Tsunami and Earthquake Damage to Coral Reefs of Aceh, Indonesia

Khaled bin Sultan Living Oceans Foundation

REEF CHECK

IUCN The World Conservation Union

Acknowledgements and Citation Information

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Front cover photo. Raised reef at Simeulue Island, courtesy of C. Shuman. February 2, 2005.
Back cover photo. Overturned table coral at Pulau Rondo, courtesy of A. Hagan. October 29, 2005.

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Executive Summary

The December 26, 2004 earthquake and tsunami precipitated one of the greatest humanitarian crises in history with an estimated 232,000 lives lost and 1.2 million people displaced. It was also feared that the earthquake and ensuing giant tsunami waves, reaching as high as 20 meters in some areas, had severely damaged coral reefs. These fears were confirmed by a rapid Reef Check, Quiksilver and Surf Aid expedition in February 2005 that documented large areas of reef raised out of the water at Simeulue Island, resulting in widespread coral mortality. In April 2005, a review of post-tsunami assessments of damage to coral reefs revealed that with the exception of Western Sumatra, Indonesia, many of the areas hit by the tsunami, (e.g. Thailand, Maldives, Sri Lanka, and India) had already been well-surveyed. Recognizing the importance of closing the remaining knowledge gap, Reef Check asked the Khaled bin Sultan Living Oceans Foundation and the World Conservation Union (IUCN) to partner in a survey of Aceh's coral reefs to determine the extent of tsunami damage in close proximity to the earthquake and tsunami epicenter.

A multinational team of seven scientists and three support crew carried out the Aceh expedition from 17 to 30 October aboard the vessel, *Mermaid of the Equator*. Starting from Sibolga, the expedition covered the area affected by the earthquakes and tsunami -- over 660 kilometers to Pulau Rondo, the northern-western tip of the Indonesian archipelago. Unfortunately, high turbidity due to heavy rainfall limited the ability of the team to effectively survey many of the reefs adjacent to the mainland coast. Surveys were carried out using manta tows and the globally-standard Reef Check protocol. The surveys recorded food fish sizes and abundance, as well as mobile and attached invertebrates including corals. A special survey was carried out to detect newly settled corals as a measure of recovery.

The results of the underwater surveys indicated that relatively minor physical damage to coral reefs was caused by the tsunami as compared with the well-documented devastation experienced on land. Tsunami damage recorded included overturned corals and swathes of broken corals where large tree branches and tree trunks had been washed across the reef as the waves receded.

No tsunami damage was observed at more than half of the reefs surveyed. Even in areas where severe tsunami damage was recorded, there were still large areas of intact, living coral reef present nearby. These areas may act as an important source of larvae for recolonization of the damaged reefs. However, of the 5,280 quadrats surveyed for recruits, only 18 recruits were recorded, and 15 of these were in the Banyak Island group. This low density of coral recruits indicate that recovery is proceeding very slowly.

The earthquake damage to coral reefs was more severe than that caused by the tsunami. Damage included uplifted reefs, shattered beds of coral, and overturned coral colonies. Several islands such as Simeulue were tilted, with one end rising as much as 2 m while the other end descended a similar amount. This caused tens of hectares of living coral

reef to be raised above the high tide level and killed, while other reefs descended into deeper water, altering the ecological zonation.

On land, the earthquakes and tsunami caused slope failures and removed vegetation facilitating increased erosion, sediment transport, and discharge during rainy periods. A longer-term and more insidious type of reef damage could occur if the observed turbidity and sedimentation continue. In addition to inhibiting coral settlement, sedimentation can directly injure and kill adult corals.

A low abundance and small mean size of the ten primary food fish families in Aceh was recorded suggesting that stocks of these fish are overfished. Evidence of destructive fishing practices was common. Overfishing can lead to an imbalanced ecosystem in which the lack of herbivorous fish allows fleshy algae to overgrow corals and dominate the coral reef.

The findings from this study suggest that sedimentation (exacerbated by the tsunami), overfishing, and the use of destructive fishing methods may represent a greater threat to Aceh's reef ecosystems than the immediate impacts of the earthquakes and tsunami.

The earthquakes and tsunami have left the Acehenese more dependent than ever on their marine resources for survival. Coral reefs can recover relatively quickly following a reduction in fishing pressure. There is now an opportunity to invest in a long-term strategy to rehabilitate the marine resources of Aceh through education, coastal management, regular monitoring and the establishment and maintenance of marine protected areas.

Introduction

The December 26, 2004 earthquake and tsunami precipitated one of the greatest humanitarian crises in history with an estimated 232,000 lives lost and 1.2 million people displaced (USGS 2005; Walls 2005). It was also feared that the giant tsunami waves, reaching as high as 20 meters in some areas, would damage coral reefs. In April 2005, a review of post-tsunami assessments of damage to coral reefs revealed that, with the exception of Western Sumatra in Indonesia, many of the areas hit by the tsunami (e.g. Thailand, Maldives, Sri Lanka, and India) had already been surveyed. Recognizing the importance of closing the remaining knowledge gap regarding the status of Western Sumatran reefs, Reef Check asked the Living Oceans Foundation and the World Conservation Union to partner in a survey of Aceh's coral reefs to determine the extent of the damage in close proximity to the earthquake and tsunami epicenter.

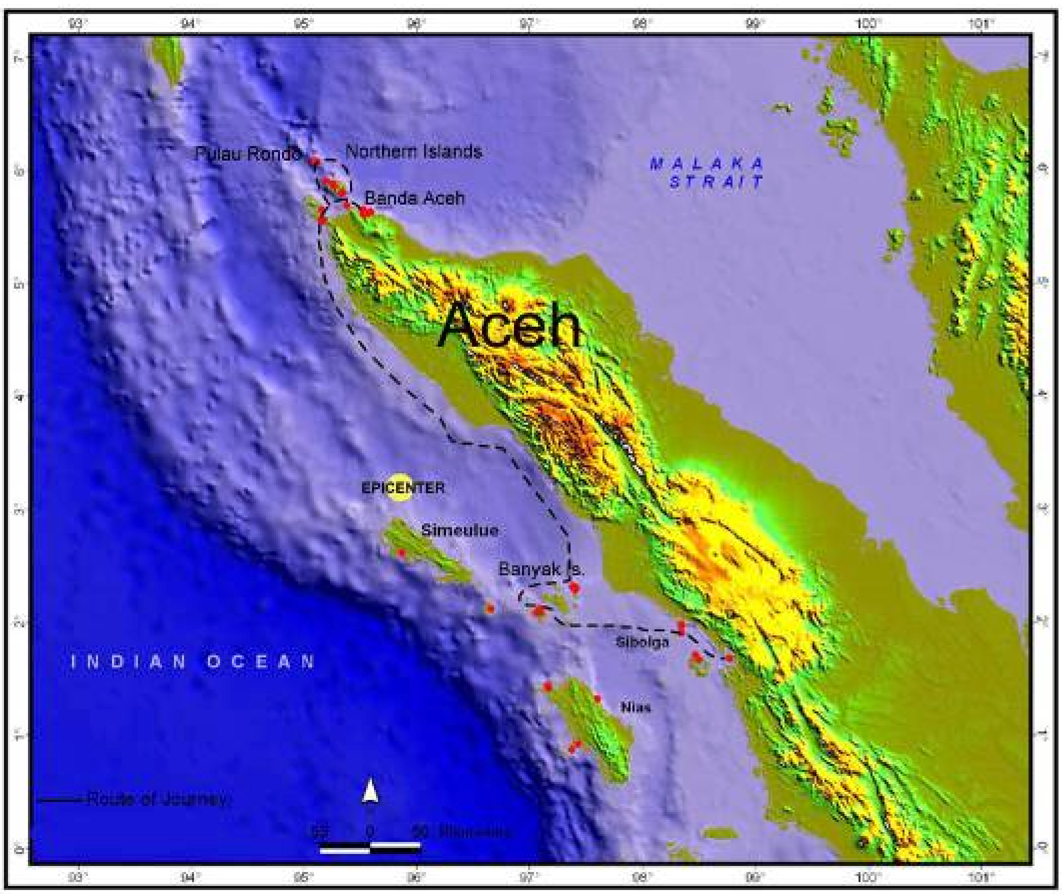

Figure 1. Sites surveyed during the Aceh expedition. Dashed line indicates the path of the boat from Sibolga to the westernmost point in Indonesia, Pulau Rondo. Red dots denote survey sites. Nias sites were surveyed in July 2005. The Simeulue site was surveyed in February 2005.

