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Strengthening a blue economy after habitat loss: assessing anti-trawling structures and small-scale fisheries impacts in Cambodia's Mission Blue Hope Spot

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This study introduces the potential of fisheries productivity structures (FPSs), as passive conservation infrastructure, to enhance habitat recovery and sustainable small-scale fisheries. The Cambodian coastline is devastated by illegal unregulated fishing activities and lacks reliable historical data, complicating monitoring and conservation efforts. By providing the only comprehensive benthic distribution data for the region, this study supports the placement of anti-trawling FPSs within the protected Kep Marine Fisheries Management Area (MFMA), in order to support these sustainability strategies for widespread future use. A grid survey was conducted across four survey zones at 250 m intervals covering 62,146 ha: 1) Kep MFMA, 2) Outer Kep, 3) Kampot, and 4) Koh Seh. These data are the first documentation of habitat decline in the region, showing a 39% reduction in seagrass coverage in Kampot between 2013 and 2023. Trawling destroys benthic habitats in areas deep enough for trawling vessels to operate, but in areas protected by FPSs, seagrasses were observed to persist at trawler-accessible depths. Further, observations of seagrass regrowth near FPSs indicate recovery and possible fisheries benefits. Ongoing monitoring will be necessary to document productivity trends in response to FPS implementation. Our results demonstrate that FPSs show early signs of supporting seagrass recovery and offer a scalable, low-cost conservation tool that could support blue economies, not only in Southeast Asia, but also in other coastal regions facing similar challenges.

KEYWORDS

fisheries productivity structure, FPS, anti-trawling structures, small-scale fisheries, blue economy, benthic distribution, seagrass recovery, destructive fishing

Introduction

Seagrass meadows, coral reefs, and bivalve beds are key coastal ecosystems that promote biodiversity, fisheries, coastal protection, water filtration, and carbon sequestration (Unsworth and Cullen-Unsworth, 2010; Voe et al., 2015; Adams et al., 2015). While destructive fishing remains the most immediate driver of habitat loss in Cambodia, chronic pressures such as warming seas, ocean acidification, and nutrient enrichment exacerbate the vulnerability of seagrass and coral ecosystems. For example, increased turbidity from coastal development compounds the effects of trawling by further reducing light availability to seagrass meadows (Orr et al., 2005; Carter et al., 2014; Unsworth et al., 2014; Voe et al., 2015; Fisheries Administration, 2020; Dao et al., 2021; Krause-Jensen et al., 2021; Vanyuth, 2021; Sivutha, 2022; Masanja et al., 2023; Joppien and Morgan, 2025). Unsustainable commercial bottom trawling is the most significant threat to benthic habitats in Cambodia, despite being illegal in all waters less than 20m deep (Adulyanukosol, 2002; Fisheries Administration, 2020).

Historically, fisheries in Cambodia ran on a blue economy model of small-scale, sustainable practices (Cockerell et al., 2016). Starting in the 2000s, there was a reported increase in illegal and destructive fishing in the region, including electric trawling as well as dynamite and cyanide fishing (Blomberg, 2015; Cockerell et al., 2016). The introduction of bottom trawling and purse seining allowed fishers to catch at an unsustainable rate, depleting fish and bycatch populations (Blomberg, 2015; Duffy et al., 2023). Bottom trawling also increases suspended sediments, which have been shown to decrease photosynthesis in seagrasses and corals (Ruiz and Romero, 2003; Mengual et al., 2016; Tuttle and Donahue, 2022; Corell et al., 2023). Additionally, the hazardous practice of surface-supplied diving to harvest shellfish is a central threat to bivalve populations. This commercial exploitation outcompetes small-scale community fishers while decimating benthic habitats (Voe et al., 2015). In addition to this ecological concern, habitat losses also threaten coastal livelihoods dependent on sustainable small-scale fisheries.

