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A matrix approach to tropical marine ecosystem service assessments in South east Asia

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ABSTRACT

Ecosystem service assessments are increasingly used to support natural resource management, but there is a bias in their application towards terrestrial systems and higher income countries. Tropical marine applications are

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Confidence scores
Evidence gaps

particularly scarce, especially in SE Asia. Given the growing coastal population and expansion in blue economy sectors in SE Asia, evidence to support effective marine planning, such as ecosystem service assessments, is urgently needed. Data deficiencies for marine systems, especially (but not only) in lower income countries is a significant obstacle for ecosystem service assessments. To overcome this, we develop an ecosystem service potential matrix which combines evidence taken from an extensive literature review together with expert opinion. The matrix includes both natural and modified habitats as the service providing units. The ecosystem service potential for habitats are scored at the macro level (e.g. mangrove) due to insufficient evidence to score micro-habitats (e.g. fringe, basin or riverine mangroves). The majority of evidence is available for biogenic habitats (mangroves, coral reefs and seagrass meadows) with comparatively little for sedimentary habitats. While provisioning, regulating and cultural services are scored, published evidence is more readily available for provisioning and regulating services. Confidence scores, indicating the uncertainty in the ecosystem service potential scores are included in the matrix. To our knowledge this is the first attempt to systematically capture the provision of ecosystem services from tropical marine habitats. Although initially developed for four marine biosphere reserves and protected areas in SE Asia, the generic nature of the evidence included suggests that the matrix constitutes a valuable baseline for marine ecosystem service assessments within SE Asia and provides a robust foundation for development in future work.

1. Introduction

Ecosystem service assessments are increasingly used to support environmental management, with applications at local (e.g. Tamayo et al., 2018; Bana and Sakti, 2019), national (e.g. Schröter et al., 2016) and global scales (e.g. the Millennium Ecosystem Assessment, 2005, and more recently IPBES, 2019, Díaz et al., 2019). Although global assessments cover all biomes, national and local assessments typically focus on terrestrial environments, with marine equivalents lagging significantly behind (Townsend et al., 2018; Lautenbach et al., 2019). This bias towards terrestrial systems has been attributed to the challenges faced by marine assessments including a scarcity of marine spatial data, the mobile nature of marine resources, the three dimensional character of marine ecosystems and the spatial disconnect between where services are produced and where they are used in the marine environment (Townsend et al., 2018; Hooper et al., 2019). The application of ecosystem service assessments is also biased by geographical location. The vast majority of assessments have occurred in Europe, the USA and China with comparatively few having taken place in lower income countries (Lautenbach et al., 2019). Marine applications that have occurred in lower income countries have typically been in Africa (e.g. Lange and Jiddawi, 2009; Abunge et al., 2013) and South America (e.g. Castaño-Isaza et al., 2015).

Evidence to support marine management and planning in tropical locations, such as ecosystem service assessments, is urgently needed. Demand for marine space and resources is increasing due to growing populations and expanding blue economies (Roberts and Brink, 2010), especially in lower income tropical countries (World Bank and United Nations Department of Economic and Social Affairs, 2017; Bennett et al., 2019). This is coupled with recognition of the deteriorating state of many components of the marine environment (Worm et al., 2006; Canonico et al., 2019) and concerns over increased conflict for marine space and resources (Pomeroy et al., 2014). In Asia, one of the centres for coastal population and blue economy growth, the development and implementation of integrated coastal management incorporating marine spatial planning has been identified as a priority investment needed to support the blue economy (Whisnant and Reyes, 2015). Examples of marine planning in the region are few, but lessons learnt from small-scale marine planning initiatives (e.g. Bataan, Philippines and Wakatobi National Park, Indonesia) suggest that the capacity to implement marine planning throughout SE Asia is largely lacking partly due to limitations in the data and information needed to develop it (Pomeroy et al., 2014).

The data deficiency in many marine and coastal areas, especially (but not only) in lower income countries, has been described as the greatest obstacle to the advancement of ecosystem service assessments (Eigenbrod et al., 2010). One method that may overcome this challenge is the capacity matrix approach (Burkhard et al., 2009; Campagne et al., 2017), in which the capacity or potential of an ecosystem service providing unit (typically land use or habitat types) to supply ecosystem services is assessed and scored. The method can draw on multiple data sources (e.g. literature, model output, observational data), but where data are scarce, expert judgement and knowledge can be incorporated (Campagne and Roche, 2018). The method enables a rapid assessment of ecosystem service supply and/or demand for a specific area (Burkhard et al., 2012). It is now one of the most popular ecosystem service assessment methods available (Jacobs et al., 2015) and results have been used for policy making and the development of management measures for target areas (e.g. Tao et al., 2018). Marine applications of the matrix approach are relatively few, but include six European focused studies (Salomidi et al., 2012; Galparsoro et al., 2014; Potts et al., 2014; Burdon et al., 2017; Depellegrin et al., 2017; Farella et al., 2020) and one from New Zealand (Geange et al., 2019); no tropical studies have been identified. Of these seven studies, each uses marine habitats as the ecosystem service providing units, but Potts et al. (2014), Burdon et al. (2017) and Farella et al. (2020) also assess the potential of marine species to provide ecosystem services. The number of services assessed varies from 12 to 25 with most studies including supporting ecosystem services alongside provisioning, regulating and cultural services. Only Geange et al. (2019) base their assessment on an internationally accepted ES classification, drawing from both TEEB (TEEB, 2010) and CICES (Common International Classification of Ecosystem Services; Haines-Young and Potschin (2018)).

Despite the advantages of the matrix approach, the reliance on expert judgement may produce unacknowledged or hard-to-quantify uncertainties (Hou et al., 2013). In a review of 109 matrix studies, Campagne et al. (2020) found that only 15% considered the variability and uncertainty in their scores. The reproducibility and transparency in the scoring process is also criticised (Jacobs et al., 2015), which may lead to inconsistent findings when the matrix approach is repeatedly applied to the same area (Tao et al., 2018). To standardise the matrix creation process, Jacobs et al. (2015) produced guidelines for improving the scientific quality of the matrix model, which have been further developed by Campagne and Roche (2018). Campagne and Roche (2018) recommend a seven-step process: goal preparation, harmonising understanding of the ecosystem service and ecosystem type classifications, initial scoring of the matrix, filling in the matrix, compiling values, checking the reliability and validation of the matrix, and the creation of outputs.