A multinational team of seven scientists and four support crew carried out the Aceh expedition from October 17 to October 30, 2005 aboard the vessel, *Mermaid of the Equator*. The expedition covered the area affected by the earthquakes and tsunami - a 660-kilometer stretch of coastline from Sibolga to east of Banda Aceh on the mainland, and from Pulau Karang to Pulau Rondo, the westernmost point in Indonesia (Figure 1).

Methods

Two methods were used to survey reefs: 1) a modification of the *Tsunami Damage to Coral Reefs Protocol* (ICRI/ISRS 2005) that is primarily based on the manta tow and 2) the *Reef Check Plus* Protocol. Manta tows are useful for surveying up to several kilometers of reef per day and for determining where to collect more detailed data (Hill and Wilkinson, 2004). These two methods were used in combination in order to cover a large distance within a short time as well as obtaining detailed quantitative data on the status of the reef.

Manta Tow

The method used was based on Hill and Wilkinson (2004), modified to collect the tsunami and earthquake damage information. A diver was towed behind a skiff at two km/hr for two minutes while recording observations on a slate. GPS positions were recorded at the start and end of each tow. The instances of overturned/broken pieces of coral were recorded using the following criteria: Low/Medium/High, where 0-10 pieces = Low, 10-30 = Medium, 30+ = High. A "piece of coral" was defined as any coral greater than 15 cm in diameter in the longest direction. An Overturned Coral Index was created by re-assigning numerical values to each class: Low = 1, Medium = 2 and High = 3 and taking the mean value recorded from multiple manta tow surveys. In addition, an estimation of the percentage cover of the following was recorded: live coral, rubble, sand, mud, rock, and recently killed coral.

ReefCheck Plus Survey

The Reef Check surveys followed the standard protocol (Hodgson et al. 2005) with the addition of ten important food fish families. Two 100 m transect tapes marked at centimeter intervals were run adjacent to each other and parallel to the shoreline along two depth contours (2-5 m and 6 -12 m). In addition to recording a site description, three surveys were carried out along each transect: a fish belt transect survey, an invertebrate belt transect survey, and a point intercept transect survey. Each belt transect comprised four 20 m long sections separated by 5 m gaps for a total reef area surveyed of 800 m^2.

Fish belt transect: Surveys were carried out 3-5 minutes after laying the tape in order to allow fish to settle. A diver swimming along the tape recorded fish within 2.5 m on either side of the tape at every 5 m along the tape. The following 15 taxonomic groups of fish were recorded for the fish belt surveys.

Acanthuridae
Carangidae
Chaetodontidae
Chromileptes altivelis
Grouper *(Epinephelus, Plectropomus, Cephalopholis, Mycteroperca)*
Haemulidae
Cheilinus undulates
Other Labridae
Lethrinidae
Lutjanidae
Mullidae
Muraenidae
Bolbometopon muricatum
Other Scaridae
Siganidae

All fish were assigned to one of three size classes: 1 to 25 cm, 26 to 49 cm, and 50 cm or more.

Invertebrate Belt Transect:

The following taxa were recorded within the 5 m wide invertebrate belt transect:

Long-spined black sea urchin	*Diadema* (and *Echinothrix diadema*)
Banded coral shrimp	*Stenopus hispidus*
Lobster (spiney and slipper/rock)	Malacostraca (Decapod)
Sea Egg/Collector urchin	*Tripneustes* spp.
Giant clams (give size/species)	*Tridacna* spp.
Triton	*Charonia tritonis*
Edible sea cucumbers (3 species)	
Prickly redfish	*Thelenota ananas*
Greenfish	*Stichopus chloronotus*
Edible sea cucumber	*Holothuria edulis*
Crown of thorns starfish	*Acanthaster planci*
Pencil urchin	*Heterocentrotus mammilatus*

Substrate and Coral Recruits

Substrate type and coral recruits were recorded at 0.5 m intervals along the transect, i.e., at 0.0 m, 0.5 m, 1.0 m, 1.5 m etc. up to 19.5 m. A coral recruit was defined as any coral < 2 cm in diameter found within a 10 x 10 cm quadrat. Quadrats were centered on each sample point along the transect (i.e., every 0.5 m).

Coral Disease/Bleaching, Trash and Coral Damage

The level of bleaching and the presence of coral disease, trash and coral damage was recorded. Corals that were still alive, but bleached were recorded as live hard coral (HC) on the line transect. If bleaching was present, the percentage of coral colonies on the transect that was bleached and the mean percent of each individual colony that was bleached were also recorded.

Reef Check Guidelines for Determining Substrate Types:

Hard coral (HC): Live coral including bleached live coral. Also includes fire coral (*Millepora*), blue coral (*Heliopora*) and organ pipe coral (*Tubipora*).

Soft coral (SC): All soft corals including zoanthids.

Recently killed coral (RKC): Coral that may be standing or broken into pieces, but appears fresh, white with corallite structures still recognizable or partially or completely overgrown by encrusting algae etc.

Nutrient Indicator Algae (NIA): All algae except coralline and turf algae were recorded. Where turf algae was present the substrate immediately below it was recorded and the presence of algae was noted. The aim is to record blooms of algae that may be responding to high levels of nutrient input.

Sponge (SP): All sponges were recorded with the aim of detecting sponge blooms that may be an indicator of disturbance.

Rock (RC): Any hard substrate other than hard coral and recently killed coral and may be covered by other organisms such as turf algae. This category also includes dead coral more than one year old.

Rubble (RB): Includes rocks and coral pieces between 0.5 and 15 cm diameter in the longest direction.

Sand (SD): Loose material less than 0.5 cm in diameter but that does not remain in suspension.

Silt/Clay (SI): Sediment that remains in suspension if disturbed.

Other (OT): Any other sessile organism including sea anemones, tunicates, gorgonians or non-living substrate.

Survey Area

Surveys took place in five areas: Nias Island, Simeulue Island, the Banyak Island group, the islands north of Aceh, and along a stretch of coast immediately east of Banda Aceh. Reef Check surveys were performed by team members in Simeulue and Nias in February and July of 2005 prior to the main expedition, and Reef Check Plus surveys were carried out at the latter three locations in October 2005. A total of 171 manta tows were carried out in the Banyak Archipelago, in the islands north of Aceh, and along coastal fringing reefs east of Banda Aceh.

Results

Patterns of Earthquake and Tsunami damage

There were two major earthquakes in the waters offshore of Aceh during 2004 and 2005. The first, which occurred on 26 December 2004 and generated the destructive tsunami, was reported to measure magnitude 9.15, and the second in March 2005, registered 8.7. Hundred of large aftershocks have since occurred. Both of the major earthquakes destroyed buildings on land and tilted several islands including Simeulue, Nias and parts of the Banyak archipelago. This pushed shallow water reef flats above the high tide mark, resulting in 100% mortality (cover photo). Underwater, sections of reef that were previously on the upper reef slope were raised closer to the surface to become the new reef flat, and apparently survived.

Underwater, large stands of toppled broken coral lined the south coast of Pulau Weh (Fig. 2). The damage was found along a 7 km long, 50 m wide series of patch reefs comprised of blue coral (*Heliopora coerulea*) at 2 - 6 m depth. This damage was likely caused by the earthquake. *Heliopora* skeletons are robust, but somewhat brittle and no large boulders or tree trunks that could have caused such extensive damage were visible in the area. No underwater slope failures were observed.