In recent years, community-based management efforts and bottom-up conservation initiatives from Marine Conservation Cambodia (MCC) have promoted sustainable fishing practices and the greater blue economy. MCC's work was essential in the establishment of the Kep Marine Fisheries Management Area (MFMA) in order to protect the livelihoods of local fishermen in Kep and allow only small-scale fishing, except within two no-take zones and one seasonal-take zone (Strong et al., 2023). The MFMA in Kep was established in April 2018 and has helped to regulate and monitor destructive fishing while preserving the livelihoods of local fishers in the Kep Archipelago, 80% of whom still use small-scale methods (Cockerell et al., 2016; IUCN, 2018). MFMA management depends on MCC's deployment of fisheries productivity structures (FPSs), concrete structures assembled underwater, which are designed to entangle bottom trawling nets. FPSs were deployed around small fishing villages in the Kep MFMA to reduce trawling impacts and increase catch for local fishers (IUCN, 2018). Similar anti-trawling structures in the Mediterranean have shown a positive effect on fish biomass and seagrass meadow recovery (Iannibelli and Musmarra, 2008; Serrano et al., 2011).

Despite the importance of seagrass, coral, and bivalve habitats in Cambodia's blue economy, there remains a notable lack of comprehensive and reliable data on their distribution in the region, with existing research only offering fragmented and incomplete assessments of their extent and condition (UNEP, 2004; Ouk et al., 2010; Supkong and Bourne, 2014; Reed et al., 2015; Reid et al., 2019; Strong et al., 2023). Supkong and Bourne (2014) suggested a decline in seagrass distribution between their study and Ouk et al. (2010) but did not quantify this decline. There are no prior distribution data for corals or bivalves in this region. In the absence of long-term benthic datasets, data on associated species such as epifauna, fishes, or macroalgae could serve as indirect indicators of habitat change, but such data remain sparse for Cambodia. This lack of recent, reliable, large-scale data is particularly concerning given the ongoing threats to these ecosystems (Sudo and Nakaoka, 2020). Seagrasses, corals, and bivalves are interconnected ecosystems that provide more benefits together than in isolation and need to be studied holistically (Davis et al., 2014).

This study evaluates the effectiveness of FPSs in protecting economically important seagrass, coral, and bivalve ecosystems within the Kep MFMA and their role in strengthening Cambodia's blue economy. By combining distribution data with predictive habitat modelling, this study provides the first comprehensive assessment of benthic habitats in the region. Ultimately, this research aims to inform management strategies in other regions of Southeast Asia where illegal bottom trawling is disrupting progress toward traditional blue economies.

Materials and methods

The survey area was divided into four zones—Kep MFMA, Outer Kep, Kampot, and Koh Seh—where Kep MFMA refers to the region within the MFMA, and Outer Kep refers to all of Kep with the MFMA excluded (Figure 1). The MFMA is the only survey zone with FPSs. Data collection was conducted using grid-point-intercept (GPI) surveys with points evenly distributed across the study area at 250-m intervals. At each survey point, a team member free-dived to observe the species, density, and percent coverage of seagrass, coral, and bivalves, as well as sediment type within an approximate 2-m radius. Aerial imagery was used on high-visibility days for shallow regions in which the boat could not navigate. Seagrass species and proportional coverage of each species were recorded. Note that seagrasses *Halodule pinifolia* and *Halodule uninervis* were both observed and therefore factored into diversity indices; however, they will be referred to as *Halodule* spp. in distribution analyses due to the low confidence in some observations. Seagrass percent cover was recorded on a scale of 0–4: 0 = no seagrass, 1 = less than 5%, 2 = 5%–25%, 3 = 25%–75%, and 4 = over 75%. Coral percent cover and bivalve percent cover were recorded as two categories: less than 10% or greater than 10%. Both hard and soft corals were recorded. Sediment types were categorized as coarse sand, fine sand, and mud. Depth measurements were

