Coral reef damage and recovery related to a massive earthquake (March 2005) in Nias Island, Indonesia

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Abstract. Threats to coral reefs are not only coming from anthropogenic factors, but also from natural disasters, such as earthquakes, tsunamis, cyclones, and volcanic eruptions. We carried out a comprehensive study from 2004 until 2010 on changes in the coral reef in North Nias (eastern Indian Ocean) off North Sumatra, which was impacted in March 2005 by a massive earthquake of 8.6 Mw, with eight aftershocks, measuring between 5.5 and 6.0 Mw, only a few months after the larger earthquake 9,1 Mw of December 2004. This resulted in a 1.65-m uplift of the coral reef and temporal changes in live coral cover and coral species composition. Our studies showed the development of recovery conditions after the shock with time-series data and illustrated the essential factors that affected the recovery of the coral reef structure. We used line intercept transect (LIT), underwater visual census (UVC), and quadrat transect methods to observe the dynamic changing of coral reef structure, coral reef fishes biomass, and coral recruitment. Across six stations surveyed, we found 48.5% live coral cover in the pre-earthquake condition (2004). The coral cover plummeted significantly down to 28% three months after the shook . *Porites* was the dominant coral genus in 2004, but it was replaced with *Montipora* in 2010. Recovery took place in the form of coral recruitment. Fish abundance was highest before the earthquake, decreased three months after the earthquake, and was lowest in 2007, but in 2008 the reef fish composition had recovered. Our finding emphasizes the destructive impact of an earthquake on a coral reef structure and its species composition due to the physical damage and the seabed uplift. We also found that the time to recover for coral reef and coral reef fishes was four years after the earthquake.
Key Words: coral cover, coral life form, massive, natural disturbance, recovery.

Introduction. The moment magnitude (Mw) of the earthquake in the Sumatra Subduction Zone (SSZ) off the west coast of Sumatra was unusually high (Briggs et al 2006). On March 28, 2005, at 11:09 p.m. local time (16:09 UTC), the earthquake (Mw) 8.6 was generated by a rupture of a 400 km section of the Sunda megathrust offshore Sumatra at a depth of 30 km, shaking Nias and the Simeulue islands (Boen 2006; Qiu et al 2019). The epicenter of the earthquake was on the Great Sumatra fault and located at approximately 2.074° N, 97.013° E (USGS) (Boen 2006; Borrero et al 2011) and 115 km from Gunung Sitoli, the capital district of Nias. The large earthquake resulted in deformation and uplifting of the coral reefs along the west coast of Sumatra, which were also hit by a large tsunami. The Sumatran GPS Array (SuGAr) recorded a high moment magnitude in a portion of the megathrust, which continued slipping and generating the surface deformation three months afterwards (Qiu et al 2019). Based on the study of Briggs et al (2006) the uplift after the event was as high as 1.65 m on the south-eastern part of the island, and the last effect from the earthquake has considered relative to land level changes that happened as the tsunami was generated and immediately before its arrival on land (Borrero et al 2011).

The earthquake had a tremendous impact on the flora and fauna of Nias Island, especially in the coral reef community along the west coast of Nias Island (Borrero et al 2011). The coral damage was clearly demonstrated by the formation of coral fractures and the upturned coral blocks. The damage to the coral has became worse due to the uplifting process, which caused reef areas to become exposed to the surface (Wilkinson et al 2006).

Severely damaged coral reefs need much time to regenerate and recover to their original state. The abundance of herbivorous fish to control algal growth also affects the recovery speed of the damaged coral reefs (Williams et al 2001). The presence of Crustose Coralline Algae (CCA) also supports the calcification process and provides a suitable substrate for attaching coral larvae (Roth et al 2018). Also, a complex habitat structure with high abundance and diversity will increase the duration of the recovery process of coral reefs more than homogeneous habitat conditions (Bracewell et al 2018).

A change of coral reefs has occurred since the beginning of the Nias earthquake in 2005, which lasted until the following years. The structure of coral reef communities, primarily the stony coral, is essential in determining the health of coral reefs (English et al 1998; Giyanto 2013). The ability to endure pressure to recover (resilience) is an indicator that confirms that the coral reef condition is healthy (Hoegh-Guldberg et al 2007; Hoegh-Guldberg 2011). Additionally, the ecological services such as economic important reef fishes provided by healthy coral reefs meanwhile needs to be well maintained (Halford et al 2004; Acosta-González et al 2013).

The catastrophe impact of coral reefs is varied according to the location and intensity of the earthquake (Wilkinson et al 2006). The earthquake in Nias in March 2005 showed a different impact from the shock in December 2004, which resulted in the lifting of the seabed included coral reef with an altitude of about 1.7 up to 2.7 meters in 2005 (Suyarso 2008). Studies of changes in coral communities were carried out at several locations in Indonesia and other countries (Baird et al 2005; Wilkinson et al 2006), but the changes in hard coral communities over a long period of time that result from uplifting are not clear, except that reef flats that become permanently exposed will become dead.

A comprehensive survey, consisting of observations of the coral reef ecosystem in time series before the earthquake (2004), 2005, and after the quake until 2010 provide a better understanding of the coral reef ecosystem's recovery process. The purpose of this study is to find out temporal changes in live coral cover, coral species composition, and potential recovery of coral. The understanding of the dynamics in coral reefs caused by natural disasters and knowing the essential factors that affect their recovery will contribute to the sustainable management and conservation of the area (Godfray & May 2014).

Material and Method

Description of the study sites. For this research, six coral reef sites across the Nias Islands were studied during before and after the earthquake (Table 1). Based on the geography, the island is facing the eastern Indian Ocean and is characterised by big waves and strong currents (Kurnio 2007). Nias Island was formed by the uplifting during tectonic processes and is located near the collision line between the Indo-Australian Plate and the Eurasian plate (Risqi et al 2020). We installed permanent transects at each observation site. We put three of 10 m line permanent transect in each sites at various depth between 5-7 m (Figure 1).

