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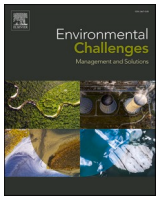

Managing Indonesian coral reefs: Integration of stressors in Marine Protected Area (MPA) management plans

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ABSTRACT

Indonesia is recognized as a biodiversity hotspot within the Coral Triangle and is rapidly expanding its network of Marine Protected Areas (MPAs). MPAs are critical tools for conserving coral reefs, and MPA management plans serve as the foundational guidelines for conservation. Their effectiveness depends partly on how adequately coral reefs' stressors are addressed and integrated into actionable mitigation strategies. This study assessed the inclusion of stressors in current government-issued Indonesian MPA management plans. We analyzed the inclusion of stressor words within the comprehensive management plans and reviewed the action plan. By 2022, only 20% of Indonesian MPAs had comprehensive management plans, comprising an introduction, zoning plan, and action plan. We found that most plans address stressors related to fishing. In contrast, less than one-third of the plans address land-based stressors, with nutrient pollution and plastic waste largely overlooked. While climate change was identified in about half of the plans, specific climate change impacts, such as rising sea surface temperature, were identified in only very few plans. Most management plans were broad, non-specific, and highly similar across locations, with stressors identified in the introduction rarely integrated into zoning and action plan sections, which may limit site-specific conservation efforts. Nevertheless, some plans showed a more targeted approach by addressing local stressors and proposing actionable responses. This study highlights the need for more site-specific and adaptive MPA plans. It offers a checklist to assess stressors in future Indonesian MPA management plan development, guiding increased responsiveness to evolving environmental challenges.

1. Introduction

Coral reefs offer significant ecological and socioeconomic benefits, supporting millions of people worldwide. However, over two-thirds of reefs face increasing threats from fishing, land-based, and climate change stressors (Burke et al., 2011; Eddy et al., 2018; Halpern et al., 2019; Hughes et al., 2017, 2018). Indonesia is home to ~16% of the world's coral reefs, is recognized as a marine biodiversity hotspot, but faces increasing pressures from both local (e.g., fishing and pollution) and global stressors (e.g., increasing sea surface temperature and ocean

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acidification) (Burke et al., 2012a). Since the 1970s, Indonesia has established a network of Marine Protected Areas (MPAs) to safeguard marine ecosystems (Amkieltiela et al., 2022). Over the past decades, the number and coverage of MPAs have expanded significantly, reaching over 400 MPAs (28.41 million hectares) by December 2021 (Meilana et al., 2023). Aligned with global conservation goals, Indonesia aims to designate 30% of its marine area (97.5 million hectares) as MPAs by 2045 (MMAF, 2024), requiring the establishment of new MPAs and the effective management of existing ones. The majority of MPAs in Indonesia are governed by the Ministry of Marine Affairs and Fisheries (MMAF). The MPAs under MMAF primarily aim to conserve marine biodiversity and manage fisheries, necessitating a management plan.

MPA management plans are foundational documents critical for guiding conservation actions, outlining MPA characteristics and conservation objectives, and integrating actionable strategies for threat mitigation (Álvarez-Fernández et al., 2020; Bennett and Dearden, 2014; Lausche, 2011). According to the International Union for Conservation of Nature (IUCN), a well-structured MPA management plan should include three key components (Table 1). First, an introduction section including a clear description of stressors and quantifiable objectives. Second, a zoning plan delineating boundaries, permitted and restricted activities, and their associated conservation priorities. Zoning plans promote conservation and regulate fishery resources, contributing to management effectiveness (Meilana et al., 2023). Third, a management actions section specifying concrete actions to address stressors and achieve conservation goals (Thomas and Middleton, 2003a).

Each MPA exists within a unique ecological context, with varying vulnerabilities that require tailored management approaches. However, it remains unclear which stressors are targeted in Indonesia and how explicitly they are addressed in each plan. When stressors are not clearly identified or linked to measurable objectives, developing targeted zoning regulations and effective management actions becomes challenging. Similarly, vague zoning plans and the absence of well-defined management actions can hinder threat mitigation. To ensure successful implementation and long-term conservation outcomes, MPAs must explicitly define stressors, align zoning with conservation objectives, and specify concrete management actions (Álvarez-Fernández et al., 2020; Collie et al., 2013; Di Cintio et al., 2023; Thomas and Middleton, 2003b).

Well-managed MPAs have been shown to support healthier ecosystems and significantly higher biodiversity and biomass (Edgar et al., 2014). For example, protected areas (no fishing zone) can host twice as many large fish species (>250 mm total length), five times more large fish biomass, and fourteen times more shark biomass than fished areas (Edgar et al., 2014). Historically, marine conservation efforts have focused on marine-based activities, particularly fisheries management (Agardy, 1994), while often overlooking land-based and climate-related threats. However, MPA effectiveness depends on addressing multiple interacting stressors. Fishing and water pollution, through nutrient loading and sedimentation, account for over 60% of the pressure on reefs worldwide (Andrello et al., 2022). Furthermore, the majority of all designated Indonesian MPAs are in coastal areas (MMAF, 2020a). This proximity to the shore means that often land-based activities, such as deforestation, agriculture, and urban development, can directly influence coral reef health through sedimentation, nutrient loading, and pollution (Adams et al., 2020a; McClanahan et al., 2012a). Additionally, MPAs face large-scale threats, such as climate change and industrial-scale pollution. Mining operations destroy habitats and introduce harmful chemicals into marine environments, while agricultural runoff leads to eutrophication, promoting excessive algal growth that disrupts reef recovery and weakens reef resilience (Adams et al., 2020b; Baum et al., 2015; McClanahan et al., 2012b). Climate change stressors (e.g., rising sea surface temperatures) amplify reef degradation by driving coral bleaching, altering ocean chemistry, and increasing extreme weather events (Reaser et al., 2000a, 2000b). Given the complexity of these challenges, integrating scientific research into MPA management plans is vital for designing effective conservation strategies and ensuring resilience (Susanto et al., 2015; Cook et al., 2010; Pullin et al., 2004).

This study provides a systematic assessment of Indonesian MPA management plans and evaluates the incorporation of site-specific stressors, focusing on marine-based stressors (e.g., fisheries), land-based stressors, and climate change. Specifically, this study (1) identifies the stressors included within MPA management plans, (2) examines the alignment and integration of the stressors into zoning and management actions, and (3) assesses the specificity of the MPA plans in relation to stressors. While previous studies have examined aspects of MPA effectiveness (e.g., Amkieltiela et al., 2022; Estradivari et al., 2022; Meilana et al., 2023), this study represents the first comprehensive review of stressor integration in MPA planning across Indonesia. With our approach, we aim to highlight critical gaps and opportunities for improving MPA management. We discuss ways to refine conservation strategies tailored to local conditions, ensuring that Indonesian MPAs effectively mitigate threats and contribute to long-term marine biodiversity protection.

2. Materials and methods

2.1. List of stressors to Indonesian coral reefs

In this paper, a 'stressor' refers to a threat, pressure, or other factor that negatively impacts the coral reef ecosystems. To create a comprehensive list of stressors affecting Indonesian coral reefs, we first referenced the most comprehensive stressors assessment conducted by the World Resource Institute (WRI). These included *Reefs at Risk Revisited, Reefs at Risk in Southeast Asia, and Reefs at Risk in the Coral Triangle* (Burke et al., 2002, 2011, 2012a), which provide detailed insights into global and regional reef threats. To ensure their relevance to Indonesia, we supplemented these sources with Indonesia-specific stressors identified in *The Status of Indonesian Coral Reefs* by the National Innovation and Research Agency (BRIN) (Hadi et al., 2020). Our synthesis yielded 40 relevant stressors (Table S1), which we further categorized into four main groups: *fishing activities* (11 stressors, e.g., destructive fishing and blast fishing), *land-based stressors* (15 stressors, e.g., eutrophication and

Table 1
Description of key components within an MPA management plan based on the International Union for Conservation of Nature (Thomas and Middleton, 2003b).

Component	Description
Introduction - Description of MPA - Issues and problems (stressors) - Objectives	The introduction component comprehensively describes the MPA and identifies key stressors and management aims. It also contains scope, legislative foundation, essential details about the area, resource utilization, constraints, opportunities, threats, and a vision with objectives. Objectives must be clearly defined and quantifiable to facilitate the assessment.
Zoning plan	The zoning plan describes the different management zones within the MPA, typically including each zone's boundaries, classification, permissible or restricted activities, and corresponding objectives.
Management actions	The management actions section outlines the actions taken to achieve the objectives. Typically, a list of management actions or activities required (prescriptions) indicates which actions will be carried out by whom, which priority activities will be performed, and which staff or financial resources will be necessary for their execution.

runoff), *climate change-related stressors* (7 stressors, e.g., bleaching and increasing sea surface temperature), and *other stressors* (7 stressors, e.g., coral mining and disease). These stressors and categories formed the foundation for our scientific literature analysis and MPA management plans. To facilitate a systematic assessment of MPA management plans, we developed a comprehensive list of Indonesian terms, synonyms, and related keywords corresponding to each identified stressor (Table S1).