A further challenge to the matrix approach is the inconsistent incorporation of cultural ecosystem services. This risks cultural ecosystem services being overlooked by decision makers, and is recognised as a particular problem in lower income countries (Martin et al., 2016). Some authors exclude cultural services entirely (e.g. Geange et al., 2019), while others use a single cultural service (e.g. Depellegrin et al., 2017) or a mixture of benefits, components of well-being and values (e.g. Burdon et al., 2017). Such inconsistency may be attributed to the lack of clarity in the literature about what constitutes a cultural ecosystem service or what the explicit contribution of the natural environment is to their provision (Satz et al., 2013). Chan et al. (2012), Chan et al. (2018) indicate the need to recognise that cultural ecosystem services are co-produced and co-created through interactions between people and ecosystems. To operationalise this concept, Fish et al. (2016) recommend distinguishing between environmental places, cultural practices, benefits and goods. Given the place-based nature of the matrix approach, this suggests that a more standardised approach to capture the cultural ecosystem services can be developed through the inclusion of different types of environmental places of cultural importance.

This paper reports the process used to develop a tropical marine ecosystem service potential matrix that captures all ecosystem services (i.e. provisioning, regulating and cultural services) in a standardised manner, provides a transparent evidence trail for each score, and assesses the confidence in the evidence used. The development of the matrix results from the need to support marine planning within four marine biosphere reserves and protected areas in SE Asia, which form the case study sites for the GCRF Blue Communities Programme (https://www.blue-communities.org; Fig. 1): Taka Bonerate Kepulauan Selayar Biosphere Reserve, Indonesia; Palawan, the Philippines; Cu Lao Cham-Hoi An, Vietnam; and the Tun Mustapha Park, Malaysia. While each biosphere reserve and marine park has its own management needs, what they have in common is similar habitats and a shared lack of data on which to base management decisions. While the resulting matrix cannot be expected to capture all the spatial variability in ecosystem service provision across all sites, it can provide a starting point for more tailored ecosystem service assessments in future. To our knowledge, this is the first attempt to systematically capture the provision of ecosystem services from tropical marine habitats. As such, it constitutes a valuable baseline for marine ecosystem service assessments within SE Asia and provides a robust foundation for development in future work.

2. Method

Focusing initially on the four tropical marine biospheres and protected areas, a modified version of the Campagne and Roche (2018)'s seven-step process was used for the creation of the tropical marine ecosystem service potential matrix (Fig. 2). Given the absence of a standardised classification system for tropical marine ecosystem service providing units (SPUs), the initial preparation stage was divided into two: 1) identifying the ecosystem SPUs and 2) selecting and modifying an appropriate ecosystem service classification. This was followed by an extensive literature review to document the available evidence on the potential of each SPU to provide each ecosystem services (step 3). Step 4 involved scoring the matrix (ecosystem service potential, and confidence in the evidence used to generate the potential score) and harmonising the scores using a consensus approach. Step 5 focused on validating outputs by cross-checking the scores with the evidence and peer review of the evidence base. Step 6 (mapping the outputs and application in management decisions) is not reported in depth, but an example is given.

2.1. Defining the ecosystem service providing units

Following Geange et al. (2019), habitats were selected as the most suitable SPUs for each case study site. In all but the Indonesian case, some level of habitat mapping had occurred and macro biogenic habitats (mangrove forests, coral reefs, seagrass meadows) had been identified. Each of the macro biogenic habitat types were further classified into micro-habitats (e.g. mangrove fringe, basin and riverine) to enable the capture of how these sub-units may potentially provide different levels of ecosystem services (Appendix A).

Knowledge of the existence of sedimentary habitats was scarce. As no standardised habitat classification for marine tropical habitats exists, sedimentary habitats were subdivided into sand, mud, rock, and coarse following a EUNIS-type approach (European Nature Information System; EUNIS, 2019). Sand, mud, rock and coarse habitats were split into intertidal and subtidal sub-categories to capture how depth may influence the capacity to provide ecosystem services (e.g. recreational capacity of intertidal sandy beaches is generally much higher than subtidal sand). A generic pelagic class was also included to capture ecosystem services provided by the water column, a habitat frequently missing in marine ecosystem service assessments (Hooper et al., 2019).

Given the extent of human activities within the case study sites, a series of modified habitats were defined to account for differences in their ecosystem service provisioning compared to natural habitats. Modified habitats included those that had artificial substrata introduced, and for the case study areas these comprised:

Seaweed farms where seaweed germlings are attached to cultivation lines connected to buoys or poles and then grown out until they are of harvestable size. These structures may cover extensive shallow coastal areas, particularly in the Asia-Pacific region (Chung et al., 2017). Found in Palawan, Tun Mustapha Park and Taka Bonerate Kepulauan Selayor.

Fish cages used for the mariculture of finfish that take place in both

Fig. 1. Location of the four GCRF Blue Communities case study sites (source: *Blank world map (green color) by OSeveno, used under CC BY-SA 4.0 / cropped, changed colours and added case study sites*). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

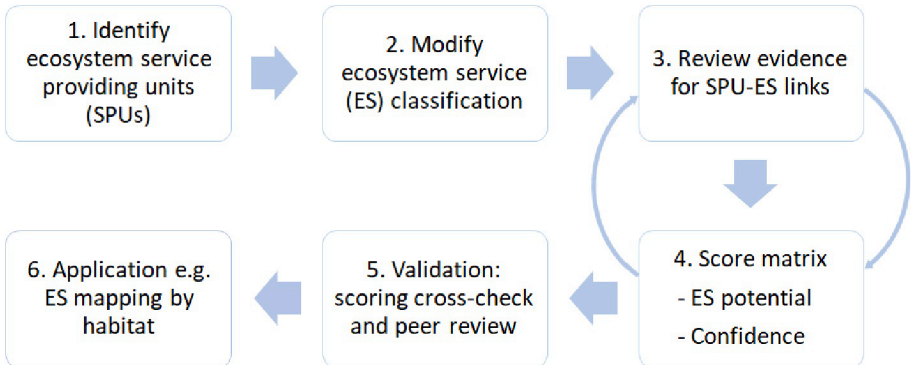


Fig. 2. Flow-chart of approach to matrix preparation, modified from Campagne and Roche (2018).

brackish and marine environments. Small fish are grown on to a harvestable size, fed on either pellets or wild caught fish. In Vietnam and Philippines finfish cages are often located over coral reefs as they require both good water quality and sheltered conditions (Hedberg et al., 2015; Hedberg et al., 2017). Found in all case study sites.

Invertebrate aquaculture farms including pearl oyster farms. These are often cultured in nets or baskets suspended on long lines to reduce predation. Oysters are highly sensitive to their growing environment. Good water quality is necessary for optimum growth and health of the oysters, which in turn lead to higher quality pearls and lower mortality from disease. Pearl farms, like finfish cages, are often located over coral reefs for this reason. Found in Palawan.

Artificial structures such as breakwaters, pontoons, seawalls or jetties that have been constructed for access or to prevent flooding. Found in all case study sites.