Figure 2. Shattered *Heliopora* on Pulau Weh 28 October 2005 (A. Hagan). The pattern of destruction suggests that an earthquake shattered the 7 km-long series of patches of blue coral (*Heliopora coerulea*). Brown patches indicate living coral.

The most common tsunami damage was overturned corals and broken coral fragments (Figs. 3 and 4). The greatest number of overturned coral heads was seen on the islands north of Aceh as indicated by the Overturned Coral Index (Table 1). The pattern of damage recorded in embayments on the north coast of mainland Aceh suggests that wave energy was greatest in the central section of the bays.

Figure 3. Live overturned table coral at 10 m water depth, Pulau Rondo, 29 October 2005 (A. Hagan). Some overturned corals on offshore islands were alive ten months after the tsunami.

Figure 4. Overturned dead table *Acropora* sp. at 10 meter depth, Pulau Rondo, 29 October 2005 (A. Hagan). Most overturned table corals were dead on mainland reefs.

Many overturned corals were observed on the fringing reefs off the islands north of Aceh, especially at Pulau Bunta (Table 1). At Pulau Rondo, where the manta tow estimate of live coral cover was 45.9%, many of the overturned corals were still alive. On the Aceh mainland, however, where high numbers of overturned corals were limited to the middle of bays, the vast majority of the overturned table corals were dead.

Table 1. Manta tow results for three regions in Aceh. The Overturned Coral Index evaluates the number of overturned/broken pieces of coral greater than 15 centimeters in diameter. The following criteria were used: 0-10 pieces = 1, 10-30 pieces = 2, 30+ = 3 (n = 171).

Region	*Site*	*% Live Coral*	*Overturned Index*	*% Rubble*	*% Sand*	*% Mud*	*% Rock*	*# of tows*
Banyak	Pulau Karang	30.0	1.0	34.6	17.7	0.0	16.9	13
Banyak	Pulau Bangkaru	55.3	1.3	10.1	13.2	0.0	15.7	35
Banyak	Pulau Baleh and Bagu	31.3	1.0	12.3	28.0	0.0	18.0	15
Mainland Aceh	East of Banda Aceh	28.3	1.2	9.4	25.3	0.0	37.1	55
Northern Islands	Pulau Weh	23.1	1.5	15.6	17.5	0.0	43.8	8
Northern Islands	Pulau Rondo	45.9	2.1	23.3	0.3	0.0	16.7	15
Northern Islands	Pulau Bunta	4.0	2.7	31.1	4.8	0.3	56.1	30

Figure 5. Raised reef, Pulau Karang, Banyak Region, 19 October 2005 (R. Foster). Earthquake-induced uplift (December 2004) killed several hundred square meters of reef-flat coral by raising the seabed above sea level.

Previously unreported uplifted reefs were observed at Pulau Karang (Banyak) (Fig. 5). The virtual absence of overturned corals (Overturned Index mean = 1) observed during the manta tows at this site suggests that the reef remaining underwater was relatively unaffected by the tsunami waves.

Substrate Composition

Substrate composition varied considerably among sites and much of this was due to natural differences. Numerous areas of rocky subtidal habitat were not colonized by corals. For example, rock cover ranged from 15.7% at Pulau Bangkaru to 56.1% at Pulau Bunta. Coral reefs were never well developed at some locations, such as on the south side of Pulau Beras. Coral cover typically ranged between 20% and 55%, except at Pulau Bunta (where it was only 4%). The distance from the origin of the earthquakes and tsunami just east of Simeulue (3.4º N 95.7º E) did not correlate with the degree or extent of the coral reef damage. It is possible that the passage of time has made it difficult to determine what percentage of rubble was created by the tsunami and earthquakes.

Based on the Reef Check surveys, the mean coral cover amongst all surveyed sites was almost 40% which is above the global average 33% reported by Hodgson (1999). Recently Killed Coral averaged below 1% while algae, soft corals and sponges were also less than 3% (Figs. 6 – 10).

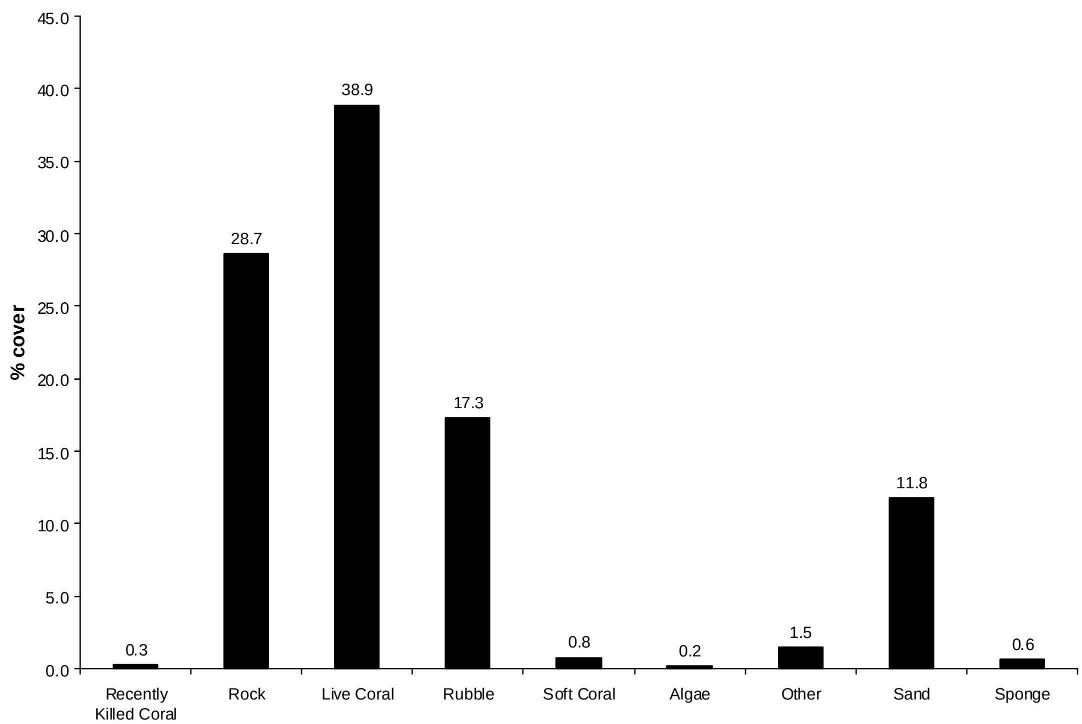

Figure 6. Reef composition in the Banyak region based on Reef Check surveys (n=5) .

