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RESEARCH ARTICLE

Assessing impact risk to tropical marine ecosystems from human activities with a Southeast Asian example

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Abstract

1. Society relies on intact marine ecosystems for ecosystem services such as nutrition, livelihoods, health and well-being. Yet, to obtain these benefits, we carry out activities, introducing pressures to ecosystems, damaging and degrading habitats and reducing their capacity to optimally provide ecosystem services. Biodiversity and ecosystem services are consequently being lost globally but impact chains from these activities are poorly understood, especially in tropical marine ecosystems.
2. We identified for the first time impact chains linking activities with pressures they introduce in five tropical coastal and marine habitats, specifically through application in four Southeast Asian case study sites. Using expert elicitation based on existing evidence, we weighted each impact chain according to pressure extent, frequency and persistence, and habitat resistance and resilience. Assigning each impact chain an impact risk score allowed identification of activities and pressures introducing most risk, and habitats most under threat.
3. Of 26 activities we considered, we found fishing activities, specifically trawling, gill nets and seine nets introduce most risk, along with tourism and recreation. Litter and pollution were among the greatest pressures on habitats, with coral reefs being most vulnerable overall. Destructive fishing practices were associated with physical pressures like abrasion, smothering and siltation and total habitat loss, while tourism activities were associated with organic enrichment, litter and pollution. The risk levels depended on the habitat and on local case study context.

For affiliations refer to page 2909.

4. *Synthesis and applications*: A contextualised risk-based approach can help to prioritise sustainability issues for management in data-poor regions by making use of a range of knowledge types from local experts to broader scientific knowledge. A multisectoral, and ecosystem-based risk assessment can help decision makers to consider trade-offs in marine resource management and highlight priorities transparently, where coordination of multiple administrative organisations, sectors and local actors is required to meet multiple sustainability objectives. Physical pressures from fishing activities combined with pollution from tourism indicate effective management requires a multi-use zoning approach that not only considers impacts at the site of activities but also integrates regional coordination to tackle dispersive pressures from pollution or sediment disturbance that occur at a distance from the source.

KEYWORDS
coral reefs, ecosystem-based management, mangroves, marine litter, marine-protected areas, overfishing, seagrass, sustainable resource use

1 | INTRODUCTION

Marine ecosystems provide many services essential to or that enhance people's lives, livelihoods and well-being, for example, seafood, raw materials, waste bioremediation and recreation (Hattam et al., 2021). To obtain ecosystem service benefits, people carry out activities that introduce pressures into ecosystems; which cause ecosystem state changes and modify service supply (Culhane et al., 2019). Cumulative impacts of local activities, has led to global scale environmental crises (O'Higgins et al., 2020), with increasing threats to marine ecosystems from multiple sources (O'Hara et al., 2021). Impacts on marine ecosystems have potentially stark consequences for human well-being, since essential ecosystem services are compromised (O'Higgins et al., 2020). This is relevant worldwide, but particularly true in global south, low-income coastal communities whose livelihoods and well-being are closely linked to the sea and to tropical marine ecosystems (OECD, 2020). Achieving sustainable ecosystem service use is a delicate balance between protecting ecosystems and carrying out activities essential to people's lives and livelihoods.

Traditionally, ecosystem management has been oversimplified, focusing on single sectors, ecosystem services or species, leading to poor management (Defries & Nagendra, 2017). For example, coral reef management often focuses on excluding activities causing direct physical damage (Hargreaves-Allen et al., 2017) but chronic, non-point source pollution can inhibit reef recovery (Ortiz et al., 2018), making management less effective than expected (Jameson et al., 2002). In dynamic and interconnected marine systems, the inherent complexity of multiple ecosystem services, the multiple ways they are used, and diverging stakeholder interests, create 'wicked' problems for which solutions do not readily exist to support management efforts (Defries & Nagendra, 2017). A classic wicked problem is non-point pollution source management, because there can be multiple pollution sources and a lag in improvement after implementing management measures. Wicked problems require a holistic, ecosystem-based and adaptive approach to management that allows consideration of trade-offs and multiple sectors, but complex management can also lead to indecision (Defries & Nagendra, 2017). Indecision is further exacerbated by a scarcity of relevant data, which is particularly a problem in marine environments, and in low-income countries. Thus, tools to help decision makers organise and consider complexity when making decisions, even in data-poor situations, are needed (Robinson & Culhane, 2020).

Linkage frameworks, building on the Drivers, Pressures, State, Impact, Response (DPSIR) concept (EEA, 1999), have been used to systematically organise available knowledge (including expert judgement) to consider multiple sectors and pressures, ecosystem services and stakeholders in social-ecological systems, thereby retaining system complexity and overcoming data limitations (Robinson & Culhane, 2020). Within these frameworks, a risk assessment approach can be used to consider relationships between human activities, pressures they introduce and ecosystem components they impact in a semi-quantitative way (Borgwardt et al., 2019; Knights et al., 2015). Risk assessments rely on understanding and using appropriate criteria to capture ecosystem exposure to activities and pressures, and ecosystem sensitivity to interactions (e.g. Tyler-Walters et al., 2018). This can facilitate activity, pressure and ecosystem component prioritisation based on risk (Borgwardt et al., 2019, Knights et al., 2015), revealing emergent properties of complex social-ecological systems, while retaining whole system perspective (Robinson & Culhane, 2020). Such risk assessment frameworks, developed for European contexts, have not (as far as we are aware) been applied to tropical marine ecosystems use by low-income coastal communities.

Seas around Southeast Asia form part of the Coral Triangle, a globally significant region for its high marine biodiversity (Sanciangco et al., 2013), which has high risk of exposure to pressures (O'Hara et al., 2021). For example, a recent global review identified this region as having the highest decline in mangrove coverage (Bhowmik et al., 2022). In this region, local coastal communities rely heavily on the sea for their well-being and livelihoods through activities such as fisheries, aquaculture and tourism (Lim et al., 2021; Ngoc, 2018; Praptiwi et al., 2021; Sumeldan et al., 2021). These activities introduce pressures to marine ecosystems, which are exacerbated by climate change (Bhowmik et al., 2022). In this region, managers lack data but urgently require evidence on which to base decisions (Hattam et al., 2021). This study aims to identify activities and pressures introducing most risk to marine habitats and the biodiversity they support across Southeast Asia and determine those most at risk. We considered four Southeast Asian case studies (Section 2.1) and used an iterative consultation process with local and non-local experts to build the underlying dataset. We structured this information systematically into activity–pressure–habitat impact chains that are weighted according to risk (Sections 2.2 and 2.3). Our results are designed to show how analysis of this data can provide insights to prioritise management in terms of risk—to habitats (Section 3.1), from activities (Section 3.2) and from pressures (Section 3.3). We interpret these results in terms of identifying trade-offs, conservation priorities and the main sustainability challenges (Section 4). This type of tool is crucial for sustainable management in a complex system, where multiple objectives need to be met, such as the UN Sustainable Development Goals on life below water, zero hunger and no poverty. This approach has the potential to be widely applied across regions and habitats. It is especially useful for data-poor areas where management decisions need to be, and are being made without a formal way to organise a broad range of information and consider the trade-offs.

2 | MATERIALS AND METHODS

2.1 | Case study sites

We studied four marine reserves and protected areas across four countries in Southeast Asia (Figure 1; Table 1). Each case study site includes the habitats coral reefs, mangroves and seagrass. While each has unique socio-economic contexts, all sites have strong links between people's livelihoods and well-being and marine ecosystems. Various activities such as fishing, aquaculture, tourism and recreation are important to local livelihoods and unsustainable practices are a threat to habitats (Ngoc, 2018; Praptiwi et al., 2021; Primavera & Esteban, 2008; Sumeldan et al., 2021; Wulandari et al., 2022; WWF-Malaysia, 2017). All sites have designated areas where almost all activities are prohibited, with other zones where activities can occur. Highly destructive fishing techniques, such as blast and poison fishing, are illegal at all sites but still carried out. All sites encompass several administrative boundaries, meaning management decisions related to the reserves/park are made by multiple actors and at multiple levels, requiring cooperation to meet objectives (Fortnam et al., 2022).

