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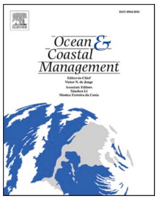

Prospective ecological contributions of potential marine OECMs and MPAs to enhance marine conservation in Indonesia

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ABSTRACT

Other effective area-based conservation measures (OECMs) represent a new frontier in conservation, aiming to acknowledge efforts that contribute to biodiversity beyond marine protected areas (MPAs). Many nations, including Indonesia, are establishing country-specific criteria to define what qualifies as an OECM. However, demonstrating the biodiversity contributions of Indonesia's 382 identified potential OECMs (i.e., non-MPA areas, governed and managed, and likely contributing to biodiversity conservation) poses a challenge due to the absence of national monitoring systems outside MPAs. A spatial approach was used to provide an overview of the expected ecological contributions of potential OECMs upon formal recognition. Potential OECMs were, on average, five times smaller (26,838 ha) than MPAs (133,524 ha). Together with MPAs, they formed a denser conservation network, with many encompassing climate refugia reefs. Upon full recognition, potential OECMs could contribute to conserving $<1\%$, 12%, and 8% of the nation's mangroves, seagrass, and coral reef areas, respectively. Potential OECMs were restricted to coastal areas, and situated in various ecological contexts, including areas typically excluded from MPA designation, such as turbid reefs. Recognizing these OECMs could potentially add 10 million ha to national marine conservation areas. Collectively, MPAs and potential OECMs could contribute to conserving 13% of the nation's waters by 2030. Potential OECMs are effective locally and offer unique strengths, including diverse governance approaches, long-term presence, and potential socioeconomic benefits. Nonetheless, they face challenges from human pressures that may compromise their effectiveness. Formal recognition and strengthening of these areas could help mitigate these risks. This study highlights the potential of recognizing OECMs to enhance conservation efforts in Indonesia, complementing the existing MPA network.

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1. Introduction

Coastal and marine biodiversity globally face increasing pressures from human activities and climate change (Andrello et al., 2022; Hoegh-Guldberg et al., 2017). Impactful solutions are needed to mitigate these threats and reverse biodiversity decline. Marine protected areas (MPAs) have been the primary area-based conservation strategy to protect biodiversity and safeguard the functionality, integrity, and resilience of marine ecosystems. A rapid increase and widespread development of MPAs occurred across our oceans after the Aichi Target 11 (i.e., conserving 10% of marine areas by 2020) was enacted in 2010 (Maestro et al., 2019; Maxwell et al., 2020). Despite increasing coverage, MPAs cover less than 9% of Earth's marine areas (www.protectedplanet.org, accessed in January 2024). Further, while management effectiveness varies across MPAs and regions (e.g., Kirkman et al., 2021; Claudet et al., 2020; Sullivan-Stack et al., 2022; Meilana et al., 2023), most MPAs remain poorly managed (Meilana et al., 2023; Gill et al., 2017; Weeks et al., 2010), raising concerns about the effectiveness of MPAs alone in safeguarding oceans.

Introduced in 2010 and officially defined in 2018, the concept of Other Effective Area-Based Conservation Measures (OECMs) presents an alternative conservation strategy (IUCN-WCPA Task Force on OECMs, 2019; CBD COP, 2018). OECMs are a marine conservation tool besides MPAs. They are defined as '*a geographically defined area other than a protected area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in-situ conservation of biodiversity, with associated ecosystem functions and services and where applicable, cultural, spiritual, socio-economic, and other locally relevant values*' (IUCN-WCPA Task Force on OECMs, 2019; CBD COP, 2018). OECMs can have diverse management purposes, mechanisms, and governing authorities, and when they are effectively managed over the long term, they can deliver a valuable contribution to conserving biodiversity (IUCN-WCPA Task Force on OECMs, 2019; Jonas et al., 2021). OECMs could encompass a broad spectrum, ranging from community-based no-take zones to privately managed ecotourism resorts and from locally managed fishing areas to government-led military areas. OECMs are distinct from regular open-access areas where various activities occur without specific management systems or adherence to sustainability principles.

The inclusion of OECMs in the 2020 Aichi Target 11 (Secretariat of the Convention on Biological Diversity, 2010) and Global Biodiversity Framework (GBF) Target 3, aiming to conserve 30% of marine areas through MPAs and OECMs by 2030 (Secretariat of the United Nations Convention on Biological Diversity, 2021), has spurred the Convention on Biological Diversity (CBD) signatory parties to incorporate the OECM framework into national policies (e.g., Rodríguez-Rodríguez et al., 2021; Marnewick et al., 2021; Estradivari et al., 2022; Shiono et al., 2021). This development is motivated by the widespread existence of diverse area-based management (ABM) practices globally that may qualify as OECMs (Gurney et al., 2021). Evidence suggests that other forms of area-based management can be more effective for conservation than restricted-use protected areas (Nolte et al., 2013; Nelson and Chomitz, 2011; Hayes and Ostrom, 2005) or areas with no management at all (Lester et al., 2009), offering alternative avenues for marine conservation beyond MPA boundaries.

Considering that the recognition of OECMs is still in its infancy, many countries are actively formulating national definitions and criteria for "what counts" as OECMs, delineating scope and standards, and evaluating their contributions to biodiversity. At the global level, the International Union for Conservation of Nature (IUCN) provides guidance to constitute a site as OECM, using four broad criteria: the site (a) is not a protected area, (b) is bounded, governed, and managed, (c) is confirmed to contribute to sustained biodiversity conservation, and (d) maintains ecosystem functions and services, and locally relevant values (IUCN-WCPA Task Force on OECMs, 2019). Among these, criterion (c) is pivotal because the OECM has to demonstrate that it contributes to biodiversity conservation and its governance and management are expected to be sustained so the OECM can continue to conserve biodiversity in the long-term (IUCN-WCPA Task Force on OECMs, 2019). However, showing this contribution is often the most challenging part for many nations, mainly due to the lack of comprehensive data on biodiversity outcomes in these areas.

Indonesia, the world's marine biodiversity hotspot, hosts numerous potential marine OECMs (i.e., areas that are managed, governed, and likely contribute to biodiversity conservation; Estradivari et al., 2022). These potential OECMs are widespread nationwide. Many have existed for decades and are likely to be effectively managed. Recognizing these ABM practices as OECMs offers a transformative opportunity, fostering effective, inclusive, and equitable conservation by empowering collaboration among various stakeholders and enhancing synergy between formal and informal conservation frameworks and social aspects of conservation (Estradivari et al., 2022). Coupled with MPAs, which have been the primary conservation tool in Indonesia (Meilana et al., 2023; Estradivari et al., 2022; Amkieltiela et al., 2022), OECMs have the potential to substantially contribute to safeguarding the nation's marine biodiversity and achieving national and international targets for area-based conservation. Most importantly, Indonesia may overlook many effective conservation areas in its national reporting if OECMs are not recognized.

In Indonesia, assessing the role of potential marine OECMs in enhancing biodiversity faces challenges due to the absence of standardized national monitoring systems outside MPAs. In this case, a spatial approach offers a promising opportunity to help identify areas likely to benefit biodiversity. Such information is particularly important to foster a nuanced understanding of coverage of different habitats and environmental conditions within potential OECMs, which can help to prioritize existing ABM practices for recognition as OECMs when *in-situ* biodiversity outcomes are assessed. This information is also relevant and timely, given Indonesia's substantial investment in integrating the global OECM framework into its policy.

This study applied a rapid and cost-effective spatial approach to offer a preliminary overview of the prospective ecological contributions of potential marine OECMs and MPAs in Indonesia. We focused on key coastal habitats - mangroves, seagrasses, and coral reefs - due to the current distribution of MPAs and potential OECMs along coastal areas. Using the potential marine OECMs identified by Estradivari et al. (2022), we estimated the size of each managed area. We then overlaid them with spatial data on coastal habitat extent, environmental characteristics, and human pressures. We then compared the prospective ecological contributions of potential OECMs and MPAs in terms of habitat coverage. The findings are contextualized with regards to Indonesia's national goal to implement 32.5 million ha of MPAs by 2030. This study represents an academic exercise to demonstrate how Indonesia could estimate the prospective ecological contributions from numerous potential OECMs and MPAs, given the lack of comprehensive *in-situ* data.