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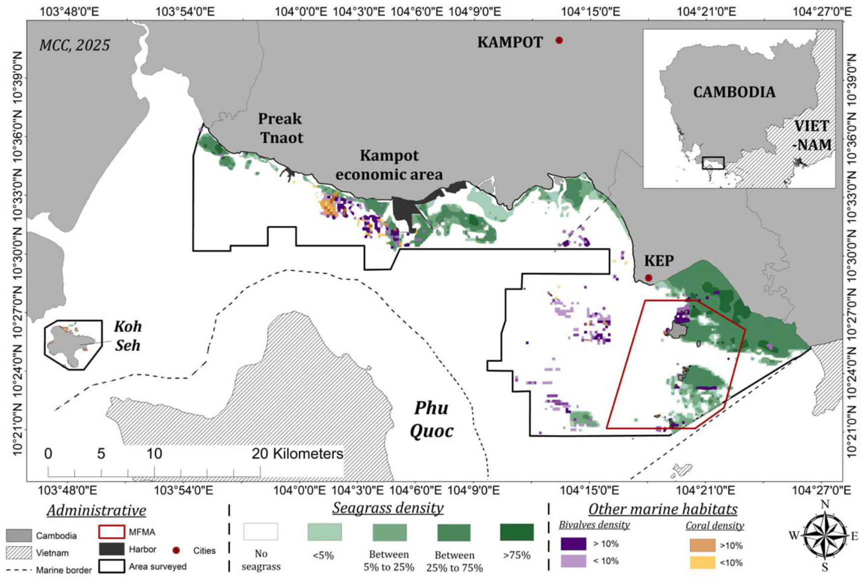

FIGURE 1
A map of seagrasses, corals, and bivalves observed in Koh Seh, Kampot, Outer Kep, and Kep MFMA (left to right). The short dashed line within the survey area separates the Kampot and Kep survey zones.

obtained using the onboard depth sounder. Surveys were conducted in the dry seasons (January to March) of 2022 and 2023. Coverage data were chosen to maximize survey efficiency across the very large study area, allowing broad distribution mapping within logistical and budgetary limits. Dry season surveys were selected because higher visibility and calmer sea conditions ensured safety and data reliability. Physico-chemical parameters and quadrat sampling were not feasible given budgetary and logistical constraints; however, future surveys should incorporate these data to refine habitat condition assessments. Due to resource constraints and the large survey extent, the study prioritized distributional data rather than condition indicators such as bleaching or epiphyte load. Future monitoring should incorporate health metrics to complement baseline maps.

Data from GPI surveys and aerial imagery were entered into ArcGIS to produce maps (ESRI, 2024). Microsoft Excel and the R software with RStudio integrated development environment were used for data analysis (Posit team, 2024; R Core Team, 2024). Using the GPI survey data, Generalized Additive Models (GAMs) were produced using the "mgcv" package to assess the relationship of depth and substrate type with seagrass, bivalve, and coral presence (Guisan et al., 2002; Wood, 2011; Bučas et al., 2013; Detenbeck and Rego, 2015; Kantún-Manzano et al., 2018; Liu et al., 2023). Habitat presence was entered as the response variable with depth, substrate, and their interaction as the explanatory variables. The interaction was selected using the Akaike information criterion (AIC). Spatial coordinates were incorporated into the model to control for spatial autocorrelation and any unmeasured effects that depend on location using a thin plate regression spline with a smoothing parameter that was optimized using GAM diagnostics (Guisan et al., 2002). A binomial family was used with a complementary log–log link to model presence and absence, where presence is less common than absence, and was compared to the logit link function using AIC (Yee and Dirnböck, 2009). Model validation included the examination of residual patterns, Moran's I test for spatial autocorrelation, and cross validation to assess predictive performance; overfitting was assessed by examining model summary and cross-validation results, and multicollinearity was assessed using variance inflation factor (VIF) (Gelman and Hill, 2007; Hamylton and Barnes, 2018; Shrestha, 2020; Yates et al., 2022). Diversity was measured using the Shannon–Wiener Diversity Index and alpha diversity.