2.2. Data collection

2.2.1. Scientific literature

To assess the use of our acquired list of stressors in the scientific literature over time, we used the Pybliometrics library in Python to conduct a systematic literature search available in Scopus. Our analysis focused on peer-reviewed research papers published in English. We selected the time range from 1970 to 2023 to cover the most recent five decades of research articles and allow sufficient time for data accumulation. This timeline aligns with the establishment of Indonesia's first MPA in the 1970s, providing historical context on how worldwide research into coral reef stressors has evolved alongside Indonesian MPA management efforts.

We restricted our search to titles, abstracts, and keywords, following a two-step process. First, we conducted a broad search to compile an overview of articles related to coral reefs using the simple query *"coral*."* Second, within these papers, we searched for terms related to the identified stressors within the four categories: fishing activities, land-based stressors, climate change, and other stressors (Table S2). All searches in the Scopus database were completed on 28 October 2024. To assess the relative attention given to different stressor categories within the broader coral reef research, we calculated the proportion of papers (hits) associated with each stressor category relative to the total number of hits for the coral query.

2.2.2. Management plans

We obtained a list of Indonesian MPAs from the Indonesian Government Protected Area website (*Sistem Database Konservasi,* http://sidako.kkp.go.id*, accessed in November 2023)*, resulting in 409 MPAs. Indonesian MPA management falls under the jurisdiction of two ministries, i.e., the Ministry of Marine Affairs and Fisheries (MMAF) and the Ministry of Environment and Forestry (MoEF). For this study, we focused on MMAF-managed areas, which are publicly available and constitute the majority (379 out of 409 MPAs), covering nearly 85% of

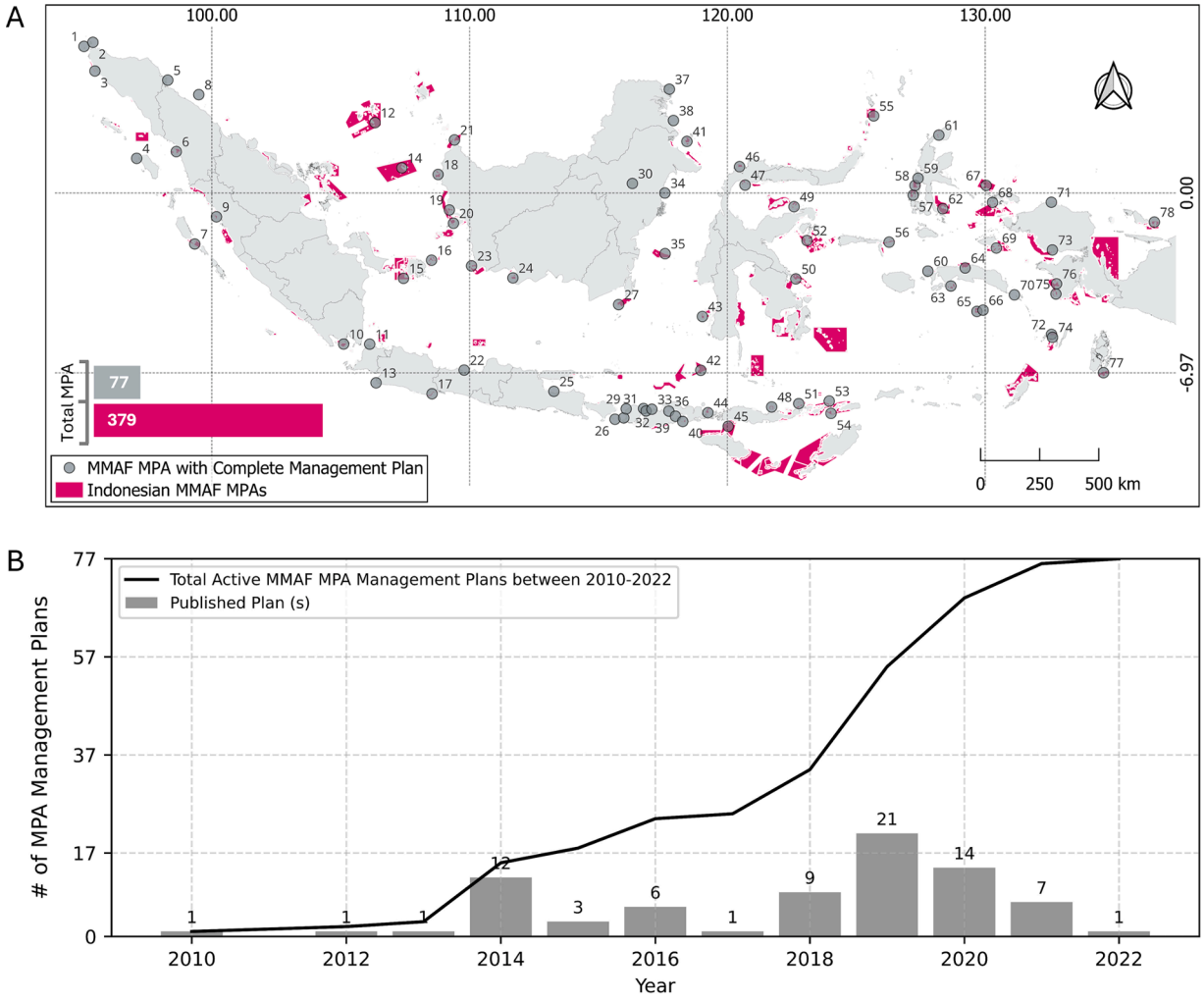

Fig. 1. Overview of Marine Protected Areas (MPAs) in Indonesia managed by the Ministry of Marine Affairs and Fisheries (MMAF). A). A total of 379 MMAF-managed MPAs were identified in 2022, shown on the map in pink (polygon shape). There are management plans for 105 MPAs, of which 77 are comprehensive, including an introduction, a zoning plan, and an action plan. These comprehensive plans are used for our analyses and are represented by grey dots with an ID number in different regions numbered from the west to the east (for the full list of MPA names, see Fig. 4). The bar graph inside the map shows the number of Indonesian MMAF-managed MPAs and the number of MMAF-managed MPAs with comprehensive management plans. B) Number of comprehensive MMAF-managed MPA management plans published in Indonesia over time (2010–2022) (bar graph, grey) and the cumulative total number of active plans over time (line graph, black).

Indonesia's total MPA area, making them a strong representative sample. Furthermore, every newly developed MPA will be governed by the MMAF and/or the provincial government.

For each MMAF MPA, we downloaded publicly available management plans from the government's official website (*Sistem Database Konservasi*, http://kkp.go.id/djprl/kkhl/page/2107-sk-penetapan, *accessed on 30 June 2023*). Plans were systematically assessed for readability, and unreadable or duplicate versions were excluded. The search was finalized on 30 June 2023, yielding 105 MMAF MPAs with accessible plans (Table S3). Some plans contained scanned text, impeding accurate optical character recognition. To address this, we converted all plans from PDF to text files (*.txt*) format for systematic analysis.

To ensure consistency in our analysis, we include only comprehensive MPA management plans comprising all three key sections of a management plan (*Table 1*): an introduction, zoning plan, and management actions. With this criterion, we make sure that all analyzed plans are comparable and provide the necessary context for evaluating stressor inclusion and management action strategies. For instance, if a plan lacks management actions, assessing whether stressors are actively being addressed within the management framework would not be possible. Our final dataset comprises 77 MMAF-managed MPAs with comprehensive management plans (Fig. 1, Table S3). These plans were published between 2010 and 2022 (Fig. 1B).

2.3. Text analysis

We systematically identified stressor-related terms in the texts of all the comprehensive plans. We examined the surrounding context for each occurrence by reviewing 25 words before and after the term. A stressor term was only included in our analysis if it was explicitly used in the context of a stressor or threat to coral reefs; irrelevant mentions were excluded.

The data analysis involved four steps. First, we counted the number of plans in which each stressor was identified at least once to determine how frequently stressors were acknowledged across MPAs. Second, to further evaluate how well stressors were incorporated into different sections of the plans, we counted the number of plans with occurrences of the stressors in three key sections (i.e., introduction, zoning plan, and management actions). Third, we manually reviewed the management actions section of each plan to extract specific actions or strategies documented in the text. Last, we applied the Term Frequency – Inverse Document Frequency (TF-IDF) to assess the relative emphasis of stressors within individual plans. TF-IDF measures word importance in a document while adjusting for its frequencies across documents. A higher TF-IDF score indicates that a term (stressor) is more prominent in a certain plan than others, suggesting its relative importance within that plan. To analyze structural similarities among the texts within the plans, we used cosine similarity, which quantifies textual resemblance between documents. A cosine similarity score of 1 indicates identical documents, while a score of 0 suggests no similarity. This approach allowed us to assess the degree of similarity of variation across management plans in terms of their content and emphasis on stressors. Our workflow was executed in Python 3.9.16, and all the code is available on https://github.com/agustincsn/MPAManagementPlanIndonesia.

