. Later, the dead areas turned green with filamentous algae. The size of the dead area was highly variable, from just the center of the table to almost all except a thin rim around the edge of the table. Presumably sand settled more in the lower center of the table than the edge, although it is also possible that the center was less able to clear itself of sand, either because the tissue was less capable of clearing itself, or because the surface was nearer to being flat in the center, and lacked any holes through the table like the edge has, through which the sand could drain. The latter seems more likely than the former. At least one digitate colony had a similar appearance, with the center area dead and the outer edge alive, however, there was no sand on this colony so the exact cause of death could not be ascertained.

Figure 53. Table corals at Afono which were killed in some areas by sediment deposited by the tsunami.

Because tsunamis have been striking the reefs of American Samoa and other reefs around the world for millions of years, it may be that they have effects on the reefs which play an important role in shaping the reefs and affecting how they grow. Hurricanes and other powerful storms certainly do, so for instance strong winter storms in Hawaii rip corals off of the substrate outside of bays, and coral reef buildups of carbonate only occur in bays in Hawaii (Grigg, 1998). The same process probably happens on the north shore of Tutuila, since reefs are only found within bays there, and only small corals without reef buildup outside bays. Tsunamis might have effects such as removing coral from avas and thus keeping them deep and unable to fill in. Also, tsunamis may mobilize rubble beds and reduce the area that corals occupy. They may help to create or maintain ridge and groove formations by causing destruction of corals in the grooves and filling the grooves with rubble that is hard for coral to grow on, and they may accentuate sharp dropoffs at the edge of some reef flats by scouring out rubble at the base of the dropoff.

It is good to try to get a perspective on this event for the coral reefs. Tsunamis are natural events, neither produced by humans nor controllable by humans. There is every reason to believe that the Tongan Trench has been producing tsunamis like this for the entire life of the Samoan islands, so for Tutuila for 1.5 million years. They are infrequent events, with the last Tongan Trench earthquake of this sort of magnitude in 1917. Even if they only occurred an average of once in 150 years, there would have been 10,000 of them since the volcano built the island. In spite of that, the reefs are still here and relatively healthy (Fenner, 2011). The damage from tsunamis is acute and dramatic, that is, sudden and obvious. However, the time between events is long and certainly adequate for natural, healthy reefs to recover. Further, as noted above, most of the reefs were lightly damaged or not damaged at all. No detailed observations of reef damage, let alone quantitative measurements, of damage from any of the many hurricanes to hit the island have been recorded. So it is difficult to compare damage intensity with previous hurricanes. Reef observations within a year of Hurricane Heta which struck in January, 2004, failed to reveal major damage. Thus, while hurricanes such as those in 1990 and 1991 may have caused significant damage, it is possible that the 2009 tsunami caused as much or more damage than they caused. There is some data on the effects of mass coral bleaching in 1994 (Goreau and Hays, 1994) and 2002 (Green, 2002), but not in 2003. The available evidence indicates some mortality, but not major mortality. Thus, the tsunami may have had effects of the same rough order of magnitude as some of the bleaching events. On the other hand, it is clear that the tsunami did not cause nearly as much damage as the 1978 crown-of-thorns starfish outbreak, which killed over 90% of all corals around the island. So far as is known, the starfish did not spare large areas of the reefs, as the tsunami did. Thus, on a scale of major disturbances to the coral reefs of Tutuila, the tsunami ranks up with recent major hurricanes and mass coral bleaching events, but way lower than the crown-of-thorns outbreak. It is quite likely that some earlier hurricanes did more damage than this tsunami, and that future mass coral bleaching events will cause more damage than this tsunami.

