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Wastewater pollution undermines coastal marine protection: Implications for 30x30 and effective conservation

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ABSTRACT

Marine Protected Areas (MPAs) are a cornerstone of global ocean conservation strategies. However, they face multiple pressures from anthropogenic land-based pollution. Untreated and poorly treated domestic wastewater represents a widespread, under-recognized threat to tropical coastal ecosystems and adjacent coastal human populations. We present the first global assessment of total nitrogen (TN) loads from wastewater pollution within coastal MPAs associated with tropical coastal ecosystems: coral reefs, seagrass meadows, and mangrove forests. Using modelled spatial data, we quantified TN exposure across 1855 MPAs located within 50 km from the coast, and assessed both distribution and magnitude of exposure across six tropical regions associated with the three ecosystem types. The results revealed great variability in the level of exposure to wastewater pollution across the different regions. The East Africa and the Middle East & North Africa regions had the highest mean, median, maximum, and standard deviation of pollution loads. Overall, across all regions, mean TN loads were consistently higher than median values, highlighting the disproportionate levels of pollution some MPAs are exposed to compared to the rest. Additionally, pixel-level analysis revealed that in four regions, MPAs showed higher median pollution than their non-MPA counterparts, suggesting that protection status does not guarantee benefits in reduced pollution exposure. This research highlights that wastewater pollution reduction should be prioritized as part of global biodiversity objectives around effective area-based conservation, simultaneously benefiting coastal ecosystem health and resilience to climate change, and human health and wellbeing in adjacent local communities.

1. Introduction

Land-based pollution, particularly untreated or poorly treated domestic wastewater, is among the most pervasive and poorly managed threats to coastal ecosystems such as coral reefs, seagrass meadows, and mangrove forests (Andrello et al., 2022; Tuholske et al., 2021; Wear et al., 2024). Globally, it is estimated that 55% of coral reefs and 88% of seagrass ecosystems are exposed to wastewater pollution (Tuholske et al., 2021). Despite its well-known extent, wastewater pollution is often overlooked in marine conservation initiatives (Wear, 2016), resulting in these ecosystems facing an unaddressed critical challenge.

The ecological impacts of wastewater pollution on tropical coastal ecosystems are well documented. Nutrient enrichment from wastewater reduces coral reproductive processes, growth rates, and survival of early life stages, while increasing the prevalence of coral diseases and bioerosion processes (De'ath and Fabricius, 2010; Fabricius, 2005; Tebbett et al., 2025). As a result, pollution pressures have led to measurable declines in coral reef species abundance and diversity worldwide (Wenger et al., 2020; Delevaux et al., 2018; Duprey et al., 2016; Ennis et al., 2016; Tebbett et al., 2021; Cleary et al., 2016). Wastewater pollution also inhibits light penetration, limiting photosynthetic activity in seagrass meadows, while also introducing pathogens and promoting the growth of competing macroalgae and epiphytes (Cabaço et al., 2008). Mangrove forests become more vulnerable to erosion and less effective at storing carbon when exposed to wastewater pollution (Santos-Andrade et al., 2021; Naidoo, 2009). Altogether, these impacts undermine the structure, function, and long-term persistence of tropical coastal ecosystems, threatening their associated biodiversity and essential ecosystem services on which millions of people rely.

Not only does wastewater pollution have major ecological impacts on tropical coastal ecosystems, it also synergistically aggravates the impacts of climate change that they are already experiencing. Chronic

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nutrient loading heightens coral vulnerability to bleaching events and slows post-disturbance recovery (Wang et al., 2018; Joppien and Morgan, 2025; Claar et al., 2020; Gove et al., 2023; Donovan et al., 2020; Wagner et al., 2010; DeCarlo et al., 2020). Mangroves also become more likely to die under nutrient enrichment conditions when facing drought caused by climate change (Lovelock et al., 2009). Marine heatwaves aggravate eutrophication and hypoxic events caused by wastewater pollution, threatening the perseverance of the rich fish biodiversity associated with tropical coastal ecosystems (Wear et al., 2024; Brauko et al., 2020). Additionally, these ecosystems become more vulnerable to increased erosion rates and reduced light availability with increasing sea level rise, also exacerbated by wastewater pollution (Intergovernmental Panel on Climate Change (IPCC), 2022; Wear and Thurber, 2015). These widespread impacts highlight the urgent need for improved wastewater management to protect the health and promote resilience of coastal ecosystems.