Artificial beaches used either for coastal protection or to enhance existing beaches for tourism purposes. Not present in the case study sites, but of interest to them.

Shrimp ponds, although common across SE Asia, were not included in this assessment as they are not present in the marine ecosystems within the case study sites (e.g. they occurred in riverine mangrove sites outside the boundary of Tun Mustapha Park). Intertidal clam culture and mangrove plantations were also not included as modified habitats. While there are areas seeded/planted within case study sites, there are no new habitat types from introduced structures and for the purposes of this exercise, they were considered similar to their unmanaged ‘natural’ habitats. They are included within intertidal mud and mangrove forests respectively.

2.2. Classifying ecosystem services

Relevant marine ecosystem services were selected and defined following a combination of both CICES 5.1 and TEEB ecosystem service classifications with division, groups and class combined for simplicity. Cultural ecosystem services were adapted based on Fish et al. (2016) in recognition of their place-based and relational nature (Appendix B). Ecosystem services were excluded if they had no relevance to SE Asian marine habitats or the supporting evidence was lacking (e.g. pest and disease control). Gaps in the existing frameworks necessitated the creation of new categories. For example, “provision of habitat for charismatic species” was included given the dependence of some charismatic species on critical habitat (e.g. green turtles and dugongs graze in seagrass meadows). As this service can be specifically managed for, its inclusion was considered justified, however, as with other regulating services, in some circumstances it may be considered a supporting service. Where ambiguity was found in definitions prior to evidence collection, these were modified for clarity. For example, ‘genetic material from plants and animals’, which has been used in a variety of ways elsewhere, was refined to include the collection of broodstock or material for mariculture and restocking respectively.

Due to the inclusion of modified habitats in the habitat classification, provisioning services attributed specifically to mariculture activities were removed from the service classification to avoid double counting. The provision of food, energy and other materials from plants and animals from mariculture sites is therefore captured in generic provisioning service categories. Inclusion of the modified habitats in this way also enabled the capture of other potential ecosystem service delivery by these habitats that would otherwise have been lost (e.g. their contributions to regulating and cultural services).

2.3. Evidence review

Given the general lack of empirical data relevant on the provision of ecosystem services by habitats in the case study sites, especially for regulating services, evidence was gathered through a review of existing literature, both peer reviewed and non-peer reviewed (e.g. government and NGO reports). Although systematic reviews are now the gold standard in evidence synthesis, due to the number of review permutations possible for this assessment, a more targeted approach was used. While this may potentially introduce bias into the findings, the purpose of this review was not to identify all the available evidence, but to demonstrate that evidence for a link between a habitat and an ecosystem service exists. A structured approach was taken to ensure a comprehensive review and traceability. Searches were undertaken in English and local languages by teams from Indonesia, Malaysia, Philippines, the UK and Vietnam.

2.3.1. Bibliographic Database Searches

Searches were performed in Web of Science and Google Scholar using the search terms: “habitat” AND “ecosystem service”, where “habitat” stands for each of the habitats including both macro and micro-habitats. “Ecosystem service” stands for each of ecosystem services included. For each service, variations of terms were used to ensure comprehensive retrieval of information. For example, variations for “Treatment and assimilation of wastes or toxic substances” included “bioremediation” and “remediation of waste”. For habitats that also occur in freshwater the search terms were extended to include “AND marine”. If the habitat also occurs in temperate or polar regions, the term “AND tropical” was added. Refine search filters were used to reduce the number of hits if searches returned studies from other disciplines such as geology or engineering. See Appendix C for a list of search terms.

To augment this approach, a snowballing technique was used in which references of articles relevant to the study were scanned for further useful publications. Reverse snowballing was also undertaken, where appropriate, by accessing the “times cited” lists of relevant articles in the search engines. Review articles were often used as they contained helpful summaries of existing bodies of literature.

2.3.2. Search for grey literature and regional reports

To gather grey literature, the same search technique was used in Google, Dogpile (https://www.dogpile.com); the British Library (http://explore.bl.uk/primo_library/libweb/action/search.do?vid = BLVU1); British Library ethos, a collection of academic theses created in the United Kingdom and held in the British library (https://ethos.bl.uk/Home.do;jsessionid = 6838C3BA0AB07238A6CAD49F1D6CA6F2); the World Bank elibrary (https://elibrary.worldbank.org/); and Opengrey (http://www.opengrey.eu/). Targeted searches were also undertaken of the websites of NGOs and multinational organisations (e.g. FAO and WWF).

2.3.3. Article screening

Search results were scanned first by title and if deemed relevant to the study question, the full text was downloaded. Where more than 500 publications were returned by a search query, only the titles of first 500 publications were scanned for relevance. The abstract of each relevant publication was then assessed for inclusion in the study. Literature from the case study countries was prioritised, followed by those from the Indo-Pacific. Literature from outside the Indo-Pacific was excluded unless no Indo-Pacific literature was found and it reported generic principles relevant to habitats, irrespective of location. Ecosystem service valuation studies were also removed unless they provided evidence for the ecosystem services that were valued. More general reviews or reports that stated that a particular habitat provides a service without showing evidence for such a statement were searched for valid references to obtain evidence. Searches were carried out between October 2018 to May 2019.

Where evidence was lacking, the authors of this study, particularly those working in the SE Asian case study sites, added their local knowledge and field observations to the evidence base. In some cases, regional experts or authors of studies were contacted to confirm information or find further information that they may have obtained but not used in their publications.

2.4. Scoring the matrix

The potential for each habitat to provide each ecosystem service was scored using a four-point scale where zero indicates no relative potential and three indicates high relative potential, following a similar approach by Geange et al. (2019). The potential of a habitat to provide an ecosystem service may not be the same as the habitats' actual capacity to provide the service due to the presence of human activities. Potential scores therefore represent what the habitat could be capable of, should human pressures be alleviated. Scores do not consider who the beneficiaries of these services are or where those beneficiaries are located. They were primarily based on the evidence collated from literature search, but also drew on the expert knowledge of the research team. Where no evidence or relevant knowledge was available the link was unscored and the matrix cell left blank. The justification for each score was captured alongside the score (Appendix F). For each ecosystem service, habitats were scored relative to each other in terms of magnitude of service provision, with the habitat with the highest and lowest potentials (as indicated by the evidence) scored first. Only whole number scores were used. While it was initially anticipated that scoring would occur at the micro-habitat level, it soon became apparent that this level of evidence was unavailable in most instances, partly due to the presence and absence of certain micro-habitats at the case study sites. Consequently, scores were only allocated at the macro-habitat level that were present across case study sites unless specific evidence was available.