Natural disturbance events are often more dramatic, but less damaging in the long run to coral reefs than damage caused by humans. Natural events are typically very brief, such as hurricanes, tsunamis, and starfish outbreaks. The much longer periods between such events allow the reefs to re-grow and recover. Human damage, however, is usually chronic and ongoing. Sediment, nutrients, and pollutants are continually produced by human activities and are washed into the sea every time it rains. Fishing is continuous and continually depleted portions of the natural fish community and reduces guilds that perform functions necessary for healthy reef functioning. Climate change produces a continuous increase in average temperatures and acidification. Most damaging human activities, then, do not have long periods between events, when the corals can re-grow and the reefs can recover. Further, the reefs have had many millions of years to evolve the ability to cope with natural disturbances, while the human damage is all very recent. Coral reefs are well adapted to survive and recover from natural events. They are not adapted to survive and recover from human disturbance. Further, human damage is likely to interact with natural disturbances, such that human damage is likely to reduce reef resilience to natural events. The chronic human stresses on reefs will reduce the ability of the reefs to recover from natural disturbances. The effects of human stress can be hidden, with no visible effects on the reef of massive overfishing in a place like Jamaica, until a hurricane broke the coral and a disease killed the last remaining herbivore (a species of sea urchin). The result was most corals dead and a massive algal growth that covered the reef and remains to this day.

The reefs of American Samoa are relatively healthy (Fenner, 2011), and should be able to recover from this tsunami. Early signs of recovery are already appearing, with new branches beginning to grow on staghorns where branches were broken off, and the branch tips of finger corals that were toppled starting to curve upward to grow upward towards the sun once again. However, the reef in some ways may be left more vulnerable by this tsunami. If debris is left on the reefs it can serve as battering rams in the next hurricane. And there are areas where rubble was mobilized and left in large quantities, which could be more easily mobilized by future hurricanes and act as battering rams. Human debris left on the reef could also act as battering rams. Over time, coralline algae will once again start to stabilize rubble beds. Within a year of the tsunami, coralline algae had already covered all rubble in Fagatele Bay, but very little of the rubble in Vatia Bay, so this is occurring at different rates in different places.

For coral reef monitoring, it is very important to document the effects of these disturbances. Coral reefs naturally go through a series of disturbances and recovery. It is important to document the magnitude of natural disturbance events, and the course of recovery. If human stresses have reached levels that are too intense, recovery from natural events may be delayed or even not happen. It is important to document the rate of recovery as well as the cause and amount of disturbance. All these are necessary to understand why the reef is the way it is at any one point in time.

American Samoa is in a very good position to document the effects of the tsunami and recovery. There are multiple, partly complimentary and partly overlapping, monitoring programs, all of which have quantitative baseline data from before the tsunami. Much of that monitoring data will be collected once again in 2010, and allow a quantitative before versus after comparison. This is probably the first tsunami in history to have both qualitative and quantitative coral reef data available from before the tsunami for comparison with after the tsunami. The Ache tsunami of 2004 was the first to have extensive studies of the effects on coral reefs (Baird et al. 2005; Foster, et al. 2006; Wilkinson et al. 2006; Campbell et al. 2007; Satapoomin et al. 2007), yet there was little if any baseline information for any locations (Baird et al. 2005). Although tsunamis are relatively rare in places like Indonesia and American Samoa, they are common in places like Japan and Hawaii, where reefs may be affected in unknown ways, but certainly survive in spite of the tsunamis. Tsunamis have not been appreciated as an important force helping to shape the nature of coral reefs. A better knowledge of the effects of tsunamis on coral reefs is an important part of learning how coral reefs survive and how to best minimize human damage.

Methods

No “power analysis” has been performed to find out how small an effect this program could detect. Such power analyses are standard. However, they are based on the assumption that the data comes from randomized sampling, as all statistical tests assume. Thus, the results tell you how large a change has to be for your program to detect it, given that you have transects that are randomly placed each year, with new randomization each year. The power analysis will likely tell you can only detect huge changes like 30%. However, most people try to place their transects in the same location. In fact, if a transect can be replaced in EXACTLY the same location, so all points are less than 1 mm from where they were before, then all changes recorded will be real, and you can detect any change that happens in the points where you record, no matter how small.