Aiming to protect tropical coastal ecosystems, global efforts have focused on the development of marine protected areas (MPAs). MPAs are a cornerstone of global biodiversity conservation and a key mechanism for achieving the Kunming-Montreal Global Biodiversity Framework Target 3, commonly referred to as "30x30," which aims to protect 30% of the ocean by 2030 (Stephens, 2023). The success of MPAs is generally measured in terms of enforcement, size, longevity, no take, and location (Edgar et al., 2014). However, it has been well documented that MPA effectiveness at protecting biodiversity and delivering their expected ecological outcomes is lost when they are exposed to pollution (Lamb et al., 2016; Wenger et al., 2016; Halpern et al., 2013; Suchley and Alvarez-Filip, 2018; Bégin et al., 2016).

Despite the fact that pollution reduces the ability of MPAs to deliver biodiversity outcomes, pollution in MPAs remains largely unquantified, and where efforts have been made, it is often underestimated or insufficiently monitored to support effective management (Abessa et al., 2018; Partelow et al., 2015). Additionally, wastewater pollution exposure has not been included in global assessments that quantify human impacts on marine coastal systems and in MPAs (Halpern et al., 2025; Jones et al., 2018; Williams et al., 2021), which has been identified to be a major knowledge and research gap that hinders their effective management (Abessa et al., 2018). These gaps highlight the critical need for a systematic assessment of pollution exposure within MPAs to ensure they can deliver their intended conservation and ecological targets.

In this study, we conduct a global spatial analysis of MPA exposure to domestic wastewater pollution in tropical regions with high levels of diversity associated with coral reefs, seagrass meadows, and mangrove forest ecosystems. We aim to quantify the extent, magnitude, and variability of pollution exposure across MPAs, and to assess how MPA protection compares to surrounding non-MPA areas, thereby evaluating whether existing protection status is effectively mitigating exposure to wastewater-derived pollution.

2. Methods

This study assessed the exposure of MPAs, as established by the World Database on Protected Areas, to domestic wastewater pollution using modelled total nitrogen (TN) load as a proxy (Tuholske et al., 2021; UNEP-WCMC and IUCN, 2025). The TN load data is a ~1 km resolution raster produced by Tuholske et al. (2021) that summarizes modelled wastewater-derived nitrogen output based on country level population and settlement type data, protein consumption, accessibility to various levels of wastewater treatment facilities. The dataset provides spatial information on nitrogen loads coming from treated, septic, and open effluent into coastal areas globally. For the purpose of this study, the TN load raster layer was used, which combines all three types of wastewater effluent types. A 50 km coastal buffer was applied to both the pollution dataset and the MPA boundaries, following the approach used in Williams et al. (2021) (Williams et al., 2021), to ensure that MPAs located within or intersecting with this coastal zone were included. For MPAs extending beyond 50 km from shore, only the area within the coastal buffer was analyzed to maintain consistency with coastal influence.

The TN load dataset, measured in grams (g) per pixel, was spatially intersected with each MPA polygon worldwide within the 50 km buffer boundary using the QGIS software version 3.44 (Solothurn). The total TN load per MPA was calculated by summing all the per-pixel TN values within each MPA polygon. Using the QGIS software, the TN load per MPA was converted to kilograms (kg), and the area per MPA polygon was calculated and converted to square kilometres (km^2) for further analysis. To compare pollution exposure, the TN load was normalised by area of each MPA polygon to give a relative concentration of pollution per square kilometer (kg/km^2). Global mean, median, minimum and maximum loads were calculated across all MPAs worldwide, as well as percentile thresholds (25th, 50th, 75th, and 90th percentiles) allowing MPAs to be classified into percentile-based bins in later regional analyses.

