CORAL TRIANGLE INITIATIVE
ON CORAL REEFS, FISHERIES AND FOOD SECURITY

IDENTIFYING GAPS IN THE CORAL TRIANGLE MARINE PROTECTED AREA SYSTEM AS CONSERVATION PRIORITIES

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Executive Summary

The Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI-CFF) is a multilateral partnership of six countries aiming (1) to establish a representative system of marine protected areas that covers 20% of each marine habitat (goal 3); (2) to manage and improve the status of threatened species (goal 5); and (3) to implement climate adaptation measures (goal 4). Here we assess the Coral Triangle Marine Protected Area System in light of these goals, and identify future conservation priority areas for different objectives on a regional scale, as well as risks and data gaps.

Representation

Current MPA System: Coral Reefs 14.7%, Mangroves 5.4%
Current No-Take System: Coral Reefs 2%
Ecoregions: High protection Gulf of Papua, Papua, S.Kuroshio
No protection: Arafura Sea, Halmahera, SE Papua New Guinea, Eastern Solomons (Vanuatu)

- Objective: capture 20%, 30%, 40% of all habitats in a representative network
- Priorities: Northern Borneo, Banda, Solomons Mangroves in East Borneo, southwest New Guinea

Threatened Sites

- Objective: capture 100% of fish spawning aggregation sites and 50% of aggregation habitats
- Priorities: Northern Borneo, Banda Sea, Southern Raja Ampat

Threatened Species

- Objective: capture 50% of important sea turtle habitat (feeding, nesting sites) and turtle migration pathways
- Priorities Northern Borneo, Banda Sea, Sulu archipelago, Sanghie-Talaud, and eastern Java Sea

Dispersal Connectivity

- Objective: incorporate modeled larval dispersal for coral trout *Plectropomus leopardus* and black teatfish *Holothuria whitmaei* to capture network connectivity
- Priorities: Important source reefs for current MPAs in Banda Sea, Raja Ampat, southern Sulawesi, and eastern Philippines

Climate Change

- Objective: incorporate historical and modeled future thermal stress to evaluate potential refuges;
- Priorities: conservation priorities unclear as thermal exposure is uniformly high across the region

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Introduction

Globally imperiled coral reef ecosystems are the subject of many local, regional and international conservation efforts that aim to sustain coral reef biodiversity and ecosystem services. One regional coral reef conservation effort, established in 2007, is the Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI-CFF), a multilateral partnership of six countries (Philippines, Malaysia, Indonesia, Timor Leste, Papua New Guinea and the Solomon Islands: Figure 1) located in the center of reef biodiversity, threat, and human reliance on coral reef products. The Coral Triangle has been named for its high scleractinian (hard) coral diversity of over 600 species (Veron *et al.* 2009). Similarly, the territories of Malaysia, Indonesia, the Philippines, Timor Leste, Papua New Guinea and the Solomon Islands are reported to support around 3250 species of reef fishes (Sanciangco *et al.* 2013), 51 of the world's 70 species of mangroves (Polidoro *et al.* 2010), and six of the world's seven threatened sea turtle species. The Coral Triangle's marine and coastal habitats are also among the most threatened in the world (Burke *et al.* 2011, 2012), with heavy reliance of local people upon marine resources for subsistence, income, and cultural identity. More than 120 million people depend directly on fish and other marine resources as their principle source of income, food, and livelihoods. The Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security aims to unite and expand the work of the participating countries to achieve the best possible outcomes for marine biodiversity conservation and sustainable use. In 2009, the CT6 developed a CTI-CFF Regional Plan of Action (CTI-CFF RPoA) that includes five goals. One goal (Goal 3, Target 1) is to establish a comprehensive, ecologically representative and well-managed region-wide Coral Triangle Marine Protected Area System (CTMPAS) that is composed of prioritized MPAs/MPA networks that are connected, resilient, and sustainably financed, and designed in ways that generate significant income, livelihoods, and food security benefits for coastal communities and conserve the region's rich biological diversity.

The CTI-CFF Regional Plan of Action states that the Coral Triangle Marine Protected Area System will ultimately include a significant percentage of total area of each major nearshore habitat type within the Coral Triangle region (e.g., coral reefs, seagrass beds, mangroves, beach forests, wetland areas and marine/offshore habitat) in some form of designated protected status, with 20% of each major marine and coastal habitat type in strictly protected "no-take replenishment zones" (to ensure long-term, sustainable supplies of fisheries). If well designed and effectively managed, the Coral Triangle Marine Protected Area System will also contribute to achieving the other four goals of the CTI-CFF Regional Plan of Action regarding: designating and effectively managing priority seascapes; applying an ecosystem approach to management of fisheries and other marine resources; climate change adaptation; and improving the status of threatened species (including sharks, sea turtles, corals, seagrass, and mangroves).

Any decision about expending resources or effort towards improved environmental management must sensibly be preceded by assessing the existing state of both the environment and existing management. While many coastal zone management and conservation activities are underway in the region, the proportion of currently protected marine habitats is unknown. Also unknown is where additional broad areas of conservation interest might be, and how these factors might change as we seek to implement the aims of the coral triangle initiative in a step-wise manner. These aims include: (1) to establish a representative system of marine protected areas that covers 20% of each marine habitat (goal 3); (2) to manage and improve the status of threatened species (goal 5); and (3) to implement climate adaptation measures (goal 4) (Coral Triangle Initiative 2009; Coral Triangle Initiative on Coral Reefs Fisheries and Food Security (CTI-CFF) 2013). Multi-national coordination of these efforts is expected to increase mutual benefit of management actions, particularly for reef areas connected through larval dispersal or adult migration.

Here we provide the first regional analysis of gaps in the existing Coral Triangle MPA system. We define the region as the EEZs of the six participating countries (Figure 1) and identify priority areas for additional new marine protected areas to be considered by the six countries (or the CTI-CFF). We identify such broad priority areas focusing on the following objectives:

(a) Create a representative reserve system of major habitat types;

(b) Protect critical sites and connections for threatened sea turtles and groupers;

(c) Integrate connections among reefs driven by larval dispersal; and

(d) Integrate historical and projected future thermal stress.

This is a spatial analysis concerned with building upon established no-take areas, or sanctuaries. In the Coral Triangle, no-take areas exist as small community-based protected areas, but also as parts (zones) of larger marine protected areas. This contrasts with other analyses in the region that report on all marine protected areas with some level of protection (Dirhamsyah *et al.* 2012; Lim 2012; National CTI Coordinating Committee Papua New Guinea 2012; National CTI Coordinating Committee Timor Leste 2012; Saad 2012; Sulu *et al.* 2012; White *et al.* 2013 in press). Our analysis is about identifying future conservation priorities, and these could well be the expansion of no-take areas within existing marine protected areas. No-take areas provide more certainty in the context of achieving conservation benefits for multiple aspects of marine biodiversity (e.g. multi-species systems, and varied habitat types) and associated processes (e.g. larval dispersal, trans-ecosystem habitat use by turtles, recruitment features such as spawning aggregations) (Abesamis & Russ 2005; Robbins *et al.* 2006; Vandeperre *et al.* 2011; Miller *et al.* 2012), than other management zones where benefits are more difficult to quantify (Mills *et al.* 2011; Makino *et al.* in revision, 2013). In this analysis, we apply the precautionary principle and assume that no-take areas are the main vehicle for biodiversity conservation in the Coral Triangle. We acknowledge the caveat that this assumption likely underestimates the conservation benefit that is truly being achieved by the collective suite of marine protected areas across the region.

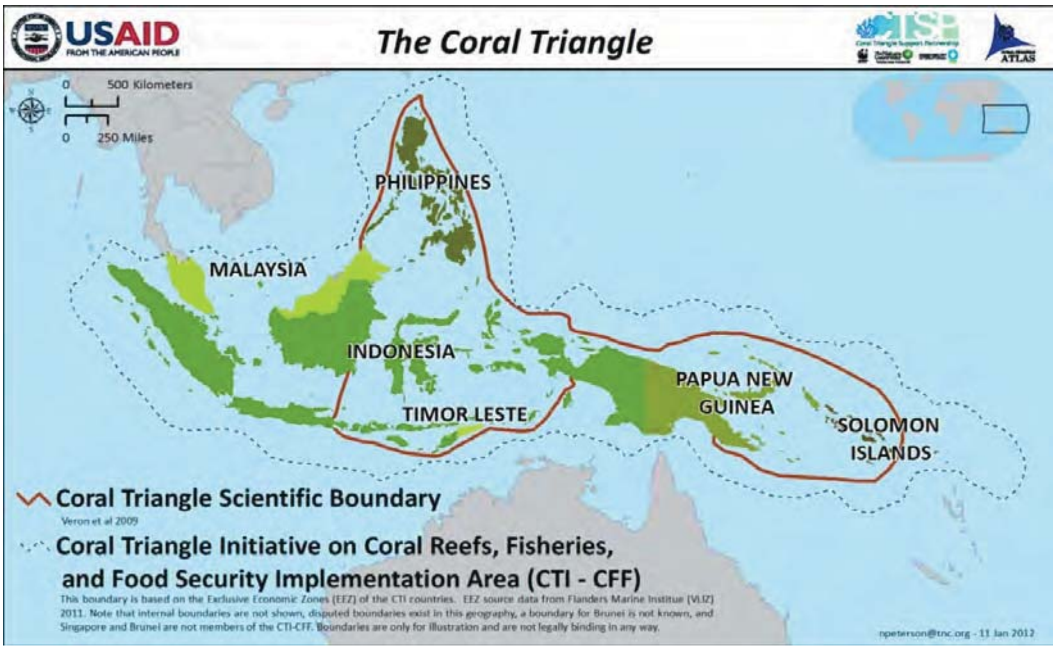


Figure 1: The six countries of the Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security, with their estimated national jurisdiction (outer boundary representing their approximate Exclusive Economic Zones). Created under the Coral Triangle Atlas by Nate Peterson (TNC).

Methods

We collated spatial data for biodiversity, socio-economic and climate features from open and closed sources (Appendix 1). We corrected errors and discrepancies to fit the data into a consistent database. Based on this spatial database, we explore conservation objectives (a-d) using the spatial decision support tool for conservation, Marxan (freely available at www.biology.uq.edu.au/marxan) (Ball *et al.* 2009). Marxan implements the objective of achieving user-defined conservation targets (i.e. amounts of habitat in protected areas) for biodiversity representation and connectivity constraints whilst minimizing the overall cost of a protected area system (Ball *et al.* 2009). For example, a conservation goal could be to identify protected area systems that represent 20% of all habitats and leatherback turtle migration pathways with minimal losses to fisheries profit. Management efficiency is modeled by maximizing the spatial compaction and by minimizing the cost of the resulting reserve system. We elected not to pursue spatial compactness as a parameter (excluding connectivity analyses), as it would bias results towards established marine protected areas at the expense of identifying new conservation priorities. In each scenario, 100 runs were performed to assess the spatial variability in conservation priorities in the different solutions found. We thus calculate selection frequencies of reef, benthic and mangroves habitats in Marxan as a proxy for conservation priority areas across the Coral Triangle. We explore the conservation objectives (a-d) with different scenarios in Marxan while accounting for the following cost and other parameters.

The total annual economic value of coastal and marine habitats in the Coral Triangle (coral reefs, mangroves, and seagrass) is an estimated US $2.3 billion for Indonesia and the Philippines alone (Burke *et al.* 2012). Many valued economic activities generating this wealth will be constrained when new protected areas are implemented to protect these ecosystems. Therefore, this analysis considers the human dimension as an indicator of potential conflict with users arising from limiting their activities (e.g. prohibiting fishing) (Halpern *et al.* 2008). We model them as foregone artisanal fishing profit for coral reef no-take reserves. For mangroves, we use the number of prospective local users (average population density per 10 km^2 area) (Center for International Earth Science Information Network (CIESIN) *et al.* 2005) as a proxy for potential conflict arising from mangrove protected areas. The resulting socio-economic cost index represents the “cost” value used in Marxan, covering mangrove and reef habitats (Figure 2).

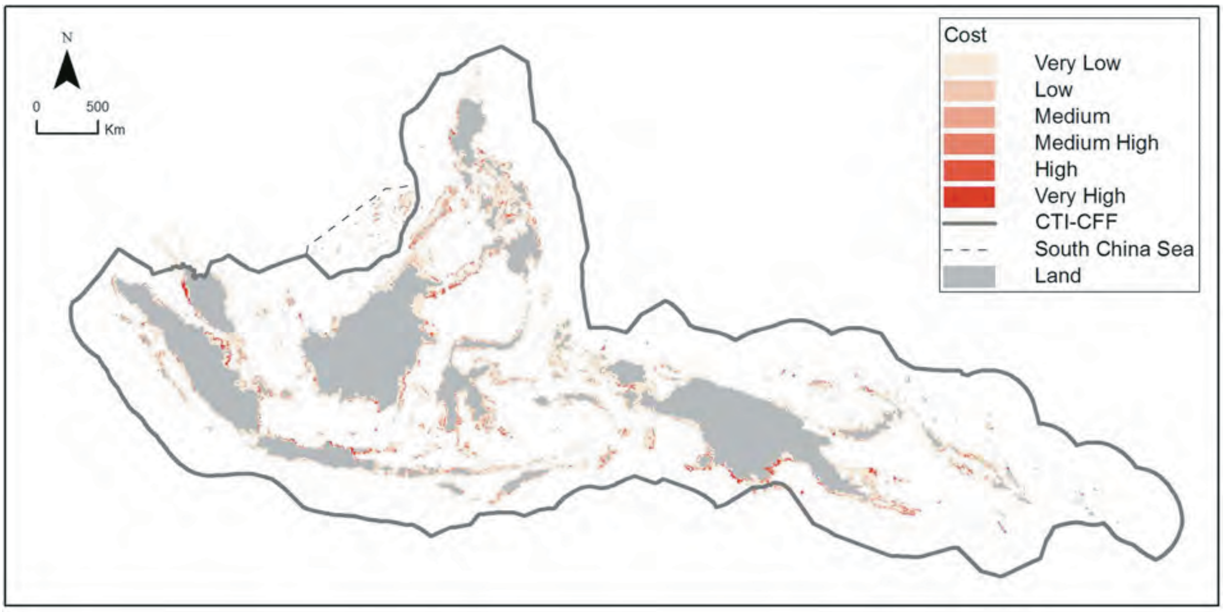


Figure 2. Spatial distribution of different levels of the socio-economic cost index as proxy for foregone fisheries benefit when MPAs are established.

The countries in the Coral Triangle have successfully established more than 1,900 marine protected areas (Figure 3) (Coral Triangle Initiative on Coral Reefs Fisheries and Food Security (CTI-CFF) 2013). We collated and corrected outlines and point coordinates of marine and coastal protected areas throughout the region (Appendix 1). We use two strategies to incorporate protected areas in Marxan scenarios, depending on their size and data format (Figure 4). Protected areas defined by point coordinates only (n=809) are assumed to reside entirely on their designated habitat (reef, seagrass or mangroves) and be entirely no-take. Their sizes are either reported in the data, and where they are not, they are assigned as the country median of all small point protected areas. We calculate the proportion of protected habitat in planning units from point protected areas and where the cumulative reserved area per planning unit exceeds 50% of the total planning unit habitat, the planning unit is treated as an existing protected area in our analysis (Figure 4a). This approach is primarily used in the Philippines and Solomon Islands.

Many locally managed protected areas throughout the region with known boundaries (n=498) are often smaller than a single planning unit (10 x 10 km). While shown to have local fisheries management benefits (Cinner *et al.* 2005; Abesamis *et al.* 2006), treating the entire planning unit as an existing marine protected area would overestimate the amount of protected habitat in our analysis. Thus, we assume the boundaries of small marine protected areas to be correctly placed, and the habitat therein is calculated in the same fashion as point protected areas. If the cumulative habitat protected by both point and small marine protected areas is more than 50% of the total habitat, we incorporate the planning unit as an established protected area in our analysis.

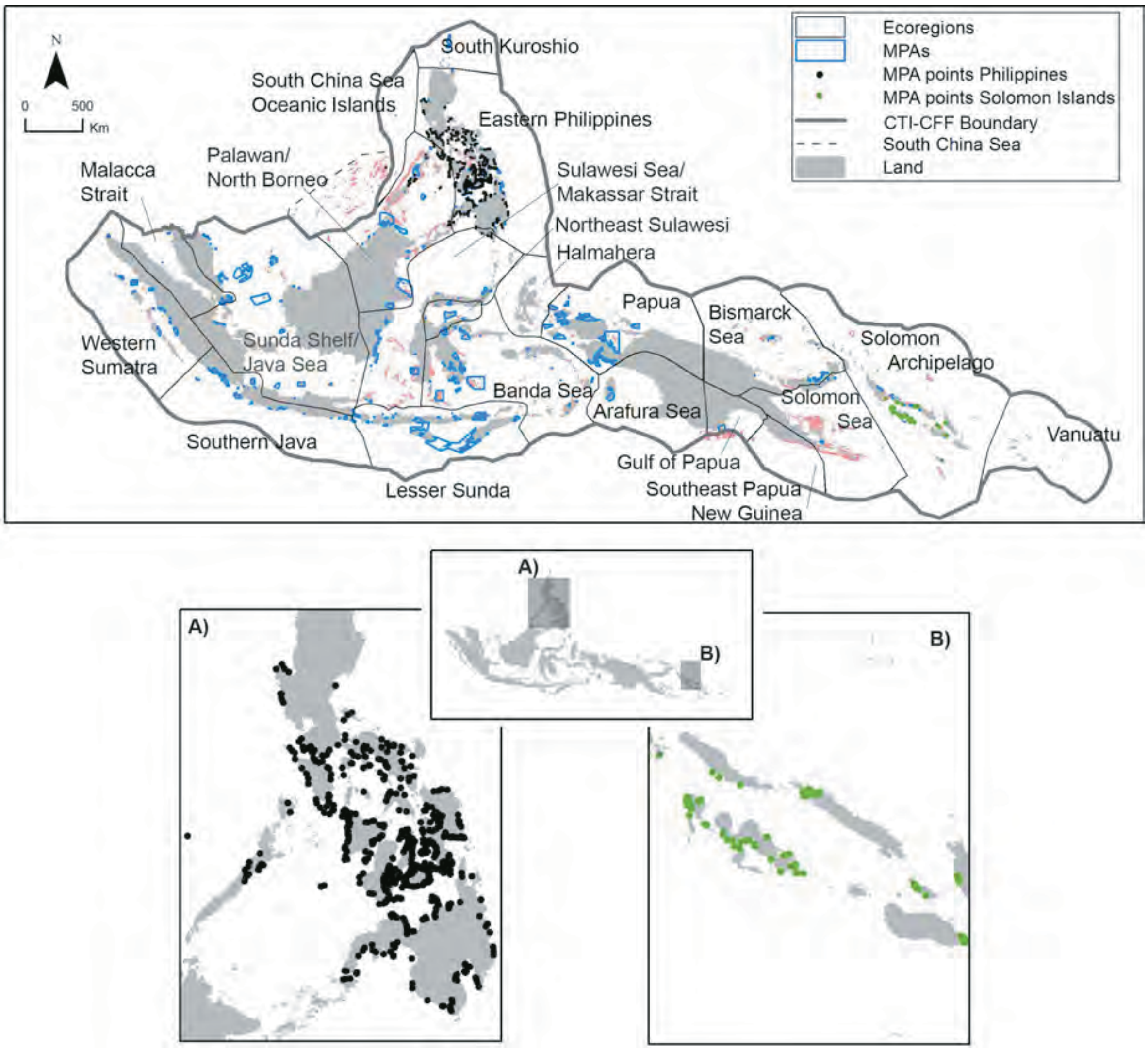


Figure 3. Existing marine protected areas (MPAs) in Coral Triangle by ecoregions. Insets show MPA points in the Philippines (A) and Solomon Islands (B), as reserves where only point coordinates are known.

Throughout the Coral Triangle, there are also large, delineated protected areas (i.e. Savu Sea Marine National Park) that encompass multiple planning units (n=58), for which zoning plans were unavailable. We therefore assume the actual no-take area would range between 10 to 30% (pers. comm. A White) and we randomly select 10% of the planning units within to be protected in our Marxan analyses (Figure 3b). This approach assumes that all the habitats contained within the chosen planning units are conserved. This method is fair across all large marine protected areas, but it possibly over- or under-estimates actual habitat protection levels.

Figure 4. Assignment rules for locking in planning units as protected areas in Marxan: a) point and small MPA locations provide full protection for their entire planning unit area (if total MPA area > 50% of total habitat in a cell); and b) large MPAs are assumed to protect habitat within 10% of randomly chosen planning units. .