A confidence score was given to each ecosystem service potential score based on the confidence the team had in the potential score and the supporting evidence (Table 1). Confidence was scored on a three-point scale where one indicated low confidence and three high confidence.

Table 1
Scoring system for ecosystem service potential and confidence scores.

	Score	Definition	Explanation
Ecosystem service potential score	3	High relevant potential	
	2	Medium relevant potential	
	1	Low relevant potential	
	0	No relevant potential	
	Blank	No evidence	
Confidence scores	3	Strong, consistent evidence and/or intuitive scientific support.	Most likely to be supported by extensive published material (both peer reviewed and grey literature). High level of agreement among sources and/or united scientific support. If it is intuitive and unchallenged by other scientists, united expert opinion can also carry high confidence. This may also be supported by local observations and information from other regions.
	2	General scientific support, but some uncertainty.	There may be some published material, although some may be from grey literature. Some disagreement among sources. Evidence available is more limited. There may also be some observations from the study team.
	1	Evidence is limited and there is considerable uncertainty, inconsistency, or variability in the evidence.	Published material may not exist or may be limited/inconsistent. Expert opinion maybe the only evidence available. There may be disagreement among sources or expert opinion is particular to an individual expert rather than widely held.
	Blank	There is no evidence for a link	

Scoring was undertaken on two separate occasions. Once the evidence had been collated, scoring was first undertaken by the individual research teams from Indonesia, Malaysia, Philippines, the UK and Vietnam. Teams comprised 3–5 academics with marine ecological and social science backgrounds and drew from across the GCRF Blue Communities project team (78 researchers in total). To ensure that all teams approached scoring in a similar manner, a guidance note was created (Appendix D) and multiple virtual meetings were held to discuss scoring approaches. Knowledge gaps identified during the scoring process led to further targeted evidence searches and consultation with experts. This first round of scoring took the individual teams between three and four days to complete.

The second round of scoring took place at a two-day workshop in Plymouth, UK (August 2019) attended by 21 researchers representing teams from all five countries. During the workshop, the following were discussed: concerns about the habitat classification, differences in interpretation of the different ecosystem services and additional scoring rules that teams had developed to reach their final ecosystem potential scores. Given the similarities in scores allocated by all teams for most provisioning and regulating services and some cultural services, it was decided to harmonise the scores across all locations to create a unified ecosystem service potential matrix that could be applied beyond the case study sites. The researchers divided into three self-selected groups with representation from each participating country. Each group was allocated a mix of ecosystem services and was provided with the existing matrix scores (potential and confidence from the five country teams) and the evidence base. Each score was discussed with a view to define a consensus score and a unified justification for this score. Any deviations from the consensus scores were noted. This was particularly true for Cu Loa Cham-Hoi An, Vietnam, where many of the cultural service scores were distinct from those of the other case study sites. Consensus scores from each group, alongside important discussion points, were shared during plenary sessions to ensure agreement.

2.5. *Validation: cross-checking the scores against the evidence and peer review*

The penultimate stage in the preparation of the matrix involved cross-checking the scores from the workshop with the evidence base, followed by expert peer review of both the evidence base and the matrix scores. After cross-checking, minor revisions were made to the confidence scores to better reflect the status of the evidence base. Peer review was undertaken by four experts with knowledge of both tropical marine habitats and ecosystem services in SE Asia. The outcome of the peer review resulted in modifications to two scores (the potential for seagrass to provide habitat for charismatic species was increased from two to three and the confidence score for mangroves to provide invertebrates for food was increased to three). One additional piece of peer reviewed evidence and six personal communications were also incorporated into the evidence base.

2.6. *Visualisation example: Biton Island, Palawan*

To illustrate the potential use of this ecosystem service assessment, a habitat map for the Black Rock MPA, Taytay Bay, Palawan (Philippines) was created and overlaid with the matrix scores. The habitat maps were generated using a supervised Machine Learning approach (Random Forests; Breiman, 2001) which was trained using a combination of existing mapping and manual image interpretation. The classification was applied to Sentinel 2B satellite data from the 7th May 2020 for the Tay Tay bay region to assign each pixel with the habitat it was most spectrally similar to. Due to the lack of high resolution bathymetry data for the area only spectral information was used and all areas where no spectral information could be defined as one of the key habitats (seagrass, coral reef, sediment or mangrove), and that were marine (as opposed to terrestrial and visually cross-checked) were then added to the “pelagic habitat”. This classification was then manually refined for Black Rock MPA using GPS points collected during fieldwork to improve the accuracy for the specific area. The final habitat maps were then converted to 50 $\times$ 50 m cells with each cell assigned the majority class falling within it. These gridded habitat maps were used to generate ecosystem service maps.

3. Results

3.1. *Modifications to habitat and ecosystem service classifications*

Across the four SE Asia case study sites, an initial total of 13 macro and 21 micro habitats were identified as relevant ecosystem SPUs with some further subdivisions to the micro habitats (Appendix A). To support disaggregated scoring of the matrix, the evidence review initially aimed to identify how each of the macro and micro-habitat classes provides each of the ecosystem services in the classification. The evidence base including the use of expert opinion, however, did not support this finer level of classification. Habitats were therefore scored at the macro level only (Table 2), unless specific evidence for a disaggregated score was available.

Workshop discussions about scoring led to modifications to the ecosystem service classification and some definitions (Table 3). For example, squid were removed from the “food from invertebrates” service (which became “food from other invertebrates”) and were incorporated into food from pelagic fish (which became “food from pelagic animals”) to better reflect their pelagic nature and to distinguish them from less mobile invertebrate species. “Genetic materials from plants” and “genetic materials from animals” were combined into one category due to insufficient evidence to score them independently. Ranching was also excluded from the definition of “genetic materials from plants and animals” as it was considered not to involve the removal of genetic material from one location to another. “Disease control” and the “treatment and assimilation of waste” services were combined due to overlaps between these and the inability to score them independently.

The cultural service “places for recreation” was originally disaggregated into places used by residents and visitors in anticipation that tourists and residents may utilise different locations, but the evidence base did not support this division and the two categories were combined. All habitats were considered to have the potential to provide “places for knowledge-based activities” and “places for ceremonial activities”. However, for ceremonial activities, it was decided that relative scoring of the habitats for this service was not possible. In some cases, there was no available evidence to score this service. Consequently, habitats were scored 1 where evidence indicated some potential. Cells were left blank were there was either no evidence or no known potential.

One cultural service was removed from the classification (“places for gathering activities”). Gathering activities (e.g. fishing and gleaning) have a clear cultural component and make significant contributions to individuals beyond the transactions made over the products harvested. It was difficult, however, to disentangle the physical location of gathering from the object being gathered (i.e. the provisioning service). Scores replicated those for food provisioning services. Consequently, the gathering service was dropped from the matrix, but it must be recognised that provisioning services contain a cultural component that is not easy to separate, at least through matrix assessments. These revisions resulted in 18 ecosystem services being scored (Table 3).