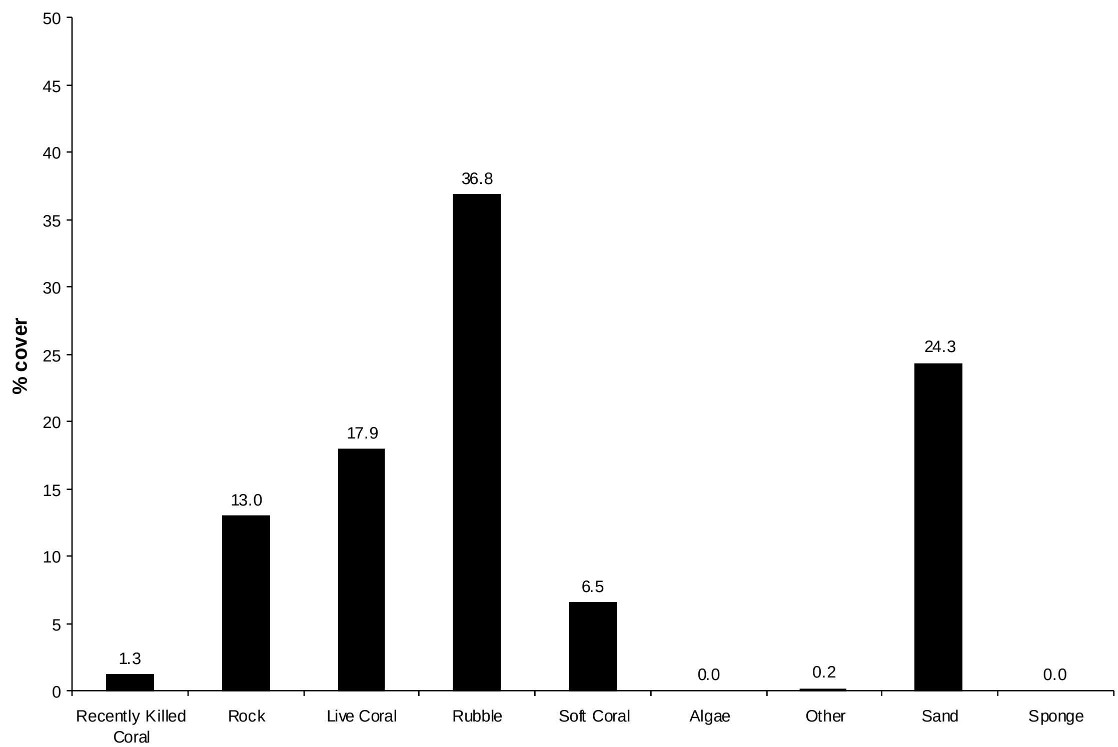

Figure 7. Reef composition in the Nias region based on Reef Check surveys (n=9) .

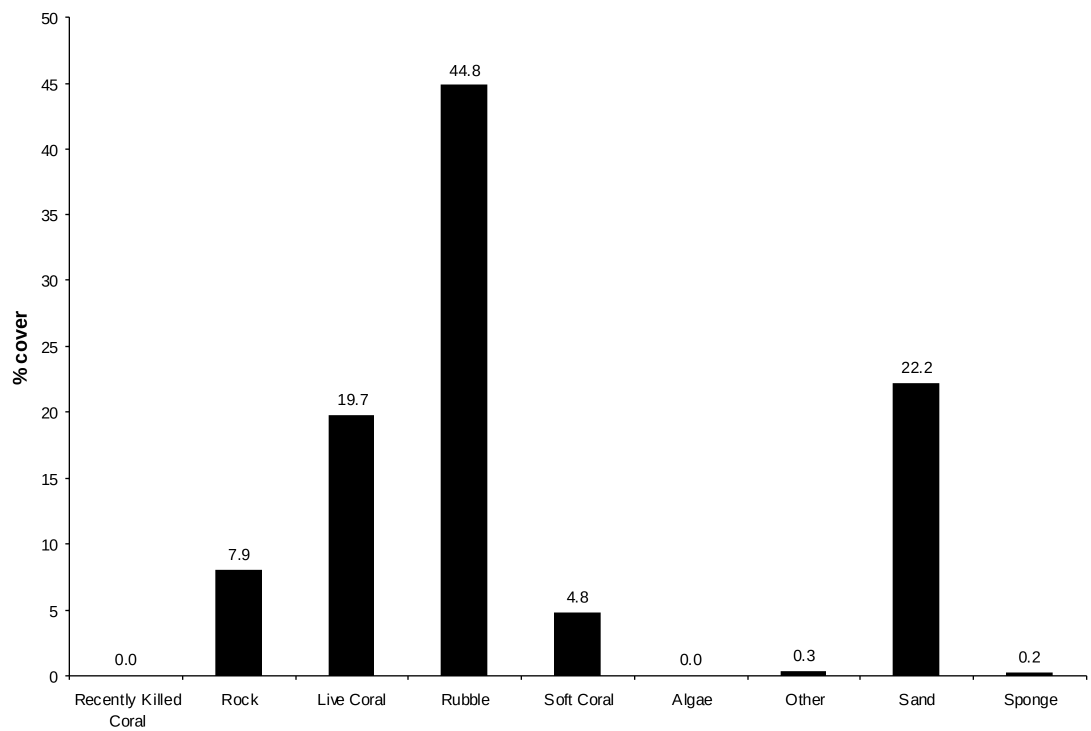

Figure 8. Reef composition in the Sibolga region based on Reef Check surveys (n=6) .

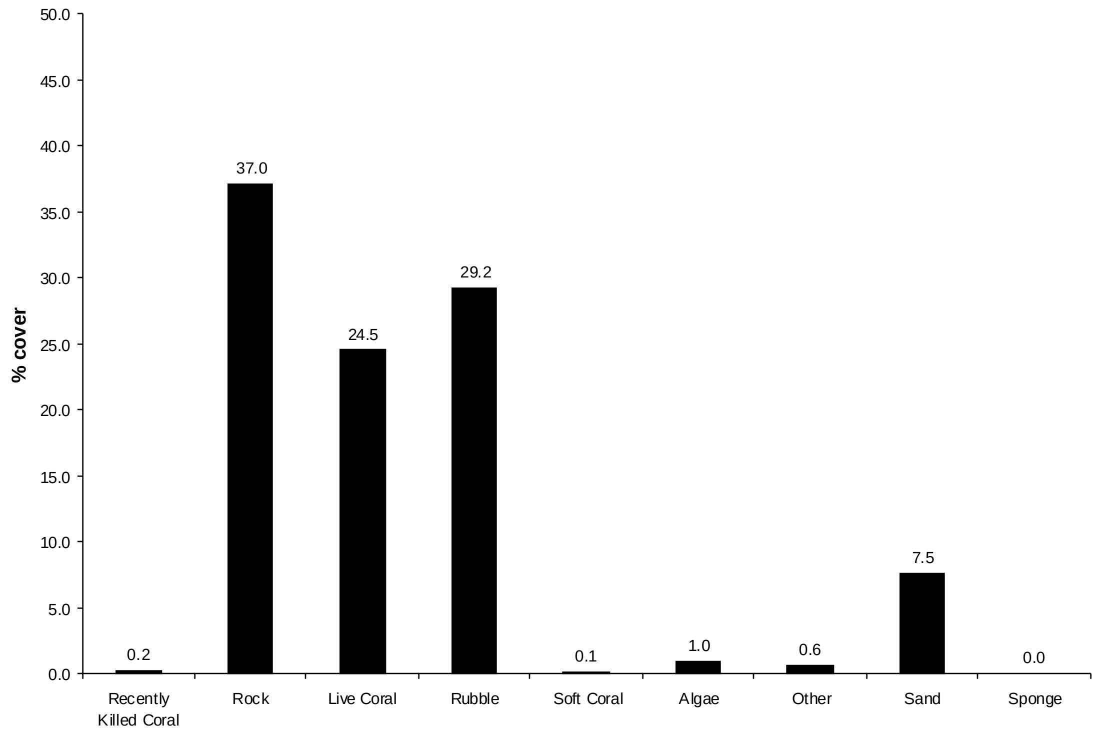

Figure 9. Reef composition in the islands north of Aceh region based on Reef Check surveys (n=8) .