Aim 1: Representation of marine habitats

Habitat representation is a basic approach used in conservation prioritization that guides the placement of protected areas to ensure the persistence of biodiversity (Margules & Pressey 2000). Here, we used 10 habitat classes (Appendix 1) belonging to three main categories: mangroves, coral reefs, and other benthic habitats (Figure 5) in our base representation scenarios. These habitat classes were delineated from an unprocessed unsupervised classification of satellite imagery (Kakuta *et al.* 2010), and while we used the categories associated with the dataset, we recognize that the terminology is highly likely to be inappropriate and is in need of updating, ground-truthing and systematic review. Nevertheless, we used this dataset as it was the only available dataset of marine habitats spanning the entire region. This dataset was appended with coral reef data from the global WCMC dataset (UNEP-WCMC 2010) in areas not covered – these sites were mostly remote islands and submerged reefs. The Coral Triangle is delineated into 21 geographically distinct areas, or ecoregions (Spalding *et al.* 2007) that act as a basis for ecological assessments (Figure 4). We identified regional conservation priorities for objectives aiming to represent 20%, 30%, and 40% of all habitat types with at least 20% of all ecoregional habitats protected. We consider 20% representation to be the baseline from which we conduct inter- and cross-scenario comparisons. All scenarios share socio-economic cost index, habitat data and the locations of existing marine reserves.

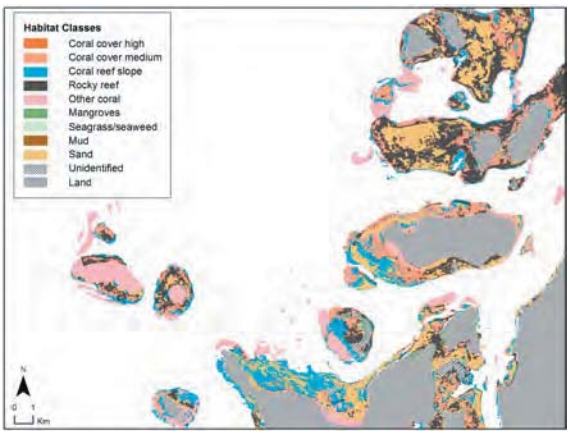


Figure 5. Example of habitat types from Duroa Island, Malukku, Indonesia. Coral cover high, Seagrass/ seaweed, and Mud habitats not shown.

Aim 2: Conserving threatened species and vulnerable sites

The Coral Triangle region hosts many threatened species and critical habitat locations. Here we use two examples: 1) fish spawning aggregations and 2) sea turtle habitat and migration, to show how threatened sites and species conservation objectives alter regional conservation priorities. *The data used in both cases is biased towards the central part of the region where the majority of research is conducted; thus our analyses will need to be updated as more information becomes available.* The data bias also highlights the need to fill data gaps or improve data sharing arrangements to achieve the best outcomes in assessing regional conservation needs for threatened species.

Many species of fish aggregate to spawn in locations within (resident spawning aggregations) and sometimes outside their normal territory (transient spawning aggregations) (Sadovy de Mitcheson et al. 2008). Fish spawning aggregations (FSAs) are a crucial, and predictable part of fish life cycles that create an easy and often heavily exploited fisheries target (Hamilton et al. 2012). Protecting spawning aggregation sites is important to maintain regional larval supplies, and has been effectively demonstrated in Melanesia and Micronesia, where fish biomass increased up to 10 fold after fishing ceased (Golbuu & Friedlander 2011; Hamilton et al. 2011). In this analysis we used spawning aggregation data for 11 fish families including groupers (Serranidae), snappers (Lutjanidae) and emperors (Lethrinidae), under license from the Society for the Conservation of Reef Fish Aggregations (SCRFA) (Sadovy de Mitcheson *et al.* 2008) (compare Appendix 2 for full species list) (Figure 6). To represent fish spawning aggregations, we aim to protect all known active and historical aggregation site locations. Additionally, we aim to include 50% of fish spawning aggregation catchment reefs in marine protected areas (Figure 6). As transient spawning aggregations may draw individuals from a large catchment, we identified catchments as reef areas within a 20 km radius from known fish spawning aggregation coordinates, a number representative for the home range of large spawners such as *Plectropomus areolatus* or *Epinephelus polyphekadion* (Green *et al.* in prep.). If species belonging to more than one family used an aggregation site, we use overlapping catchment reefs for each family.

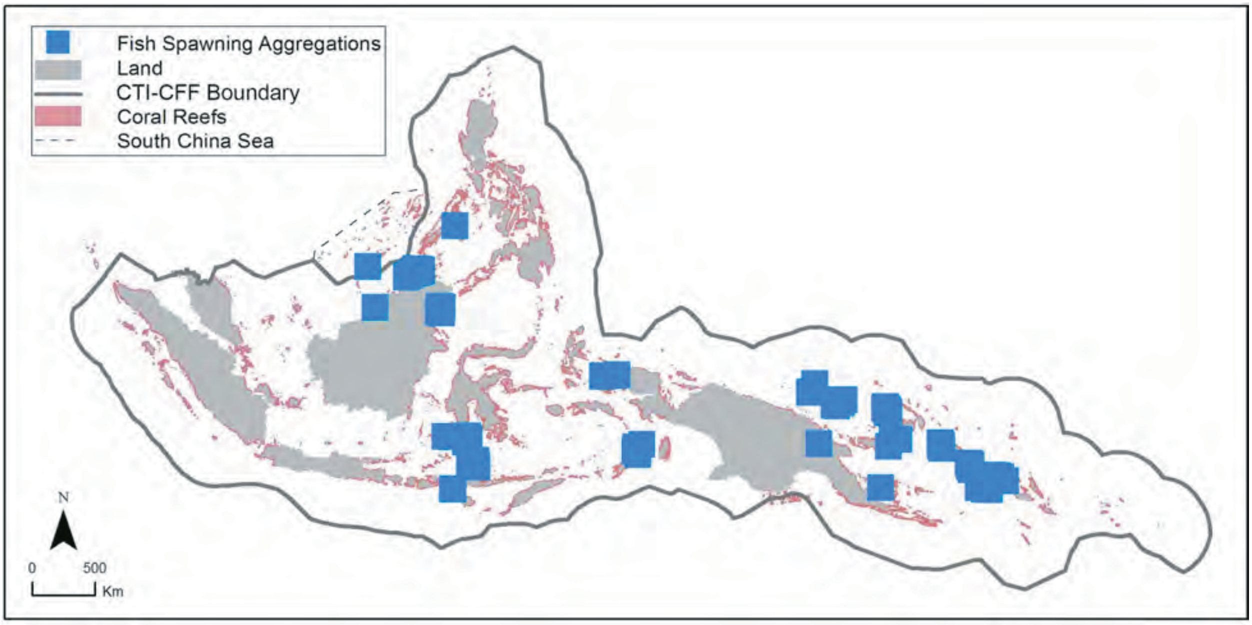


Figure 6. Coarse resolution location of known fish spawning aggregations in the coral triangle, with schematic example for assigning reefs to spawning aggregation catchments shown as blue shaded reefs. Real data cannot be shown, but were used in the analysis.

All marine turtle species are threatened, with hawksbill and leatherback turtles classified as critically endangered (IUCN 2013). Sea turtles routinely migrate long distances between nesting and foraging habitats. During pelagic migration and while feeding on coral reefs or seagrass beds, sea turtles experience high fishing mortality by being targeted by fishers, incidental artisanal catches, and commercial bycatch. To effectively protect turtles, important habitat areas such as nurseries and feeding grounds and their migration pathways must be protected. In our study, important turtle habitat areas were assigned to known nesting and feeding sites and the beginning and terminal points of satellite-derived turtle tracks (Figure 7). As with spawning aggregations, we identified catchments of 30 km radius around important turtle habitat to incorporate the typical spatial extent of beaches and foraging areas. We set conservation targets of 50% to represent turtle habitat.

Records of long-distance marine turtle migration highlight movements that connect nations and span continents. We used tracking data for four species of marine turtle: green (*Chelonia mydas*), leatherback (*Dermochelys coriacea*), olive (*Lepidochelys olivacea*), and hawksbill (*Eretmochelys imbricata*) (Figure 7).

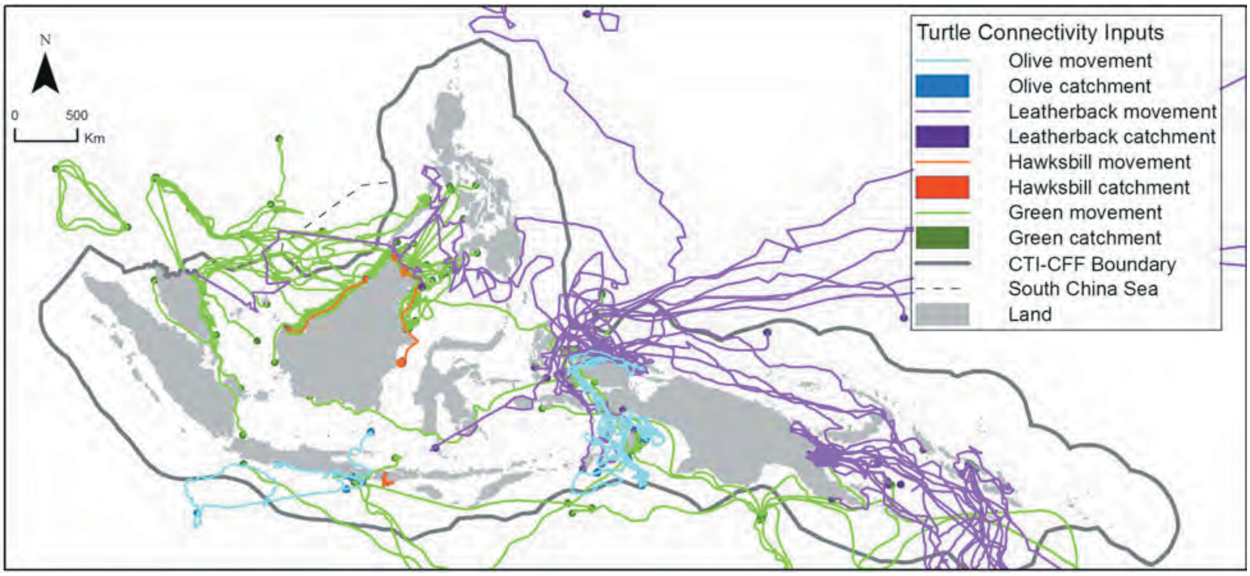


Figure 7. Significant turtle catchments and turtle track connections for 4 species of sea turtle in the central Coral Triangle.

A turtle can only complete its journey if it escapes dangers along the entire track. Thus, we developed a new method to incorporate into Marxan based on individual turtle migration tracks as a measure of connectivity between the planning units it passes through. We express these relationships in a connectivity matrix where all pairs of migratory planning units associated with the track are assigned the connection of 1. In the resulting connectivity matrix, multiple turtle tracks are added together, so that pairs of planning units that connect more than one track have higher connection strength values. The final connectivity matrix connects all planning units travelled through by all turtles. Turtle track connectivity matrices were used in planning with Marxan with Connectivity, with and without turtle catchment targets.

Aim 3: Connecting marine reserves for dispersing larvae

We model connectivity strength among reefs based on an individual-based larval dispersal model (Treml *et al.* 2008; Treml & Halpin 2012) using modeling parameters characteristic for coral trout (*Plectropomus leopardus*) and a sea cucumber (*Holothuria whitmaei*). Transporting larvae by advection and diffusion processes in surface ocean currents, the dispersal model combines larval biological traits (pelagic larval duration, survival rates) and larval behavior (ascent/ decent in water column, homing towards a reef) to obtain the likelihood of larvae moving among reefs (Treml & Halpin 2012; Treml *et al.* 2012). Larval traits for the two species were collated from the literature for pelagic larval duration, pre-competency period, mortality, swimming and homing behavior, and spawning time (Appendix 3). Average connectivity c_{ij} as the proportion of larvae arriving at a site *j* from source reef complexes *i* is calculated between each pair of sites in each direction (Treml *et al.* 2012). Due to limited computing power, the biophysical dispersal model is based on reefs that are clustered into regionally important reef complexes. We therefore use the terminology "*reef complex*" and "*reef*" to refer to reef complexes used in dispersal models or actual reefs respectively. Subsequently, discrepancies exist in the spatial scale of reef complexes (n= 425 for entire region) and the scale of reef habitat used in spatial planning (planning units = 10x10km, n= 17264).

Based on the existing marine protected area system, we firstly identify the unprotected source reef complexes that contribute the greatest proportion of larvae arriving at protected areas. This was done by treating reef complexes that were part of the existing system as either sinks or sources of larvae. Because many of the marine protected areas are small compared with the reef complexes, often multiple MPAs intersected with the same reef complexes. The reverse was also true for some of the larger protected areas, which in some cases intersected with multiple reef complexes (Appendix 4). As a result, the identified source reef complexes represent broad source regions that supply larval flows to marine protected areas, rather than individual reefs.

Regional connectivity centers are identified as the top 10% of reef complexes acting as either sources or sinks. We define *sources* as reef complexes that contribute the greatest proportion of larvae that arrived at sink reef complexes; and *sinks* as reef complexes that are the most dependent on other reef complexes for larval supply. An important incentive for collaboration of countries in conservation is shared resources. Larval dispersal is an example of a shared functional domain, where reef complexes in one country may supply or depend on reefs of its neighbor. To determine which reefs connect the adjacent Coral Triangle countries, we calculated the relative amount of larval traffic each country receives from sources outside of their EEZ. Discounting self-recruitment for each reef complex, we calculated the cumulative percentage of the influx from external sources for each species.

The connectivity values are based on a bio-physical dispersal model applying coarse reef outlines to define habitat (reef complexes) (Spalding *et al.* 2001). The reef complexes and their centroid node points were used to define reef complex neighborhoods for planning units used in our analysis, and based on Thiessen polygons that delineate polygons with lines equidistant between each pair of centroids (Appendix 4) (Beger *et al.* in press 2014). Assigning planning units to reef complex neighborhoods allowed us to determine which reef habitats are represented by which reef complex in the connectivity model (Figure 8).

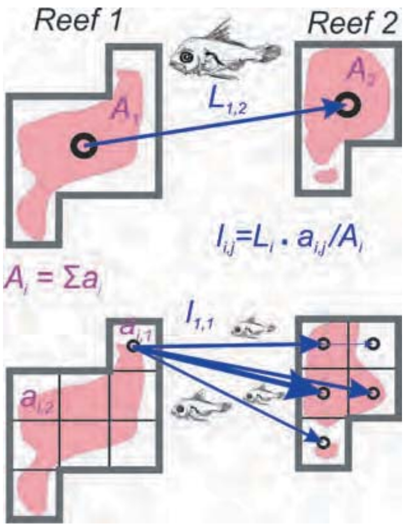


Figure 8. Larval dispersal upscaling from reef complexes to planning units. The upper panel shows coarse reef outlines from biophysical modeling, lower panel shows how amounts of larval flow are scaled according to the reef area contained in each planning unit. A_i is the total area of each reef complex *i*, L_i is the number of larvae originating from a reef complex (e.g. $L_{1,2}$ is larval flow from reef complex 1 to reef complex 2). Each planning unit *j* contained in reef *i*, has an area of reef habitat $a_{i,j}$, with A_i defined by the sum of habitat contained in all planning units part of reef complex *i*.

Marxan's algorithm identified sets of reserve sites fulfilling conservation targets whilst minimizing the cost under an assigned weight for connectivity (Beger *et al.* 2010). Asymmetric connectivity matrices, defined by CV_{ij} for flows $l_{i,j}$ between all pairs of planning units i and j in Marxan (CV_{ij}, (Beger *et al.* 2010)), provide directional larval dispersal strengths for *P. leopardus* and *H. whitmaei*. The resulting spatial changes in selection frequencies are mapped to illustrate highly connected areas that maintain the lowest cost, with the caveat that results do not illustrate all of the highly-connected reefs in the region.

Aim 4: Climate change

Our changing climate poses two major threats to coral reef ecosystems, increasing thermal stress and ocean acidification. Reef-building scleractinian corals respond to prolonged thermal stress with the expulsion of symbiotic zooxanthellae, resulting in reduced fitness and often death if thermal stress is severe. Ocean acidification reduces calcification rates for many tropical corals (Hoegh-Guldberg *et al.* 2007), resulting in reduced settlement and growth and changed reef carbonate balances pushed from growth towards erosion (Kennedy et al. 2013). Given regional inhomogeneity in these impacts, it is unclear which thermal and chemical regimes promote more resistant and resilient reefs. For example, are reefs with greater historical exposure better prepared for future impacts? In contrast, will more climatically and chemically stable parts of the Coral Triangle provide refuges for coral reefs? Here we explore these ideas using the historical and predicted probabilities of exposure to thermal stress (Table 1).

Thermal stress was defined by the Degree Heating Week (DHW) metric (Liu *et al.* 2003). The DHW is an accumulation of temperature anomalies that exceed the warmest long-term climatological monthly mean (the maximum of the monthly means, MMM) by 1^{o}C or more, therein combining the magnitude and duration of stressful temperatures. At 50km resolution, values of DHW = 4 have been linked to significant coral bleaching (Liu *et al.* 2003; Eakin *et al.* 2010). Here, we consider this same threshold to identify thermal stress events using higher resolution data, acknowledging the differences in the production methodology of the SST datasets (Figure 8). The return period was calculated at each pixel by dividing the full duration of the dataset by the number of stress events observed. The return periods ARP_i served to calculate the probability of experiencing thermal stress events over one year, p_i, to be experienced by the reefs contained within a planning unit i as,

$$p_i = \exp\left(\frac{-1}{ARP_i}\right) \qquad (1)$$

As the relationship between DHW = 4 and severe bleaching has not yet been established at the 4 km resolution, we also consider values of DWH = 8 to identify conservation priority sites.

Table 1. Scenarios to represent climate change threats.

What	Source	Timeframe	Scenario	Event
Historical thermal stress probability	here	1983 – 2008	-	4 DHW, 8 DHW
Future short-term thermal stress probability	(van Hooidonk *et al.* 2013)	2006 – 2030	RCP45	4 DHW, 8 DHW

The average return period (ARP) of **historical thermal stress** was determined using a 25-year record (1985-2009) of 4km-weekly satellite sea surface temperature (SST). The SST data were derived from the Pathfinder5.0 4km-daily dataset (pathfinder.nodc.noaa.gov; Casey *et al.* 2010) and data gaps were filled following the method of Heron *et al.* (2010). With many possible events that could define heat stress, we contrast DHW=4 (large-scale bleaching threshold, Figure

9a) and DHW=8 (as potential maximum adaptable extreme value to be achieved in the near future, Figure 9b) in this analysis.

Future thermal stress was calculated from predicted annual maximum DHW values (van Hooidonk *et al.* 2013). These data were derived by averaging the monthly SST temperature outputs from multiple models, calculating the number of times and magnitude of the temperature exceeding the maximum monthly mean to define the DHW heat stress events. To evaluate near-term future trends that are relevant to management now, we calculated the return periods ARP_i of thermal stress events in 2030 as the number of events in the 25 years prior to and including 2030. The corresponding probabilities of experiencing thermal stress p_i were derived with equation 1. As with historical thermal stress, we contrast DHW=4 (Figure 9c) and DHW= 8 (Figure 9d) in this analysis.

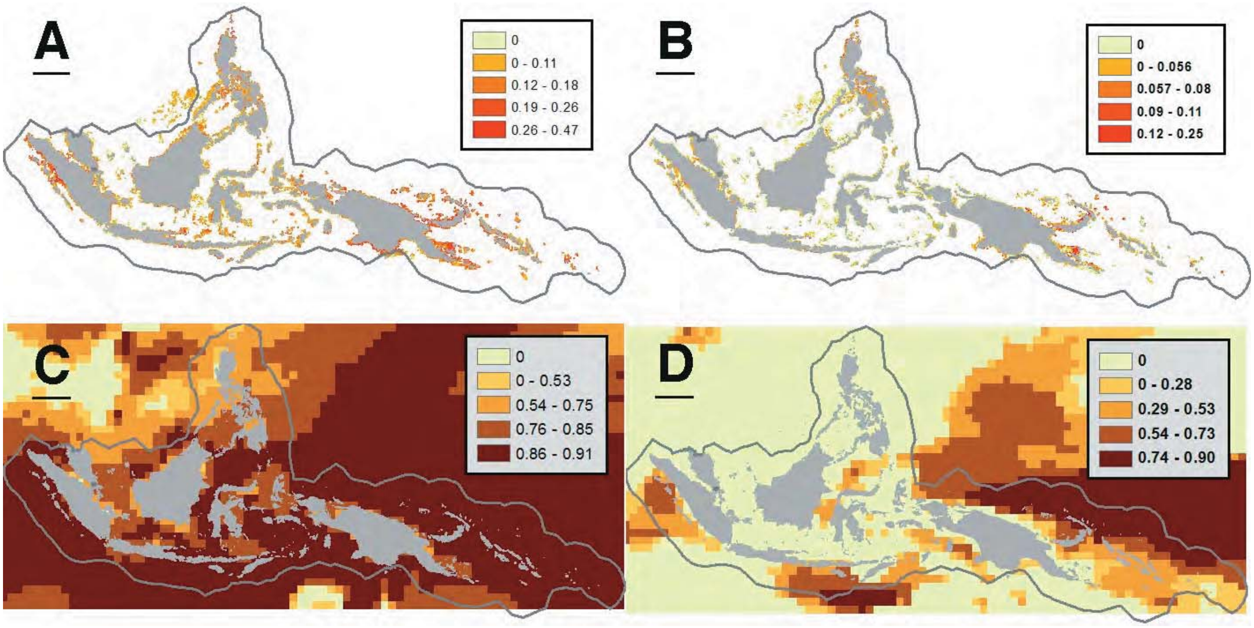


Figure 9. Probabilities of experiencing thermal stress in the coral triangle defined as, A) DHW=4 (historical), B) DHW=8 (historical), C) DHW = 4 (future), and D) DHW=8 (future). Historical data from 25 years pre-2008 at 4km resolution, and future data from 25 years pre-2030 predicted under rcp45 with model ensemble.

