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Evaluating annual severe coral bleaching risk for marine protected areas across Indonesia

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ABSTRACT

Coral reefs face an uncertain future under global climate change, with thermal-induced bleaching increasing in frequency such that corals will soon experience annual severe bleaching (ASB). Marine Protected Areas (MPAs) are therefore becoming increasingly important as a conservation tool. Here we evaluate (i) Indonesia's coral reefs' spatial variation in ASB, (ii) whether reefs projected to have a later onset of ASB (i.e. possible climate refugia) are protected within MPAs, and (iii) the ASB risk profiles for reefs related to MPAs receiving priority investments. Our results highlight considerable variability across Indonesia's reefs being at risk of ASB. The ASB risk before 2028 is greater for coral reefs protected by MPAs versus those outside MPA boundaries. The ASB risk before 2025 is greater for coral reefs protected by priority MPAs versus those protected by non-priority MPAs. Overall, our results show that only ~45% of the coral reef areas that are currently located within MPAs will likely act as thermal refugia (ASB > 2044). This is unsurprising given that the MPA network in Indonesia has been established over many decades, with most MPAs designated before suitable bleaching risk projections were available to inform MPA placement. Our results highlight the scope to further incorporate potential climate refugia for reefs into new MPA designations. This study also provides strategic information, which can support the development of Indonesia's long-term MPA and coral reef conservation strategy to effectively manage, mitigate, and adapt to the impacts of climate change on coral reefs.

1. Introduction

Local and global-scale stressors are impacting coral reef ecosystems [55]. While local stressors such as over- or destructive fishing can be addressed through effectively implemented local management actions, such as marine protected areas (MPAs), managing global impacts such as those driven by the climatic and chemical stressors of ocean warming and acidification are particularly challenging [13,56,68,73]. Anthropogenic climate change and current CO_2 emission trends have caused heatwave temperatures to increase and can cause global-scale coral mortality [71]. Due to the frequency and intensity of heatwaves, bleaching events, from which full impacts are still unknown, are likely to impede coral recovery [11]. While several local factors may contribute to bleaching, thermal stress is the main and globally most important driver of bleaching. Van Hooidonk et al., (2016) [65] projected that globally > 75% of coral reefs will experience annual severe bleaching (ASB) events before the year 2070 under the Representative Concentration Pathway (RCP) 4.5. Since 2010, the number of years between

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severe bleaching events has drastically reduced to 5.9 years compared to 25 years in the 1980s, reducing the time coral reefs have to recover from the damage [80]. Addressing global stressors to reefs requires coordinated global actions to address climate change.

The Coral Triangle, and more specifically Indonesia, is projected to be one of few regions that have climate change refugia present under future warming [5]. Indonesia hosts the greatest tropical coral reef extent within the Coral Triangle, covering around 25,000 km^2 [81]. Indonesia's reefs are some of the most biodiversity-rich in the world, with more than 70% of all reef-building coral species and a high number of reef fish species [67,76]. Coral reefs provide ecosystem services benefiting around 500 million people globally through benefits such as food provisioning, coastal protection, and cultural value [37,64]. Approximately 140 million Indonesian people live in coastal areas (the total Indonesian population is around 270 million), with over half of the Indonesian cities and towns located on the coasts [17]. Thus, coral reef-related resources are critical for Indonesia's economic and social well-being. In Indonesia, 35% of coral reefs are projected to be climate change thermal refugia, i.e. experience ASB later than 2044 [82]. Thermal refugia are regarded to be more resilient and able to retain environmental conditions that support diverse coral species in certain regions longer-term, which is relevant to Resilience Based Management – i.e. using knowledge to prioritize, implement and adapt management strategically in relation to current and future drivers that affect ecosystem functions [21,26,48]. The concept of thermal refugia for coral reefs was first considered by Glynn [62] and identifies regions with lower impacts of climate change stressors, potentially extending the time for coral reefs to build resilience [35].

While at the global level, Indonesia is regarded as a hotspot of coral reef thermal refugia [65,82], a record of multi-year bleaching events has been affecting Indonesian reefs since the 2016 El Niño–Southern Oscillation (ENSO) marine heatwave [11]. Historically, coral bleaching has been observed in West Sumatra, the south shore of Central Java, Bali and the Lombok area, and Southern Sulawesi [31,57,75]. Due to the recent increase in the magnitude of coral bleaching events, it is important for the Government of Indonesia to consider climate change adaptation within their long-term conservation strategy. This strategy, amongst other concerns such as the well-being of coastal communities, should consider the identification and sustainable management of thermal refugia sites to secure Indonesian efforts in coral reef conservation.

Indonesia has a target to protect 3,250,000 km^2 of marine areas within MPAs by 2030 – in alignment with the Aichi Target 11 of having 10% of its national waters protected and the commitment to the Sustainable Development Goal (SDG) 14 to conserve and sustainably use the oceans, seas and marine resources for sustainable development [6,46]. Indonesia defines MPAs as 'spatially defined, marine, coastal or small island areas that are protected and managed by a zoning system to achieve sustainable management of fisheries resources and environmental outcomes' (PP RI No. 60/2007; [6]). As of January 2020, Indonesia had designated 196 Marine Protected Areas (MPAs), which are governed by the Ministry of Marine Affairs and Fisheries (MMAF) (166 MPAs) and the Ministry of Environment and Forestry (MoEF) (30 MPAs) (Fig. 1; KKP, 2020 [46,6]). These 196 MPAs cover approximately 23,100 million km^2, representing 7% of the national waters [6]. These MPAs also include 43% of the coral reefs found in Indonesia, with estimates suggesting an average hard coral cover of approximately 36% [6,46].