Results

Benthic habitat distributions

Across the 62,146 ha surveyed, this study found 15,320 ha of combined seagrass meadows, bivalve beds, and corals along the coastline of southeastern Cambodia (Figure 1). Specifically, this study identified 11,569 ha of seagrass, 2,688 ha of bivalves, and 1,063 ha of coral throughout the four survey zones. Kampot had the highest overall habitat cover and percent coverage per area surveyed (Table 1). Koh Seh exhibited the least overall habitat presence. Bivalve presence was the highest in Kampot with 1,238 ha (5.09% coverage), followed by 1,153 ha (4.55% coverage) in Outer Kep, 297ha (2.66% coverage) within Kep MFMA, and 0ha in Koh Seh. Coral had the lowest observed coverage overall and was the most abundant in Kampot, covering 861ha (3.54% coverage), followed by 59ha in Koh Seh (4.46% coverage), 68ha within the Kep MFMA (0.61% coverage), and 75ha in Outer Kep (0.29% coverage). The greatest seagrass extent was observed at 5,158 ha in Kampot

TABLE 1 Total seagrass, bivalve, and coral coverage in each survey zone.

Survey zone	Survey area (ha)	Seagrass coverage (ha)	Bivalve coverage (ha)	Coral coverage (ha)	Total habitat coverage
Kep MFMA	11,168	2,757 (24.69%)	297 (2.66%)	68 (0.61%)	3,122 (27.95%)
Outer Kep	25,333	3,642 (14.38%)	1,153 (4.55%)	75 (0.29%)	4,870 (19.22%)
Kampot	24,321	5,158 (21.32%)	1,238 (5.09%)	861 (3.54%)	7,257 (29.84%)
Koh Seh	1,324	12 (0.91%)	0 (0.0%)	59 (4.46%)	71 (5.36%)
Totals	62,146	11,569	2,688	1,063	15,320

MFMA, Marine Fisheries Management Area.

(21.32% coverage), followed by 3,642 ha (14.38% coverage) in Outer Kep, 2,757 ha (24.69% coverage) within the Kep MFMA, and 12ha around Koh Seh (0.91% coverage) (Table 1).

Seagrass diversity analysis

There was remarkably high seagrass diversity, with 10 species recorded during the surveys and up to six species observed in one free-dive (Table 2). The greatest species richness was found in Kampot with 10 species, but the greatest Shannon–Weiner Diversity was observed within the Kep MFMA ($H' = 1.60$), followed closely by Kampot ($H' = 1.55$) and then Outer Kep ($H' = 1.25$). Koh Seh had only one species present, *Thalassia hemprichii* ($H' = 0$, $\alpha = 1$). Kampot, Outer Kep, and Kep MFMA had high alpha diversities of $\alpha = 10$, $\alpha = 9$, and $\alpha = 9$, respectively.

Seagrass, corals, and bivalves were recorded at mean depths of 2.7, 3.9, and 3.7m, respectively, and at maximum depths of 6.9, 6.5, and 11.0m, respectively. The average depth of the entire survey area was 4.4m. Sediment analysis revealed that benthic habitats were primarily found in areas with coarse and fine sand, with less habitat cover observed in muddy substrates (Figure 2).

The GAMs revealed significant influences on habitat presence (Figure 2). The GAMs explained 86.9%, 60.4%, and 56.7% of the deviance for seagrass, bivalve, and coral presence, respectively. Muddy substrate has a negative effect on seagrass presence compared to both coarse substrate ($p = 0.006$) and fine substrate ($p = 0.008$). Substrate type had no other significant effects on habitat presence ($p > 0.05$). The interaction between the effects of mud and depth on seagrass presence was marginally significant ($p = 0.049$), indicating that the negative effect of mud varied with depth. Depth had a negative relationship with seagrass, bivalves, and coral ($p = 1.08e{-}10$, $p = 0.0004$, and $p = 0.02$, respectively). The spatial smooth term was significant for all habitat type models, indicating that all habitat distributions were influenced by spatial factors.