We used Marxan with Probability (Ball *et al.* 2009), an extension of Marxan that can explicitly incorporate probabilities of experiencing thermal stress ($\boldsymbol{p_i}$). It minimizes a scoring function that includes socio-economic data, probabilities of experiencing thermal stress, as well as targets for habitat representation in a reserve system. An extra parameter allows us to set certainty targets as a measure to ensure each feature is protected from thermal stress in the reserve system (Game *et al.* 2008). In this analysis, we explored climate scenario prioritization under 50% and 90% certainty targets for threat avoidance. It is plausible that most reefs in the Coral Triangle have experienced bleaching as a result of thermal stress, therefore we use both baseline feature representation targets, as well as 10% targets for habitats and ecoregions.

Results and Discussion

Current reserve systems

The current marine protected area system across Coral Triangle countries (Figure 3) protects approximately 15% of coral reefs habitat in general MPAs, with a subset of 2% in no-take areas or zones (Table 2, Appendix 5). We base our prioritization analyses on no-take areas that we estimate to protect less than 3% of habitats in the region. These numbers are based on the amount of coral reef habitat found within protected areas with known boundaries. The levels of protection and enforcement within these areas vary both individually by MPA and by the managing country. In contrast, only 2% of mangroves are protected in the reported marine protected areas (no-take estimates not available) (Table 2). However, the accounting for mangrove protection in this analysis used only protected areas included in the Coral Triangle Atlas data that specified whether the domain was terrestrial or marine-terrestrial (polygon MPAs) or included mangrove in the title (point MPAs). Additional national-level strategies for mangrove protection are not reflected here, and contribute to a higher realized percentage of habitat protection than what we report for the Coral Triangle as a whole. While there are high numbers of small community-based marine protected areas in the Philippines and the Solomon Islands (termed Point MPAs), they only contribute a small fraction towards overall habitat protection in the region: 3.9 km^2 for mangroves and 344 km^2 for coral reef habitats (Table 2), and which we consider to be entirely no-take due to their small, locally administered management.

Table 2. Amount of habitat within existing protected areas considered in the analysis, compared to measured.

Features	Total Amount of Habitat (km^2)	Amount in MPAs (km^2)	Amount in No-take (km^2)*	Base scenario (Locked in Habitat)
Total Mangroves	**42,760**	**2,295 (5.4%)**	**	**1,113 (2.6%)**
Point MPAs		3.9		
Total Coral Reef	**62,738**	**9,195 (14.7%)**	**1,272 (2%)**	**1,810 (2.9%)**
Point MPAs		344	344	
Coral cover high	17	7.1	0.75	0.26
Coral cover medium	3,320	729	76	144
Coral reef slope	20,439	2,088	219	524
Corals other	22,669	3,261	341	680
Rocky reef	16,293	2,764	290	461
Total Seagrass/seaweed	**3,263**	**414**	**44**	**108**
Points		0.8	0.8	
OTHER				
Sand	8,361	1,234	129	218
Mud	27,907	418	42	102
Unidentified	3,732	337	35	96

*No-Take area calculated as 10 % of habitats within large MPAs; 50% of habitat for small (< 10km^2) MPAs and all area designated by point MPAs, compare Figure 4.
**No estimates of no-take areas was possible for mangroves.

The Coral Triangle contains 21 marine ecoregions with distinct assemblages of marine organisms (Spalding *et al.* 2007) which we use here as units for regional representation. Looking at all types of marine protected area, in the Coral Triangle Marine Protected Area System, the protected habitats for reefs and mangroves are not equitably distributed among ecoregions (Figure 10) for main habitat types (Appendix 5). We use Lorenz curves (see Box) to assess how equitable the distribution of protected areas is among ecoregions based on the proportion of habitat protected (Barr *et al.* 2011; Halpern *et al.* 2013).

For example, the Halmahera, SE PNG, and Vanuatu ecoregions have none of their mangroves or coral reefs protected (Figures 10, 11, Appendix 5). Similarly, the South China Sea Islands only target one turtle nesting beach and protect less than 0.05% of coral reefs and no mangrove habitat. The ecoregions with the largest amount of coral reef protection in place are the Gulf of Papua (>80%), Papua (>60%), S. Kuroshio (>60%) and Northwest Sulawesi (~ 40) (Appendices 5,6). Alternately, Lesser Sunda (>35%) and the Sulawesi Sea (>37%) maintain the highest proportions of protected mangrove habitats. Yet, equity in protected area distribution here is not assessed relative to the amount of habitat available (Barr *et al.* 2011). Thus, whilst the Banda Sea ecoregion contributes the largest amount of protected area to the overall MPA system for corals, the size of the ecoregion means that only 30% its reefs are protected (Appendices 5, 6). Viewing protected areas through the lens of equity often tells a different story than looking at the proportion of habitat protected alone (Fig.10).

An important point here is that the ecoregions on the left side of the graph contribute no or very little protected habitat to the marine protected area system. These areas are getting neither the benefits nor the socio-economic burden of protecting reef or mangrove habitats. On the right hand side of the graph, ecoregions contribute the largest amount of habitat to the system. These regions have a disproportionate amount of protected areas, with higher socio-economic burden but also immense local benefit for biodiversity and fisheries. Ideally, both benefit and burden should be equitably distributed.

How to read a Lorenz curve

Lorenz curves are often used in economics as a metric to calculate and display equity with respect to incomes of citizens of a country. Here, it is used as an approach to evaluate equity with respect to the amount of habitat protected per ecoregion. In theory, if all ecoregions contribute the same amount of protected habitat, the curve is a straight line (where for every step, the same amount of habitat is added to the total). The curved (red and green) lines are the real contributions to the total area protected in the system, and are sorted by the amount of protected area contained in each ecoregion. The contributed amount of protected habitat is plotted from left to right, starting with the ecoregion hosting the smallest amount of protected habitat. The ecoregion with the next smallest amount of protected habitat is added to the cumulative total at the next step, then the next smallest value etc. That way, the lower curve shows how protected habitat amount accumulates as more ecoregions are added (in sequence from smallest to largest) until the total amount of habitat protected in the reserve system is reached.

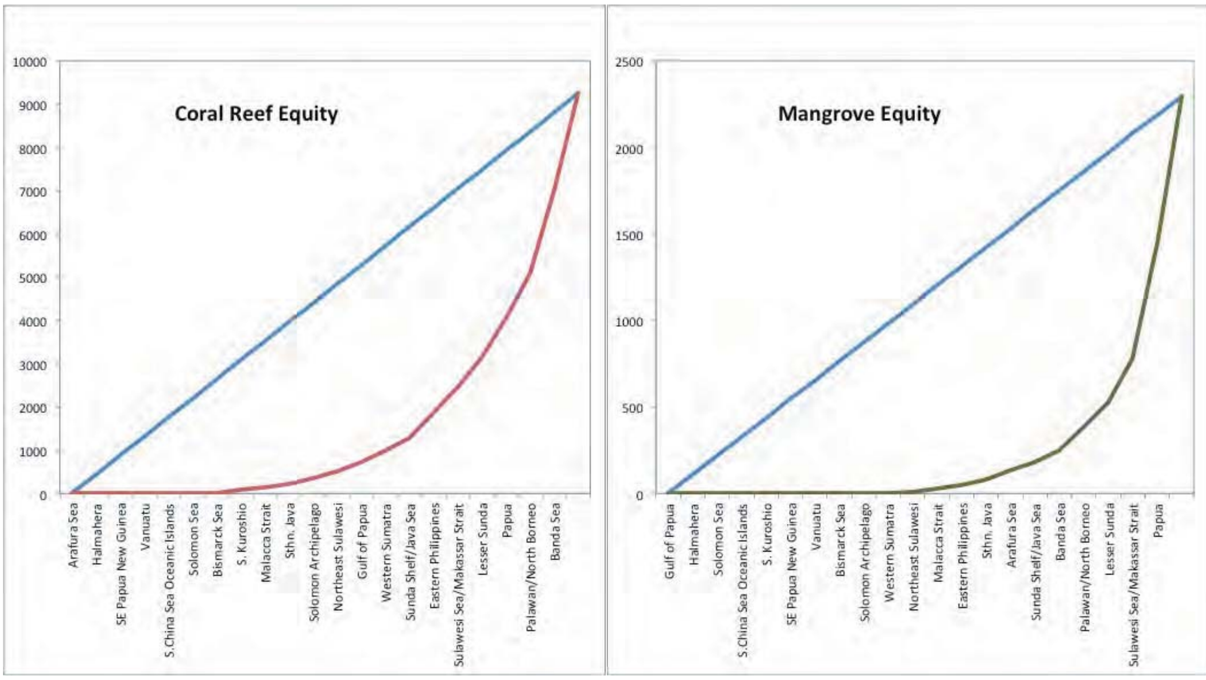


Figure 10. Equity among bioregions of holding proportions of the total amount of protected mangrove and coral reef habitat in the coral triangle. The red line represents a situation where all ecoregions have equal parts of total protected area network. The lower line represents the present protected habitat equity. The larger the gap between the two lines, the less even is the distribution of protected habitats. Y-axis shows the accumulative amount of protected habitat in a protected area system.

Similar to ecoregions, the proportion of habitat within marine protected areas differs among Coral Triangle countries (Figure 11, Table 3). Most countries have very little of their mangrove habitats in conservation areas that are accounted for in the Coral Triangle Atlas and reported by our sources (Appendix 1). In Indonesia and Malaysia, 23.5% and 32.5% of coral habitat respectively receive some form of marine protection. Countries with predominantly community-based management, such as the Philippines, PNG, and the Solomon Islands, have a high proportion of their overall conservation areas legislated as no-take sanctuaries (Table 3).

Table 3. Presence of habitats in each country with proportions within MPAs and no-take areas.

Habitat Class (km2)	Indonesia		Malaysia		Philippines		PNG		Solomon Islands		East Timor	
	Total	MPAs	Total	MPAs	Total	MPAs	Total	MPAs	Total	MPAs	Total	MPAs
Protected Habitats												
% Mangrove Protected	**7.9**		**1.2**		**2.3**		**0.02**		**0.4**		**0**	
% Coral in MPA	**23.5**		**32.5**		**5.5**		**3.6**		**3.0**		**5.9**	
% Corals in No-take	**2.7**		**3.3**		**2.5**		**0.4**		**2.0**		**1.1**	
Mangroves	27,376	2,166	5,335	65	2,602	57	4,837	1	444	2	7	0
Coral cover High	7	3	0	0	10	4	0	0	0	0	0	0
Coral cover Medium	1,226	653	167	23	641	46	807	7	257	3	15	0.2
Coral cover slope	8,197	1,599	900	238	4,317	110	4,048	110	1,446	27	126	6
Other Corals	9,078	1,843	605	293	5,594	149	3,717	98	1,204	11	18	3
Rock	8,663	2,291	402	120	3,773	194	2,004	169	810	8	48	2
Seagrass/ seaweed	1,598	301	125	40	1,270	50	153	22	80	0.2	25	0.2
Sand	4,042	1,040	458	96	1,587	64	1,397	39	370	6	55	3
Mud	17,876	207	4,503	89	550	18	4,930	102	4	0	13	2
Unidentified	1,851	233	150	24	478	55	726	25	329	3	2	0.3

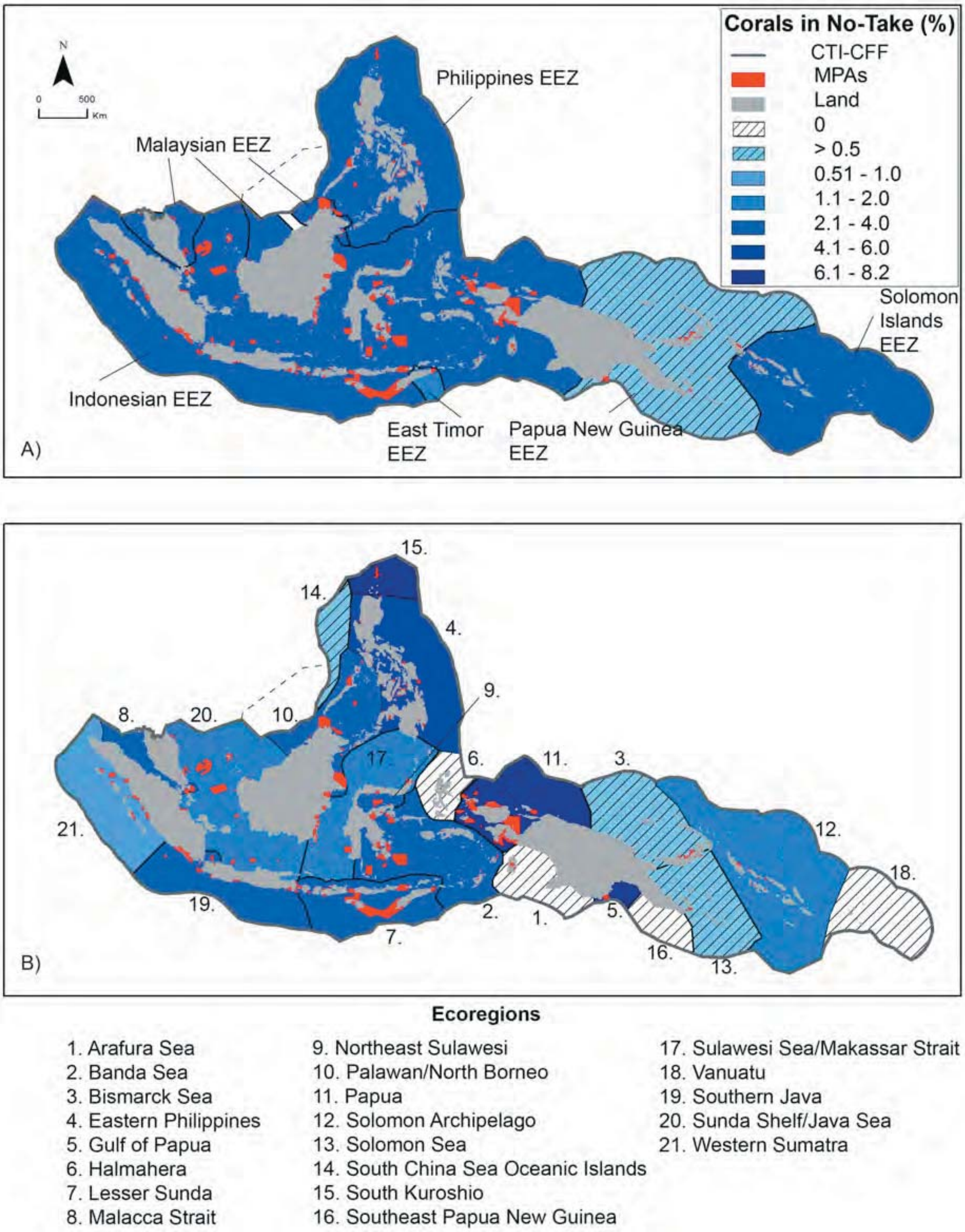


Figure 11. Comparison of the proportion of no-take areas present in each A) country and B) ecoregions.

1: Representation of marine habitats

The goal of the Coral Triangle Initiative on Coral Reefs, Fisheries and Food Security is to protect at least 20% of coastal and coral reef habitat (Coral Triangle Initiative on Coral Reefs Fisheries and Food Security (CTI-CFF) 2013). As the mean protected habitat areas for reefs and mangroves is 10% and 2 % respectively, more conservation areas are needed, particularly in mangrove habitats. With the uneven distribution of protected habitats among ecoregions, there are particular areas that have high conservation priority based on objectives aiming to represent 20%, 30%, and 40% of each habitat type in the protected area system (Figure 12, Appendix 8). With so few mangrove areas in the existing reserve system, the main conservation priorities include large areas of mangroves in north-eastern Borneo, northeastern Sumatra and West Papua. For coral reef habitats, high priority areas include the southern Banda Sea, Halmahera, the atolls and oceanic reefs in the Java Sea/ Makassar Strait, Belitung Island east of Sumatra, and large reef tracts in the Solomon Sea. Scattered priority reefs are also evident in the Solomon Archipelago. In the Philippines, more protection is needed for central Sulu Sea reefs (Cagayancillio Islands, and north) and outer reefs in the South China Sea. Outer South China Sea reefs are shown as high priorities in this analysis, which is both an artifact of their remoteness (low socio-economic cost index) and the absence of any protection in this ecoregion. Although political instability in this region may prevent any conservation work in the near future, we included this region for illustrative purposes and because it contains important source reefs (compare section 3, connectivity).

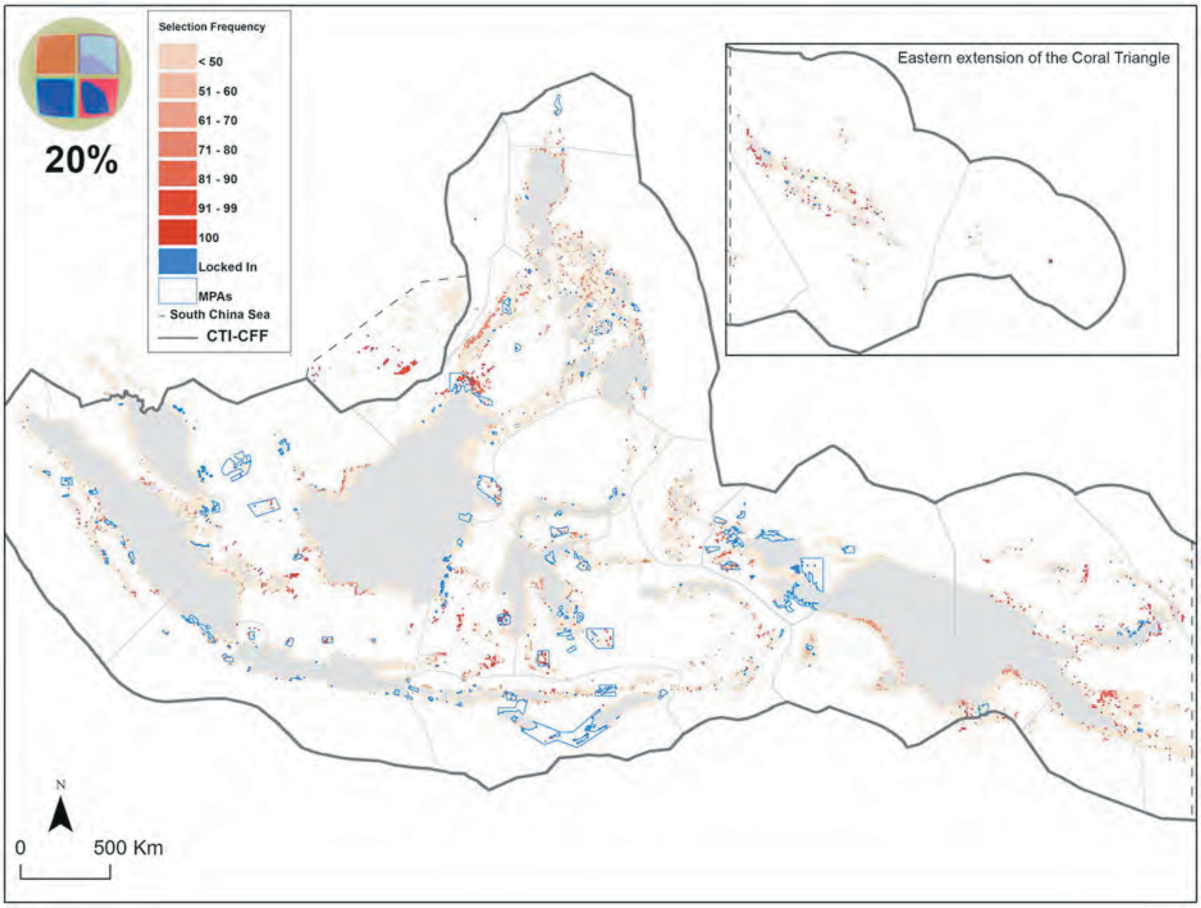
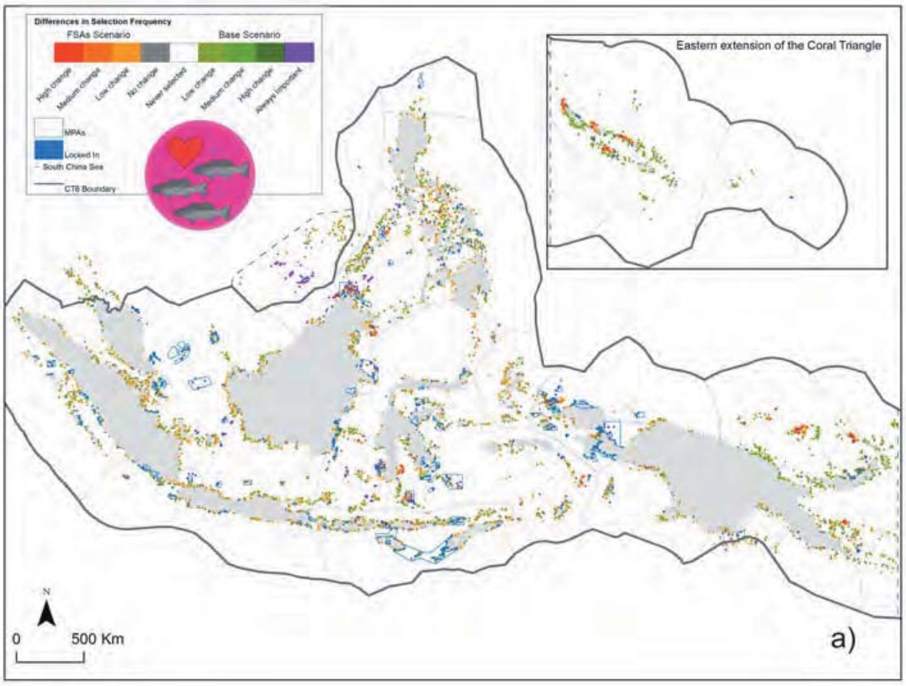


Figure 12. Selection frequency as a proxy for conservation priorities to represent 20% of all habitat types in the Coral Triangle region.

