Large scale study of benthic communities in Eastern Indonesia's reef systems

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ABSTRACT

Broad-scale studies and regional comparisons of Indonesia's coral reefs are critical given the relative lack of information about these large, diverse, and threatened ecosystems. Most studies on reef benthic composition and distribution have largely focused on rather short transects spanning relatively small areas. Here, we quantify the shallow large-scale spatial distribution of benthic communities in four locations in Eastern Indonesia, i.e. the Spermonde Archipelago in South Sulawesi, and Ambon, Halmahera and Lucipara in Maluku Islands. Shallow coral reef ecosystems (0.5-2 m depth) were assessed using a georeferenced photoquadrat survey method that can cover larger proportions of reefs, as well as benthic assemblages in deeper reefs (~8 m depth) recorded with photoquadrats. A total of 27.8 km of shallow and 4.8 km of deeper reef ecosystem transects were surveyed in this study. We found that reef benthic communities at the study locations were mainly characterized by low to moderate cover of live hard corals and relatively high cover of dead corals or abiotic components. Ninety percent of the surveyed reefs at both depths exhibited < 50% cover of live hard corals, whereas 88% of shallow and 78% of deeper reef sites consisted of > 25% dead corals or abiotic components. A combination of georeferenced photoquadrats and CoralNet machine learning rapidly identified benthic composition across a large area, which is useful for mapping or other large-scale applications. This information can support decision-makers for better management of resources and marine spatial planning, crucial for an archipelagic state with tens of thousands of islands such as Indonesia. Our broad-scale reef surveying, focusing on under-studied areas of Indonesia, can contribute to this effort, as well as others seeking to better map coral reef habitats, as an important foundation for their conservation amidst growing threats.

1. Introduction

Despite their size, diversity, and threatened status, Indonesian coral reefs have remained infrequently studied compared to many other coral reef-rich countries (Ampou et al. 2018). Studies on coral reefs led by Indonesian scientists have largely focused on monitoring spatial distribution and composition of coral communities (e.g. Abrar et al. 2019, Johan et al. 2019, Putra et al. 2019), and are now approaching over two decades of data acquisition on habitat and benthic compositions (Ampou et al. 2018). Over 640 publications, both peer-reviewed and grey literature, on reef benthic community compositions from around 6,000 sites/transects all over Indonesia have been published between 2000 and 2020 (Razak, unpublished data). However, the available monitoring data on local reef condition are rarely integrated in decision making or used for natural resource conservation and management in Indonesia.

Most of the studies on reef benthic composition and distribution have also largely focused on relatively small areas, with short transects necessitated by acknowledged methods (e.g. English et al. 1997) and logistical restrictions. Broad-scale comparisons, both regionally and for larger reef tracts, are still lacking. Additionally, relatively little work captures the shallow coral reef ecosystems of Indonesia, particularly within Eastern Indonesia that is most remote but also harbors highly diverse reefs. For example, reef flats are one of the largest habitats on coral reefs and play an extremely important role in primary production and turf grazing fish biomass (Bellwood et al. 2018).

Our study compares shallow and deep benthic assemblages in four locations of coral reef ecosystems in the eastern part of Indonesia: the Spermonde Archipelago in South Sulawesi; and Ambon, Halmahera and Lucipara in Maluku Islands. We quantify large scale spatial distribution of benthic communities in the shallow coral reef ecosystems (0.5-2 m depth), using a georeferenced 1 × 1 m^2 photoquadrat survey method that employed machine learning for identification (Roelfsema & Phinn 2010). Additionally, we examine benthic communities in deeper reefs (~8 m depth) surveyed with a manually-annotated photoquadrat transect method. Since Indonesia is an archipelagic state with tens of thousands of islands, such large scale and detailed information on reef benthic communities is much needed to support decision-makers for better management of resources and marine spatial planning.

2. Materials and methods

2.1. Study locations

The study was conducted at Spermonde Archipelago, South Sulawesi between June 19^{th}-29^{th} 2019, and around the island of Halmahera, Ambon and Lucipara within the Maluku Islands region between October 2^{nd}-27^{th} 2019 (Fig. 1, Table 1). These regions were chosen as they represent reef systems with a gradient of impacts in the Indonesian Archipelago.

The Spermonde Archipelago (Fig. 1A) is located in the Makassar Strait to the west off the coast of Makassar City, South Sulawesi Province. There are about 150 coral cays and islands, and data from 2004 estimated 60 km^2 of live coral and 50 km^2 of dead coral cover within the Spermonde Archipelago (Rauf & Yusuf 2004, Yusuf & Jompa 2012). The Spermonde shelf is divided into four zones based on distance to the coastline and bathymetry: first or innermost zone (up to 5 km off the coastline and maximum sea floor depth of ~20 m); second zone (5-12.5 km and ~30 m depth), third zone (12.5-30 km and ~30-50 m depth), and lastly, the outer rim or barrier reef zone (30-40 km offshore and > 40 m depth) (Hoeksema 2012).

Ambon Island (Fig. 1B) is a small island located in the Maluku Province with 775 km^2 of land area and 1,256 km of coastline (Noija et al. 2014, Limmon et al. 2017). Halmahera Island (Fig. 1C) is the largest island in the North Maluku Province, with a land area of 17,780 km^2 and more than 1,000 km^2 of coral reef ecosystems (Ardiwijaya et al. 2008). The islands of Lucipara (Fig. 1D) are located in the middle of the Banda Sea about 200 km south of Ambon Island, and administratively are part of the West Seram Regency, Maluku Province, and consist of seven small and uninhabited islands (Indonesian Institute of Science 2010). Detailed information regarding the number of reefs, transects and photoquadrats acquired for each survey location are documented in Table 1, Supplementary Table S1 and Table S2.

2.2. Data collection

2.2.1. Shallow reefs (0.5-2 m): georeferenced photoquadrat method and CoralNet benthic image annotation tool

Surveys were conducted at several sites at each location, chosen to represent a cross-section of perceived human impacts, using proxies such as proximity to land-based threats and distance to fishing village. At each site, detailed information on benthic communities was gathered on shallow reef ecosystems at a depth of 0.5-2 m, using a repeatable and fine spatial scale technique for surveying benthic cover across a variety of shallow nearshore habitats (Roelfsema & Phinn 2010) – as such our method cannot discern benthic community composition at microhabitat scales. This method involved collecting between 13 and 86 photoquadrats (average of 42 photoquadrats) of the seabed at intervals of 2-4 m along a 100-m long transect line. A waterproof digital camera (Olympus TG-5) captured the required footprint (1×1 m^2) while the photographers' track, at an interval of 2 seconds, was logged by a standard GPS (e.g. Garmin eTrex) floating at the surface (Fig. 2a). Each photoquadrat was assigned a position by time synchronisation of GPS and camera using photo-linking software, GPS Photo (version 1.0.10) (Passenger 2017).

Percentage cover of the benthic community composition (e.g. hard coral, dead coral, algae, sand, rubble, seagrass; see Supplementary Table S1 for details) was determined through machine learning using CoralNet benthic image annotation tool (Beijbom et al. 2015). This semi-automated approach allows the maximization of spatial coverage within reasonable time-frames and resource limitations (González-Rivero et al. 2020, Nunes et al. 2020), and has previously been found to generate site level coral cover estimates that were highly comparable to those generated by human analysts (Pearson's $r > 0.97$, and with bias of 1% or less) (Beijbom et al. 2015, González-Rivero et al. 2016). To automatically derive the benthic community per photoquadrat, the machine learning algorithm had been trained with a subset of manually annotated photoquadrats using the global label set. Using 50 simple randomly generated points, over 10% of photoquadrats were manually annotated (i.e. 1,780 images) (Fig. 2b). The accuracy for all benthic groups, distinguishing between coral and algae genera, was 64% (with a 100% confidence threshold). When looking at functional groups (Hard Coral, Other Invertebrates, Algae, Abiotic (Hard and Soft Substrates), Seagrass and Other), the accuracy was 74%. Benthic community classes were part of a globally created category scheme similar to González-Rivero et al. (2014).

In this study, we surveyed 13 shallow reefs on Spermonde Archipelago, 15 on Ambon Island, 24 on Halmahera Island (17 on the west and 7 on the east coast of Halmahera) and 6 reefs on Lucipara Islands, totaling 27.8 km of surveyed shallow reef ecosystems (Table 1 and Supplementary Table S1). Transects were located to represent a variety of reef locations and benthic habitats.

2.2.2. Deeper reefs (~8 m): photoquadrat transect method and CPCe benthic image analysis

The benthic community on deeper reefs (~8 m; Supplementary Table S2) was estimated by placing a series of photoquadrats along a 30-m transect line, using 60 quadrats of 50×50 cm^2 in Spermonde, and 30 quadrats of 1×1 m^2 at the other locations (Fig. 2c). Percentage cover was estimated using Coral Point Count with Excel extension (CPCe) software (Kohler & Gill 2006), applying 10 points to each Spermonde photo, and 20 points to the others. For deeper reef benthic communities, a total of 4.8 km reef ecosystem transects were surveyed including 12 reefs each on Spermonde Archipelago, Ambon Island, and Halmahera Island, as well as 4 reefs on Lucipara Islands (Table 1 and Supplementary Table S2).

2.3. Statistical analyses

All shallow transects were standardized to a length of 100 m, and the mean of all benthic categories across transects was calculated for reefs where more than one 100-m transect was surveyed. Furthermore, the values for the benthic categories (Supplementary Table S1 and Table S2) were used in non-metric multidimensional scaling (nMDS) to investigate variation in benthic community composition among locations. The analyses were based on the mean percent cover of each substratum category at each site, and grouping the study sites according to similarity in benthic assemblages. To assess which benthic organisms are responsible for any variation between locations (Spermonde, Ambon, East and West Halmahera, and Lucipara), we conducted similarity percentage (SIMPER) and one-way analysis of similarity (ANOSIM) analyses with location as factor. All statistical analyses were conducted using the PRIMER statistical package (Clarke & Warwick 2001).

3. Results

3.1. Reef benthic composition on shallow reefs (0.5-2 m)

Across the four study locations, and in a variety of shallow nearshore habitats, the mean cover of live hard corals (28.8 ± 14.3%, mean ± SD) was lower than the mean dead coral cover (39.8 ± 11.8%) (Figs. 3 and 4, Supplementary Table S1). Together, these two categories made up nearly 70% of the overall benthic community cover on shallow reefs, and along with other categories (e.g. soft corals, algae, rubble) are presented in detail in Supplementary Table S1.

