Earth-Science Reviews 107 (2011) 147–155

Contents lists available at ScienceDirect

Earth-Science Reviews

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

Coral reefs as buffers during the 2009 South Pacific tsunami, Upolu Island, Samoa

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ARTICLE INFO

Article history:
Received 14 July 2010
Accepted 18 November 2010
Available online 7 December 2010

Keywords:
Samoa
2009
tsunami
coral reef
cyclones
vulnerability
disaster
ecosystem
buffer
fisheries

ABSTRACT

The coral reef bordering the coastline of Samoa affected by the 29 September 2009 tsunami provides a variety of ecosystem services — from nurseries for fisheries and inshore source of food for local communities, to aesthetics for tourists, and the width of the lagoon may have been a factor in reducing the onshore wave height. To understand the complex interactions between the onshore human population and the offshore coral, we formed an interdisciplinary survey team to document the effects the tsunami had on the nearshore coral reef, and how these changes might affect local inhabitants. The scale of reef damage varied from severe, where piles of freshly-killed coral fragments and mortality were present, to areas that exhibited little impact, despite being overrun by the tsunami. We found that many coral colonies were impacted by tsunami-entrained coral debris, which had been ripped up and deposited on the fore reef by repeated cyclones and storm waves. In other places, large surface area tabular coral sustained damage as the tsunami velocity increased as it was funneled through channels. Areas that lacked debris entrained by the waves as well as areas in the lee of islands came through relatively unscathed, with the exception of the delicate corals that lived on a sandy substrate. In the lagoon on the south coast with its steep topography, coral colonies were damaged by tsunami-generated debris from onshore entrained in the backwash. Despite the potential for severe tsunami-related damage, there were no noticeable decreases in live coral cover between successive surveys at two locations, although algal cover was higher with the increased nutrients mobilized by the tsunami. While there was an immediate decrease in fish takes in the month following the tsunami, when supporting services were likely impacted, both volume and income have rapidly increased to pre-tsunami levels. Long-term monitoring should be implemented to determine if nursery services were affected.

Contents

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0012-8252/$ – see front matter
doi:10.1016/j.earscirev.2010.11.005

1. Introduction

The earthquake sequence that began on 29 September 2009 generated a tsunami that killed 192 people in Samoa, American Samoa and Tonga (Lay et al., 2010). Samoa was the hardest hit, where 148 people were killed, most on the southeast coast of Upolu Island (EM-DAT: The OFDA/CRED International Disaster Database, 2010). Coastal ecosystems are the first line of defense against tsunami (as well as tropical cyclones), however the consistency of the physical buffering services offered by coral reef, seagrass beds, dunes and mangroves is not clear (e.g. Cochard et al., 2008). Furthermore, these critical ecosystems offer services beyond physical buffers — from nurseries for fisheries and extractive industries such as coral mining and mangrove forestry, to ecotourism (Moberg and Folke, 1999). These services provide food and income to coastal residents, reducing their overall vulnerability, and increasing their resilience to natural hazards (Sudmeier-Rieux et al., 2006).

Much of the work done on coastal ecosystems as tsunami buffers began following the devastating 2004 Indian Ocean tsunami (e.g. Baird, et al., 2005; Danielsen et al., 2005; Fernando et al. 2005; Dahdouh-Guebas and Koedam, 2006; Chatenoux and Peduzzi, 2007; Cochard et al., 2008). These studies suggest that the role of ecosystems as a defense against the massive 2004 tsunami is inconclusive. Rather than use a tsunami of this considerable scale as a reference, we associate the 2009 South Pacific tsunami with more moderate tsunami of similar scale, such as the 2007 Solomon Islands event, where wave heights at the coast averaged around 4 m and inundated up to 200 m inland (Fritz and Kalligeris, 2008; McAdoo et al., 2008). These lower magnitude earthquakes produce smaller tsunami that do not pile up on steep-sloped volcanic islands like Samoa as they do on coastlines with broad continental shelves (Briggs et al., 1995). In this paper, we explore the interactions between the 2009 South Pacific tsunami and coastal ecosystems to determine their role as a physical buffer against this moderate tsunami. Depending on the geomorphology, health and species makeup of the reef, it may reflect some of the tsunami energy back out to sea while allowing a large volume of water to pour over the reef, into the lagoon, and eventually on to land (Kunkel et al., 2006; McAdoo et al., 2008). Damage to coral in the lagoon will depend upon local wave properties.

Over a three day period, we studied the reefs around Namu'a Island, Lalomanu and Vaovai adjacent to locations of substantial terrestrial damage (Fig. 1). The objectives of the survey were to assess and report on reef health and the damage caused by the tsunami, and to see if there were any detectable changes in the inshore reef fisheries that could affect the livelihoods of adjacent communities. The Government of Samoa Ministries of Fisheries and Natural Resources and Environment collected baseline data of fish takes as recorded at the Apia fish market before and after the tsunami. The Ministry of Fisheries also surveyed reef substrate at both Vailoa in 2007, and Vaovai in 2003 and 2004. The Cyclone Environmental Recovery Planning project also surveyed Vaovai in 2006 following cyclone *Heta* (Zann and Lovell, 2006). The coastline was also inspected for beach erosion, as were the islands where sensitive turtle nesting sites are present.

2. Methods

Post-tsunami observations of the reef were made using a combination of satellite remote sensing, a side-scan sonar and bathymetry system with integrated Global Positioning System capability, snorkeling and SCUBA using swim transects with underwater photography, point intercept transects, and manta towing (English et al., 1997). Our primary goal was to observe changes to the benthic communities and substratum. The secondary goal was to observe changes to animals in the water column and the adjacent coastal communities.