2.2 | Linkage framework

For this approach, we firstly built a linkage framework (sensu Robinson & Culhane, 2020), including the system elements. We included activities, pressures and habitats, and the links between them.

We included five broad habitat types crucial to supplying ecosystem services: coral reefs, mangroves, pelagic (open water), seagrass

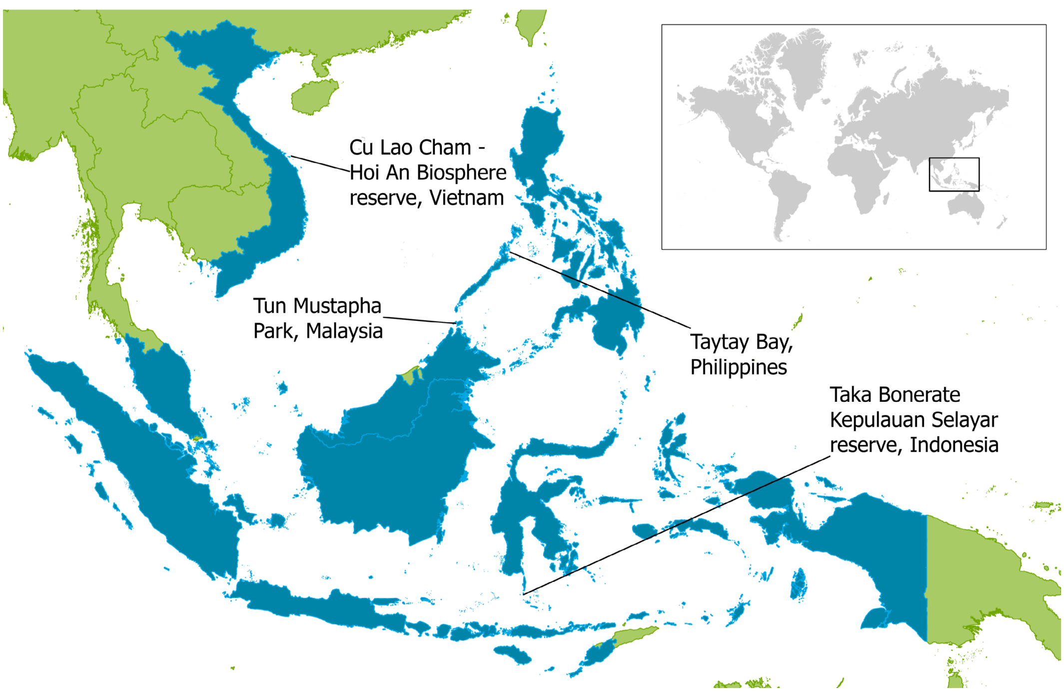

FIGURE 1 Case study site location. Data source GADM v4.1.

TABLE 1 Description of case study sites.

Case study	Location	Catchment population size	Area (km^2)
Cu Lao Cham (CLC)—Hoi An Biosphere Reserve	East Vietnam Sea, Vietnam	95,227 (Vietnam Statistical Yearbook, 2018)	337.37
Tun Mustapha Marine Park (TMP)	Sabah, Malaysia	>85,000 (WWF-Malaysia, 2017)	8987.6
Taytay Bay (TTB), part of Palawan UNESCO UNESCO Man and Biosphere (MAB)Reserve	Sulu Sea, Philippines	39,942 (Philippine-Statistics-Authority, 2021)	1920.0
Taka Bonerate Kepulauan Selayar (TBKS) UNESCO MAB Reserve	South Sulawesi, Indonesia	135,624 (Statistics Bureau of Selayar Regency, 2020)	10,503.69

and sediment (which includes intertidal and subtidal mud, sand, coarse and rocky habitats). The habitat divisions are coarse, our first iterations included greater granularity in habitats, but data scarcity meant we could not consistently consider this more detailed level across such a large regional scale. Habitat presence in the case studies was previously verified by Hattam et al. (2021).

Here, activities refer to those activities people carry out, which interact with marine habitats and directly introduce pressures into marine ecosystems, where pressures are the mechanism through which activities affect ecosystems (Knights et al., 2013). Through previous and ongoing studies, contact with local stakeholders, and personal observations during site visits, case study experts identified all human activities associated with aquaculture, fishing, tourism and land-based/other occurring in case study sites (Table S2). We identified 11 pressures that can interact with the benthic and pelagic habitats (Table S3; Figure 2).

We identified links between linkage framework elements systematically, firstly identifying links between activities and pressures, then between activity–pressure combinations and habitats in the case study sites. We call the activity–pressure–habitat combination an impact chain (sensu Knights et al., 2013). Impact chains were identified by local expert teams using their expert judgement, supported by literature evidence where available. Local expert teams consisted primarily of researchers on marine resource management working in the case study sites and biosphere reserve or national park managers. Teams consisted of 3, 4, 5 and 7 individuals from Vietnam, Indonesia, the Philippines and Malaysia, respectively. Each team was provided with written guidance, a matrix template to complete and was taken through the process during an online meeting. Support was provided throughout (online and email) to clarify ambiguities. The starting point of the matrices was the typologies of activities, pressures and habitats. In the first round, each activity–pressure interaction potential was considered in turn, available evidence was discussed and expert elicitation was used to come to an agreement within the case study team and then across case studies as a group. In the second round, the process was repeated, this time discussing the potential for the identified activity–pressure interactions to overlap with each habitat. An indication of confidence was given for each link (Table S4). The matrices developed were shared between teams and reviewed for consistency in the approach taken; any inconsistencies were discussed with the full group to reach consensus. The specific methods and sources (e.g. whether information was derived from previously carried out stakeholder surveys, ad hoc stakeholder consultation or literature) used varied by case study, but this approach allowed collection of knowledge from these diverse sources in a systematic framework and allowed for local specificities as well as generalities. Where ad hoc stakeholder consultations were carried out, informal consent was chosen over written consent to facilitate a more open and flexible dialogue, allowing stakeholders to freely express their views and concerns without the constraints of formal documentation. This approach was deemed appropriate given the exploratory nature of the consultation and the need to quickly gather diverse perspectives in a dynamic environment.

2.3 | Risk assessment

Here, we define impact risk as the likelihood of an ecological impact following interaction with an activity–pressure (Sharp et al., 2014). We take a standard environmental risk assessment approach that considers impact risk to consist of exposure to, and consequences of activity–pressures, or habitat sensitivity to the activity–pressures (e.g. Arkema et al., 2014; Borgwardt et al., 2019; Knights et al., 2015). Each impact chain in the linkage framework was weighted according to five scored criteria that capture either the exposure or sensitivity (Table 2). Each category is assigned a score between 0 and 1, where higher scores indicate greater risk to habitats, with scores adapted from Knights et al. (2015) and Borgwardt et al. (2019).