2. Methods

2.1. Data sources

This study is based on publicly available datasets. Potential marine OECMs (referred to as potential OECMs or pot.OECMs) across Indonesia in 2019 ($n = 382$, Fig. 1) were compiled by Estradivari et al. (2022) and defined as preexisting ABMs outside MPAs, governed and managed independently with likely positive impacts on biodiversity conservation, evidenced by their long-standing implementation or demonstrable ecological improvements. They were identified through national workshops and a literature review in 2019 (Estradivari et al., 2022). Meanwhile, MPA data as of 2020 ($n = 193$) were obtained from the Indonesian Ministry of Marine Affairs and Fisheries/MMAF (Kementerian Kelautan dan Perikanan, 2020). We included all MPAs in

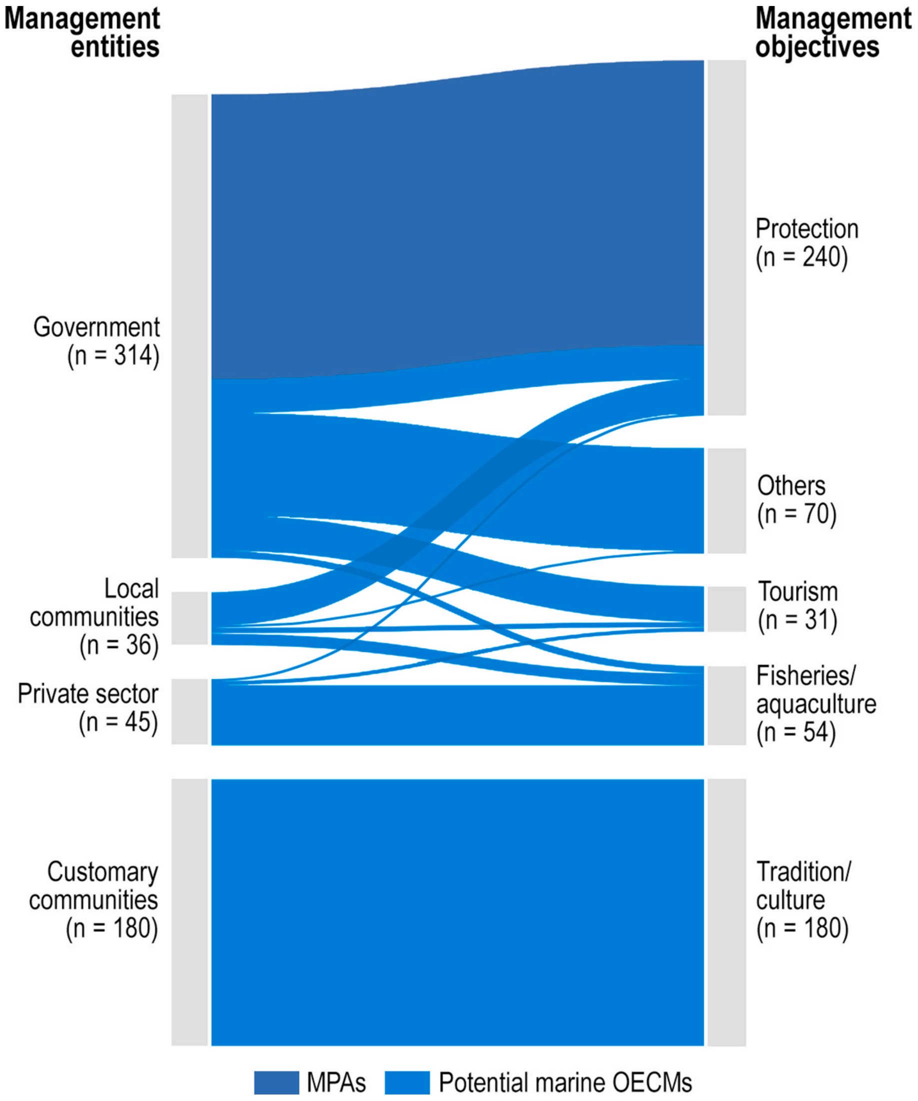

Fig. 1. Connection between managing entities **(left)** and primary management purposes **(right)** of 382 potential OECMs and 193 MPAs in Indonesia. Note: Local communities encompass diverse societal groups, not all of which depend on marine resources. In contrast, customary communities specifically refer to traditional fishing communities that possess recognized rights to fish and conduct various activities within designated marine areas (Government Regulation No 21/2021).

Indonesia governed by MMAF, regardless of their stage of establishment, ranging from the designation phase (i.e., formally designated as an MPA and having an outer boundary), establishment phase (i.e., formally established, having zoning system, management plans, and governing entity), to the actively managed phase (i.e., fully enforced with monitoring and evaluation system in place, see Lazuardi et al., (2020) for detailed MPA governance structure in Indonesia). We analyzed four variables to depict proxies of prospective ecological contributions from potential OECMs and MPAs (hereafter "management types" or "managed areas"), i.e., coastal habitat (mangroves, seagrasses, and coral reefs) coverage within managed area, representativeness of coastal habitats within managed areas, spacing among managed areas, and resilience to climate change impacts ("reef refugia"). This study focuses on three key coastal habitats and does not encompass other important habitats such as mudflats and rocky beaches. Additionally, we examined seven human and environmental pressures affecting managed areas, including small-scale fishing, coastal population, industrial development, tourism, nitrogen and sediment exposure, and turbidity. Brief information on each variable is available in Table 1, and a summary of methods to generate spatial layers for some variables is available in the Supplementary Materials (Table S1). Furthermore, full descriptions of public spatial datasets should be sourced directly from the references listed in Table 1.

2.2. Potential marine OECM polygons

Estradivari et al. (2022) provided a comprehensive list of potential OECMs in Indonesia gathered from two national workshops conducted in 2019 and literature reviews. All of these potential OECMs were found to be restricted to coastal waters. The assessment was limited by the lack of coordinates due to inaccessible or unavailable data. To address this, we relied on three key assumptions tailored to Indonesia's diverse governance and management contexts to create potential OECM polygons.

1) We assumed OECM boundaries to align with administrative boundaries, whether at the village or (sub-)district level, acknowledging the unique authority at each level for marine resource management decisions. Exceptions were made for 121 *Panglima Laôt* sites in Aceh and eight marine access and reserve areas in Southeast Sulawesi that extended beyond one village, where actual boundaries were accessible.

Table 1
Variables, sources, descriptions, and resolutions used in this study.

Variables and sources	Descriptions	Resolutions
Identified potential OECMs (Estradivari et al., 2022)	The dataset started with 397 potential marine OECMs across Indonesia identified in 2019. After overlaying them with the 2020 MPA polygons, 15 potential OECMs within MPAs were removed, leaving a final count of 382 potential OECMs. They were classified based on primary management purposes (i.e., protection, fisheries/aquaculture, tourism, tradition/culture, or other management purposes such as national sovereignty or military areas), governing bodies (i.e., government-led, private sector-led, local community-led, or customary community-led), and locations with village or (sub-)district as the lowest unit. Local communities and customary/traditional communities follow customs and values in their daily lives but have different focuses and legal statuses (Government Regulation No 21/2021). Local communities include various societal groups with generally accepted/permitted practices/norms, and they are not always reliant on specific coastal or small island resources. In contrast, customary communities, including customary law communities (Ministry of Home Affairs Regulation No. 52/2014), are traditional fishing communities with recognized fishing rights and engage in other activities within marine territories.	Site-level information
MPAs (Kementerian Kelautan dan Perikanan, 2020)	193 MPA polygons distributed across Indonesia as of 2020. Most MPAs (84%) in Indonesia are managed and governed by MMAF, and the remaining are managed by the Ministry of Environment and Forestry (MoEF), with the primary objectives of protecting marine biodiversity and supporting sustainable fisheries. The management of these MPAs is standardized through MMAF Regulation No. 31/2020, which includes several key mechanisms such as governance approaches, zoning systems, and monitoring and evaluation systems.	Vector (polygon)
Administrative boundaries (BIG, 2016)	The 2020 urban village-level administration boundary vector data. The data comprise 38 provinces in Indonesia and cover all sub-district- and village-level areas.	Vector (polygon)
Ecological features		
Mangrove extent (Bunting et al., 2018)	Mangrove habitat from the year 2016 generated by Global Mangrove Watch using ALOS PALSAR and Landsat images.	Vector (polygon)
Seagrass extent (BIG and Peraturan Kepala BIG (PERKA BIG), 2014)	Seagrass habitat from a time series image analysis from 2004 to 2013 using Landsat ETM+, ALOS AVNIR, IKONOS, and ASTER images. These data are compiled from several agencies, including the National Geospatial Information Agency (BIG), the former Indonesian Institute of Sciences (LIPI), and The Nature Conservancy (TNC).	Vector (polygon)
Coral reef extent (UNEP-WCMC et al., 2001)	Coral reef habitat compiled from 1954 to 2009 from several sources by UNEP World Conservation Monitoring Centre (UNEP-WCMC) and the WorldFish Centre, in collaboration with World Resources Institute (WRI) and The Nature Conservancy (TNC).	Vector (polygon)
Coastal habitat representativeness (this study)	Occurrence of three key coastal habitats (mangroves, seagrass, and coral reefs, identified as described above) in each managed area.	Presence/absence data
Spacing among managed areas (this study)	Spacing among managed areas was measured by counting the number of other managed areas within a 20- and 30-km buffer from the outer boundary of each managed area. The 20 and 30-km distances (Green et al., 2014; Fernandes et al., 2012) are expected to cover most of the larval dispersal for most marine species, thus enhancing larval connectivity among managed areas. The number of managed areas within a specified distance serves as a proxy that accounts for both the distance and the number of managed areas. This makes it a composite indicator of the ecological network density, offering insights into the connectivity among these managed areas within the seascape.	Count data within a specified distance
Coral reef climate refugia (Beyer et al., 2018, 2019)	Reef refugia data modeled using past, present, and future climate data, cyclone patterns, and larval connectivity. Each refugium, represented as a bioclimatic unit (BCU), covers approximately 500 km^2 of coral reef habitat. Indonesia has sixteen BCUs. These areas are anticipated to face minimal climate change impacts, such as thermal stress and coral bleaching, and include reefs capable of replenishing other reefs over time, less susceptible to frequent natural disasters.	500 km^2 vector (polygon of coral reef habitat)
Human and environmental pressures		
Six human pressures on tropical reefs (Andrello et al., 2022)	Given the absence of publicly available nation-wide absolute data on human pressures on coral reefs in Indonesia, we used the recent human pressure data modeled by Andrello et al., (2022). Pressures are factors that, under certain conditions, can degrade coral reef function, productivity, or resilience (Andrello et al., 2022). Human pressures on tropical reefs were assessed using six variables: 1) small-scale fishing intensity measured by market gravity. Market gravity was calculated as (number of people)/(hours of travel to coral reef areas)^2, where higher gravity can reduce fish biomass and top predator occurrence (Cinner et al., 2016, 2018); (2) coastal population density, estimated from the number of people living within a 5 km buffer of each coral reef cell (Center for International Earth Science Information Network - CIESIN - Columbia University, 2018); 3) industrial development, based on the number of port locations (source: https://goo.gl/Yu8xxt) grouped within 5 km^2 to account for dredging impacts; 4) tourism use, estimated from annual tourist visits driven by coral reefs (Spalding et al., 2017); 5) sediment delivery to coral reefs, incorporating land cover, rainfall-runoff erosivity, slope, steepness, and soil erodibility, estimated as tons of sediment/km^2 (Andrello et al., 2022); and 6) nitrogen delivery to coral reefs, based on catchment-level crop cover and national nitrogen fertilizer use (Andrello et al., 2022). The human pressures were evaluated in 10.573-reef containing raster grid cells across Indonesia.	0.05° resolution (5 km discrete raster grid)
Top threat (this study)	Using the spatial dataset provided by Andrello et al., (2022), the top threat of a managed area was identified by selecting one out of six human pressures with the highest frequency of occurrence from all grid cells within that managed area.	
Turbidity (Allen Coral Atlas, (2022) and this study)	Turbidity indicates the presence of suspended particles in marine waters. We used data on the third quarter of 2021 from the Allen Coral Atlas (downloaded in October 2023), which exhibited the	10 m discrete raster grid