Table 1

The position of study sites

Sites	*Location*	*Longitude*	*Latitude*
NIAL01	Sifahandro, Sub District of Sawo	97^o10’14.18” E	1^o25’21.35” N
NIAL02	Sisarahili Teluk Siabang, Sub District of Sawo	97^o24’23.34” E	1^o30’40.33” N
NIAL03	Teluk Bengkuang, Sub District of Sawo	97^o25’30.67” E	1^o30’53.80” N
NIAL04	Panjang Island, Sub District of Lahewa	97^o14’33.90” E	1^o27’33.34” N
NIAL05	Lafau Island, Sub District of Lahewa	97^o12’47.09” E	1^o25‘23.22” N
NIAL06	Pasar Lahewa, Sub District of Lahewa	97^o10’41.25” E	1^o24’39.20” N

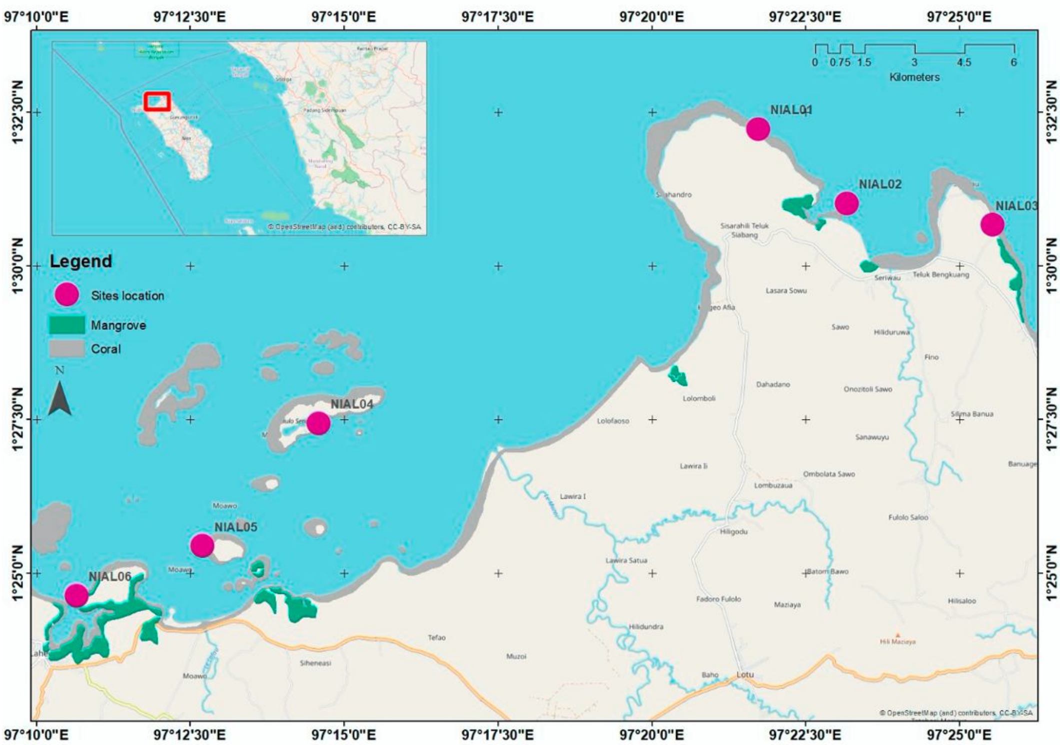

Figure 1. The location of study area of coral and reef fishes monitoring at Nias Island.

The benthic communities structure. The benthic community was evaluated by using the line intercept transect (LIT) method based on the standard of Coral Reef Health Monitoring (RHM) protocol in Indonesia (Giyanto 2013). The LIT is recommended by the Global Monitoring Reef Network for coral surveys (Uychiaoco et al 2010; Lu et al 2020) and has been widely applied in coral reef assessments, especially in the Coral Triangle region (Jordan & Samways 2001). The LIT was carried out using SCUBA dives to estimate the percentage of benthic community structure coverage (live coral, fleshy seaweed, dead coral, dead coral algae, rubbles, soft coral, sand, silt, and sponge) (Manikandan et al 2016). The transect of the LIT was modified from English et al (1998) and laid out parallel to the coastline at each study site (Bruno & Selig 2007; Facon et al 2016; Sabdono et al 2019) with a tape measure on the reef along 100-m transects which divided into three segments of 10 m in 0-10 m, 30-40 m and 60-70 m. The transect was placed along the slope and follows the depth contour from 5 to 10 m of water depth. The survey was held on June (2004), July (2005), May (2007), August (2008), June (2009) and June (2010). For a more comprehensive analysis, we took pictures of the benthic structures attached to the live corals. Identifications up to the genus level were based on the works by Hoeksema (1989), Veron & Stafford-Smith (2000), and Wallace et al (2012).

Data analysis. We devided the data into pre-earthquake (2004), few months after the shook in 2005, and post-earthquake (2007-2010). Then, data of the percent cover of benthic communities were collected, tabulated, and calculated using MS. Excel (Edinger et al 1998; English et al 1998; Giyanto 2013). The percentage of benthic community was calculated by converting the LIT data by the number of points recorded to the percentage for each benthic category. Where percent cover of each category = (number of points in that category ÷ total number of points on the transect) x 100 (Wilson & Green 2009). The percentage of benthic categories for pre, three months afterwards and post-earthquake was analyzed using "ggplot2" packages (Wickham 2009) by R statistical software analysis. The condition of coral reef was determined by the percentage of hard coral (HC) cover and divided into four categories according to the Ministry of Environment and Forestry of Indonesia decree No. 4 the year 2001 regarding the criteria of coral reef damage, specifically HC $\leq$ 25% (poor); 25% $<$ HC $\leq$ 50% (fair); 50% $<$ HC $\leq$ 75% (good); HC $>$ 75% (excellent). Subsequently, to compare and to investigate the dynamics of two categories of benthic communities structure (hard coral and dead coral-algae) we use a non-parametric Kruskal-Wallis using "ggstatsplot" packages in R Software (Patil 2021). The non-parametric test was used since the normal distribution assumptions cannot be obtained by data transformation. The post hoc test using Pairwise Wilcoxon shows significant changes in coral reef conditions with a significant difference, p-value < 0.05 (Booth & Beretta 2002). Analysis of changes in benthic community structures for the conditions before the earthquake, sometime after the earthquake and after the earthquake is using non-parametric Kruskall-Wallis followed by Pairwise Wilcoxon analysis using the "ggstatsplot" package from R Statistical Software with p-value < 0.05 (Patil 2021). The Corresponding Analysis (CA) performed on the percentage cover benthic communities' structure and reef fishes categories using" factoextra" packages was implemented in the R Statistical software analysis. The benthic community and reef fishes categories data were log-transformed for normality to facilitate interpretation of the coefficient for CA analysis.