Table 2
Habitat classes used in the final version of the matrix.

Habitat type	Macro-habitat	Micro-habitat	Comments
Natural habitats	Mangrove		Including mangrove plantations
	Coral		Includes dead coral that still maintains reef structure, but excludes coral rubble
	Seagrass		
	Sand	Intertidal subtidal	
	Mud	Intertidal subtidal	
	Rock		
	Coarse substrata		
	Pelagic		
Modified habitats	Seaweed farms		
	Fish cages		
	Invertebrate mariculture		Excludes shrimp ponds as they are not present within the boundary of case study sites
	Artificial substrate		Including breakwaters, seawalls, pontoons and jetties
	Artificial beaches		

3.2. *Evidence base*

In total 452 individual publications were included in the evidence base to justify matrix scores. Some publications were used more than once as they contained information pertinent to more than one ecosystem service or habitat. This evidence base was supported by expert judgement with 95 references to expert or study team opinions or observations. Within the evidence base, 60% of all references were made

Table 3
Final ecosystem service classification and definitions used.

Ecosystem service class	Ecosystem service	Definition	Example
Provisioning	Food from plants	Food for consumption by humans from harvested plants.	Edible products from mangroves.
	Energy from plants	Energy source from harvested plants.	Mangrove for charcoal.
	Other materials from plants	Fibres or other biotic material from harvested plants used for other purposes including medicine, decoration, fashion, handicrafts, souvenirs, etc.	Products harvested from mangroves and nipa.
	Food from pelagic animals	Food for consumption by humans from pelagic animal species from wild capture fisheries and mariculture sources.	Pelagic species harvested for food e.g. tuna, mackerel and squid.
	Food from demersal fish	Food for consumption by humans from demersal animal species from wild capture fisheries and mariculture sources.	Demersal and farmed fish for food e.g. grouper, rabbitfish and snapper.
	Food from other invertebrates	Food for consumption by humans from invertebrate species from wild capture fisheries, gleaning and from mariculture sources.	Invertebrates harvested from the wild and from aquaculture e.g. molluscs, crustaceans, sea cucumbers.
	Other materials from fauna	Fibres or other biotic material from harvested animals used for other purposes, including medicine, decoration, fashion, handicrafts, souvenirs, etc.	Wild caught pearls, seashells, fish leather.
	Genetic material from plants and animals	Genetic material from marine plants and animals (including seeds, spat, spores, whole plants or animals, individual genes) for use in non-medicinal contexts, such as maintaining or establishing a population, breeding new strains or varieties, construction of new entities (from genes).	Seed or broodstock collection for aquaculture; mangrove seedlings/seeds/cuttings for plantations and mangrove replanting.
Regulating	Treatment and assimilation of wastes or toxic substances	The removal of contaminants and organic nutrient inputs of human origin, including sewage waste and other wastes.	Removal of heavy metals, agri-chemicals and other pollutants, as well as the removal of bacteria and viruses e.g. *E. coli.*
	Erosion control	The contribution of a particular component of the marine ecosystem to coastal erosion prevention and sediment retention (also including sediment stabilisation).	The role that mangrove roots play in stabilizing sediments and preventing erosion.
	Water flow regulation	The contribution of a particular component of the marine ecosystem to the dampening of the intensity of environmental disturbances such as storm, floods, tsunamis, and hurricanes and the maintenance of localized water flows such as coastal current structures. (It is recognised that tsunamis behave differently to wind and tidally formed waves and that nothing will stop some tsunamis).	The role of coral reef structures in dissipating wave energy before it reaches shorelines.
	Maintaining nursery habitats	The provision by a particular component of the marine ecosystem of critical habitat for reproduction and juvenile maturation (nursery and feeding functions).	Some bioengineered habitats with complex topographic structures have been reported to play a role in providing a refuge and feeding area for juvenile stages of fish, e.g. mangroves.
	Climate regulation	The contribution of a particular component of the marine ecosystem to the maintenance of a favourable climate through impacts on the hydrological cycle, temperature regulation, and the contribution to climate-influencing substances in the atmosphere.	This includes habitats that sequester carbon and long-term, decadal storage, e.g. mangroves
	Maintaining habitats for charismatic species	The provision by a particular component of the marine ecosystem of critical habitat for different charismatic species either as a shelter, feeding habitat or a resting place during migration and that is or could be managed for the presence of these species.	Charismatic species include plants reptiles, mammals, birds, fish and invertebrates (see Appendix E for full list considered).
Cultural	Recreation	Places that are used for recreation activities by residents (local people) and visitors	The use of beaches for recreational activities.
	Ceremonial activities	Places where customs, rituals and or religious activities occur and/or are	Sacred sites within mangroves used for ceremonial activities.

(*continued on next page*)

Table 3 (*continued*)

Ecosystem service class	Ecosystem service	Definition	Example
		significant for local beliefs	
	Creative activities	Places where the collection of objects/ materials or experiences are important for crafts and for creative processes occur.	Seagrass beds and the seagrasses themselves are used as inspiration for creative activities.
	Knowledge-based activities	Places that are used for educational activities	Visits by school children to learn about a site, citizen science or community environmental activities e.g. reef monitoring, mangrove planting and monitoring

to peer reviewed literature, 24% to grey literature and 16% to expert opinion. The majority of publications (86%) were published after 2000 and came from the case study countries or the wider Indo-Pacific (66%) (Fig. 3a). Evidence was much more readily available for mangroves, coral reefs and seagrass meadows, followed by the pelagic ecosystem and seaweed farms (Fig. 3b). Evidence for sedimentary and modified habitats (other than seaweed farms) was scarce.

In terms of ecosystem services, most evidence was found for provisioning services (49%), followed by regulating services (34%) and cultural services (12%). Approximately 5% of publications used in this study were not specific to SE Asia as they included, for example, global studies that described a habitat, ecosystem service or process. For individual ecosystem services, evidence for the "provision of food by invertebrates" was supported by the largest volume of literature (Fig. 3c) followed by the "provision of habitat for charismatic species" and "nursery habitat" (both regulating services). With the exception of "places for recreational activities", relatively little evidence was available for cultural services.