(continued on next page)

Table 1 (*continued*)

Variables and sources	Descriptions	Resolutions
	highest turbidity levels in Indonesian waters. This data was grayscale imagery with a 10-m resolution and 16-bit integer format, providing 65,536 grayscale shades. Turbidity values were presented as Formazin Nephelometric Units (FNU), with values > 8 FNU indicating extreme turbidity.	

2) All potential OECMs were assumed to correspond to nearshore waters, given their proximity to the coastline. Consequently, inshore boundaries were delineated from the coastline following shapefiles provided by the National Geospatial Information Agency/BIG (BIG and Peraturan Kepala BIG (PERKA BIG), 2014).
3) The offshore boundaries were assumed to correspond to the extent of the authority of the respective management entity, resulting in three groups. a) Local and customary community-managed areas were allocated a 4 nautical-mile (nm) offshore buffer, aligned with MMAF regulation no. 18/2021 for small-scale fisheries (vessels <5 gross tons). Exceptions were made for 23 areas managed by customary- or locally-led communities where a 2 nm buffer was applied to match reported sizes in Estradivari et al. (2022). b) Government-managed areas were buffered to 12 nm offshore, in accordance with Law No. 23/2014 and Ministry of Marine Affairs and Fisheries Regulation No. 28/2021, authorizing provincial governments to manage waters within 12 nm. c) Private sector-managed areas with specified and regulated total sizes under permits had polygons manually created to correspond to these sizes.

During data processing, village name mismatches between potential OECMs and administrative shapefiles were addressed by identifying villages with similar names or randomly selecting a village within the identified district. These mismatches often stemmed from inconsistencies in administrative nomenclature, village expansion, or division, leading to the creation of new villages or the merging of existing ones. Additionally, 59 OECM polygons overlapped with MPA polygons due to new MPA designations after the initial identification of potential OECMs in 2019. Since an area could not be classified as both an MPA and an OECM, the overlapping OECM polygons were removed to prevent double counting, preserving the MPA polygons. Fifteen OECMs were excluded from the dataset as their areas were entirely within MPAs, resulting in 382 potential OECMs for further analysis.

2.3. *Analysis*

After 382 potential OECM polygons were generated, together with 193 MPA polygons, we overlaid them with ecological, human and environmental pressure spatial layers (Table 1). In some areas, turbidity data were incomplete due to cloud coverage and sun glint in satellite images. If more than 25% of the grid cells within a managed area had missing turbidity data, that managed area was excluded from the analysis, and this resulted in 292 potential OECMs and 184 MPAs with turbidity data included in the analysis. We considered managed areas (potential OECMs or MPAs) as the unit of analysis. For ecological variables: 1) the percent coverage (%) of mangrove, seagrass, and coral reef habitats within a managed area was determined by dividing the extent of each habitat by the size of the managed area, 2) coastal habitat representativeness (ranging from 0 to 3) was assessed based on the presence or absence of these habitats within a managed area, 3) spacing among managed areas was evaluated by counting the number of other managed areas within 20 km and 30 km buffers from a given managed area, and 4) managed areas potentially serving as reef climate refugia were identified by calculating the percentage of grid cells classified as refugia within a managed area; areas with over 50% refugia coverage were classified as climate refugia for reefs.

For human pressure data, Andrello et al. (2022) used percentiles (0–1) relative to the global distribution rather than absolute values. For example, a grid cell with 0.1 percentile indicates a low human pressure value, falling within the bottom 10% of human pressure values across all grid cells globally. While this percentile approach allows for standardization and comparison of pressures across all reef grid cells, it is important to note that different pressures may have varying ecological impacts on coral reef health at the same percentile level. For example, the 0.9 percentile of fishing pressure likely has a more significant ecological impact than the 0.9 percentile of sediment exposure. Given this consideration, the percentile values should be interpreted cautiously, complementing the results with local knowledge and existing literature. A summary of data and methods to calculate human pressures in coral reefs is available in the Supplementary Materials (Table S1), while a more detailed, concise overview should refer to Andrello et al. (2022).

For the overall human and environmental pressure variables: 1) the magnitude of individual human pressure was estimated by averaging percentile values of the given human pressure across all grid cells within a managed area, 2) the top threat was identified by selecting the pressure with the highest frequency of occurrence across all grid cells within the managed area; the top threat of a grid cell was assessed based on the pressure with the highest percentile value, and 3) turbidity levels were determined by measuring the percentage of waters (in ha) with extreme turbidity (>8 FNU) relative to the total size of available turbidity data within a managed area, accounting for grid cells with missing data. Turbidity levels were categorized as follows: not turbid (<25% of the managed area with water turbidity level >8 FNU), slightly turbid (25–50%), moderately turbid (50–75%), and very turbid (75–100%).

The results were visualized with two approaches. First, we generated individual maps for each variable, illustrating their distribution across Indonesia and managed areas. Second, we created graphs to depict the average or proportion of each variable based on the managing entities (i.e., government (GT), private sector (PS), local community (LC), and customary community (CC) for potential OECMs) and management types (i.e., potential OECMs or MPAs) to facilitate a comprehensive comparison. A one-way analysis of variance (ANOVA) was fitted two times to test whether the average values for each variable observed differed 1) among potential OECMs' management entities (GT, PS, LC, CC), and 2) between management types (potential OECMs and MPAs). The one-way ANOVA was conducted using type III sums of squares due to an unbalanced number of observations. A Tukey pairwise analysis with Bonferroni adjustment was used when a statistically significant difference was detected. Statistical analysis was done with R studio version 4.2.3 (R Core Team and R, 2023), and all spatial analyses were conducted using QuantumGIS ver. 3.16 (QGIS.org, 2023).

3. Results

3.1. *Sizes of potential marine OECMs and MPAs*

Our investigation estimated that the 382 potential OECMs spanned a total coastal marine area of 10.2 million ha, roughly equivalent to four-fifths of Java Island's size. Sumatra had the largest total area and highest number of potential OECMs, mainly due to *Panglima Laôt* areas managed based on local wisdom to ensure marine sustainability, covering nearly all of Aceh's nearshore marine areas at the upper tip of Sumatra (Fig. 2a). Conversely, Java & Bali, Lesser Sunda, and Kalimantan collectively had the smallest potential OECM areas (Fig. 2a). These potential OECMs were distributed nationwide, often situated between or surrounding MPAs and in remote areas far from main population centers.