2: Threatened species: sea turtles and fish spawning aggregations

Adding fish spawning aggregations and sea turtle requirements to the basic representation objectives considerably changed conservation goals (Figure 13a). Spawning aggregations change priorities towards sites with several reported aggregation sites, as 68.5% of known aggregations are not yet protected in the current reserve system (Appendix 9). Similarly, under turtle conservation objectives, higher priority is now given to corridors connected by turtle migrations (Figure 13b, Appendix 10), particularly along the western Borneo coast, and the Sulu archipelago across the northeastern Sulawesi Sea to West Papua, connecting four countries.



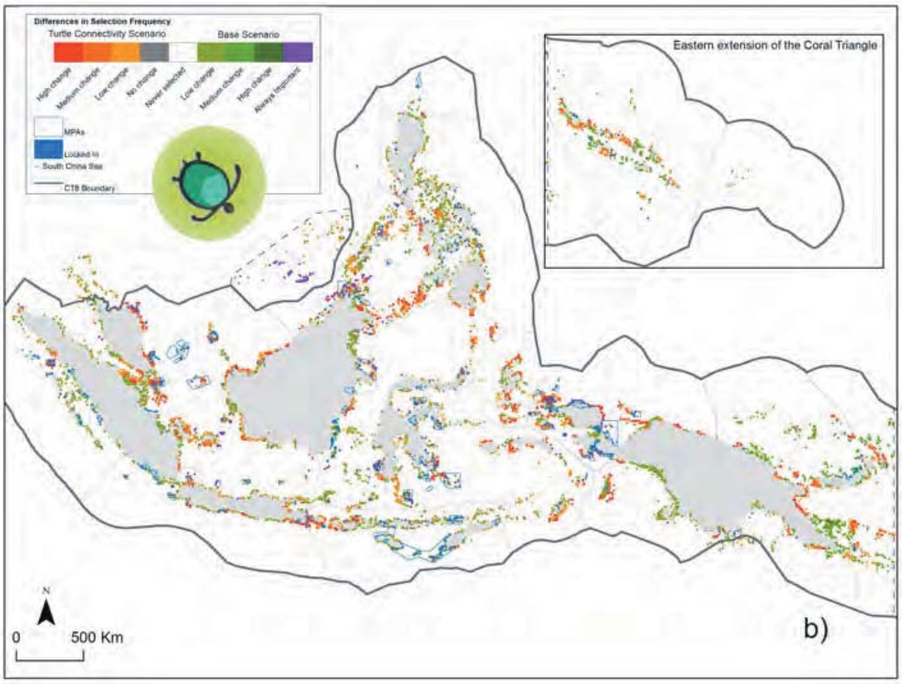


Figure 13. Difference maps showing spatial changes to conservation priorities from a 20% habitat representation objective by adding: a) fish spawning aggregation sites and catchments; b) significant turtle areas (catchments) and tracks. Light grey boundaries delineate ecoregions.

Other iconic and commercially important species that should be considered here are the Humphead wrasse *Cheilinus undulatus* and the Bumphead parrotfish *Bolbometapon muricatum*. While these species are threatened and relatively well known, a lack of data (*Bolbometopon*) or lack of time to process existing data (*C. undulatus*) prevented us from including them (except for one spawning aggregation site for *C. undulatus*). These two species should be prioritized for analysis in the future. Preliminary data indicates that these species are now only present in significant numbers inside effective no-take areas or in inaccessible places.

3: Connecting marine reserves for dispersing larvae

As expected from different life histories, larval dispersal patterns differ for coral trout and black teatfish (Appendix 11). This is reflected in different larval source regions for the existing MPA system for these species (Figure 14). Most important source regions are concentrated in the center of the Coral Triangle where there is also a concentration of reefs and protected areas. Clearly, in regions with many existing marine protected areas, the surrounding reefs will deliver larvae to many MPAs.

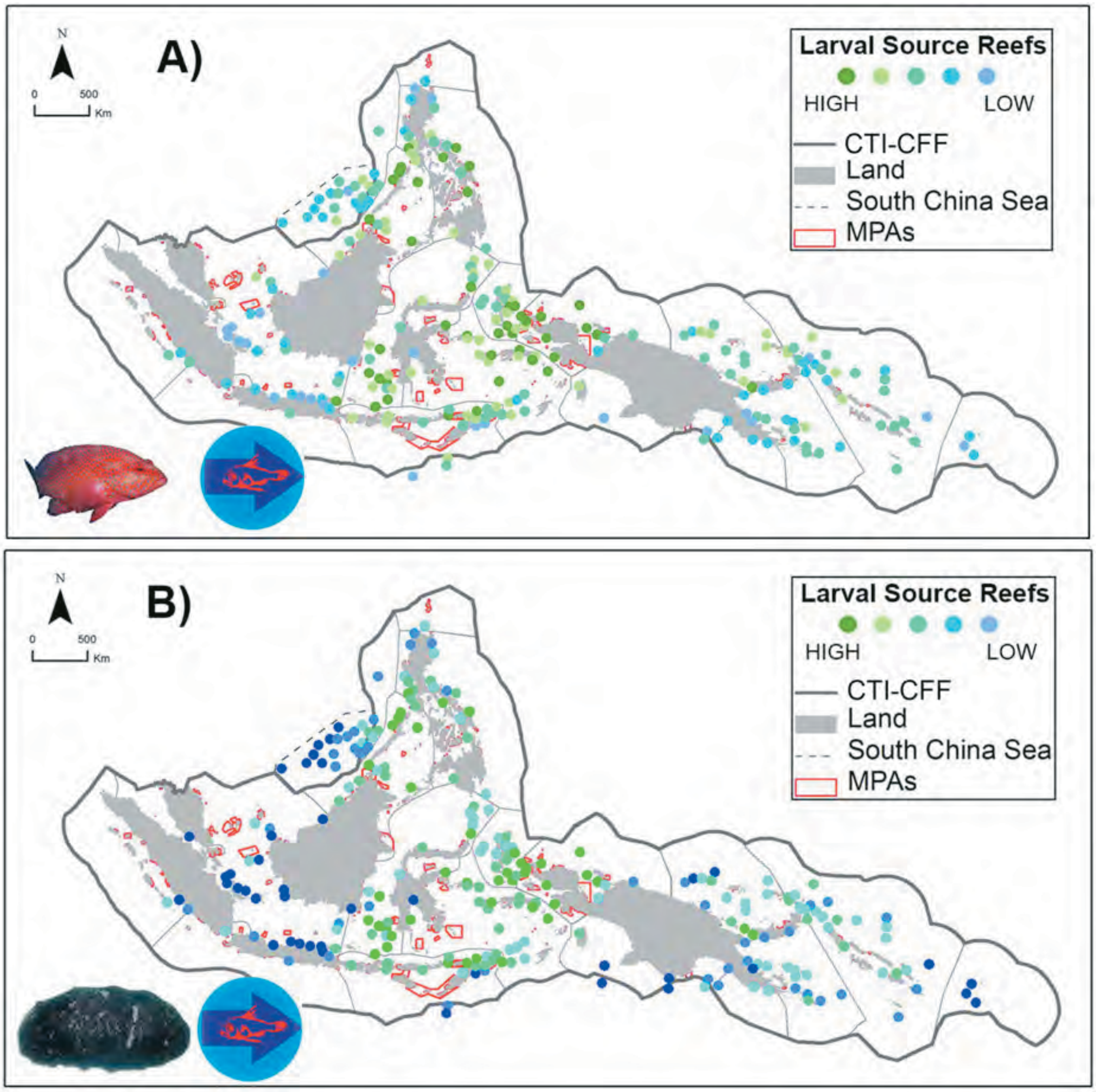


Figure 14. Relative importance of source reef complexes for MPAs, ranked by the number of connections they had to MPAs and the strength of their connection to these MPAs, for A) coral trout *Plectropomus leopardus* and B) black teatfish *Holothuria whitmaei*. No data for Indian Ocean Sumatra, Malaysian Peninsular, and SW New Guinea (Appendix 4).

There are several areas, however, that are important larval sources to existing marine protected areas even though the region is relatively remote, and in areas identified as lacking MPAs, such as the Banda Sea, Northern Sulu Sea and the Flores and Makassar Seas (Figure 14). Peripheral areas with relatively small reef complexes, such as the Solomon Islands, Java and western Borneo show lower importance in our analysis, but may still be locally important, given the relatively lower connectedness of reefs in the region. No connectivity data exist for the Malaysian Peninsular and Sumatra.

When analyzing the importance of all larval sources and sinks, many of the top 10% of sources and sinks are protected in existing marine protected areas, particularly in West Papua, northern Borneo and in the Philippines (Figure 15).

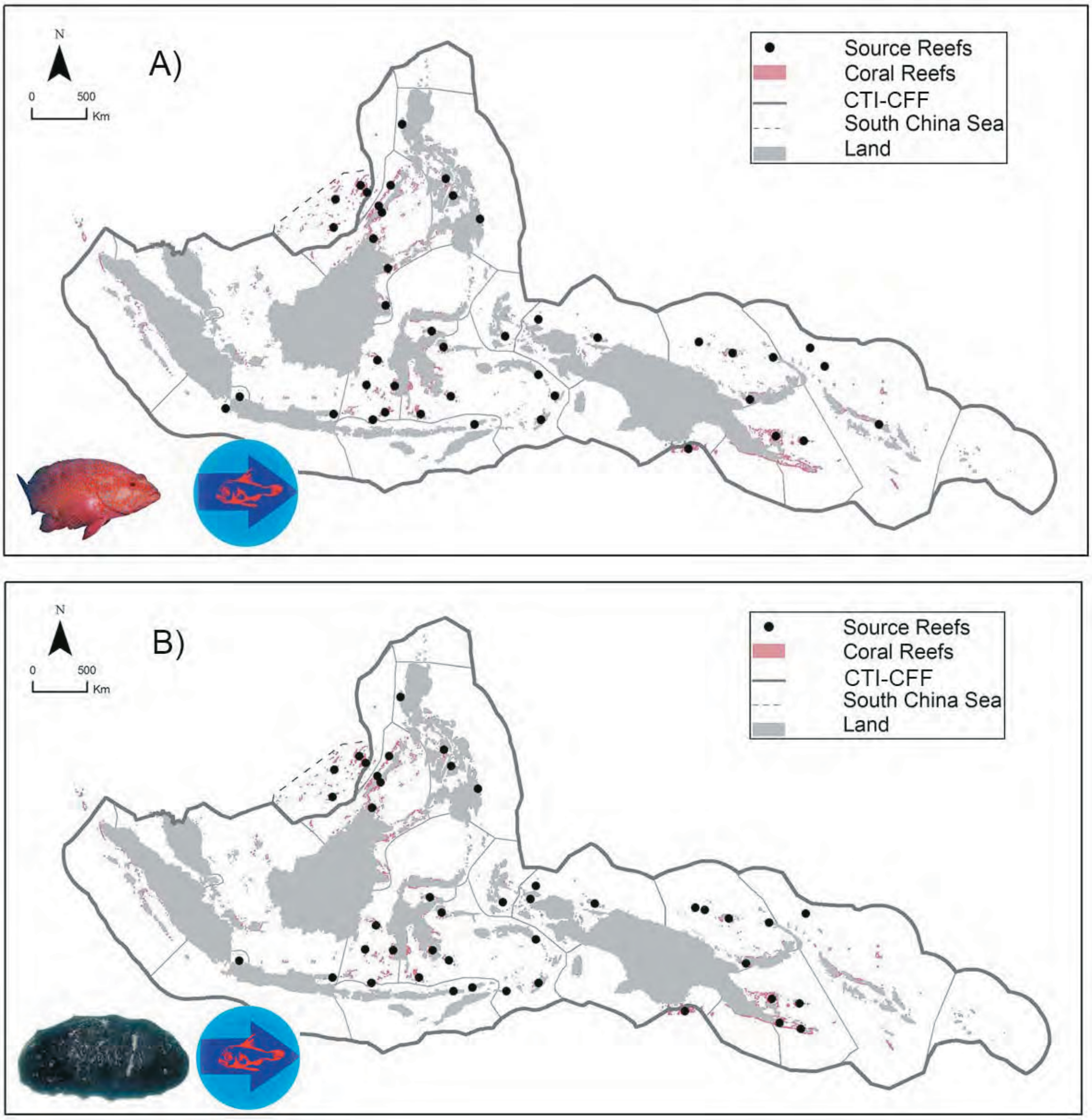


Figure 15. Top 10% most important source reef complexes that contributed the greatest proportion of larvae that arrived at sink reef complexes for A) coral trout *Plectropomus leopardus* and B) black teatfish *Holothuria whitmaei*. No data for Indian Ocean Sumatra, Malaysian Peninsular, and SW New Guinea (Appendix 4).

Trout and sea cucumber populations are connected throughout the Coral Triangle. The coral trout is a better disperser, with more overall and stronger connections between pairs of reef complexes (Figure 16). This is particularly important in parts of the region where larval exchange is relatively limited, such as the north of the island of New Guinea, where limited larval exchange occurs for coral trout, but very little for sea cucumbers. This pattern is consistent with a strong genetic barrier present at northern New Guinea (von der Heyden *et al.* in press 2013). Similarly, connectivity for sea cucumber is relatively limited west of Borneo, but more important for coral trout populations. Particularly intense areas of larval exchange between Coral Triangle countries occur in Northern Borneo, the South China Sea and between PNG and the Solomon Islands (Figure 16).

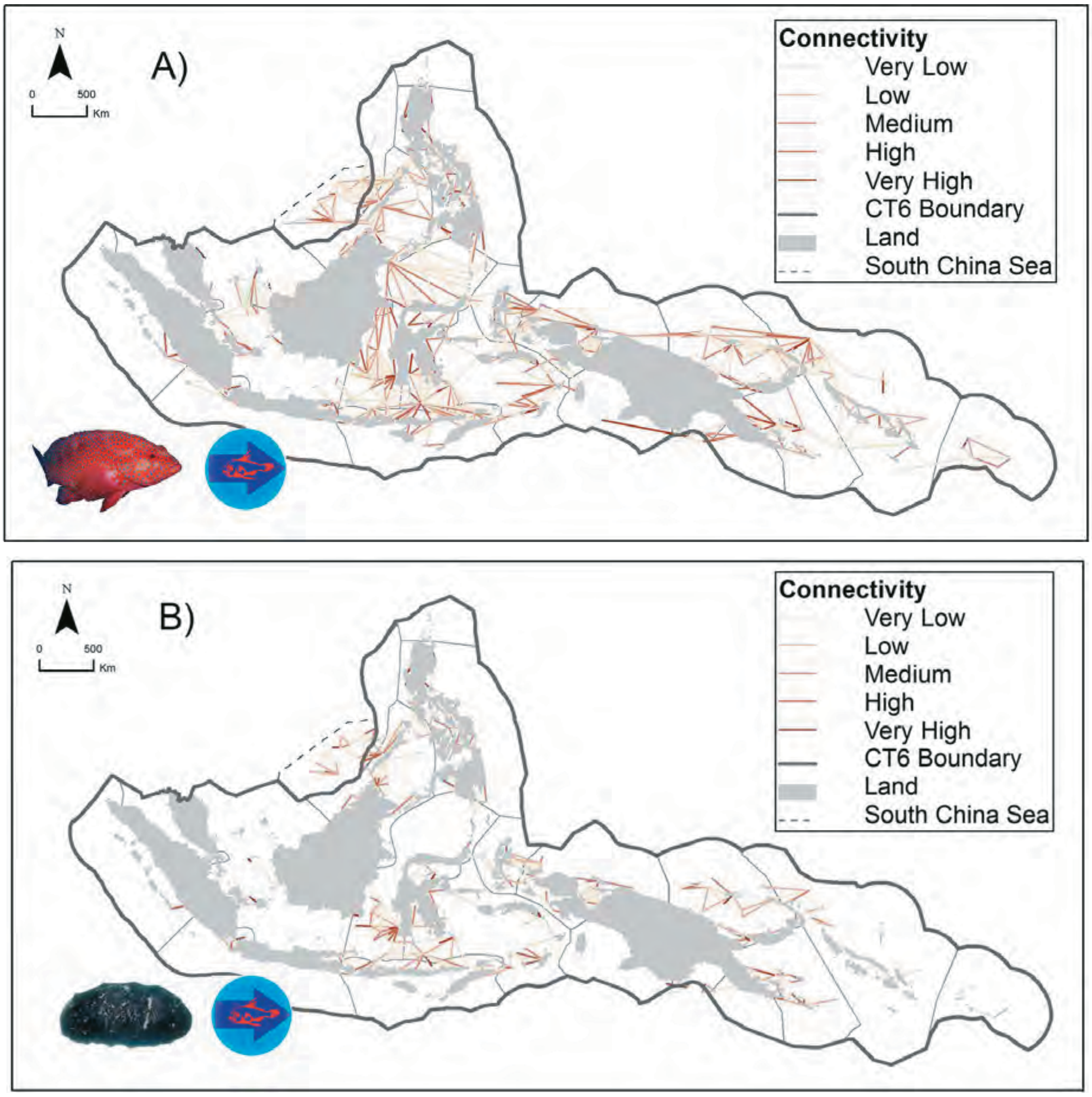
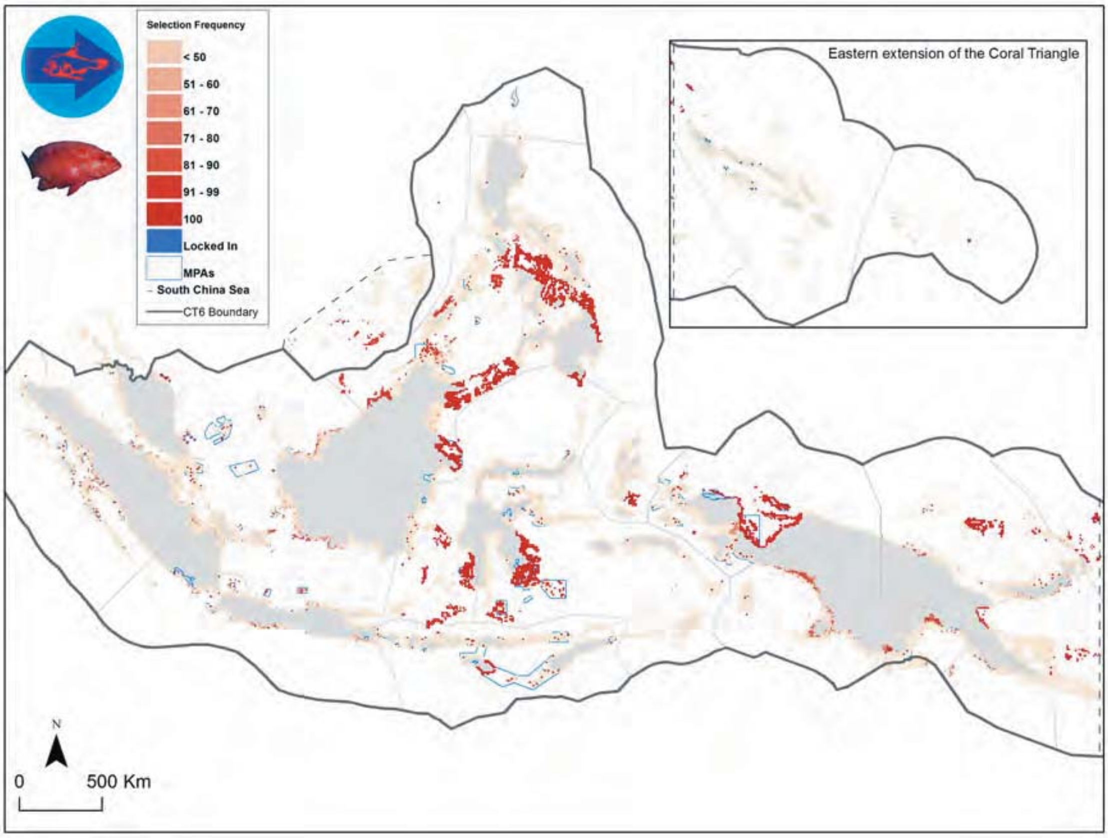


Figure 16. Proportional larval flow to destination reef complexes in the coral triangle, for a) *Plectropomus leopardus*, and b) *Holothuria whitmaei*, capped at above 0.1. No data for Indian Ocean Sumatra, Malaysian Peninsular, and SW New Guinea (Appendix 4).