The nMDS of benthic community composition on shallow reefs showed no distinct groupings among the four study locations (Fig. 6a). For instance, Ambon and Lucipara is much smaller in size compared to Halmahera, however both areas showed great variability in benthic composition among reef sites as can be seen in nMDS graph (Fig. 6a). ANOSIM revealed significant differences between Spermonde and Ambon, Halmahera East, and Lucipara ($p <$ 0.05; Table 2). These four locations were characterized by the domination of dead corals (SIMPER analyses, 43-60% contribution to similarity), with hard coral cover at 18 out of 19 surveyed reefs consistently lower than dead corals (16-32% contribution, Supplementary Table

S3). The differences between locations were driven mostly by hard coral (25-30% contribution to dissimilarity), dead coral (16-27% contribution), and soft coral (9-16% contribution, Supplementary Table S4).

In Spermonde Archipelago, the mean live hard coral cover was 31.1 ± 8.1% (*Acropora* 14.0% and non-*Acropora* corals 17.0%), whilst mean dead coral cover was 44.8 ± 7.1%. Observations around the Maluku Islands showed that hard coral cover in Ambon averaged 26.2 ± 15.4% (*Acropora* at 8.4% and non-*Acropora* at 17.9%), whilst the average of dead coral cover was 35.2 ± 10.0%. Of all study locations, the highest mean live hard coral cover was recorded around Halmahera Island at 32.4 ± 15.7% (*Acropora* 17.2% and non-*Acropora* 15.2%); whereas mean cover of dead corals was 37.4 ± 11.7%. Reefs on the west coast of Halmahera showed higher live coral cover (35.4 ± 14.5%) than the east coast (25.2 ± 17.2%), whilst mean dead coral cover was 36.1% and 40.6%, respectively. Lucipara Islands showed the lowest shallow live hard coral cover compared to the other locations at 16.0 ± 9.1% (*Acropora* at 3.9% and non-*Acropora* at 12.1%). Mean cover of dead corals was the highest among all study locations at 50.4 ± 16.3%.

3.2. Reef benthic composition on deeper reefs (~8 m)

In contrast to the domination of dead corals in shallow reefs, deeper reef substrates were covered mainly in abiotic components (46.4 ± 22.0%), i.e. rock (10.9%), rubble (19.9%) and sand (15.6%), followed by live hard corals (30.9 ± 16.3%) (Figs. 3 and 5). Details on the coverage of reef benthic communities at this depth are presented in Supplementary Table S2.

The nMDS of benthic community composition showed distinct groupings in deeper reefs, with Ambon and Halmahera more similar to each other, and Spermonde differing from Lucipara reefs (Fig. 6b). ANOSIM showed that Spermonde was significantly different from Ambon, Halmahera, and Lucipara ($p < 0.05$; Table 2). Spermonde Archipelago showed relatively high dead coral cover compared to Ambon, Halmahera and Lucipara Islands where cover of dead corals was very low (Fig. 3). Similarity in these deeper reefs was driven by hard coral (32-43% contribution), rubble (12-27% contribution), and rock (13-31% contribution, Supplementary Table S5). On the other hand, drivers of dissimilarity were rubble (17-24% contribution), hard coral (10-22% contribution), and dead coral (no to 20% contribution) (SIMPER analysis, Supplementary Table S6).

Reef benthic communities across the 12 sites in Spermonde Archipelago were dominated by abiotic components at 36.9 ± 16.4% that consisted of rubble (25.7%) and sand (11.3%). Live hard corals averaged 34.1 ± 14.3% (*Acropora* 3.5% and non-*Acropora* 30.7%). Dead coral cover in Spermonde was much higher than that recorded in Maluku, with an average of 20.4 ± 8.2%. Of the 12 sites on Ambon Island, nearly half of the reef substrate was dominated by abiotic components (48.7 ± 22.4%) which consisted of rock (14.1%), rubble (17.3%) and sand (17.3%). The average of live hard corals was 29.2 ± 18.2% including *Acropora* at 10.3% and non-*Acropora* with 18.9%.

More than half of the reef substrates surveyed around Halmahera Island were covered in abiotic components (58.3 ± 23.8%) which consisted of rock (12.7%), rubble (22.9%) and sand (22.8%). Ten out of 12 sites surveyed in Halmahera were covered by more than 50% of abiotic components. The condition of hard coral communities around Halmahera was not much different from those in Ambon with an overall mean of 28.3 ± 19.2% (*Acropora* 14.5% and non-*Acropora* 13.8%). Around Lucipara Islands, the mean cover of abiotic and live hard corals was comparable at 32.5 ± 2.5% and 33.6 ± 3.1%, respectively. The hard coral assemblages consisted of *Acropora* (2.6%) and non-*Acropora* (31.1%).

Benthic community data from shallow and deeper reefs were not compared statistically, because surveys were conducted using different methods, and cover data was also extracted using different software (CoralNet vs. CPCE) by different observers.

4. Discussion

General condition

Our study found that reef benthic communities at four different locations in the eastern part of Indonesia were mainly characterized by low to moderate cover of live hard corals and high cover of dead corals or abiotic components (i.e. coral rubble, rocks and sand). Ninety percent of the surveyed reefs at both depths (0.5-2 and ~8 m) exhibited less than 50% cover of live hard corals, whereas 80-90% of the reef sites consisted of 25% or more dead corals or abiotic components. None of the 98 reefs monitored (both shallow and deeper reefs) had >75% cover of live hard coral, and only 11% of the reefs had 50 to 71% of healthy coral cover. The difference in nMDS groupings between shallow and deeper reefs may reflect that the shallow habitats tend to be heavily impacted and are thus similarly simplified communities. It should be noted that the methodology we employed for shallow reef surveys targeted a wider range of habitats (including reef flats, seagrass beds, etc.) than traditional reef ecology surveys, which target the reef slope that tends to have higher live coral cover (e.g. Purwanto et al. 2012, Welly et al. 2017).

Previous studies from the area

Our assessment of shallow reef ecosystems in addition to the deeper reef slope provides a dataset that complements other work and that can serve as a valuable backdrop for future monitoring of reef trajectories in Eastern Indonesia. While the 2019 Status of Indonesian Coral Reefs found only 6.4% – from the total 1,153 surveyed sites – in an excellent state (>75% healthy hard coral), and the majority (71.2%) in poor to fair conditions, in general the survey found that reefs in the eastern part of Indonesia were in better condition than those in the western and southern parts of the country (Hadi et al. 2019). Reefs in the eastern part of Indonesia were also reported to be more resistant to ocean warming (Peñaflor et al. 2009, Hadi et al. 2018); thus protecting, preserving and restoring reefs in Eastern Indonesia is crucial in an era of a rapidly changing climate.

The current study expands existing research on these locations in Spermonde, Ambon, Halmahera and Lucipara (e.g. Polónia et al. 2015, DeVantier & Turak 2017, Teichberg et al. 2018). In several locations, we found lower coral cover in most survey sites than previously reported; however, as we targeted shallow reefs for the most part, a direct comparison may be inappropriate. Nevertheless, the general low coral cover we found is consistent with a potential ongoing decline over the past few years, possibly mediated by recent thermal stress and slow recovery.

Between 2005 and 2019, 34 studies were conducted on 301 reef sites around Spermonde Archipelago (Supplementary Table S7). Recent data collected between 2018-2019 (average depth 5-7 m) reported hard coral cover between 8.5% in Bonetambung Island and 77.8% in Kodingareng Keke (Sari et al. 2018, Arifin et al. 2019, Sutomo et al. 2019, Tudang et al. 2019). Although no direct comparison should be made, the upper range of our data both on shallow reefs (16.5-42.5%) and deeper water (8.0-57.0%) are much lower than previously reported. However, both Sari et al. (2018) and our study confirmed very poor condition of deeper reefs (> 5m) on Bonetambung Island with around 8.0% of hard coral cover. In addition, we did not observe an increase in hard coral cover along the on-to-offshore gradient, as a function of water quality and human impacts, reported by several studies from this location (Plass-Johnson et al. 2016, Teichberg et al. 2018) (Supplementary Fig. S1).

A total of 13 studies around Ambon Island recorded benthic community compositions from 160 reefs (depth 1.5 to 17 m deep) between 2009 and 2020 (Supplementary Table S7). Most of these studies used 50-m linear or point intercept transects to assess the benthic composition (e.g. Adji et al. 2016, Mustofa et al. 2017). The most recent reef benthic data, collected in 2018, found the mean hard coral cover at 3-10 m depth varied between 10.0% (Pia, Saparua Island) and 66.5% (Negeri Morella, north of Ambon Island) (Ihsan et al. 2018, Rabiyanti et al. 2019, Hukubun 2020). Our results are within the same range as previous findings from around Ambon Island, where live coral cover on shallow reefs ranged between 8.6% and 58.2%, and on deeper reefs between 8.4% and 61.0%. Despite our findings of some reefs with low coral cover, a study by Asaad et al. (2018) stated Ambon Island, together with the northern tip of Sulawesi, Kei Island, and Raja Ampat Archipelago of Papua, to be an area of significant biodiversity importance containing endemic and threatened species. They recommended these areas should be prioritized to be included in a network of protected reserves in the Coral Triangle. As such, large-scale survey methods such as those used in this study could help quickly identify reef areas at Ambon Island of a high diversity of coral reef species and high habitat diversity for priority protection areas.

Turak and DeVantier (2008) stated that Halmahera hosts an exceptionally rich coral fauna, with a total of 468 reef-building coral species from 73 genera in 15 families confirmed from 24 sites on North Halmahera. Similarly, exceptionally high densities of polyps of mushroom coral (*Halomitra clavator*), known from only a few localities in the central Indo-

Pacific, were observed on deep reefs (17-22 m) off West Halmahera (Hoeksema & Gittenberger 2010). Between 2009 and 2020, a total of 14 reports on benthic composition were available from approximately 225 reefs (1-12 m depth) around Halmahera Island (Supplementary Table S7). The most recent study, conducted in 2019 on 12 reefs around Makian and Moti Islands, West Halmahera, reported live coral cover ranging from 19.4 to 71.3% with an overall average of 48.5% (Muhidin et al. 2020). This range of hard coral cover is comparable to our findings from West Halmahera, both on shallow (14.7% to 66.3%) and deeper reefs (3.0% to 71.3%). Both Muhidin et al. (2020) and our study found that a better reef condition, with the highest coral cover observed, was located around Makian Island, an island off the west coast of Halmahera. Thus, we recommend this site for further study and detailed mapping of surrounding reefs to identify good quality reefs. Consideration of reef condition is crucial for effective protection and conservation of reef systems (Vercammen et al. 2019).