3. Results

3.1. Occurrence of stressors in scientific literature

A total of 56,025 peer-reviewed papers related to corals were retrieved from Scopus between 1970 and 2022 (Fig. 2, Table S2). Subsequent refined searches, including specific stressor categories: *fishing activities, land-based, climate change, and other stressors,* resulted in 1530, 5057, 7132, and 3235 papers in total (Table S2). Over time, the relative attention given to *fishing activities, land-based stressors, and other stressors* in coral reef research has remained stable, with only minor fluctuations.

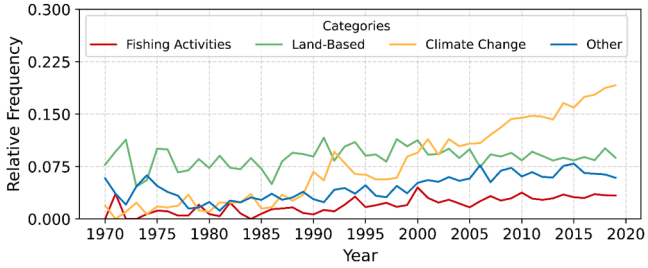

Fig. 2. Relative frequency of scientific papers published between 1970 and 2022 on corals that mention at least one term related to each of the categories of stressors in their titles, keywords, and abstracts (Table S2).

However, the most notable change is increased climate change-related coral reef research since 2000 (Fig. 2).

3.2. Occurrence of stressors in MPA management plans

More than 50% of the plans identified stressors related to blast-fishing, cyanide, destructive fishing, anchoring, hookah, purse seine, sand mining, deforestation, abrasion, sedimentation, aquaculture ponds, climate change, and coral mining (Fig. 3). However, the extent to which stressors were identified varied across plans. Within the *fishing activities* category, blast fishing and cyanide fishing were the most frequently identified stressors, appearing in 67 and 62 out of 77, respectively. In contrast, illegal fishing (21 plans), bycatch (19 plans), and muroami (15 plans) were the least identified stressors in this category. Within the *land-based stressors* category, eutrophication (8 plans), coastal development (7 plans), and runoff (3 plans) emerged as the least identified stressors, despite their well-documented impacts on coral reefs. In *the climate change* category, this term was identified in over half of the plans (40 plans), but was often used as a broad umbrella term. More specific climate-related stressors, such as heatwaves, increasing sea surface temperature, and extreme weather events, were either absent or identified in only a few plans. In the *other stressors* category, coral mining was identified in over 60% of the plans (49 plans), while ballast water pollution was identified in only one plan (Fig. 3 and Fig. S1).

We further investigated how frequently stressors were included across different sections of MPA plans (Fig. 3, Figure S2, Table S5). Within the *fishing activities* category, blast fishing (blast fishing) was identified in different sections with varying frequencies: 23.3% of the plans identified it only in the introduction, 10.3% included it only in the zoning sections, 31.2% included it in both introduction and zoning sections, and 2.6% incorporated it in both introduction and management actions (Fig. 3A). Only 18.2% (14 plans) comprehensively addressed blast fishing across all three sections (Fig. 3B and *Table 2*), including Nusa Penida, Alor, and Koon MPA.

Similarly, within the *land-based stressors* category, most stressors were only identified in the introduction but were less frequently addressed or entirely absent from the zoning and management actions sections (Fig. 3B and Figure. S2). For instance, sedimentation appeared in the introduction of over 40% of plans, yet only a small fraction included it in the zoning section (2.6%) and the actions section (1.3%) (Fig. 3A). Notably, only one plan (Kaimana MPA, published in 2018) consistently identified sedimentation as a stressor across all sections of the document (Fig. 3B).

Within the *climate change* category, bleaching was the most frequently identified stressor in the introduction of over 25% of plans, while the term 'climate change' was the most frequently mentioned stressor in the management actions sections (36%). Only two plans (Kaimana and Sawu MPAs) addressed climate change across all sections (Fig. 3B and *Table 2*). In contrast, global warming, extreme weather, and increasing sea surface temperature were rarely mentioned, except in only one or two plans (Fig. 3A). Within the *other stressors* category, only

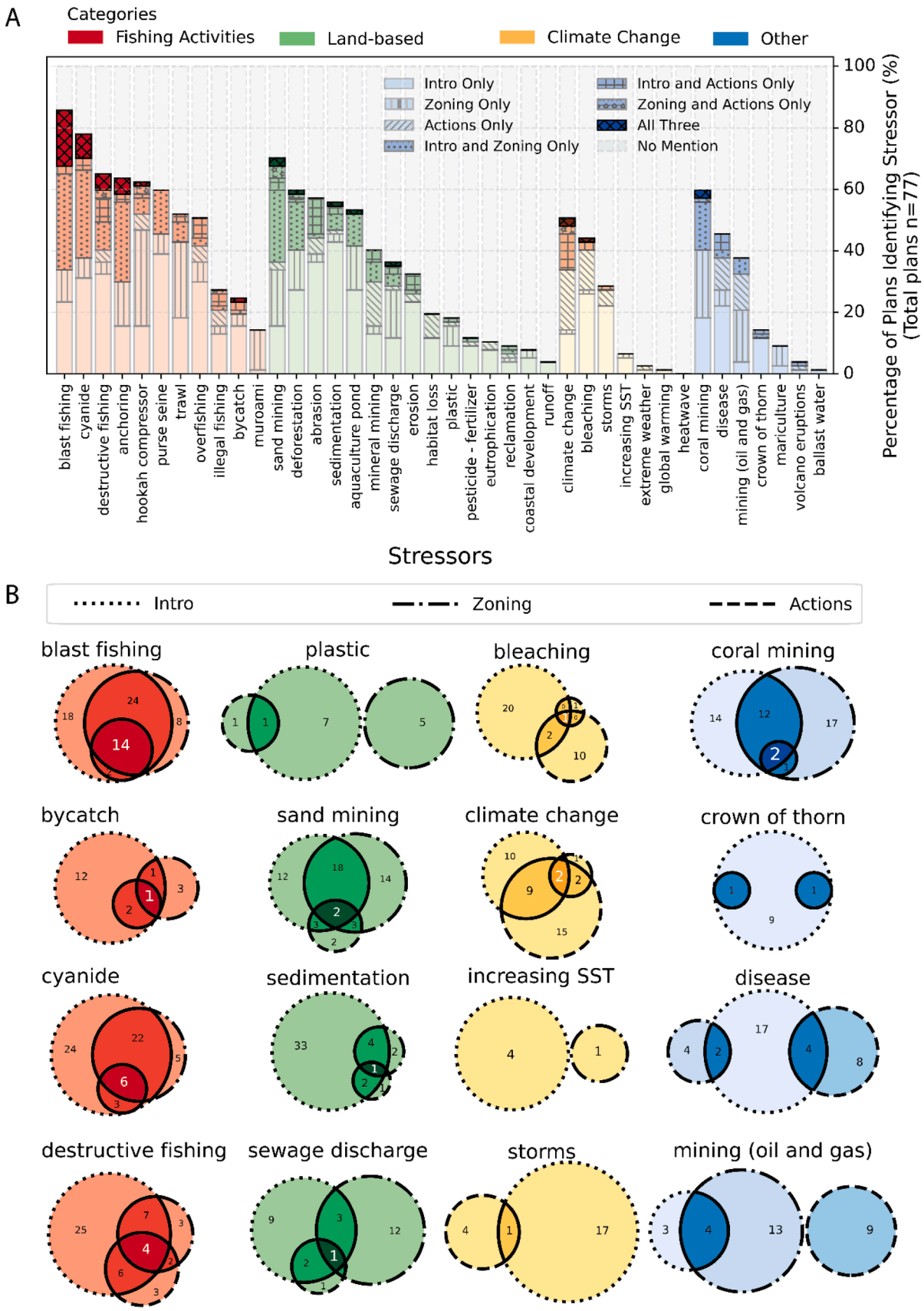

Fig. 3. Stressors are identified in the three different sections of the MPA management plans (introduction, zoning, and management actions. A) Percentage of plans in which each stressor is identified at least once in one of the sections or in multiple sections. B) Venn diagram displaying the intersection of three sections for the most frequently identified stressors. The overlapping areas show the number of plans in which that stressor was identified in both, or in all three sections. See N materials Figure S2 and Table S5 for the Venn diagram of all stressors.