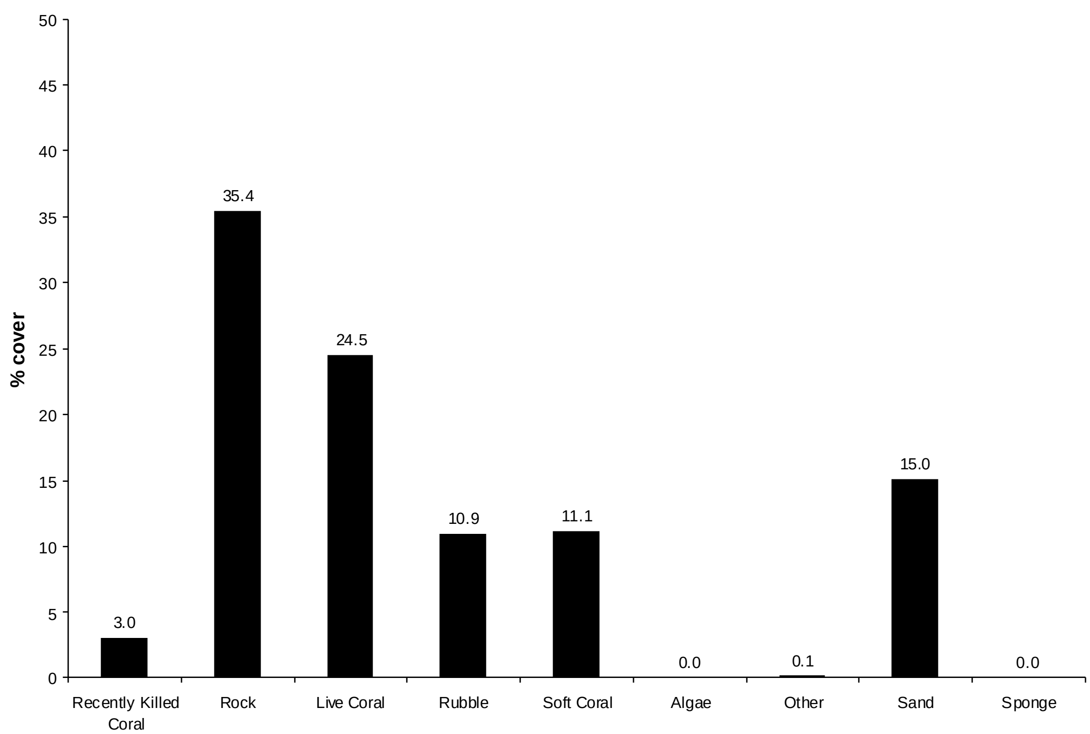

Figure 10. Reef composition in the East Banda Aceh region based on Reef Check surveys (n=5).

Reef Fish

The results of the fish surveys show that with the exception of Pulau Rondo, an uninhabited island far from the mainland, few food fish greater than 50 centimeters were observed (Figs. 11, 12 and 13; also see Appendix 1). Jacks (Carangidae) were the most common family recorded in the largest size class.

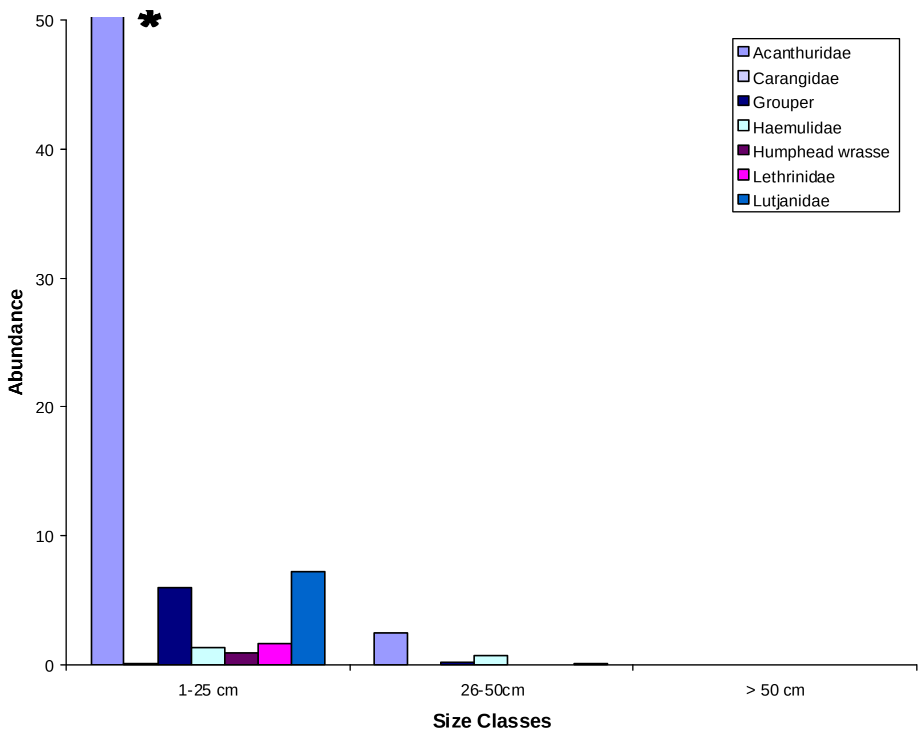

Figure 11. Food fish in the Banyak Archipelago. Mean abundance per 100 m^2 of three different size classes of ten common food fish taxa. Few fish greater than 25 cm in length and none longer than 50 cm were recorded (n = 10 surveys). * indicates mean number of Acanthurids in the 1-25 cm size class was greater than 50 (mean = 84).

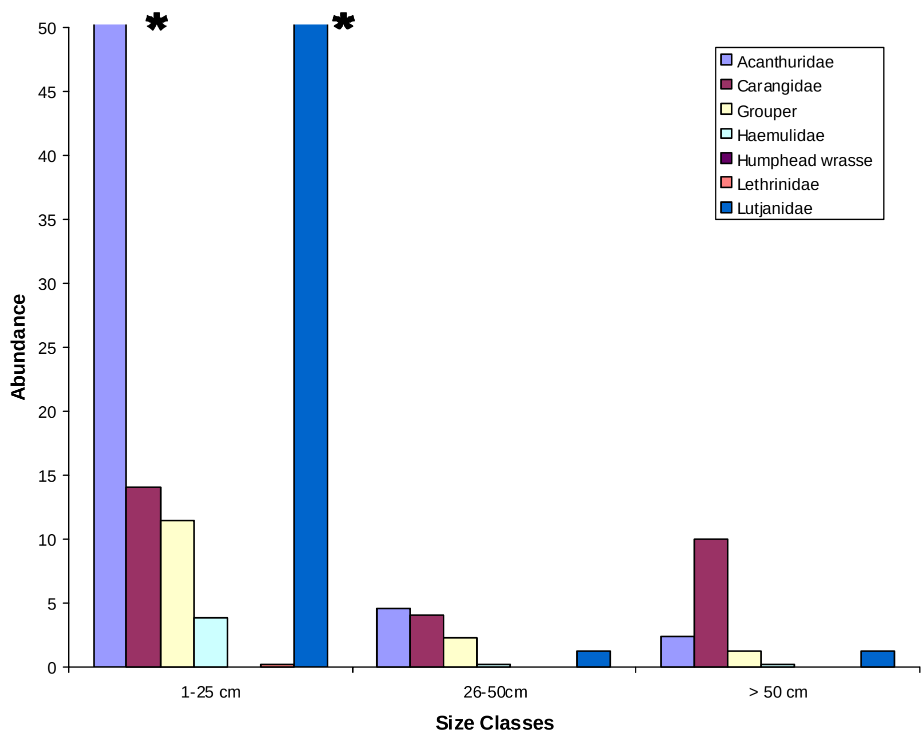

Figure 12. Food fish in the islands north of Aceh. Mean abundance per 100 m2 of three different size classes of ten common food fish taxa. Few fish greater than 25 cm in length were observed. Very few fish greater than 50 cm were recorded (n = 5 surveys). * indicates mean number of Acanthurids and Lutjanids in the 1-25 cm size class was greater than 50 (mean Acanthuridae = 244.2, mean Lutjanidae = 107.4).

Of the indicator fish families, Acanthuridae were the most common, with more than 200 individual fish per 100 m^2 of reef in the smallest size class in the islands north of Aceh. The Lutjanids were the second most common group with over 100 fish per 100 m^2 in the smallest size class in the same region. Certain high value species for the live fish trade, such as Humphead Wrasse (*Cheilinus undulates*), Barramundi cod (*Cromileptes altivelis*) and Bumphead Parrotfish (*Bolbometopon muricatum*), were very poorly represented as were moray eels (Muraenidea).