Residual plots showed most of the binned residuals sitting within the 95% confidence interval with no clear pattern. This indicates that there is a good model fit with no bias and little heteroscedasticity. A histogram of the residuals shows a high kurtosis, which is expected for binary data since the residuals are constrained to a limited range. This indicates that most predictions are close to the observed values, with some spread in the tails likely linked to spatial outliers. The residuals of the GAMs did not exhibit spatial autocorrelation (Moran's I statistic = −0.0002, $p = 0.5$); however, by splitting the entire region into sufficiently small areas, some of those areas generated a Moran's I $p < 0.05$, indicating that some smaller-scale spatial autocorrelation remains. Multicollinearity was assessed using VIF, of which each variable had a value < 3, indicating some moderate correlation but no problem of collinearity.

TABLE 2 Seagrass species and proportional coverage of each species across the four survey zones.

Species	Kep MFMA (%)	Outer Kep (%)	Kampot (%)	Koh Seh (%)
Thalassia hemprichii	50.38	59.20	45.05	100
Enhalus acoroides	21.67	38.99	34.70	0
Halophila ovalis	12.85	1.02	10.85	0
Halophila decipiens	7.67	0.11	0.43	0
Halophila minor	0	0	0.22	0
Cymodocea rotundata	0	0.04	1.26	0
Oceana serrulata	1.18	0	3.62	0
Halodule spp.	6.04	0.58	3.06	0
Syringodium isoetifolium	0.21	0.05	0.81	0

MFMA, Marine Fisheries Management Area.

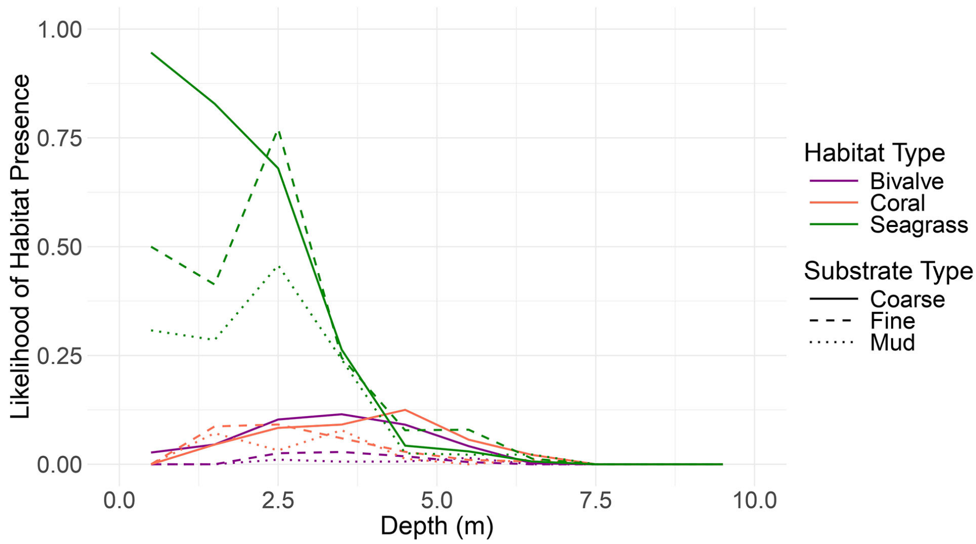

FIGURE 2
The probability of presence of each habitat type plotted against depth for each substrate type.

Discussion

Our findings show a 39% decline in seagrass in the period from 2013 to 2023 (Supkong and Bourne, 2014), highlighting the urgent need for scalable restoration and enforcement strategies within Cambodia's changing blue economy.

Anthropogenic drivers, particularly destructive trawling practices, remain the dominant factor shaping benthic habitat distribution in the Kep Archipelago. Coastal development, sediment runoff, and nutrient enrichment also exacerbate pressures on seagrass and corals. While natural variables such as depth and substrate influence distributions, our results indicate that human activities ultimately set the limits for habitat persistence and recovery in the region.

Effect of FPSs

The pioneer species *Halophila* spp. were observed in abundance in close proximity to FPSs, indicating regrowth in areas now protected from trawlers.