Table 2
Overview of MPA management plans in Indonesia that have identified stressors in all three sections (Introduction, Zoning, Actions). 'NONE' indicates that there are no MPA management plans that have an alignment of the specified stressor in the three sections of the plans. The number preceding the MPA names corresponds to its location on the map in Fig. 1a.

Categories	Stressors	MPA name(s) that identified specific stressors across all three sections (Introduction, Zoning, Action)	Publication year of the plan
Fishing Activities	Anchoring	9. Pulau Pieh	2014
		12. Kepulauan Anambas	2014
		29. Gili Air, Gili Meno, and Gili Trawangan	2014
		64. Seram Utara dan Seram Utara Barat	2019
	Blast fishing	9. Pulau Pieh	2014
		12. Kepulauan Anambas	2014
		26. Nusa Penida	2017
		27. Angsana, Loban, Sembilan	2019
		32. Pulau Panjang	2020
		45. Laut Sawu	2014
		48. Sikka	2016
		49. Banggai Dalaka	2018
		51. Flores Timur	2018
		54. Selat Pantar	2013
		61. Pulau Rao-Tanjung Dehegila	2019
		64. Seram Utara dan Seram Utara Barat	2019
		70. Koon, Gorogos, Nukus, Neden	2016
		73. Pulau Kei Kecil	2015
	Bycatch	21. Paloh	2019
	Cyanide	12. Kepulauan Anambas	2014
		26. Nusa Penida	2017
		45. Laut Sawu	2014
		49. Banggai Dalaka	2018
		54. Selat Pantar	2013
		70. Koon, Gorogos, Nukus, Neden	2016
	Destructive fishing	12. Kepulauan Anambas	2014
		43. Kapoposang	2014
		70. Koon, Gorogos, Nukus, Neden	2016
		73. Seribu Satu Sungai Teoebikia	2020
	Hookah compressor	64. Seram Utara dan Seram Utara Barat	2019
	Illegal fishing	NONE	
	Muroami	NONE	
	Overfishing	NONE	
	Purse Seine	NONE	
	Trawl	NONE	
	Abrasion	NONE	
	Aquaculture pond	37. Binusan dan Pulau Sinelak	2020
	Coastal development	NONE	
Land-Based	Deforestation	37. Binusan dan Pulau Sinelak	2020
	Erosion	NONE	
	Eutrophication	NONE	
	Habitat loss	NONE	
	Mineral mining	NONE	
	Pesticide-fertilizer	NONE	
	Plastic	NONE	
	Reclamation	NONE	
	Runoff	NONE	
	Sand mining	45. Laut Sawu	2014
		64. Seram Utara dan Seram Utara Barat	2019
	Sedimentation	74. Kaimana	2018
	Sewage discharge	48. Sikka	2016
Climate Change	Bleaching	45. Laut Sawu	2014
	Climate change	45. Laut Sawu	2014
		74. Kaimana	2018
	Extreme weather	45. Laut Sawu	2014
	Global warming	NONE	
	Heatwave	NONE	
	Increasing sea surface temperature	NONE	
	Storms	NONE	
Other	Ballast water	NONE	
	Coral mining	27. Angsana, Loban, Sembilan	2019
		45. Laut Sawu	2014
	Crown of thorns	NONE	
	Disease	NONE	
	Mariculture	NONE	
	Mining (oil and gas)	NONE	
	Volcano eruptions	NONE	

two plans (Sawu and Angsana MPAs) comprehensively identified coral mining as a stressor in their introduction, zoning, and actions sections (Fig. 3B).

To get an impression of which MPAs focus on a particular stressor, we listed all MPAs that identify a stressor in all three sections of their management plan (Table 2). Note that several MPAs, such as Kepulauan Anambas and Laut Sawu, identified multiple stressors in all sections of their plans (Table 2). When reading all management plans, we found that management action sections were generally broadly described rather than outlining concrete and detailed strategies (Table S6). Across all plans, strategies were largely consistent among MPAs, primarily emphasizing capacity building for stakeholders, strengthening area resource management, and enhancing social, economic, and cultural values. While these overarching strategies were similar for most MPAs, there were nuanced differences in the emphasis of some MPA strategies. Some MPAs, such as Nusa Penida and Raja Ampat, prioritized governance, biophysical considerations, or community empowerment (Table S6).

3.3. Highlighted stressors in MPA management plans

An alternative way to look at the specificity of plans with an emphasis on particular stressors is to examine the Term Frequency – Inverse Document Frequency (TF-IDF) of the various stressors across the management plans (Fig. 4). The majority of plans exhibited low TF-IDF scores for all stressors (Fig. 4 and Figure S3), reflecting that the text was largely generic and did not strongly emphasize site-specific stressors. Still, some plans highlighted particular stressors more prominently. For instance, within the *fishing activities* category, bycatch received notable emphasis in the Paloh and Seribu Satu Sungai Teoenobikia MPA plans. This matches with the observation that the management plan of the Paloh MPA mentions bycatch in all three sections (Fig. 3B).

In the *land-based* stressors category, abrasion was highlighted in Ujungnegoro Roban, sedimentation in Kaimana (identified in all three sections (*Table 2*)) and Ujungnegoro Roban MPA plans, and aquaculture pond activities in Binusan and Sinelak MPA plans (identified in all three sections (*Table 2*)). The *climate change* stressors category was most prominently addressed in Gili Meno, Gili Air, and Gili Trawangan, Kaimana (identified in all three sections (*Table 2*)), and Sawo Lahewa MPA plans (Fig. 4).

Overall, ten MPA plans with the highest total TF-IDF scores, indicating a greater emphasis on stressors compared to other plans, were