Conservation priorities under the connectivity scenario largely correspond to areas that are best connected for both species (Figure 17). This reflects the use of larval flow as a boundary cost in Marxan, aiming to maximize connectedness, but giving less emphasis to isolated areas. The connectivity conservation priorities here therefore are located in regions that are well mixed, such as Northern Palawan and central Philippines in the north, southern Sulawesi, Cenderwasih Bay, and in the Bismarck Sea (Figure 17). A different formulation of the conservation objective will be required to represent rare connections, that may be ecologically very important, such as those along northern New Guinea, or in the Java Sea. Local connections, especially at peripheral locations such as the Solomon Islands, therefore play a less important role in this analysis. Future analyses need to consider connectivity separately by country to identify local priorities.



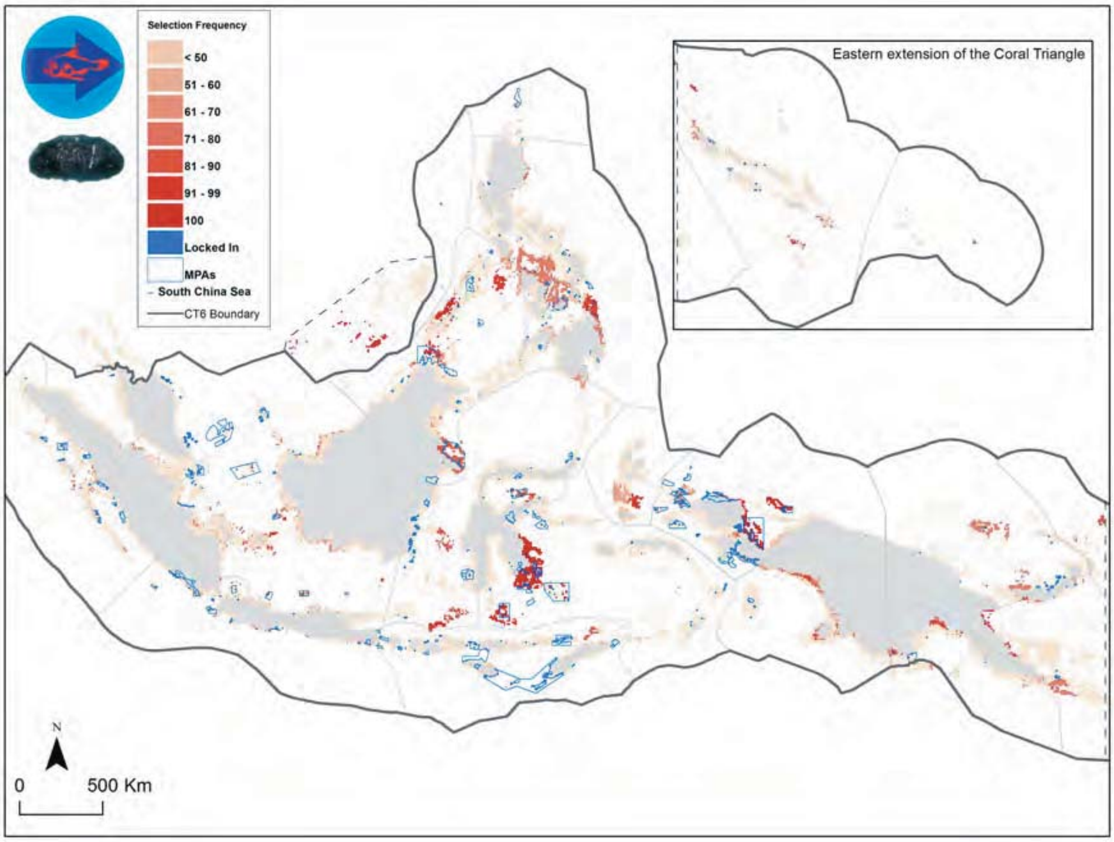


Figure 17. Conservation priorities for a reserve network connecting populations of A) coral trout *Plectropomus leopardus* and B) black teatfish *Holothuria whitmaei*. No data for Indian Ocean Sumatra, Malaysian Peninsular, and SW New Guinea (Appendix 4).

An important incentive for conservation-based collaboration between countries is shared resources. Larval dispersal is an example of a shared functional domain, where reefs in one country may supply or depend on reefs of its neighbor. To determine which reefs connect the adjacent Coral Triangle countries, we calculated the relative amount of larval traffic they receive from sources outside of their EEZ (Table 4). Discounting self-recruitment for each reef, we calculated the cumulative percentage of the influx from external sources for each species.

The larval exchange among Coral Triangle countries relates to geographic proximity, such as Timor Leste mostly exchanging larvae with Indonesia. There are differences between the sea cucumber and the coral trout connections among countries. Sea cucumbers are generally worse dispersers compared to trout. For example, Philippines and PNG share a low number of connections for trout, but none for sea cucumber (Table 4). The Spratly Islands adjoin the Coral Triangle and were included here as they support significant larval connectivity to Malaysia and the Philippines, as well as Indonesia for coral trout. Although most bilaterally beneficial conservation areas supporting larval connectivity are situated in bordering areas between two countries (Figure 17), connections between non-neighboring countries (e.g. Spratley Islands - Indonesia, Philippines - PNG) illustrate the importance of the Coral Triangle Initiative collaboration.

Table 4. How many connections exist between countries for A) coral trout *Plectropomus leopardus* and B) black teatfish *Holothuria whitmaei*?

	A: Count	destination						
		Malaysia	Philippines	Indonesia	East Timor	Solomon Islands	Papua New Guinea	Spratly Islands
source	Malaysia		273	315	0	0	0	173
	Philippines	226		1253	0	0	10	443
	Indonesia	147	531		376	0	283	47
	East Timor	0	0	211		0	0	0
	Solomon Islands	0	0	0	0		567	0
	Papua New Guinea	0	12	587	0	567		0
	Spratly Islands	156	512	73	0	0	0	

	B: Count	destination						
		Malaysia	Philippines	Indonesia	East Timor	Solomon Islands	Papua New Guinea	Spratly Islands
source	Malaysia		140	34	0	0	0	114
	Philippines	72		187	0	0	0	210
	Indonesia	69	226		126	0	58	0
	East Timor	0	0	160		0	0	0
	Solomon Islands	0	0	0	0		123	0
	Papua New Guinea	0	0	59	0	138		0
	Spratly Islands	24	248	0	0	0	0	

4: Climate change

McLeod et al. 2010 (McLeod *et al.* 2010) highlighted areas of more stable future climate in northern Borneo/ southern Palawan, and the South China Sea. Similarly, northern Borneo and South China Sea reefs were identified as sites that may experience annual bleaching conditions (i.e. DHW = 4) later than average (van Hooidonk *et al.* 2013). These regions were identified as potential refuge sites that will experience annual bleaching conditions up to a decade later than average. In that study, reefs in the eastern part of the Coral Triangle (Solomon Islands, and eastern PNG) will experience bleaching conditions sooner than average. This pattern is consistent with our data, both for historical and future (2030) thermal stress (Figure 8). However, it is unclear how this links to actual bleaching events, as few records exist across the region.

The marine protected areas in the Coral Triangle have been exposed to severe thermal stress events in the past 25 years, the most significant being the global bleaching event in 1998 (Goreau *et al.* 2000). The 1998 event affected most of the Philippines and Indonesia (West & Salm 2003). Other events happened at smaller scales, but are poorly documented. As a result, most marine reserves have already experienced thermal stress events of DHW4 in the past 25 years. For example, a mean probability of $p_{DHW4} = 0.1$ corresponds to experiencing a DHW4 event once in 10 years (Table 5a).

Table 5. Mean probabilities of experiencing thermal stress in marine protected areas by country for A) historical and B) future (2030) timeframes, calculated by the mean of all planning unit probabilities within delineated marine reserve boundaries. Excludes point marine protected areas.

A	Historical mean probability of thermal stress within MPAs	
Country	**DHW 4**	**DHW 8**
Indonesia	0.076	0.011
Malaysia	0.056	0.006
Papua New Guinea	0.153	0.044
Philippines	0.092	0.0315
Solomon Islands	0.116	0.023
East Timor	0.0425	0

B	Future mean probability of thermal stress within MPAs	
Country	**DHW 4**	**DHW 8**
Indonesia	0.838	0.063
Malaysia	0.809	0
Papua New Guinea	0.871	0.350
Philippines	0.707	0
Solomon Islands	0.881	0.279
East Timor	0.882	0

The identification of conservation priorities using Marxan did not yield satisfactory results at this stage (see Appendix 13 for exploratory analysis). The climate change objectives for identifying conservation priorities are to maximise reef persistence into the future. The difficulty lies in identifying appropriate proxies for reef persistence – here we evaluated the measure of thermal stress probabilities as a proxy for the inverse of persistence, the probability of destruction. We found that this indicator does not differentiate areas across the Coral Triangle well, because future threats of thermal events are ubiquitous at the modelled scale. We aim to develop future methods that are better suited to Marxan with Probabilities, where high probabilities of destruction in planning units mean that conservation targets cannot be achieved.

Analysis Gaps and Next Steps

This baseline analysis is the first step towards comprehensive and updatable conservation accounting and evaluation under multiple objectives. A more detailed analysis or improved data sets would be desirable in the following areas, highlighting future priorities for more research and resource investment:

A - DATA:

1. MPA information
   - Data of existing MPAs is incomplete and occasionally incorrect despite extensive edits (particularly small MPAs in the Philippines recorded as geographic coordinates (points);
   - Data of MPA boundaries seldom align with coastline/ reef data where it seems logical. In the future, better, fine scale resolution data is required to avoid inaccurate accounting, such as calculations of habitat area within MPAs using spatial analysis tools;
   - Management types and zoning schemes are largely unmapped, and management types are not yet standardized or assessable (e.g. what does “conservation zone” mean in terms of conservation benefits achieved); Incorporating existing or proposed zoning plans into the CT Atlas data layers will greatly improve future conservation efforts and is a logical next step to improve the robustness of the CT Atlas;
   - The countries are just starting to monitor management effectiveness of their MPAs so the level of conservation benefits are difficult to assess accurately in most cases;
   - No-take area data are ambiguous or non-existent with no spatial delineations showing which reef habitats are located in no-take reserves; and
   - Protection areas for mangrove habitats and information on the level of protection are poorly reported and incomplete across countries.

2. Habitat data
   - Seagrass data are out of date and often wrong/ non-existent;
   - Coral layer from WCMC has inconsistencies throughout that need to be adjusted;
   - Japanese coral layer was extensively edited, but can still be improved. It is limited by containing only 8 habitat types that are poorly defined. Creating high resolution data on coral reef habitats across the region is crucial for future analyses – support to complete the Millennium map data is a priority to improve future conservation prioritization work;
   - Our accounting for reef habitat based on both WCMC and the Japanese coral layer results in discrepancies between the amount of habitats reported here and in the CT Atlas who only uses WCMC habitat data.

3. Socio-economic cost index
   - Artisanal fishing cost and the population proxy for cost were not adjusted for national or regional peculiarities; and
   - No data for management cost or social acceptance are available that are consistent across the region.

4. Threatened sites and species

We only used fish spawning aggregations and sea turtles to represent threatened species, because of a general lack or inaccessibility of data. For example, no reef-specific data on sharks, sea snakes, humphead wrasse or bumphead parrotfish exist in spatial format. More spatially differentiated data about threatened species is needed, ideally using abundance distributions. The IUCN threatened species spatial database cannot be used, as it just shows the potential range of species. Of the data we know of, a spatially targeted habitat specific predictive analysis of humphead wrasse abundance is possible but is excluded here because of time constraints. Of the data used, we encountered these challenges that need to be addressed:

- Spawning aggregation sites are incomplete for the region, and despite edits, some existing locations are still incorrectly placed.
- Turtle nesting beaches are unspecified and it is unclear if turtles are still present.
- Turtle tracks do not represent the entire study region and are biased towards where tagging programs are in place.

B – ANALYSIS:

5. Connectivity

The scale of the biophysical model used here is coarse, representing the entire Coral Triangle region with 425 reef complexes. While this is the best available data/ model, this model will only resolve very large scale connectivity processes that are mostly relevant to regional allocation of conservation priorities. Smaller spatial scales, such as our 10x10 km planning units, may not be well represented by these connectivity data. We assigned connectivity strengths between pairs of planning units based on the amount of habitat contained in each planning unit – while this is a workable proxy for scenario comparisons, this approach is problematic for the following reasons:

- The biophysical model used coarse scale outlines to represent reef complexes and released model larvae according to the shape if these outlines; these do not represent habitats (shapes or outlines) used in Marxan and downscaling larval flow to these habitats is unlikely to be linear.
- At the smaller scale of the Marxan analysis, larval dispersal is likely to be different – for example local scale eddies are not represented.
- Downscaling of larval flow does not add any information, it just allows us to create scenarios in Marxan that are comparable with other conservation objectives. The actual resolution of connectivity data remains at 425 reefs per Coral Triangle.

These challenges will be difficult to address as running the model with smaller reef complex outlines is computationally prohibitive.

Further, the connectivity objective function here prioritizes highly connected reef complexes. A future question is to examine how targeting rare connections (that could be genetically or ecologically important) would change conservation priorities.

6. Climate change

Representing thermal stress events using return periods of stressful conditions (e.g. DHW4) allows us to calculate the probability of a reef to experience a stress event, but it is unclear how reef communities respond to these events on a large scale. This is particularly challenging for future predictions with 1 degree resolution.

Careful consideration should be given to the assumptions of the objective function in Marxan with Probability. In this instance, only the probability of a planning unit experiencing thermal stress was considered in our metric. As almost everywhere in the Coral Triangle has or will experience thermal stress, targets cannot be met with any assurance to guarantee a spatially-explicit, representative and climate-proof MPA network. However, generating a probability metric that also includes recovery rates, habitat condition, and the probability of experiencing a climate stress event (thermal and acidification) may increase the capacity of MarProb to be able to find effective solutions. This is a critical priority for further work on planning for climate change.

7. Reef health and resilience

Underlying all our analyses are remotely sensed habitat data that has not been ground-truthed. We assume that habitat types are correctly mapped, which is unlikely to be true. Moreover, we assume that each record of a habitat type is of the same quality. This means we are saying that a reef in Sabah contributes the same amount of conservation benefit to the overall system as a reef in Kimbe Bay, or in Negros, or in remote Solomon Island atolls. This is a simplification that ignores different susceptibility of reefs to impacts, levels of impacts, reef types, resilience and their exploitation history. Incorporating reef health or resilience levels of reefs will considerably change priorities and is an urgent research need.

8. Land-sea planning

This analysis did not include connections between terrestrial and marine habitats. There is benefit to place no-take areas for coral reef species next to associated ecosystems such as mangroves or seagrass meadows, thus supporting species that use multiple ecosystems during their diurnal or life cycles. Future analysis would benefit from representing these relationships.

Summary and Conclusion

This assessment of conservation priorities in the Coral Triangle region calculates the current protection status of coastal and marine habitats as 10% for coral reefs and 2% for mangroves across the entire region. Comparing different objectives of habitat representation, threatened species and sites, connectivity and thermal stress (climate change), we find that priority no-regret areas are in Northern Borneo, Raja Ampat, in the Bismarck Sea around Manus, the Banda Islands, the central Philippines (northern Visayas) (Appendices 14-16, Figure 18). These areas are high priorities in two or more scenarios (Figure 18). Some priority areas switched for different objectives. This leads to conservation trade-offs between contrasting objectives that require different areas to achieve conservation targets. For example, the Central Visayas region is not assigned high conservation priority under the representation scenario, but is very important for connectivity.

Broad-scale conservation priorities are concentrated in the central parts of the Coral Triangle region, and there are two main reasons for this:

1) This central region of the Coral Triangle houses the majority of reef area. While many MPAs exist, the habitats are currently still underrepresented because of their proportionally larger habitat area, compared to peripheral areas.
2) Peripheral parts of the Coral Triangle suffer from a relative lack of data (e.g. western region, Solomon Islands) particularly for threatened species and connectivity objectives. Moreover, edge effects are present in the connectivity data (turtle migrations and dispersal) as connections are cut off to other non-Coral Triangle neighbors.

Specifically, broad conservation priority areas, according to our analyses, exist in all countries. This analysis, however, is not exhaustive, because it was impossible to include reliable data everywhere for some of the objectives. Results for the countries and their particular issues are listed below:

INDONESIA: Indonesia, as the largest country in the Coral Triangle, has high importance as a central biodiversity depository that provides ecosystem links to all other CTI-CFF countries. Indonesia has legislated spatially large MPAs, but the zoning is unreported and therefore their relative conservation benefit is unclear. Based on expert opinion, we allocated 10% of large MPAs as no-take areas for our analysis. Until a better analysis of existing zoning plans can identify the correct amount of no-take habitat, it would be prudent to err on the side of caution and assume the 10% no-take be an overestimate. Much of the effort in Indonesia therefore might need to be in the management of existing MPAs – but this is difficult to evaluate. One Indonesian ecoregion, the Halmahera, currently has no recorded MPAs – this is a major conservation priority as this area was identified as important in all scenarios (Figure 18).

Western Sumatra, although less than 10% of reef is in marine protected areas, did not receive priority status here. This is an artifact of data availability (Appendix 17). Much more spatial data exists for the extent of the "Scientific Coral Triangle boundary" which cut through the EEZ's of Malaysia and Indonesia through Borneo, excluding the areas to the west of the line. With better and more consistent data, Western Sumatra will likely contain regional conservation priority areas. Another highly data deficient area is the southeastern part of the Banda Sea ecoregion. The Banda Sea is a large ecoregion, but only the western part of this region has good MPA coverage (Appendix 17).

PHILIPPINES: The Philippines support a myriad of small community-based MPAs and are known leaders in bottom-up marine conservation. Philippine MPAs having the highest proportion of no-take areas reflects this – most of the MPAs are entirely no-take. Despite the many MPAs, our analysis identified the Central Visayas as a priority, an area where the highest density of MPAs is recorded, and where records are reliable. This is partially an artifact of how we assigned no-take areas to planning units, whereby a planning unit was only set as protected when more than half of its habitat was inside an MPA. However, it also indicates that given the habitat area in the region, the current amount of protection is insufficient. Further, an important part of our analysis is the opportunity cost of lost fishing or extractive use income when establishing no-take areas. High cost (a function of heavy fisheries use and high population density) in the Visayas prevents this area from being selected by Marxan to achieve representation (appendix 14), as habitat targets can be achieved more cheaply elsewhere. Additional information such as connectivity data can update the conservation priority, as now achieving connected protected area networks becomes more important than opportunity cost.

A high conservation priority area in the Philippines is Southern Palawan – ecologically linked to northern Sabah, as well as the South China Sea. Southern Palawan currently has a low density of MPAs in our records.

MALAYSIA: As with Indonesian Sumatra, Malaysia's peninsular region suffers from a paucity of relevant data because it was excluded from the Coral Triangle "Scientific Coral Triangle boundary" that guided the spatial extent for data collation in the past. However, with strong datasets for turtle sites and migration tracks, the data gaps are mostly in spawning aggregations and connectivity for this study. High recorded turtle activity in Malaysia supports the identified turtle conservation priority areas in both the peninsular and Borneo parts (Appendix 16). Strong management and enforcement in Malaysia support a strong MPA network for coral reefs and ongoing efforts in Tun Mustapha Marine Park will further strengthen this system. A major remaining priority is the northeastern corner of Borneo (e.g. Semporna), identified as important for turtles, connectivity, and spawning aggregations). Borneo also hosts two areas of regional importance for mangrove conservation (Figure 18).

TIMOR LESTE: Being a small country in comparison, Timor Leste has a large part of its reef habitat under protective legislation. It is a peripheral area suffering from a lack of data for all objectives except representation. Therefore the lack of identified priority sites in Timor Leste could be a data artifact. Timor Leste is part of a large area in the southern Banda Sea that has virtually no data and constitutes the biggest overall data gap in the region.

PAPUA NEW GUINEA: PNG contains a major regional conservation priority in the Bismarck Sea, with priorities for all scenarios (Appendix 14-16, Figure 18). The MPA system in PNG still has major gaps; PNG contains several ecoregions that have no or under 5% of their habitat conserved (Figure 11). Apart from the Bismarck Sea, these encompass the Solomon Sea and Southeast PNG ecoregions. These two southern ecoregions are also among the largest data gaps in the region (Appendix 17).