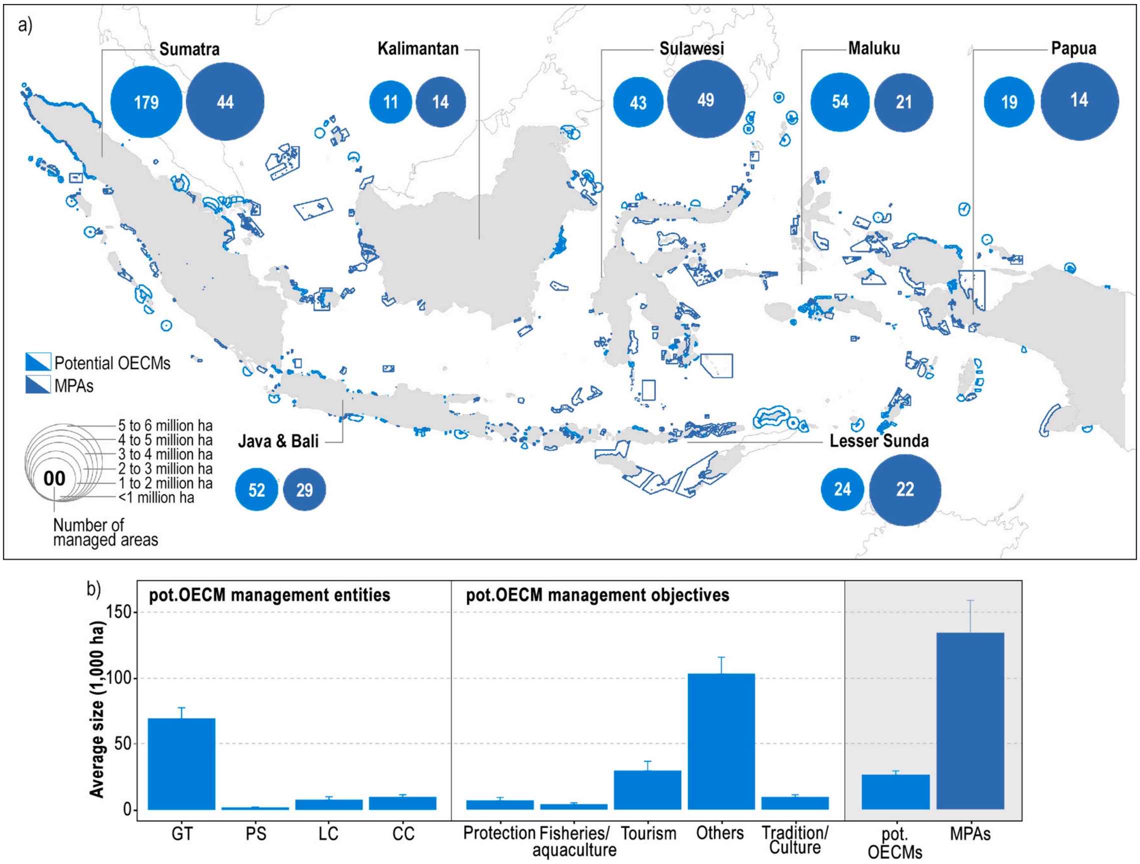

Fig. 2. Number and size distribution of potential OECMs and MPAs (in 1,000 ha) **a)** across regions in Indonesia, and **b)** across management entities (for potential OECMs, left panel), management objectives (for potential OECMs, middle panel), and management types (potential OECMs and MPAs, right panel). Bars represent average values, and whiskers are standard errors. Abbreviations refer to government (GT), private sector (PS), local community (LC), and customary community (CC).

Potential OECMs varied widely in size, ranging from <1 ha to 759,000 ha, with an average size of 26,838 ± 3,219 ha (mean ± SE; Fig. 2b) and a median of 11,754 ha. Potential OECMs managed by the government for "other" purposes, such as national sovereignty or military areas, were significantly larger on average than those managed by other entities (Fig. 2b). Very small potential OECMs (<50 ha, 12% of total) were typically managed by the private sector for specific business activities (e.g., sustainable aquaculture, private resorts) under permits with limited durations, boundaries, and allowable activities. Small potential OECMs (>50–10,000 ha, 53% of total) were mainly customary community-led managed areas, while medium ones (10,000–50,000 ha, 19% of total) had diverse management entities and purposes. As expected, large potential OECMs (>50,000 ha) were predominantly government-led, largely comprising outermost islands serving to safeguard the nation's sovereignty (Presidential Decree No. 6/2017), likely influenced by the method using a 12-nm buffer for delineation.

Similar to potential OECMs, MPAs in Indonesia also exhibited a broad size spectrum, from 36 to 3,474,000 ha with an average of 133,524 ± 24,790 ha (Fig. 2b) and a median of 31,834 ha. Of 193 MPAs, 29% were smaller than 5,000 ha, while 27% exceeded 100,000 ha. Notably, the average size of potential OECMs was five times smaller (p-value <0.001) than the average size of MPAs in Indonesia (Fig. 2b).

3.2. *Ecological characteristics of potential OECMs and MPAs*

Both potential OECMs and MPAs included diverse ecological features. Indonesia's coastlines typically feature extensive mangroves, seagrasses, and coral reefs, with significant coverage primarily concentrated in central to eastern Indonesia (Fig. 3a, 3b, 3c, S1, S2, S3). On average, the percent coverages of individual coastal habitats in a potential OECM area were low (i.e., mean ± SE values of 0.2% ± 0.1% for mangroves, 0.2% ± 0.1% for seagrass, and 4.1% ± 0.7% for coral reefs, Fig. 3g, 3h, 3i). This indicates that 95% of potential OECM areas consisted of other habitats such as open ocean, sandy beaches, salt marshes, and mudflats. Percent coverages of mangrove and coral reef within a managed area were significantly higher within MPAs than potential OECMs (p-value <0.05), but seagrass coverage did not differ significantly (Fig. 3g, 3h, 3i). While there were variations in habitat covers among management entities, they were statistically similar, except for coral reefs (p-value <0.001, Fig. 3i), where areas managed by local communities and the private sector featured higher coverage. Many potential OECMs and MPAs were located in regions with limited or no cover by these habitats (Fig. 3d, 3j, S4). Approximately 43% of potential OECMs lacked mangroves, seagrasses, and coral reefs, whereas 13% contained all three, and the rest had one or two coastal habitats within their boundaries. These coverages were lower than those of MPAs, of which only 24% lacked these three habitats, and 36% had all three habitats.

The addition of potential OECMs would significantly improve Indonesia's ecological network among managed areas, complementing or sometimes buffering the MPAs (Fig. 3e, S5). Without potential OECMs, 33% of MPAs had no nearby MPAs, 36% of MPAs had just one nearby MPA, and 31% had more than one nearby MPA within a 30 km radius (Fig. 3k, S5a). However, when potential OECMs were included, there was a significant increase: only 13% of MPAs had no nearby managed areas (MPA and potential OECMs), 26% of MPAs had another nearby managed area, and 61% had more than one nearby managed areas within a 30 km radius. On average, one managed area commonly had