The very poor hard coral condition on Siko Island, West Halmahera, averaging 3.0% on deeper reef and 16.4% on shallow reef, was presumably caused by dynamite fishing activities, as the reef substrate was mostly covered in coral rubble (68.6%), and rock and sand (27.0%). Turak and DeVantier (2008) suggested that loss of the live coral cover in the area was mostly attributable to the effects of predation and dynamite fishing. Evidence of predation by *Acanthaster planci* (the crown-of-thorns starfish, COTS) and to a lesser extent *Drupella* snails was also widespread (Turak & DeVantier 2008), but not observed during our study. Population outbreaks of COTS had been recorded from several islands nearby, where an estimated 20 hectares of fringing reef surrounding Kayoa Island were seriously degraded as a consequence of COTS predation (Baird et al. 2013).

Unlike the other study locations, there is very little information available on reef benthic composition from Lucipara Islands. Shallow reefs at Lucipara Islands, remote reefs in an unpopulated area revealed the lowest live corals and highest dead corals among the four study locations. This is not unexpected as illegal fishing practices are known to have targeted these empty islands for decades (Cesar 1998, Hadi et al. 2019). In the case of Indonesia, the most remote reefs are often the most damaged by destructive fishing practices due to a nearly-complete lack of enforcement in these regions (Erdmann et al. 2000, Hadi et al. 2019). In Lucipara, the shallow communities surveyed covered reef flats and upper crests with a variety of communities that form in response to very exposed conditions e.g. seagrass beds and branching coral communities. In contrast, the deeper transects at ~8 m were in very steep terrain, and sometimes overhanging. It is therefore plausible that the steep/overhanging communities are less varied, as the lack of light limits many coral reef species. The only report available on Lucipara reefs is in contrast to our findings; the survey found that reef ecosystems at all eight sites surveyed at Lucipara were in good and excellent condition (Hadi et al. 2019). It is possible that most reef studies in Indonesia targeted high-cover locations for their transect surveys, as the use of random transect locations was not always specified.

In this study, many sites with extended rubble fields in all locations at the deeper sites (reef slopes, ~8 m) displayed characteristics of old blast fishing damage; many of these rubble fields were old (>5 years) areas that had not recovered. In the shallows, it is difficult to work out the main reason for reef degradation, but we would estimate that these shallow reefs experience impacts such as blast fishing (but not in the really shallow areas), physical damage from boats, and storms. Most of Indonesia's reefs experienced coral bleaching between 2016 and 2020

(Trialfhianty et al. 2020), but it is unclear whether the reef degradation we observed was related to bleaching mortality.

Implications for large scale mapping

A combination of georeferenced photoquadrats and CoralNet machine learning to identify benthic composition is a quick way to cover a large area within a short period of time, which is useful for mapping or other large-scale applications (Roelfsema & Phinn 2010). This method covered a large area of reef, a total of 27.8 km of shallow reef ecosystems, with up to 18,000 benthic images taken. Of these images, ~10% needed to be annotated manually, which took approximately 120 hours to complete (3-4 minutes per photo). Following the manual training, the neural network classifier annotated the remaining images in just a few hours. The biggest advantage of this semi-automated approach is that once training for a region is sufficient, new surveys can be undertaken with only minimal manual annotation and verification. The 64% accuracy for the automated annotation could improve with more effort on the manual annotation for the mapping categories that have a low individual accuracy. However, the manual training process is stopped once accuracy reaches a steady state as accuracy in unlikely to improve. The accuracy of automated labelling depends on both the quality of photos and complexity of classes.

As an archipelagic state with tens of thousands of islands, improving the relatively weak state of reef data is crucial. This wealth information can support decision-makers for better management of resources and marine spatial planning. Recognizing this, in 2011 the Republic of Indonesia launched a *One Map Policy* (Law No. 4 of 2011 about Geospatial Information) to introduce a single standardised geographic reference, scale and spatial data symbols – in particular to avoid potential conflict from different types of spatial data collected by various national government institutions (Yudono 2017). Our broad-scale reef surveying, focusing on under-studied areas of Indonesia, can contribute to this effort, as an important foundation for their conservation amidst growing threats.

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Figures and Tables

Fig. 1. Map showing the four study locations in Eastern Indonesia: Spermonde Archipelago in South Sulawesi (A), and Ambon (B), Halmahera (C) and Lucipara (D) in Maluku Islands. The yellow dots represent the survey sites.

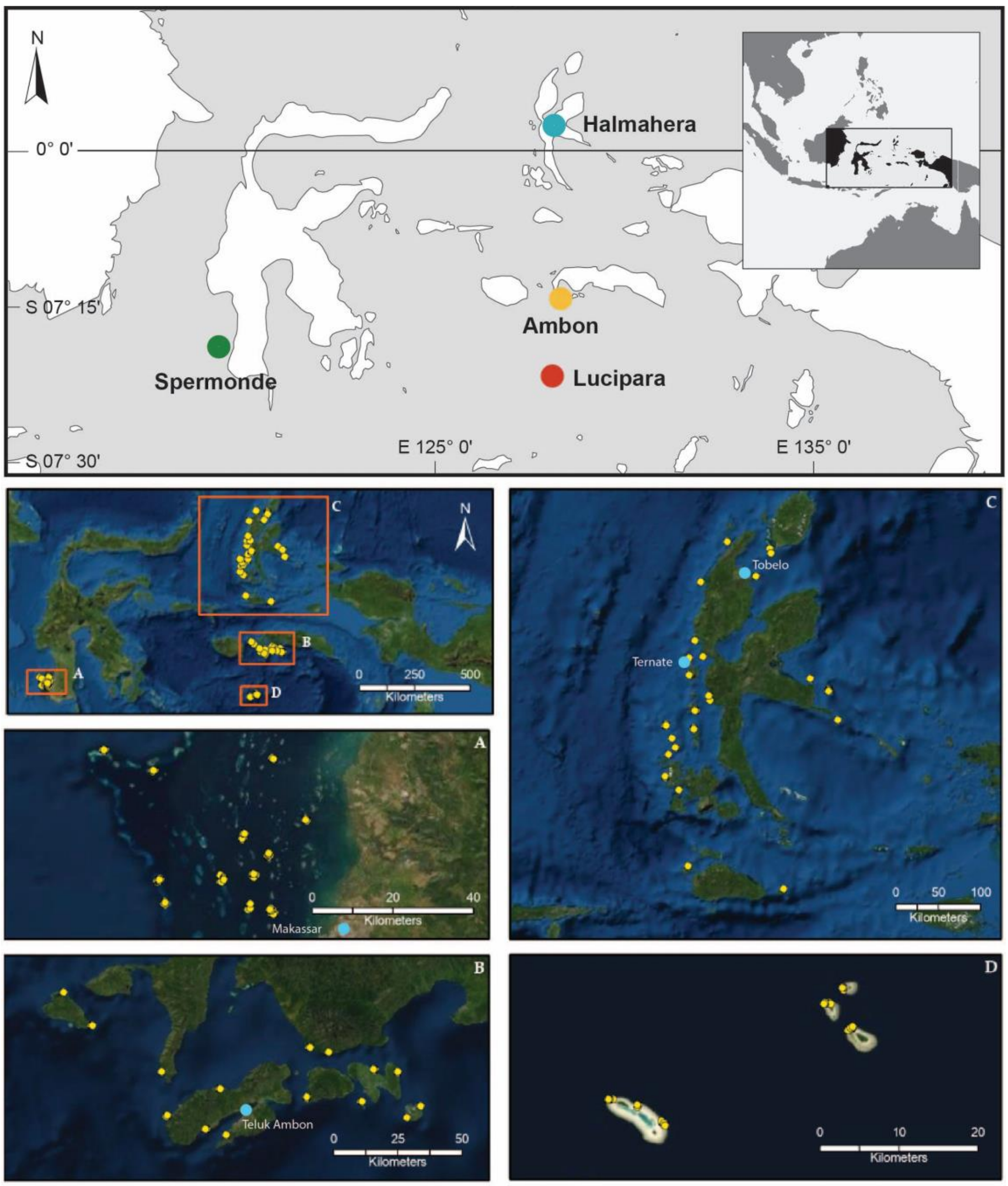


Fig. 2. Conceptualization of snorkeler towing a GPS and taking pictures for the georeferenced photoquadrat transect surveys (a); a sample of a benthic photoquadrat with automated annotation done in CoralNet (b); and a deeper (~8 m) 50 × 50 cm^2 photoquadrat for later CPCe analysis (c).