Exposure criteria were the activity–pressure extent, frequency and persistence. These capture the spatial and temporal exposure of habitats and the mean score of these criteria was used as the overall exposure (Equation 1). Sensitivity criteria were the habitat resistance and resilience to activity–pressure, capturing the likely severity of habitat damage, including taking into account the intensity or magnitude of the activity–pressure, and potential recovery. The mean of these criteria was taken as the overall sensitivity (Equation 2). The same local expert teams as above weighted the extent and frequency criteria, which are specific to the case study sites. Again, each team was provided with written guidance, a matrix

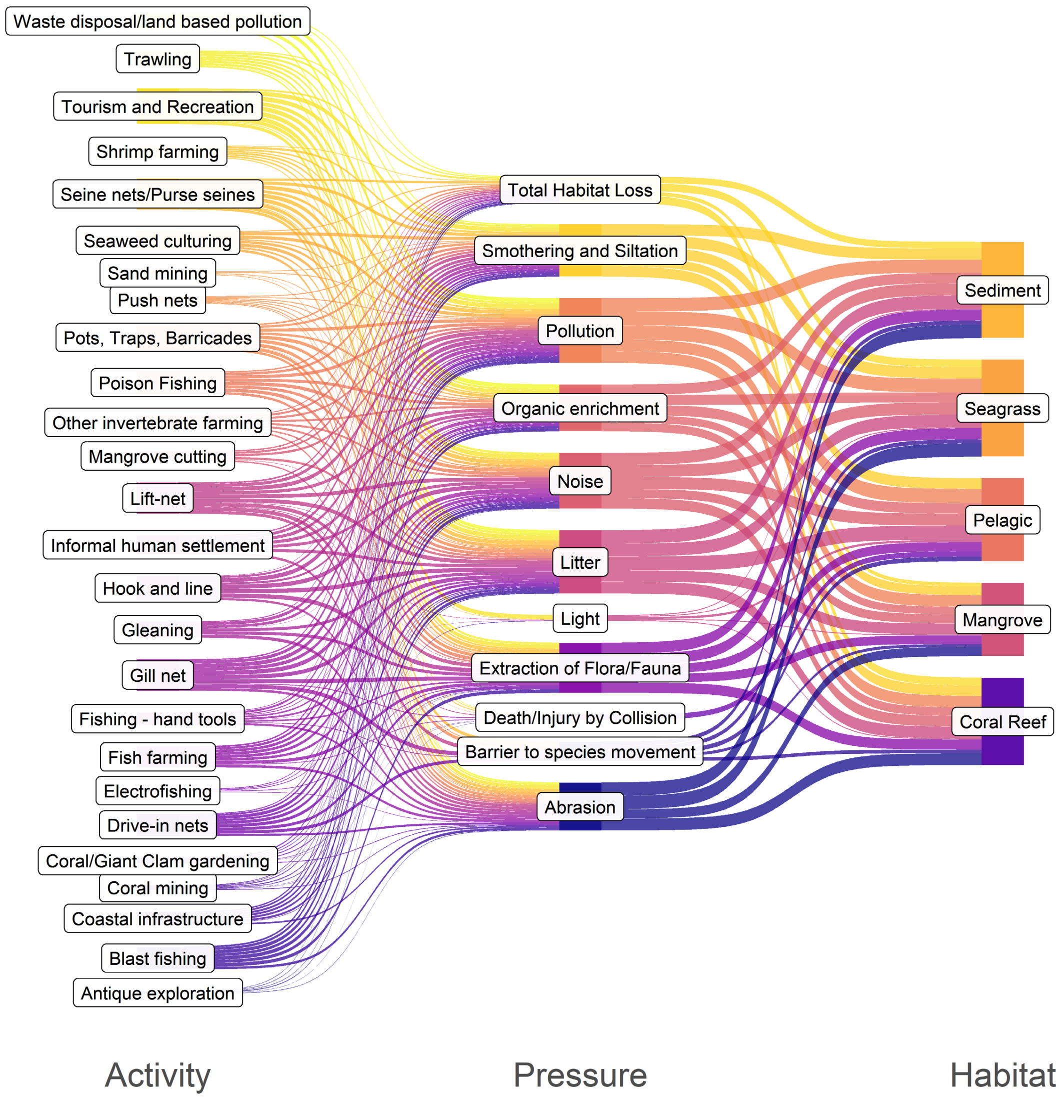

FIGURE 2 Impact chains (i.e. links between activities, pressures and habitats) across Southeast Asian case study sites.

template, online meetings and ongoing support. The starting point was the identified impact chains, which were each considered in turn, available evidence was discussed and expert elicitation was used to come to an agreement among the group. The other criteria, persistence, resistance and resilience, were weighted during a series of workshops with a research team with expertise on ecology of the habitats and on activity–pressure interactions with habitats. Eleven people attended seagrass–coral reef workshops, while 10 people attended mangrove–sediment workshops. These criteria were considered specific to the activity–pressure interaction with the habitat rather than the specific location, and weightings were applied to generic impact chains rather than location-specific chains. The intensity of the specific activity–pressure–habitat combination was taken into account where, for example, organic enrichment from shrimp farming overlapping with sediment habitats would result in lower resistance and resilience categorisation than from informal human settlements introducing the same pressure type and overlapping with the same habitat. The team were provided with training on the process and the workshops were facilitated by a researcher with expertise in the method. The evidence for the weighting of each criterion for each impact chain was discussed in turn and expert elicitation used to reach a consensus on categorisation. The generic weightings were then applied to the case study-specific matrices and a further review was carried out by local expert teams in case of any exceptions to the generic weightings, for example, if an activity–pressure combination had a greater magnitude of intensity in one location and/or habitat, making the consequence more severe, the score would be adjusted to account for this. An indication of confidence was given for each weighting (Table S4). Specific activities varied across regions (see Culhane et al., 2024). For robust cross-comparison across them, we harmonised these to a list of 26 activities (Table S2; Figure 2). Activities were grouped when the same/similar activities were called different names in different regions or had slight differences but introduced the same pressures. In some case study teams, the specific activities were specified in great detail, but in others they were broad; therefore, in order to make

TABLE 2 Risk assessment criteria categories and scores.

Aspect of risk	Pressure criterion	Category	Description	Scoring
Exposure (descriptions modified from Borgwardt et al., 2019)	*Extent*: the spatial overlap between each activity–pressure and habitat	Site	Activity overlaps with the habitat by up to 5% of the area occupied by the habitat in the case study area	0.03
		Local	Activity overlaps with the habitat by between 5% and 50% of the area occupied by the habitat in the case study area	0.37
		Widespread	Activity overlaps with the habitat by between 50% and 100% of the area occupied by the habitat in the case study area	1
	Frequency: The most likely number of times the activity–pressure interacts with each average km^2 occupied by the habitat in an average year, where they overlap in space	Rare	Not more than three times in a 12-month period	0.08
		Frequent	Approximately half the months in a 12-month period	0.67
		Continuous	Interactions occur in every month in a 12-month period	1
	Persistence: The time taken for the pressure associated with an activity to disappear after cessation of any further activities causing the pressure	Low	0 to <2 years	0.01
		Moderate	2 to <10 years	0.55
		High	Pressure lasts >10 years or never leaves the system	1
Sensitivity (descriptions from Holling, 1973); here we take into account the potential interaction with the specific pressure (whether it is acute, chronic or low in severity, and the magnitude of the specific activity–pressure–habitat combination; see Borgwardt et al., 2019; Piet et al., 2023)	*Resistance*: The degree to which a habitat can absorb disturbance or stress without changing in character	High	No ecologically significant effect on the physical structure, nor effect on viable populations of associated benthos (i.e. any mortality caused is not noticeable against background variation), but may affect feeding, respiration and reproduction rates in those species	0.01
		Medium	Some noticeable mortality to some species and some noticeable damage to the structure	0.55
		Low	Effects on physical and biological structure of the habitat and widespread mortality where the disturbance occurs. It could result in all characteristics being lost and removal of habitat, for example, change in habitat type because the characteristic physical features and fauna and flora have been removed or lost.	1
	Resilience: habitat ability to return to pre-disturbance condition once the stressor is removed and depends on the habitat ecology and other factors	High	Less than 2 years	0.01
		Medium	2–10 years	0.55
		Low	>10 years	1

Note: A greater score indicates higher risk.

more comparable, these activities were grouped at the broader level where possible. Where an activity would introduce different pressures, or at a different magnitude, it was kept separate. To aggregate the sub-activities, we took a precautionary approach by taking the maximum risk score per category for each activity–pressure–habitat combination per case study.