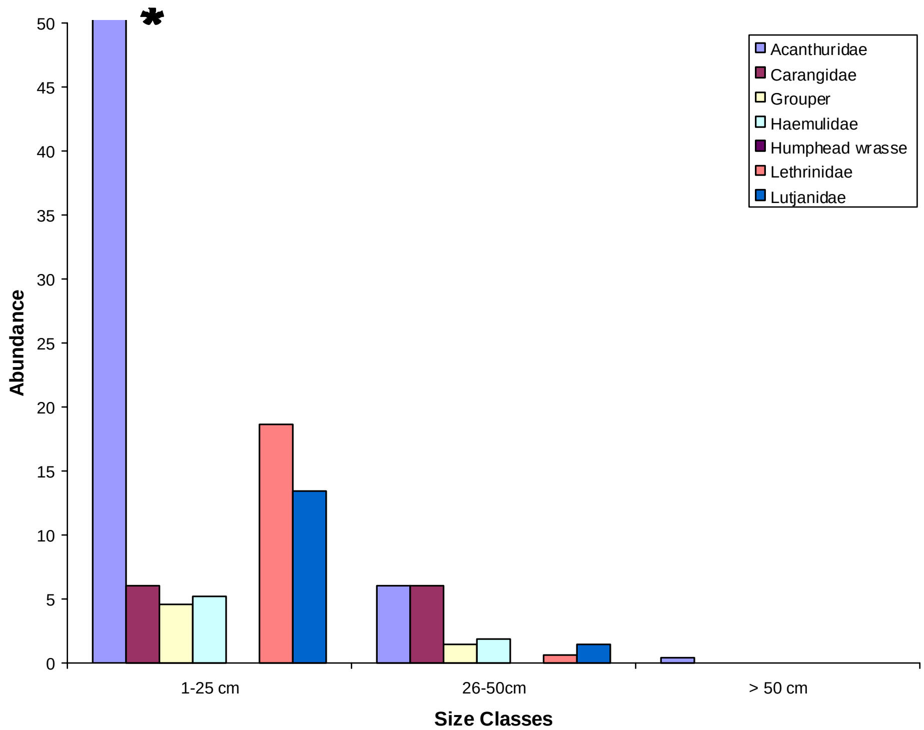

Figure 13. Food fish East of Banda Aceh. Mean abundance per 100 m2 of three different size classes of ten common food fish taxa. Few fish larger than 25 cm were recorded (n = 5 surveys). * indicates mean number of Acanthurids in the 1-25 meter size class was greater than 50 (mean = 55.8).

Coral Recruitment

From the 5,280 quadrats surveyed for recruits, only 18 recruits were recorded, and 15 of these were in the Banyak Island group (Table 2). This is considered to be a low recruitment rate.

Table 2. Density of coral recruits. Recruits were defined as any juvenile less than 2 cm in diameter.

Region	**Coral Recruits** (n)	**Total area surveyed** (m^2)	**Density** (n/m^2)
Banyak Archipelago	15	16	0.938
Northern Islands	1	8	0.125
East Of Banda Aceh	2	8	0.250

Turbidity and Sedimentation

During the course of the expedition high turbidity was encountered along most of the west coast of Aceh (Fig. 14). Horizontal underwater visibility along the mainland fringing reefs between Sibolga and Banda Aceh was usually less than 3 m. The observed widespread sediment discharge associated with heavy rainfall and flooding in Aceh during the survey suggests that high turbidity and sedimentation may already be damaging reefs along the mainland coast. Surveys after the rainy season will be needed to determine this.

Figure 14. Heavy rainfall prior to the survey resulted in high turbidity and sedimentation along the Aceh coast.

Discussion

The two Aceh earthquakes and earthquake-induced tsunami were powerful natural events that destroyed villages and cities, yet apparently caused relatively limited immediate damage to the vast majority of coral reefs in the surrounding seas (Fig. 15). These results are consistent with reports on tsunami damage to reefs in Thailand, Sri Lanka, and the Seychelles (Chavanavich et al. 2005; NARA/IUCN/SLSAC 2005; Obura and Abdulla 2005, Rajasuriya 2005).

The actual cause of specific types of damage observed can only be inferred since previous surveys of Sumatra by Reef Check teams were carried out further south, in the Mentawai Islands. No pre-2005 published reports on the reefs of Aceh surveyed during this expedition are known. Overall, the low percentage cover of algae, sponges, soft coral, and recently killed coral indicates a low mortality of living corals during or following the earthquakes and tsunami.

Figure 15. Lumba Lumba dive shop on Pulau Weh (A. Hagan). Note arrow points to line across window indicating tsunami water level (~5 m above sea level) on 26 December 2004.

Earthquake Damage

The December earthquake was the fourth largest in history and lasted almost ten minutes – extremely long by earthquake standards. The total energy released has been estimated as 1.1×10^{18} joules or about 0.25 gigatons of TNT. The earthquake was so powerful that it moved the Earth's surface vertically by up to 1 cm and altered the Earth's rotation. In many areas, the earthquakes caused instantaneous uplifting of the seafloor by several meters. The second earthquake was also powerful. Such energy and movement could easily dislodge and break up corals located nearby.

It is likely that the toppled large coral heads and the large area of broken blue coral seen on reefs along the south coast of Pulau Weh were caused by the earthquakes. The *Heliopora* skeletons appeared to have been overturned in place. No other causes of such extensive damage were observed in the area such as large tree branches or boulders that could have been rolled across the reef by waves.

The most dramatic damage to Aceh reefs was also caused by the earthquakes. Hectares of reef flat at Pulau Bangkaru Island and Simeulue were uplifted to a level above the high tide mark resulting in total mortality of corals and other attached organisms that were previously healthy and intact. Other reports indicate areas of uplift on many other islands (USGS 2005). Less extensive damage of a similar type was reported in the Andaman Islands (Searle 2005).

The coral recruitment rate recorded was low (Table 2) and consistent with rates recorded following disturbances such as coral bleaching in Belize and the Maldives (Aronson et al. 2002; Schumacher et al. 2005).

Tsunami Damage

Damage from a tsunami can occur from the rapid lateral flow of water, from falling water in a breaking wave, or from large objects such as trees and anthropogenic debris being carried with the water flow (in either direction) and smashing into the reef. Along the mainland of Aceh, the highest frequency of overturned corals was found on fringing reefs inside bays while the reefs at adjacent headlands were mostly undamaged. This could be due to wave energy being concentrated by bathymetry or to more fragile corals growing in these locations.

The tsunami may have been less damaging to the reefs of Aceh than initially expected for two reasons. First, the tsunami involved only three large waves. Once the waves had passed and receded the event was over. In contrast, major storm events create hundreds to thousands of large waves that may dislodge coral heads and roll them across the reef for 24 hours or more.

Secondly, there is evidence that tsunami damage is greater in areas with gently sloping bathymetry (Searle 2005). According to eyewitness reports from the Reef Check team on

Pulau Weh, the tsunami wave swiftly inundated the island rather than forming a breaking wave on the fringing reefs. In cases where tsunami waves can shoal and build up, they may break. The weight of the falling water could crush and dislodge corals. In the Andaman Islands, for example, low lying islands with shallow shelving coasts suffered heavy damage while islands with steeper offshore bathymetry or outlying fringing reefs that absorbed some of the tsunami energy suffered much less damage (Searle 2005). In both the Seychelles (Obura and Abdulla 2005) and Sri Lanka (Rajasuriya 2005) reefs located further offshore steeper seabed gradients suffered significantly less damage compared to shallow inshore reefs. Similarly, the oceanic atoll reefs of the Maldives archipelago were not heavily affected by the tsunami (CORDIO 2005).

Coral reefs are well known to protect the coast from storm waves (Hodgson and Liebeler 2002). However, the Ikonos images (Fig. 16) of Banda Aceh indicate that there was little difference in the inundation level and damage caused in areas protected by coral reefs and those without reefs. This is because the size and speed of the tsunami wave and the water level were so high that a shallow fringing reef would have little effect in protecting the coastline.

Figure 16. Ikonos imagery of tsunami damage in Banda Aceh showing pre-tsunami (January 2003) and post-tsunami (December 2004) views. Post-tsunami image clearly shows extent of water inundation on land and resulting terrestrial damage (Image printed with the permission of the Respond Consortium).