Study locations were chosen based upon the degree of onshore damage adjacent to coral reef/island/lagoon systems with an aim of determining the degree to which the corals acted as physical buffers against the tsunami. For example, the villages of Vailoa, Satitoa and

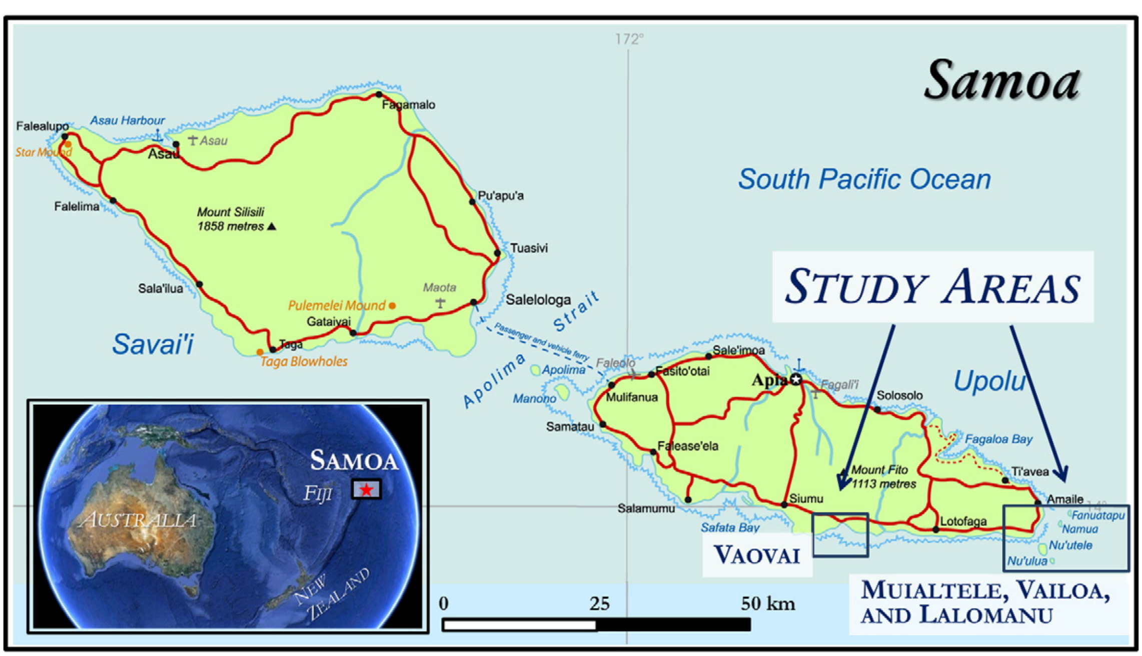

Fig. 1. Location of survey sites, Samoa. Basemap from http://commons.wikimedia.org/wiki/File:Samoa_map_800px.png.

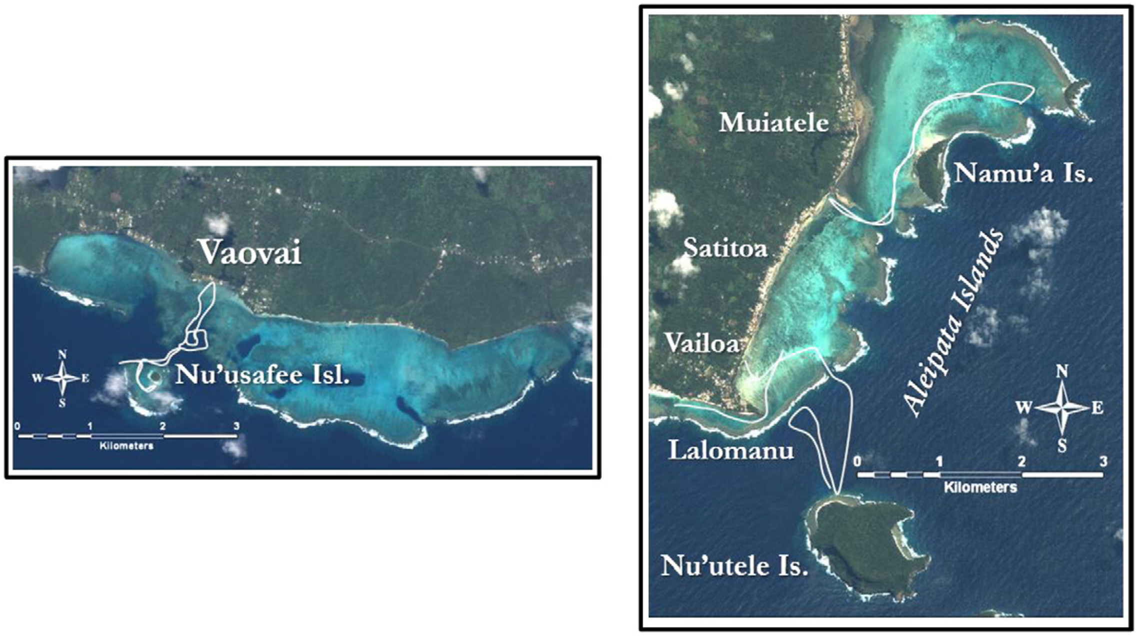

Fig. 2. Ikonos satellite, Vaovai and Aleipata Coast, Samoa. White lines indicate GPS tracks of sonar surveys.

Muiatele on the east coast of Upolu Island were hard hit by the tsunami, despite being fronted by a broad lagoon, barrier reef and series of small islands (Fig. 2). The Samoan Ministry of Fisheries had completed point intercept transects of the substrate at Vailoa on 21 November 2007, providing a pre-tsunami baseline. Lalomanu, adjacent to Vailoa but on the south-facing coast, also experienced significant damage, but the onshore topography is steeper, and the lagoon is narrower thus providing an opportunity to examine how the morphology of the coastal zone might have affected the actions of the tsunami (Fig. 2). The third location visited was offshore Vaovai, where the Ministry of Fisheries had completed substrate transects in 2003 and 2004, and another survey was completed in 2006 by Zann and Lovell (2006).