While expanding MPA networks are important for the sustainable management of marine resources, it is well recognised that for MPAs to deliver conservation outcomes they must have effective management [69,70]. Management effectiveness has gradually improved across MPAs in Indonesia, though there is substantial scope for further improvement [4,6]. In 2019, 35 MPAs were identified by the MMAF as pilot example MPAs to rapidly develop effective management ([52]; Fig. 1; Table S1). The intention was that the 35 MPAs could showcase best practices for MPA management effectiveness and identify "lessons learned" from building effective management, which then can be applied to the rest of the MPA network [16,46]. Of the 35 MPAs, 10 are managed at a national level by the National Technical Unit (Balai/Loka Kawasan Konservasi Nasional) directly by MMAF from Jakarta (this unit

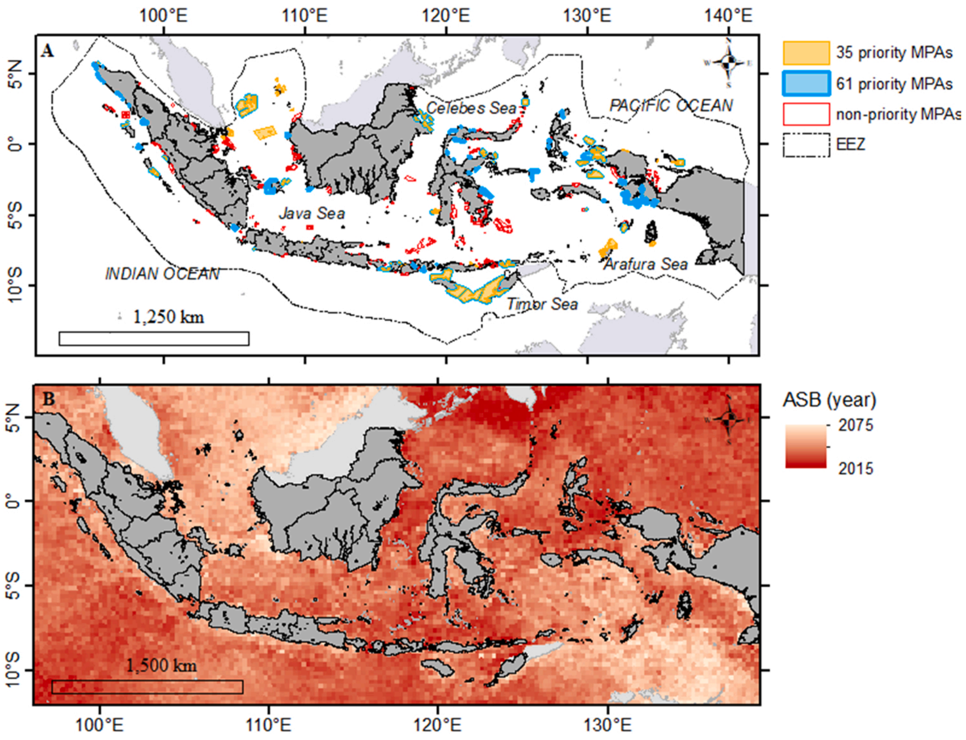

Fig. 1. (A) Map showing the location of the Economic Exclusive Zone (EEZ) around Indonesia and its marine protected areas (MPAs). The dark grey land mass represents Indonesia. The light grey landmasses represent non-Indonesian countries. (B) Map showing the modelled year when annual severe bleaching (ASB) would start.

directs local staff within the MPA), whilst the remaining 25 are managed by the provincial government fisheries offices [46]. The 35 selected MPAs cover 108,545 km^2 across 17 provinces within 6 regions of Indonesia – mostly in the Lesser Sunda Islands (34% of the MPA extent), and Sumatra (28%). Kalimantan and Java have the lowest percentage of extent from the 35 MPAs (3% and <1%, respectively) [12]. In December 2021 the 35 priority MPA strategy was changed and now focuses on building effective management for all MMAF MPAs that have been formally 'established' (see [49] for a summary of MMAF MPAs stages of establishment). At the time of this change there were 61 MMAF MPAs that were established and prioritised for formal management effectiveness building activities. All of the original 35 priority MPAs are included within this new group of 61 MPAs. Given limited resources, it is important to strategically implement MPA management capacity building efforts to maximise conservation outcomes, including considering potential future thermal refugia and ensuring these areas are under effective and sustainable management.

This study uses an Annual Severe Bleaching (ASB) predictive model to identify coral bleaching risk across Indonesia and which Indonesian MPAs are more likely to be thermal refugia. ASB represents the projected year beyond which a reef is expected to experience severe bleaching conditions annually. We consider MPAs at three management levels: (i) individually across Indonesia (i.e. per MPA), (ii) at the provincial level, and then (iii) between those MPAs prioritised for management effectiveness building activities vs those currently not prioritised. This study aims to support and/or inform the development of Indonesia's long-term MPA and coral reef conservation strategy toward efficiently managing and adapting to the impacts of climate change on coral reefs.

2. Methods

2.1. Data layers

2.1.1. Coral reef extent

A vector layer of the coral reefs globally present was sourced from the National Oceanic and Atmospheric Administration (NOAA), and contains data gathered from three different reef-location datasets; ReefBase, Reefs at Risk Revisited, and millennium Maps [53]. The Indonesian Exclusive Economic Zone (EEZ) boundary was downloaded from Marineregions.org [51]. This layer was used to ensure that only the coral reefs present within Indonesia's EEZ were used in this study.

2.1.2. MPAs located in Indonesia's national jurisdiction

A vector layer of the 196 MPAs, which have been legally recognised as of January 2020, was provided by WWF-Indonesia and used in this study (Fig. 1; KKP, 2020 [46,83]). This dataset was originally sourced from the MMAF protected area database, and was standardised as described in Handayani et al., 2020 [12]. Priority MPAs for management effectiveness were sourced from MMAF. In this analysis, we separately considered MMAF's 35 priority MPAs for management effectiveness capacity building in place from 2019 to 2021, and the 61 priority MPAs for management effectiveness capacity building adopted in December 2021.

2.1.3. Bleaching projection data

ASB is calculated as the projected year beyond which a reef is expected to experience severe bleaching conditions annually based on the reef being exposed to at least 8 Degree Heating Weeks (DHW) [82]. As the ASB is highly sensitive to the Maximum of the Monthly Mean (MMM) and the emission scenario used, the year of onset of ASB should be used with care, although spatial patterns are reliable and arguably more useful when trying to find out what areas should be prioritized in terms of management. For example, eight DHWs is higher than the mean optimum bleaching predictor of 6.1 DHWs for the globe [84]; i.e., at 8 DHWs there is a greater degree of confidence that thermal stress will be sufficient for bleaching to occur [85].