Given the sensitivity of tropical coastal ecosystems to wastewater pollution, we focused on MPAs located in six regions where there are high levels of biodiversity associated with coral reefs, seagrass meadows, and mangrove forests (Andrello et al., 2022; Jayathilake and Costello, 2018; Giri et al., 2011; Beyer et al., 2018): Australasia and Melanesia, the Caribbean and Bahamas, the Coral Triangle, East Africa, the Indian Ocean, and the Middle East and North Africa. Within each region, mean, median, minimum and maximum TN loads (kg/km^2) were calculated and MPAs were classified into the global percentile bins to assess the distribution of TN exposure (Fig. S1).

To contextualise pollution exposure within MPAs, we compared pixel-level TN loads in MPAs to those in non-MPA areas. Non-MPA areas were defined by the same 50 km coastal buffer used for each region's MPAs, ensuring that the comparison encompassed the same coastal zones. These non-MPA areas were defined as all pixels within the buffer that did not overlap with existing MPA polygons, providing a regional baseline of wastewater exposure for areas lacking formal protection (Fig. 1).

To capture both the regional average and the variability of pollution exposure within each region, we derived the mean, median, maximum, and standard deviation of the pixel-level TN load values within MPA and non-MPA areas. Statistical significance of differences between MPA and non-MPA pollution exposure was assessed using a Mann-Whitney U (MWU) test, a non-parametric test appropriate for the highly skewed distribution and extreme outliers observed in the data. Tests were performed for each region individually and for all regions combined. Global metrics across all the regions were calculated, for both MPA and non-MPA areas, providing a summary that accounts for both within- and between-region variability in pollution exposure.

3. Results

The distribution and magnitude of wastewater-derived TN exposure across MPAs varied across the six focus regions (Fig. 2). In the Australasia & Melanesia region, most MPAs experienced relatively low exposure, with nearly 80% falling below the 50th percentile and a low median TN load of 6.8 kg/km^2 (Table 1). MPAs in the Caribbean & Bahamas and the Coral Triangle showed similar metrics, with 57% of MPAs below the 50th percentile for both regions, as well as similar mean TN loads of 161.8 and 166.9 kg/km^2, respectively. The East Africa and Middle East & North Africa regions presented similar proportions of MPAs above the 50th percentile (53% and 57% respectively), while also showing the highest mean, median, and maximum TN loads as well as the highest standard deviations, indicating that several MPAs experience extremely elevated TN pollution. Across all regions, mean TN loads were consistently higher than medians, reflecting the influence of a subset of MPAs with extremely high wastewater-derived nutrient pollution. The wide range of standard deviations further illustrate the heterogeneous nature of wastewater pollution exposure within and across regions,