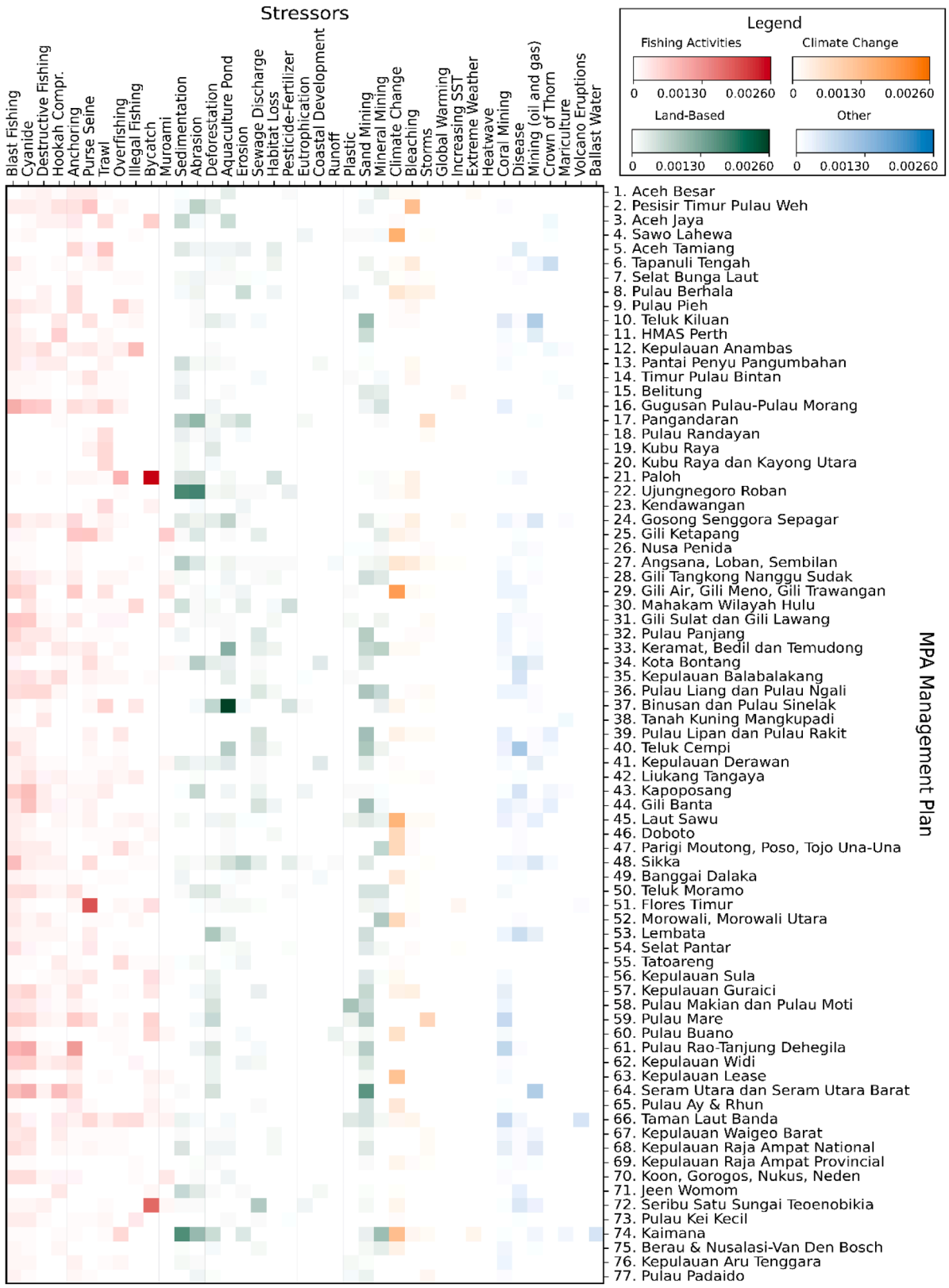

Fig. 4. Heatmap displaying the Terms Frequency – Inverse Document Frequency (TF-IDF) to assess the relative emphasis of stressors among 77 MPA plans in Indonesia. TF-IDF measures word importance in a document while adjusting for its frequencies across documents. A higher TF-IDF score indicates that a term (stressor) is more prominent in a certain plan than others, suggesting its relative importance within that plan. Each column represents a specific stressor, and each row represents a specific MPA. The intensity of the color indicates the TF-IDF score, with darker shades representing higher scores, signifying greater emphasis on the corresponding stressor within that plan. White cells indicate the complete absence of specific stressors in the plan.

Kaimana; Seram Utara dan Seram Utara Barat; Pulau Mare; Binusan and Pulau Sinelak; Paloh; Taman Laut Banda; Pulau Rao-Tanjung Dehegila; Gili Air, Gili Meno, and Gili Trawangan; Sikka; and Keramat Bedil Temudong MPAs (Figure S4). Additionally, cosine similarity analysis of the full text of management plans revealed a high degree of similarity across most plans, suggesting a standardized textual and systematic structure with limited regional differentiation (Figure S6).

4. Discussion

As Indonesia expands its Marine Protected Areas (MPAs), many remain in the early stages of management planning. Assessing how existing plans address coral reef stressors is crucial for improving future MPA plan development. We found that most MPAs lack comprehensive management plans, and those that exist primarily emphasize fishing-related stressors, reflecting traditional fisheries and conservation priorities. Land-based stressors appear in over half of the plans, but key threats such as runoff and coastal development are largely absent despite their significant impact on coral reef ecosystems. Climate change is acknowledged but rarely detailed. Many plans follow standardized templates, limiting site-specific management. We discuss these gaps, highlight positive developments, and propose recommendations for more effective MPA planning.

4.1. Stressors included in MPA management plans

Our word frequency analysis reveals that *fishing activities* were the most frequently recognized stressors across plans (Fig. 2). The strong emphasis on *fishing activities* likely stems from the foundational objectives of MMAF-managed MPAs, which were primarily established for fisheries management and biodiversity conservation (Tranter et al., 2022). Given that approximately 140 million Indonesians depend on coral reefs and fisheries for their livelihoods, the Indonesian government also strategically utilizes MPAs as a tool to regulate unsustainable fishing practices (MMAF, 2020b; Wiadnya et al., 2011). Despite the widespread acknowledgment of fishing-related stressors across Indonesia (Burke et al., 2012b), over 20% of the plans failed to identify destructive fishing, overfishing, or illegal fishing. For instance, Gili Ketapang, Pulau Padaido, and Pangandaran MPA plans did not reference any of these stressors, even though fishing activities are prevalent in these regions (Novaczek, 1998; Supriharyono, 2003). Given the well-documented fishing pressures in these areas by scholars, the absence of explicit references to such stressors suggests a significant gap in management strategies. This oversight raises concerns about the comprehensiveness of ensuring that MPAs effectively address harmful fishing practices, particularly in high-pressure regions.

Some of the *land-based* stressors, such as sand mining, deforestation, abrasion, and sedimentation, were recognized in over half of the plans. This is likely due to the well-documented environmental impacts of these activities in Indonesia (Ponti et al., 2016; Science, 1992). Mining (oil and gas) was recognized as a stressor in over 30% of the plans. Given their known negative impacts on reef degradation (Haywood et al., 2016; Martinez-Escobar and Mallela, 2019). A growing concern is that many MPAs are located in areas with potential for metal mining, especially for minerals critical for the energy transition. For example, Raja Ampat MPA, a globally significant marine biodiversity hotspot, is among the regions increasingly exposed to mining pressures (Sujana et al., 2012; CI Unpublished data).

Despite the inclusion of some land-based stressors, others remain largely absent. Runoff, coastal development, and eutrophication—key stressors that are highly harmful to coral reefs and can be managed locally—were missing from nearly ~90% of the plans (Fig. 3A). This omission may have serious implications for MPA operationalization, as management plans have served as the primary guiding document for over 20 years, influencing conservation strategies, partnership building, and fundraising efforts based on identified gaps. The lack of attention to several *land-based* stressors in plans is particularly concerning, as all Indonesian MPAs are coastal (Amkieltiela et al., 2022) and directly influenced by land-based activities. Additionally, these stressors are globally recognized as key local drivers of reef degradation, contributing to over 30% of reef pressures (Andrello et al., 2022). They are linked to coral disease outbreaks (Bruno et al., 2003; Voss and Richardson, 2006), a 30–60% reduction in coral diversity, and increased macroalgae cover (Edinger et al., 1998).

Our analysis revealed that none of the plans identified runoff and coastal development in all sections (Fig. 3, Table S5), despite all MPAs being located in coastal areas. This omission is likely attributed to Indonesia's institutional framework. Historically, the MoEF was the primary agency for managing marine conservation in Indonesia (Alder et al., 1994). However, in 2009, authority over MPA management was transferred to the MMAF. While MMAF now manages most MPAs, it does not have jurisdiction over terrestrial areas, which remain under MoEF's or other ministerial authorities (e.g., ATR/BPN, Bappenas). This institutional separation likely explains the limited identification of *land-based* stressors in MPA management plans and underscores the fragmented governance framework overseeing Indonesia's coastal and marine ecosystems. Such governance challenges reflect broader issues observed in marine spatial planning worldwide. Van Tatenhove (2017) discusses how fragmented institutional frameworks create barriers to integrating ocean management, especially in cases requiring transboundary coordination. These governance gaps mirror challenges in Indonesia, where institutional fragmentation may prevent the development of cohesive, cross-sectoral management strategies, particularly for stressors that span both marine and terrestrial ecosystems.

Surprisingly, plastic received limited attention in the plans, with <20% of the plans including it as a stressor (Fig. 3A). This is particularly surprising given Indonesia's national initiatives to address marine plastic pollution, such as the National Action Plan for Marine Debris Handling and Presidential Regulation 83/2018 on marine plastic pollution prevention. This disparity underscores the urgent need to incorporate plastic pollution into site-specific conservation efforts, particularly as coastal population growth and tourism continue to rise in MPAs (Maas et al., 2020; Thur, 2010; Whitelaw et al., 2014).

Climate change was acknowledged as a stressor in over 50% of the plans (40 out of 77), possibly following the increasing scientific attention to climate-related reef threats in scientific literature (Fig. 2). We, however, did find that most plans used the broad term 'climate change' without explicitly identifying key stressors, such as increasing sea surface temperature, marine heatwaves, and extreme weather events (Fig. 3A). Globally, there seems to be limited attention to climate change as a stressor within MPA management plans (O'Regan et al., 2021) due to the limited technical capacity among MPA managers to incorporate climate adaptation strategies (Whitney and Ban, 2019). Furthermore, MPA managers often do not perceive climate change as an urgent stressor due to its global scale, which extends far beyond the coverage and mandate of an MPA (Lopazanski et al., 2023). While MPAs cannot directly mitigate the root causes of climate change, they can still play a role in buffering its impacts and dealing with the repercussions that come in different forms of stressors (Delevaux et al., 2019; Gurney et al., 2013).

4.2. Little alignment of recognized stressors in zoning and action plans

Management plans are expected to outline detailed operational strategies for addressing key stressors (Corelli et al., 2024). However, our analysis showed a critical gap: while stressors were frequently identified in the introduction sections, they were rarely incorporated in the zoning and action plans sections. This lack of integration has been found previously, where <5% of 213 plans around the globe contained concrete management actions (Corelli et al., 2024). Strengthening the alignment between stressor identification and management actions is crucial to ensure MPAs move beyond passive recognition of threats

toward effective, site-specific conservation strategies.