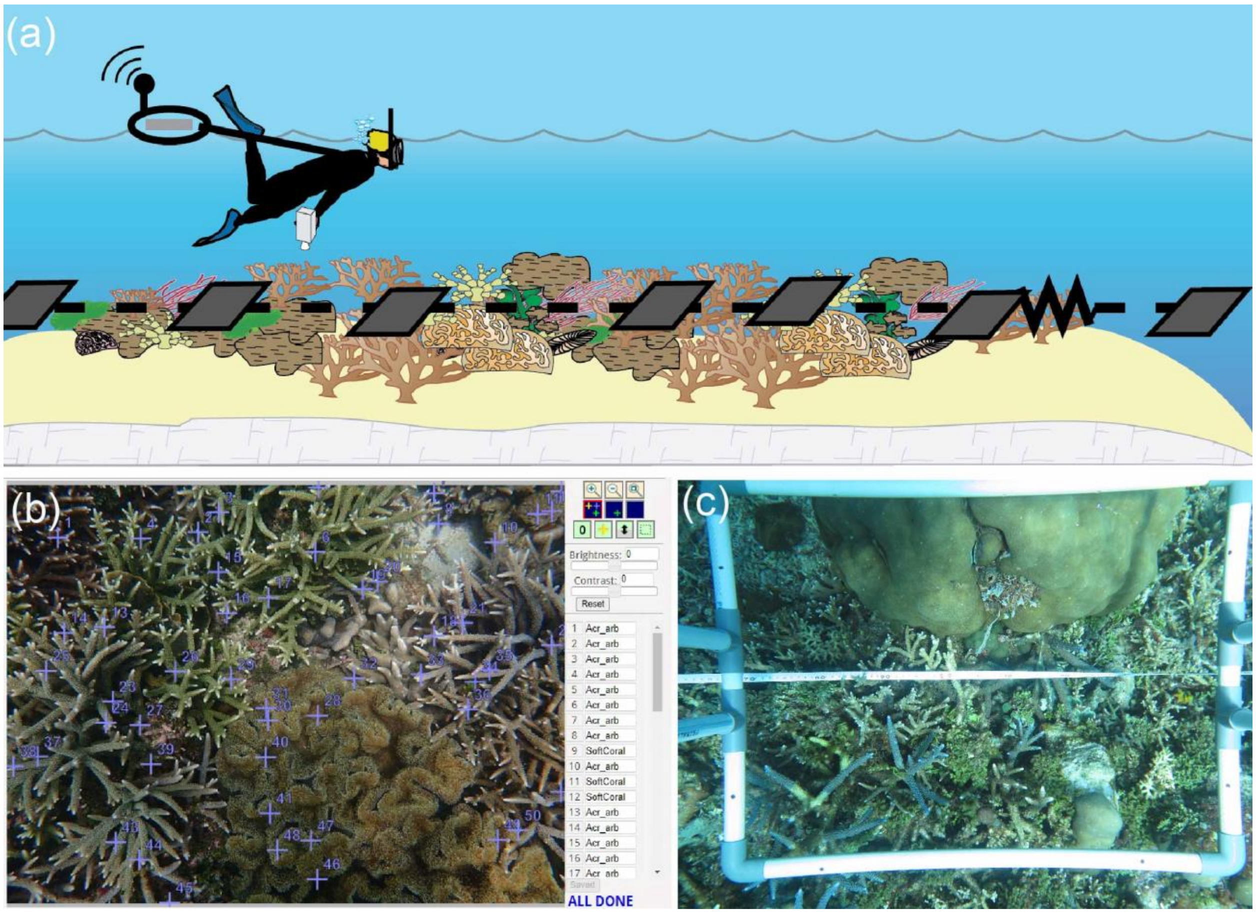


Fig. 3. Boxplot of four major reef benthic categories i.e. live hard corals, dead corals, soft corals, and abiotic components on shallow and deeper reefs at the four study locations.

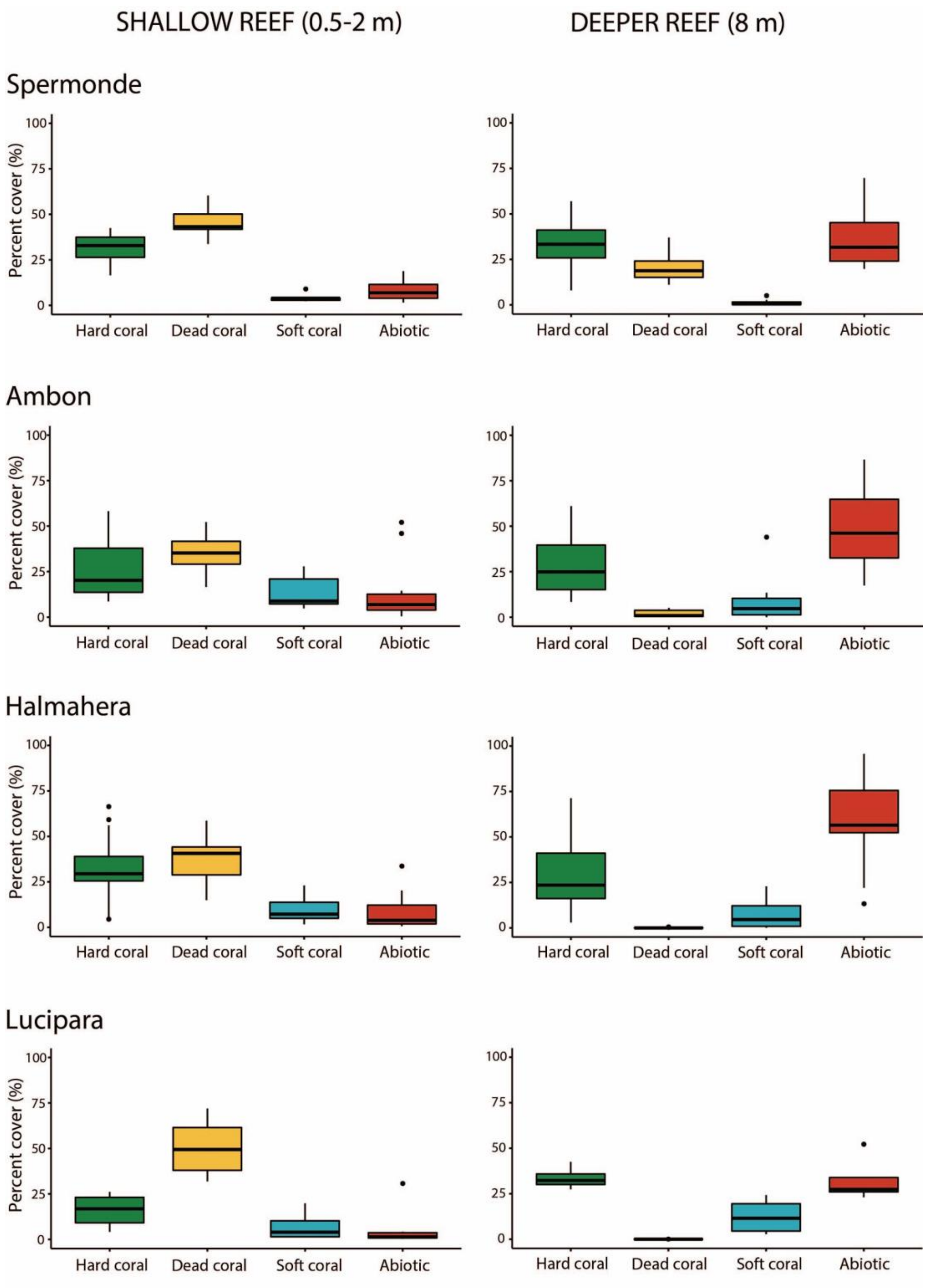
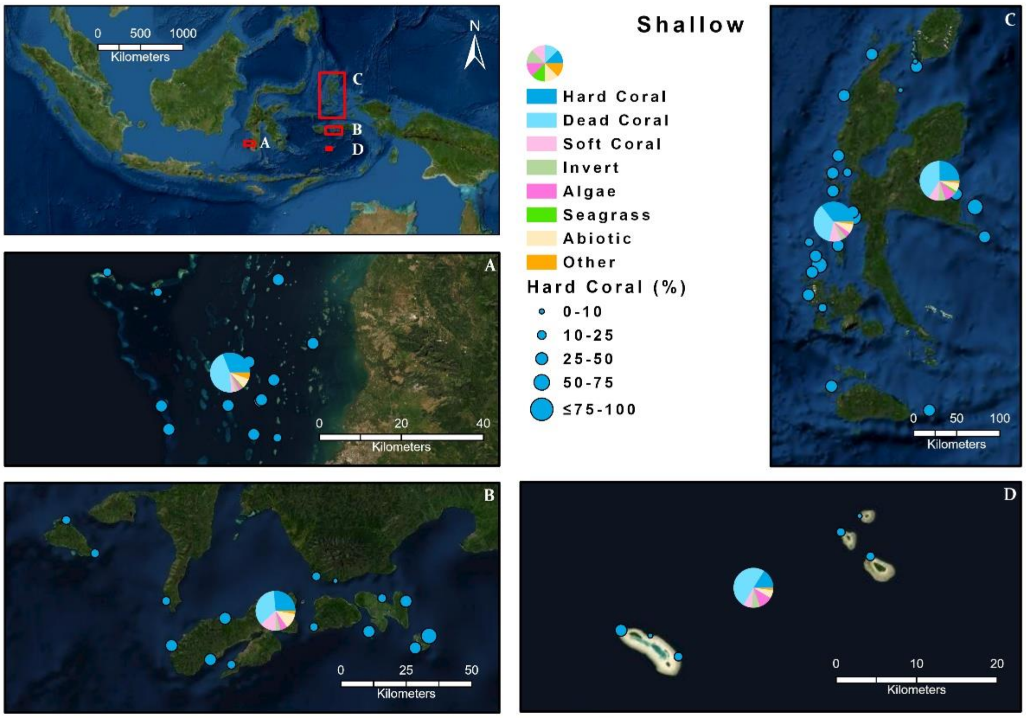


Fig. 4. Compositions of hard coral and dead coral on shallow reefs in Eastern Indonesia.