Results. The results showed a change in the percentage of benthic substrate communities (Table 2). Among ten categories of benthic coverage, two are dominant i.e. live coral and dead coral with algae (Table 2). There is a significant change in live coral cover and dead coral algae over the years. Before the earthquake (2004), the percentage of live coral cover was in the fair category (48.45±3.62) (Table 2). The earthquake caused significant devastation to coral ecosystems. Live coral cover experienced an extreme drop in 2005 with more than 50% (20.45±3.64) (poor category), and to 17.20±4.30 in 2007. Coral recovery occurred in the third year after the earthquake (2008: 19.82±5.75) and rose to 29.83±7.01 in 2009 and 32.04±6.59 in 2010, respectively (Table 2). On the other hand, the percentage of dead coral algae increased three months after the disruption. Dead coral algae (DCA) also show a fluctuating trend from year to year, in contrast with live coral cover. The most significant increase in DCA coverage occurred in 2009 (53.68±8.76) and shows a significant decline in 2010 (22.48±6.30) (Table 2).

Table 2

The mean percentage of benthic category year of 2004, 2005, 2007, 2008, 2009 and 2010

Benthic categories	*Percentage of mean benthic communities structure (%) ± SE*					
	2004	*2005*	*2007*	*2008*	*2009*	*2010*
Live coral	48.45±3.62	20.45±3.64	17.20±4.30	19.82±5.75	29.83±7.01	32.04±6.59
Fleshy seaweed	0.52±0.19	0.99±0.91	0.76±0.68	4.22±3.90	1.71±1.12	4.79±3.01
Dead coral	0.03±0.03	0.00±0.00	0.00±0.00	0.08±0.08	0.00±0.00	0.52±0.42
Dead coral alga	34.53±4.59	50.56±2.80	50.23±5.15	49.45±6.08	53.68±8.76	22.48±6.30
Others	0.97±0.46	1.41±0.90	0.53±0.24	0.15±0.08	0.64±0.25	0.40±0.12
Rubble	1.73±0.69	15.57±4.70	15.55±6.20	17.10±5.50	1.12±0.73	26.68±13.19
Sand	5.99±3.52	8.77±3.84	10.32±6.32	8.08±3.81	8.56±4.48	9.32±5.35
Soft coral	0.76±0.54	0.00±0.00	0.17±0.13	0.21±0.15	0.17±0.11	0.12±0.07
Silt	0.96±0.61	0.40±0.40	2.65±1.30	0.00±0.00	3.15±3.10	0.00±0.00
Sponge	4.59±1.35	1.86±0.91	2.59±1.18	0.87±0.34	1.15±0.59	3.66±0.94

The changing of hard coral and dead coral alga. Based on our analysis, the hard coral (HC) and dead coral algae (DCA) were two dominant benthic categories with higher percentage than the others. The changing percentage of HC and DCA could be used to explain the conditions of coral reef ecosystems in the earthquake event. The analysis percentage of HC cover revealed a significant difference between the data before earthquake, sometimes after the shook and afterwards (Kruskal-Wallis, p = 0.0088) (Figure 2a). Three months after the disturbance, the HC cover in Nias Island decreased more than expected with the internal Pairwise Wilcoxon test showing significant differences compared to the pre-earthquake condition of 2004 and sometimes after the earthquake in 2005) (Pairwise Wilcoxon test, p-value = 0.022). Two years post-earthquake disturbance (2007), the HC was still hard to recover, and the percentage of coral cover was decreased but did not vary significantly (Pairwise Wilcoxon test, p-value = 0.48). After three years of major earthquake disturbance in 2008, the percentage of HC cover started to recover and increased but not significantly (Pairwise Wilcoxon Test, p-value = 0.82). The recovery of hard coral cover to its original state occurred in 2010 (Wilcoxon Paired Test, p-value = 0.173) (Figure 2a; Table 3). During the great earthquake in Nias in 2005, the percentage of DCA cover was increased and remained flat until 2007 (Pairwise Wilcoxon test, p-value = 0.94) (Figure 2b). The decline in the percentage of DCA started from 2009 (Pairwise Wilcoxon test, p-value = 0.026) (Figure 2b).

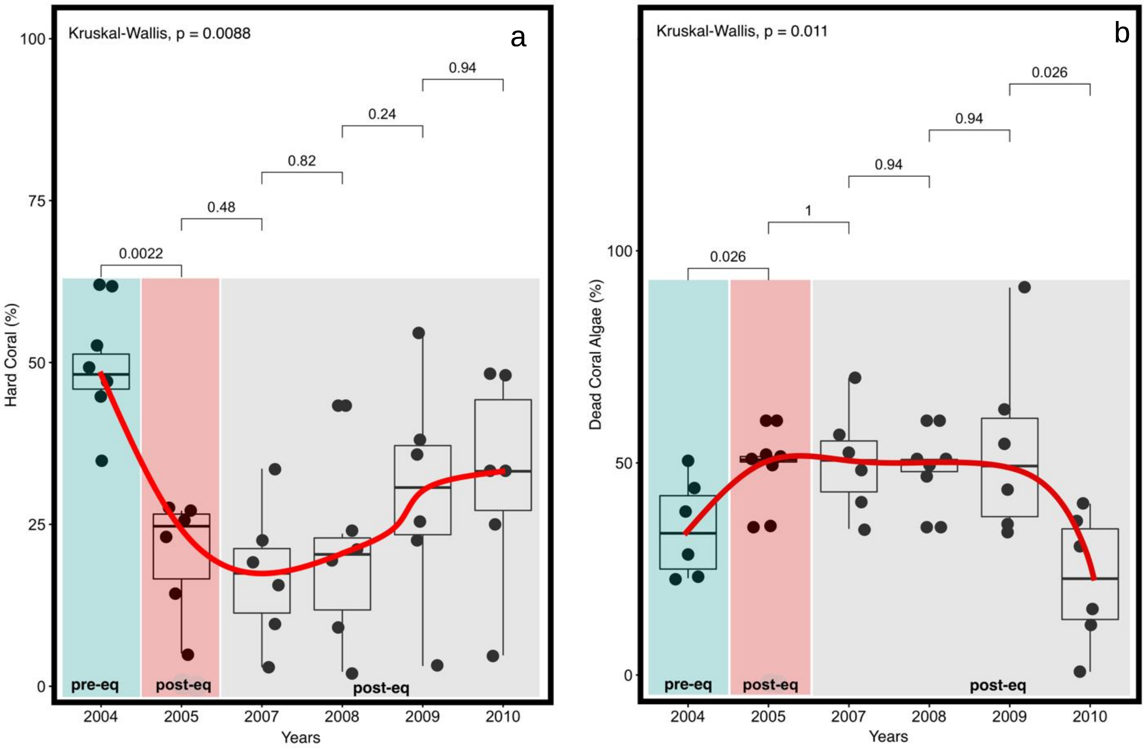

Figure 2. The Kruskal Wallis with internal Pairwise Wilcoxon test from hard coral cover and dead coral algae cover before and several years after the earthquake to recovery process a in northern Nias Island. The pink color showed earthquake condition (2005) and the grey color presented the post-earthquake condition (2007-2010).