SOLOMON ISLANDS: The Solomon Islands have an extensive MPA network with a high proportion of no-take areas. Overall expansion of this system to reach the 20% target is required, as no particular part of the country was identified that needs individual focus.

However, as a peripheral country the Solomon Islands might receive lower priority than they deserve for turtle and connectivity scenarios (Appendices 15, 16), as the majority of the connections are with other neighbors that are not part of the Coral Triangle Initiative. There also is a general lack of data for spawning aggregations and turtle habitats. In the far east of the Coral Triangle, the Vanuatu ecoregion belongs to the Solomon Islands, but little is known about this area. Because it is small, and on the periphery of the study area, Marxan solutions do not highlight it as a priority, even though no known marine protected areas exist.

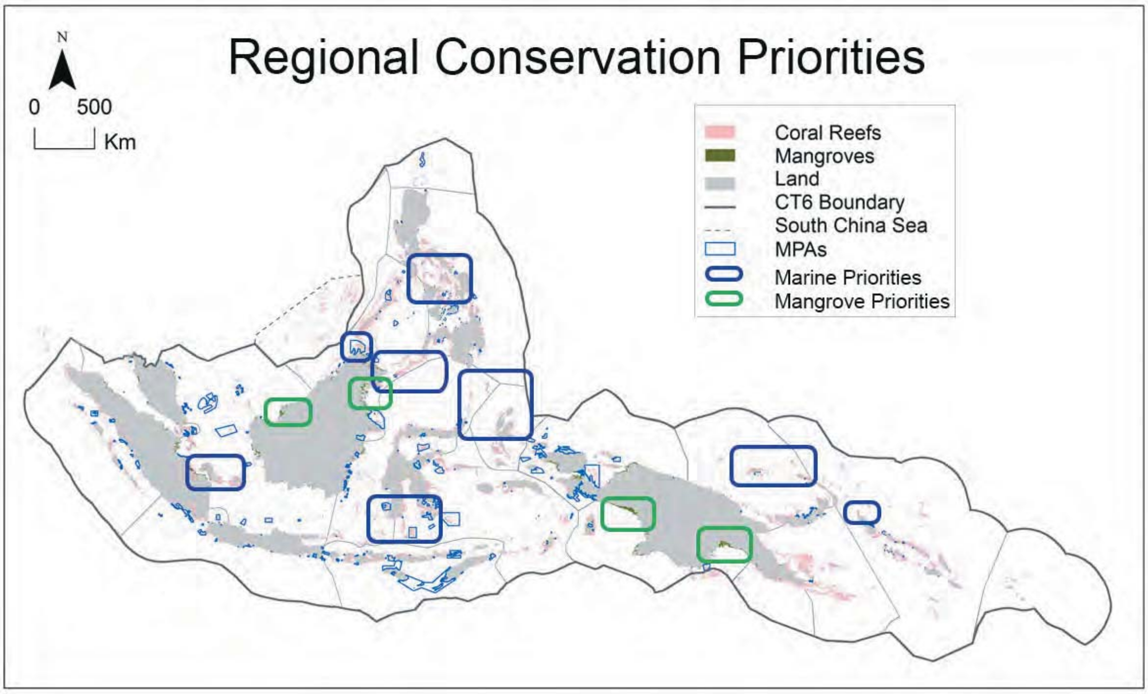
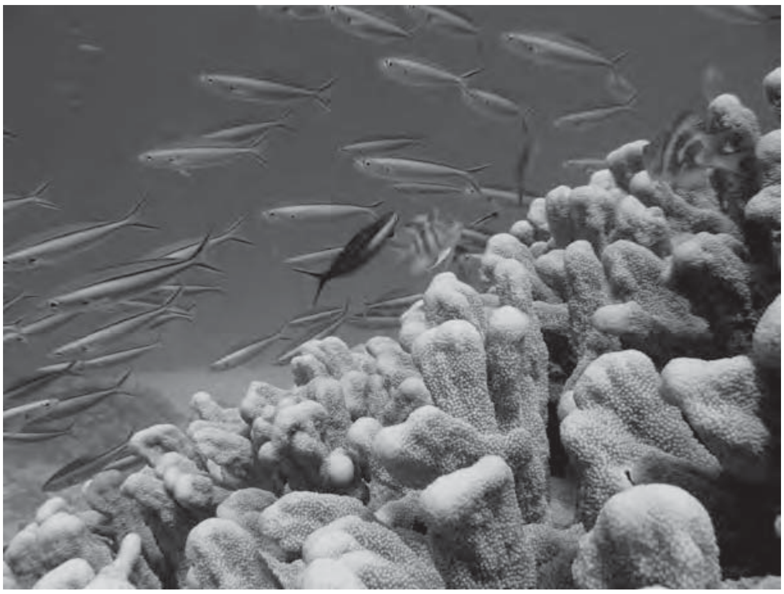


Figure 18. Coral triangle wide conservation priorities for representation, spawning aggregations, turtles, connectivity, and avoiding thermal stress.



Appendices

Appendix 1. Spatial data used in the analysis, sources and edits conducted for this project.

Data layer	Features	Source	Edits	Reference
Coral reef habitat layers	Coral cover high Coral cover medium Coral reef slope Rocky reef Seagrass/ algae Sand Mud Other	Download http://coralmap.coremoc.go.jp/	Remove duplicates Remove reefs on land Cut overlapping polygons	(Kakuta *et al.* 2010)
World corals 2010	Corals	WCMC	None	
Mangroves	Mangroves	NASA	None	
Marine bioregions	bioregions	WCMC	None	(Spalding *et al.* 2007)
MPAs from CTA	Polygons and points	Download/ agreement	Polygons: readjust some locations Points: amalgamate with Philippine and Solomons point sources	
MPA points from SILMMA	Solomon Islands	agreement	Remove duplicates Move points to correct location	SILMMA
MPA points	Visayas, Philippines	agreement	Remove duplicates Move points to correct location	(Alcala *et al.* 2008)
MPA points	Bohol Sea, Philippines	agreement	none	R Abesamis
MPA points	Philippines	agreement	Remove duplicates Move points to correct location	UP-MSI
Artisanal fishing	Opportunity cost for marine areas	NCEAS	none	(Halpern *et al.* 2008)
World gridded population, 2010	Proxy for opportunity cost in mangrove areas	//sedac.ciesin.columbia.edu/data/collection/gpw-v3	none	(Center for International Earth Science Information Network (CIESIN)/Columbia University 2005)
Turtle sites	5 species	collaboration, OBIS Seamap	None	
Turtle tracks	4 species	collaboration	Develop connectivity matrices from	

			tracks	
Spawning aggregation sites	Aggregation sites for 11 fish families	Agreement, collaboration	Site edits to correct location	(Sadovy de Mitcheson *et al.* 2008)
Biophysical connectivity	Matrices of mean dispersal probability among 624 Indo-Pacific sites	collaboration	Extract connectivity for domain Expand to 17K pu's	(Treml *et al.* 2012)
Historical thermal stress	CT6, 4 and 8 DHW, 4km resolution	NOAA collaboration	Aggregated to 10km planning unit size	S Heron
Future thermal stress	CT6, 4 and 8 DHW, 1 degree resolution	NOAA collaboration	Aggregated to 10km planning unit size	(van Hooidonk *et al.* 2013)

Appendix 2. Details of families of fishes represented in spawning aggregation data and turtle species.

Family	Catchment area (km^2)
Acanthuridae	5,026
Caesionidae	1,256
Carangidae	2,513
Haemulidae	1,257
Labridae	2,513
Lethrinidae	5,850
Lutjanidae	8,244
Mugilidae	2,217
Scaridae	1,257
Serranidae	71,437
Sphyraenidae	1,257

Species name	Common name	Catchment area (km^2)
Caretta caretta	Loggerhead	2,487
Chelonia mydas	Green	437,647
Dermochelys coriacea	Leatherback	282,224
Eretmochelys imbricata	Hawksbill	117,155
Lepidochelys olivacea	Olive	55,196

Appendix 3. Connectivity model values for modeled species.

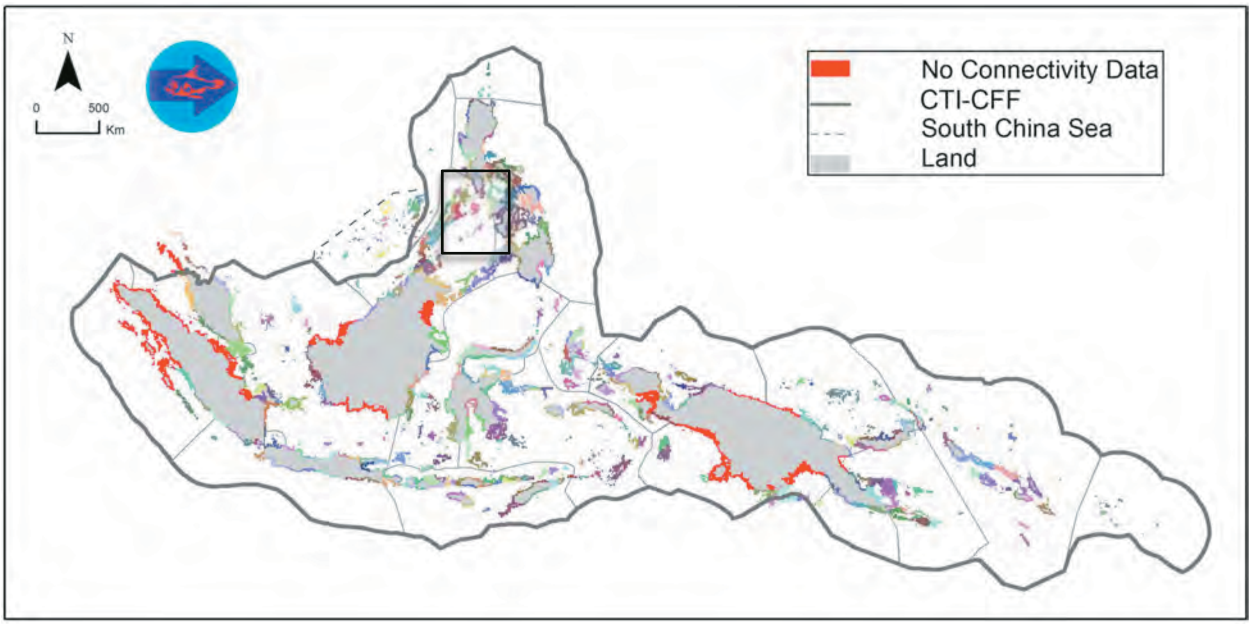
A. Coral Trout (*Plectropomus leopardus*)

- Spawning at 3 consecutive new moons (over 5 days) during warm months (Aug – Dec in N. GBR) (Samoilys 1997), >24deg C cue.
- Sep-Nov prime (Doherty *et al.* 1995).
- Minimum pelagic larval duration 25days, settlement at 19-31 days (Doherty *et al.* 1995), but 'almost certainly an underestimate'. Therefore max PLD at 35days; competency at ~19 days.
- Horizontal swimming speed approach reef ~18cm/ (Leis & Carson-Ewart 1997).
- 5-17% settlement mortality at reef (Leis & Carson-Ewart 1997)
- Some auditory and olfactory abilities at several kilometers (Leis 2007; Wright *et al.* 2008)
- Form aggregations, but not far from reef.

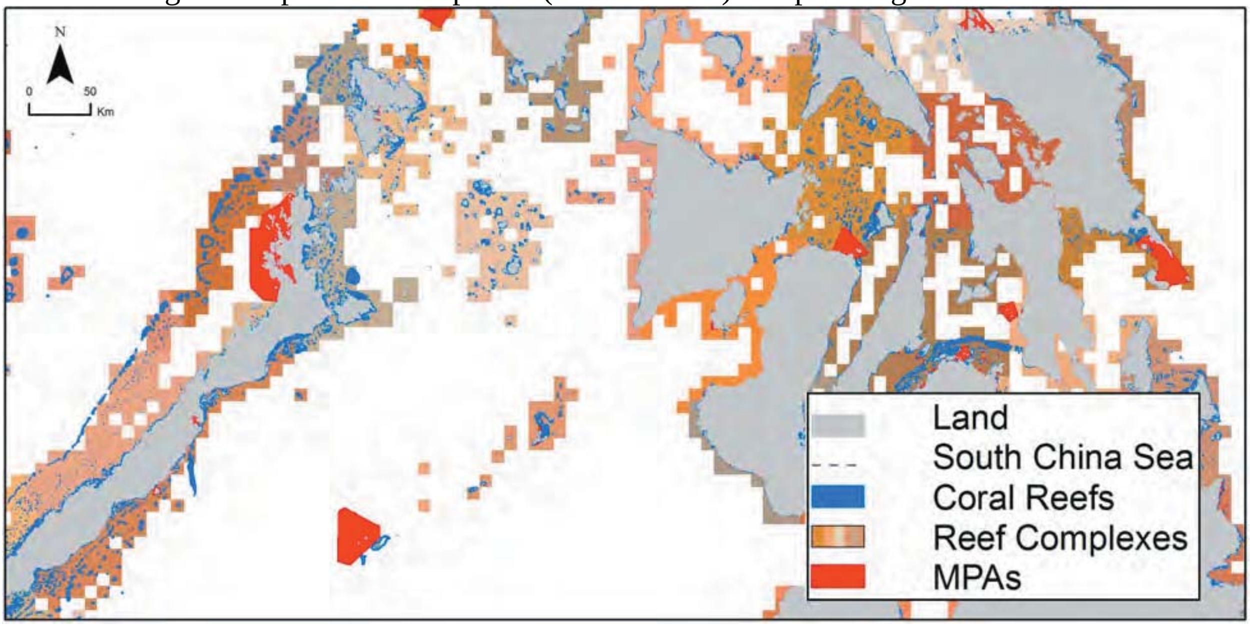
B. Sea cucumber (e.g., commercially important *Holothuria whitmaei*).

- PLD ~ 10 days (Uthicke 2001; Uthicke & Benzie 2002; Benzie & Uthicke 2003)
- GI of both populations peaking typically between April and June in Ningaloo & N GBR (Shiell & Uthicke 2006). One of the few winter-spawning tropical inverts. July – Nov in New Caledonia. Spawn year-round in equatorial regions.
- Larvae are 3-stage; single-cilia to barrel three-cilia (competent), to pentacularia stage (creeping) with tentacles. Free-swimming at ~day 3, weak swimming (Asha & Muthiah 2002). The similar *Holothuria spinifera* (popular in India) had ciliated swimming from day 10-15.
- Relatively high larval survival in lab (Asha & Muthiah 2002).

Appendix 4. Planning units assigned to connectivity model reef complex neighborhoods. Red areas have no connectivity data.



Inset showing close-up of reef complexes (colour-coded) and planning units.



Appendix 5. Habitat present in 21 marine ecoregions (MEAM, Spalding et al. 2007) and their proportion protected.

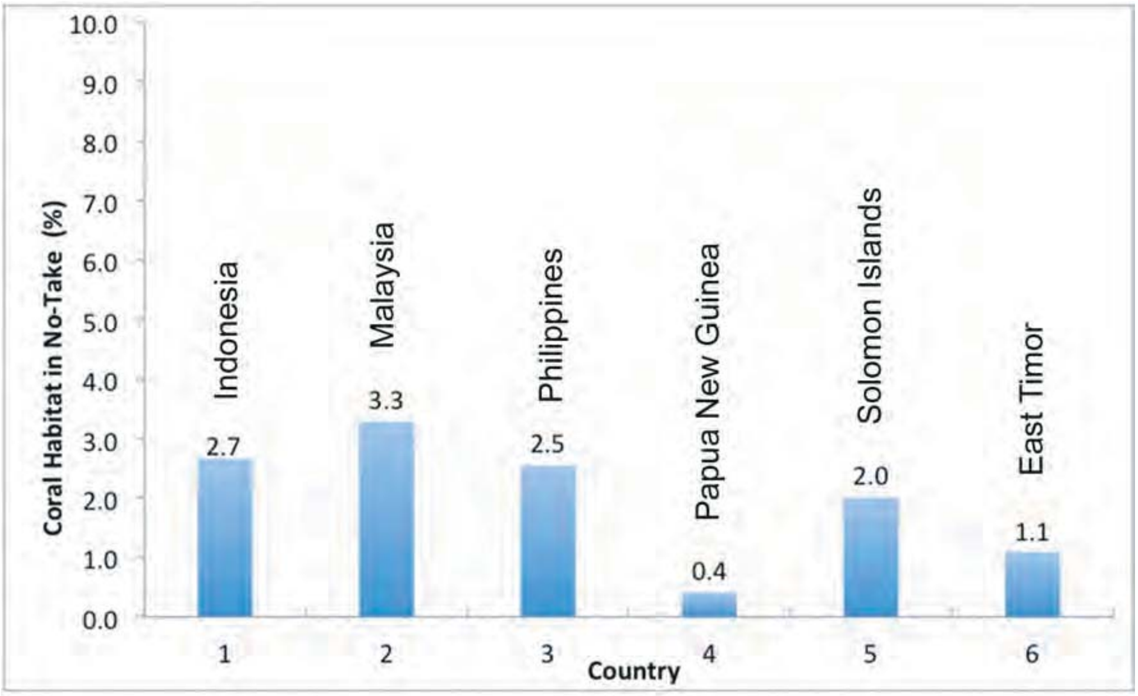
		ECOREGIONS						
	Habitat Class	Arafura Sea	Banda Sea	Bismarck Sea	Eastern Philippines	Gulf of Papua	Halmahera	Lesser Sunda
Total Area of Habitat per Ecoregion (km2)	Mangroves	6910	1390	384	1637	3115	315	694
	Coral cover High	0	0	0	10	0	2	0
	Cover cover Medium	40	490	152	375	24	42	129
	Deep cover slope	412	1816	904	1748	78	153	746
	Other Corals	0	2399	1066	2521	82	340	688
	Rock	486	2634	514	1978	149	289	818
	Seagrass/ seaweed	5	575	50	716	14	105	407
	Sand	220	1272	239	900	45	185	181
	Mud	6802	316	70	540	3845	15	187
	Unidentified	249	309	122	134	240	8	69
	Protected Habitats							
Area of Habitat in MPAs and Percentage	Mangroves	51	140	1	34	0	0	248
	% Protected	**(0.7)**	**(10)**	**(0.25)**	**(2.1)**	**(0)**	**0**	**(35.8)**
	All Corals	0	2235	61	602	271	0	914
	% Protected	**0**	**(30.5)**	**(2.3)**	**(9.1)**	**(81.6)**	**0**	**(38.4)**
	%Coral in No-Take	**0**	**3.1**	**0.38**	**4.7**	**8.2**	**0**	**3.9**

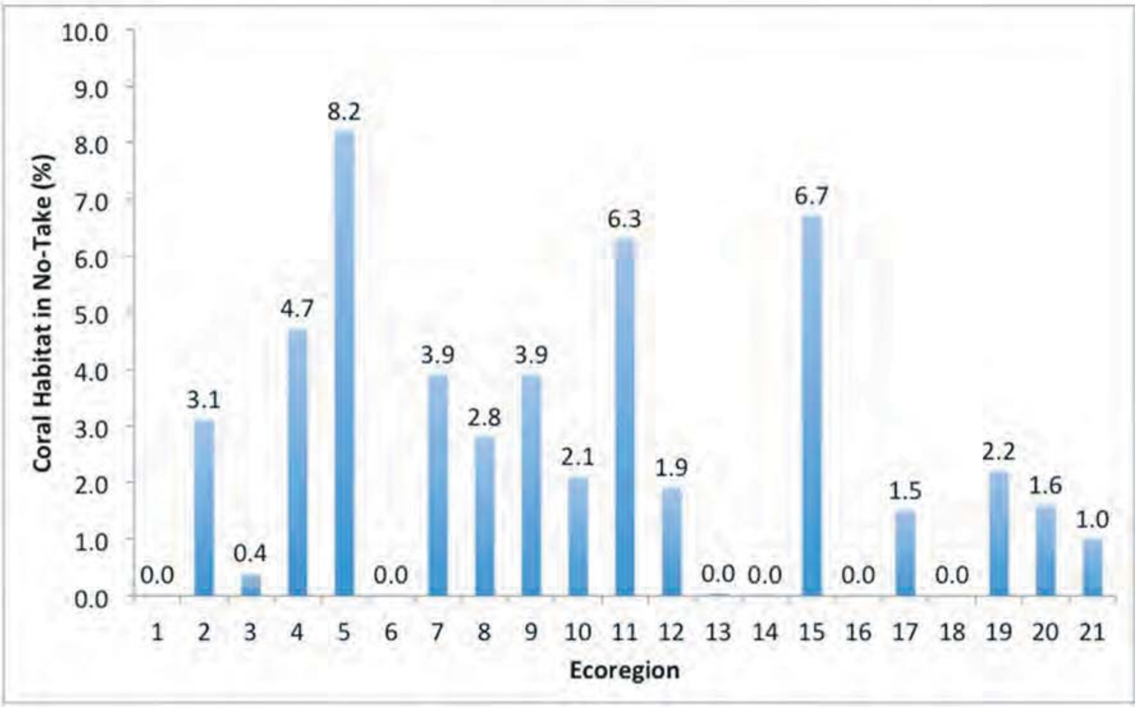
		ECOREGIONS						
	Habitat Class	Malacca Strait	Northeast Sulawesi	Palawan/ North Borneo	Papua	Solomon Archipelago	Solomon Sea	S.China Sea Oceanic Islands
Total Area of Habitat per Ecoregion (km2)	Mangroves	2318	182	6809	6002	482	385	0
	Coral cover High	0	0	0	5	0	0	0
	Cover cover Medium	0	18	29	142	258	576	117
	Coral cover slope	98	164	3814	203	1511	2591	1034
	Other Corals	190	203	3591	348	1432	1380	1976
	Rock	11	162	2685	981	858	1071	238
	Seagrass/ seaweed	0	30	691	190	85	34	0
	Sand	38	28	1157	1173	443	902	122