This predictive model was calculated under the SSP5–8.5 high emissions scenario [82] and has a 25 × 25 km resolution. Sea surface temperature (variable TOS) data from climate models were obtained from the CMIP6 portal [14] for the SSP5–8.5 scenario [43]. SSP5–8.5 was considered a high emissions scenario. It represents current rates of emissions and emissions growth. In this scenario, it is assumed that climate policy is not implemented or not successful. SSP5–8.5 represents a growing world economy heavily dependent on fossil fuels. Data were concatenated where needed, to create complete monthly time series (2015–2100), and multiple runs were averaged when present. A climate Data Operators (CDO) (https://mpimet.mpg.de/cdo) bilinear interpolation (function remapbil) was used to regrid each model output to a 0.25° grid, which is roughly 27.7 × 27.7 km at the equator. Missing data was filled in the zonal direction using National Center for Atmospheric Research (NCAR) command language's Poisson grid fill function. All model runs were adjusted to the mean of NOAA's Coral Reef Watch coraltemp_v3.1 2005–2019 climatology by subtracting the mean of the first 5 years of the model run from the entire period and then adding the mean of the CoralTemp climatology. Degree Heating Weeks were calculated for each year between 2015 and 2100 as summed anomalies above the warmest monthly temperature (the maximum monthly mean or MMM) from the CoralTemp climatology (see [82] for more detailed methods and models used for bleaching projections). An ensemble standard deviation raster of the year of ASB was also used to calculate the model's minimum and maximum ASB year. However, to convey a clear message, emphasis will be given to the discussion of the obtained mean estimates.

2.2. Spatial analysis

To understand which Indonesian MPAs might act as thermal refugia for coral reefs, we compare the year of ASB onset between (i) coral reefs inside vs outside MPAs, (ii) coral reefs inside priority MPAs vs non-priority MPAs and (iii) coral reefs inside MPAs across the different provinces.

Data visualisation and analysis was conducted in the software programme ArcGIS ArcMap version 10.8.1. Several layers were produced using the "clip tool". An "Indonesian coral reef" polygon layer was created by clipping the global coral reef polygon with the Indonesia's EEZ polygon to ensure only the coral reefs located inside the EEZ were included in the analysis. To separate the coral reefs present inside vs outside MPAs, the "Indonesian coral reef" polygon was clipped with the 196, 35 and 61 MPA polygons, creating "coral reefs inside MPA" and "coral reefs outside MPA" polygons. To find the projected year at which ASB would start per coral reef (inside and outside each MPA), the "extract by mask" tool was used. This tool was used to create "coral reefs inside MPA" and "coral reefs outside MPA" raster. Depending on the area and location of the original reef polygons, one or more ASB pixels of 25 × 25 km were included. To obtain one value per reef polygon and per MPA polygon, a mean and standard deviation (SD) raster of the ASB year was calculated using the "zonal statistics" tool. The SD was also used to indicate how sudden an MPA might experience change. The function cor.test in the statistical software R was used to test if there is a significant correlation between SD and the size of the MPAs. A low SD could indicate the entire MPA is projected to experience a sudden change, while a large SD for an MPA indicates a more gradual change across reef pixels in the MPA. Finally, a polygon centroid coral reef and MPA layers were created using the "Feature to point" tool. The "extract values to point" was used to extract the mean and SD ABS values from the rasters. Once this step was completed, the attribute table of the layers of interest were exported in a.csv format to be used for analysis.

2.3. Statistical analysis

Using the ASB values per coral reef polygon inside vs outside MPAs, and coral reefs inside priority MPAs vs non-priority MPAs, Kernel density estimates were calculated to compare the differences in their year of onset of ASB. There are two groups of priority MPAs: the 35-priority MPAs (2019–2021) and the 61-priority MPAs (2021 – present). The bandwidths of the Kernel density estimates were selected using the Sheather-Jones selection procedure with the ‘dpik’ function in the “Kernsmooth” package in the software program R [50]. Differences in the distribution of the year of onset were tested using the permutational “sm.density.compare” function in the R package “sm” [18,19,79]. This function randomly allocates the year of onset of coral bleaching in coral reefs between the MPA categories of interest and then calculates how different the data is from this randomisation across the distribution of the year of onset. To understand the status of the coral reefs at a provincial scale, the average year of onset of annual severe bleaching events of the coral reefs within the MPAs per province was calculated and compared. Since the analysis is based on areas covered by coral reef polygons, any MPAs that did not include reef area were excluded from the analysis.

3. Results

3.1. National conservation management level

In total, 161 of the 196 Indonesian MPAs contain coral reefs. Overall, 289,207 km^2 of coral reef area was found inside Indonesia’s EEZ, with 21% (60,530 km^2) of the reef area contained within MPAs and 79% (228,677 km^2) outside MPAs. Based on the mean ASB model, the majority of MPAs, 99 in total, are projected to experience ASB by 2044 (61%), of which 12 (8%) will experience ASB by the year 2030 (Fig. 2; Table S2). In total 73 MPAs (45%) could act as thermal refugia, as they are modelled to experience ASB after 2044 (Table S2). Minimum and maximum ASB years and SD for all MPAs can be found in Table S2.

The average projection of the onset of ASB for reefs within and outside Indonesia’s MPAs is similar at the year 2042 ± 2 (mean ± SD) and 2043 ± 1.4, respectively (Fig. 3). While the Kernel distribution plot indicates no overall significant difference across all years, significant differences exist within some parts of the distribution (the distribution lines are located outside the grey standard error band of no significant difference; Fig. 3). A significant difference can be seen for the coral reef areas projected to experience ASB prior to 2028, with more reefs vulnerable to ASB prior to 2028 located inside MPAs (Fig. 3). After, 2028 there is no significant difference between the ASB years of the coral reefs inside vs outside MPAs.

The extent of coral reef area and the mean projected year of onset of ASB varies within MPAs (see Table S2). A total of 36 MPAs have reefs projected to reach ASB during the same year (i.e. no SD), and are therefore more likely to experience sudden MPA-wide reef degradation. In contrast, 39 MPAs are projected to experience more gradual changes, with different reefs within the same MPA reaching ASB over more than five years.