One of our primary tasks was to rapidly survey offshore water depths and coral habitat, as changes in bathymetry and seafloor roughness may have had an effect on tsunami wave energy. We used a Humminbird 997c SI Combo depth-finder that records bathymetry along with coral reef morphology using a side-scan sonar system with integrated GPS. This relatively affordable, easy to use, off-the-shelf technology is valuable when mapping the nearshore environment (Trond-Inge et al., 2002), and is useful for making qualitative assessments of bottom roughness as well as providing water depths for tsunami inundation models. In the shallow lagoon, we made shore-normal transects by walking and snorkeling. In deeper water where channels and deeper pools are present, we used manta tows as outlined by the UNESCO guidelines (Mumby and Green, 2000), with location data collection tied into the shipboard and handheld GPS units. Side-scan imagery, combined with SCUBA and snorkeling, and satellite data provide a swath of seafloor data that shows different coral habitats and sediment characteristics within the lagoon. Seaward of the barrier reef, data collection is more difficult as high wave energy compromises the quality of the data.

A secondary task that emerged from our work on the reef was to examine how the changes to the coral reef ecosystem, specifically the inshore fisheries, might affect human populations on land. The vulnerability of populations living in small island developing states is intimately linked to availability of natural coastal resources (Kaly et al., 1999; Turner et al., 2003). In Samoa, we tracked changes in fish takes and sales from the Apia fish market before and after the tsunami, based on monthly data collected by the Samoan Ministry of Fisheries. We present both the estimated total fish catch (measured in metric tonnes) as well as the estimated sales from the catch so as to account for possible changes in demand associated with the tsunami.

3. Observations

3.1. Eastern Upolu: Namu'a Island and Vailoa reefs

The Aleipata Lagoon offshore Muiatele and Vailoa lies within a Samoan Ministry of Natural Resources and Environment Marine Protected Area (MPA), and is designated as a fish reserve under the Community Fisheries Management Program (Samoan Ministry of Natural Resources and Environment, 2003). About 10% of the MPA consists of 'no-take zones', including marked areas offshore from Lalomanu, where

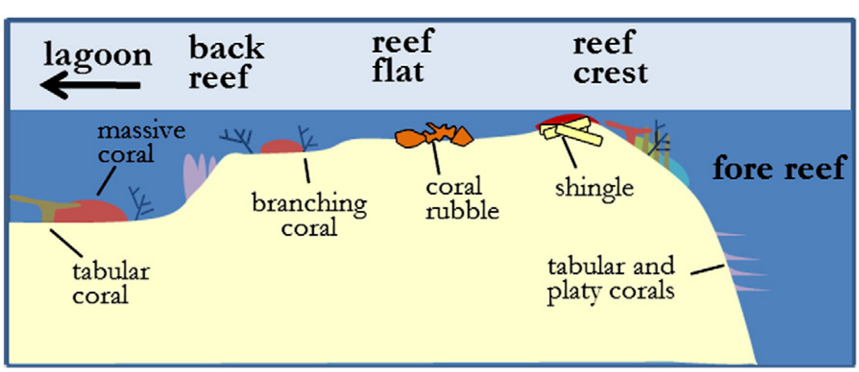

Fig. 3. Coral reef morphology and terminology.

Fig. 4. Coral rubble deposited by the tsunami in the lagoon north of Namu'a Island. Both tabular (left image) and branching (right image) coral were damaged in this area. Notice also the thin layer of algae growing on the coral skeletons. Local fishermen and scientists recall a sandy substrate in this area before the tsunami.

fishing and sand mining are prohibited. This wide, well-managed lagoon, therefore, provides an excellent test bed for observing how the tsunami interfaces with a relatively healthy coral reef ecosystem.

3.1.1. Namu'a Island

The Aleipata Lagoon around Namu'a Island has a typical barrier reef-lagoon morphology, with a steep fore reef seaward of the rounded and relatively smooth reef crest and reef flat, and a lower energy lagoon between the back reef and land (Fig. 3). Between Namu'a Island and Muiatele the lagoon is 800 m to 2.5 km wide, with an observed water depth range from zero (subaerially exposed during low tides) to 7.5 m deep. High surf restricted the inspection of the reef flat to the lower energy, soft bottom habitats and deeper areas of the lagoon. We surveyed the northern part of the lagoon offshore of Muiatele in the back reef zones on both sides of Namu'a Island (Fig. 2).

On the back reef, north of Namu'a Island, there was considerable deposition of both recently killed and long-dead coralline material (Fig. 4). These ranged from gravel sized clasts and small, identifiable tabular and branching coral fragments to large boulders up to 1 m in diameter. This material is graded in size, with the largest boulders close to the reef crest, and the smaller, mixed coral material deposited landward. Many of the large boulders were not rounded, but had a flat aspect, suggestive of shingle ripped up from the reef crest by high wave energy storms. The tsunami also moved finer material — employees of the Department of Environment and Ministry of Fisheries as well as local fishermen recall significant pre-tsunami sediment accumulations in the areas that are now hard substrate, suggesting that the tsunami was responsible for moving large amounts of loose material, changing the habitat type from sandy to hard boulder and rubble substrate.

Newly deposited coral fragments represent the varied benthic components of both the reef flat and back reef areas, along with isolated colonies that grow in the sandy lagoon. In this area of new rubble veneer, the percentage of living coral colonies ranged between 10 and 30%. The cover of live coral was higher near the broad stands of the branching *Acropora sp.* that remained standing. Large colonies of *Porites sp.* (<1 m diameter) presumably displaced from the reef flat were strewn amongst the shore-normal rows of boulders and rubble that extended into the lagoon. Much of this rubble had a green hue resulting from the growth of green and blue–green filamentous algae that colonized the abraded and recently killed surfaces of the colonies (Fig. 4).