In practice it is not possible to place transects exactly where they were before. Some methods of relocating transects are better than others. The closer the transect is to the exact previous location, the smaller the real changes that can be detected. The power test cannot tell you how small a change you can detect, if you do not do a new randomization of the transect locations each year. It will tell you the absolute worst case, but you can easily do much better than that by trying to place your transects close to where they were the last time. The secret to getting good data is to work hard at getting your transects at the exact same location, not by doing a power analysis. In fact, if your transect is not in exactly the same location, you do not know for sure whether the changes you record are because of changes in the reef, or changes in the transect locations, or both. You can get a measure that shows how much variation is due to the changes in transect location if you repeatedly run your transects at the same site, using methods that will produce the same variation in location that you normally have. If you repeat the transects within a relatively short length of time, like days or weeks, since it is unlikely there will be any real changes in the reef. The data in this project show relatively small amounts of variation from year to year, except in a few cases where a moved transect is suspected, or a bloom of algae was noticed. Even lower variation would occur if the transects were marked, such as with a stake or tied on float. If the tape were tied between stakes that were not far apart, the tape would be even closer to the same location and variation would be reduced further. National Parks uses a system like this.

The large swings in coral cover recorded by the monitoring done by Ali Green and others, graphed in Craig et al. (2005), cannot be ascribed with any certainty to actual changes in the reef, since some part of that variation may have been due to changing transect locations. This program has recorded essentially no changes over similar time periods, suggesting that those large swings may not have been due to real changes in the reef, but there is no way to know for sure.

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Appendix 1.

Reef Damage Rapid Assessment, Tsunami of 9/29/09

Tutuila, American Samoa

Douglas Fenner

Summary:

No effects: 10 sites
Minor effects: 11 sites
Medium effects: 5 sites
Major effects: 6 sites
Catastrophic: 2 sites

No damage: Gataivai reef flat, Larson's Bay slope, Pola Island west, Pola Island east, Polautu Ridge, Samua Ridge, Utelei slope, Fagagogo, Fagasa Bay slope

Minor effects: Airport pool, Coconut point Pool, Fagasa Crest, Onososopo Reef Flat & pool, Alofau slope and outer reef flat, Aua Transect Reef Flat, Paloa slope, Amanave slope, Vatia Bay west side, Afono Bay

Medium effects: Fagaalu outer slope, Paloa reef flat, Leone reef flat, Leone slope, Amaouli slope

Major effects: Fagaalu Park Pool, Fagatele Bay Slope, Vatia Bay east Slope, Fagaitua Bay west Reef Flat, Alofau Pool and Inner Reef Flat

Catastrophic: Fagaitua Ava, Matafau school slope

Very little debris from on land has so far been found on the reefs in our surveys.

Descriptions:

1. Airport pool: 9/30/09. Nearshore there was no detectable damage. On the ocean side of the pool, there were areas where there were the white disc on a staghorn where a branch had been broken off. In some areas, there were dense staghorn thickets with no breakage, in other areas there were colonies with several branches broken off. In some areas, it appeared that the strong current had rolled and mixed the living staghorns from the surface of the thicket with many dead branches from below that. The dead branches had patches of coralline algae on them, dark pink, but no filamentous algae. The dead branches predominated in these areas. The living staghorns were in a variety of orientations. There are few table corals in the pool, but one table coral was upsidedown,

and two others had sand on the lower parts of their surface. So quite a bit of sand may have been flying along in the current. The nearshore part of the reef flat was checked, and showed signs of strong current- lots of sand and pieces of coral rubble that had been turned over or tumbled. Overall, there was damage but it was relatively light (minor = 1).