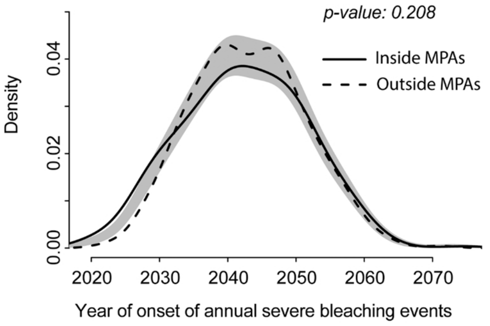

Fig. 3. Kernel density estimation comparing the distribution of model predictions for the mean annual severe bleaching year per coral reef polygon inside MPAs (number of reef polygons = 332) with coral reef polygons outside MPAs (number of reef polygons = 747). The grey shaded band represents one standard error on either side of the null model of no difference between the kernel density estimates for inside vs outside MPAs. Therefore, locations where the distribution lines lie outside the grey band indicate years where significant differences occur. The significance test (generating the p-value) was based on a permutation test across the full density distributions (i.e. testing for significant differences across the full distribution).

3.2. Coral reefs inside vs outside priority MPAs

In total, only ~9% of Indonesia’s coral reef area is included within priority MPAs – with 25,752 km^2 (8.90%) reef extent inside the 35 priority MPAs and 26,212 km^2 (9.06%) inside the 61 priority MPAs. Our spatial layers identified coral reefs in 33 of the 35 priority MPAs and in 50 of the 61 priority MPAs. Based on the mean ASB model, ~6% of these “priority” reefs will likely act as thermal refugia reefs (ABS > 2044) – with 17,850 km^2 (6.61%) reef extent for thermal refugia inside the 35 priority MPAs and 16,648 km^2 (5.76%) inside the 61 priority MPAs. When comparing priority MPAs for management effectiveness with non-priority MPAs there is no overall significant difference across all years (Fig. 4). However, the distribution lines and grey band indicate that significant differences exist for pre-2025 (Fig. 4). A greater proportion of coral reefs likely to experience ASB pre-2025 are contained within the 35 priority MPAs (Fig. 4A) and the 61 priority MPAs (Fig. 4B) when compared to non-priority MPAs.

There is high variation (i.e. as indicated by a high SD) in the projected year of ASB for the reefs protected by the priority MPAs (Table S2). In some cases reefs polygons within a MPA (e.g. in Raja Ampat) are projected to have already reached ASB, i.e. in 2020, while other reef areas are not projected to reach ASB until 2054. There are 12 priority MPAs that are projected to be subject to a more gradual

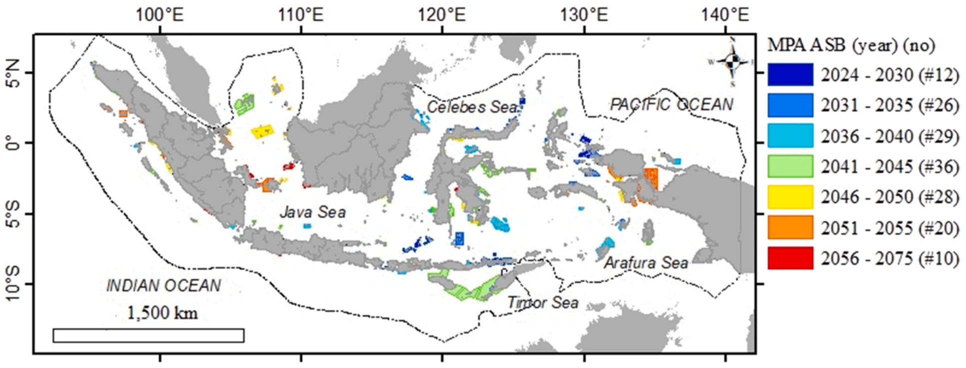

Fig. 2. Overview of the average year of onset of annual severe bleaching (ASB) events in all the marine protected areas (MPAs) based on the mean ASB year of the coral reefs found within the MPAs. The number (no) of MPAs that can be found in each bin is mentioned in the legend as (#number) (Shapefile can be downloaded from pangaea.de [86]).

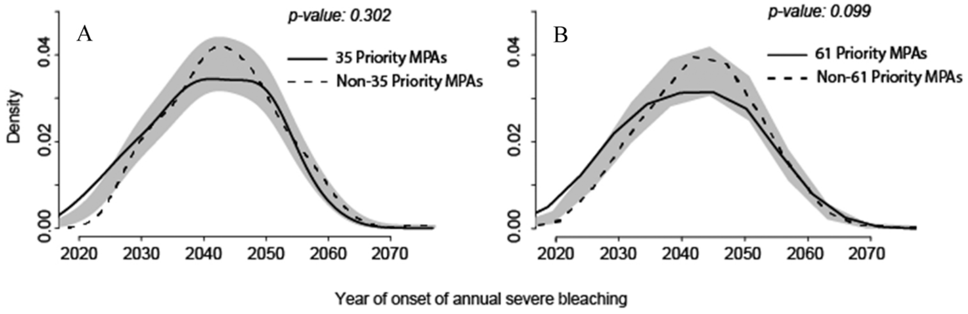

Fig. 4. Kernel density estimation comparing the distribution of model predictions per coral reef polygon inside the (A) 35 priority marine protected areas (MPAs) (number of reef polygons = 117) with coral reefs polygons from non-priority MPAs (number of reef polygons= 204) and (B) 61 priority MPAs (number of reef polygons= 151) with coral reefs polygons from non - 61 priority MPAs (number of reef polygons= 192). The grey shaded band represents one standard error on either side of the null model of no difference between the kernel density estimates for priority vs non-priority MPAs. Therefore, locations where the distribution lines lie outside the grey band indicate years where significant differences occur. The significance test (generating the p-value) was based on a permutation test across the full density distributions (i.e. testing for significant differences across the full distribution).

degradation, as different reefs within these MPAs are projected to reach ASB over a longer period (>5 years). Three priority MPAs (Lombok Utara (2026 ± 0), Lombok Timur (2027 ± 0) and Sumbawa (2035 ± 0)) all contain reefs with no variation in projected ASB, and so may face sudden degradation across the whole MPA when ASB is reached. The five priority MPAs projected to reach ASB the soonest versus the latest are given in Table 1. There was no significant correlation between the area of the MPAs and the SD ($p < 0.05$).