3.1.2. Vailoa

The Ministry of Fisheries collected substrate data from Vailoa in 2007 (Fig. 5). Data show that at that time, 30% of the substrate was

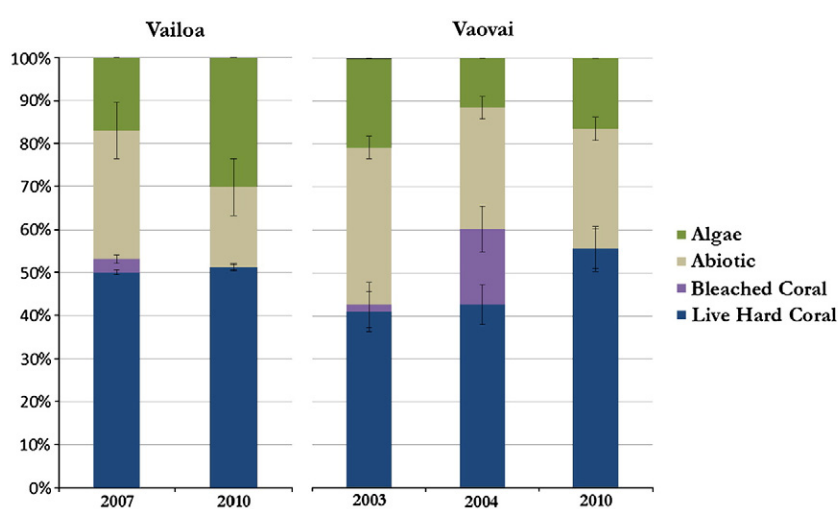

Fig. 5. Substrate character as recorded in shore-normal, point intercept surveys in the lagoons at Vailoa (390 points in both 2007 and 2010, post-tsunami) and Vaovai (312 points in 2003 and 2004, and 390 points in 2010), as recorded by the Samoan Ministry of Fisheries. Error bars represent one standard error. Algae include both the encrusting varieties as well as filamentous growth over a variety of substrates. Abiotic includes both coral boulders and rubble (with no living colonies) as well as the sandy bottom.

Fig. 6. The lagoon in front of Vailoa. In the left image, massive and branching *Porites sp.* colonies form a low relief, consolidated reef that was able to withstand the force of the tsunami with minimal damage. On the right, the more delicate skeletal remains of *Pocillopora sp.* and *Pavona sp.* coral that stuck up above the low relief *Porites sp.* reef were strewn along the beach at Vailoa.

abiotic, which includes unconsolidated sands. The inshore fringing reef was composed largely of *Porites sp.* coral. After the tsunami, the three contiguous point intercept transects showed the presence of both branching and massive *Porites sp.* (e.g. *Porites rus, P. cylindrical, P. lobata, P. lutea, and P. anne*), as well as colonies of *Pocillopora damicornis* and *Pavona spp*. The beach and intertidal flats were littered with recently deceased colonies of *P. damicornis* and *Pavona spp*. that had, according to local eyewitnesses, been washed up by the tsunami (Fig. 6). The abiotic substrate dropped to less than 20% — from 116 before the tsunami to 71 of 390 points after, and the algal cover on the lagoon bottom almost doubled from 17% to 30% (from 66 before to 115 after). Live coral coverage remained largely unchanged (195 to 196).

3.1.3. Nu'utele Island

The largest of the four islands of the Aleipata district lies approximately 3.5 km to the southeast of Lalomanu. This uninhabited volcanic island is exposed to strong swells, however the protected leeward side of the island is an important refuge for sea birds and is a nesting habitat for sea turtles. We surveyed the leeward side of the island down to 25 m depth using SCUBA, snorkeling, visual

Fig. 7. Debris from Lalomanu Village strewn along the beach (left image), also found in the 5 m deep channel in the lagoon amongst a debris field of branching *Acropora sp.* (right image).

Fig. 8. Large *Acropora sp.* tabulate coral fragments in the channel of Lalomanu lagoon.

observations from the beach, and sonar bathymetry. The channel between Nu'utele Island and the mainland is over 50 m deep in places, and the seafloor rises rapidly to the island and the fore reef adjacent to the mainland. Tsunami impact here was minimal in a depth range between 5 and 25 m, although there was some localized damage to coral colonies above 5 m, where large tabulate corals (*Acropora spp.*) were toppled by the tsunami. On the exposed (south) side of the island, there was ample evidence of beach erosion along with coral rubble strewn on the beach, yet there was scant evidence of erosion or coral transport on the leeward side.

3.2. Southeastern Upolu: Lalomanu and Vaovai

3.2.1. Lalomanu

The village of Lalomanu, on the southeast corner of Upolu, suffered some of the worst damage from the tsunami. The beach was littered with rubbish and material from the destruction of buildings inland. Debris from the village extended into the lagoon, where pieces of clothing and roofing material were found up to 100 m from the beach (Fig. 7). The lagoon is relatively narrow here with the reef crest less than 300 m offshore at the widest point. Furthermore, there is a nearshore channel 3–5 m deep inside the reef crest. The channel was littered with large, tabular coral plates, as well as large, rounded boulders (Fig. 8). Some of the rubble in the channels had living coral on areas exposed to sunlight, and recently deceased coral on the undersides. Large, tabular boulders (shingle) and fragmented platy coral were also evident on the back reef slope. Closer to the reef crest, damaged coral occurred as rubble piles, with intervening areas of bare reef rock. On the inner reef flat, however, there were large, *in situ* coral colonies with little damage, protected by their position within reef holes or other rugose features. Larger reef structures such as aggregated colonies of large coral heads also offer some protection from damage on their lee margins.

3.2.2. Vaovai

The lagoon/reef offshore of Vaovai was also monitored by the Ministry of Fisheries, who had conducted previous substrate surveys in 2003 and 2004 (Fig. 5) in response to a regional coral bleaching event in early 2003 (NOAA, Coral Reef Watch, 2010). In September of 2006, the reef offshore the village of Vaovai was surveyed in a post-cyclone *Heta* assessment, and found little damage due to the effects of the cyclone (Zann and Lovell, 2006).

Around 1 km offshore of Vaovai, the barrier reef is cut by two broad channels that are linked to streams on shore (Fig. 2). These channels allow local fishermen to access the deeper water outside the barrier reef. The low-lying, coralline Nu'usafee Island is 500 m south of the barrier reef, separated from it by a 40 m deep channel. Nu'usafee Island has its own small lagoon and reef crest system. The lagoon varies in width from 300 m to 450 m, but rapidly disappears on the east side of the island. On the east side of the island, the beach has been stripped of sand, exposing beach rock and piles of shingle (Fig. 9). Clean scars on the beach rock in the intertidal zone are free of the algae covering adjacent areas on the southeast side of the island. At the border of the beach with the inland vegetation, large pieces of shingle (~100 kg) were deposited against living trees scarred from multiple recent impacts. As far as 30 m inland, collapsed, living and/or recently dead plants with large boulders deposited on top suggest that the tsunami overran most of the island (Fig. 9).