The overall Impact Risk score was the Euclidean distance, that is, distance from the origin, between the consequence (or sensitivity) and the exposure (Arkema et al., 2014; Borgwardt et al., 2019) (Equation 3). This assumes an increase in exposure and an increase in sensitivity leads to increased risk. The final score was scaled to be between 0 and 1.

$$\text{Exposure}\,(E) = \frac{E_{\text{Extent}} + E_{\text{Frequency}} + E_{\text{Persistence}}}{n_E} \quad (1)$$

where E_{Extent}, exposure criterion score given based on extent of an activity pressure combination; $E_{\text{Frequency}}$, exposure criterion score given based on frequency of an activity pressure combination;

$E_{\text{Persistence}}$, exposure criterion score given based on persistence of an activity pressure combination; n_E, number of exposure criteria used.

$$\text{Sensitivity}\,(S) = \frac{S_{\text{Resistance}} + S_{\text{Resilience}}}{n_S} \qquad (2)$$

where $S_{\text{Resistance}}$, sensitivity criterion score given based on resistance of a habitat to an activity pressure combination; $S_{\text{Resilience}}$, sensitivity criterion score given based on resilience of a habitat to an activity pressure combination; n_S, number of sensitivity criteria used.

$$\text{Impact risk} = \sqrt{(E-1)^2 + (S-1)^2} \qquad (3)$$

where E is exposure (Equation 1) and S is sensitivity (Equation 2).

2.4 | Data analysis

Each activity–pressure–habitat combination, that is, impact chain, has an impact risk score. All analyses were carried out in R (R Development Core Team, 2016). The full linkage framework was visualised with a Sankey diagram produced using *ggsankey* (Sjoberg, 2021). Impact risk scores were aggregated by summing the scores for each habitat, activity and pressure in each case study, to assess the cumulative risk of these. All other factors being equal, a habitat with more activities that introduce more pressures has a greater risk score. This assumes cumulative risk from activities and pressures are additive; we acknowledge this is a simplified relationship and interacting pressures do not always act additively (Crain et al., 2008). Box plots of summed impact risk from activities, pressures and for habitats, across case studies were produced using *ggplot2* (Wickham, 2009).

Lastly, differences in risk across case studies and habitats, in terms of risk per impact chain, were investigated using a general linear model (GLM) with post hoc Tukey test. Broad drivers of human activities that may explain variability in risk per impact chain across case studies, namely the total size of the case study area, and the case study catchment human population size (Table 1), were investigated using a GLM for their effects on impact chains. Significant interactions were explored using *interactions* (Long, 2021).

3 | RESULTS

3.1 | Cumulative risk to habitats

The full linkage framework (Figure 2) consisted of 1954 impact chains. Seagrass had the highest number of impact chains (434), followed by sediment (430), coral (391), pelagic (371) and mangrove (328). When impact chains were weighted according to risk criteria, coral reef had the highest risk across all case studies and habitats, while mangrove had the lowest (Figure 3). Across habitats, Malaysia, the Philippines and Indonesia case studies had a greater risk than Vietnam.

3.2 | Cumulative risk from activities

The activities introducing greatest risk across case studies were tourism and recreation, trawling and gill nets (Figure 4). The activities introducing least risk were fishing with hand tools and instruments and coral and giant clam gardening. There was variation across case studies, with, for example, high risk coming from seine nets in Vietnam, fish farming in Malaysia and pots, traps and barricades in the Philippines.

The main activities introducing greatest risk differed across habitat types (Figure 5). In coral reefs, activities introducing high risk included trawling, blast fishing, poison fishing, tourism and recreation and seine nets/purse seines. Shrimp farming, sand mining, mangrove cutting and coral and giant clam gardening introduced the lowest risk to coral reef. In mangrove, the highest risk came from shrimp farming, and to a lesser degree pots, traps and barricades, mangrove cutting and informal human settlement, while blast fishing and sand mining had low risk to mangrove. For pelagic waters, gill net, lift net, trawling, push net and tourism and recreation introduced the highest risk, while mangrove cutting, fishing with hand tools and gleaning introduced the lowest risk. In seagrass, trawling and tourism and recreation introduced the highest risk. Coral and giant clam gardening introduced the least risk to seagrass habitats. Finally, in sediment habitats, trawling introduced the greatest risk, while underwater antique exploration introduced the least.

3.3 | Cumulative risk from pressures

Across activities, habitats and case studies, the pressures introducing the most risk included litter and pollution, followed by extraction of flora and fauna (Figure 6). Light, death or injury by collision and barrier to species movement represented the least risk. There was variation across case studies, with risk from total habitat loss being the greatest risk in the Indonesian and Malaysian case studies.

The risk from pressures also varied depending on habitat type (Figure 7). For coral reef habitats, abrasion and pollution were the pressures introducing the highest risk, but there was also high variability for total habitat loss. In mangrove, extraction of flora and fauna, litter, pollution and habitat loss introduced the greatest risk. In pelagic habitats, litter was identified as introducing the greatest risk, and to a lesser degree pollution. In seagrass habitats, extraction of flora and fauna introduced the greatest risk, but there was high variability for total habitat loss and pollution. In sediment habitats, there was a high risk from litter and pollution, with high variability for total habitat loss. Across all habitats, barrier to species movement and light introduced the least risk.

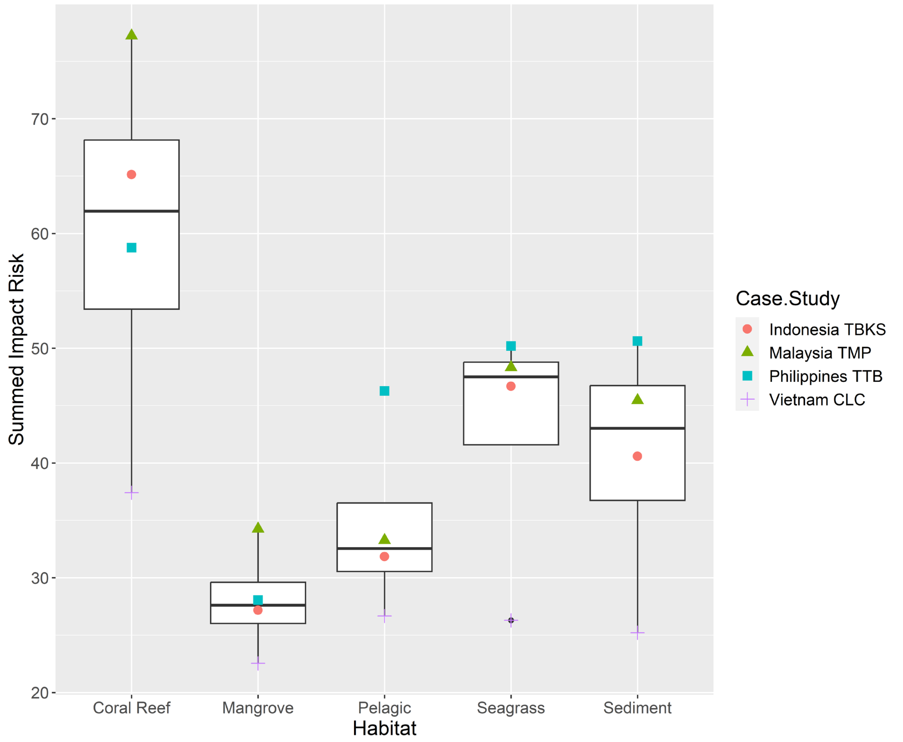

FIGURE 3 Cumulative impact risk introduced to habitats in each case study. Median, interquartile range and minimum and maximum values of impact risk ($n=4$).