Fortunately, there are some MPAs that can serve as an example of an aligned MPA plan. An example of strong alignment between stressor identification throughout the introduction, zoning, and action plans sections is the Kaimana MPA management plan (*Table 2* and Fig. 4). This plan consistently identifies sedimentation (among other stressors) as a key stressor across all sections, demonstrating a proactive approach to address this issue. For instance, in its management action sections, the Kaimana plan includes the following action: "*sosialisasi dan kampanye pelestarian spesies, habitat, dan ekosistem (mangrove, terumbu karang, lamun, penyu, hiu, ikan terbang, sasi, mamalia laut, dan pemanfaatan yang tidak ramah lingkungan, abrasi dan sedimentasi"* which translates to "conduct socialization and campaigns for the conservation of species, habitats, and ecosystems (mangroves, coral reefs, seagrass, turtles, sharks, flying fish, *sasi*, marine mammals, and environmentally unfriendly utilization, erosion, and sedimentation).

4.3. Generic MPA plans

Our analysis shows that a large portion of the plans exhibited a high degree of textual similarity (Fig. 4 and Figure S6). This suggests that many plans follow a standardized text despite the vast differences in geographic locations, ecological characteristics, and local development pressures. These generic MPA plans may not fully capture the unique challenges faced by each MPA. For example, 90% of plans have standard statements such as "Penguatan kelembagaan, penguatan pengelolaan sumber daya kawasan, dan penguatan social, ekonomi, dan budaya," which translates to *"Institutional strengthening, strengthening of area resource management, and strengthening of social, economic, and cultural aspects.* While these broad objectives are valuable, they fail to specify targeted interventions for specific stressors, which can vary significantly between locations.

This uniformity among MPA plans is likely influenced by the standardized development process of MPA management plans. According to MMAF regulations (Ministerial Degree 02/2009 on Procedure for Marine Conservation Areas), establishing an MPA involves five steps: proposal (plan development), survey and appraisal, designation, endorsement, and boundary marking. Currently, a standard template is used in MPA plan development to ensure consistency, facilitate plan review, and streamline monitoring across MPA plans. However, plans are often replicated with minimal site-specific adaptation rather than fully tailored to each MPA (Figure S6). The MPA establishment process is complex, and authorities may face tight deadlines and budget limitations when developing management plans (Jentoft et al., 2011). Additionally, Indonesia's commitment to global conservation goals (e.g., protecting 30% of marine areas by 2030) may place greater emphasis on MPA expansion rather than ensuring that management plans are highly detailed and site-specific. This could possibly lead to a focus on completing required documents to rapidly designate MPAs with generic plans rather than ensuring that plans are comprehensive and tailored to each site. While a generic MPA plan can be a good start, it is important to develop it further with adequate involvement from local communities, scientists, and resource users, and reflect site-specific threats and conservation needs.

Having generic MPA plans can have consequences. For instance, if sewage discharge and pollution are primary threats in an MPA but are not addressed in the management plan, they may continue to degrade coral reefs without active measures, leading to severe ecological consequences (de Bakker et al., 2017; Ford et al., 2018; Reverter et al., 2020). Furthermore, without clear and actionable steps, it becomes difficult to track the progress of conservation efforts and assess whether the actions being taken meaningfully address the right stressors. An example of this challenge can be seen in Portugal, where eight MPAs followed a homogeneous management approach (Álvarez-Fernández et al., 2020). Similarly, in Spain, certain Marine Reserves lacked a specific process for the development and validation of management plans, which may have led to inconsistencies in their regulatory frameworks (Álvarez-Fernández et al., 2020).

Despite the lack of specific action plans for mitigating site-specific stressors, conservation efforts are still being conducted. In many cases, the critical gaps are filled by local government and conservation NGOs. For instance, coral mining, although identified comprehensively in only two MPA plans (Fig. 3B), is emphasized in the reports by three NGOs: Yayasan Alam Konservasi Nusantara (YKAN), Konservasi Indonesia (KI), and Coral Triangle Center (CTC) (Pakiding et al., 2020; White et al., 2022). Similarly, increasing sea surface temperature and heat waves are absent from MPA action plans, yet CTC has actively led climate-resilience coral research and provided training for the local community to monitor reef health and bleaching events in Nusa Penida MPA and Lease MPAs (CTC, Unpublished data).

Several NGOs, including the CTC, World Wide Fund for Nature (WWF) - Indonesia, YKAN, KI, and the Wildlife Conservation Society (WCS), have been deeply involved in supporting MPA management across Indonesia. These organizations provide technical assistance, such as conducting reef health monitoring programs and biodiversity assessments. CTC, for instance, actively conducts reef health monitoring and water quality assessments in several MPAs, such as Lease, Banda, and Ay-Rhun MPAs. Moreover, WWF, YKAN, and KI are focusing on the Raja Ampat MPA and have helped bridge roles in planning, science, local knowledge, and funding sources. Such examples highlight the importance of NGOs in fulfilling some of the actions that are missing in conservation management.

4.4. Ways forward: developing specific MPA plans with actionable targets to reduce stressors

Looking ahead, several steps could help to develop more specific MPA plans with actionable targets, moving towards a more science-based and adaptive approach, ensuring the long-term resilience of coral reef ecosystems against both local and global stressors. *First,* there is a need to increase the number of comprehensive MPA plans. Currently, <30% of MMAF MPAs have a plan, and of those, only ~20% are comprehensive, including an introduction, zoning, and management actions sections. *Second,* we recommend strengthening the integration of stressors and management actions in MPA plans and moving away from generic plans. A checklist of key stressors, such as the one in this study, can guide MPA managers in evaluating and integrating stressor management into planning and implementation. The introduction of MMAF Ministerial Regulation No.31/PERMEN-KP/2020 will likely play a role in improving plan specificity. This regulation mandates that the head of the management unit develop management plans rather than rely solely on external consultants, as previously often practiced, and requires new management plans to explicitly identify specific stressors relevant to each MPA (verse 31, clause 4d). *Third*, we recommend that MPA management units or managers utilize the mandatory five-year review period to integrate new challenges and developments (MMAF Ministerial regulation No. 31/Permen-KP/2020) (Verse 32: 3). This scheduled review presents an opportunity to incorporate emerging stressors, advancements in conservation science and monitoring, and adjust to shifting social-environmental conditions and human pressures. *Fourth*, integration of a ridge-to-reef approach into MPA management will address the interconnectedness of terrestrial, coastal, and marine ecosystems. Given that many stressors originate beyond MPA boundaries, effective management will require strong cross-sector collaboration among MPA authorities, ministerial agencies (e.g., MoEF, ATR/BPS), local government, key stakeholders, and community groups.

5. Conclusion

Our textual analysis highlights gaps in Indonesian MPA management plans related to a lack of specificity in stressor identification and integration into zoning and action plans. While destructive fishing is widely

acknowledged, land-based stressors such as runoff and coastal development are largely overlooked despite their critical impact on reef health. The reliance on standardized templates and limited site-specific data further contributes to the generic nature of these plans. Moving forward, strengthening the integration of stressor management, enhancing stakeholder involvement, and leveraging periodic plan reviews will be essential in improving MPA effectiveness. Strengthening regulatory frameworks and fostering cross-sectoral governance will be needed to ensure MPAs effectively address fishing, land-based, and climate change stressors.

CRediT authorship contribution statement

Agustin Capriati: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ingrid A. van de Leemput:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Estradivari:** Writing – review & editing, Validation, Investigation. **Yvonne Kunz:** Writing – review & editing, Validation, Resources. **Tries B. Razak:** Writing – review & editing, Validation. **Rili Djohani:** Writing – review & editing, Validation. **Hesti Widodo:** Writing – review & editing, Visualization, Resources. **Handoko Adi Susanto:** Writing – review & editing, Validation. **Ririn Widiastutik:** Writing – review & editing, Validation, Data curation. **Purwanto:** Writing – review & editing. **Leontine E. Becking:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

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Supplementary materials

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Data availability

Data will be made available on request.

References

Adams, J.B., Taljaard, S., van Niekerk, L., Lemley, D.A., 2020. Nutrient enrichment as a threat to the ecological resilience and health of South African microtidal estuaries. Afr. J. Aquat. Sci. 45 (1–2), 23–40. https://doi.org/10.2989/16085914.2019.1677212.

Alder, J., Sloan, N.A., Uktolseya, H., 1994. A comparison of management planning and implementation in three Indonesian marine protected areas. Ocean Coast Manag 24.

Álvarez-Fernández, I., Freire, J., Naya, I., Fernández, N., Sánchez-Carnero, N., 2020. Failures in the design and implementation of management plans of Marine Protected Areas: an empirical analysis for the North-east Atlantic Ocean. Ocean Coast. Manage. 192 (April). https://doi.org/10.1016/j.ocecoaman.2020.105178.