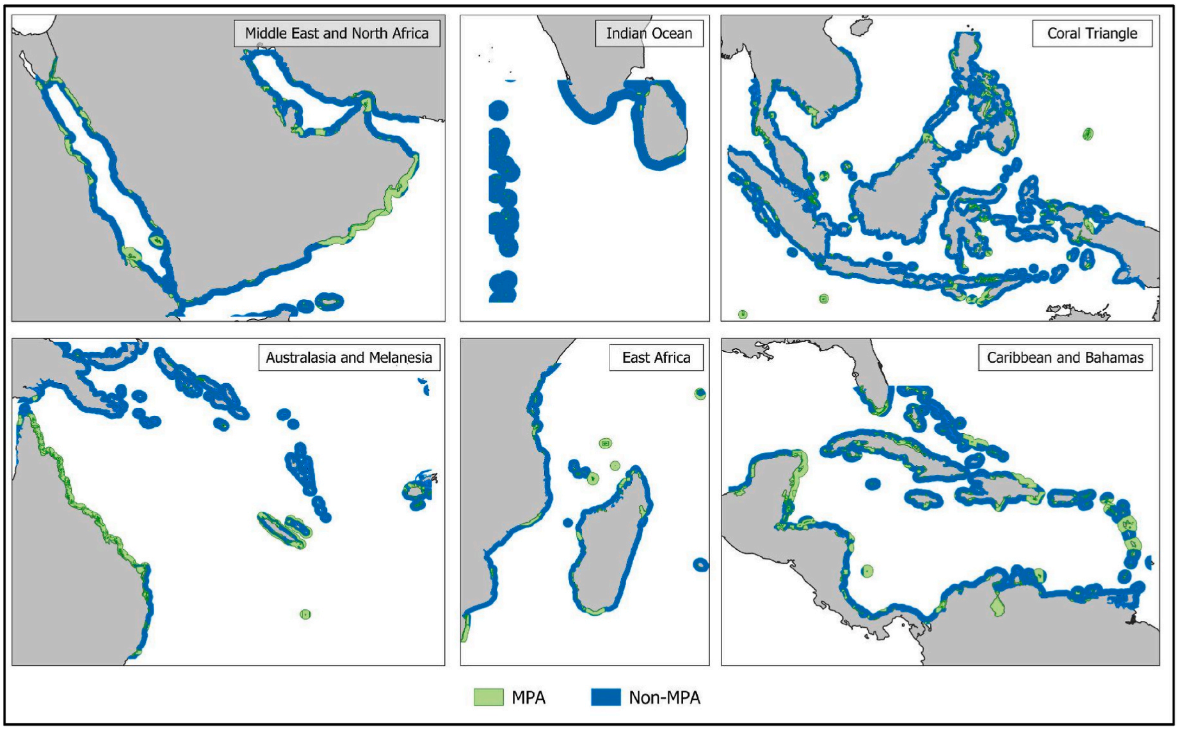

Fig. 1. Study regions, distribution of MPAs, and extent of non-MPA areas within the 50 km coastal buffer.

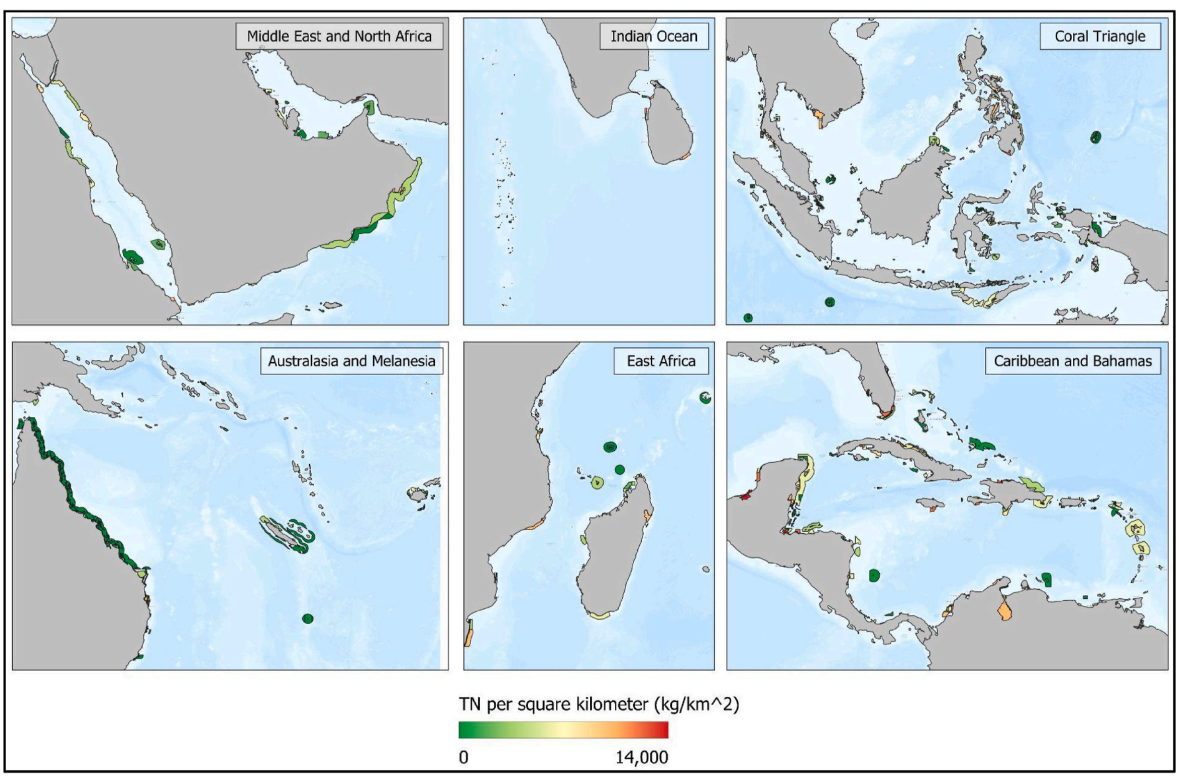

Fig. 2. Spatial distribution of wastewater pollution exposure across MPAs within 50 km from the coast in tropical coastal ecosystem regions.

emphasising the disproportionate pollution that some MPAs are experiencing.