	Mud	5528	23	1002	789	4	43	0
	Unidentified	465	18	455	86	345	259	134
	Protected Habitats							
Area of Habitat and Percent in MPAs	Mangroves	23	17	144	842	2	0	0
	% Protected	**(0.98)**	**(9.4)**	**(2.1)**	**(14)**	**(0.39)**	**0**	**0**
	All Corals	85	217	1919	1042	145	20	0.04
	% Protected	**(28.4)**	**(39.7)**	**(18.9)**	**(62.1)**	**(3.5)**	**(0.4)**	**(<0.1)**
	%Coral in No-Take	**2.8**	**3.9**	**2.1**	**6.3**	**1.9**	**0.04**	**0.001**

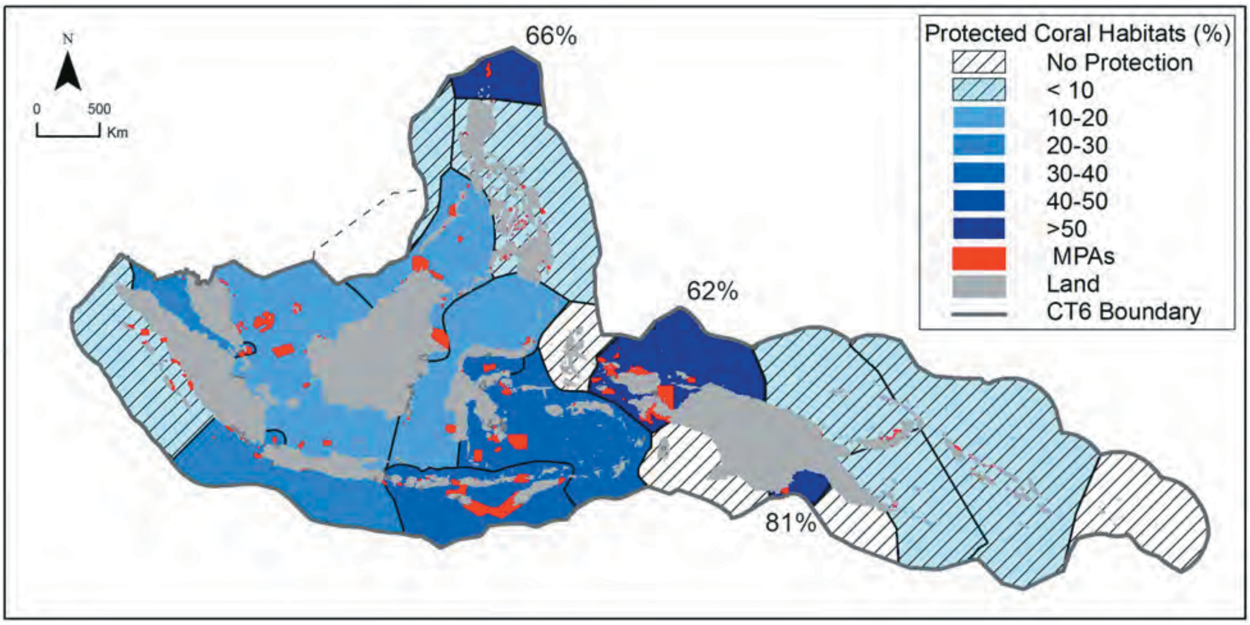
		ECOREGIONS						
	Habitat Class	S. Kuroshio	SE Papua New Guinea	Sulawesi Sea/ Makassar Strait	Vanuatu	Sthn. Java	Western Sumatra	Sunda Shelf/ Java Sea
Total Area of Habitat per Ecoregion (km2)	Mangroves	0	693	2147	24	267	308	7031
	Coral cover High	0	0	0	0	0	0	0
	Cover cover Medium	3	31	142	26	19	69	88
	Coral cover slope	0	246	1633	108	271	1514	895
	Other Corals	70	774	1641	193	172	1196	1860
	Rock	30	74	1309	105	130	344	1053
	Seagrass/ seaweed	2	46	280	0	1	6	17
	Sand	7	88	396	40	71	149	367
	Mud	0	104	1000	0	514	110	6992
	Unidentified	0	20	263	20	47	85	308
	Protected Habitats							
Area of Habitat and Percent in MPAs	Mangroves	0	0	678	0	50	6	61
	% Protected	**0**	**0**	**(37.6)**	**0**	**(18.6)**	**(1.8)**	**(0.9)**
	All Corals	68	0	673	0	128	278	587
	% Protected	**(66.2)**	**0**	**(14.2)**	**0**	**(21.5)**	**(8.7)**	**(15.1)**
	%Coral in No-Take	**6.7**	**0**	**1.5**	**0**	**2.2**	**1**	**1.6**

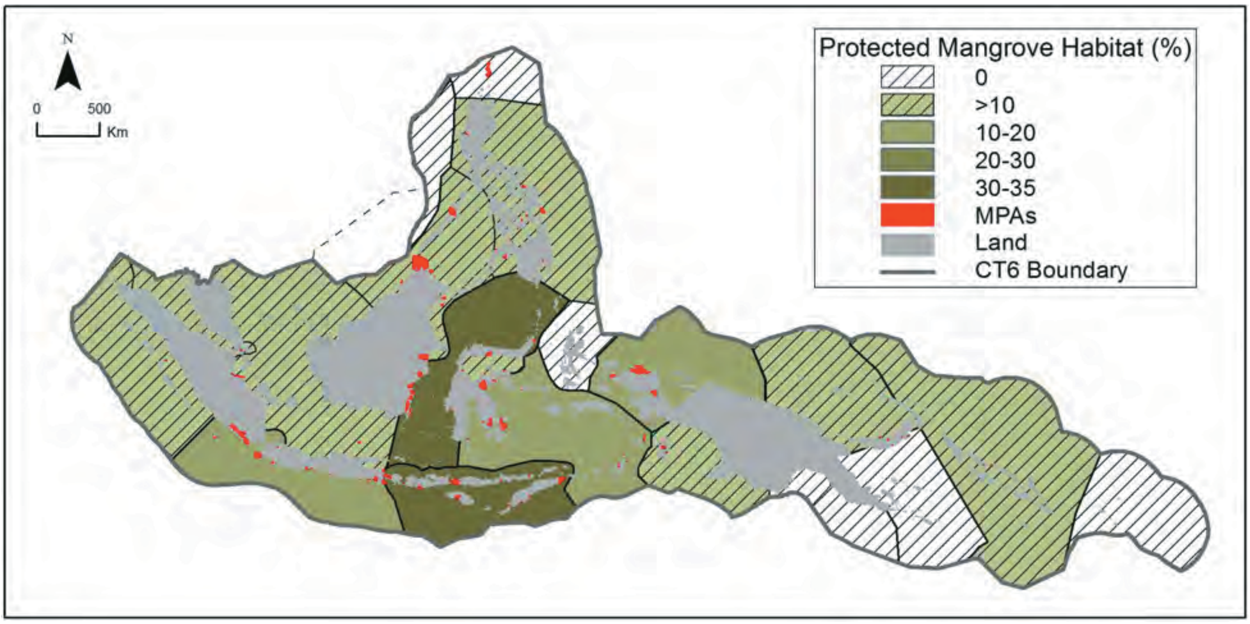
Appendix 6. Percentages of coral reef habitats in no-take areas by country and ecoregions, ecoregion names listed in Figure 3).



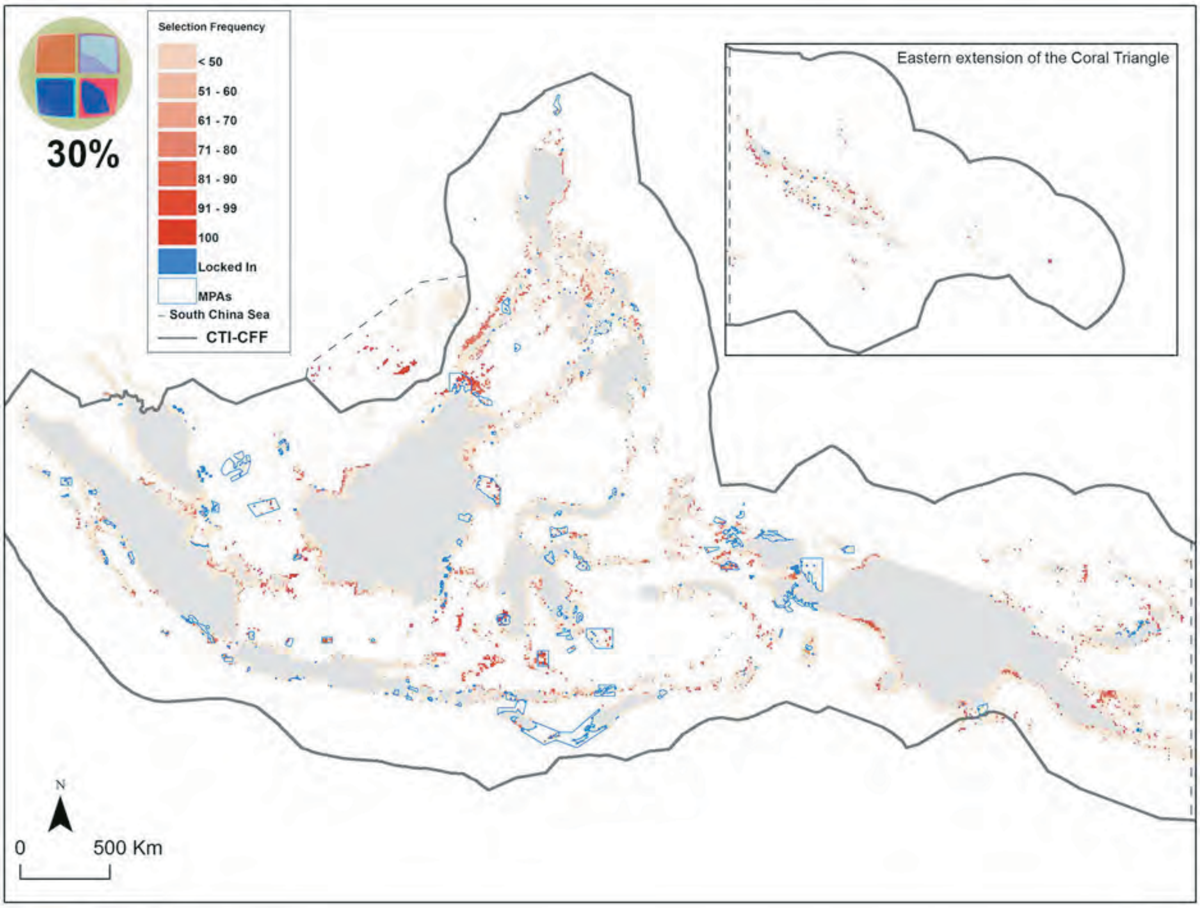


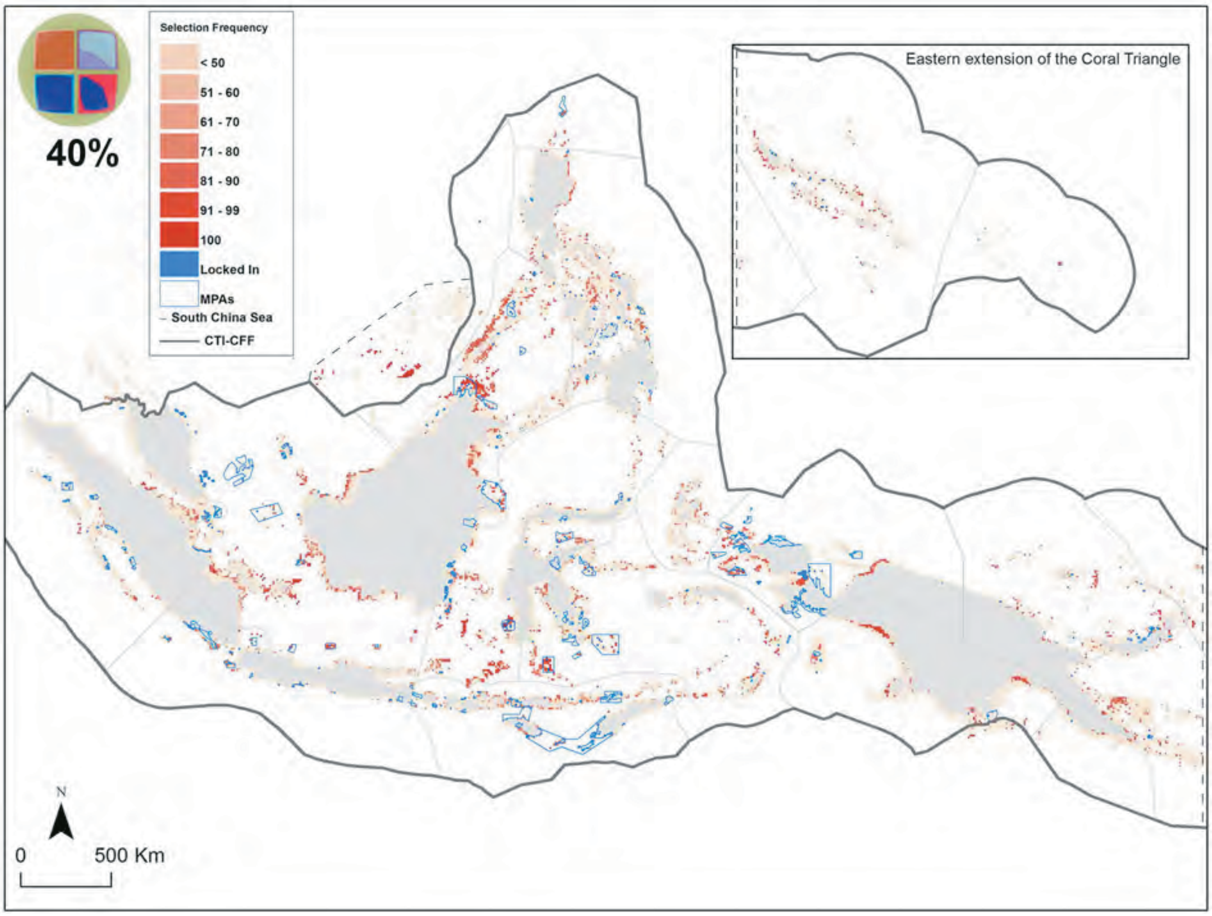
Appendix 7. Percentage of coral (blue) and mangrove(green) habitat protected within the existing MPA network by ecoregion.



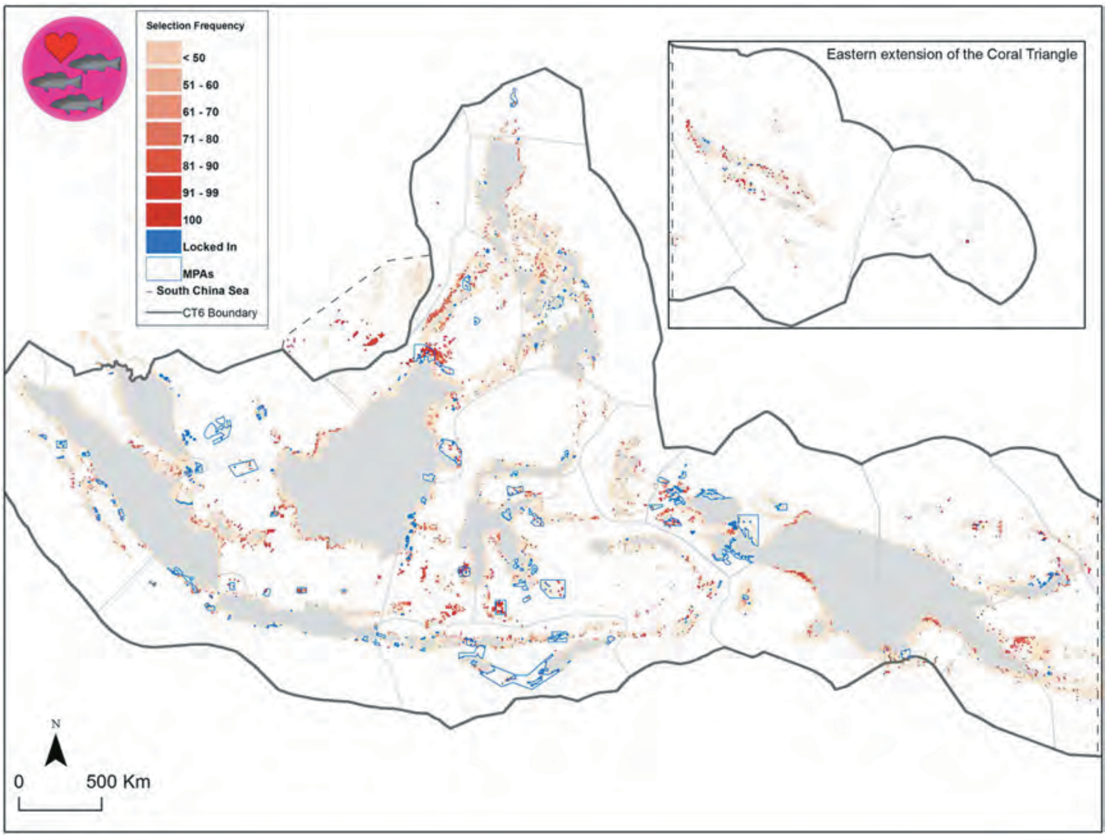


Appendix 8. Selection frequency maps for 30% and 40% representation objectives.

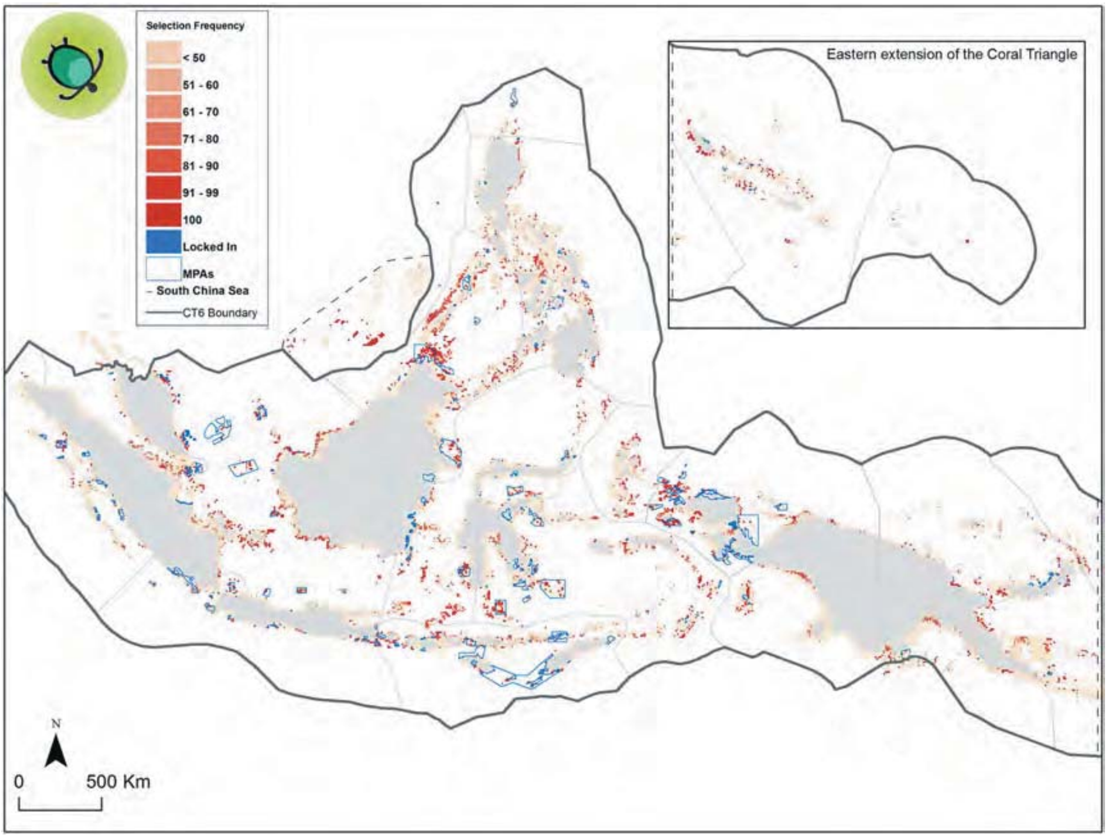




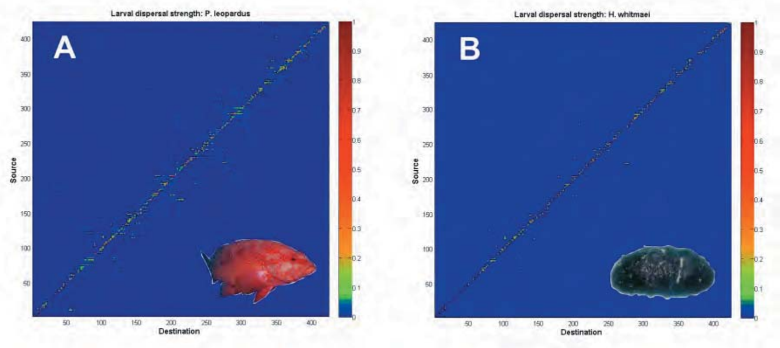
Appendix 9. Selection frequency maps for protecting spawning aggregations and significant turtle habitats and turtle migration corridors.