(a) Hard coral



(b) Dead coral

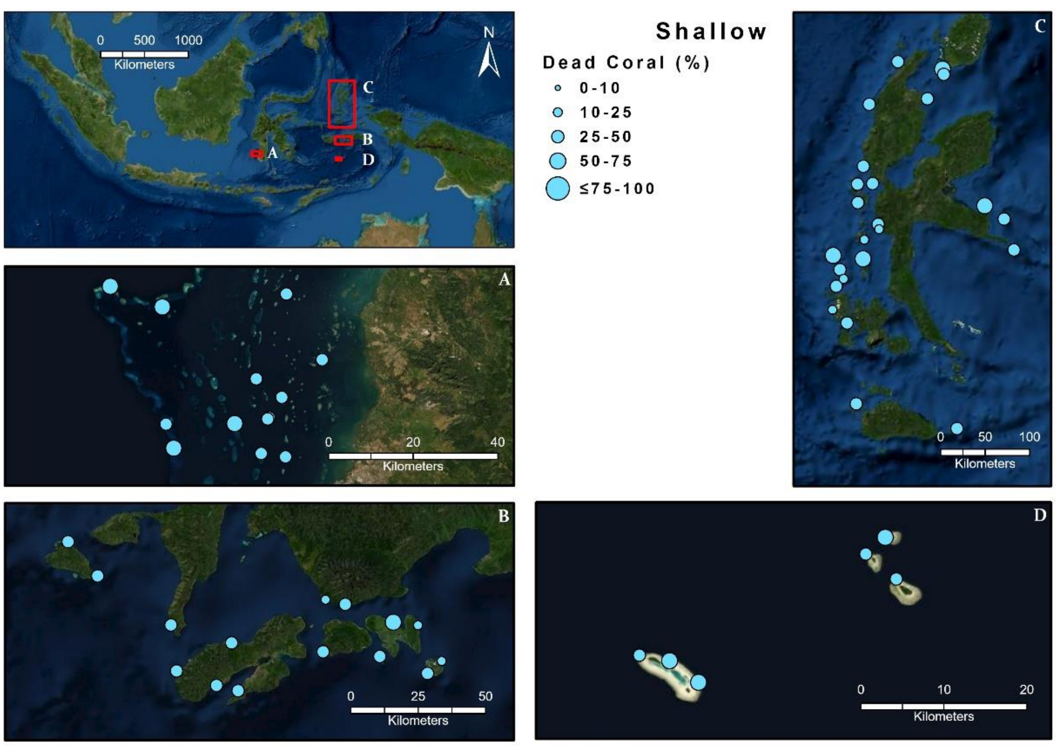
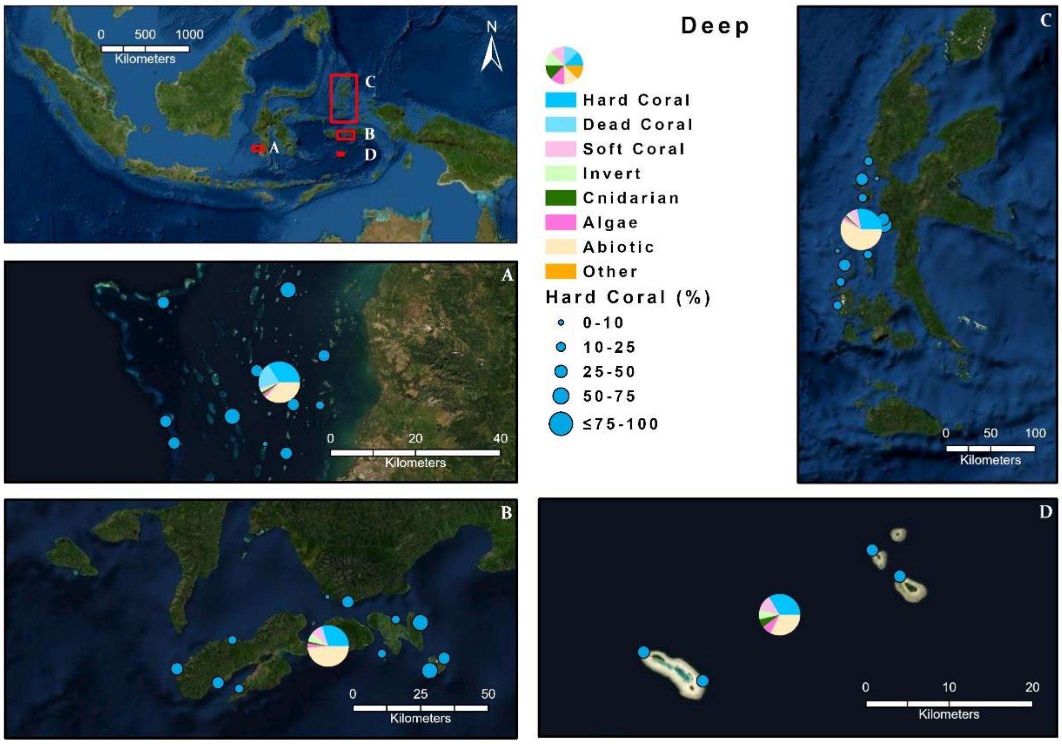


Fig. 5. Compositions of hard coral and abiotic components on deeper reefs in Eastern Indonesia.

(a) Hard coral



(b) Abiotic component

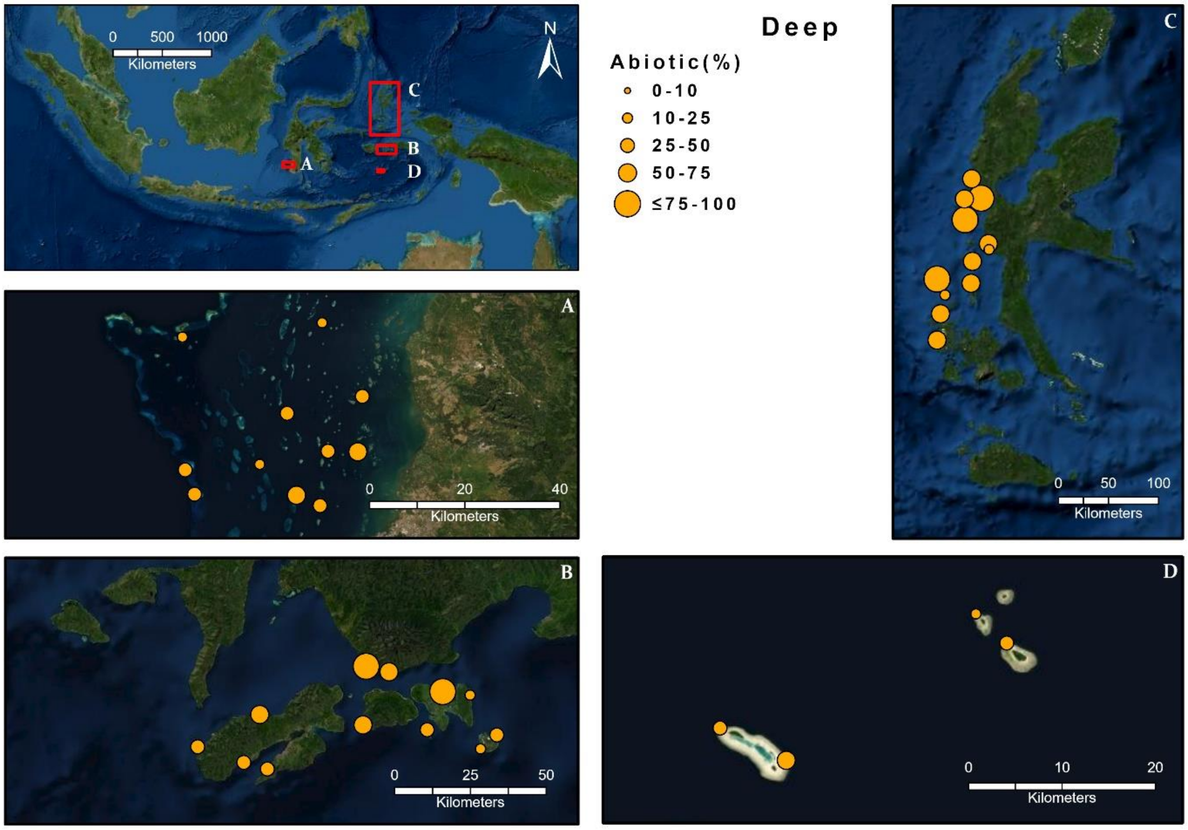


Fig. 6. Non-metric multi-dimensional scaling (nMDS) of benthic assemblage at four study locations: Spermonde Archipelago (*purple, triangle*), Ambon Island (*yellow, triangle down*), Halmahera Island (West: *blue, square* and East: *green, diamond*) and Lucipara Islands (*red, circle*) in shallow (a) and deeper reefs (b).

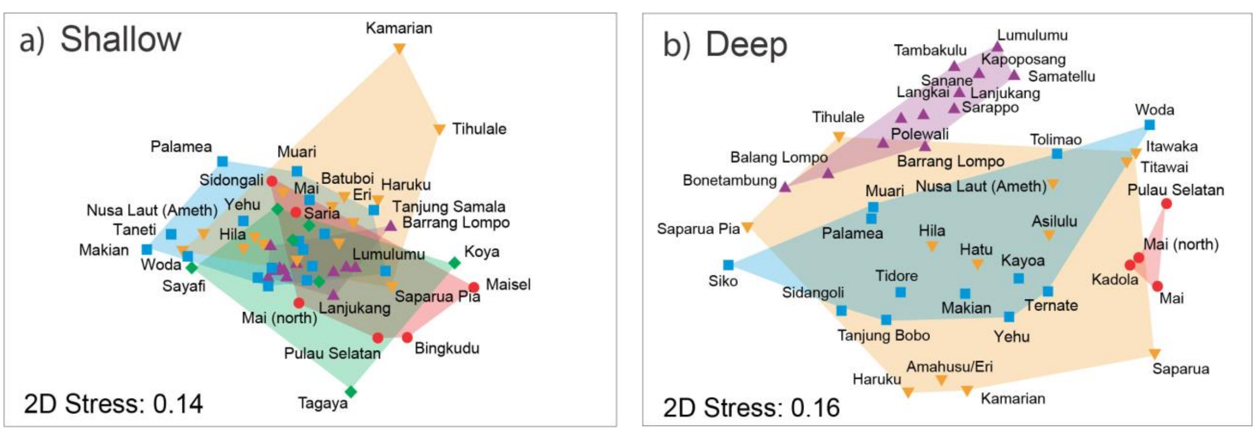


Table 1

Summary of the field data: total number of reef sites, transects and photoquadrats at each study location.

Location	**Spermonde Archipelago**	**Ambon Island**	**Halmahera Island**	**Lucipara Islands**
Survey period	19-29 Jun 2019	2-10 Oct 2019	11-24 Oct 2019	26-27 Oct 2019
Shallow reefs (2-4 m)				
Reef sites	13	15	24	6
Transects (range per site)	91 (2-13)	43 (1-6)	104 (1-8)	40 (5-9)
Photoquadrats	4,752	1,931	3,676	1,431
Deeper reefs (~8 m)				
Reef sites	12	12	12	4
Transects (range per site)	48 (4)	48 (4)	48 (4)	16 (4)
Photoquadrats	2,880	2,880	2,880	960

Table 2

ANOSIM tests to assess significance of differences between the locations for shallow and deeper reef ecosystems. The bold numbers represent the significant values ($p < 0.05$).