3.3. *Matrix scores*

Modifications to the habitat and ecosystem service classification compilation resulted in 270 possible habitat-ecosystem service combinations available for scoring (15 individual habitats and 18 ecosystem services). Evidence was insufficient for all combinations to be scored, for example, no evidence could be found for the contribution of seagrass habitats to "energy from plants" or rock habitats to "maintaining nursery grounds". In total 64.4% of all combinations were scored, including 55% of all habitat-provisioning service combinations, 75.6% of all habitat-regulating services combinations and 66.7% of all habitat-cultural service combinations (Table 4). The lower level of assessment for provisioning services can be attributed primarily to a lack of evidence for services generated from plants, especially "energy from plants" which could only be assessed for mangroves.

The harmonised matrix (Fig. 4) provides an overview of the scores allocated to each habitat-service combination (see Appendix F for the evidence and justification behind each score). Where harmonisation was not possible (on all but five occasions), this is noted with the score justification. Where a score could not be agreed, the score presented represents agreement for three case study sites, with the alternative score and its corresponding case study location noted below. Horizontal reading of the matrix indicates how each habitat potentially provides ecosystem services, while vertical reading provides a summary of the potential for each habitat, relative to the others, to provide a service. Gaps in the matrix, where scoring was not possible, are mostly associated with modified and sedimentary habitats as suggested by the limited availability of evidence for these habitats (Fig. 3b).

In general, there were fewer scoring gaps for the potential of biogenic habitats to provide ecosystem services, but only mangroves were assessed for all services. Mangroves show considerable potential for ecosystem service provision with 13 out of the 18 ecosystem services assessed scored as 3 (high potential). Sedimentary habitats received low potential scores across all services, while modified habitats generally scored higher for provisioning services (for which some of them are specifically designed), but less well for regulating and cultural services. Scores for the pelagic habitat were mixed. In no case, however, were individual ecosystem services assessed across all habitats. In general, regulating services were the most frequently assessed across habitats, with "maintaining nursery habitats" being assessed for all macro habitats and one micro-habitat. This was followed by "food provision from invertebrates", "water flow regulation" and "places for knowledge-based activities". Despite the inclusion of intertidal and subtidal sand and mud habitats, these micro-habitats were only scored for two and five ecosystem services respectively.

Confidence scores mirror the ecosystem service potential scores insofar as confidence is correspondingly greater for mangroves and corals and lower for sedimentary and most modified habitats. This reflects the smaller published evidence base and the greater use of expert opinion to score the ecosystem service potential for these habitats. In terms of ecosystem services, the highest confidence scores were allocated to "food from invertebrates" and "places for recreation". Confidence scores were also higher for regulating services from biogenic habitats with the exception of "water flow regulation" and "erosion control" as the roles of these habitats in these services is less clear (e.g. mangroves can act as a buffer against storm surges, but can also funnel water upstream). Confidence scores for cultural services are also generally lower, reflecting the difficulty in harmonising these scores and the absence of documented evidence for these services.

3.4. *Data visualisation example: Biton Island, Palawan*

As an illustration, the information derived from the matrix for four provisioning services (Fig. 4) was converted into ecosystem service potential maps for the Biton Island, Palawan (Fig. 5). The absence of detailed habitats maps, and challenges associated with using satellite data to create habitats maps, has meant that only five distinct habitats could be included (mangroves, corals, seagrasses, sand and pelagic). Nevertheless, the relative importance of these habitats for provisioning services can be seen.

4. Discussion

To our knowledge this is the first attempt to systematically capture the provision of ecosystem services from tropical marine habitats. Ecosystem service scores together with the evidence base and our confidence in this evidence, constitute a considerable advance in the assessment of ecosystem services in marine tropical regions, where the state of knowledge lags behind temperate systems (Townsend et al., 2018; Lautenbach et al., 2019). We believe the harmonised ecosystem service scores for marine and coastal habitats constitute a valuable baseline for marine ecosystem service assessments within SE Asia, and highlight the gaps and research needs to improve our understanding of ecosystem service provision from tropical marine systems.

4.1. *Uncertainty within the matrix*

The absence of reporting on the uncertainties associated with the development of an ecosystem service potential matrix is one of the main criticisms of this approach (Jacobs et al., 2015; Campagne et al., 2017). The primary method used in this study for dealing with uncertainty involved the creation of a clear evidence trail and justification for each