3.3. *Provincial level*

The year that reefs are projected to reach ASB varies across Indonesia, with reefs in western Indonesia likely to experience ASB later than those in central and eastern Indonesia (Fig. 5, S1, S2). For example later projected ASB years are found for MPAs in western provinces such as Sumatra Barat (ASB mean: 2046 ± 1.8), Kalimantan Barat (2054 ± 3.33), and Jawa Barat (2054 ± 0.93). A higher thermal risk is found for provinces such as Papua Barat (2042 ± 4.94), Kalimantan Timur (2033 ± 0.95), and Nusa Tenggara Timur (2037 ± 6.22). Within the Kalimantan province there is a high variation, with Kalimantan Timur projected to be affected earlier (2033 ± 0.95) compared to Kalimantan Barat (2054 ± 3.33) and Kalimantan Selatan (2045 ± 4.9). There is no data provided for Kalimantan Tengah as no coral reefs in our spatial data layer intersected with MPAs in this province. The number of MPAs within the province did not cause variation in the ASB year. For example, Papua Barat has nine MPAs, and an average ASB onset of 2042 ± 4.94. Kalimantan Barat (2054 ± 3.33) has a lower SD despite only having three MPAs. Two of the 28 provinces had only two MPA. These were Banten (2041 ± 0.35), which has a low SD and Bengkulu (2050 ± 7.81), which has the highest SD of any province.

Table 1
Overview of the five marine protected areas (MPAs) earliest and latest affected by annual severe bleaching (ASB) from the 35 priority MPAs, based on the mean ASB model. A full list can be found in Tables S1 and S2.

Province	District	MPA name	Year ASB (mean)	SD
Earliest affected				
Nusa Tenggara Barat	Lombok Utara	TWP Gili Ayer, Gili Meno, Gili Trawangan	2026	0.00
Nusa Tenggara Timur	Alor	KKPD Selat Pantar - Alor	2026	5.57
Nusa Tenggara Barat	Lombok Timur	KKPD Gili Sulat dan Lawang - Lombok Timur	2027	0.00
Papua Barat	Raja Ampat	SAP Kepulauan Waigeo Sebelah Barat	2028	5.52
Sulawesi Utara	Kepulauan Sangihe	KKPD Tatoareng - Kep Sangihe	2028	0.65
Latest affected				
Kep. Bangka Belitung	Belitung Timur	KKPD Gugusan Pulau-Pulau Momparang - Beltim	2049	3.27
Kep. Riau	Bintan	KKPD Bintan	2050	3.14
Sumatra Barat	Kota Pariaman	TWP Pulau Pieh	2052	2.57
Sumatra Utara	Nias Utara	KKPD Sawo Lahewa - Nias Utara	2054	3.56
Jawa Barat	Sukabumi	KKPD Pantai Penyu Pangumbahan - Sukabumi	2055	4.34

When comparing the priority MPAs per province some patterns emerge (Fig. 6). Nusa Tenggara Barat province contains five priority MPAs, the greatest of any province. Yet these will experience early and sudden ASB (2035 ± 2.7). Therefore, the prioritised MPAs in Nusa Tenggara Barat are unlikely to act as thermal refugia. In contrast, Kepulauan Riau contains four priority MPAs, all with a later onset of ASB (2049 ± 4.8). Therefore, the existing prioritised MPAs within Kepulauan Riau are likely good thermal refugia candidates. Nusa Tenggara Timur (2037 ± 6.2) has some of the greatest variation in ASB risk across its three MPAs. For example, the Selat Pantar MPA in Nusa Tenggara Timur is projected to reach ASB as early as 2026 ± 5.6 years. While its other two priority MPAs have mid-range (Sikka: 2039 ± 5.6) to late onset ASB (Laut Sawu: 2044 ± 10.1) Therefore, priority MPAs in Nusa Tenggara Timur include both climate-vulnerable and potential thermal refugia sites. Priority MPAs that are located in provinces important for tourism, such as Bali (e.g. Nusa Penida MPA), Nusa Tenggara Barat (e.g. Gili Ayer, Gili Meno, Gili Trawangan MPA), and Papua Barat (e.g. several Raja Ampat MPAs) are projected to be among the first to experience ASB.

4. Discussion

4.1. *Thermal refugia – recommendations for identifying areas of prioritization*

Under the high emissions SSP5–8.5 climate change scenario, the average year of the projected timing of ASB of Indonesia's coral reefs is 2044. This is eight years later than the projected global average of 2034 under the high emission scenario [82] and confirms that Indonesia has the potential to act as a thermal refugia for coral reefs. However, our results demonstrate that Indonesia-wide conservation strategies could give greater consideration to Indonesia's potential thermal refugia for coral reefs – especially as sustaining coral reef-associated biodiversity and the communities that depend on them are important aims of MPAs in Indonesia. This greater consideration could be achieved through aligning areas identified as likely thermal refugia and those prioritised for coral reef protection and MPA management effectiveness, as building activities in future conservation strategies. Our study aims to provide a methodology that can assist in the identification of areas and MPAs that