Amkieltiela, Handayani, C.N., Andradi-Brown, D.A., Estradivari, Ford, A.K., Beger, M., Hakim, A., Muenzel, D.K., Carter, E., Agung, F., Veverka, L., Iqbal, M., Lazuardi, M. E., Fauzi, M.N., Tranter, S.N., Ahmadia, G.N., 2022. The rapid expansion of Indonesia's marine protected area requires improvement in management effectiveness. Mar. Policy 146. https://doi.org/10.1016/j.marpol.2022.105257.

Andrello, M., Darling, E.S., Wenger, A., Suárez-Castro, A.F., Gelfand, S., Ahmadia, G.N., 2022. A global map of human pressures on tropical coral reefs. Conserv. Lett. 15 (1), 1–12. https://doi.org/10.1111/conl.12858.

Baum, G., Januar, H.I., Ferse, S.C.A., Kunzmann, A., 2015. Local and regional impacts of pollution on coral reefs along the thousand islands north of the megacity Jakarta. Indonesia. *PLoS ONE* 10 (9), 1–26. https://doi.org/10.1371/journal.pone.0138271.

Bennett, N.J., Dearden, P., 2014. From measuring outcomes to providing inputs: governance, management, and local development for more effective marine protected areas. Mar. Policy 50 (PA), 96–110. https://doi.org/10.1016/j.marpol.2014.05.005.

Bruno, J.F., Petes, L.E., Harvell, C.D., Hettinger, A., 2003. Nutrient enrichment can increase the severity of coral diseases. Ecol. Lett. 6 (12), 1056–1061. https://doi.org/10.1046/j.1461-0248.2003.00544.x.

Burke, L., Reytar, K., Spalding, M., Perry, A., 2011. Reefs at risk revisited. Defenders 74 (3).

Burke, L., Reytar, K., Spalding, M., Perry, A., 2012a. Reefs at risk revisited in the Coral Triangle. World Research Institute.

Burke, L., Reytar, K., Spalding, M., Perry, A., 2012b. Reefs at risk revisited in the Coral Triangle. World Research Institute. https://www.wri.org/research/reefs-risk-revisited-coral-triangle.

Burke, L., Selig, E., Spalding, M., 2002. Reefs at risk in Southeast Asia. World Fishing.

Collie, J.S., Vic Adamowicz, W.L., Beck, M.W., Craig, B., Essington, T.E., Fluharty, D., Rice, J., Sanchirico, J.N., 2013. Marine spatial planning in practice. Estuar. Coast. Shelf. Sci. 117, 1–11. https://doi.org/10.1016/j.ecss.2012.11.010.

Cook, C.N., Hockings, M., Carter, R.W., 2010. Conservation in the dark? The information used to support management decisions. Front. Ecol. Environ. 8 (4), 181–188. https://doi.org/10.1890/090020.

Corelli, V., Boerder, K., Hunter, K.L., Lavoie, I., Tittensor, D.P., 2024. The biodiversity adaptation gap: management actions for marine protected areas in the face of climate change. Conserv. Lett. 1–10. https://doi.org/10.1111/conl.13003. *December 2023*.

de Bakker, D.M., van Duyl, F.C., Bak, R.P.M., Nugues, M.M., Nieuwland, G., Meesters, E. H., 2017. 40 Years of benthic community change on the Caribbean reefs of Curaçao and Bonaire: the rise of slimy cyanobacterial mats. Coral. Reefs 36 (2), 355–367. https://doi.org/10.1007/s00338-016-1534-9.

Delevaux, J.M.S., Stamoulis, K.A., Whittier, R., Jupiter, S.D., Bremer, L.L., Friedlander, A., Kurashima, N., Giddens, J., Winter, K.B., Blaich-Vaughan, M., Burnett, K.M., Geslani, C., & Ticktin, T. (2019). *Place-based management can reduce human impacts on coral reefs in a changing climate*. 29(4), 1–24. https://doi.org/10.2307/26669258.

Di Cintio, A., Niccolini, F., Scipioni, S., Bulleri, F., 2023. Avoiding "Paper Parks": a global literature review on socioeconomic factors underpinning the effectiveness of marine protected areas. Sustainability (Switzerland). MDPI. https://doi.org/10.3390/su15054464. Vol. 15, Issue 5.

Eddy, T.D., Cheung, W.W.L., Bruno, J.F., 2018. Historical baselines of coral cover on tropical reefs as estimated by expert opinion. PeerJ 2018 (1), 1–16. https://doi.org/10.7717/peerj.4308.

Edgar, G.J., Stuart-Smith, R.D., Willis, T.J., Kininmonth, S., Baker, S.C., Banks, S., Barrett, N.S., Becerro, M.A., Bernard, A.T.F., Berkhout, J., Buxton, C.D., Campbell, S. J., Cooper, A.T., Davey, M., Edgar, S.C., Försterra, G., Galván, D.E., Irigoyen, A.J., Kushner, D.J., Thomson, R.J., 2014. Global conservation outcomes depend on marine protected areas with five key features. Nature 506 (7487), 216–220. https://doi.org/10.1038/nature13022.

Edinger, E.N., Jompa, J., Limmon, G.V., Widjatmoko, W., Risk, M.J., 1998. Reef degradation and coral biodiversity in Indonesia: effects of land-based pollution, destructive fishing practices and changes over time. Mar. Pollut. Bull. 36 (8), 617–630. https://doi.org/10.1016/S0025-326X(98)00047-2.

Estradivari, Agung, M.F., Adhuri, D.S., Ferse, S.C., Sualia, I., Andradi-Brown, D.A., Campbell, S.J., ... & Ahmadia, G.N., 2022. Marine conservation beyond MPAs: Towards the recognition of other effective area-based conservation measures (OECMs) in Indonesia. Marine Policy, 137, 104939.

Ford, A.K., Bejarano, S., Nugues, M.M., Visser, P.M., Albert, S., Ferse, S.C.A., 2018. Reefs under siege-the rise, putative drivers, and consequences of benthic cyanobacterial mats. Front. Mar. Sci. 5 (FEB), 1–15. https://doi.org/10.3389/fmars.2018.00018.

Gurney, G.G., Melbourne-Thomas, J., Geronimo, R.C., Aliño, P.M., Johnson, C.R., 2013. Modelling coral reef futures to inform management: can reducing local-scale stressors conserve reefs under climate change? PLoS One 8 (11). https://doi.org/10.1371/journal.pone.0080137.

Hadi, T.A., Abrar, M., Giyanto, B.P., Johan, O., Budiyanto, A., Dzumalek, A.R., Alifatri, L. O., Sulha, S., Suharsono, 2020. The status of Indonesian coral reefs 2019. *Res. Center Oceanography-Indones. Instit. Sci., Jakarta*.

Halpern, B.S., Frazier, M., Afflerbach, J., Lowndes, J.S., Micheli, F., O'Hara, C., Scarborough, C., Selkoe, K.A., 2019. Recent pace of change in human impact on the world's ocean. Sci. Rep. 9 (1), 1–8. https://doi.org/10.1038/s41598-019-47201-9.

Haywood, M.D.E., Dennis, D., Thomson, D.P., Pillans, R.D., 2016. Mine waste disposal leads to lower coral cover, reduced species richness and a predominance of simple coral growth forms on a fringing coral reef in Papua New Guinea. Mar. Environ. Res. 115, 36–48. https://doi.org/10.1016/j.marenvres.2016.02.003.

Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen, M.L., Bridge, T.C., Claar, D.C., Eakin, C.M., Gilmour, J.P., Graham, N.A.J., Harrison, H., Hobbs, J.P.A., Hoey, A.S., Hoogenboom, M., Lowe, R.J., Wilson, S.K., 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359 (6371), 80–83. https://doi.org/10.1126/science.aan8048.

Hughes, T.P., Barnes, M.L., Bellwood, D.R., Cinner, J.E., Cumming, G.S., Jackson, J.B.C., Kleypas, J., Van De Leemput, I.A., Lough, J.M., Morrison, T.H., Palumbi, S.R., Van Nes, E.H., Scheffer, M., 2017. Coral reefs in the anthropocene. Nature 546 (7656), 82–90. https://doi.org/10.1038/nature22901.

Jentoft, S., Chuenpagdee, R., Pascual-Fernandez, J.J., 2011. What are MPAs for: on goal formation and displacement. Ocean Coast. Manage. 54 (1), 75–83. https://doi.org/10.1016/j.ocecoaman.2010.10.024.

Lausche, B., 2011. Guidelines for protected areas legislation. In *environmental policy and law*. http://data.iucn.org/dbtw-wpd/exec/dbtwpub.dll?AC=GET_RECORD&XC=/dbtw-wpd/exec/dbtwpub.dll&BU=http://data.iucn.org/dbtw-wpd/commande/index_newsite.htm&TN=iucn&SN=AUTO5511&SE=258&RN=0&MR=20&TR=0&TX=1000&ES=0&CS=1&XP=&RF=WebRes&EF=&DF=WebAff&RL=0&EL=0&DL=0.