The back reef of Vaovai lagoon (the lagoon attached to the mainland) sustained the greatest tsunami damage in the area. There were significant quantities of larger displaced coral colonies, rubble piles and broken coral fragments. The larger, recently killed coral colonies (*Porites sp., Acropora sp.*) were associated with large, older coral boulders that had abraded and impacted them during the tsunami. By contrast, the reef flat (seaward of the back reef) showed significantly less tsunami-related damage. Coralline algae encrusted surfaces and robust reef colonies adapted to high energy waves showed minimal damage. On the reef crest, there was significant damage and fragmentation on the inshore side, whereas the offshore area showed little or no damage. Large platy corals (*Acropora hyacinthus, A. cytherea, A. clathrata*) were generally intact, with the occasional chipped or toppled colony. While many colonies of branching coral species such as *Acropora nobilis* and *A. intermedia* were left intact, many were up-ended, broken or still standing, but dead, suggesting that something other than the impact of the tsunami killed them — perhaps the 2003 bleaching (NOAA, Coral Reef Watch, 2010).

Fig. 9. Limestone shingle on the easternmost side of Nu'usafee Island, offshore Vaovai. The top picture shows fresh scars on the beachrock where the tsunami ripped up clasts and deposited them inland. The piles of shingle on the beach (middle picture) are most likely ripped up beachrock clasts placed on the beach during successive cyclones. The tsunami remobilized some of this material, depositing it as far as 30 m inland (bottom picture).

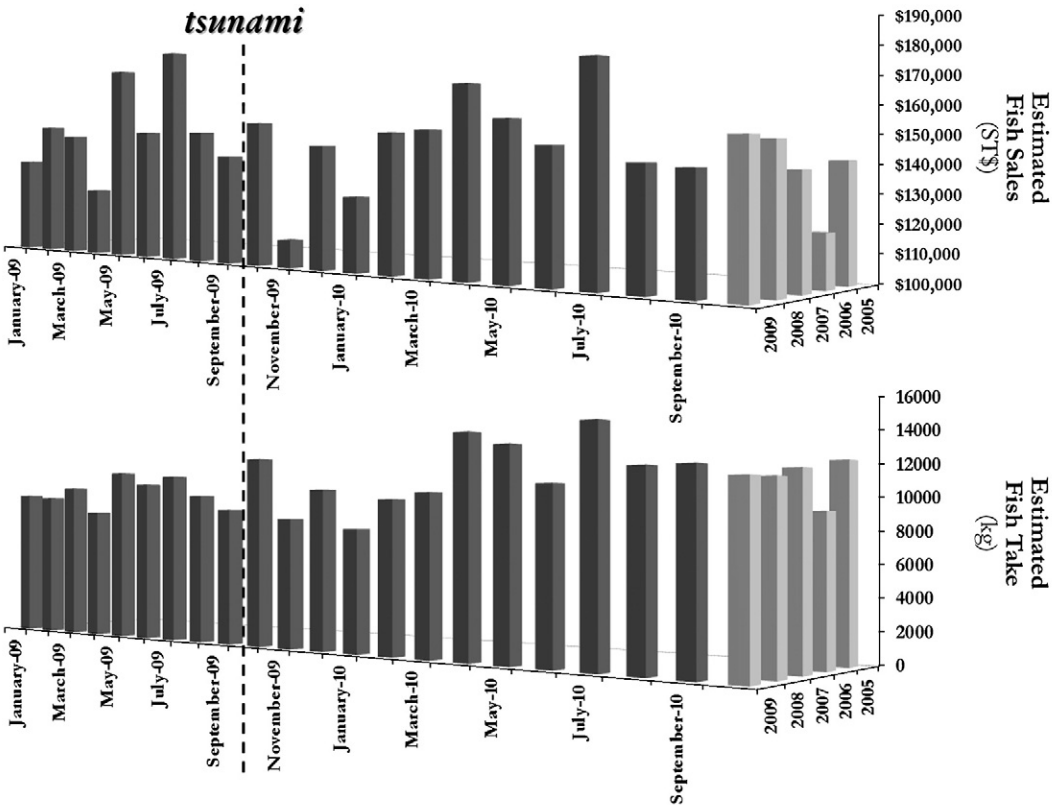

Fig. 10. Estimated fish sales and total take recorded by the Samoan Ministry of Fisheries at the Apia fish market. Dark bars show the total sales and take for the month, and the grey bars on the right show average monthly sales for the years prior to the 2009 tsunami.

3.3. Coral and communities

According to the Coastal Infrastructure Management Plan, the southeast coast of Upolu has a 'ribbon like' development, where villages have two centers — one inland for access to the main road, and the other closer to the coast, allowing access for fishing (Ministry of Natural Resources and Environment, MNRE, 2002). Other economic activities include tourism, health and government facilities, as well as a number of stores. According to the Samoan Tourism Authority's blog (Samoan Tourism Authority, 2010), the industry was dramatically affected by the tsunami, however an analysis of the tsunami's impact on tourism is beyond the scope of this paper which will focus on the fisheries.

Fig. 10 summarizes the January 2009 to September 2010 fish catch and sales data from the Apia fish market. The commercial fishery on the north side of Upolu was not physically damaged by the tsunami, but the catch may reflect changes on the reef as the fishermen worked the waters all around Samoa. So it is curious that in October 2009, immediately after the tsunami, both the estimated total income and catch weight experienced overall increases. Between August and September 2009, the number of large fish (finfish) and income received decreased and then increased in October following the tsunami. During this time, however, crustaceans exhibited significant decreases, while echinoderm takes, though not particularly lucrative, increased by 500% after the tsunami. Most of the October 2009 data reflects data collected in September, prior to the tsunami, and hence did not reflect changes, yet both the overall estimated take and income were higher than the monthly average over the previous 5 years. The data collected on 9 November 2009, which represents the data from October 2009, shows a drastic decrease in income (−29%) and catch (−32%), which likely reflects disruption of the industry associated with the earthquake and tsunami, including power outages and the redirection of resources to other more critically affected facilities.