2. Nu'uuli pool: 9/30/09. Nearshore at the stairs of the grocery store, there was lots of sand and medium pieces of dead rubble, none of which was there before. It clearly had all that sand and rubble swept in by currents. A bit farther out there is an area with some living large massive *Porites* colonies. Some had damage marks from being hit by rubble or corals. Some had chips knocked out of them, the largest chip being about 4 inches diameter. Two coral heads of about 1 m (3 feet) diameter each had been moved and were leaning against other corals or upsidedown. Those would be way too heavy to lift. Seaward of the stream delta there used to be an area of soft mud with some *Halimeda* that had very large plates. Some of the *Halimeda* could be found, but the bottom was now covered with sand with some rubble. In the deeper part of the pool, there was no sign of any damage. Where the reef flat meets the pool, there were in places a number of pieces of rubble or live coral, on the order of 1-2 feet diameter that were clearly moved and deposited there.

On the reef flat, there was evidence of strong current, with sand and small corals that were loose moved along. In the pool, one massive *Porites* had sand in dips in its surface, which when removed revealed living coral that was starting to bleach. Overall, there was damage but it was relatively light (minor = 1).

3. Rock wall between DMWR and the docks: 10/1/09. Corals are fine where the rock substrate was not moved, but 2/3 or more of the rocks underwater were moved or removed, and on any moved rocks there was no sign of corals. One 20-30 foot section was completely removed, with nothing left under half of the sidewalk. (medium damage = 2)

4. Gataivai reef flat near the sewage pipe: 10/1/09. No damage to the reef flat or the corals alongside the pipeline. (no damage = 0)

5. Fagaalu at the park: 10/1/09. Only minor damage to *Porites cylindrica* (finger coral). A few branches were broken off in a few places, a few small colonies thrown around. But damage to the staghorn (*Acropora muricata* = *formosa*) was extensive. There are large areas in which the staghorns were moved and broken and jumbled up with the dead staghorn that was beneath the living staghorn. The dead staghorn was light colored, had some coralline algae on it, but no filamentous algae. There are also smaller places that look like a bulldozer went through, with nothing but sand and rubble. In one spot, large amounts of sand were removed, leaving white reef rock that had been covered by sand. A depth of over 5 feet of sand had been removed from that channel through the reef. (major damage = 3)

6. Fagatele Bay: 10/1/09. All plants on the ground at the base of the rock wall above the beach were removed except the tree. Plants were damaged up to about 20-25 feet above the water level. The stairs were fine. Damage was extensive on the "shelf," that is the

nearly flat slope between about 10 feet deep (at the dropoff from the reef flat) and 40 feet deep. Upward projecting ridges had little damage, with live coral and coralline algae cover as before, though some coral branches were broken. Gullies and flat areas between ridges were covered with debris/rubble, most of which was a light yellow and long dead. Pieces up to about a foot diameter dominated. There is zero live coral in these debris areas. The debris appears to be debris from previous events such as the hurricanes or crown-of-thorns outbreak, which had coralline algae growing over it, but was ripped up by the tsunami and spread around. There were a few larger blocks, the largest of which was about 8 feet by 4 feet. There had been several large growths of the thin plate coral, *Echinopora lamelosa*, up to about 20 feet across, but no trace of any of those growths were found. Below about 40 feet deep it appeared that there was little damage, and most of the damage was to table corals. (major damage = 3)

7. Fagasa: 10/2/09. The rock wall cladding of the shoreline above the waterline was ripped apart with boulders and rocks scattered below the wall and smaller rocks thrown over the road. The ramp was not affected. On the reef flat and upper reef slope, encrusting corals were not damaged. Most *Pocillopora* colonies were fine, though a couple had most of their branches broken off. Most *Acropora hyacinthus* recruits were damaged, perhaps around 80%. Some were broken around the edge of the table top. Others had only the encrusting base and the base of the pedestal left. Many were intermediate with significant damage to the table top. Many had clothes or grass or other human debris caught on the table. A few had dead areas in the center that were covered with dark green turf, and thus that area had died some time prior to the tsunami, probably weeks to months earlier. Many had areas around their edge that did not look healthy. Corals other than table recruits on the slope and reef flat looked healthy, but some other *Acropora* colonies had broken off branches. There were some pieces of corrugated iron roofing on the slope at around 20 feet deep. There was no sand or rubble visible. One area in a notch looked scoured with white rock surfaces. Rocks near the shore had white areas where they had been hit by other rocks. It appears that there may have been a number of rocks moved back and forth over the crest area breaking corals. (minor damage = 1)