Human Impacts

Indonesia is part of the global center of marine biodiversity (Tomascik 1997), however the country is so large that many reefs in the country have not yet been well surveyed. Although previous survey work in Aceh was limited, it is known that coral reefs in Sumatra were severely damaged by the 1997-98 cycle of drought, forest fires, erosion, sedimentation and plankton blooms (Abram et al. 2003). Some of the fires were the result of slash and burn agriculture and some reefs in the Mentawai Islands lost almost all their living corals. Surveys in that area in 1998 by Reef Check teams showed very low live coral cover (6%) (WRAS 2006).

Figure 17. Cast net fisherman near Sibolga (A. Hagan).

One of the major concerns raised in the aftermath of the earthquakes and tsunami was the potential for coral reef habitat to be lost, thereby threatening food-fish stocks in tsunami-affected countries (Fig. 17). Other than the nearshore reefs killed by uplift, there has been little decrease in the amount of reef habitat since the tsunami, implying that fish stocks have not been significantly altered by the earthquakes and tsunami. Future monitoring should be used to determine if any effects on fisheries are delayed, as was observed in the Seychelles following bleaching (Spalding and Jarvis 2002).

Sedimentation exacerbated by the earthquakes and tsunami is a serious long-term threat to reef health in Aceh. Rapid increases in sedimentation can kill corals directly, facilitate diseases (Hodgson 1990), inhibit larval settlement (Hodgson 1993) and slow growth (Hodgson and Dixon 1989, 1992). The observed widespread sediment discharge associated with heavy rainfall and flooding in Aceh during the survey suggests that high turbidity and sedimentation may already be damaging reefs there. Ikonos imagery (Fig. 16) of Banda Aceh before and after the tsunami illustrates the extent of the land area cleared of vegetation and exposed to erosion. Moreover, demand for construction materials may cause additional land clearing of forests damaged by the 1998 fires and therefore result in additional sources of sedimentation.

Another concern is that the destruction of key infrastructure in the region has already stunted economic growth and may force more residents to rely on ocean resources for survival. The survey results indicate that the fish stocks in Aceh are far from robust. Both the abundance and size of the ten common families of food fish are very low. Only in Pulau Rondo were food fish greater than 50 cm in length commonly observed. Additional demands on the already overfished stocks could push local coral reef fish populations to the point of collapse.

Prospects for Recovery of Aceh Coral Reefs

Corals killed by uplift of reefs are now above sea level and will not recover. The other types of damage that will recover with time are broken and overturned corals and patches of dead coral.

Many of the overturned and broken corals were still completely living or included patches of living tissue. Barring further disturbances, most of these colonies will recover, cement to the seabed and grow. In areas where tsunami damage was observed, most of the reef was still intact with a high cover of living coral, which will serve to re-populate the damaged reefs.

Patches of dead coral will recover based on growth and reproduction of any remaining live colonies as well as larval settlement and growth of new colonies. Given the low percentage of Recently Killed Coral recorded, recovery of patches of dead coral is not a major issue.

The results from Aceh are similar to those from other locations hit by the tsunami. Post-tsunami reef studies in Thailand found that 66% of the 174 sites surveyed showed no or very little damage, with only 13% exhibiting severe damage (> 50% of colonies affected) (Satapoomin et al. 2005). A recovery time of 3-5 years was postulated (Satapoomin et al. 2005). The reefs of Sumatra appear to have suffered similar levels of damage.

In regional terms, it is possible that reefs along as much as 1000 km in the Andaman and Nicobar Islands were also damaged by uplift (Brown, 2005, pers. comm.). Consequently the cumulative mortality of reef flat corals in the region may be quite high.

It is critical that monitoring is continued to determine the long-term effects of the earthquakes and tsunami. Recovery of fast-growing branching coral species will occur quickly, however, corals with massive growth forms grow more slowly and so full recovery of these species may take decades. Based on previous cases of recovery following e.g. the 1997/8 global bleaching event, partial recovery of Aceh reefs should occur within 3 -5 years. The major threats to rapid recovery are overfishing, destructive fishing and sedimentation.

Conclusions

The rapid underwater assessment of the 2004 tsunami and 2004-5 earthquake impacts along the west coast of Aceh Province indicated that relatively minor damage occurred to the coral reef systems, with over half the reefs surveyed showing no related damage. The level of Recently Killed Coral was low. The most significant damage observed was overturned coral heads caused by tsunami waves, and smashed beds of blue coral and hectares of uplifted reef caused by the earthquakes. Turbidity and sedimentation due to increased erosion following the earthquakes and tsunami were high and could present a long-term threat to Aceh reefs.

More alarming than the extent earthquake and tsunami damage was the evidence of anthropogenic stress on Aceh's coral reefs. Overfishing and destructive fishing practices are destabilizing these reef ecosystems. When these stresses are combined with increased sedimentation, the reef systems are more susceptible to shifting to an algal dominated, low diversity system. It is essential to establish a routine, long-term monitoring program to guide management decisions and to involve the local community in actively protecting their valuable reef resources (Hodgson 2001). Millions of people depend on these reefs for their sustenance and the continued degradation of Aceh's coral reef ecosystem will have a long term negative impact on human welfare and quality of life. Relatively modest funding and human resources are needed to implement resource monitoring and management that could reduce anthropogenic stress and reverse the methodical degradation of Aceh's invaluable coral reef ecosystem.

It is unfortunate that one of the greatest tragedies in recorded history was the catalyst for increased attention to the reefs of Aceh. The events of 26 December 2004 have left the Acehenese more dependent than ever on their marine resources for survival. True concern for the tsunami survivors will be demonstrated by implementing a strategy that considers the long-term needs of the people. Rapid and effective conservation efforts are needed to ensure the survival of Aceh's reefs and people.

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Appendix I. Substrate Cover

Region	Site	Recently Killed Coral	Rock	Live Coral	Rubble	Soft Coral	Algae	Other	Sand	Sponge
Banyak	Pulau Karang	0	36.9	43.1	10	2.5	0	0	6.9	0.6
Banyak	Pulau Karang	0	31	27.5	14	1	0	12.5	14	0
Banyak	Pulau Karang 1	0.6	32.5	52.5	3.8	0	0		8.1	2.5
Banyak	Pulau Karang 1	0	15.6	61.9	19.4	1.3	0	0	1.9	0
Banyak	Pulau Bangkaru 2	0	41.9	52.5	1.9	0	0	0	1.9	1.9
Banyak	Pulau Bangkaru 2	0	7.5	39.4	50	2.5	0	0.6	0	0
Banyak	Pulau Baleh	0.6	23.1	40	23.8	0	0	0	12.5	0
Banyak	Pulau Baleh	1.3	17.5	31.9	11.3	0	0	0.6	37.5	0
Banyak	Pulau Bagu	0	53.8	13.1	12.5	0	1.9	1.3	17.5	0
Banyak	Pulau Bagu	0.6	26.9	26.9	26.3	0.6	0	0	17.5	1.3
N. Islands	Nasi Besar	0	29.4	5.6	12.5	0	1.3	0.6	50.6	0
N. Islands	Pulau Buro	0.8	52.3	22.7	22.7	0	0	0	1.5	0
N. Islands	Pulau Buro	0	72.5	20.6	2.5	0	0.6	1.3	2.5	0
N. Islands	Pulau Weh	0.6	21.9	37.5	36.3	0	1.9	1.3	0.6	0
N. Islands	Pulau Rondo	0	42.5	36.3	18.1	0	2.5	0.6	0	0
N. Islands	Pulau Rondo	0	18.1	38.1	41.3	0.6	0	0	1.9	0
N. Islands	Pulau Rondo	0	50.6	17.5	30	0	1.3	0	0.6	0
N. Islands	Pulau Rondo	0	8.8	17.5	70	0	0	1.3	2.5	0
Aceh Mainland	Ug Batukapal	0.6	24.4	33.1	0	14.4	0	0	27.5	0
Aceh Mainland	headland	0	50.6	6.3	1.9	26.9	0	0	14.4	0
Aceh Mainland	Coastline	11.3	33.1	27.5	13.1	10	0	0	5	0
Aceh Mainland	Coastline	2.5	31.3	20.6	21.3	3.1	0	0	21.3	0
Aceh Mainland	Coastline	0.6	37.5	35	18.1	1.3	0	0.6	6.9	0
Sibolga	Air Terjun Mursala	0	8.75	11.25	5	0.625	0	0	74.375	0
Sibolga	Air Terjun Mursala	0	11.25	45	19.375	20.625	0	0	2.5	1.25
Sibolga	Labuhan Kapal Mursala	0	0	12.5	71.875	5	0	0	10.625	0
Sibolga	Labuhan Kapal Mursala	0	2.5	20	68.125	2.5	0	0	6.875	0
Sibolga	Karang Kasih	0	25	8.75	36.875	0	0	1.875	27.5	0
Sibolga	Karang Kasih	0	0	20.7	67.5	0	0	0	11.3	0
Nias Island	Pelabuhan Lahewa	0.0	3.8	29.4	58.1	5.6	0.0	0	3.1	0.0
Nias Island	Pelabuhan Lahewa	2.5	23.1	8.8	40.6	7.5	0.0	0	17.5	0.0
Nias Island	Karang Umang	5.0	12.5	17.5	44.4	18.1	0.0	0	2.5	0.0
Nias Island	Karang Umang	0.0	8.1	19.4	64.4	3.8	0.0	0	4.4	0.0
Nias Island	Musium Gunungsitoli	0.0	18.8	61.9	0.0	18.8	0.0	0	0.6	0.0
Nias Island	Musium Gunungsitoli	3.8	13.8	5.0	8.8	1.3	0.0	0	67.5	0.0
Nias Island	Lafandra	0.0	22.5	6.9	50.0	1.3	0.0	2	17.5	0.0
Nias Island	Lafandra	0.0	4.4	0.6	0.0	0.0	0.0	0	95.0	0.0
Nias Island	Pulau Langu	0.0	10.0	11.9	65.0	2.5	0.0	0	10.6	0.0
Simeulue	Linggan	5.6	24.4	41.3	3.8	3.8	7.5	5.6	1.3	0.6