Groups	Shallow		Deep	
	R Statistic	p-value	R Statistic	p-value
Spermonde, Ambon	0.192	**0.001**	0.49	**0.001**
Spermonde, Halmahera			0.53	**0.001**
Spermonde, Halmahera West	0.077	0.071		
Spermonde, Halmahera East	0.435	**0.004**		
Spermonde, Lucipara	0.71	**0.001**	0.99	**0.002**
Ambon, Halmahera			0.03	0.682
Ambon, Halmahera West	0.008	0.352		
Ambon, Halmahera East	-0.013	0.504		
Ambon, Lucipara	0.144	0.154	0.02	0.385
Halmahera West, Halmahera East	0.091	0.184		
Halmahera, Lucipara			0.34	**0.006**
Halmahera West, Lucipara	0.358	**0.013**		

Halmahera East, Lucipara	-0.017	0.485		

Supplementary Materials

Large scale study of benthic communities in Eastern Indonesia's reef systems

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Fig. S1. Hard coral cover on the surveyed sites in Spermonde Archipelago, South Sulawesi.

Table S1. Survey dates, locations, numbers of transects and photoquadrats, and mean percent cover (%) of benthic communities on shallow reefs (0.5-2 m deep) using georeferenced photoquadrat survey method.

No.	Date	Location	Site	Latitude	Longitude	Transect	Photo-quadrat	Hard Coral			Other Invertebrate		Algae	Seagrass	Abiotic		Other
								Live	Dead	Bleached	Soft Coral	Other Invert.			Rubble	Sand	
1	22-Jun-19	Spermonde	Barrang Lompo	5°3′8.26″ S	119°19′25.69″ E	10	515	16.50	38.24	0.00	2.82	1.46	3.67	12.01	9.65	9.12	6.52
2	23-Jun-19	Spermonde	Lanjukang	5°2′1.39″ S	119°5′9.73″ E	2	75	26.40	60.29	0.00	4.40	1.12	2.99	0.24	1.39	1.09	2.08
3	23-Jun-19	Spermonde	Langkai	4°58′58.35″ S	119°4′12.13″ E	12	460	32.87	43.06	0.00	2.95	2.87	5.54	0.37	3.76	5.12	3.45
4	24-Jun-19	Spermonde	Samatellu Lompo	4°42′23.98″ S	119°19′32.99″ E	3	132	42.47	43.18	0.00	2.36	3.76	2.33	0.09	2.61	1.27	1.92
5	24-Jun-19	Spermonde	Polewali	4°50′46.37″ S	119°24′4.85″ E	5	344	33.87	37.10	0.00	8.98	4.11	4.25	0.44	0.69	0.85	9.72
6	25-Jun-19	Spermonde	Kapoposang	4°41′25.85″ S	118°57′4.21″ E	7	331	20.14	51.17	0.00	2.24	3.20	4.59	0.52	5.02	9.26	3.87
7	25-Jun-19	Spermonde	Tambakulu	4°44′2.51″ S	119°3′43.30″ E	6	321	21.01	51.65	0.00	3.98	2.62	4.98	0.52	6.52	5.57	3.15
8	26-Jun-19	Spermonde	Lumulumu	4°58′53.36″ S	119°12′56.82″ E	9	426	27.44	50.16	0.00	2.65	1.22	1.81	0.39	6.24	5.22	4.87
9	26-Jun-19	Spermonde	Sarappo	4°53′12.75″ S	119°15′41.41″ E	2	129	32.39	42.78	0.00	3.86	3.41	4.09	0.48	1.88	0.57	10.54
10	27-Jun-19	Spermonde	Bonetambung	5°2′42.79″ S	119°16′20.44″ E	6	390	37.41	33.72	0.00	4.03	5.34	1.91	0.69	2.34	6.16	8.39
11	28-Jun-19	Spermonde	Badi	4°58′8.13″ S	119°17′19.82″ E	9	448	38.25	43.91	0.00	3.96	2.69	1.13	0.25	1.69	3.90	4.23
12	29-Jun-19	Spermonde	Badi no. 2	4°58′19.09″ S	119°17′9.07″ E	7	377	38.28	41.80	0.00	2.96	1.43	1.47	0.31	2.06	4.81	6.87
13	29-Jun-19	Spermonde	Bontosua	4°55′32.94″ S	119°18′57.85″ E	13	804	36.66	44.82	0.00	4.49	2.47	1.55	0.18	3.20	2.01	4.62
14	2-Oct-19	Ambon	Kamarian	3°26′28.42″ S	128°25′18.62″ E	3	202	10.52	16.56	0.00	24.54	0.67	0.70	0.00	9.88	36.04	1.07

15	2-Oct-19	Ambon	Tihulale	3°27′27.26″ S	128°29′16.13″ E	1	41	8.63	28.44	0.00	6.20	1.12	2.34	0.05	32.20	19.85	1.17
16	3-Oct-19	Ambon	Saparua Pia	3°30′59.18″ S	128°38′53.27″ E	2	109	10.61	52.18	0.00	7.61	0.92	13.30	0.07	11.50	2.94	0.86
17	3-Oct-19	Ambon	Itawaka	3°31′36.26″ S	128°43′47.69″ E	1	44	50.00	23.50	0.00	8.50	1.45	10.41	0.00	0.00	3.36	2.77
18	4-Oct-19	Ambon	Nusa Laut (Ameth)	3°38′44.86″ S	128°48′33.86″ E	2	98	58.18	22.55	0.00	6.90	4.90	3.00	0.22	0.35	0.08	3.82
19	4-Oct-19	Ambon	Nusa Laut (Titawaai)	3°41′13.26″ S	128°45′41.56″ E	2	86	28.47	42.42	0.00	5.40	8.67	6.91	0.28	0.60	3.07	4.19
20	5-Oct-19	Ambon	Molana	3°37′51.00″ S	128°36′8.68″ E	4	211	38.05	35.22	0.00	8.79	1.57	9.93	0.13	1.86	2.81	1.64
21	5-Oct-19	Ambon	Haruku	3°36′54.20″ S	128°24′47.38″ E	3	159	12.82	46.97	0.00	27.82	1.13	1.80	0.05	1.74	6.10	1.57
22	6-Oct-19	Ambon	Hila	3°35′9.12″ S	128°6′31.05″ E	4	190	38.89	29.84	0.01	4.84	8.11	7.87	0.16	3.44	3.44	3.39
23	6-Oct-19	Ambon	Asilulu	3°40′45.13″ S	127°55′31.16″ E	6	256	37.65	30.85	0.00	8.10	3.38	6.85	0.14	1.72	5.16	6.16
24	7-Oct-19	Ambon	Eri	3°44′40.33″ S	128°7′49.25″ E	3	125	20.22	39.46	0.00	18.37	4.37	4.51	0.00	0.38	11.28	1.41
25	7-Oct-19	Ambon	Hatu	3°43′37.22″ S	128°3′31.08″ E	4	130	27.98	32.91	0.00	23.66	2.86	2.94	0.18	0.06	2.22	7.18
26	10-Oct-19	Ambon	Wae Yase	3°31′33.16″ S	127°54′21.41″ E	3	102	17.94	45.61	0.00	13.69	10.37	6.98	0.25	2.59	1.51	1.06
27	10-Oct-19	Ambon	Tanjung Samala	3°21′45.62″ S	127°39′42.30″ E	2	55	19.20	40.87	0.00	10.87	1.31	2.22	9.02	5.31	8.22	2.98
28	10-Oct-19	Ambon	Batuboi	3°14′56.49″ S	127°33′49.43″ E	3	123	14.46	40.37	0.00	23.53	5.80	6.70	0.05	2.36	5.61	1.12
29	11-Oct-19	Halmahera W	AMB16	1°21′53.46″ S	127°20′56.41″ E	3	93	31.31	39.83	0.00	9.27	1.33	4.54	0.19	1.81	7.59	4.13
30	12-Oct-19	Halmahera W	AMB17	0°33′2.50″ S	127°15′14.48″ E	1	36	14.67	44.39	0.00	15.83	0.89	1.39	0.06	8.00	12.22	2.56
31	12-Oct-19	Halmahera W	Palamea	0°24′53.92″ S	127°6′33.3″ E	4	156	35.22	16.10	0.01	14.35	4.59	15.71	0.18	10.09	2.41	1.35
32	13-Oct-19	Halmahera W	Muari	0°10′45.19″ S	127°8′38.36″ E	3	115	25.58	27.06	0.00	23.03	3.44	6.71	0.03	5.48	6.63	2.03