8. Vatia Bay: 10/2/09. The eastern side was examined. There was lots of white or light brown/orange rubble in chutes on the reef slope. Such chutes began in ava-shaped (V-shaped) cuts in the edge of the reef flat. Near the reef flat they show signs of powerful scouring, with several feet of white reef rock exposed on the lower side of the chute, and no rubble on the bottom. Farther from the edge of the reef flat, the rubble began in the chute, and extended down to around 40 feet or more in some of the chutes. There may have been some sorting so that small stick rubble was nearest the top of the slope, and pieces of table tops were near the bottom of the chute. In between chutes there were steep slopes that had coralline algae and coral and were undisturbed. In some places there were large lumps with coral on their tops and sides. *Porites cylindrica* and *Porites rus* colonies rarely had any damage, though in a few places many branch tips of P. cylindrical were broken off. On large colony of *P. cylindrica*, perhaps 8 feet by 4 feet, was tipped on its side, with the live branches pointing toward the center of the bay, as

though it had been pushed over by water coming from the direction of the shoreline. Many tables, perhaps 20% of tables, had central areas that appeared to be a light brown and were partly filled between branchlets. Feathering water by hand revealed it was sand that had settled on the table and killed the tissue under it, so the lower sand was often black. These areas ranged from around 10 cm diameter up to nearly the entire surface of large tables over a meter diameter. Nearer to the head of the bay the chutes were larger and more abundant than out closer to the mouth of the bay. The direction of the chute of rubble was straight down the slope toward the center of the bay, so perpendicular to the shoreline, at right angles to a line from the head of the bay to the mouth of the bay. The V-shaped cuts in the edge of the reef flat that led to lower areas of the reef slope than surrounding areas was a pre-existing feature of this reef slope, that somewhat resembles spur and groove formation. The bottom of the grooves had some coral and some sand and rubble. No live coral remains in these rubble fields. It appears that the scoured chute heads were formed by large volumes of water pouring off of the reef flat, when the tsunami had covered the reef flat with a water perhaps 15 feet deep, and then the water level quickly dropped, and the water on the reef flat cascaded over the edge of the reef flat in huge volumes which scoured the head of the chute, removing large amounts of buried rubble from the head of the chute where it had accumulated from prior disturbance events such as hurricanes and/or the crown-of-thorns outbreak of 1978, and moving it down slope. Rubble on the rubble bar in the middle of the reef flat had also been moved such that white and orange rubble that had been buried there were moved to the surface. There are also some microatolls on the reef flat there, and they showed strong scour around them, exposing about 20 cm depth of while rock that had been buried. (major damage = 3)

9. Onososopo pool: 10/3/09. This shallow and apparently natural pool is located near the Origin gas facility in Onesesopo, and has abundant coral of a number of species in about 3 feet of water. The corals were almost entirely intact, with a very few small colonies that were not attached that where overturned, and at least one colony with broken off branches. But the rest of thousands of colonies that were observed showed no damage, and there was no evidence of scour, sand, rubble or anything else indicating damage. (minor damage = 1)