4. Discussion

While damage to the coral reef on the south and south east coasts of Samoa was severe in places, it appears to be concentrated in areas where there were loose coral rubble, boulders and shingle available for the tsunami to mobilize. This loose material served as an entrained debris field that struck living coral colonies, causing them to be dislodged. In places, these dislodged colonies were pushed into channels, where current velocities were higher, creating a new, rugose substrate. Areas where there was little or no debris prior to the tsunami had minimal damage to the coral colonies.

It was evident from the sites visited that damage was greater on the back reefs and more inshore portions of the fringing reef. This damage pattern appears to be due to the wave transport of shingle, boulders and displaced coral colonies. Coral colonies that live on a sandy substrate, like that offshore Vaovai, are particularly prone to mobilization (Baird et al., 2005). When a tsunami overtops the steep fore reef, it behaves more like a strong current or turbulent bore, rather than a breaking wave. When a tsunami has a significant bedload component, it becomes particularly destructive to the attached coral colonies and other biota with limited protection (McAdoo et al., 2008).

On this southeastern coast of Samoa, frequent tropical storms and cyclones create high wave energy that impacts the fore reef and reef crest, creating considerable shingle and coral boulder debris (Fig. 9). At Namu'a Island, Lalomanu and Vaovai, the tsunami entrained some of this material from the reef crest and seaward side of the reef flat, pushing it into the lagoon, where most of the coral species had evolved in a low wave energy environment. In contrast, at Vailoa, which is protected in part by a rocky headland and by Nu'utele Island, there was no shingle available, and the damage was limited to the coral that was dislodged from the sandy substrate. This situation is similar to observations of the Achenese reefs in Indonesia following the 2004 tsunami (Baird et al., 2005). As the debris-laden wave cascaded across

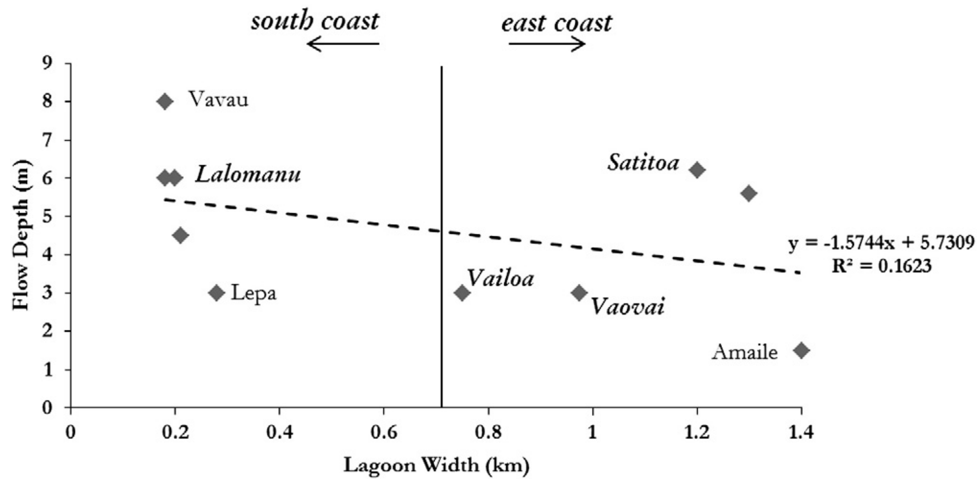

Fig. 11. Flow depth vs. lagoon width. Linear trend line shows that there is a tendency for flow depth to decrease with increasing lagoon width. Notice that most of the south coast lagoons are more narrow than those on the east coast, with the exception of Vaovai. Regardless, there seems to be no systematic correlation between lagoon width and flow depths on land.

the reef flat, it abraded and impacted the benthos in its path, with strong currents focusing damage in the channels. Without the bedload component, currents are similar to a very strong tidal flow (around 5 m/s for a typical 5 m high tsunami), and as such, tabular colonies that are adapted to live in lower energy environments are vulnerable.

There were also areas where corals were damaged but there was no clear indication of entrained debris. Large plate corals were indeed broken and up-ended, and many were still standing upright, but dead. Upon closer inspection, many of these corals would have been long dead, perhaps associated with the 2003 coral bleaching event or disease (NOAA, Coral Reef Watch, 2010). Unspecified diseases were observed in the tabulate corals in each of the visited areas, and predisposed colonies to bioerosion which weakens the footings, making them more susceptible to breakage and displacement (ICRI/ISRS, International Coral Reef Initiative/International Society for Reef Studies, 2005). Adding to the coral's vulnerability are the relatively thin attachment points and large surface areas of the platy corals (*Acropora sp.*) that are exposed to high stresses in a turbulent flow. For colonies with lower exposed surface areas (e.g. *Porites sp.* and *Pocillopora sp.*), currents alone were not enough to dislodge them, unless they lived on a poorly consolidated, sandy substrate, as illustrated by the fragile *Pocillopora* and *Pavona* communities of the low wave energy environment offshore of Vaovai.

Coral colonies on the lee side of the islands (Namu'a, Nu'utele and Nu'usafee) were mostly protected from the larger debris entrained by the tsunami, although some were damaged through burial by rubble and sand. Where the reef is most narrow on Nu'usafee Island, the tsunami came onto the east side of the island with enough power to rip up limestone bedrock from the shoreline and deposit sizeable pieces of shingle inland. The damage was not as pronounced on the west side of the island, suggesting that wave direction perhaps played a role in limiting the damage, or perhaps the reef offered some physical protection by refracting the wave around the island. This refraction may have also reduced the power on the back side of the island as the fine sediment that partially buried some of the colonies would have been washed away by a stronger current.