33	13-Oct-19	Halmahera W	Taneti	0°6′11.42″ S	127°13′14.54″ E	3	116	59.16	18.28	0.00	6.03	0.66	7.45	0.36	2.09	4.29	1.69
34	13-Oct-19	Halmahera W	Tolimao	0°0′40.60″ S	127°10′54.63″ E	6	158	35.44	39.68	0.00	4.85	15.03	2.33	0.03	0.32	0.78	1.54
35	16-Oct-19	Halmahera W	Siko	0°7′53.22″ N	127°6′48.94″ E	7	168	16.39	58.61	0.00	4.63	1.63	1.51	0.04	8.40	7.46	1.32
36	16-Oct-19	Halmahera W	Kayoa	0°5′50.46″ N	127°24′55.63″ E	6	207	29.21	50.96	0.00	8.50	4.38	2.56	0.09	1.09	1.72	1.50
37	16-Oct-19	Halmahera W	Makian	0°17′26.76″ N	127°25′44.07″ E	3	105	66.30	14.99	0.00	5.50	4.76	2.40	0.08	0.93	1.66	3.37
38	17-Oct-19	Halmahera W	Woda	0°23′48.87″ N	127°34′36.66″ E	5	168	56.00	22.51	0.00	5.38	7.29	2.88	0.15	0.87	1.21	3.70
39	17-Oct-19	Halmahera W	Yehu	0°26′52.66″ N	127°34′9.37″ E	5	155	42.58	29.42	0.00	13.60	3.42	2.04	0.18	0.75	5.12	2.89
40	17-Oct-19	Halmahera W	Tidore	0°39′53.01″ N	127°21′47.54″ E	8	243	45.74	41.86	0.00	5.00	2.12	2.91	0.02	0.13	1.48	0.75
41	18-Oct-19	Halmahera W	Ternate	0°51′4.18″ N	127°21′35.26″ E	2	77	37.74	41.79	0.00	4.86	6.16	3.51	0.10	0.18	1.27	4.39
42	19-Oct-19	Halmahera W	Sidongali	0°51′28.13″ N	127°30′40.20″ E	6	247	24.34	34.56	0.00	15.05	4.09	3.72	3.67	9.01	3.53	2.03
43	19-Oct-19	Halmahera W	Saria	1°1′53.57″ N	127°25′13.83″ E	6	204	25.47	42.52	0.00	11.75	2.00	3.04	0.13	1.80	11.58	1.71
44	20-Oct-19	Halmahera W	Tiro	1°39′34.65″ N	127°28′45.71″ E	5	161	26.99	45.83	0.00	6.07	12.77	5.35	0.29	0.75	0.88	1.07
45	20-Oct-19	Halmahera W	Tuotuo	2°5′20.44″ N	127°46′5.14″ E	4	160	29.73	44.13	0.00	9.96	2.86	7.06	0.00	0.85	4.11	1.30
46	21-Oct-19	Halmahera E	Koya	2°0′44.51″ N	128°13′13.49″ E	5	175	5.49	50.93	0.00	3.04	1.73	1.61	2.71	3.87	29.84	0.79
47	21-Oct-19	Halmahera E	Mitita	1°57′41.49″ N	128°13′51.67″ E	4	158	27.28	40.13	0.00	15.38	1.47	4.35	4.29	1.78	3.87	1.44
48	22-Oct-19	Halmahera E	Tagaya	1°42′57.66″ N	128°3′59.80″ E	4	157	4.48	41.38	0.00	2.87	15.03	26.76	5.87	0.71	1.30	1.59
49	23-Oct-19	Halmahera E	Woto	0°38′0.38″ N	128°38′48.35″ E	5	270	25.90	51.05	0.00	5.16	3.95	10.03	0.10	1.41	0.88	1.52
50	23-Oct-19	Halmahera E	Sayafi	0°30′0.33″ N	128°50′29.10″ E	3	111	55.69	26.00	0.00	1.68	3.17	9.48	0.04	2.32	0.27	1.35

51	23-Oct-19	Halmahera E	Muor	0°11′15.42″ N	128°56′28.46″ E	3	110	27.58	33.53	0.00	17.33	7.89	8.05	0.05	0.95	0.24	4.38
52	24-Oct-19	Halmahera E	Tobalai	1°36′46.61″ S	128°21′51.76″ E	3	126	29.84	41.19	0.00	13.22	7.35	5.41	0.08	0.30	0.40	2.21
53	26-Oct-19	Lucipara	Pulau Selatan	5°30′6.82″ S	127°33′56.07″ E	7	262	11.24	61.92	0.00	2.29	4.84	16.21	0.82	0.39	0.38	1.91
54	26-Oct-19	Lucipara	Maisel	5°28′42.97″ S	127°32′3.14″ E	5	159	4.21	60.14	0.00	1.06	0.64	1.99	0.86	1.95	28.79	0.36
55	26-Oct-19	Lucipara	Mai	5°28′21.02″ S	127°30′4.92″ E	6	237	26.11	37.77	0.00	19.80	4.99	8.39	0.03	0.09	0.27	2.55
56	27-Oct-19	Lucipara	Kadola	5°21′47.21″ S	127°44′48.30″ E	9	348	22.40	31.93	0.00	11.72	15.25	14.61	0.17	0.45	0.38	3.09
57	27-Oct-19	Lucipara	Bingkudu	5°20′42.14″ S	127°46′3.17″ E	6	171	8.49	71.93	0.14	1.20	1.32	10.11	0.88	0.96	3.26	1.71
58	27-Oct-19	Lucipara	Mai (north)	5°23′24.57″ S	127°46′46.43″ E	7	254	23.34	38.69	0.00	5.69	12.57	14.97	0.39	0.79	1.25	2.31

Note: Other invertebrate (COTS, mobile and sessile invertebrate, sponge, urchin); Algae (cyanobacteria, benthic microalgae in sand, crustoce coraline algae (CCA), *Halimeda*, macroalgae); Other (transect, trash, unclear, unknown objects)

Table S2. Survey dates, locations, numbers of quadrat transects, and mean percent cover (%) of benthic communities on deeper reefs (~8 m) using quadrat transect survey method.

No.	Date	Location	Site	Latitude	Longitude	Quadrat transect	Hard Coral			Other Invertebrate		Other Cnidarian*	Algae	Abiotic			Other*
							Live	Dead	Bleached	Soft Coral	Other Invert.*			Rock	Rubble	Sand	
1	19-Jun-19	Spermonde	Barrang Lompo	5°3′9.25″ S	119°19′17.72″ E	190	30.89	19.67	0.11	2.78	3.78	1.50	1.39	0.00	23.94	15.94	0.00
2	19-Jun-19	Spermonde	Bonetambung	5°1′56.49″ S	119°16′38.42″ E	240	8.00	17.83	0.04	0.50	1.67	0.88	1.38	0.00	42.00	27.67	0.04
3	20-Jun-19	Spermonde	Lumulumu	4°58′27.77″ S	119°12′28.40″ E	240	52.16	23.86	0.71	0.25	0.85	0.46	1.09	0.00	19.14	1.47	0.00
4	20-Jun-19	Spermonde	Sarappo	4°52′40.98″ S	119°15′34.13″ E	240	35.36	15.34	0.00	1.46	2.25	0.33	0.29	0.00	36.35	8.61	0.00
5	21-Jun-19	Spermonde	Sanane	4°56′58.59″ S	119°20′13.56″ E	240	49.98	14.50	0.08	0.17	1.80	1.35	0.54	0.00	25.44	6.14	0.00
6	21-Jun-19	Spermonde	Balang Lompo	4°57′3.17″ S	119°23′35.27″ E	240	17.22	11.09	0.00	0.04	2.92	1.17	4.46	0.00	43.97	19.13	0.00
7	23-Jun-19	Spermonde	Lanjukang	4°59′6.61″ S	119°4′3.00″ E	240	37.79	24.83	0.29	0.63	2.17	0.75	4.38	0.00	18.46	10.71	0.00
8	23-Jun-19	Spermonde	Langkai	5°1′50.45″ S	119°5′4.67″ E	240	25.92	33.71	0.08	5.04	1.42	0.50	1.50	0.00	13.50	18.33	0.00
9	24-Jun-19	Spermonde	Samatellu	4°42′27.43″ S	119°19′33.06″ E	240	56.97	11.97	0.80	0.59	4.21	1.77	1.34	0.00	19.87	2.38	0.08
10	24-Jun-19	Spermonde	Polewali	4°50′46.32″ S	119°24′4.86″ E	240	25.56	15.56	0.00	0.04	4.56	3.05	5.46	0.00	33.65	12.08	0.08
11	25-Jun-19	Spermonde	Kapoposang	4°41′15.25″ S	119°57′1.76″ E	240	31.26	37.00	0.00	1.93	2.65	3.48	3.86	0.00	8.51	11.31	0.00
12	25-Jun-19	Spermonde	Tambakulu	4°44′2.54″ S	119°3′43.20″ E	240	38.14	19.78	0.08	0.50	1.40	8.92	6.42	0.00	23.54	1.18	0.04
13	2-Oct -19	Ambon	Kamarian	3°26′29.72″ S	128°25′19.67″ E	240	8.42	0.33	0.08	10.13	1.54	0.00	1.58	28.04	12.21	37.58	0.08

14	2-Oct-19	Ambon	Tihulale	3°27′29.84″ S	128°29′21.44″ E	240	26.33	5.13	0.38	0.29	2.88	0.04	0.33	7.58	55.79	1.13	0.13
15	3-Oct-19	Ambon	Saparua Pia	3°30′59.83″ S	128°38′54.06″ E	240	11.06	1.42	0.00	0.00	0.87	0.00	0.00	7.15	67.95	11.47	0.08
16	3-Oct-19	Ambon	Itawaka	3°31′37.24″ S	128°43′48.93″ E	240	61.02	4.43	0.00	13.40	3.46	0.08	0.17	14.56	0.88	2.00	0.13
17	4-Oct-19	Ambon	Nusa Laut (Ameth)	3°38′42.21″ S	128°48′30.6″ E	240	48.19	4.81	0.00	3.46	3.96	3.79	1.60	18.25	8.81	7.05	1.21
18	4-Oct-19	Ambon	Nusa Laut (Titawaai)	3°41′8.7″ S	128°45′37.69″ E	240	57.45	3.52	0.00	11.01	1.67	3.68	0.29	18.20	3.14	1.05	0.42
19	5-Oct-19	Ambon	Molana	3°37′47.06″ S	128°36′8.24″ E	240	21.00	0.75	0.00	44.00	5.60	0.17	0.55	24.11	0.58	3.25	0.21
20	5-Oct-19	Ambon	Haruku	3°36′55.04″ S	128°24′44.78″ E	240	9.25	0.96	0.00	2.56	7.87	0.29	13.48	7.89	11.77	45.88	0.17
21	6-Oct-19	Ambon	Hila	3°35′3.16″ S	128°6′23.36″ E	240	23.42	0.57	0.00	0.46	5.12	7.56	1.37	15.50	23.70	22.22	0.34
22	6-Oct-19	Ambon	Asilulu	3°40′46.92″ S	127°55′21.79″ E	240	36.71	0.11	0.00	5.88	14.27	2.40	6.29	13.97	4.52	15.68	0.83
23	7-Oct-19	Ambon	Amahusu/Eri	3°44′42.47″ S	128°7′46.92″ E	240	16.51	0.13	0.00	1.59	25.36	3.10	10.53	6.12	7.26	29.36	0.63
24	7-Oct-19	Ambon	Hatu	3°43′35.47″ S	128°3′32.87″ E	240	31.52	0.54	0.00	6.29	8.63	0.21	2.83	8.05	10.84	30.71	0.46
25	12-Oct-19	Halmahera W	Palamea	0°24′53.21″ S	127°6′34.24″ E	240	22.56	0.63	0.13	17.05	0.54	0.29	2.42	2.64	37.02	16.63	0.08
26	13-Oct-19	Halmahera W	Muari	0°10′43.32″ S	127°8′36.13″ E	240	24.41	0.33	0.04	22.80	0.71	0.08	1.38	1.00	35.43	13.81	0.08
27	13-Oct-19	Halmahera W	Tolimao	0°0′39.96″ S	127°10′54.44″ E	240	40.58	0.17	0.08	5.17	2.55	11.26	18.15	5.59	10.93	5.51	0.13
28	16-Oct-19	Halmahera W	Siko	0°7′54.15″ N	127°6′42.69″ E	240	3.04	0.00	0.00	0.46	0.71	0.00	0.21	12.96	68.63	14.00	0.00
29	16-Oct-19	Halmahera W	Kayoa	0°5′48.84″ N	127°24′53.17″ E	240	20.96	0.00	0.00	18.88	1.75	0.88	0.83	28.83	16.33	11.50	0.04
30	16-Oct-19	Halmahera W	Makian	0°17′27.02″ N	127°25′45.73″ E	240	33.50	0.00	0.08	0.08	4.71	0.08	0.00	7.46	11.00	43.08	0.00
31	17-Oct-19	Halmahera W	Woda	0°23′52.04″ N	127°34′36.16″ E	240	71.25	0.00	0.00	10.54	0.63	0.00	4.29	9.83	3.17	0.29	0.00