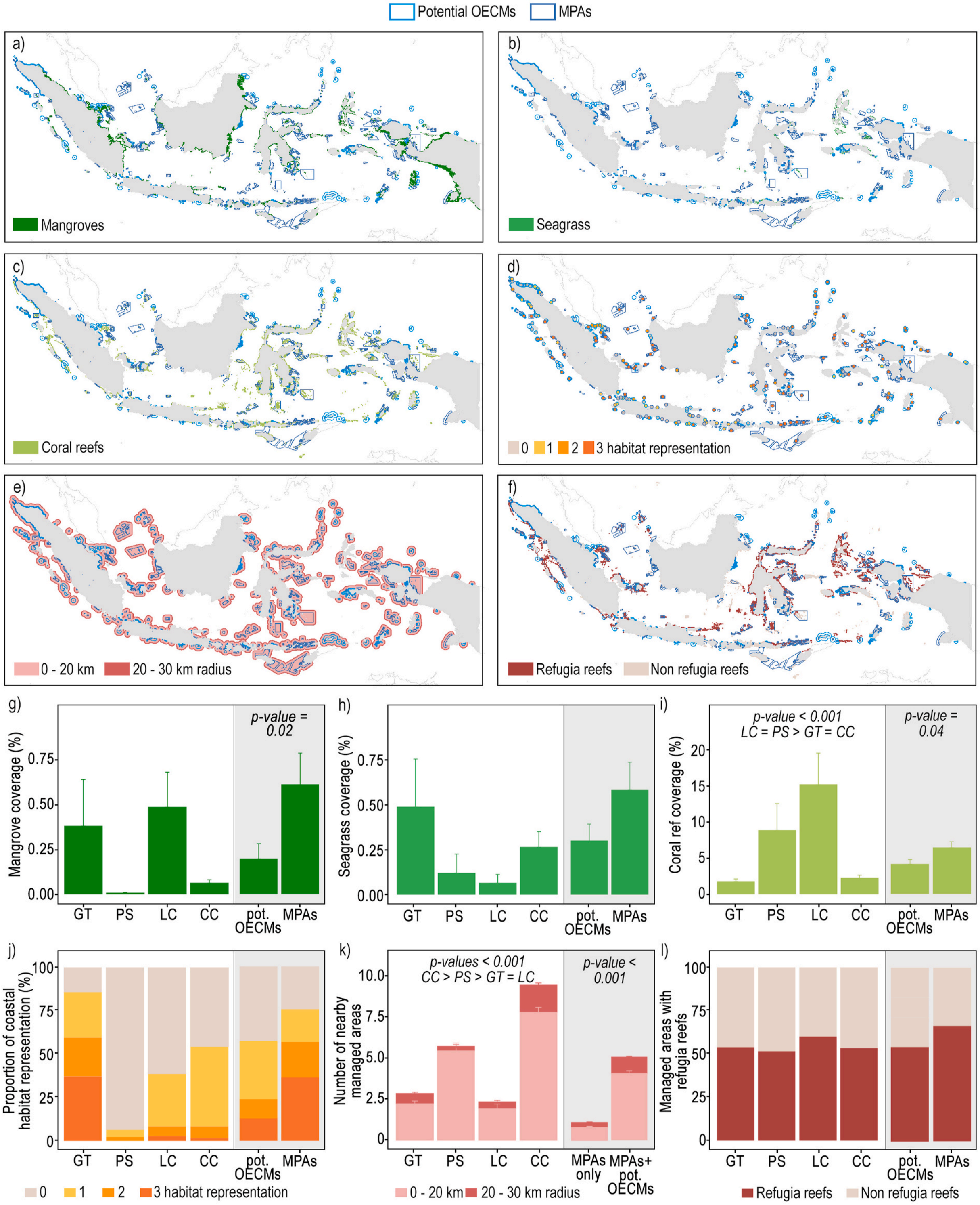

Fig. 3. Potential OECMs and MPAs across ecological features. Distributions of **a)** mangroves, **b)** seagrass, **c)** coral reefs; **d)** number of coastal habitats represented; **e)** spacing among managed areas at 20 km and 30 km radius; **f)** distribution of climate refugia reefs, and proportions of **g)** mangrove coverage, **h)** seagrass coverage, **i)** coral reef coverage within managed areas, **j)** coastal habitat representation, **k)** number of managed areas within 20 and 30 km radius, and **l)** managed areas with climate refugia reefs. Abbreviations refer to government (GT), private sector (PS), local community (LC), and customary community (CC). One graph contains two separate analyses, i.e., based on different management entities for potential OECMs (left, white background) and management types (potential OECMs and MPAs, right, grey background). Bars represent average values, and whiskers are standard errors. When a statistical difference in average or proportions exists, the corresponding p-value is provided above the bars, and pairwise results are denoted by four abbreviations (GT, PS, LC, CC). Larger maps for a) to f) are available in the Supplementary materials (Fig. S1-S6).

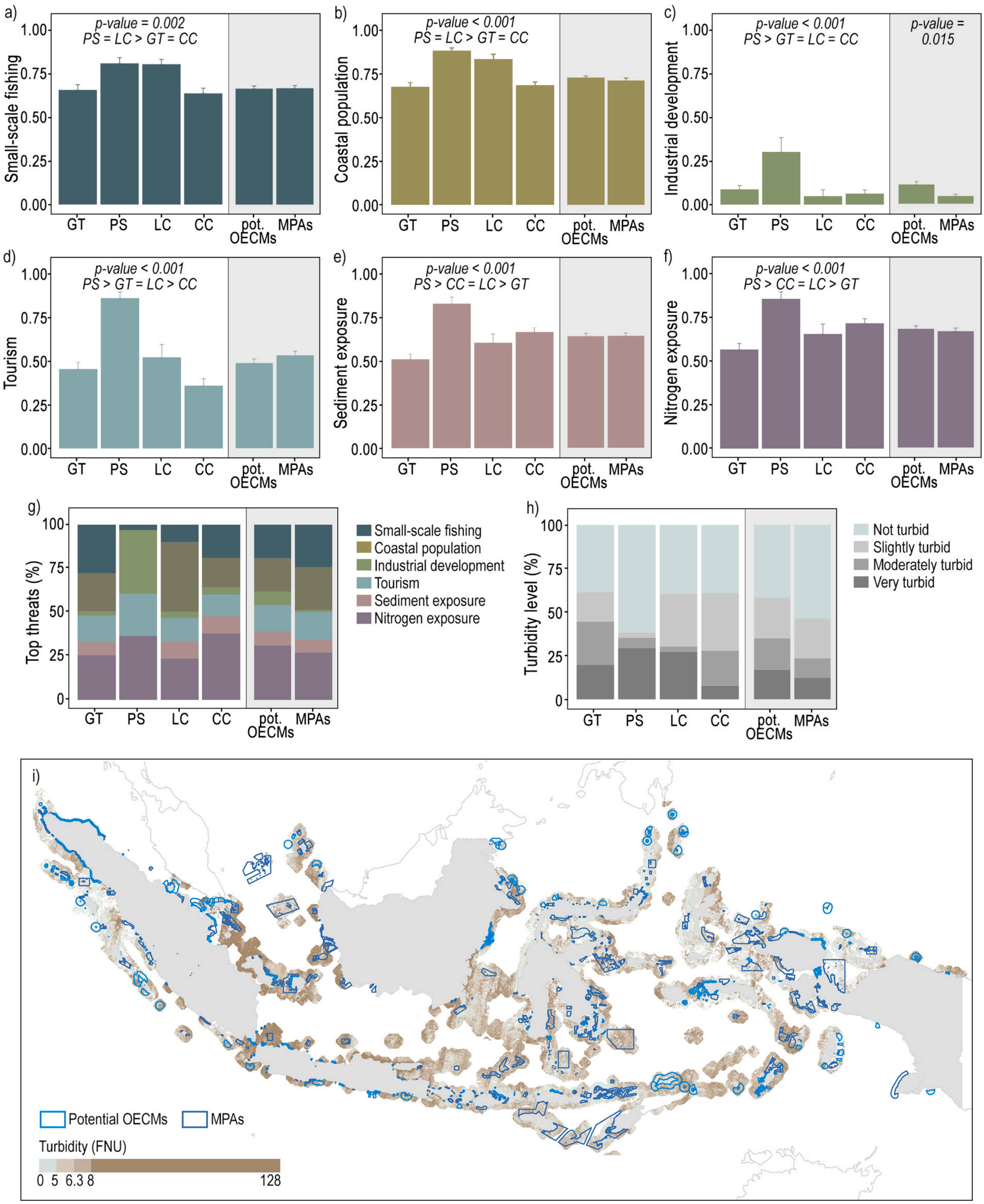

Fig. 4. Potential OECMs and MPAs across human pressure magnitudes. Average percentiles of **a)** small-scale fishing, **b)** coastal population, **c)** industrial development, **d)** tourism, **e)** sediment exposure, and **f)** nitrogen exposure across managed areas. Proportions of **g)** top human pressure threats and **h)** turbidity levels across managed areas. Distribution of **i)** turbidity across Indonesia. Abbreviations refer to government (GT), private sector (PS), local community (LC), and customary community (CC). One graph contains two separate analyses, i.e., based on different management entities for potential OECMs (left, white background) and management types (potential OECMs and MPAs, right, grey background). Bars represent average values, and whiskers are standard errors. When a statistical difference in average percentiles/proportions exists, the corresponding p-value is provided above the bars, and pairwise results are denoted by four abbreviations (GT, PS, LC, CC). The distribution of the six human pressures and top threats across Indonesia, potential OECMs, and MPAs is available in the Supplementary Materials (Fig. S7-S12).

five nearby managed areas when potential OECMs were considered (Fig. 3k, S5b). Many Indonesian reefs demonstrated high potential for resilience to climate change (Fig. 3f, S6), with lower coverage in Java and Kalimantan (Fig. 3f, S6). MPAs tended to have a higher proportion of sites (66%) with climate refugia reefs than potential OECMs (54%, Fig. 3l). Additionally, potential OECMs led by local communities showed a higher proportion of climate refugia reefs than those managed by other entities (Fig. 3l).

3.3. Environmental and human pressures within potential OECMs and MPAs

Potential OECMs and MPAs were found to face considerable environmental and human pressures (Fig. S7-S12), with most percentiles exceeding 0.5 out of 1, except for industrial development and tourism (Fig. 4a–g). Human pressure percentiles varied significantly across different management entities for potential OECMs (p-value <0.001, Fig. 4a–g). Areas managed by the private sector displayed the highest human pressure percentiles, with industrial development, tourism, sediment, and nitrogen pollution percentiles exceeding those from areas managed by other management entities. Conversely, customary community and government-managed areas generally had lower human pressure percentiles, though many still exceeded 0.5. Potential OECMs and MPAs had similar human pressure scores, except for industrial development, which was lower for MPAs (p-value = 0.007, Fig. 4c). Among the six human pressures, small-scale fishing, coastal population, and nitrogen exposure emerged as the most consistently top-ranked factors impacting reefs across all managed areas (Fig. 4g). These three pressures affected 69% of potential OECMs and 75% of MPAs, with nitrogen exposure being the most frequently observed, followed by coastal population and small-scale fishing. Furthermore, MPAs had slightly fewer areas (24%) with moderately and very turbid waters compared to potential OECMs (36%, Fig. 4h). Approximately 35% of potential OECMs and 23% of MPAs experienced moderate to very turbid waters, notably along the Sunda shelf in western Indonesia (Fig. 4i). Interestingly, the turbidity levels in managed areas were not solely determined by land-based sediment delivery, except for potential OECMs with very turbid waters (p-value = 0.003, Fig. S13), indicating potential influences from local oceanographic conditions on sediment retention or dispersion. Moreover, approximately 18% of potential OECMs and 10% of MPAs with moderate to high turbidity hosted climate refugia reefs (Fig. S13c).