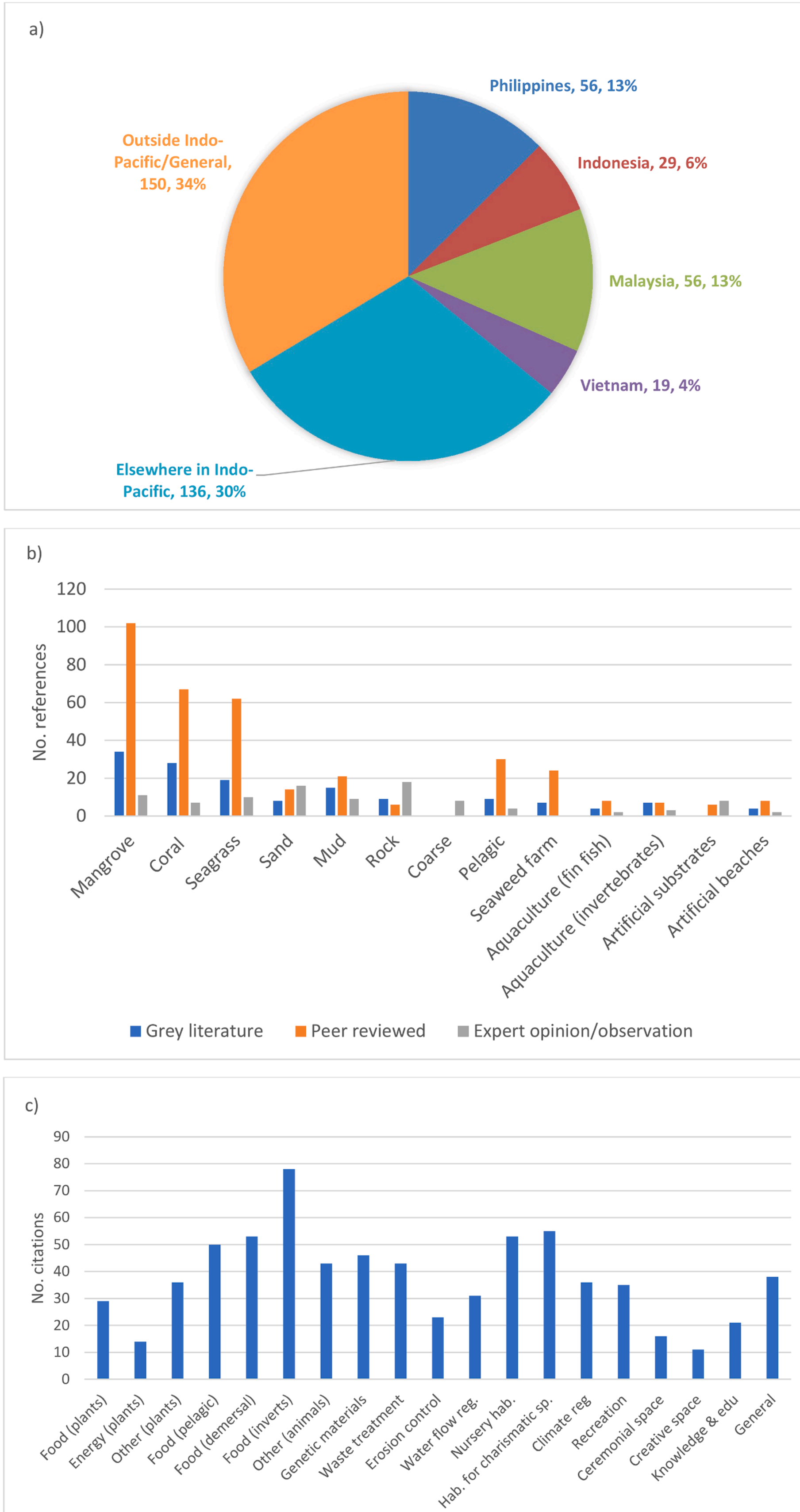


Fig. 3. a) Study location of literature cited; b) Categorisation of evidence used and c) Citations by ecosystem service.

Table 4
Habitat-ecosystem service combinations scored.

	Provisioning	Regulating	Cultural	Total
Possible habitat-ecosystem service combinations	120	90	60	270
Combinations assessed	66	68	40	174
% combinations assessed	55.0	75.6	66.7	64.4

score, the assignment of confidence scores to ecosystem service potential scores and a validation stage. However, not all aspects of uncertainty can be removed in this way. While Müller et al. (2020) and Hou et al. (2013) discuss potential uncertainties associated with matrix approaches at length, we focus on four areas of particular relevance to this study.

4.1.1. Absence of habitat information

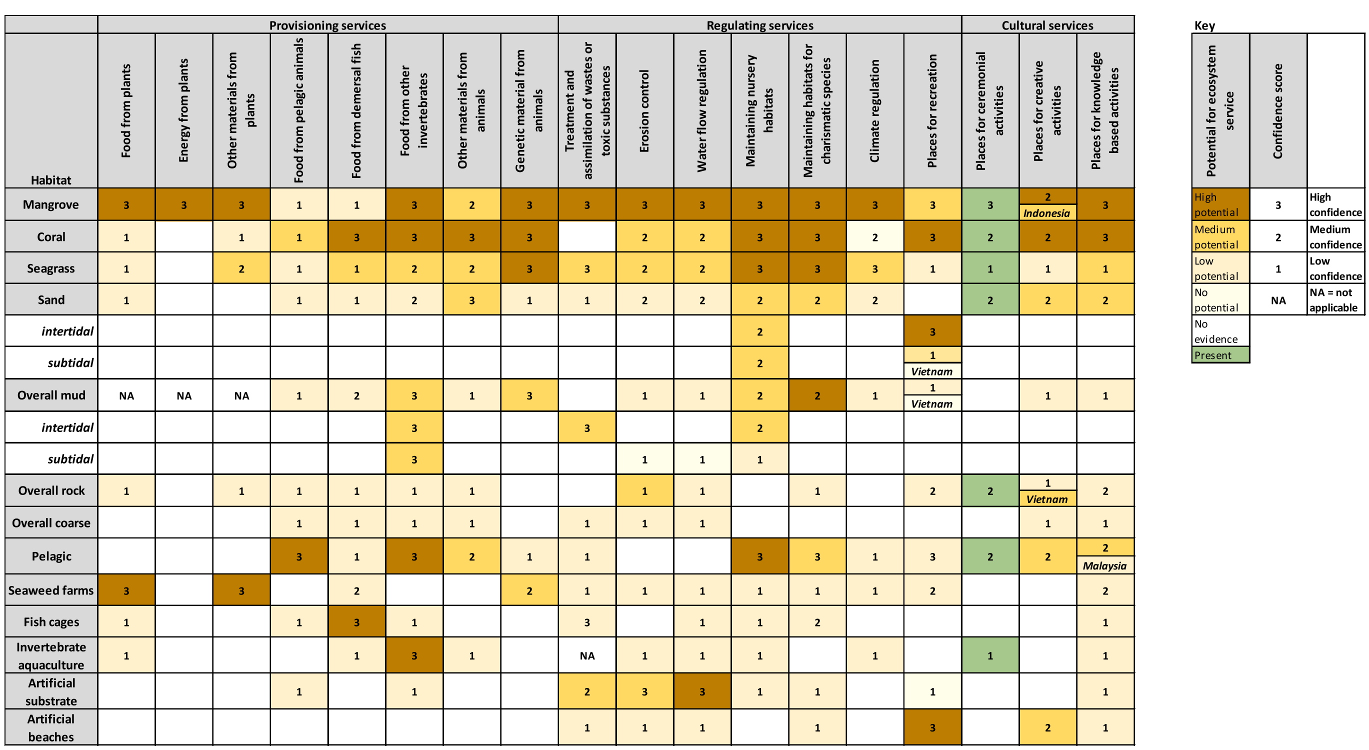
The accuracy of matrix-based assessments depends not only on the judgment of the experts completing the scoring, but also on the quality of baseline data on the habitats for which the scores are assigned. Ideally, information on the habitats supplying the ecosystem services should be gathered in as detailed manner as possible, in a resolution and scale appropriate to the context for which the assessment is made (Burkhard et al., 2012). The general absence of habitat data faced by this project, beyond knowledge of the location of the broad biogenic habitats, resulted in the need to generate a generic habitat classification. It has not been possible to ground truth this classification beyond consultation with local stakeholders. Considerable uncertainty exists about the sedimentary habitats in particular, yet despite these habitats generally receiving low ecosystem service potential scores, combined they form the majority of the marine habitats in the case study sites in spatial terms. Their overall contribution to ecosystem services by these habitats may therefore be substantial.

Whether habitats are the most appropriate service providing unit (SPUs) can also be questioned. Spatial approaches in the marine environment do not capture the horizontal and vertical movement of species through the water column, nor the temporal differences in use of habitats by species at different stages of their lifecycle (Townsend et al., 2018; Hooper et al., 2019). Culhane et al. (2018) therefore recommend the use of both habitats and biotic taxa as SPUs. Being flexible, the matrix approach can accommodate this suggestion (e.g. Potts et al., 2014), and this may be a useful approach for assessing areas and ecosystems with shared species.