Documenting the success of FPSs in Cambodia is important so that other countries with high levels of subsistence fishing may also benefit. FPSs have been positively received by small-scale fishermen and villages in Cambodia; however, these conservation measures have been underutilized as a way to combat illegal, unregulated, and unreported (IUU) trawlers in other parts of the world. FPSs present an opportunity for blue economies with limited resources for Marine Protected Area (MPA) enforcement. Cambodia will serve as a case study of the benefits that these passive marine protections can bring to the livelihoods of fishermen who have struggled with the ecological impacts of rampant IUU activities and suggests that habitat protections provided by FPSs can form the basis of a regionally scalable solution to illegal fishing within the blue economy framework.

Effect of depth

Depth is a key driver with a strong negative effect on benthic habitats, which can most likely be explained by reduced light availability from the region's high turbidity and increased trawler accessibility, as local trawlers can only operate in deeper waters. Outside of areas protected by FPSs, seagrass was only found in shallow nearshore areas. For instance, the regions of the Kampot and Outer Kep survey zones exhibited their highest seagrass concentrations in shallow waters naturally restricted to trawling vessels (Figures 1, 2), while Kep MFMA exhibited seagrass meadows at greater depths, suggesting that protections offered by the MFMA allow for benthic habitat recovery beyond the shallow zone. In our study, seagrass meadows were generally concentrated in shallow areas less accessible to trawling gear. The shallow depth profile is expected for *T. hemprichii* and *Enhalus acoroides*; however, this was particularly surprising for *Halophila* spp. and *Halodule* spp., which have been commonly recorded at 20m or deeper in other Southeast Asian countries (Green and Short, 2003; Duarte, 1991). In this study, *Halophila* spp. were recorded with maximum depths reaching 6.90 m in the Kep MFMA and 3.87 m on average. *Halodule* spp. were observed at depths of up to 4.00m, averaging 2.51m. These patterns are most likely due to persistent bottom trawling at greater depths. The comparatively low habitat presence in Koh Seh likely reflects both deeper bathymetry and greater trawling accessibility. In contrast, Kampot benefits from extensive shallow areas that restrict trawling vessels, supporting higher seagrass and coral cover.

Our observations suggest that bottom trawling activity is a strong determinant of benthic habitat presence in the region, as seagrass was primarily located in areas too shallow for trawling to occur, except in the MFMA, where FPSs reduce trawling activity. These findings underscore the importance of integrating FPSs into marine spatial planning efforts, aligning with blue economy goals of sustainable resource management. The average depths of seagrass in Kampot, Outer Kep, and Kep MFMA were 2.02, 2.56, and 3.41m, respectively, indicating that seagrass can grow in deeper areas with FPS protections. This is in agreement with a report by the Cambodian Department of Fisheries, which found that overfishing and destructive fishing are among the highest risks to benthic habitats in the region (Sitha, 2005; Fisheries Administration, 2020). However, future studies should quantify trawling activity in the region in order to further support this claim.

Effect of substrate

Mud had a significantly negative relationship with seagrass presence compared to fine and coarse sediment, which may be explained by higher turbidity interfering with light availability (Zabarte-Maeztu et al., 2021). Substrate type had no significant effect ($p > 0.05$) on coral or bivalve presence, despite the differences seen in Figure 2. The spatial smooth term revealed significant localized variability, which would be indicative of unmeasured effects such as trawler activity, water quality, or other unobserved processes.

Seagrass diversity

The Indo-Pacific contains the greatest seagrass species diversity on the planet, with up to 14 distinct species inhabiting a single reef flat (Short et al., 2007). This study found 10 species across the four survey zones, with prior studies finding 10–11 species in the same region, constituting one of the highest species richness globally (Table 2) (Leng et al., 2014; Ouk et al., 2010; Supkong and Bourne, 2014; Coles et al., 2011). The Kep MFMA had the highest Shannon–Weiner Diversity, suggesting that the additional fishing protections, FPSs, and patrolling occurring in the MFMA are aiding conservation. Despite the high species richness, only two species dominate across the region—*E. acoroides* and *T. hemprichii*—both of which have been found to have increased tolerance for high sedimentation rates (Terrados et al., 1998).