Table 3

The Pairwise Wilcoxon test of significant difference from two benthic communities (hard coral and dead coral alga)

Years		*Hard coral*		*Dead coral with algae*	
		p	*ns < 0.005*	*p*	*ns < 0.005*
2004	2005	0.002	*	0.07	ns
2004	2007	0.002	*	0.09	ns
2004	2008	0.004	ns	0.18	ns
2004	2009	0.093	ns	0.93	ns
2004	2010	0.065	ns	0.24	ns
2005	2007	0.485	ns	0.94	ns
2005	2008	0.589	ns	1	ns
2005	2009	0.485	ns	1	ns
2005	2010	0.173	ns	0	ns
2007	2008	0.818	ns	0.94	ns
2007	2009	0.093	ns	0.94	ns
2007	2010	0,128	ns	0.02	ns
2008	2009	0.24	ns	1	ns
2008	2010	0.128	ns	0.02	ns
2009	2010	0.936	ns	0.03	ns

Note: * - significance; ns - no significance.

The comparison between percentage of DCA cover shown different trend conditions with HC cover trend but not statistically significant (Kruskal-Wallis, p = 0.023). The changing percentage of DCA cover demonstrated different trends from pre-earthquake condition (2004) to post-earthquake recovery in 2010 with the trend increased during pre-earthquake (2004) to earthquake condition (2005) (Pairwise Wilcoxon test, p-value = 0.065). After three years studies, the percentage of DCA cover still decreased but not significantly (Pairwise Wilcoxon test, p-value = 0.094) and the lowest of percentage DCA cover show in 2010 (Pairwise Wilcoxon test, p-value = 0.094) (Table 3).

The temporal variation in mean percentage of major coral life form. Changes in coral cover based on the coral life-form occur during the observation time. The hydrocorals *Millepora* spp. disappeared as a result of the earthquake. Foliose corals, encrusting corals, branching corals, and the blue octocoral *Heliopora* were the most affected with drops of up to 97%, 91%, 73%, and 64% respectively. On the other hand, submassive corals showed an increase in cover three months after the earthquake. In 2004, the most dominant coral life form was branching coral followed by *Heliopora* and massive corals (Figure 3). In 2005, the coral species composition changed. Massive corals became the most dominant surviving coral group. A growing number of submassive corals were present sometimes after the earthquake and reached their peak in 2010 (Figure 3). In 2009, four years after the earthquake, each coral group showed recovery. *Acropora* corals, foliose corals, encrusting corals, and branching corals were showing recovery of over 50%. The year of 2010 is showing a similar abundance between massive corals, branching corals, and *Heliopora*. Corals of the genus *Millepora* were observed to start recovery in 2010, with a percentage of 0.06%.

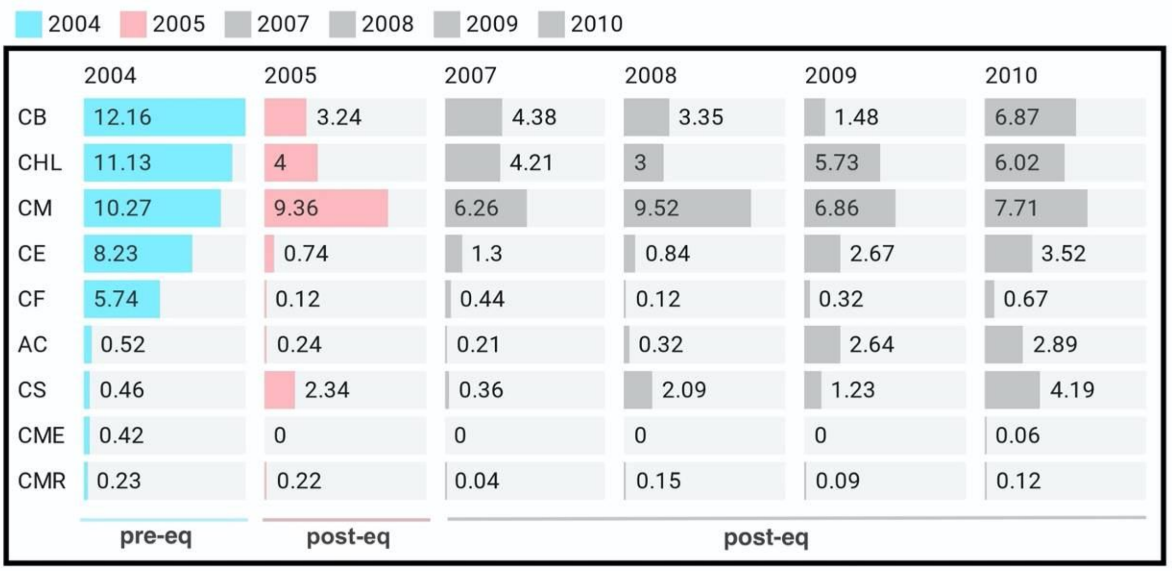

Figure 3. Temporal variation in mean percentage of live coral cover of major coral life forms (CB = branching coral; CHL = heliopore coral; CM = massive coral; CE = encrusting coral; CF = foliose coral; AC = *Acropora*; CS = submassive coral; CME = *Millepora*; CMR = mushroom coral) at the study sites in 2004, 2005, 2007, 2008, 2009, and 2010.