The degree of damage at Lalomanu, and other south coast villages where the lagoons are narrower than on the east coast, suggests the possibility of a correlation between lagoon width and degree of damage on shore. While structural damage appeared to be higher in these villages, other factors may have been more important than lagoon width. The depth of water on land (flow depth) will have a significant effect on structure stability. Fig. 11 shows that the highest flow depths occur where the lagoon is most narrow, and there is a weak correlation between flow depths and lagoon width, suggesting that the lagoon may provide a degree of buffering. The flow depths, however, do not vary drastically so the tsunami would have applied similar stresses to the structures on both coastlines. As there were no obvious differences in construction between the south and east coast villages – most buildings were either concrete block or traditional Samoan *fale* design, where a wooden platform sits on wooden stilts, with a wood-frame roof covered by thatched palm leaves – there must be another explanation for why the damage was more pronounced on the south coast.

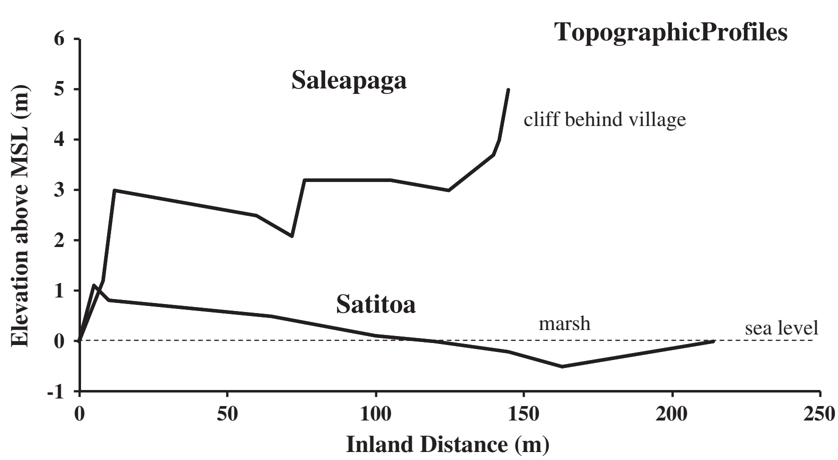

Fig. 12. Topographic profiles from the beach toward land, at Saleapaga, on the south coast (4.5 km west of Lalomanu), and Satitoa on the east coast, between Muiatele and Vailoa. These profiles are typical of the overall morphology of the land in the villages on each coast. The flat topography of the east coast allows for greater inundation distances, and the marsh behind many of the villages impeded rapid evacuation. Steep slopes limit inundation distances and provide natural inland refuges, but depending on the steepness and degree of vegetation, may impede rapid evacuation.

While there is no correlation between the presence of coral damage and the distance the tsunami propagated inland, there are places on the south coast where the reef was damaged by debris in the tsunami backwash. At Lalomanu, there is a high density of large volcanic boulders and construction material in the lagoon, while on the east coast, the amount of material on land was considerably less. This distribution likely reflects variations in the onshore topography. The east coast villages (Muiatele, Satitoa, etc.) are mostly backed by a marsh that drops below sea level 150 m from the shoreline. It is important to note that according to local residents, the wetlands behind the village also impeded rapid evacuation, as residents had to move along the beach before heading inland as the tsunami approached. South coast villages (Lalomanu, Saleapaga), by contrast, rise to 3 m within 10 m of the shoreline and are backed by a steep cliff ca. 150 m inland (Fig. 12). Steeper topography causes a much more vigorous backwash, and this high velocity return flow carries more material from damaged structures offshore. The material from damaged structures on the east coast, however, was deposited in the wetlands behind the villages.

While there is evidence that the coral reef and lagoon system offered a degree of physical buffering services from the tsunami, it is unclear how the other ecosystem services were affected. Damage to the reef was inconsistent, which may aid the resilience of the reef, as recolonization of coral on the newly-formed rubble substrate has begun in some places. If the perceived damage to the reef was significant enough to affect tourism, however, long-term damage to the local economy could ripple past the immediate losses sustained by damaged resorts.

The other major economy that relies on the services provided by the coral reef is fisheries, both subsistence and commercial. Residents of the acutely affected south coast of Upolu engage mostly in artisanal subsistence fishing, as the major commercial port is in the protected Apia harbor on the north side of the island. According to the Ministry of Fisheries, loss of equipment stored on south coast beaches resulted in a four month fishing hiatus, and people had to find food elsewhere. Immediate food aid was supplied by the Government of Samoa and additional income for food came from remittances from abroad. The commercial fishery had some immediate negative effects, evidenced by a 30% drop in fish take and income, but quickly rebounded when supporting services came back on line. Regardless of this initial evidence of rebound, however, long-term monitoring is critical as the effects of damage to the reefs' nursery services may not be seen for some time.

5. Conclusions

The damage to the coastal marine environment following the tsunami was quite varied. As with every tsunami, the offshore bathymetry played a major role in guiding the wave. Onshore topographic variation affected both the damage encountered on land as well as some of the damage seen on the reef, as stronger backwash in steeper coastlines carried debris on to the reef. But the majority of damage to coral in the lagoon was caused by impacts from tsunami-entrained coral rubble, sand, and shingle. Where no debris was available for the tsunami to entrain, less damage occurred. The large tropical cyclones that hit the area create coral boulders and shingle, increasing the risk to the coral by the tsunami that entrains this material. While the colonies affected by disease and bleaching are more prone to bioerosion and hence tsunami entrainment, the new rugose rubble substrate will likely provide suitable habitat for recolonization. In several places, we witnessed living coral in the freshly deposited rubble, leading us to believe that the reef ecosystem will recover in a reasonable time frame. While the lagoon provided a degree of physical buffering against the tsunami, as the reef system recovers, it should be able to continue providing services for tourism and fisheries. Although the commercial fisheries do not seem to be affected at this time, reef recovery should be closely monitored.

Acknowledgements

The Fisheries Division under the Samoan Ministry of Agriculture and Fisheries provided personnel, transportation, boat, and dive equipment, as did the Ministry of Natural Resources and Environment and the Pacific Regional Environment Programme. Funding for fuel and dive tanks was paid by UNESCO. Travel and field expenses were provided by The University of the South Pacific's Vice Chancellor's office, the University of New South Wales (Australia), and the US National Science Foundation Partnership in International Research and Education grant (OISE-0530151). We also appreciate the help of two anonymous reviewers.