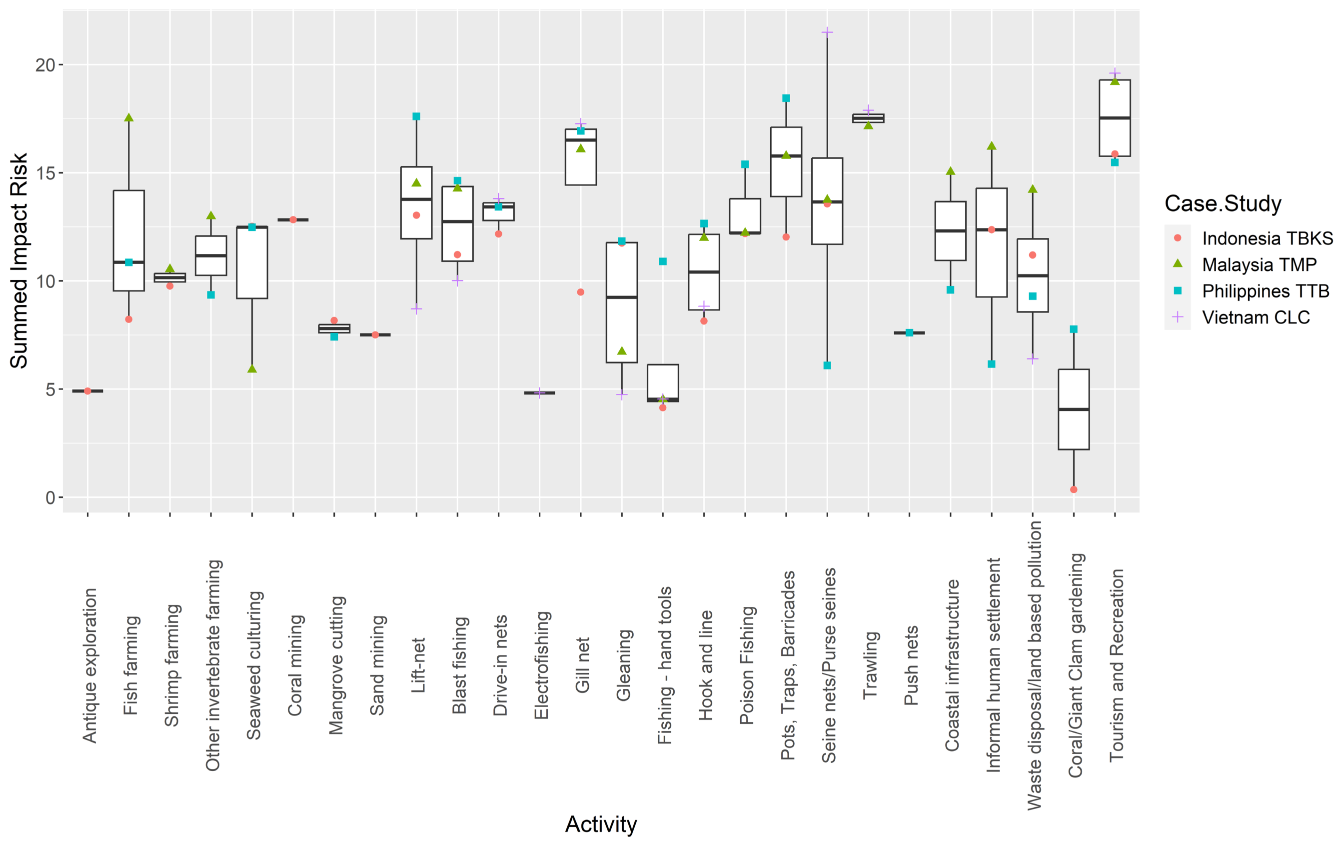

FIGURE 4 Cumulative impact risk introduced by each activity in each case study. Median, interquartile range and minimum and maximum values of impact risk; not every activity occurs at every site.

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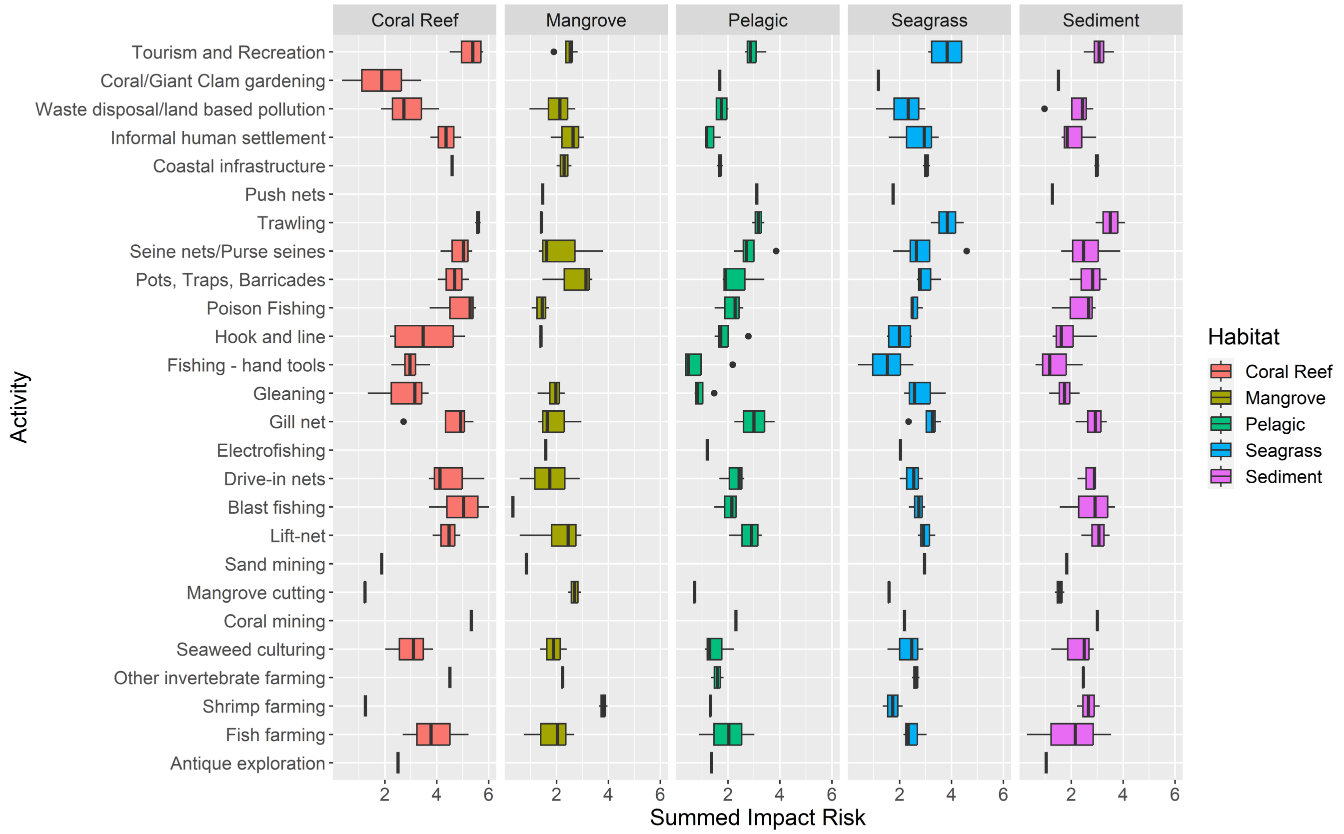

FIGURE 5 Cumulative impact risk introduced by each activity in each habitat. Median, interquartile range and minimum and maximum values of impact risk.