The composition of coral genera pattern. Benthic structure data during various conditions lead us to recognize the differences in the composition of coral genera patterns. Before the earthquake in 2004, corals of the genera *Porites, Montipora*, and *Heliopora* dominated the coastal ecosystem of North Nias (Figures 4a, 4b, and 4c). A year after the earthquake in 2005, *Porites* and *Heliopora* seemed to have survived and started to dominate even though their presence had decreased due to the earthquake (Figures 4a and 4b). A different result was shown by *Montipora* corals, which were severely damaged by the earthquake (Figure 4c). In 2010, *Montipora* and *Heliopora* corals returned to become dominant (Figures 4b and 4c) together with *Acropora* (Figure 4d), which became less common during the previous years.

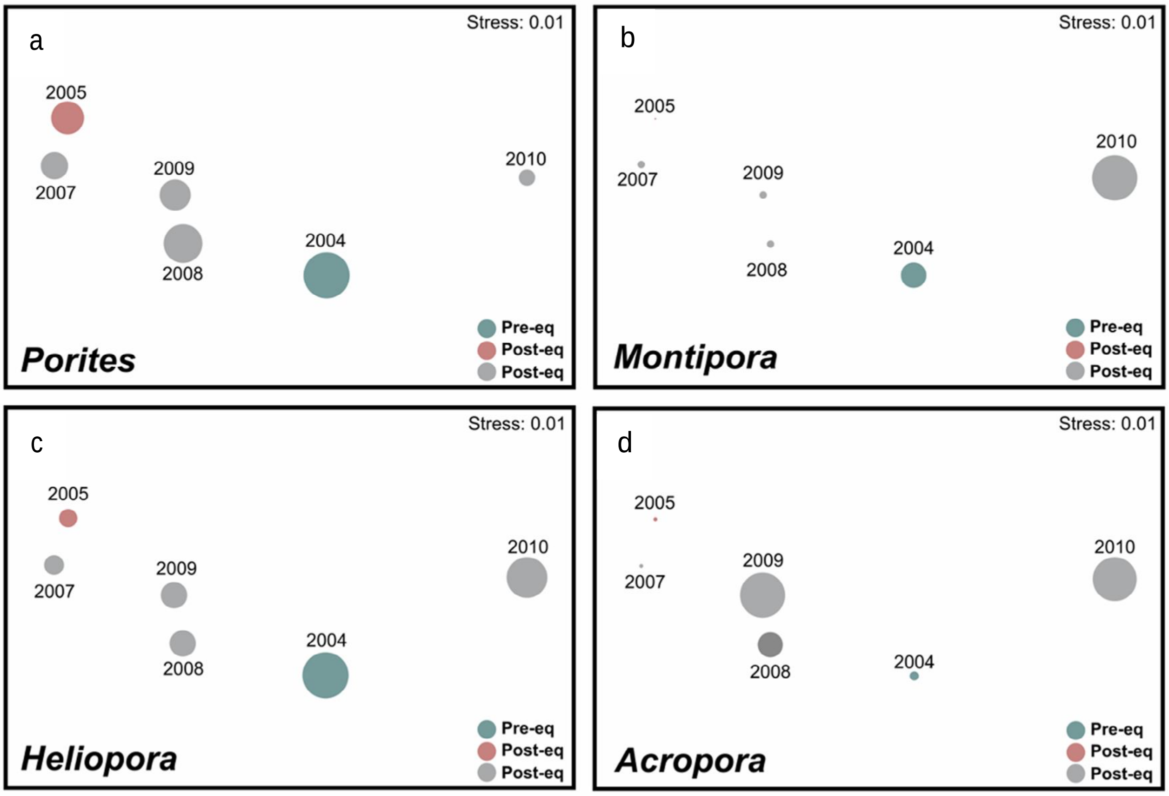

Figure 4. The presence of coral genera changing before and after earthquake disturbance. Size of dots show the number of genera per years.

Discussion. The Nias large earthquake geological disaster in 2005 produced the movement of the lithosphere followed by attributable seafloor uplift (Orcutt 2013) about 1 up to 2 m (Baird et al 2005). The uplift condition caused localized coral mortality and continues to threaten some reefs. Several islands such as Simeulue and Nias were tilted, with one end rising as much as 2 m while the other end descended a similar amount (Chavanich et al 2005; Foster et al 2006; Wilkinson et al 2006). Recent studies from Suppasri et al (2015) recorded that the tsunami run-up height during a large earthquake in Nias was approximately 4 m or less in areas near the epicenter. Although several species of coral get more damage from large earthquake disturbance in Nias Island, and Baird et al (2005) recorded that not even a single live colony from *Acropora* was found at this site in April 2005.

Observations showed that the coral coverage from 48.5% in 2004 dropped to 20.5% in 2005 while the rubble coverage rose to 16.1% (Manuputty et al 2007). This illustrates that branching coral was the most affected by the earthquake. The changes in benthic communities in Nias Island from 2004 to 2005 were indicated by live coral and rubble categories. All of the coral growth including branching corals, *Celiopora*, massive corals, encrusting corals, foliose corals, and *Acropora* showed a decline (Cappenberg 2010). The structure of the coral reef community before the earthquake showed that it was dominated by branching coral followed by coral *Heliopora*, massive coral, encrusting coral, foliose coral, and *Acropora* groups. When the earthquake occurred, it brought damage to the coral and changed the composition of the coral reef structure. Massive coral is known to be more resistant to physical disturbance (Hopley 2011; Pisapia et al 2016). The massive coral often found in the northern Nias waters is the species of *Porites lutea* (Siringoringo et al 2019).

The dominant coral species before the earthquake were *Porites cylindrica*, *Porites lutea*, *Montipora* sp., and *Heliopora coerulea*. *P. cylindrica* is a branching coral that usually grows in large colonies (Seebauer 2001; Hopley 2011). Furthermore, coral *Heliopora* also has a very wide distribution, especially on the west coast of Sumatra, including in North Nias Island (Siringoringo et al 2019). *Montipora* frequently dominated in coral reef areas (Crane et al 2016; Luthfi & Wibisono 2017). After the earthquake in 2005, the composition of coral species experienced significant changes (Chavanich et al 2005; Wilkinson et al 2006; Stoddart 2007; Guo et al 2017). *P. cylindrica* coverage decreased while *P. lutea* coverage has not changed much. Drastic changes were seen in *Montipora* and *P. cylindrica* coverage. The species of coral with branching life-form known as resistance species to environmental disturbance (West & Salm 2003; Grimsditch & Salm 2006; Hopley 2011). Furthermore, coral *Pocillopora* disappeared as well as *Seriatopora*, *Galaxea*, and *Pectinia*. These corals might be flung and covered by sediment (Wilkinson et al 2006; Zhao et al 2016) but in 2010 these species reappeared.