Wastewater pollution exposure differed significantly between MPAs and non-MPA coastal areas across all six focus regions (MWU test, $p < 0.001$; Table 2). Median pixel-level pollution loads within MPAs and non-MPA areas revealed contrasting regional patterns. MPA pixels exhibited higher median exposure in four regions compared to their non-MPA counterparts: Coral Triangle (0.68 vs 0.005 kg/pixel), Indian Ocean (45.65 vs 2.6×10^{-4} kg/pixel), the Caribbean and Bahamas (0.01 vs 2.6×10^{-4} kg/pixel), and the Middle East & North Africa (0.01 vs

Table 1
Distribution of TN exposure across MPAs in six tropical coastal regions. MPAs were classified into global percentile bins based on TN load (kg) per km^2. Percentages indicate the proportion of MPAs within each percentile bin. The "Global" row represents values across all MPAs including those beyond the focus regions for additional context. Minimum TN load was not included in the table because it is zero (0) for all rows. SD = Standard Deviation.

Region	Area of all MPAs (km^2)	<25th Percentile (%)	25-50th Percentile (%)	50-75th Percentile (%)	75-90th Percentile (%)	>90th Percentile (%)	Mean TN load (kg/km^2)	Median TN load (kg/km^2)	Maximum TN load (kg/km^2)	SD
Australasia & Melanesia	347,595.3	32	47	19	3	0	30.8	6.8	744.8	81.1
Caribbean & Bahamas	277,880.6	27	30	31	10	3	161.8	16.5	6608.0	533.5
Coral Triangle	288,299.5	30	27	30	10	3	166.9	14.2	9450.0	702.2
East Africa	97,618.8	17	31	34	13	6	363.13	42.3	10,751.1	1255.2
Indian Ocean	2066.7	48	25	17	7	4	182.8	4.2	6454.6	729.5
Middle East & North Africa	122,348.4	20	24	30	17	10	706.4	65.0	14,084.6	2070.3
Global	1,135,809.3	-	-	-	-	-	934.0	30.7	247,445.9	6274.4

Table 2
Statistical comparison of pixel-level wastewater pollution exposure between MPA and non-MPA areas across the six focus regions worldwide. All differences were statistically significant. SD = standard deviation. MWU = Mann-Whitney *U* test.

Region	MPA pixels	MPA mean pixel value (kg/pixel)	MPA Median (kg/pixel)	MPA SD	Non-MPA pixels	Non-MPA mean pixel value (kg/pixel)	Non-MPA Median (kg/pixel)	Non-MPA SD	MWU p-value
Australasia & Melanesia	225,887	2.9	9.4×10^{-6}	24.4	951,313	8.8	7.6×10^{-5}	124.4	<0.001
Caribbean & Bahamas	247,546	91.3	0.01	1102.5	1,055,632	72.0	2.6×10^{-4}	1434.4	<0.001
Coral Triangle	308,438	39.0	0.68	168.9	3,063,319	59.9	0.005	605.5	<0.001
East Africa	109,811	46.2	6.8×10^{-4}	355.2	510,185	168.4	0.004	2373.1	<0.001
Indian Ocean	2441	128.6	45.65	224.4	210,483	130.0	2.6×10^{-4}	692.2	<0.001
Middle East & North Africa	145,544	25.6	0.01	194.4	568,921	161.3	0.001	3726.2	<0.001
Total	1,039,667	42.7	0.01	563.6	6,359,853	74.4	0.001	1494.1	<0.001

0.001 kg/pixel). Mean pollution loads were consistently higher than medians across all regions, with large standard deviations, indicating highly skewed distribution driven by localized pollution hotspots (Fig. 3). When all regions were combined, MPAs showed higher overall median compared to non-MPAs (0.01 vs 0.001 kg/pixel) but a lower mean (42.7 vs 74.4 kg/pixel), reflecting the influence of extreme outliers in non-protected areas and regional variation in MPA placement relative to pollution exposure.