Conclusion

Limitations and assumptions

Due to budget constraints, this study largely relied on a free-diving systematic GPI survey, which assumes that each point is representative of a 250-m^2 area. Despite the lower resolution, this study's large sample size achieved wide-scale data, thus still providing an adequate estimate of benthic habitat presence. Additionally, the authors recognize that a change in the benthic composition may have occurred during the pause in surveying over the rainy season, as well as throughout the active surveying periods, due to ongoing bottom trawling. Nevertheless, this study provides the most recent data for the region.

Future research

To improve scalability, future surveys could combine GPI with remote sensing, drones, or acoustic methods to efficiently cover larger areas while retaining ground-truthing detail. Conserving essential fish habitat is a critical step to protect and prolong sustainable blue economies. Future studies should assess changes in the region's fish biomass to better examine the socioeconomic impacts of FPSs (Floyd et al., 2024). Long-term monitoring is also essential to track changes in habitat coverage over time, especially in response to the deployment of FPSs and the designation of MFMAs.

Broader ecological, economic, and policy implications

While this study offers a valuable baseline for future conservation efforts, it also underscores the urgency of addressing illegal fishing practices to preserve the remaining benthic habitats in Cambodia's coastal waters. Beyond biodiversity and fisheries values, seagrasses are globally significant blue carbon sinks, with potential to mitigate CO_2 emissions and contribute to national climate goals (Fourqurean et al., 2012). Their combined role in carbon storage, biodiversity support, and food security means that their decline has broader implications for socioeconomic stability in coastal communities. Protecting and restoring these ecosystems could help Cambodia, and potentially many more countries, to meet their carbon-neutral goals while supporting local fisheries and coastal protection (UNFCCC, 2021). These insights are particularly relevant for other Southeast Asian nations facing similar marine governance challenges, offering a model for inclusive and low-cost blue economy interventions (Strain et al., 2018). In practical terms, the most effective management strategies emerging from this work are i) continued deployment of FPSs to passively deter illegal trawling, ii) strengthening of MFMA enforcement and patrols, and iii) integration of community-led monitoring into management. Together, these strategies offer a replicable framework for coastal nations with limited enforcement capacity.

In Southeast Asia, there is both an outsized need for the ecosystem services that benthic habitats provide and a marked absence of data (Kirkman and Kirkman, 2002; Boon et al., 2014; Voe et al., 2015). This study provides the first comprehensive assessment of benthic habitats in southeastern Cambodia, offering necessary data for future conservation efforts. The results indicate that illegal trawling remains the primary threat to seagrass meadows, corals, and bivalve beds in the region. This not only impairs biodiversity but also jeopardizes the long-term viability of Cambodia's blue economy, where sustainable fisheries, tourism, and coastal livelihoods are dependent on healthy marine ecosystems. Fortunately, the continued patrolling, advocacy for protected area delineation, and deployment of FPSs by MCC will allow the region to begin to recover. The local communities in Cambodia, whose subsistence fishing is directly threatened by illegal bottom trawling, have supported MCC with their grassroots endeavors, backing MPAs and assisting in FPS construction (Hamilton, 2012; Cockerell et al., 2016). This shows promise for the uptake of FPSs by coastal communities around Southeast Asia. Governments around the globe should continue to designate, and soon enforce, MPAs and anti-trawling policies, to ensure not only longevity of the ecosystem but also food security and ecosystem services for the people of coastal Cambodia (Unsworth and Cullen-Unsworth, 2010; Boon et al., 2014). These findings demonstrate that bottom-up marine conservation strategies like FPSs can support biodiversity and fisheries simultaneously, offering a practical pathway toward strengthening a blue economy in Cambodia and beyond.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AH: Visualization, Investigation, Data curation, Conceptualization, Writing – original draft, Validation, Funding acquisition, Writing – review & editing. MM: Data curation, Validation, Methodology, Conceptualization, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. SR: Investigation, Visualization, Funding acquisition, Conceptualization, Writing – review & editing, Project administration, Supervision, Data curation, Methodology. SL: Writing – review & editing. TF: Investigation, Supervision, Funding acquisition, Conceptualization, Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1656017/full#supplementary-material

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