The composition of coral species in 2007 was similar to that in 2005. Massive *Porites* were still dominant, followed by *H. coerulea*. In 2008, the coral fauna composition started to recover. Species that were missing in 2005 began to reappear. Recovery is increasingly visible in 2009 through increasing coral coverage. Fast-growing coral groups including *Acropora*, *Pocillopora*, and *Montipora* presented rapid growth even though they are known vulnerable to environmental pressure (West & Salm 2003; Grimsditch & Salm 2006). Earthquakes can change the corals species composition (Wilkinson et al 2006; Campbell et al 2007; Stoddart 2007). Based on the temporal observations, corals showed the ability to recover. However, the recovery process is very dependent on environmental conditions, and anthropogenic factors (Baker & Weber 1975; Buddemeier & Kinzie 1976; Buddemeier et al 2004; Osinga et al 2011; Hoegh-Guldberg 2011; Mansour et al 2017). A massive shock brings modifications in the structure and composition of coral communities, including the predominant species before and after the earthquake. After four years after the earthquake in North Nias the group from *Porites* was replaced by the *Montipora* group. It is because branched *Porites* corals are physically damaged by the shock and loss of habitat in shallow waters and experienced the uplifting during the earthquake. *Montipora* corals with encrusting and laminar growth forms were also severely affected during the earthquake but recovered quickly due to the fast colony growth and recruitment throughout the year. *Montipora*, *Acropora* and *Pocillopora* corals are among the pioneer coral groups on open substrates with brooding reproduction types with year-round recruitment (Hopley 2011; Adjeroud et al 2018). The massive *Porites* group has the lower impact from the great earthquake in Nias and still exists after five years of the earthquake. The species of *Acropora* and *Montipora* had the highest number after the earthquake in 2004. Species *H. coerulea* begun to recover year by year after 2005. The branching corals of the *Porites* genus experienced a decline after the earthquake in Nias, but massive corals of the *Porites* genus were generally able to withstand from earthquakes. This decrease was due to the mortality of *P. cylindrica* species at NIAL03 site location. The location of NIAL03 is in Bengkoang Bay and close to the mainland and in this location there are many groups of macroalgae that are suspected to be the cause of coral death (Siringoringo et al 2017; Giyanto 2018). From the data obtained was known the highest fleshy seaweed cover was in 2010 of 4.79% (Table 2).

A recruitment analysis illustrates the potential for corals to recover in North Nias waters (Glassom & Chadwick 2006; Morri et al 2015; Jonker et al 2019). The distribution and the number of recruitment are closely related to the availability of stable substrates within locations (Roth et al 2018). Coral larvae need an ideal environmental condition and hard substrate to attach to (Hughes et al 1999; Price et al 2011; Martinez & Abelson 2013; Lubis et al 2018). Recruitment distribution patterns describe which locations will encounter a faster recovery. This can be seen from the high coral recruitment at NIAL05 which is reflected in the high live coral coverage.

Conclusions. The earthquake had caused alterations in coral cover and coral composition. Branching corals were severely affected by the shock, while massive corals, although experiencing decline, were more resilient and more dominant in the following years. In the fourth year, recovery obtained by the higher coverage of live coral cover, coral recruitment, and coral fish density, which are very dependent on the environment and the anthropogenic factors. The implementation of marine protected areas will accelerate coral recovery gradually. The monitoring of coral reefs also needs to be carried out regularly to see the development of the coral reef community in the future.

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Conflict of interest. The authors declare that there is no conflict of interest.

References

Acosta-González G., Rodríguez-Zaragoza F. A., Hernández-Landa R. C., Arias-González J. E., 2013 Additive diversity partitioning of fish in a Caribbean coral reef undergoing shift transition. PLoS ONE 8(6):e65665.
Adjeroud M., Kayal M., Iborra-Cantonnet C., Vercelloni J., Bosserelle P., Liao V., Chancerelle Y., Claudet J., Penin L., 2018 Recovery of coral assemblages despite acute and recurrent disturbances on a South Central Pacific reef. Scientific Reports 8:9680.
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.
Baker P. A., Weber J. O. N. N., 1975 Coral growth rate: variation with depth. Earth and Planetary Science Letters 27(1):57-61.
Boen T., 2006 Structural damage in the March 2005 Nias-Simeulue earthquake. Earthquake Spectra 22(S3):419-434.
Booth D. J., Beretta G. A., 2002 Changes in a fish assemblage after a coral bleaching event. Marine Ecology Progress Series 245:205-212.
Borrero J. C., McAdoo B., Jaffe B., Dengler L., Gelfenbaum G., Higman B., Hidayat R., Moore A., Kongko W., Lukijanto, Peters R., Prasetya G., Titov V., Yulianto E., 2011 Field survey of the March 28, 2005 Nias-Simeulue earthquake and Tsunami. Pure and Applied Geophysics 168(6-7):1075-1088.
Bracewell S. A., Clark G. F., Johnston E. L., 2018 Habitat complexity effects on diversity and abundance differ with latitude: an experimental study over 20 degrees. Ecology 99(9):1964-1974.
Briggs R. W., Sieh K., Meltzner A. J., Natawidjaja D., Galetzka J., Suwargadi B., Hsu Y. J., Simons M., Hananto N., Suprihanto I., Prayudi D., Avouac J. P., Prawirodirdjo L., Bock Y., 2006 Deformation and slip along the Sunda megathrust in the great 2005 Nias-Simeulue earthquake. Science 311(5769):1897-1901.
Bruno J. F., Selig E. R., 2007 Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. PLoS ONE 2(8):e711.
Buddemeier R. W., Kinzie R. A., 1976 Coral growth. Oceanography and Marine Biology: An Annual Review 14:183-225.
Buddemeier R., Kleypas J. A., Aronson R. B., 2004 Potential contributions of climate change to stresses on coral reef ecosystems. Coral Reefs and Global Climate Change, 44 pp.
Campbell S. J., Pratchett M. S., Anggoro A. W., Ardiwijaya R. L., Fadli N., Herdiana Y., Kartawijaya T., Mahyiddin D., Mukminin A., Pardede S. T., Rudi E., Siregar A. M., Baird A. H., 2007 Disturbance to coral reefs in Aceh, Northern Sumatra: impacts of the Sumatra-Andaman tsunami and pre-tsunami degradation. Atoll Research Bulletin 544:55-78.
Cappenberg H. A. W., 2010 Monitoring terumbu karang Nias (Lahewa Sawo). COREMAP II-LIPI, Jakarta, 47 pp. [in Indonesian]

Chavanich S., Siripong A., Sojisuporn P., Menasveta P., 2005 Impact of tsunami on the seafloor and corals in Thailand. Coral Reefs 24:535.