10. Fagaitua Bay, west side. 10/3/09. This shallow area also appears to be a natural backreef pool, and had extensive beds of the staghorn coral, *Acropora muricata* (= *formosa*). As of about 2004, this continuous bed of staghorn was all alive with essentially no dead coral. Since then low tide events and bleaching impacted it, with low tides killing the highest growing branches, and bleaching killing some other corals. It had recovered partway when the tsunami struck. Now, the bed has been disturbed heavily, rolled and churned much like the staghorn in Fagaalu. In almost all of the bed, the older dead branches that had underlain the living branches now predominate in a rubble bed, with some branches of living staghorn mixed in. Most of the living staghorn consists of broken branches. There are a few small areas of about 1-2 sq meters that appear much as they did before. (major damage = 3)

11. Alofau: 10/3/09. Near to shore on the sand flat there are several small finger coral heads (*Porites cylindrica*) that were not there before. They appear healthy, but it is not clear whether they can survive near shore. In the deep pool, some of the staghorn on mounds was moved or broken, but some is intact. In the shallow area to the west of the deep pool, damage is severe. Many of the large *Porites cylindrica* mounds were moved or broken or smashed. So much of the staghorn was tumbled, broken, and mixed with rubble that it is hard to find the staghorn areas I used to assess for bleaching. The only small patch of the staghorn *Acropora nobilis* I knew in Alofau was completely missing. Disturbance was so severe that I could not recognize where I was. An area where there was a deeper connection to the next pool to the west was scoured out and much deeper. Approaching the reef flat there is an area of *P. cylindrica* that was in the pool next to the reef flat. This finger coral was very heavily damaged, broken, tumbled, etc. The inner reef flat is unrecognizable, with scour removing considerable amounts of the rubble that was there, perhaps about 30 cm deep. A bit farther out, most of the larger microatolls remain, some with the substrate level around them lowered. A few smaller massive *Porites* heads were overturned. Farther out, a sharp line is reached where the original coralline-algae encrusted rubble bed remains, but at a sharp edge the substrate drops about 20 cm to a white rubble bed of newly exposed rubble that had been previously buried. Farther out the corals on the outer reef flat appear just as the were before the tsunami, with no visible damage. On the upper reef slope the only damage was to table corals. Most tables were undamaged, but a few had pieces broken off of their edges. Farther down the slope there were several large pieces of table corals. One *Pocillopora* had most of its branches broken off. But all other corals appeared untouched. (major damage = 3)

12. Fagaalu slope: 10/5/09. Below about 20m, most of the plate corals (*Mycedium*) were flippend and jumbled with plate rubble, all surfaces not alive were covered with brown turf. Some fujngiids (mushroom corals) were flipped upside down. In one area, healthy untouched plate *Mycedium* up slope shallower than 18 m had plates close together, and may have been better attached. There was a sharp dividing line between where plates below moved, but above they were untouched. There were some streaks where *Acropora* stick rubble was moved, with brown stick rubble revealed that was below what was removed. Past the bend on the ridge that sticks out, everything was rubble, but most had not been moved. There were a couple of sandy areas. Shallower areas were undamaged except for a few spots where corals or rubble were moved. There was no damage at the crest in just a couple feet of water. (damage medium = 2)

13. Aua Transect (reef flat): 10/5/09. The borrow pit near shore is sandy bottomed and showed no sign of disturbance, with some of the best seagrass beds on the island intact. The reef flat is all loose stick rubble, and only a small percentage of the surface rubble had been moved at all. At the reef crest, there was very little damage to any corals, including *Acropora nana* which has very thin branches about 5 mm thick. There were a very few pieces of colonies loose or overturned on the rubble near the reef flat, or colonies that had any branches broken off. (minor damage = 1)

14. Paloa slope: 10/7/09. There was very little damage here, mostly a few branches broken off branching corals. The reef is composed of big solid ridges with coralline algae and some corals. Between the ridges there is sand with corals, which did not look disturbed. (Very minor damage = 1).

15. Amanave slope: 10/7/09. There was some damage here, more than at Paloa, but still minor. The most common damage was broken or overturned table corals, but some branches were broken off branching corals, and a few plate corals turned over. There was a little plant debris, but not much. (Minor damage = 1).