32	17-Oct-19	Halmahera W	Yehu	0°26′57.34″ N	127°34′15.85″ E	240	43.92	0.00	0.00	1.04	0.92	0.00	0.92	7.08	2.83	43.13	0.17
33	17-Oct-19	Halmahera W	Tidore	0°40′0.4″ N	127°21′46.94″ E	240	17.25	0.04	0.08	0.17	1.96	0.00	0.00	28.92	26.29	25.29	0.00
34	18-Oct-19	Halmahera W	Ternate	0°51′9″ N	127°21′29.88″ E	240	42.54	0.00	0.00	1.21	2.13	0.13	0.96	21.33	0.13	31.58	0.00
35	18-Oct-19	Halmahera W	Sidangoli	0°51′26.17″ N	127°30′26.46″ E	240	6.38	0.00	0.00	4.08	5.71	0.04	0.00	17.83	38.83	27.13	0.00
36	19-Oct-19	Halmahera W	Tanjung Bobo	1°1′53.07″ N	127°25′16.57″ E	240	13.04	0.00	0.00	5.33	6.04	1.58	0.13	8.29	24.46	41.13	0.00
37	26-Oct-19	Lucipara	Pulau Selatan	5°30′10.40″ S	127°33′57.13″ E	240	42.50	0.00	0.00	2.75	0.75	1.83	0.00	47.46	3.29	1.42	0.00
38	26-Oct-19	Lucipara	Mai	5°28′18.95″ S	127°30′8.1″ E	240	33.63	0.00	0.00	24.21	9.88	0.58	3.96	24.46	0.79	2.50	0.00
39	26-Oct-19	Lucipara	Kadola	5°21′43.02″ S	127°44′53.34″ E	240	30.95	0.00	0.00	17.90	10.20	4.86	13.05	18.67	0.92	3.46	0.38
40	26-Oct-19	Lucipara	Pl Penyu Pulau Mai	5°23′23.96″ S	127°46′40.58″ E	240	27.48	0.08	0.00	5.11	8.71	18.84	12.75	25.38	0.63	1.01	0.58

*Note: Other invertebrate (ascidian, bryozoan, crinoid, giant clam, mobile fauna, sponge); Other cnidarian (anemone, *Dendophyllia*, *Heliopora*, hydroid, *Millepora*, seafan, zoanthid); Other (trash, tape, wand, shadow, unknown object).

Table S3. Shallow reef ecosystems | SIMPER Results - Similarity

	Spermonde		Ambon		Halmahera West (ns - ANOSIM)		Halmahera East		Lucipara	
Average similarity:	83.05		67.35		73.08		66.75		67.42	
	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%
Dead Coral	44.76	49.05	35.18	43.46	36.03	39.32	40.60	52.90	50.40	60.22
Hard Coral	31.05	31.70	26.24	25.88	35.40	37.16	25.18	23.17	15.97	15.51
Other	5.40	4.54								
Soft Coral	3.82	3.60	13.25	12.96	9.63	9.20	8.38	6.70		
Sand	4.23	3.02	7.45	4.76						
Algae			5.76	5.41	4.42	3.75	9.38	7.58	11.05	11.67
Other Invert.					4.55	3.43			6.60	4.50

Table S4. Shallow reef ecosystems | SIMPER Results – Drivers of dissimilarity between locations in the shallow reefs

	Spermonde & Ambon		Spermonde & Halmahera West		Ambon & Halmahera West		Spermonde & Halmahera East		Ambon & Halmahera East	
Average dissimilarity	29.36		24.56		30.07		28.07		32.92	
	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%
Hard Coral	31.05	24.95	31.05	26.51	26.24	30.21	31.05	27.28	26.24	26.91
Dead Coral	44.76	20.78	44.76	26.07	35.18	21.10	44.76	16.15	35.18	16.97
Soft Coral	3.82	16.34	3.82	12.37	13.25	12.76	3.82	10.39	13.25	13.69
Sand	4.23	10.18	4.23	7.30	7.45	10.34	4.23	11.80	7.45	13.63
Rubble	3.62	8.41			4.93	8.73			4.93	6.73
Algae	3.10	6.25			5.76	6.48	3.10	12.07	5.76	9.59
Other	5.40	5.82	5.40	6.97			5.40	6.56		
Rubble			3.62	6.86						
Other Invert.			2.75	5.98	3.78	6.16	2.75	6.91	3.78	6.60

Table S4 (continued)

	Halmahera West & Halmahera East		Spermonde & Lucipara		Ambon & Lucipara		Halmahera West & Lucipara		Halmahera East & Lucipara	
Average dissimilarity	30.54		32.18		36.43		36.03		32.36	
	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%
Hard Coral	35.40	30.25	31.05	25.14	35.18	26.04	35.40	28.43	40.60	24.97
Dead Coral	36.03	20.19	44.76	22.64	26.24	21.29	36.03	27.21	25.18	24.06
Soft Coral	9.63	10.86	3.82	8.59	13.25	13.46	9.63	10.20	8.38	11.37
Sand	4.35	11.02	4.23	10.87	7.45	12.63	4.35	9.82	5.26	12.73
Rubble										
Algae	4.42	10.98	3.10	13.00	5.76	9.39	4.42	10.75	9.38	11.72
Other			5.40	5.46						
Rubble										
Other Invert.	4.55	7.30	2.75	7.86	3.78	7.29	4.55	7.42	5.80	8.67

Table S5. Deeper reef ecosystems **|** SIMPER Results - Similarity

	Spermonde		Ambon		Halmahera		Lucipara	
Average similarity:	71.83		51.49		54.62		69.54	
	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%
Hard Coral	34.10	35.77	29.24	35.95	28.29	31.66	33.64	42.56
Rubble	25.70	26.69	17.29	12.46	22.92	21.28		
Dead Coral	20.43	22.00						
Sand	11.25	9.10	17.28	15.83	22.76	25.66		
Rock			14.12	19.37	12.65	13.10	28.99	31.16
Other Invert.			6.77	6.28			7.39	7.06
Soft Coral			8.26	5.25			12.49	8.70
Algae							7.44	4.93

Table S6. Deeper reef ecosystems **|** SIMPER Results – Drivers of dissimilarity between locations in the deep reefs

	Spermonde & Ambon		Spermonde & Halmahera		Ambon & Halmahera		Spermonde & Lucipara		Ambon & Lucipara		Halmahera & Lucipara	
Average dissimilarity	52.79		50.30		46.25		62.37		48.24		53.58	
	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%	Av. Abund	Contrib%
Rubble	25.70	20.00	25.70	17.66	17.29	23.84	25.70	19.45	17.29	16.69	22.92	20.27
Hard Coral	34.10	17.74	34.10	19.25	29.24	21.89	34.10	9.57	29.24	16.86	28.29	15.30
Dead Coral	20.43	17.53	20.43	20.21			20.43	16.34				
Sand	11.25	13.38	11.25	15.81	17.28	18.79	11.25	7.59	17.28	16.15	22.76	19.53
Rock	0.00	13.35	0.00	12.57	14.12	9.98	0.00	23.22	14.12	16.29	12.65	16.75
Soft Coral	1.16	7.29	1.16	6.72	8.26	10.30	1.16	9.15	8.26	12.17	7.23	9.55
Other Invert.	2.47	4.71			6.77	5.75			6.77	6.39		
Algae							2.68	5.05	3.25	6.85	2.44	6.76
Cnidarian											1.20	6.04

Table S7. List of reference publications from the study locations. Only studies published between 2005 and 2020 were considered.

a. Spermonde Archipelago, South Sulawesi

No.	Reference
1	Abdullah, Kasmi M. 2015. Karakteristik habitat dan kelimpahan ikan hias injel batman (*Pomacanthus Imperior*) di perairan Kabupaten Pangkep, Sulawesi Selatan. Jurnal Galung Tropika, 4 (3), 164 - 172.
2	Afni N. 2017. Kondisi terumbu karang di Pulau Samatellu Pedda Kecamatan Liukang Tupabbiring Kabupaten Pangkep Sulawesi Selatan. Undergraduate thesis, UIN Alauddin Makassar, p. xiv+85
3	Ahmad. 2013. Sebaran dan keanekaragaman ikan target pada kondisi dan topografi terumbu karang di Pulau Samatellulompo Kabupaten Pangkep. Undergraduate thesis, Universitas Hasanuddin, Makassar, p. xv+60.
4	Ali SN. 2017. Perkembangan kondisi terumbu karang di Pulau Kapoposang tahun 2009-2015 Kabupaten Pangkep. Universitas Hasanuddin, Makassar, p. xiii+55.
5	Amrullah. 2014. Analisis kondisi terumbu karang di perairan Kecamatan Liukang Tuppabiring Kabupaten Pangkep Sulawesi Selatan dengan pendekatan remote sensing (penginderaan jauh). Jurnal Biotek, UIN Alauddin Makassar, 2 (1), 1-14.
6	Arifin T, Amri SN, Arlyza IS. 2014. Karakteristik parameter nutrien dan ekosistem terumbu karang di wilayah pesisir Selat Makassar. Potensi sumber daya kelautan dan perikanan WPPNRI 713, pp. 23-42.
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