Crane N. L., Paddack M. J., Nelson P. A., Abelson A., Rulmal Jr. J., Bernardi G., 2016 Corallimorph and *Montipora* reefs in Ulithi Atoll, Micronesia: documenting unusual reefs. Journal of the Ocean Science Foundation 21:10-17.

Edinger E. N., Jompa J., Limmon G. V., Widjatmoko W., Risk M. J., 1998 Reef degradation and coral biodiversity in Indonesia: effects of land-based pollution, destructive fishing practices and changes over time. Marine Pollution Bulletin 36(8): 617-630.

English S., Wilkinson C., Baker V., 1998 Survey manual for tropical marine resources. 2nd edition. Australian Institute of Marine Science, 390 pp.

Facon M., Pinault M., Obura D., Pioch S., Pothin K., Bigot L., Garnier R., Quod J. P., 2016 A comparative study of the accuracy and effectiveness of line and point intercept transect methods for coral reef monitoring in the southwestern Indian Ocean islands. Ecological Indicators 60:1045-1055.

Foster R., Hagan A., Perera N., Gunawan C. A., Silaban I., Yaha Y., Manuputty Y., Hazam I., Hodgson G., 2006 Tsunami and earthquake damage to coral reefs of Aceh, Indonesia. Reef Check Foundation, IUCN, Living Oceans Foundation, 33 pp.

Giyanto, 2013 Metode transek foto bawah air untuk penilaian kondisi terumbu karang. Oseana 28:47-61. [in Indonesian]

Giyanto, 2018 Monitoring kesehatan terumbu karang dan ekosistem terkait di kabupaten Nias Utara tahun 2018. COREMAP-CTI, Pusat Penelitian Oseanografi - LIPI, Lembaga Ilmu Pengetahuan Indonesia, 97 pp. [in Indonesian]

Glassom D., Chadwick N. E., 2006 Recruitment, growth and mortality of juvenile corals at Eilat, northern Red Sea. Marine Ecology Progress Series 318:111-122.

Godfray H. C. J., May R. M., 2014 Open questions: are the dynamics of ecological communities predictable? BMC Biology 12:22.

Grimsditch G. D., Salm R. V., 2006 Coral reef resilience and resistance to bleaching. IUCN Resilience Science Group Working Paper Series No 1. The World Conservation Union (IUCN), Gland, Switzerland, 53 pp.

Guo H., Zhang H., Nadeau R. M., Peng Z., 2017 High-resolution deep tectonic tremor locations beneath the San Andreas Fault near Cholame, California, using the double-pair double-difference location method. Journal of Geophysical Research: Solid Earth 122(4):3062-3075.

Halford A., Cheal A. J., Ryan D., Williams D. M. B., 2004 Resilience to large-scale disturbance in coral and fish assemblages on the Great Barrier Reef. Ecology 85(7):1892-1905.

Hoegh-Guldberg O., 2011 The impact of climate change on coral reef ecosystems. In: Coral reefs: an ecosystem in transition. Dubinsky Z., Stambler N. (eds), Springer, pp. 391-403.

Hoegh-Guldberg O., Mumby P. J., Hooten A. J., Steneck R. S., Greenfield P., Gomez E., Harvell C. D., Sale P. F., Edwards A. J., Caldeira K., Knowlton N., Eakin C. M., Iglesias-Prieto R., Muthiga N., Bradbury R. H., Dubi A., Hatziolos M. E., 2007 Coral reefs under rapid climate change and ocean acidification. Science 318:1737-1742.

Hoeksema B. W., 1989 Taxonomy, phylogeny and biogeography of mushroom corals (Scleractinia: Fungiidae). Zoologische Verhandelingen 254(1):1-295.

Hopley D., 2011 Encyclopedia of modern coral reefs: structure, form and process. Springer, Dordrecht, 1205 pp.

Hughes T. P., Baird A. H., Dinsdale E. A., Moltschaniwskyj N. A., Pratchett M. S., Tanner J. E., Willis B. L., 1999 Patterns of recruitment and abundance of corals along the Great Barrier Reef. Nature 397:59-63.

Jonker M. J., Thompson A. A., Menéndez P., Osborne K., 2019 Cross-shelf variation among juvenile and adult coral assemblages on Australia's Great Barrier Reef. Diversity 11(6):85.

Jordan I. E., Samways M. J., 2001 Recent changes in coral assemblages of a South African coral reef, with recommendations for long-term monitoring. Biodiversity and Conservation 10:1027-1037.