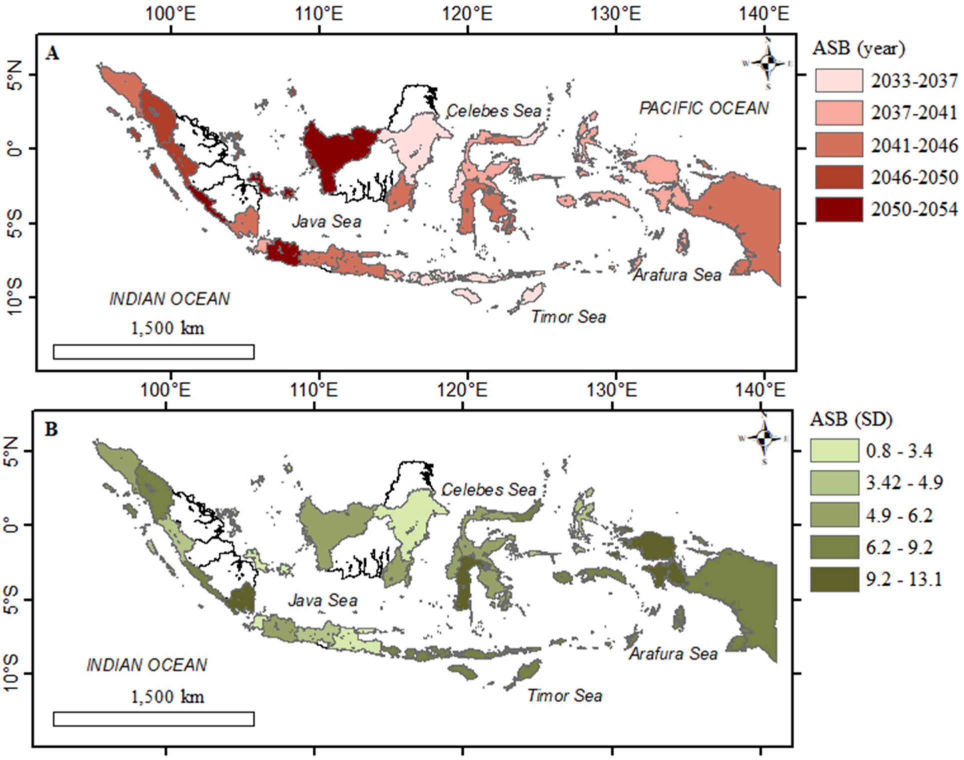

Fig. 5. (A) Annual severe bleaching (ASB) average for reefs within MPAs per province. (B) ASB average standard deviation for reefs within marine protected areas (MPAs) per province. Analysis based on coral reefs within the 196 identified MPAs across Indonesia and averaged at the province level. Provinces in white either do not have MPAs or do not have any coral reefs in the spatial datasets that intersect with their MPAs.

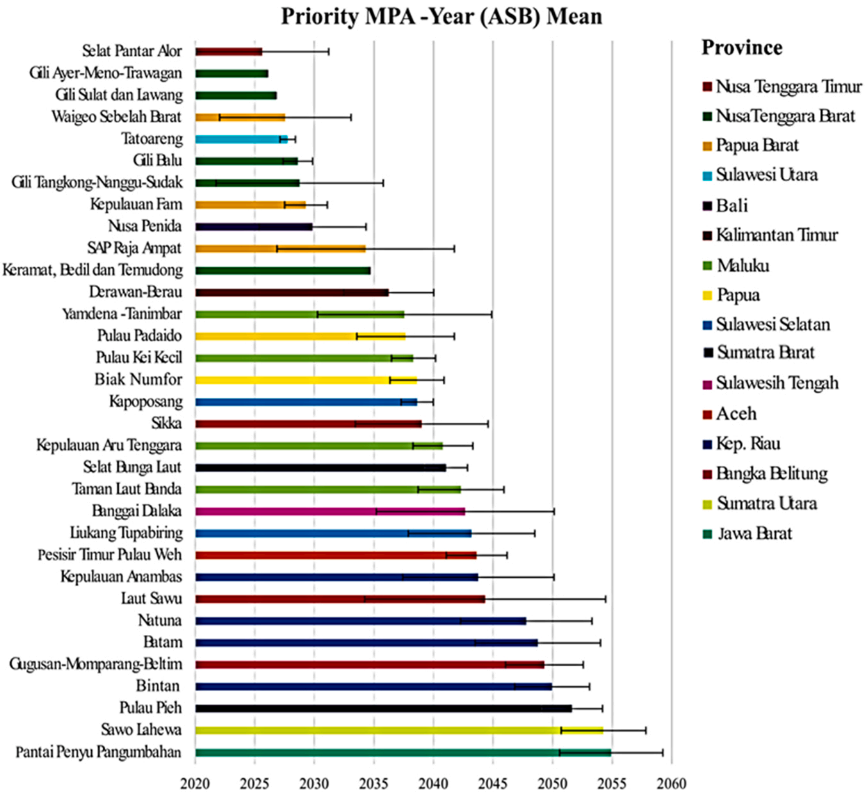

Fig. 6. The 35 Priority marine protected areas (MPAs) ordered per year of onset. Only 33 MPAs are shown as two MPAs do not intersect with our coral reef spatial layers. Colours indicate the province the MPAs belong to. Error bars indicate the one SD above and below the mean.

can act as thermal refugia and help prioritise their management.

Our results found multiple opportunities for potentially greater consideration of thermal refugia in Indonesia's marine conservation planning. Firstly, we found no overall difference in the proportion of potential thermal refugia sites included within MPAs (i.e. protection) versus those not protected – with 73 MPAs containing reefs that may potentially be thermal refugia (onset of ASB >2044). Secondly, this is further reinforced by reefs projected to face ASB soon, i.e. in the next 3–5 years, currently more likely to be included in MPAs. Thirdly, investments in management effectiveness building activities do not appear to be targeting MPAs containing potential thermal refuges, even though long-term ecosystem maintenance and habitat restoration have become important parts of Indonesia's MPA program. While the timelines will depend on the emissions scenarios and the resolution of the ASB model used (a high emissions scenario was utilised in this study), it is important to consider that across Indonesia there is a clear difference between the average onset of ASB locally and regionally, which will impact potential reef resilience.

Our results also indicate that it is important to consider variation in the onset of ASB across reefs within an MPA, as this could be a useful metric to identify MPAs that may face sudden versus a more gradual degradation. For example, the MPA Flores Timur has a mean ASB year of 2033 ± 11.4, with some reefs within Flores Timur projected to be exposed to annual severe bleaching events as soon as 2023, while other reefs in this MPA are projected to be spared ASB until 2057. Due to the variability in ASB in this area, management decisions (e.g. zonation) could further increase the resilience of this area by considering variation in ASB projections within the MPA. In some cases, the MPA-wide ASB year has a low variation and is projected to happen in the next 10 years. For example, projections suggest that all reefs in Gili Ayer, Gili Meno and Gili Trawangan MPA may reach ASB as soon as 2026. Urgent efforts to support coastal populations that depend on these reefs would therefore be advisable, as well as awareness and transparency of the limited role these MPAs can play in the face of rapid global climate change.