4. Discussion

The widespread, disproportionate exposure across MPAs underscores the pressing concern that, despite their protected status, many MPAs are vulnerable to wastewater pollution, halting their ability to provide ecological outcomes. Our results underscore the urgent need for targeted domestic wastewater management and policy interventions as a necessary complement to MPA design and management.

Regional contrasts emphasize the importance of context-specific information for management decision-making, including on the state of sanitation systems, the ecological impacts of domestic wastewater

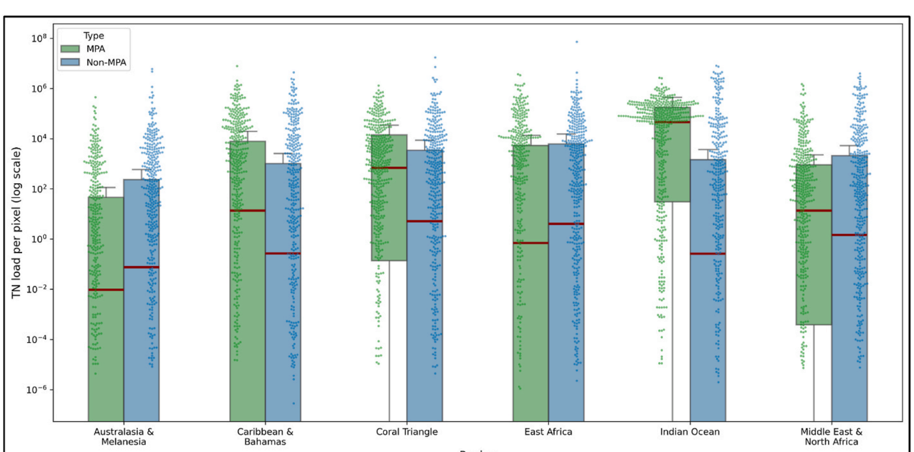

Fig. 3. Pixel-level comparison of TN pollution in MPA vs non-MPA areas for the six focus regions. The swarm plots (individual sample points) show the distribution of pixel values; box plots show median (red line), interquantile range (IQR - box), and whiskers (1.5xIQR). Data are log-scaled for visualization. Wide distributions reflect heterogeneous coastal pollution patterns with localized hotspots.

pollution, and the sanitation-enabling environment (Wenger et al., 2024). For instance, targeted infrastructure investments such as constructing and upgrading centralized wastewater treatment systems may be crucial and more appropriate in some places (Brauman et al., 2007; Gray et al., 2015), while a circular economy approach or nature-based solutions (e.g., wetland restoration), or community-based wastewater management may be more effective for other regions (Faragò et al., 2021; Smol, 2023; Vigerstol et al., 2021). In either case, aiming to increase budget and capacity building of local communities is vital for enhancing MPA effective management. Overall monitoring programs tailored to local pressures and aligned with local capacity and governance structures are essential to inform adaptive and effective management and policy.

Importantly, the regions with the highest exposure are often also the least equipped with wastewater infrastructure or monitoring capacity. This is especially urgent for tropical developing regions, where infrastructure gaps and underfunded conservation efforts leave MPAs particularly vulnerable (Wenger et al., 2024; Wakwella et al., 2023). This reflects broader environmental justice challenges where many of the most affected tropical coastal ecosystem regions are located in low- and middle-income countries, where local coastal communities depend heavily on coastal ecosystems for food security (Nasim et al., 2023; International Water Association (IWA), 2014). Addressing pollution in these contexts requires governance reform, international cooperation, and targeted investments that integrate land-based pollution management into MPA design and coastal conservation strategies. Together, these patterns underscore that effective protection of coastal ecosystems requires integrated land-based management and investment in improving sanitation systems, particularly in tropical developing regions.