3.4. Nationwide prospective contribution of potential OECMs and MPAs to habitat conservation

The 382 potential OECMs covered approximately 10.2 million ha of marine waters, equivalent to 3.1% of Indonesia's total archipelagic and terrestrial marine waters (~320 million ha). This coverage was significantly smaller than MPAs as of 2020, encompassing 25.7 million ha. Indonesia's coastlines were found to host 5,278 ha of mangroves, 20,500 ha of seagrass, and 205,725 ha of coral reefs. The potential OECMs were expected to contribute moderately to conserving these coastal habitats, representing less than 1% of mangroves, 12% of seagrass, and 8% of coral reefs (Fig. 5). These contributions were lower than those of MPAs, which accounted for 3% of mangroves, 39% of seagrass, and 43% of coral reefs (Fig. 5).

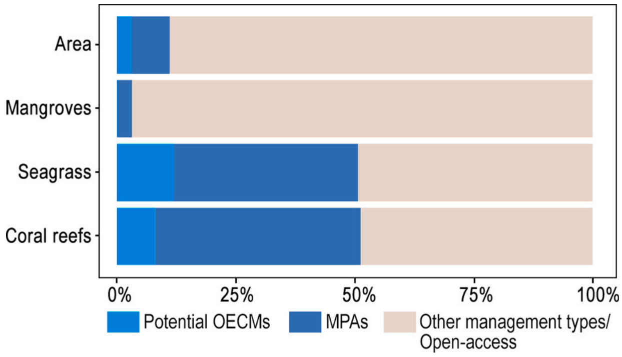

Fig. 5. Contribution of potential OECMs and MPAs to the conservation of total marine areas in Indonesia and of three types of coastal habitats.

4. Discussion

Given the multifaceted scopes encompassing various management entities, objectives, and approaches compared to MPAs, integrating the global OECM framework into Indonesia's national policies necessitates a nuanced approach. Assessing the prospective contributions of OECMs to biodiversity conservation is critical for nations that aim to develop national OECM frameworks and integrate them into their conservation policies. Our analyses shed light on the expected benefits of potential OECMs upon formal recognition, providing valuable insights to initiate concrete discussions among policymakers and stakeholders during framework development and for guiding conservation prioritization. However, it is essential to underscore that our approach does not discount the need for *in-situ* verification of actual conservation benefits, which remains a fundamental requirement for the formal recognition of an ABM practice as an OECM.

4.1. Prospective ecological contributions, limiting factors, and potential risks

Our study revealed that Indonesian potential OECMs were smaller on average compared to MPAs (Fig. 2b). Nevertheless, they were more numerous (Fig. 1) and could spatially contribute over 3% (10.2 million ha) to marine conservation areas in Indonesia (Fig. 5). When combined with the national target of implementing a total of 32.5 million ha of MPAs by 2030 (MMAF, 2020), the collective coverage of OECMs and MPAs could represent up to 13% of the nation's archipelagic and territorial marine waters. While this percentage may seem modest compared to the GBF Target 3 (i.e., 30% of conserved areas by 2030; Secretariat of the United Nations Convention on Biological Diversity, 2021), it is worth noting that both managed areas (as of 2020) together have the potential to safeguard over half of Indonesia's seagrass and coral reef habitats (Fig. 5). However, mangrove coverage within the considered marine managed areas was low (<5%) due to the former's management falling under the Ministry of Environment and Forestry (MoEF), which primarily focuses on terrestrial rather than marine conservation. A significant portion of mangrove area is conserved by MoEF within terrestrial protected areas (PAs), the boundaries of which extend to marine areas. As of 2020, over 20% of mangroves are conserved within MoEF's PAs (Amkieltiela et al., 2022). Besides this, mangroves are also sustainably managed in the form of social forestry, i.e., a sustainable forest management system involving local communities in state or customary forests, benefiting both people and the environment (Ministry of Environment and Forestry, 2022). Mangroves managed under these two mechanisms were not included in this study due to differing governmental scopes and objectives.

Potential OECMs are often situated around existing MPAs and thus could enhance ecological connectivity by forming a denser network of managed areas within a 30 km radius (Fig. 3e, 3k). Such closely spaced managed areas can provide several conservation benefits, such as serving as ecological corridors for marine species movement between managed areas (Fovargue et al., 2018), protecting a wider range of habitats and ecosystems, thereby increasing overall biodiversity conservation (Gaines et al., 2010), acting as sources of fish larvae and adults that "spill over" into surrounding waters (Green et al., 2014; Christie et al., 2010; Lenihan et al., 2021), potentially improving fish populations in non-managed areas, and providing greater resilience against environmental disturbances or localized impacts (Roberts et al., 2017). Many potential OECMs have a diversity of governance approaches, long-standing presence, high compliance, and self-sufficiency in management practices (Estradivari et al., 2022), and contribute to improving socioeconomic conditions (Miller et al., 2020; Boli et al., 2014; Kushardanto et al., 2022) and upholding human rights (Dudley et al., 2018). These examples suggest that many potential OECMs have some means to be effectively managed despite the absence of a comprehensive effectiveness assessment. In contrast, while MPAs were five times larger on average and more numerous than potential OECMs, many MPAs are relatively new (established <10 years), and only a fraction demonstrates effective management, with 61% of MPAs not effectively managed (Meilana et al., 2023; Amkieltiela et al., 2022). This highlights the unique strengths of potential OECMs in complementing and expanding conservation efforts in Indonesia, complementing the MPA network. Yet, it is unknown to what extent the presence and intensity of human pressures could be mitigated by effective management of potential OECMs and MPAs. Further *in-situ* information is required to ascertain how human pressures play on the ground and how the managed areas mitigate these pressures.

However, we identified factors that could compromise the effectiveness of potential OECMs and MPAs in achieving conservation outcomes. First, many managed areas lacked coverage of critical coastal habitats, i.e., mangroves, seagrasses, or coral reefs, either individually or in combination. This deficiency is observed in numerous potential OECMs and MPAs (Fig. 3j). Despite the huge lack of these three coastal habitats, these managed areas may contribute to protecting other types of habitats that are not considered in this study (e.g., mudflats). Second, all managed areas faced various human pressures, directly impacting reefs through activities such as small-scale fishing and tourism and indirectly through factors like coastal population density, sediment, and nitrogen exposure. Small-scale fishing and tourism are crucial livelihoods for coastal communities, with nearly 90% of Indonesia's fishers being small-scale (Halim et al., 2019) and Indonesia boasting numerous world-class marine tourism destinations (Tranter et al., 2022). It is clear that area-based management is increasingly important in mitigating high human pressures, ensuring that communities can benefit from marine resources while protecting the marine environment.

Last, nearly one-third of managed areas were situated in turbid waters, with >50% of the area experiencing turbidity levels >8.0 FNU. While turbidity can stem from natural or human-induced causes, the high prevalence of turbid areas near population centers (Fig. 4i) suggests anthropogenic origins. Interestingly, 18% of potential OECMs and 10% of MPAs across Indonesia, with moderately to very turbid waters, harbored climate refugia for reefs (Fig. S3c). Although turbid waters may pose challenges to coral reefs through reduced light availability, increased sedimentation, decreased water quality, and altered nutrient dynamics (Fabricius, 2005; Baum et al., 2015), they can also provide certain benefits that contribute to reef resilience, depending on factors such as turbid environment characteristics, species composition, and climate stressor magnitude (Mumby et al., 2007; Roff and Mumby, 2012; Fabricius, 2011). During the 2016 global-scale coral bleaching event, for example, urbanized Singaporean turbid reefs (Bauman et al., 2022) containing climate refugia (Beyer et al., 2019) experienced low coral mortality (~12%). In contrast, severe impacts were observed on Australia's Great Barrier Reefs, where 29% of coral cover was lost (Great Barrier Reef Marine Park Authority, 2017), followed by a decline in coral cover of 51% a year later (Stuart-Smith et al., 2018), where most parts were non-turbid and non-climate refugia reefs.

Our study identified turbid reefs containing climate refugia in Indonesia, such as the Kepulauan Seribu MPA off Jakarta and the USS Houston shipwreck site in Bali. Despite their differing turbidity origins—anthropogenic river runoff from the capital city and local anthropogenic activity for Kepulauan Seribu MPA (Baum et al., 2015; Estradivari et al., 2007) and hydro-oceanographic dynamics and volcanic activities for the shipwreck site (Husrin et al., 2016)—both managed areas have reefs in moderate condition (Baum et al., 2015; Estradivari et al., 2007; Cleary et al., 2014; Hoeksema and Putra, 2000). Unfortunately, reports on mass coral bleaching events in Indonesia are very patchy, primarily due to a lack of rapid and regular assessments during and after bleaching. The grey literature suggests a moderate bleaching rate (~50%) in Kepulauan Seribu reefs during the 2016 and 2023/24 El-Nino events (Tirta et al., 2017; Tirtaningtyas, 2014) and minimal bleaching extent in reefs surrounding the USS Houston wreck during the 2009 mass coral bleaching event (Reef Check Indonesia, 2009). Despite these observations, there is a notable lack of scientific data regarding whether these bleaching events resulted in widespread coral mortality or had lasting impacts on ecological processes. Given that these two sites are major marine tourism destinations with high visitor numbers annually, the absence of reports or anecdotal evidence of severe coral bleaching impacts during global mass-bleaching events in 2010, 2016, and 2023/24 suggests that these reefs may not have suffered major detrimental impacts from bleaching. This would indicate a higher resilience to elevated sea surface temperatures, although further investigation is required. As such, recognizing existing potential OECMs located in turbid waters with refugia reefs can add value for OECMs, especially considering turbid areas that are often excluded from MPA designation.