16. Fagaitua Ava: 10/7/09. Near the small boat ramp, the sandy bottom was not disturbed at all. In the ava, there had been a healthy thicket of staghorn coral. It was completely destroyed, only a few pieces could be found in the massive swaths of rubble. The rubble was nearly white and clearly had been buried for a long time, then dug up by the tsunami. There were places where the current had dug channels or pits, which usually had sides of white reef rock. One channel had been dug about 20 feet deeper than it had been previously, and clearly the rubble that was in the pit was bulldozed into the massive swaths of rubble. The ava is complete devastation, and shows evidence of the most powerful water motion yet seen underwater. The ava feeds a large reef flat area. Complete destruction. (complete destruction = 4)

17. Leone: 10/9/09. On the reef slope in front of the east end of the rubble bar on the crest, there was very little damage from the bottom to the top. The top of the reef at about 4-20 feet deep has abundant table corals and some staghorn. Going east, the next area has heavy damage, with almost all corals broken, the bottom littered with pieces of table corals and broken branches and old rubble. Broken off branch bases were still white. There is considerable debris, including two mattresses, one tree with over a foot diameter base, and many smaller debris items such as water bottles, aluminum cans, plastic, and cloth. This is the heaviest debris the author has seen yet. Going further east, the damage becomes much less, though still a bit more than in the western-most zone observed. Here, the shallow water is mainly dominated by encrusting *Acropora*, which is unusually hard. No damage was seen to encrusting *Acropora*. The water was very turbid, the most turbid water on the reef slope the author has seen outside the harbor, with innumerable bits of sediment visible in the water. (Medium damage overall because of the mix of light and heavy damage = 2).

18. Fagatele Bay: 10/9/09. The reef slope was observed by diving. Water clarity was excellent. The dive began on the outer shelf, north of the location which had been snorkled. The steep lower slope showed no sign of damage. The shelf showed only light damage. As the author moved south into the zone previously observed by snorkeling, damage became more intense, with a great deal of rubble in the valleys. The rubble had been a light yellow when snorkeling, now it was a dark yellow from the rapidly growing turf algae. The more rapid growth than for broken off branches is probably because some turf was already present on rubble, even though it was buried, while no turf was present on the broken staghorn branch (or perhaps tissue permeates the skeleton all the way

through a branch an inch in diameter). Damage: still major, but the total for the bay may well be less than thought from the first observation.

19. Larson's Bay: 10/9/09. The reef slope had very light damage at all depths. Damage consisted of a few broken or overturned tables, and a few broken branches. In shallow water coral cover is very low, cover is predominantly coralline algae. The water was clear. There is no reef flat or shelf. (no damage = 0)

20. Matafau school, Fagaalu Bay: 10/10/09. Reef flat and upper slope. Upper slope has lots of coral rubble and sand, a few very large chunks of reef, one the size of a room that appear to have been broken off the reef. Large *Goniopora* colony completely destroyed. The reef flat has much less finger coral (*Porites cylindrica*) and many of those that remain have branches broken off. Two patches of staghorns at the edge of the reef flat had one broken, rolled and scrambled with living pieces mixed with the dead. The other was pushed downslope and now forms a semicircle of similar composition. In places where a lot of rubble is on the slope, drainage channels can be seen on the reef flat, perhaps 4 feet deep, with smooth hard reef rock bottoms and some lumps of projecting rock or coral. Some coralline algae and a few corals near the edge of the reef flat that have white marks that may be scratches from flying debris. Most large microatolls show no damage. Everything on the slope is covered with grey sand & silt, and virtually nothing on the slope is alive that can be seen from the surface. (major damage = 3)