3.4 | Impact chain risk

There was very strong evidence case study sites differed in the risk introduced by individual impact chains. Overall, Indonesia TBKS and Vietnam CLC had higher risk impact chains than Malaysia TMP and Philippines TTB (Table 3; Tables S5 and S6). There was also very strong evidence coral reefs had higher risk impact chains than any other habitat across case studies and seagrass habitat had higher risk impact chains than mangroves.

There was moderate evidence the effect of population size on risk depended on the habitat (Table 4). For most habitats, a larger population size was associated with higher risk impact chains. However, for coral reefs, both low and high populations were associated with high risk impact chains (Figure S1). There was evidence both the largest (Indonesia) and smallest (Vietnam) case study areas had higher risk impact chains than the others.

4 | DISCUSSION

Maintaining ecosystem integrity, while carrying out activities essential for people, is key to sustainability. This study captures a holistic overview of human activities interacting with tropical marine habitats across four heavily populated marine reserves/parks in Southeast Asia, where each have objectives aiming to meet people's needs while maintaining healthy seas. These regions are significant contributors to global biodiversity and home to large populations highly dependent on marine ecosystems for their food, livelihood, health and well-being. We identified 26 human activities and their potential to introduce 11 pressure types across five essential service providing tropical marine habitats. The number of impact chains, 1954, highlights the scale and complexity of managing human interactions with these ecosystems. While some activities seem relatively sustainable, others are posing a high risk to crucial habitats. At the same time, management is complex because many activities and pressures occur simultaneously, and different habitats have different susceptibilities to different activities. Furthermore, management responsibility spans multiple organisations and administrations, and coordination between these actors is required to meet objectives of the reserves/parks (Fortnam et al., 2022).

The risk assessment approach used here allows prioritisation of those activities and pressures introducing most risk, in turn highlighting conflict and trade-offs. Tourism and fishing with trawling, gill nets and seine nets were identified as the activities introducing greatest risk across case studies. Both tourism and fishing are vital economic activities supporting people's livelihoods in these regions but the risk they introduce threatens ecosystem service supply and, in turn, the activities themselves. For example, local community livelihoods in TMP, Malaysia, have

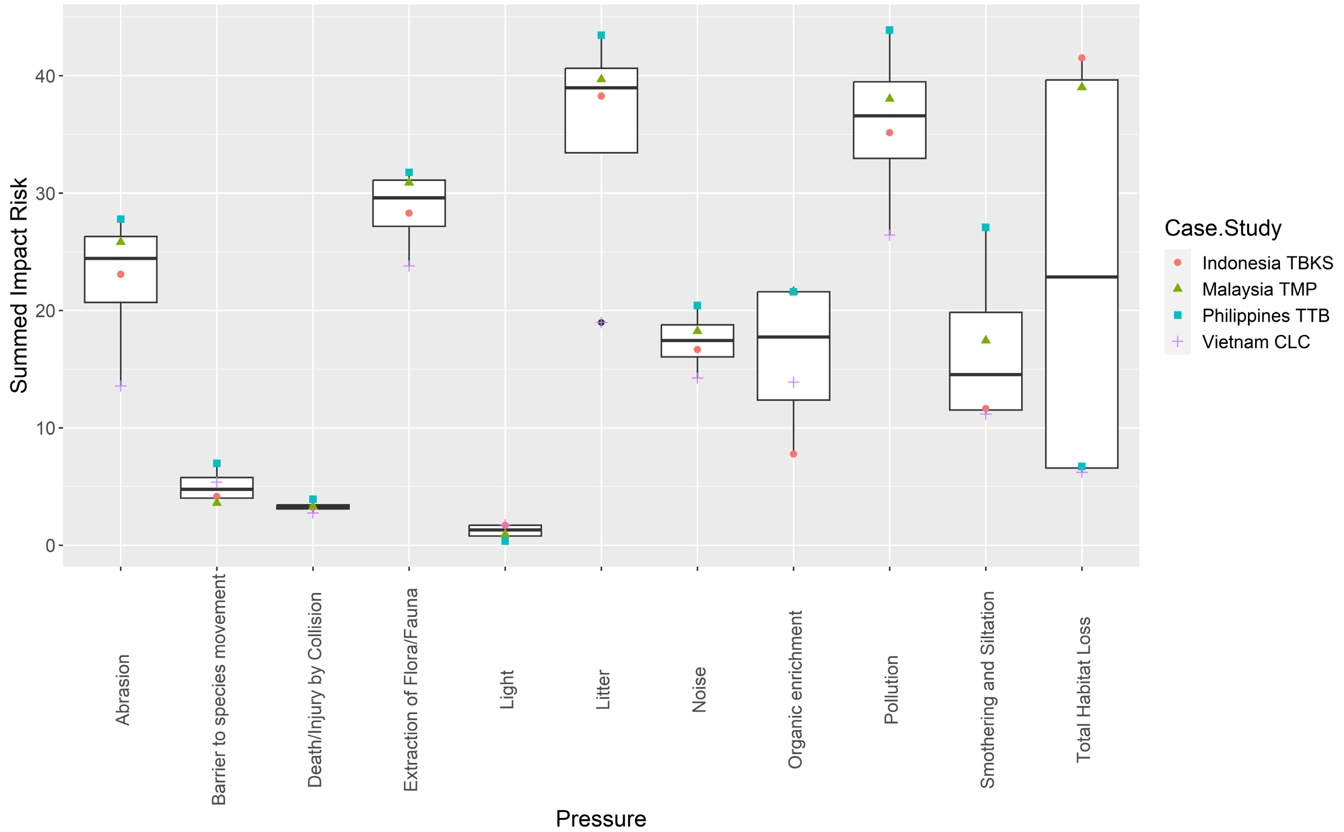

FIGURE 6 Cumulative impact risk introduced by each pressure in each case study. Median, interquartile range and minimum and maximum values of impact risk.

declined due to negative impacts on coral and mangrove habitats from destructive fishing and other activities (Lim et al., 2021), which can also damage habitats that are key attractions for tourists. In CLC, Vietnam tourism has driven fishery overexploitation to meet tourist demand for seafood (Ngoc, 2018). The complex interplay between destructive fisheries and tourism demonstrates that management decisions should consider the combined impact of multiple sectors to ensure pressures introduced do not lead to unintended consequences. However, our study also shows that several types of fishing activity introduce relatively low risk and therefore may contribute to sustainable activity in the region, going towards meeting UN Sustainable Development Goals objectives on poverty, hunger and life below water. Meeting these multiple objectives simultaneously requires management decisions that explicitly take system complexity and interactions into account rather than being focused on single issues.

Complementary and holistic approaches to consider marine ecosystems and their management are needed, since observing the system from different perspectives can highlight different issues or priority areas. Seagrass and sediment had the highest impact chain number indicating these habitats support multiple activities. They are likely to be important for economic livelihood and food provisioning, as most fishing activity is concentrated in these habitats. However, both habitats, and in particular sediments, are perceived as less valuable for supplying most provisioning, regulating and cultural ecosystem services (albeit with lower confidence) when compared to mangrove and coral reef (Hattam et al., 2021). There is a mismatch between the different values we have for marine habitats, which may be linked to lower understanding in how some habitats supply services.