Additionally, we identified a potential issue concerning the transition of potential OECMs to MPAs. Our analysis excluded 15 potential OECMs identified in 2019 because they became part of MPAs by 2020. Similarly, in identifying potential marine OECMs in 2019, Estradivari et al. (2022) removed 307 potential OECMs because they were within existing MPAs. Notably, recent developments indicate a potential increase in the number of OECMs transitioning into MPAs, especially with Indonesia's designation of 216 new MPAs in 2021-22 (Kementerian Kelautan dan Perikanan, 2022), nearly doubling the total number of MPAs compared to 2020 as used in our study. While such transitions can offer benefits like enhanced formal management systems, resources, and more focused conservation objectives (Estradivari et al., 2022) and may be more effective than top-down established MPAs (Ferse et al., 2010), they can also lead to challenges. For instance, original management entities like customary communities may lose their management rights and access to marine resources after their managed areas are transformed into MPAs, leading to increased social conflicts (Dasion, 2019; Zaelany and Wahyono, 2010; Berdej and Armitage, 2016). Besides this, such a transition will shift the focus from demonstrating management effectiveness from the beginning to implementing effective management over time, along with MPA implementation (Dudley, 2008).

We observed that potential OECMs faced slightly greater human pressures and often lacked critical coastal habitat coverage and had higher turbidity levels than MPAs. Additionally, potential OECMs managed by the private sector (PS) tended to be smaller in size and under higher pressure, whereas those managed by the government (GT) covered important ecological features, were larger, and generally faced less pressure. This discrepancy is somehow expected, considering potential OECMs are commonly designated based on the needs and location of the managing entity, leading to a diverse range of ecological contexts. In contrast, MPAs are usually chosen for their high conservation values (e.g., rich biodiversity, extensive marine ecosystems, unique habitats) and low threats (e.g., limited human activities or climate change impacts; Green et al., 2014; Gaines et al., 2010; White et al., 2021). As a result, MPAs are often located in remote areas (Devillers et al., 2015; O'Leary et al., 2018). In our dataset, for instance, 33% of MPAs lack nearby MPAs within a 30 km radius (Fig. 3e, S5a), thus requiring higher investment to be effectively implemented, although opportunity costs of implementing MPAs may be lower for remote areas with less human pressure (Campbell et al., 2020). From our findings, it is worth noting that well-performing OECMs with good coastal habitat coverage and lower human pressures could potentially be transformed into MPAs if desired by the managing entity. The presence and higher intensity of human pressures in potential OECM areas could potentially be mitigated by effective management; however, further *in-situ* information from different sites is required to understand how human pressures manifest on the ground. Additionally, data from each potential OECM, such as effectiveness, ecosystem state, and human pressures, are crucial for making reliable recommendations on the suitability of different types of OECMs.

Understanding the impact of human pressure on managed areas is crucial for addressing emerging threats and prioritizing conservation investments. However, the degree to which these pressures affect the ability of managed areas to deliver conservation benefits varies depending on the local context. For instance, some MPAs located in densely populated areas may have high fish biomass but limited capacity to maintain key ecosystem functions (Cinner et al., 2018, 2020). Multiple-use MPAs in areas of higher human population pressure are less effective in conserving fish biomass (Gill et al., 2024). Conversely, fishing restrictions in remote, low-population areas often result in high fish biomass (Campbell et al., 2020), surpassing the 500 kg/ha threshold crucial for ecosystem functionality and biodiversity conservation (MacNeil et al., 2015), and are essential for maintaining top predator presence (Cinner et al., 2018). Successful reef restoration efforts in heavily pressured areas like the Spermonde Islands demonstrate the importance of strategic placement and effective management strategies (Lamont et al., 2022; Williams et al., 2019). Similarly, agreements among villages in Southeast Sulawesi to provide exclusive access rights for fisheries to local fishers have stabilized coral reef conditions and improved socioeconomic conditions (Kushardanto et al., 2022; Domondon et al., 2021). These examples underscore the complex ecological trade-offs involved in the placement and management of managed areas, showing that conservation benefits can be achieved with clear management objectives and tailored strategies. Additionally, involving local management entities and respecting customary practices are vital for reducing human pressures within managed areas. This approach increases fish biomass and promotes effective biodiversity conservation (Fidler et al., 2022; Andradi-Brown et al., 2023; Ban et al., 2023). OECMs provide greater flexibility in designation and management approaches compared to MPAs, which typically follow standardized ecological and social considerations (Gaines et al., 2010) and mechanisms (MMAF Regulation No. 31/2020). This flexibility allows OECMs to be more adaptable to areas with diverse environmental and ecological contexts, offering a conservation tool complementary to traditional protected areas. These strengths could be harnessed and boosted with official, formal recognition and support of OECMs (Ferse et al., 2010).

Integrating OECMs into marine conservation efforts offers numerous advantages, but there are also associated risks. Considering potential OECMs are situated in diverse ecological and governance contexts, concerns arise regarding their efficacy in achieving conservation outcomes. A considerable proportion (12%) of potential OECMs were very small (<50 ha), particularly those managed by the private sector (Fig. 2b), which operated under temporary permits restricting their size, location, and activities. Although no formal size requirement exists for OECM acknowledgment (IUCN-WCPA Task Force on OECMs, 2019) and any form of protection and management is better than none (Lester et al., 2009), it is crucial to consider that very small managed areas may be insufficient in safeguarding biodiversity and sustaining ecosystem health (Gaines et al., 2010; Edgar et al., 2014), thus limiting their contribution to conservation outcomes. Still, as parts of networks of protected areas, they could provide essential functions in terms of connectivity (Airamé et al., 2003). In any case, evaluation of *in-situ* evidence on biodiversity conservation outcomes is needed to accurately determine whether such small-sized area-based management can be classified as OECMs.

Furthermore, potential OECMs often have narrow, specific management objectives (e.g., reef fish management, community-based ecotourism), and their primary management objectives do not typically address land-based threats such as industrial development, sedimentation, and nitrogen exposure. For example, nitrogen input from terrestrial runoff posed a predominant pressure on managed areas (Fig. 4h), yet none of the potential OECMs specifically included water quality improvement in their management objectives (Fig. 2b, Estradivari et al., 2022). Instead, many potential OECMs focus on addressing marine-based threats to biodiversity, such as fishing pressure and (marine) tourism development. Having such alignment between threats affecting biodiversity in an area and the primary management objective of an OECM is crucial to implementing more precise and effective management strategies, allowing for more efficient use of limited resources and better outcomes in those areas. Moreover, communities managing potential OECMs may lack the resources or capacity to accurately measure their contribution to biodiversity conservation. This situation may occur, perhaps even frequently, posing a challenge in ensuring that a potential OECM genuinely contributes to conservation rather than functioning as a facade for unsustainable behaviors under the guise of conservation (i.e., blue washing; Claudet et al., 2022). Addressing these concerns requires a robust framework, including clear definition and criteria, tailored to local contexts and governance approaches for identifying, acknowledging, monitoring, reporting, and supporting OECMs.

4.2. Management implications and future research

Given the complexities involved, it is worth exploring how OECMs can strategically enhance conservation alongside MPAs. If the government of Indonesia aims to adopt OECMs as a conservation tool along with MPAs, we offer three recommendations drawn from our findings.

First, having diverse and numerous potential OECMs with different sizes, locations, governance approaches, and ecological characteristics, prioritizing conservation investments is key. While an ABM must provide evidence of delivering biodiversity conservation outcomes and effective management to qualify as an OECM, there is significant ambiguity regarding the level, extent, and scale of outcomes and effectiveness that can benefit overall marine conservation in Indonesia. Our findings indicate that several key ecological parameters can supplement *in-situ* ecological data to provide deeper insights into determining which existing ABMs are likely to perform better and contribute more to marine conservation, thus prioritizing their recognition as OECMs. These key ecological parameters include the size and location of existing ABMs, availability and coverage of important marine habitats, forming an ecological network with other ABMs or MPAs, habitat resilience to disturbances including climate change impacts, the intensity of human pressures affecting these areas, and alignment between management objectives and threats to biodiversity. While these ecological parameters are similar to those for designing MPAs (see Green et al., 2014; Gaines et al., 2010; McLeod et al., 2009), the use of these parameters should be fairly flexible, considering OECMs have diverse management objectives and governance approaches. For example, a requirement of having 20–30% of coral reef habitats within an ABM may not be suitable for a decades-old customary-based ABM that manages a marine area as part of the local culture. Similarly, a large ABM size may not be appropriate for small-scale, private-based ecotourism areas. Additionally, social parameters such as community involvement in management, compliance with regulations, social conflicts, and governance aspects like management structure and systems are also critical to be taken into account when recognizing OECMs. A nuanced approach, evaluating each case and activity individually, supported by *in-situ* evidence on biodiversity outcomes and proof of effective management, is likely more suitable for prioritizing OECM recognition. Therefore, the government needs to develop a robust framework tailored to the local context to achieve this.