4.2. MPA designation – recommendations for increasing climate change resilience

Our results suggest that over the long-term MPAs in Indonesia may be at risk of missing their primary objectives, i.e. "achieve sustainable management of fisheries resources and environmental outcomes" [49] because of coral reef vulnerability to climate change. In the short-term (pre-2030), reefs within MPAs and also reefs within the MPAs receiving prioritised management effectiveness investments, face reaching ASB sooner. This risks that the MPAs showing the greatest environmental declines and negative human well-being impacts (caused by bleaching-induced reef degradation), reduce acceptance of MPAs as a valid conservation strategy in Indonesia. For example, faced with poorer performance from areas that have received the most funding support, core stakeholders (e.g. provincial governments, NGOs, community groups) may conclude that the MPAs are not providing benefits. Therefore, the variation in ASB across Indonesia and differential risks for each MPA must be clearly communicated to stakeholders. Longer-term, given the disparity in ASB risk across Indonesia, it makes sense to ensure that those reefs expected to reach ASB in later years receive priority management actions to avoid degradation from local stressors in the short and medium term. While management actions in MPAs that are projected to experience ASB sooner should focus on climate adaptation, accepting that it is likely that reefs will face widespread degradation is important.

The primary reason for the lack of the MPA network being able to act as thermal refugia (see Section 4.1) is because bleaching risk has not yet been specifically considered during the MPA designation process in Indonesia [6,46]. While bleaching is not the only risk to consider when designating MPAs, our findings do highlight how without specifically considering climate projections (e.g. [65]), as done in this study, the MPA network will miss possible thermal refugia. The results from this study can support: site selection for the designation of new MPAs, changes to the prioritisation approaches used for investment in building management effectiveness for the existing MPA network, and management plan changes (e.g. rezonation) to consider thermal refugia within existing MPAs. Projected vulnerability to future climate impacts should be an additional and valuable metric to include in the decision-making process.

The observed variability in ASB onset between different MPAs and regions highlights the importance of understanding differences in environmental conditions. It is thought that upwelling currents that provide seasonal cooling may facilitate coral reef resilience (e.g. [74]), and is potentially a strong factor of the delayed year in which ASB starts in western Indonesia. Seasonal cool waters caused by upwelling or strong ocean currents may ameliorate sea surface temperatures to prevent or promote recovery from a bleaching event. The changes in this seasonal cooling and upwelling occurrence need to be monitored as their ability to mitigate bleaching impacts could change depending on global climate changes ([32], 2013; [23,27]).

4.3. The importance of mitigating coral bleaching impacts for coastal communities

Coral reefs experiencing ASB are likely to cause severe impacts on the ecosystem services provided by reefs – and so have knock-on impacts on human well-being of coastal communities across Indonesia. These impacts are likely to be particularly felt in the marine tourism sector and the coastal fisheries sectors – both of which have high reliance on productive and healthy coral reef ecosystems [72]. However, there is limited evidence and evaluation of the likely impacts of ASB on these sectors [72]. Previous research has suggested that an increased understanding of the effects of bleaching can help align stakeholders' views against this common threat, when previously they had mixed priorities/perspectives on marine threats [47]. This can help build the case for effective marine area-based management to try and mitigate the worst effects of ASB on coastal communities.

Within the marine tourism sector, the diving industry (both snorkelling and scuba diving) accounts for 55% of formal marine tourism-related activities [8]. This marine tourism is not spread evenly across Indonesia, with the province of Bali the dominant destination, receiving over half of all international visitors [60]. Prior to the Covid-19 pandemic, the Government of Indonesia implemented a tourism strategy that had two main components: (i) shifting away from focusing on increasing the number of tourists visiting Indonesia to a focus on increasing the income captured by Indonesian communities and the government from tourism, and (ii) more evenly spreading tourism activities geographically across Indonesia so that more regions could benefit [7,72]. As part of this drive to increase tourism outside of Bali, the Government of Indonesia identified ten priority locations for tourism development, as well as an additional ten priority areas for underwater tourism (i.e. scuba diving- and snorkelling-based tourism) [7,72].

Unfortunately, our results show that many of the existing tourism centres and new areas that have been prioritised for marine tourism across Indonesia will be affected by early-onset ASB. The Government of Indonesia's ten priority areas for national tourism development includes several MPAs projected to experience early onset ASB, e.g. TNL Wakatobi (projected to reach ASB in 2039), TNL Kepulauan Seribu (2044), and KKPD Morotai (2044). Additionally, the ten priority areas for underwater tourism development also include several districts/regencies or provinces that have MPAs, including Togean, Lombok, Bali, Alor, Derawan, Bunaken, Wakatobi, and Raja Ampat. Several of these areas are among the earliest affected by bleaching, such as Lombok (e.g. Gili Ayer, Meno, Trawangan: 2026 ± 0), Bali (e.g. Nusa Penida: 2030 ± 4.48), Alor (e.g. Selat Pantar: 2026 ± 5.57), and Raja Ampat (e.g. Waigeo Sebelah Barat 2028 ± 5.5). Interestingly, while bleaching could completely degrade a coral reef, and therefore drastically impact communities depending on coral reef diving tourism, in the short term, studies suggest that divers still attach high value to degraded reefs [36]. This could be a consequence of most divers not recognising that there has been reef degradation and/or because public awareness through media of the effects of bleaching has caused a “coral rush” encouraging tourists to visit reefs before they “die” [2].

Research shows that coral bleaching can have mixed effects on fisheries provision from coral reefs. Studies in Indonesia suggest that the degradation of coral reefs affects reef fish species, abundance, and behaviour (e.g. [34,66]), which follows more established global patterns on the importance of live coral cover for reef fish communities [15]. However, while it is established that bleaching is disruptive to reef-associated communities, the long-term effects on reef fisheries may be more nuanced. In some parts of the world, there is growing evidence that macroalgal dominated reef ecosystems (i.e. a commonly occurring reef condition following coral mortality) can support significant fisheries [10] and alter micronutrient availability in reef fish for consumption by people. This might happen through a change in the species composition of reef fish present, as species composition is a strong predictor of micronutrient availability, or through changes in diets of fish species already present prior to bleaching [9,41]. In the Indian Ocean, macroalgae dominated reefs have been shown to be beneficial for micronutrient availability in reef fish, with iron and zinc levels greater in fish caught from reefs that had shifted from a coral to macroalgae dominated state following bleaching [41]. Long-term degradation of the dead coral reef framework on macroalgal-dominated reefs would, however, ultimately reduce the habitat complexity and therefore the ability for these areas to act as a shelter and nursery for fisheries species.