In contrast to seagrass and sediment, mangrove habitats had the lowest impact risk in CLC, Vietnam and TTB, Philippines, and less so TBKS, Indonesia and TMP, Malaysia. Hattam et al. (2021) identified mangrove in these regions as being the most important habitats for ecosystem service supply. This mismatch in high benefits from services versus lower activity use reflects intact mangrove's high potential for supplying regulating services, like coastal protection, which do not need active human input to get the benefits. However, this finding should be interpreted with caution because large amounts of mangrove habitat have already been lost (Primavera & Esteban, 2008) and the baseline here may already represent poor condition. In these case study sites, mangroves are under protection, and regeneration efforts are taking place, for example, in CLC, Vietnam and TTB, Philippines (Gef, 2018; Richter et al., 2022), meaning the perceived risk for further loss is low. This highlights two key issues, firstly, low risk does not represent no risk, and secondly, the study baseline is important, since the risk measured to habitats is the risk of current or further degradation to what is existing now. If most of the habitats have been lost already, this may not be reflected in the results, and does not reflect current condition. Depending on

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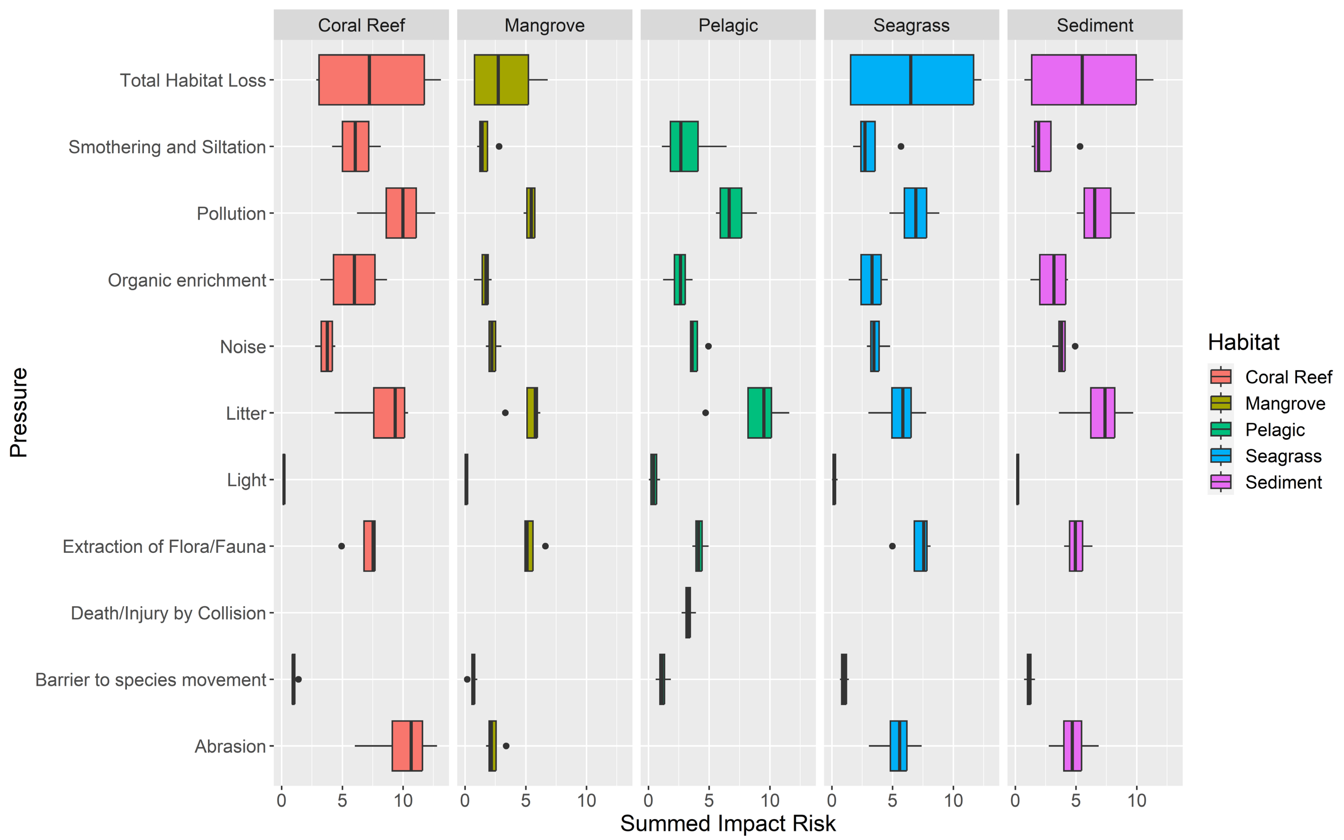

FIGURE 7 Cumulative impact risk introduced by each pressure in each habitat. Median, interquartile range and minimum and maximum values of impact risk.

TABLE 3 General linear model results for variation in risk per impact chain in habitats for four Southeast Asian case studies (impact risk ~ case study × habitat).

Term	df	*F*	*p*
Case study	3	6.516	<0.001
Habitat	4	120.318	<0.001
Case study × habitat	12	1.420	0.150

TABLE 4 General linear model results for variation in risk per impact chain in habitats in relation to population size and area for four Southeast Asian case studies (impact risk ~ population × area × habitat).

Term	df	*F*	*p*
Population	1	17.694	<0.001
Area of case study	1	9.449	0.002
Habitat	4	120.318	<0.001
Population × area	1	1.662	0.197
Population × habitat	4	2.576	0.036
Area × habitat	4	1.035	0.388
Population × area × habitat	4	1.220	0.300

Note: Plot of the significant interaction shown in Figure S1.

condition, managers may need to additionally consider restoration measures, as well as the activities currently introducing pressures to the system.

Spatial management, such as marine protected area (MPA) implementation, aims to restrict activities within defined boundaries and thereby reduce pressures on the ecosystem. This intervention mainly reduces physical pressures, including abrasion, smothering and siltation and total habitat loss, associated with activities directly interacting with ecosystems. At local scales, MPAs with adequate planning and monitoring measures are required to tackle these physical pressures. High variation between case studies shows the local context is important with each case study having its own unique activities, in addition to shared activities. Our results show management of some activities are more important for introducing risk in some places and habitats than others, for example, coral mining occurs only in the Indonesia TBKS case study and is recognised as being highly destructive but unmanaged (Praptiwi et al., 2021). We found coral reefs have fewer impact chains than other habitats but while some coral reef activities introduce relatively few impact chains they are highly destructive to these sensitive habitats, for example, blast fishing and poison fishing. Wulandari et al. (2022) found coral to be heavily degraded in TBKS, Indonesia's transition zones where fishing activities are open for fishers from local and other areas, demonstrating the need for effective spatial management that addresses the specific local conditions. However, this requires effective enforcement, which can be hampered by local and regional politics. For example, Fortnam et al. (2022) reported that lobbying of local leaders by industry in TTB, Philippines diluted rules designed to protect habitats by allowing some activities to occur in core marine zones, and in CLC, Vietnam, a top-down governance approach means that local scale enforcement is weak.

The high risk to coral reefs was not only from physical pressures, but also litter and pollution. Across habitats pollution and litter introduced the highest risk due to their widespread interactions with habitats, being introduced continuously from multiple sources, including from tourism, land, boats and aquaculture, among others. In TMP, Malaysia, shrimp farming outside the MPA impacts the protected habitats due to the influx of poor quality water Lim et al. (2021). Diffuse pressures are a risk to habitat integrity and can impede recovery (Ortiz et al., 2018). Many pollutants are emerging threats and their impacts not fully understood [e.g. impacts of sunscreen components on seagrass (Agawin et al., 2022)], while climate change impacts can intensify pollution effects [e.g. toxicity of metals (Roberts et al., 2013)]. In CLC, Vietnam, pollution was seen as a key factor in seagrass habitat loss (Tin et al., 2020) and coral cover declined by more than one third between 2004 and 2008 due to combined impacts from human activities and climate change, including litter (Trinh, 2011 cited in Ngoc, 2018). MPAs cannot protect habitats from chronic, diffuse pressures that are more complex to manage (Agardy et al., 2011).