References

Baird, A.H., Campbell, S.J., Anggoro, A.W., Ardiwijaya, R.L., Fadli, N., Herdiana, Y., Kartawijaya, T., Mahyiddin, D., Mukminin, A., Pardede, S.T., Pratchett, M.S., Rudi, E., Siregar, A.M., 2005. Acehnese reefs in the wake of the Asian Tsunami. Current Biology 15, 1926–1930.

Briggs, M.J., Synolakis, C.E., Harkins, G.S., Green, D.R., 1995. Laboratory experiments of tsunami runup on a circular island. Pure and Applied Geophysics 144, 569–593. doi:10.1007/BF00874384.

Chatenoux, B., Peduzzi, P., 2007. Impacts from the 2004 Indian Ocean Tsunami: analysing the potential protecting role of environmental features. Natural Hazards 40 (2), 289–304.

Cochard, R., Ranamukhaarachchi, S., Shivakoti, G., Shipin, O., Edwards, P., Seeland, K., 2008. The 2004 tsunami in Aceh and Southern Thailand: a review on coastal ecosystems, wave hazards and vulnerability. Perspectives in Plant Ecology, Evolution and Systematics 10, 3–40.

Dahdouh-Guebas, F., Koedam, N., 2006. Coastal vegetation and the Asian tsunami. Science 311, 37.

Danielsen, F., Sørensen, M.K., Olwig, M.F., Selvam, V., Parish, F., Burgess, N.D., Hiraishi, T., Karunagaran, V.M., Rasmussen, M.S., Hansen, L.B., Quarto, A., Suryadiputra, N., 2005. The Asian tsunami: a protective role for vegetation. Science 310, 643.

EM-DAT: The OFDA/CRED International Disaster Database, 2010. Université Catholique de Louvain, Brussels — Belgium. http://www.emdat.net. Accessed on 17 June 2010.

English, S., Wilkinson, C., Baker, V., 1997. Survey Manual for Tropical Marine Resources. Australian Institute of Marine Science ISBN 0 642 20256 7, 390 pp. 2nd ed.

Fernando, H.J.S., Mendis, S.G., McCulley, J.L., Perera, K., 2005. Coral poaching worsens tsunami destruction in Sri Lanka. EOS Transactions 86, 301–304.

Fritz, H., Kalligeris, N., 2008. Ancestral heritage saves tribes during 1 April 2007 Solomon Islands tsunami. Geophysical Research Letters 35, L01607. doi:10.1029/2007GL031654.

ICRI/ISRS (International Coral Reef Initiative/International Society for Reef Studies), 2005. Tsunami Damage to Coral Reefs. April 2005 Guidelines for Rapid Assessment and Monitoring. Victoria, Seychelles. 30 pages.

Kaly, U., L. Briguglio, H. McLeod, S. Schmall, C. Pratt, and R. Pal, 1999. Environmental Vulnerability Index (EVI) to Summarize National Environmental Vulnerability Profiles. SOPAC Technical Report 275.

Kunkel, C.M., Hallberg, R.W., Oppenheimer, M., 2006. Coral reefs reduce tsunami impact in model simulations. Geophysical Research Letters 33, L23612.

Lay, T., Ammon, C., Kanamori, H., Rivera, L., Koper, K., Hutko, A., 2010. The 2009 Samoa–Tonga great earthquake triggered doublet. Nature 466, 964–968.

McAdoo, B., Fritz, H., Jackson, K., Kalligeris, N., Kruger, J., Bonte-Grapentin, M., Moore, A., Rafiau, W., Billy, D., Taino, B., 2008. Solomon Islands Tsunami, One Year Later. Eos Transactions, American Geophysical Union 89 (no. 18), 169–170.

Ministry of Natural Resources and Environment (MNRE), 2002. http://www.mnre.gov.ws/projects/siam-2/documents/CIM/Falealili/Plan%20Development%20English/Plan%20Development.pdf. Accessed on 21 October 2010.

Moberg, F., Folke, C., 1999. Ecological goods and services of coral reef ecosystems. Ecological Economics 29, 215–233.

Mumby, P.J., Green, E.P., 2000. Mapping coral reefs and macroalgae. In: Green, E.P., Mumby, P.J., Edwards, A.J., Clark, C.D. (Eds.), Remote Sensing Handbook for Tropical Coastal Management. Coastal Management Sourcebooks, 3. UNESCO, Paris. http://www.unesco.org/csi/pub/source/rs12b.htm. Accessed online on 15 June 2010.

NOAA, Coral Reef Watch, 2010. http://coralreefwatch.noaa.gov/satellite/current/sst_series_americansamoaofu_cur.html. Accessed on 21 October 2010.

Samoan Ministry of Natural Resources and Environment, 2003. Aleipata and Safata Marine Protected Areas. http://www.mnre.gov.ws/biodiv/documents/Newspaper/030824_Aleipata%20&%20Safata%20Marine.pdf. accessed on 21 October 2010.

Samoan Tourism Authority, 2010. November 2009 Blog Archives. http://www.samoa.travel/blog/xm11xy2009/November-2009. accessed on 9 November 2010.

Sudmeier-Rieux, K., Masundire, H., Rizvi, A., Rietbergen, S. (Eds.), 2006. Ecosystems, Livelihoods and Disasters: An Integrated Approach to Disaster Risk Management. IUCN, Gland, Switzerland and Cambridge, UK. 58 p.

Trond-Inge, K., Akhir, M., Studholme, J., 2002. A low-cost procedure for automatic sea-floor mapping, with particular reference to coral reef conservation in developing nations. Hydrobiologia 474 (1), 67–79.

Turner, B., Kasperson, R., Matson, P., McCarthy, J., Corell, R., Christensen, L., Eckley, N., Kasperson, J., Luers, A., Martello, M., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences 100 (no. 14), 8074–8079.

Zann L. and E. Lovell, 2006. *Coastal Ecosystem Recovery Planning: Vaovai, Upolu Island, Samoa.* Report to the Pacific Environment Consultants Ltd. For submission to the Cyclone Emergency Recovery Project (CERP).