Appendix II. Fish Data

Sibolga

Fish	*Air Terjun*		*Labuhan Kapal*		*Karang Kasih*		***Total***	***Average***
Site	*shallow*	*deep*	*shallow*	*deep*	*shallow*	*deep*		
Butterflyfish	3	6	17	9	7	7	49	8.17
Haemulidae	1	3	0	4	0	0	8	1.33
Snapper	0	0	0	11	0	5	16	2.67
Barramundi cod	0	0	0	0	0	0	0	0.00
Grouper*	2	13	4	7	5	2	33	5.50
Humphead wrasse	0	0	0	0	0	0	0	0.00
Bumphead parrot	0	0	0	0	0	0	0	0.00
Parrotfish	0	5	0	0	0	0	5	0.83
Moray eel	0	0	0	0	0	0	0	0.00

Nias

Fish	*Pelabuhan Lahewa*		*Karang Umang*		*Musium Gunungsitoli*		*Lafandra*		*Pulau Langu*		***Total***	***Average***
Site	*shallow*	*deep*	*shallow*	*deep*	*shallow*	*deep*	*shallow*	*deep*	*shallow*	*deep*		
Butterflyfish	23	25	7	6	17	15	13	0		17	123	13.67
Haemulidae	0	24	0	9	5	3	12	2		13	68	7.56
Snapper	6	6	0	0	1	0	8	0		7	28	3.11
Barramundi cod	5	0	0	0	0	0	1	0		2	8	0.89
Grouper*	10	0	3	2	0	0	2	0		9	26	2.89
Humphead wrasse	12	0	0	0	2	0	0	0		0	14	1.56
Bumphead parrot	3	0	0	2	0	0	0	0		0	5	0.56
Parrotfish	0	0	0	0	0	0	0	0		0	0	0.00
Moray eel	1	0	0	0	0	0	0	0		0	1	0.11

Banyak

Fish	*Pulau Karang*		*bangkaru AM*		*bangkaru PM*		*Pulau Bale AM*		*Pulau Bagu*		***Total***	***Average***
Site	*shallow*	*deep*	*shallow*	*deep*	*shallow*	*deep*	*shallow*	*deep*	*shallow*	*deep*		
Acanthuridae	0	2	220	106	113	69	7	83	31	126	757	75.7
Barramundi cod	0	0	0	0	0	0	3	0	0	0	3	0.3
Carangidae	0	0	0	0	0	0	1	0	0	0	1	0.1
Chaetodontidae	21	18	57	46	29	14	18	19	11	21	254	25.4
Epinephelus/ Plectropomus	0	1	14	5	13	1	7	6	6	1	54	5.4
Haemulidae	0	0	8	2	0	0	1	1	0	0	12	1.2
Humphead wrasse	0	0	0	0	0	0	0	0	9	0	9	0.9
Other Labridae	21	31	59	89	88	67	5	38	3	44	445	44.5
Lethrinidae	0	2	1	0	0	0	4	0	9	0	16	1.6
Lutjanidae	15	13	12	3	11	2	6	3	2	2	69	6.9
Mullidae	2	0	0	2	16	1	0	0	0	2	23	2.3
Muraenidae	0	0	0	0	0	0	0	0	0	1	1	0.1
Bumphead parrotfish	0	0	0	0	0	0	0	0	0	0	0	0
Other Scaridae	21	7	21	25	3	13	5	51	5	80	231	23.1
Siganidae	0	7	0	0	15	0	7	0	0	0	29	2.9
Rare animals	0	0	0	0	0	0	0	0	0	0	0	0

Northern Islands

Fish	*Pulau Buro*	*Pulau Rondo AM*	*Pulau Rondo AM*	*Pulau Rondo PM*	*Pulau Rondo PM*	***Total***	***Average***
Site	*deep*	*shallow*	*deep*	*shallow*	*deep*		
Acanthuridae	1020	66	38	89	8	1221	244.2
Barramundi cod	0	0	0	0	0	0	0
Carangidae	0	0	50	0	20	70	14
Chaetodontidae	20	14	23	23	3	83	16.6
Epinephelus/ Plectropomus	33	1	17	0	6	57	11.4
Haemulidae	8	0	3	1	7	19	3.8
Humphead wrasse	0	0	0	0	0	0	0
Other Labridae	62	36	3	14	0	115	23
Lethrinidae	0	0	0	0	1	1	0.2
Lutjanidae	519	0	15	0	3	537	107.4
Mullidae	0	15	2	3	0	20	4
Muraenidae	0	0	2	0	0	2	0.4
Bumphead parrotfish	0	0	0	0	0	0	0
Other Scaridae	3	36	15	30	9	93	18.6
Siganidae	0	0	47	0	22	69	13.8
Rare animals	0	1	0	2	0	3	0.6

Mainland Aceh

Fish	*Ug Batukapal*	*headland*	*survey 4*	*survey 3*	*survey 5*	***Total***	***Average***
Site	*shallow*	*shallow*	*shallow*	*shallow*	*shallow*		
Acanthuridae	146	14	67	27	25	279	55.8
Barramundi cod	0	0	0	0	3	3	0.6
Carangidae	0	0	0	0	30	30	6
Chaetodontidae	60	5	29	17	20	131	26.2
Epinephelus/ Plectropomus	4	3	12	1	3	23	4.6
Haemulidae	7	1	8	8	2	26	5.2
Humphead wrasse	0	0	0	0	0	0	0
Other Labridae	58	0	93	5	8	164	32.8
Lethrinidae	4	0	79	4	6	93	18.6
Lutjanidae	18	0	19	11	19	67	13.4
Mullidae	4	0	125	0	1	130	26
Muraenidae	0	0	0	0	0	0	0
Bumphead parrotfish	0	0	0	0	0	0	0
Other Scaridae	40	0	46	0	0	86	17.2
Siganidae	34	0	44	19	5	102	20.4
Rare animals	2	0	4	0	0	6	1.2