The timeframe of bleaching impacts on overall fisheries yields, and any positive or negative realised impacts on coastal communities and the Indonesian fisheries sector are still very poorly understood. The Indonesian fisheries sector comprises 44% of fish catches of reef fish and small pelagics from/near coral reefs or ecosystems closely associated with reefs (MMAF Decree of Kepmen-KP No. 50/2017). Therefore, there is a high potential for fisheries to be affected by ASB. Elsewhere in the world, fishers generally perceive that coral bleaching has a negative impact on fisheries (e.g. [47]). For example, in the Indian Ocean, fishers have reported a loss of important fisheries species and nursery habitats and declines in income associated with bleaching-caused reef degradation [3]. Through difference-in-difference experimental designs, studies have confirmed that coral bleaching has disproportionately led to loss of income for fishers and affected the development and educational outcomes for children living within Indonesian communities reliant on reefs ([57]). This research, from the 1998 coral bleaching event in Indonesia, showed that coral bleaching caused short term reductions in household incomes, leading to changes in livelihoods, and declines in protein consumption [57]. These studies also provided evidence that this 1998 bleaching event in Indonesia negatively affected child development, with increased stunting and decreased educational outcomes for children in areas affected by bleaching [59]. However, the exact mechanisms that link coral bleaching to potential negative human well-being outcomes are complex and require further research. With many communities living within or adjacent to MPAs, delivering positive human well-being outcomes, such as sustainable fisheries or tourism, to support local livelihoods is, therefore, an essential outcome for MPAs and key to building local support for MPA implementation (e.g. see [24,63]). Establishing or maintaining positive human well-being outcomes from MPAs is likely to grow increasingly challenging as coral reefs become exposed to ASB.

4.4. MPAs and climate change – recommendations for measuring and ensuring success

The role of local management interventions — such as MPAs — in protecting and building the resilience of coral reefs in the face of global climate change has been debated (e.g. [1,38,61]). Resilience-based management approaches for coral reefs aim to protect reefs from local stressors, increase the resistance of reefs to damage during disturbance and/or increase recovery rates of reefs from damage sustained during disturbance [33]. In the context of Indonesian MPAs, these protected reefs should then provide longer-term benefits to people (e.g. through fisheries, tourism value, and coastal protection; [25]). It has been argued that MPAs can increase coral-reef recovery from disturbances such as storms, disease outbreaks, and mass bleaching by maintaining ecological functions and processes on reefs that aid recovery (e.g. [21,22], and [44]). While the role of MPAs in improving reef resilience under climate change has been criticised, given the limited evidence for increased recovery rates following bleaching within MPAs (e.g. [1,39]), more recent work has suggested that the limited evidence should be interpreted as a lack of statistical power in ecological monitoring to detect impacts, rather than MPAs having no impact on coral reef resilience [61].

To mitigate negative effects caused by bleaching, it is important that monitoring, evaluation, and learning systems are used to track MPA outcomes and inform adaptive management sufficiently to account for variation in bleaching risk across Indonesia. By, for example, considering ASB when implementing the five-year zoning reviews that Indonesian MPAs are required to conduct [49], i.e. where the levels of protection for the reefs with differing levels of ASB risk are reconsidered, more effective long-term outcomes might be achieved. These efforts can be built from the existing bleaching program that has been implemented since 2016. During that period, the MMAF issued three bleaching alerts (2016, 2019, and 2020) to all MPA management units, provincial marine and fisheries offices, NGO, universities, and the Reef Check network. Moving forward, when designating new MPAs, it will be important to recognise currently unprotected areas of refugia for coral reefs.

Adaptive management actions may be needed to mitigate the short and longer-term negative effects of coral bleaching. This likely needs more holistic management approaches and increased connections with other sectors and service provision by other parts of the government. For example, if declines in protein consumption are the primary driver of negative impacts on child development and education outcomes (e.g. [57]), then targeted efforts supporting childhood nutrition may be appropriate as part of a holistic conservation and MPA management strategy. In this case, management activities for MPAs likely to face ASB soonest (i.e. the most vulnerable to bleaching) would be different to those MPAs likely to be thermal refugia. MPAs facing ASB in the near term would need to adapt to a future with heavily impacted reefs. Management efforts in MPAs likely to be thermal refugia should focus on managing local stressors and maintaining functioning reef ecosystems. In some limited cases, direct restoration interventions may be necessary for reefs facing ASB. These should be climate-smart, recognising the ongoing stress from climate change. For example, for areas that are particularly important for tourism or as fisheries nurseries, then restoration activities such as the installation of artificial reefs might be beneficial [20,78]. Over 500 reef restoration projects since the 1990 s have been conducted in Indonesia, however, few conducted post-installation monitoring [77,78]. The implementation of long-term monitoring, evaluation, and learning programmes should be prioritised for all coral reef management interventions to support adaptive management and support the development of best practice approaches to addressing climate change nationally within the MPA network.

5. Conclusions

Our analysis highlights that there is considerable spatial variability across Indonesian national waters, provinces, and MPAs with regard to when reefs will be at risk of ASB. Identifying and understanding the risk of ASB for MPAs allows for additional adaptive management considerations to be made, including additional engagement with stakeholders or direct interventions to prepare for potential severe bleaching events. Additionally, our results highlight that there are significant opportunities for Indonesia to incorporate the many potential coral reef refugia within the nation's waters. These refugia will likely be important for maintaining coral reef-associated biodiversity and supporting the communities that depend on reefs across the nation. While MPAs are designated based upon many factors, future MPA designation and adaptive management in Indonesia should consider these potential refugia and encourage the use of higher-resolution modelled data to account for smaller-scale variability in bleaching risk. We therefore recommend that bleaching projections should be one of the tools considered by the government when implementing ambitious MPA commitments to secure the long-term future of Indonesia's marine ecosystems.

CRediT authorship contribution statement

LHDC, LAD, DAA-B, SJH, RvH: conceptualization, writing and methodology. MEL, MI, IMZ, DP, AH, FA, AD: review and editing of the manuscript and methodology. All authors contributed to the article and approved the submitted version.

Data Availability

Data can be downloaded from pangaea.de [86] and/or made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105428.

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