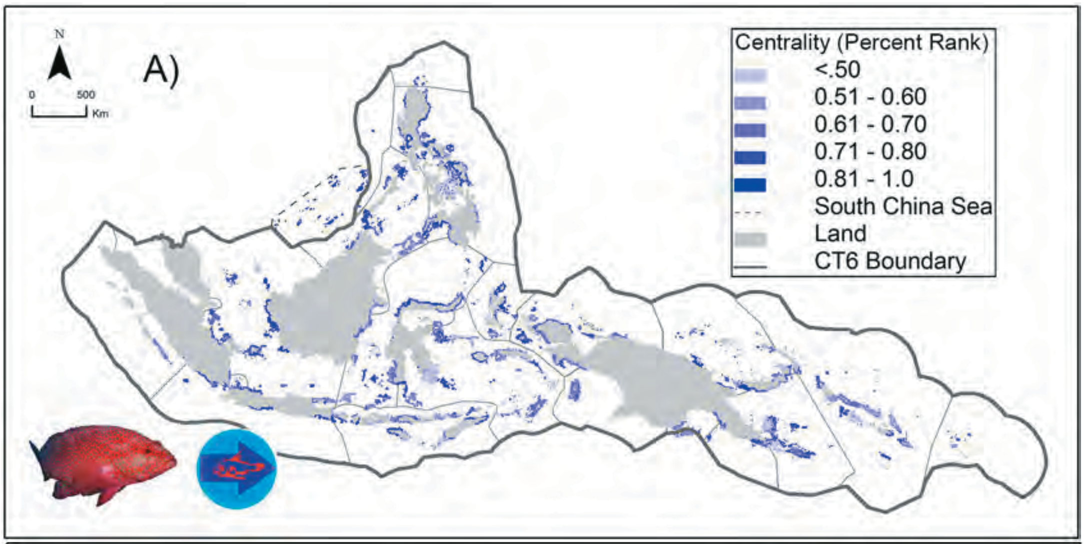
Appendix 10. Selection frequency maps for protecting significant turtle habitats and turtle migration corridors.

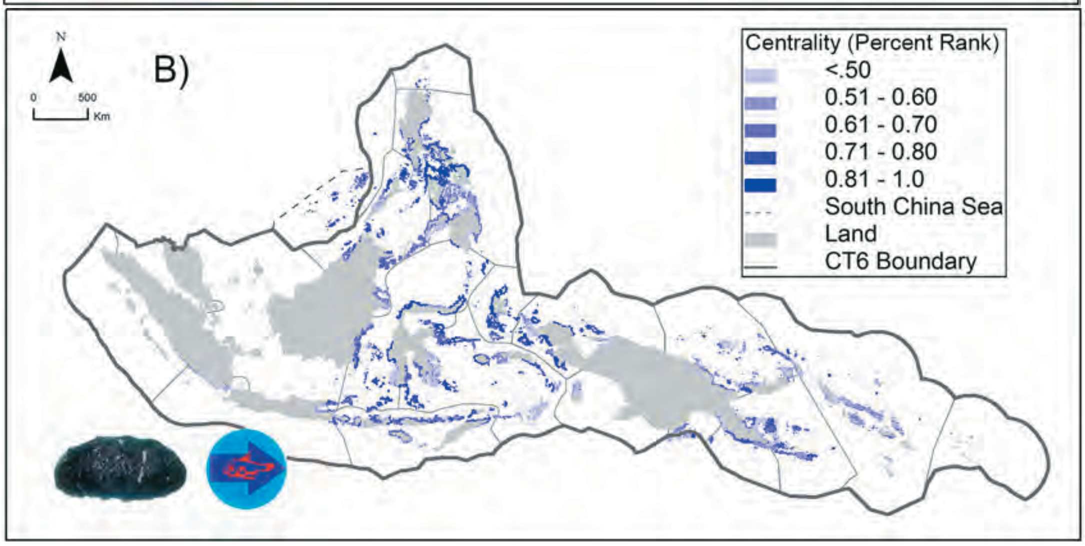


Appendix 11. Dispersal surface maps depicting the dispersal matrix as dispersal intensities from source reef complexes to destination reef complexes, where each pixel represents the proportion of larval input to a destination from a source. Values along the diagonal represent self-recruitment. A) coral trout <u>Plectropomus leopardus</u>, and B) the black teatfish <u>Holothuria whitmaei</u>.



Appendix 12. Centrality maps showing the percent ranking of connective pathways within each planning unit for A) coral trout Plectropomus leopardus, and B) the black teatfish Holothuria whitmaei, that correspond to selection frequency results in the connectivity analysis.





Appendix 13. Exploratory analysis incorporating probabilities of reef persistence in conservation prioritization for the Coral Triangle.

With thermal stress probability as indicator of reef persistence, results from the Marxan with Probability analysis suggest that establishing a climate proof network of MPAs across the Coral Triangle, while simultaneously achieving habitat and ecoregional targets, will be challenging. Our approach focused on the probability of a planning unit to experience a thermal stress event. Less than 15% of all features (N=33 excluding mangroves) were met under baseline targets (20% habitats; 20% ecoregions) at the DHW4 stress level. Better solutions are found with reduced targets of 10% in terms of the number of targets met, however, these numbers reflect ecoregions, not habitat types and therefore perform poorly as a method to identify a representative networks. Under the DHW8 scenario, all features could be met due to generally low probabilities of experiencing thermal stress at this level. This is the more severe, and therefore less probable thermal regime in our analysis and results showed no significant difference from the baseline scenario results.

We explore how the results under the historic DHW4 thermal stress scenario compare with representative baseline scenario results (Figure A13.1). In general, planning units are selected more often in the base scenario and very few new areas are prioritized under climate change. As all areas have or are predicted to experience some form of thermal stress, finding effective solutions in a ubiquitously stressed region, means the use of probabilities to inform spatial prioritization is sub-optimal and alternate methods should be pursued to explore conservation gaps under climate change.

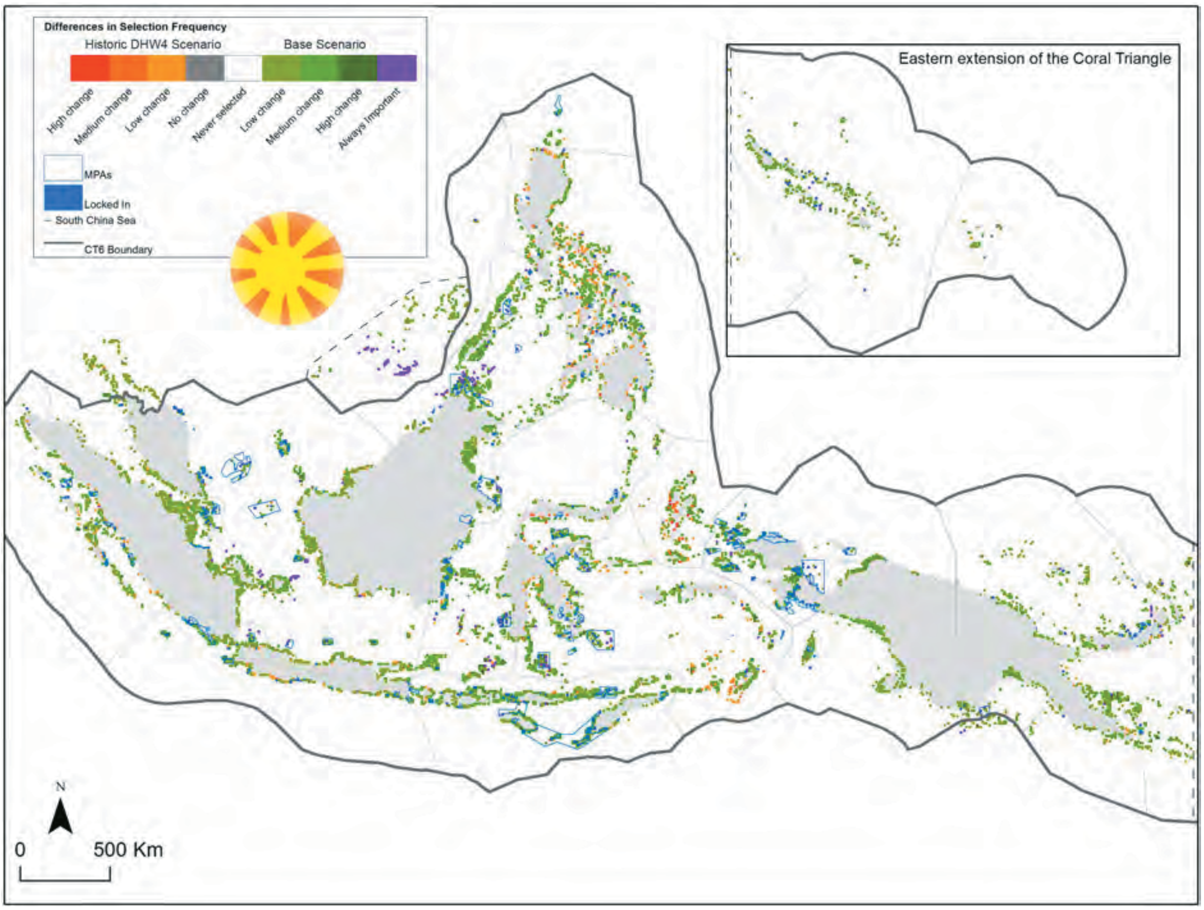
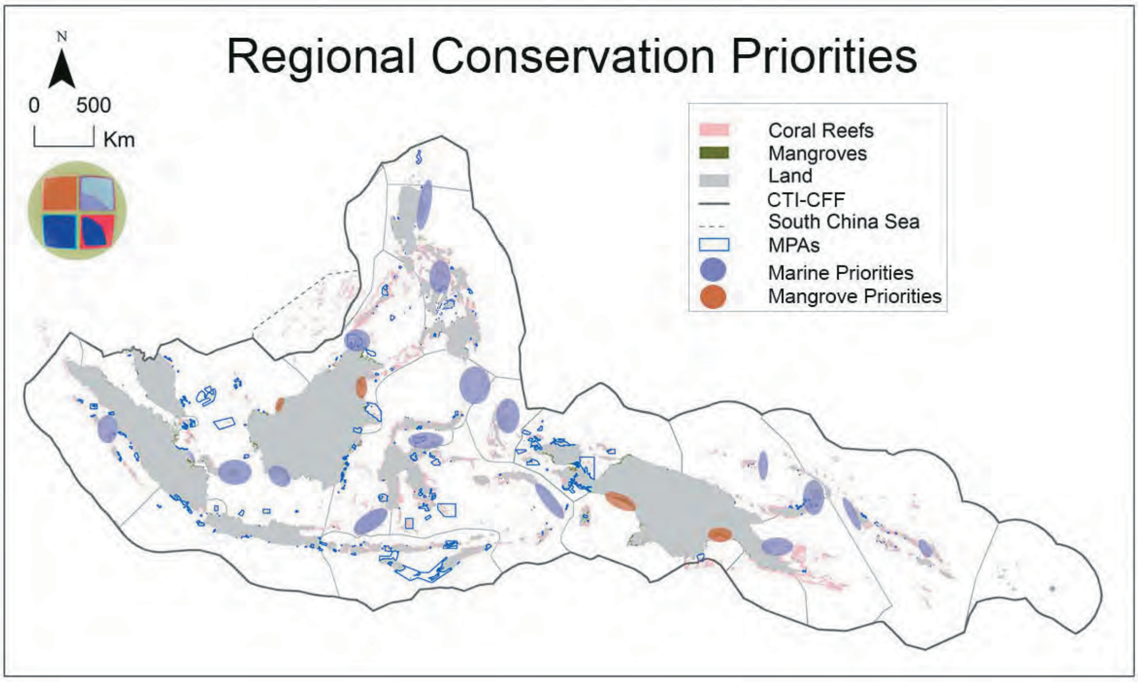
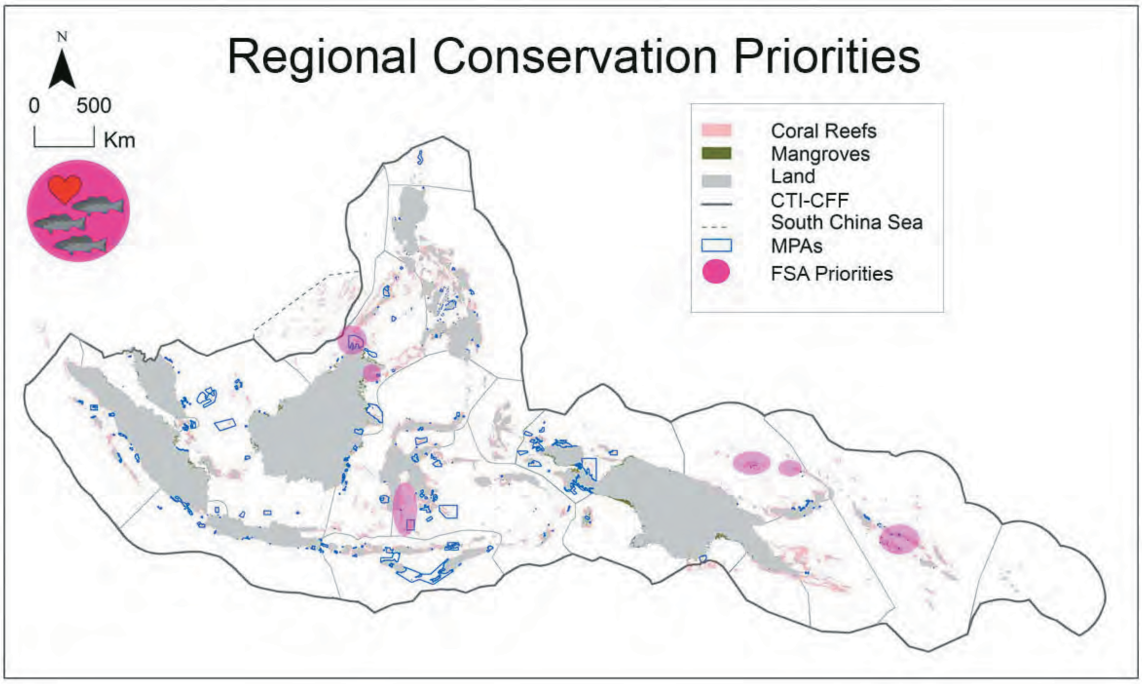


Figure A13.1. Differences in the selection frequency between the base scenario (Marxan with 10% feature targets) and threat avoidance scenario (Marxan with Probability, 50% probability of meeting 10% feature targets) under historic DHW4 thermal exposure.

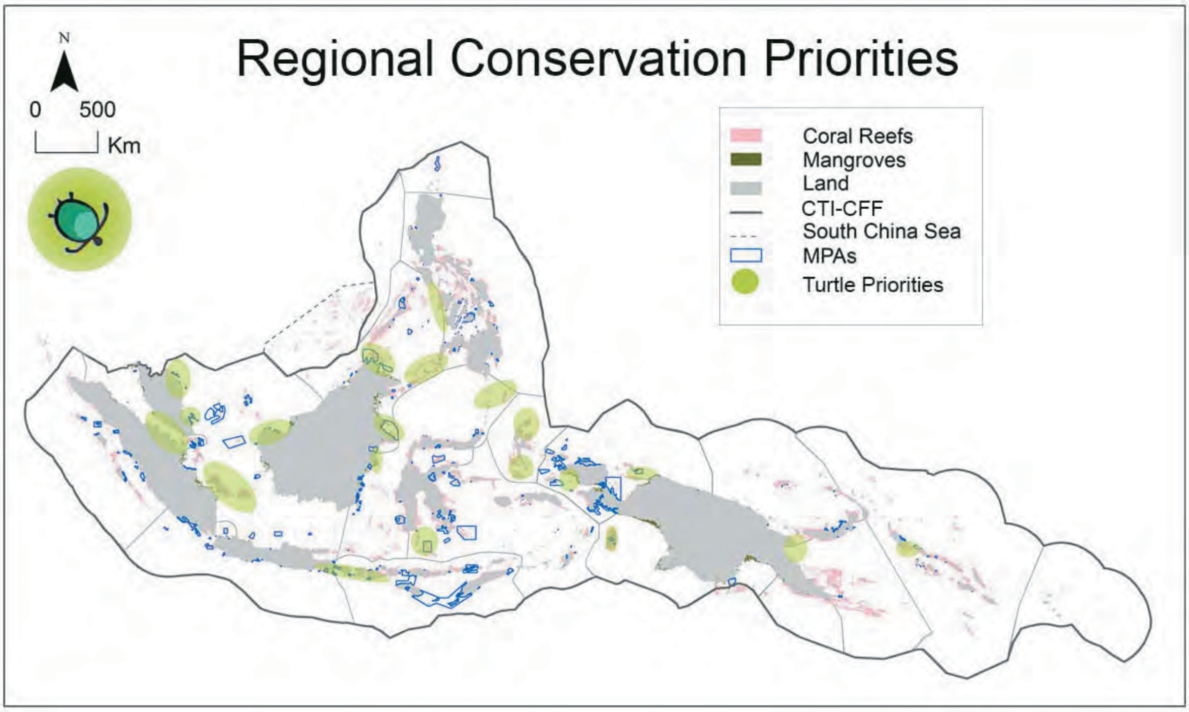
Appendix 14. Regional priorities for conserving habitat representation.



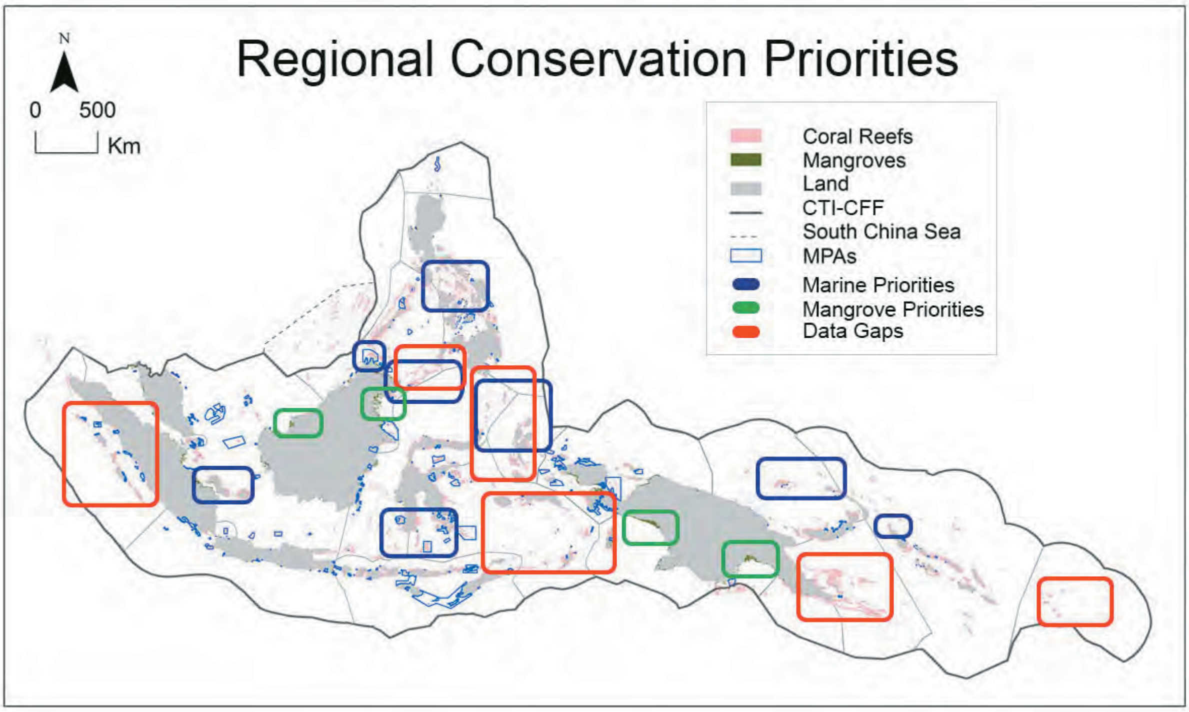
Appendix 15. Regional priorities for conserving fish spawning aggregations.



Appendix 16. Regional priorities for conserving turtle migration pathways and critical habitats.



Appendix 17. Regional priorities for data gaps, and marine and mangrove habitat representation.



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