Kurnio H., 2007 Coastal characteristics of iron sand deposits in Indonesia. Indonesian Mining Journal 10(3):27-38.
Lu Y., Ding Z., Li W., Chen X., Yu Y., Zhao X., Lian X., Wang Y., 2020 The effect of seawater environmental factors on the corals of Wailingding Island in the Pearl River estuary. Continental Shelf Research 197:104087.
Lubis M. Z., Pujiyati S. R. I., Pamungkas D. S., Tauhid M., Anurogo W., Kausarian H., 2018 Coral reefs recruitment in stone substrate on Gosong Pramuka, Seribu Islands, Indonesia. Biodiversitas 19(4):1451-1458.
Luthfi O. M., Wibisono R. V., 2017 Coral reef communities in the sand substrate of South Java Sea. Proceedings of 69th The IRES International Conference, Jeddah, Saudi Arabia, 24-25 May 2017, pp. 24-29.
Manikandan B., Ravindran J., Mohan H., Periasamy R., Murali R. M., Ingole B. S., 2016 Community structure and coral health status across the depth gradients of Grande Island, Central west coast of India. Regional Studies in Marine Science 7:150-158.
Mansour S., Al-Awadhi T., Al Hatrushi S., Al Buloshi A., 2017 The anthropogenic effects on coral reefs across northern coasts of Oman: a GIS based modeling. Geoinformatics Geostatistics: An Overview 5(1):2.
Manuputty A., Winardi, Siringoringo R. M., Salatalohi A., Haryanto R., Zulvianita D., 2007 Monitoring ekologi Nias. Jakarta: Coral Reef Rehabilition and Management Program, 51 pp. [in Indonesian]
Martinez S., Abelson A., 2013 Coral recruitment: the critical role of early post-settlement survival. ICES Journal of Marine Science 70(7):1294-1298.
Morri C., Montefalcone M., Lasagna R., Gatti G., Rovere A., Parravicini V., Baldelli G., Colantoni P., Bianchi C. N., 2015 Through bleaching and tsunami: coral reef recovery in the Maldives. Marine Pollution Bulletin 98(1-2):188-200.
Orcutt J., 2013 Earth system monitoring. Springer, New York, 524 pp.
Osinga R., Schutter M., Griffioen B., Wijffels R. H., Verreth J. A. J., Shafir S., Henard S., Taruffi M., Gili C., Lavorano S., 2011 The biology and economics of coral growth. Marine Biotechnology 13(4):658-671.
Patil I., 2021 Visualizations with statistical details: The ‘ggstatsplot’ approach. Journal of Open Source Software 6(61):3167.
Pisapia C., Burn D., Yoosuf R., Najeeb A., Anderson K. D., Pratchett M. S., 2016 Coral recovery in the central Maldives archipelago since the last major mass-bleaching, in 1998. Scientific Reports 6:34720.
Price S. A., Holzman R., Near T. J., Wainwright P. C., 2011 Coral reefs promote the evolution of morphological diversity and ecological novelty in labrid fishes. Ecology Letters 14(5):462-469.
Qiu Q., Feng L., Hermawan I., Hill E. M., 2019 Coseismic and postseismic slip of the 2005 M_w 8.6 Nias-Simeulue earthquake: spatial overlap and localized viscoelastic flow. Journal of Geophysical Research: Solid Earth 124(7):7445-7460.
Risqi A. N., Riyanto A., Hananto N. D., 2020 Identification of accretionary wedge at Sumatra subduction zone using 2D seismic reflection. IOP Conference Series: Earth and Environmental Science 538:012043.
Roth F., Saalmann F., Thomson T., Coker D. J., Villalobos R., Jones B. H., Wild C., Carvalho S., 2018 Coral reef degradation affects the potential for reef recovery after disturbance. Marine Environmental Research 142:48-58.
Sabdono A., Radjasa O. K., Trianto A., Sarjito, Munasik, Wijayanti D. P., 2019 Preliminary study of the effect of nutrient enrichment, released by marine floating cages, on the coral disease outbreak in Karimunjawa, Indonesia. Regional Studies in Marine Science 30:100704.
Seebauer J., 2001 Zoology of *Porites cylindrica*: potential for use in reef-rehabilitation transplantation efforts. Geneseo Journal of Science and Mathematics 2(1):26-34.
Siringoringo R. M., Suharsono, Sari N. W. P., Arafat Y., Arbi U. Y., Azkab H., Dharmawan I. W. E., Sianturi O. R., Anggraeni K., 2017 Monitoring kesehatan terumbu karang ekosistem terkait lainnya Kabupaten Nias Utara, Sumatera Utara. Program COREMAP-CTI, Pusat Penelitian Oseanografi, Lembaga Ilmu Pengetahuan Indonesia, 95 pp. [in Indonesian]

Siringoringo R. M., Hadi T. A., Sari N. W. P., Abrar M., Munasik, 2019 Distribution and community structure of coral reefs in the West coast of Sumatra, Indonesia. Ilmu Kelautan: Indonesian Journal of Marine Sciences 24(1):51-60.

Stoddart D. R., 2007 Tsunamis and coral reefs. Atoll Research Bulletin No. 544. National Museum of Natural History, Smithsonian Institution, Washington, 171 pp.

Suppasri A., Goto K., Muhari A., Ranasinghe P., Riyaz M., Affan M., Mas E., Yasuda M., Imamura F., 2015 A decade after the 2004 Indian Ocean tsunami: the progress in disaster preparedness and future challenges in Indonesia, Sri Lanka, Thailand and the Maldives. Pure and Applied Geophysics 172:3313-3341.

Suyarso, 2008 Topographic changes after 2004 and 2005 earthquakes at Simeulue and Nias islands identified using uplifted reefs. Journal of Coastal Development 12(1): 20-29.

Uychiaoco A. J., Green S. J., dela Cruz M. T., Gaite P. A., Arceo H. O., Alino P. M., White A. T., 2010 Coral reef monitoring for management. 2nd edition. University of the Philippines Marine Science Institute, United Nations Development Programme Global Environment Facility- Small Grants Program, Guiuan Development Foundation, Inc., Voluntary Service Overseas, University of the Philippines Center for Integration and Development Studies, Coastal Resource Management Project, Phillipine Environmental Governance Project 2, Fisheries Resource Management Project, 122 pp.

Veron J., Stafford-Smith M., 2000 Corals of the world. Vol. 1. Australian Institute of Marine Sciences, 463 pp.

Wallace C. C., Done B. J., Muir P. R., 2012 Revision and catalogue of worldwide staghorn corals *Acropora* and *Isopora* (Scleractinia: Acroporidae) in the Museum of Tropical Queensland. Memoirs of the Queensland Museum 57:1-257.

West J. M., Salm R. V., 2003 Resistance and resilience to coral bleaching: implications for coral reef conservation and management. Conservation Biology 17(4):956-967.

Wickham H., 2009 ggplot2: elegant graphics for data analysis. Springer, 212 pp.

Wilkinson C., Souter D., Goldberg J., 2006 Status of coral reefs in tsunami affected countries: 2005. Australian Government, Australian Institute of Marine Science, 154 pp.

Williams I. D., Polunin N. V. C., Hendrick V. J., 2001 Limits to grazing by herbivorous fishes and the impact of low coral cover on macroalgal abundance on a coral reef in Belize. Marine Ecology Progress Series 222:187-196.

Wilson J., Green A., 2009 Biological monitoring methods for assessing coral reef health and management effectiveness of marine protected areas in Indonesia. TNC Indonesia Marine Program Report No. 1/09. The Nature Conservancy, Indonesia Marine Program, 44 pp.

Zhao M., Riegl B., Yu K., Shi Q., Zhang Q., Liu G., Yang H., Yan H., 2016 Model suggests potential for *Porites* coral population recovery after removal of anthropogenic disturbance (Luhuitou, Hainan, South China Sea). Scientific Reports 6:33324.

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