Managing wastewater pollution and improving access to safely managed sanitation is not only beneficial to coastal ecosystems, but it also delivers public health benefits for adjacent local communities (Wenger et al., 2024; International Water Association (IWA), 2014). Untreated and poorly treated wastewater can carry pathogens and contaminants that pose a threat to human health such as waterborne diseases (e.g., cholera, hepatitis, etc.), especially for communities that rely on nearshore waters for fishing and domestic use (Jenkins et al., 2018, 2019). Additionally, food safety and security for local communities can become a challenge as pollutants such as heavy metals, excess nutrients, and organic contaminants that are carried in domestic wastewater can bioaccumulate in fish and shellfish populations on which communities rely for subsistence and income (Wardrop et al., 2016; Dehm et al., 2021; Madikizela and Ncube). Therefore, as the health of coastal ecosystems improves, local communities can continue to receive their respective ecosystem services such as coastal protection, fisheries productivity, and carbon storage. Altogether, tackling wastewater pollution represents a win-win in terms of both ecosystem health and human well-being.

Despite the well-established links between domestic wastewater pollution and coastal ecosystem and human health, wastewater pollution remains severely underfunded and deprioritised in global conservation agendas (Wear, 2016; Loiseau et al., 2021). Between 2010 and 2022, only 3.9% of philanthropic ocean funding targeted pollution reduction (Lewis et al., 2023). Additionally, the water sector faces an estimated USD 130 billion annual shortfall in funding for adequate wastewater infrastructure (Joseph et al., 2024). The global push to achieve 30x30 will fail to deliver on its promise unless the effectiveness of protection from pollution is prioritized alongside extent. For MPAs to safeguard biodiversity, pollution sources that undermine their ecological integrity, such as wastewater, must be addressed.

While our analysis provides a first global assessment of wastewater pollution exposure in MPAs across tropical coastal ecosystem regions, several limitations should be acknowledged. While quantifying the distribution of wastewater pollution exposure is crucial for effective management, this analysis likely underestimates the full extent of total pollution exposure as the approach does not capture other key processes such as hydrodynamics or biological uptake, which influence the transport and fate of the pollution (MacNeil et al., 2019). The analysis focuses solely on modelled TN loads, and therefore does not include the threats from other pollutants commonly present in wastewater (e.g., phosphorus, pathogens, pharmaceuticals, and heavy metals) (van Dam et al., 2011). Additionally, other mechanisms of land-based pollution are not included here, such as agricultural and urban sedimentation and nutrient runoff, which are widely recognized as increasing threats to coastal ecosystem health and resilience (Brown et al., 2017, 2019; Carlson et al., 2019), highlighting that the results are still underestimating the total cumulative exposure to land-based pollution. Finally, the analysis does not identify nor quantifies direct impacts to the coastal ecosystems within the regions, but it does provide evidence that suggests that there could be impacts, highlighting the need for future studies investigating and quantifying these impacts (Nalley et al., 2023).

To achieve the ambitions of the 30x30 target, protection must go beyond spatial coverage and ensure that MPAs deliver tangible ecological outcomes. This will not be possible unless land-based pollution is systematically assessed and respectively addressed. Therefore, a more holistic array of parameters to ensure MPA success must be established, where land-based pollution, including wastewater pollution, is integrated into metrics of MPA effectiveness (Bennett and Dearden, 2014; Green et al., 2014). This requires integrating wastewater management into coastal conservation interventions, including thorough spatially explicit tools, policy reform, and targeted financing mechanisms. Prioritising investment in sanitation, pollution monitoring, and context-specific management will not only strengthen MPA ecological outcomes but also deliver social, cultural, and public health benefits. Tackling wastewater pollution to tropical coastal ecosystems is therefore a crucial and actionable step towards more holistic and effective ocean stewardship.

CRediT authorship contribution statement

David E. Carrasco Rivera: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Amelia S. Wenger:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Data statement

The data used for this study is open-access and available in previously published research (Tuholske et al., 2021; UNEP-WCMC and IUCN, 2025).

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2026.108150.

Data availability

Open-access data was utilised, acknowledge, and respectively cited for this study.

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