21. Paloa reef flat Doming Ochavile and Lucy Jacob

22. Leone reef flat Doming Ochaville and Lucy Jacob

23. Masacre Bay beach: This beach was found to have about 35 coral heads thrown up on it. Brian Peck.

24. bay west of Masacre beach: more coral heads on it than Masacre. Brian Peck

25. Pola Island East: 10/9/09. No damage. (=0) Paul Brown.

26. Pola Island West: 10/9/09. No damage. (=0) Paul Brown.

27. Polautu Ridge: 10/9/09. No damage. (=0) Paul Brown.

28. Sauma Ridge: 10/9/09. No damage. (=0) Paul Brown.

29. Vatia Bay west side: 10/9/09. Only a few broken branches. (minor damage = 1) Paul Brown.

30. Afono Bay: 10/9/09. No damage except in the inner bay where there are a few broken branches. (minor damage = 1) Paul Brown.

31. Points?? 10/9/09. No damage. (=0). Paul Brown.

32. Utelei slope: 10/9/09. No damage. (=0). Paul Brown.

33. Fagagogo: 10/9/09. No damage (=0). Paul Brown.

34. Matafau School: 10/12/09. Slope damage about 60-70%, looks like a bomb hit it. Paul Brown. (catastrophic damage = 4)

35. Amalau Bay: 10/20/09. No damage to reef flat, which consists of algae covered rocks. At head of bay, no damage to corals. Center of bay nearshore has rubble fields shifted, had rubble before. Another channel with rubble on the bottom is turning green from filamentous algae. A bit farther out, some tables flipped over, some tables broken, many tables with central dead areas due to sand, which now are appearing green from filamentous algae. Farther out, some huge massive *Porites* that are undamaged (one with interesting disease), and reef slope along east side of bay has lots of *A. abrotanoides* and *Pocillopora* and no damage. (Medium damage = 2) (beach looks like little or no damage, no village damage)

36. Afono Bay: 10/23/09. Entered near the intersection with the main road. The reef flat has filamenous algae on it and only a little coral, and does not look disturbed. We entered a narrow ava, which had old rubble on the floor that had been moved. The sides of the ava are vertical or undercut, maybe 15 feet deep, and in places rubble was scoured away from the bases of the sides, probably moved nearly parallel to the wall, so it doesn’t look like the bottom of a waterfall. The narrow ava opens into a wide open area maybe 20 – 25 feet deep, floored by old rubble that looks newly moved, but covered with brown dirt. There are some reef lumps, some near the west side reef flat have lots of big table corals on them. There was one overturned table, a few pieces of tables, and several tables had areas killed by sand and now green with algae, but most tables were not damaged. No other damage, but on one lump farther out there was some wood debris at the bottom and some other debris. (minor damage = 1)

37. Masafau Bay: 10/23/09. Entered at the head of the bay near the stream. Large sandy expanses beginning shallow and yellow and becoming deep (20+ ft) and white. The reef flat (south side) looked undisturbed, but never had much coral on it. As we moved along the edge of the reef flat away from the stream, the evidence of physical damage increased. Two pieces of reef flat looked like they had been undermined and fallen. The slope was brown in place old coral rubble near the top, and white sand and smaller rubble on the slope. At least two places looked like significant amounts of rubble had been bulldozed by water coming off the reef flat. One massive *Porites* had a foot long chunk knocked off by a 5 foot boulder. No debris. (coral: minor damage = 1)

38. Fagasa Bay: 10/29/09. Reef slope, on SCUBA. Started east of NOAA temperature buoy, went all the way to the boat ramp. There are some large columnar coral colonies in the east with relatively delicate columns and plates. No damage was seen. Long-dead rubble at the base of the reef slope looked like it had been moved, but was covered with brown sediment. There was lots of debris on the sand or rubble at the base of the slope,

on the western half. The most common item was corrugated iron roofing. There was less debris on the eastern half. (no damage = 0)

39. Fagafue Bay: 7/14/2010 Shallow reef slope on both sides of the bay, on snorkel. Essentially no damage was seen. There is reef flat, then a vertical drop, in places some ledges or flat areas of reef with corals. The center of the bay is a sand flat. (no damage = 0)