Lopazanski, C., Foshay, B., Couture, J.L., Wagner, D., Hannah, L., Pidgeon, E., Bradley, D., 2023. Principles for climate resilience are prevalent in marine protected area management plans. Conserv. Lett. 16 (5), 1–14. https://doi.org/10.1111/conl.12972.

Maas, D.L., Capriati, A., Ahmad, A., Erdmann, M.V., Lamers, M., de Leeuw, C.A., Prins, L., Purwanto, P.A.P., Tapilatu, R.F., Becking, L.E, 2020. Recognizing peripheral ecosystems in marine protected areas: a case study of golden jellyfish lakes in Raja Ampat, Indonesia. Mar. Pollut. Bull. 151 (July 2019), 110700. https://doi.org/10.1016/j.marpolbul.2019.110700.

Martinez-Escobar, D.F., Mallela, J., 2019. Assessing the impacts of phosphate mining on coral reef communities and reef development. Sci. Total Environ. 692, 1257–1266. https://doi.org/10.1016/j.scitotenv.2019.07.139.

McClanahan, T.R., Donner, S.D., Maynard, J.A., MacNeil, M.A., Graham, N.A.J., Maina, J., Baker, A.C., Alemu, I.J.B., Beger, M., Campbell, S.J., Darling, E.S., Eakin, C.M., Heron, S.F., Jupiter, S.D., Lundquist, C.J., McLeod, E., Mumby, P.J., Paddack, M.J., Selig, E.R., van Woesik, R., 2012. Prioritizing key resilience indicators to support coral reef management in a changing climate. PLoS One 7 (8). https://doi.org/10.1371/journal.pone.0042884.

Meilana, L., Fang, Q., Adi, H., Widiastutik, R., Yang, S., & Liu, Z. (2023). *How Indonesian marine protected areas (MPAs) are doing : a management performance-based evaluation*. 282(April).

Meilana, L., Fang, Q., Susanto, H.A., Widiastutik, R., Syaputra, D.E., Ikhumhen, H.O., Sholihah, R., Hakim, A., Yang, S., Liu, Z., 2023b. How Indonesian marine protected areas (MPAs) are doing: a management performance-based evaluation. Biol. Conserv. 282. https://doi.org/10.1016/j.biocon.2023.110033.

MMAF. (2020). *MPA Vision 2030 and Roadmap to MPA Management: securing 10% of marine waters in Indonesia towards biodiversity protection and sustainable use*.

MMAF, 2024. KKP Galang Kolaborasi Internasional Perluas Kawasan Konservasi Laut. Https://Kkp.Go.Id/News/News-Detail/Kkp-Galang-Kolaborasi-Internasional-Perluas-Kawasan-Konservasi-Laut.Html.

Novaczek, I. (1998). *Paradise in peril: threatened by a dwindling fishery, the Biak people of Indonesia's Padaido islands are trying to cash in on their fishing culture*.

O'Regan, S.M., Archer, S.K., Friesen, S.K., Hunter, K.L., 2021. A global assessment of climate change adaptation in marine protected area management plans. Front Mar Sci 8 (September), 1–16. https://doi.org/10.3389/fmars.2021.711085.

Pakiding, F., Matualage, D., Salosso, K., Purwanto, Ratih, Anggriyani, I., Ahmad, A., Andradi-Brown, D., Claborn, K., De Nardo, M., Veverka, L., Glew, L., Ahmadia, G., Rumengan, I., Monim, H.F.Y., Pangulimang, J., Paembonan, M., Pada, D., Mascia, M. B., 2020. State of the Bird's Head Seascape marine protected area network 2019. University of Papua, Yayasan Konservasi Alam Nusantara-TNC, World Wildlife Fund, and Conservation International 1–38.

Ponti, M., Fratangeli, F., Dondi, N., Reinach, M.S., Serra, C., Sweet, M.J., 2016. Baseline reef health surveys at Bangka Island (North Sulawesi, Indonesia) reveal new threats. PeerJ 2016 (10). https://doi.org/10.7717/peerj.2614.

Pullin, A.S., Knight, T.M., Stone, D.A., Charman, K., 2004. Do conservation managers use scientific evidence to support their decision-making? Biol. Conserv. 119 (2), 245–252. https://doi.org/10.1016/j.biocon.2003.11.007.

Reaser, J.K., Pomerance, R., Thomas, P.O., 2000. Coral bleaching and global climate change: scientific findings and policy recommendations. Conserv. Biol. 14 (5), 1500–1511. https://doi.org/10.1046/j.1523-1739.2000.99145.x.

Reverter, M., Jackson, M., Daraghmeh, N., von Mach, C., Milton, N., 2020. 11-yr of coral community dynamics in reefs around Dahab (Gulf of Aqaba, Red Sea): the collapse of urchins and rise of macroalgae and cyanobacterial mats. Coral. Reefs 39 (6), 1605–1618. https://doi.org/10.1007/s00338-020-01988-6.

Science, M., 1992. *Status of coral reefs in southeast asia: threats and responses C.R. Wilkinson, L.M.Chou2, E. Gomez, A.R. Ridzwan4, S. Soekamo5*. S. Sudara 6 (3), 33–39.

Sujana, N., Agostini, V.N., Grantham, H.S., Wilson, J., Mangubhai, S., Rotinsulu, C., Hidayat, N., Muljadi, A., Mongdong, M., Darmawan, A., Rumetna, L., Erdmann, M. V., & Possingham, H.P. (2012). *Achieving fisheries and conservation objectives within Marine protected areas: zoning the Raja Ampat network*.

Supriharyono. (2003). *CORAL REEF MANAGEMENT IN PADAIDO MARINE TOURISM PARK, BIAK NUMFOR case study for the alternative solution to destructive fishing practices on Coral reefs*.

Susanto, H.A., Suraji, T.M., Tokeshi, M., 2015. Management of coral reef ecosystems in Indonesia: Past, present, and the future. Coast Ecosyst 2, 21–41.

Thomas, L., Middleton, J., 2003. Guidelines for management planning of protected areas. Guidelines for Management Planning of Protected Areas (10). https://doi.org/10.2305/iucn.ch.2003.pag.10.en.

Thur, S.M., 2010. User fees as sustainable financing mechanisms for marine protected areas: an application to the Bonaire National Marine Park. Mar. Policy 34 (1), 63–69. https://doi.org/10.1016/j.marpol.2009.04.008.

Tranter, S.N., Estradivari, A.G.N., Andradi-Brown, D.A., Muenzel, D., Agung, F., Amkieltiela, F.A.K., Habibi, A., Handayani, C.N., Iqbal, M., Krueck, N.C., Lazuardi, M.E., Muawanah, U., Papilaya, R.L., Razak, T.B., Sapari, A., Sjahruddin, F. F., Veverka, L., Beger, M., 2022. The inclusion of fisheries and tourism in marine protected areas to support conservation in Indonesia. Mar. Policy 146. https://doi.org/10.1016/j.marpol.2022.105301.

Tundi Agardy, M., 1994. Advances in marine conservation: the role of marine protected areas. Trends Ecol. Evol. 9 (7), 267–270. https://doi.org/10.1016/0169-5347(94)90297-6.

van Tatenhove, J.P.M., 2017. Transboundary marine spatial planning: a reflexive marine governance experiment? J. Environ. Policy Plann. 19 (6), 783–794. https://doi.org/10.1080/1523908X.2017.1292120.

Voss, J.D., Richardson, L.L., 2006. Nutrient enrichment enhances black band disease progression in corals. Coral Reefs 25 (4), 569–576. https://doi.org/10.1007/s00338-006-0131-8.

White, C.M., Mangubhai, S., Rumetna, L., Brooks, C.M., 2022. The bridging role of non-governmental organizations in the planning, adoption, and management of the marine protected area network in Raja Ampat. Indonesia. *Mar Policy* 141 (April). https://doi.org/10.1016/j.marpol.2022.105095.

Whitelaw, P.A., King, B.E.M., Tolkach, D., 2014. Protected areas, conservation and tourism - financing the sustainable dream. Journal of Sustainable Tourism 22 (4), 584–603. https://doi.org/10.1080/09669582.2013.873445. Routledge.

Whitney, C.K., Ban, N.C., 2019. Barriers and opportunities for social-ecological adaptation to climate change in coastal British Columbia. Ocean Coast. Manage. 179 (June), 104808. https://doi.org/10.1016/j.ocecoaman.2019.05.010.

Wiadnya, D.G.R., Syafaat, R., Susilo, E., Setyohadi, D., Arifin, Z., Wiryawan, B., 2011. Recent development of marine protected areas (MPAs) in Indonesia: policies and governance. J. Appl. Environ. Biol. Sci. 1 (12), 608–613. http://www.textroad.com/JAEBS-December2011.html.