Second, understanding the diverse human pressures faced by managed areas, both from land-based and marine-based sources, is increasingly crucial. This entails grasping their origins, magnitude, and impacts on the marine environment, as well as existing management strategies to mitigate these pressures. This knowledge provides insights into interconnected threats, the full range of potential impacts, and the root causes of ecosystem degradation, guiding decisions on mitigation approaches. While some pressures can be directly addressed by marine OECMs, such as regulating small-scale fishing and marine tourism, others, like sediment and nitrogen exposure, may require different management measures, e.g., water pollution control on the mainland. Incorporating this understanding into the criteria for formal OECM recognition is recommended to ensure comprehensive and holistic management, ultimately benefiting the long-term conservation of marine biodiversity and ecosystem health.

Third, it is crucial to recognize that OECMs, like MPAs, cannot effectively address diverse pressures in isolation, as they typically have a single, sometimes non-conservation-related, management objective. This necessitates collaboration to tackle pressures beyond the scope of the ABM. Effective OECM recognition and MPA management improvement require coordination among government agencies overseeing terrestrial and marine areas, area managers, academics, and stakeholders to mitigate pressures and address capacity gaps (e.g., monitoring and evaluation). Exploring a hybrid approach that combines community partnership (where village-level government governs marine resources) with co-management (coordination with area authorities), as seen in some successful community-based fisheries management in Indonesia (Boli et al., 2014; Domondon et al., 2021; Dudayev et al., 2023), could offer a promising approach applicable to MPA and OECM management. Moreover, stronger collaboration between MoEF and MMAF is essential for comprehensive mangrove management and conservation. Currently, MoEF primarily manages mangroves from the habitat towards inland but focuses on terrestrial management. A more integrated approach between these ministries would enhance overall coastal ecosystem conservation.

With limited comprehensive data on the conservation benefits derived from existing ABM practices, our study provides an effective approach to overview how much and where potential OECMs may contribute to conservation. Given the scarcity of research on OECMs due to their recent introduction as a conservation tool, future investigations hold ample opportunity. We identify several essential future studies necessary for Indonesia to inform policies, develop OECM criteria and guidelines, and pilot OECM recognition. These include conducting more comprehensive identification and prioritization of existing ABM sites qualifying as OECMs, mainly since many ABMs were not included in the 2019 identification process (see Estradivari et al., 2022). Additionally, it is crucial to update the study using updated and prioritized OECM and MPA data from 2023 and overlaying them with marine and terrestrial spatial plans. Furthermore, assessing *in-situ* conservation outcomes from potential OECMs is essential to provide an overview of when and how potential OECMs contribute to conservation. These future research endeavors will significantly enhance our understanding and implementation of OECMs in Indonesia's conservation seascape.

4.3. Methods and limitations

We recognize three key limitations in our analysis. First, delineating potential OECM boundaries using 4 nm and 12 nm distances from coastlines and administrative boundaries may not accurately capture their actual size. Some managed areas could be much smaller or larger, spanning multiple villages and potentially governed by local marine tenure rather than administrative boundaries. Due to the lack of accessible maps for each potential OECM, and the complexities, or sometimes overlap, of the authorities and entities responsible for managing marine areas, determining precise boundaries posed challenges. For example, fisheries management in nearshore areas in Aceh involves two primary authorities. According to national regulation (Law No. 23/2014), the provincial government is responsible for managing marine resources up to 12 nm from the shore. However, at the local level, decisions and daily management are often made by a *Panglima Laôt* (sea commander), who is elected by fishers. The *Panglima Laôt* oversees various aspects of fisheries management within a *lhok*, i.e., a socio-ecological unit based on the fishing area for most fishers landing their catch at a major port, up to 4 nm. Their responsibilities include supervising fishing activities, resolving conflicts among fishers or communities, imposing sanctions on violators, and determining fishing schedules (Wilson and Linkie, 2012). This dual responsibility, often with overlapping management systems, with different sizes each, can be found in many parts of Indonesia. Our decision to consider only two metrics for estimation, 4 nm and 12 nm distances from shore, and administrative boundaries, was a pragmatic choice to simplify the analysis. However, for formal recognition, a comprehensive map with coordinates delineating the locations of potential OECMs, including the detailed management and governance or the area, is essential, in line with the criteria defining OECMs.

Second, we acknowledge limitations related to the spatial data used in our analysis, which often relied on models with coarse resolutions (up to 500 km^2 polygons), potentially resulting in incomplete representations of actual conditions. For instance, the coral reef data encompassed various elements, including hard corals, other biota, and sandy areas, meaning that a large coral reef area may not necessarily indicate high coral cover or richness. Similarly, the human pressure percentile data, such as coastal population and small-scale fishing, lacked granularity in distinguishing the percentage of fishers in coastal cities versus remote islands and the specific types of fishing gear employed. The use of percentiles representing the global distribution, instead of absolute values, to measure six human pressures should also be interpreted carefully. For example, when potential OECMs had an average percentile value for sedimentation of more than 0.5 (>50th percentile), this means the sedimentation pressure in that area was higher than the pressure in at least 50% of the world's coral reefs. Nevertheless, this information lacked the severity of the pressures and the impacts on coral reefs at the site level. Additionally, this study does not incorporate temporal changes in coastal habitat coverage. This decision stems from the lack of available or accessible national-level spatial data on coastal habitat trends over time, with the exception of mangroves. Although these data provide valuable estimates at regional, national, or global scales and offer general insights for policymaking, they should be supplemented with more detailed, on-the-ground biodiversity studies to designate an area as an OECM.

Last, provincial marine spatial plans (known as *Rencana Zonasi Wilayah Pesisir dan Pulau-Pulau Kecil/RZWP3K*) were not integrated into our analysis. These plans allocate marine areas for various purposes, such as conservation, fisheries, tourism, and mining. Although vital for prioritizing existing ABMs as OECMs, particularly by avoiding areas designated for non-sustainable, extractive activities like mining, ports, and reclamation, these plans are currently available in less than 50% of provincial waters, with limited public access to the spatial layers. Once these plans are completed and publicly accessible, it is crucial to use them to prioritize existing ABMs as OECMs, ensuring they are not located in areas with significant risks and impacts on the marine environment.

5. Conclusions

Our study underscores the significant yet underexplored potential of OECMs in enhancing marine biodiversity conservation in Indonesia. By applying a rapid spatial analysis, we identified the prospective ecological contributions of potential marine OECMs, highlighting their ability to complement the existing network of MPAs in Indonesia. Our findings reveal that while OECMs tend to be smaller and more numerous than MPAs, their collective impact is substantial, contributing to the coverage and connectivity of critical marine habitats, safeguarding biodiversity in diverse contexts, and recognizing effective management practices outside formal protected area frameworks. This supports the notion that integrating OECMs into national conservation policies can bridge gaps left by MPAs, especially in densely populated and high-pressure areas where traditional MPAs may fall short.

However, the study also points out the challenges and limitations inherent in the current recognition and management of potential OECMs. Many potential OECMs face significant human pressures and lack comprehensive data on *in-situ* conservation outcomes, complicating efforts to formally recognize and optimize these areas for biodiversity conservation. Addressing these challenges requires a robust, context-specific framework that includes clear criteria, continuous monitoring, and multi-stakeholder collaboration. Furthermore, recognizing the diverse governance approaches and ecological contexts of OECMs is crucial for their effective integration into national conservation strategies. Future research should focus on providing *in-situ* evidence on the conservation outcomes of OECMs, enhancing understanding of human pressures, and exploring synergies between OECMs and MPAs to achieve holistic marine biodiversity conservation in Indonesia.

CRediT authorship contribution statement

Estradivari: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Indah Kartika:** Writing – review & editing, Visualization, Formal analysis. **Dedi S. Adhuri:** Writing – review & editing. **Luky Adrianto:** Writing – review & editing. **Firdaus Agung:** Writing – review & editing. **Gabby N. Ahmadia:** Writing – review & editing. **Sonia Bejarano:** Writing – review & editing. **Stuart J. Campbell:** Writing – review & editing. **Faridz Rizal Fachri:** Writing – review & editing. **Hari Kushardanto:** Writing – review & editing. **Cliff Marlessy:** Writing – review & editing. **Beby Pane:** Writing – review & editing. **Oscar Puebla:** Writing – review & editing. **Ray Chandra Purnama:** Writing – review & editing. **I Wayan Veda Santiadji:** Writing – review & editing. **Wahid Suherfian:** Writing – review & editing, Formal analysis. **Mardha Tillah:** Writing – review & editing. **Hesti Widodo:** Writing – review & editing. **Christian Wild:** Writing – review & editing, Supervision. **Sebastian C.A. Ferse:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107411.

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