The broader risk drivers across these regions, though not extensively considered here, included the human population size. However, coral reef habitat risk was high regardless of population size. This may be linked to, for example, fishers from outside local communities carrying out destructive fishing practices (Lim et al., 2021; Ngoc, 2018). The fisheries sector in the region is influenced by regional and global markets (e.g. Hong Kong, China and South Korea), which foster marine resource expansion and exploitation (Lampe, 2017). Conservation status is also likely to have an influence on risk. For example, CLC, Vietnam showed lower risk to coral reef than other sites. Coral in this area may be improving due to community engagement with coral reef conservation and restoration (Ngoc, 2018; Richter et al., 2022).

Pressures operating at regional scales will constrain the effectiveness of management measures implemented at local scales. As this study highlighted, dispersive pressures (pollution, litter and organic enrichment) represent a high risk to these regions, and a regional response and coordination with local actors is simultaneously required to address both local and regional scale issues. Coordinated regional resource governance with application of measures at appropriate geographical scales is essential to preventing ocean ecosystem collapse (Gómez-Baggethun et al., 2013; UNEP, 2012). Collaborative forums involving multiple stakeholders and multiple levels have been established in each of these regions in order to coordinate meeting park/reserve objectives, though these have several issues that inhibit their effectiveness, including the divergent priorities of members (Fortnam et al., 2022). To facilitate and inform this coordination, we need methods, such as this risk assessment approach, that can be implemented at regional scales and in evidence poor locations, and that can provide a multisectoral, ecosystem-based prioritisation of sustainability risks in a transparent way. This study shows multiple activities are interacting and introducing threats to tropical habitats. Habitats have the capacity to recover (GCRMN, 2020) but key to this is reducing direct physical pressures, as well as diffuse pressures, to increase their resilience to climate-driven pressures predicted to increase in the future. Consideration of both spatially defined and diffuse pressures is needed for effective sustainable management of activities and holistic regional perspectives are needed to complement site specific studies. This cannot be achieved by local scale management alone, and requires a concerted effort at several scales and from multiple actors to tackle broad scale issues such as pollution and litter.

To achieve regional assessments, a systematic approach to organising available knowledge is required, especially in data-poor regions. This study included information taken from local studies and scientific literature, as well as expert knowledge from stakeholders and scientists familiar with local areas. With this knowledge base comes a range of confidence and the potential for introduced bias due to shifting baselines and human memory or people prioritising issues they are most aware of. For example, we found high potential risk from litter but low confidence (Culhane et al., 2024). This fits with findings like that of the exponential increase in plastic found in Red Sea and Arabian Gulf mangrove sediments (Martin et al., 2020). However, while various impacts to marine life and marine ecosystem service supply from plastic litter are known (Napper & Thompson, 2020), we still understand relatively little about the full extent and consequences of ongoing accumulation of plastic and other litter pollution in the region and how this and other pressures interact to contribute to cumulative risk to habitats (Piet et al., 2023). We also have limited knowledge of the less charismatic sediment and pelagic habitats because, despite taking up the most space and being widely used for fishing, they are less studied in tropical systems.

In using this approach, choices related to the typologies of activities, pressures and ecosystem components, and how they are aggregated, can affect results (Piet et al., 2017). For example, fishing contains 13 different types of sub-activity, while tourism and recreation is aggregated to one type. These types of choices can reflect not only the knowledge base of the local experts, where in this case, the experts are more familiar with fishing activities than touristic activities, but also the choice to aggregate activities for comparison across the four regions in this study. When implementing this approach at the individual case study scale, it is advisable to retain detailed sub-activities, as recommended by Piet et al. (2017). In this study, we took a precautionary approach in aggregating sub-activities, that is, adopting the worst outcome when combining sub-activities. Therefore, this may overestimate the risk from tourism and overshadow touristic and recreational activities that can be sustainable. Similarly, if all fishing activities had been aggregated, we would not see that some types of fishing introduce much less risk than others. Nevertheless, the risk from tourism is a real threat in these regions, for example, in CLC, Vietnam, where local actors voiced fears about the risk to coral reef and seagrass, after the licencing of a large-scale luxury resort (Fortnam et al., 2022).

While our approach facilitates making management decisions using the best available knowledge, we should also work towards improving our understanding in areas of low confidence. In the meantime, wicked problems require an adaptive management approach, with approximations of the problems (being aware of high uncertainty) and incremental steps towards solutions (Defries & Nagendra, 2017). This approach allows for approximating the problem factors and where potential solutions could fit but must allow for goal re-evaluation and adaptation. Much of the marine environment lacks data; yet managers need to make decisions. This framework systematically organises the information and knowledge we have, using expert elicitation from academic experts and local stakeholders and supported by literature.

5 | CONCLUSION

Sustainable use of marine ecosystems requires an understanding of the complexity of the social-ecological system, to recognise trade-offs and unintended consequences of management actions. This study has highlighted the high risk for coral reef ecosystems at a regional scale. These coral reef systems are part of the globally important Coral Triangle which actively provides ecosystem services essential to local and global communities (GCRMN, 2020). Furthermore, the pollution risk indicated here shows that spatial planning alone will not be effective at protecting these ecosystems (Agardy et al., 2011). This study reiterates the need for a systems approach, working at multiple scales and the need for using multiple tools simultaneously to address sustainability issues, that is, managers need to use bespoke spatial management approaches at local scales to address relevant physical pressures while also cooperating at broader scales to take a coordinated regional approach to address chronic diffuse pressures. Management has typically focussed on one or a few activities, pressures and ecosystem components, but this narrow focus might neither reduce key pressures from the system nor fully protect ecosystem service supply (Robinson & Culhane, 2020). We have presented a tool which can help to prioritise management where multiple actors are required to coordinate to meet sustainability objectives. Taking a multisectoral approach allows consideration of the cumulative impacts across activities. Any management actions taken, need to be enforced to ensure sustainable use of these ecosystems and continued equitable ecosystem service supply.

AUTHOR CONTRIBUTIONS

Paper conception and overall approach: Fiona Culhane, Olivia Langmead, Melanie C. Austen, Stefanie Broszeit, Matthew Ashley. *Data collection and expert elicitation*: Fiona Culhane, Melanie C. Austen, Matthew Ashley, Jonson Javier, Sui Hyang Kuit, Nguyen Phuc Hung, Tran Duc Hau, Radisti A. Praptiwi, Sainal Sainal, Eva Justine, Prawesti Wulandari, Stefanie Broszeit, Jean Beth Jontila, Sofia Johari, Lota Creencia, Amy Yee-Hui Then, Lea Janine Gajardo, Carya Maharja, Hong Ching Goh, Wan Mohd Syazwan, Yang Amri Affendi, Le Ngoc Thao, Jito Sugardjito, Tom Mullier, Olivia Langmead. *Data analysis and visualisation*: Fiona Culhane. *Data interpretation*: Fiona Culhane, Olivia Langmead, Jonson Javier, Sui Hyang Kuit, Nguyen Phuc Hung, Tran Duc Hau, Radisti A. Praptiwi, Sainal Sainal, Prawesti Wulandari, Lota Creencia, Amy Yee-Hui Then, Carya Maharja and Wan Mohd Syazwan. *Original draft*: Fiona Culhane; and Final draft: All authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.msbcc2g6s (Culhane et al., 2024).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Further information on the four case studies included in the assessment.

Table S2. List of activities found in each case study, 'x' indicates presence of activity in the case study.

Table S3. List of pressures with descriptions.

Table S4. Categories and scales used in the confidence assigned to links.

Table S5. Tukey multiple comparisons of means between case studies with 95% family-wise confidence level.

Table S6. Tukey multiple comparisons of means between habitats with 95% family-wise confidence level.

Figure S1. Interaction plot of population and habitat based on the model impact risk.

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