4.1.2. Resolution and location of evidence

The literature review was the main source of evidence used to score the matrix. Despite extensive searches, data could not be found relevant to all habitats and ecosystem services, and hence the quality and coverage of the literature found was variable. While care was used to check the appropriateness of the studies for inclusion, differences in the species, environmental conditions or cultural circumstances of each study increase the uncertainty in the matrix scores. Where possible, this uncertainty is reflected in the confidence scores and the validation stage, but inconsistencies may remain.

The gaps in the evidence base indicate clear research needs for advancing ecosystem service assessments for the SE Asian marine environment. Sedimentary habitats require particular attention. Marine soft sediments are among the largest habitats globally and in SE Asia, but little is known about the species assemblage and associated ecological role (Gray, 2002; De Brauwer et al., 2019). Elsewhere, the biota within marine sediments is recognised for its role in ecosystem service provision, especially regulating services (Weslawski et al., 2004; Hope et al., 2020). In terms of ecosystem services, provisioning services are well documented especially when the focus is on food from marine animal species, but cultural services, other than recreation are poorly represented in the evidence found. This is not uncommon (Liquete et al., 2013); Garcia Rodrigues et al. (2017) highlighted an absence of cultural ecosystem service research in SE Asia.



Habitat	Food from plants	Energy from plants	Other materials from plants	Food from pelagic animals	Food from demersal fish	Food from other invertebrates	Other materials from animals	Genetic material from animals	Treatment and assimilation of wastes or toxic substances	Erosion control	Water flow regulation	Maintaining nursery habitats	Maintaining habitats for charismatic species	Climate regulation	Places for recreation	Places for ceremonial activities	Places for creative activities	Places for knowledge based activities
	Provisioning services								Regulating services							Cultural services		
Mangrove	3	3	3	1	1	3	2	3	3	3	3	3	3	3	3	3	2 Indonesia	3
Coral	1		1	1	3	3	3	3		2	2	3	3	2	3	2	2	3
Seagrass	1		2	1	1	2	2	3	3	2	2	3	3	3	1	1	1	1
Sand	1			1	1	2	3	1	1	2	2	2	2	2		2	2	2
intertidal												2			3			
subtidal												2			1 Vietnam			
Overall mud	NA	NA	NA	1	2	3	1	3		1	1	2	2	1	1 Vietnam		1	1
intertidal						3			3			2						
subtidal						3				1	1	1						
Overall rock	1		1	1	1	1	1			1	1		1		2	2	1 Vietnam	2
Overall coarse				1	1	1	1		1	1	1						1	1
Pelagic				3	1	3	2	1	1			3	3	1	3	2	2	2 Malaysia
Seaweed farms	3		3		2			2	1	1	1	1	1	1	2			2
Fish cages	1			1	3	1			3		1	1	2					1
Invertebrate aquaculture	1				1	3	1		NA	1	1	1		1		1		1
Artificial substrate				1		1			2	3	3	1	1		1			1
Artificial beaches									1	1	1		1		3		2	1

Fig. 4. Matrix of potential ecosystem service scores by habitat. Shading indicates service score while numbers represent confidence scores. Scoring for places for ceremonial activities differed from other ecosystem services with shading indicating potential presence of the service; a blank cell means no known potential or evidence for ceremonial activities in this habitat. A single country is noted when the distinct score from one case study could not be harmonised with scores from other case studies.

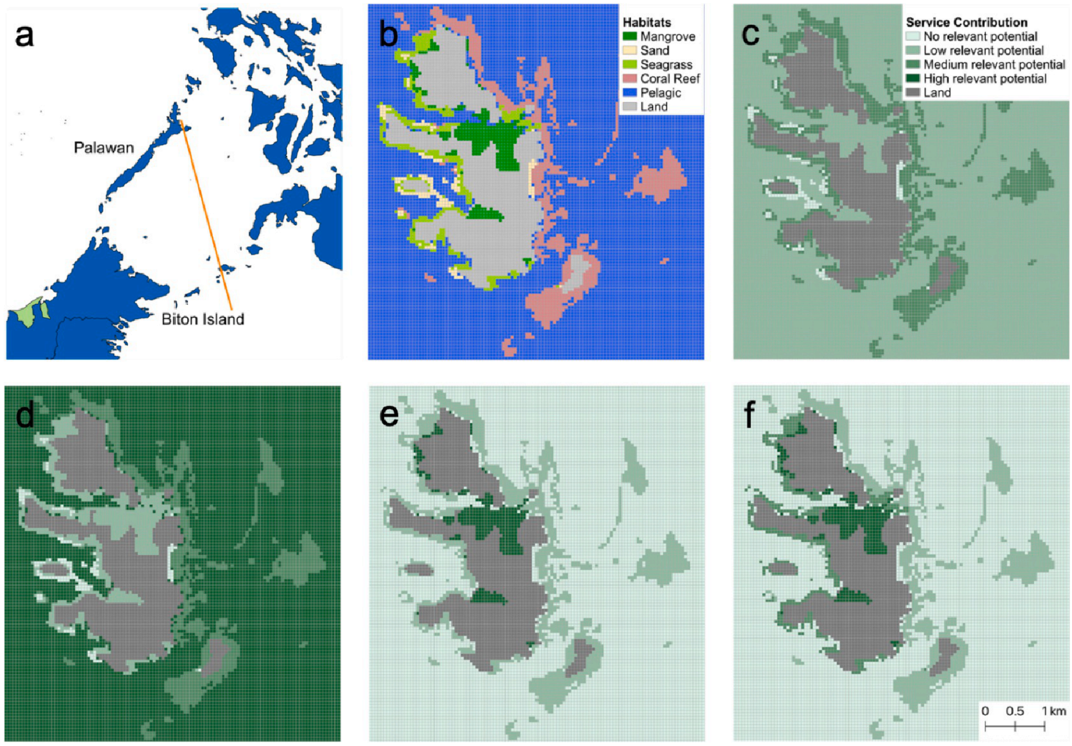


Fig. 5. Visualisation of the potential for provisioning service delivery from the Biton Island, Tay Tay, Palawan in the Philippines. a) Location of the site; b) Habitat map; c) Food from demersal fish; d) Food from pelagic animals; e) Food from plants; f) Other materials from plants.

4.1.3. Modified habitats: Pressure or ecosystem service providers?

In terrestrial applications of the matrix approach, modified habitats such as agricultural land and urban areas are included in the matrices as land cover types, following the use of land use land cover (LULC) geospatial mapping approaches to define the ecosystem SPUs. The absence of an analogous marine mapping approach has meant that previous marine matrix applications have used either natural, unmodified habitat types (e.g. Geange et al., 2019) or seabed biotopes (e.g. Salomidi et al., 2012), or a mixture of habitats and key species (e.g. Potts et al., 2014) as SPUs. Given the focal applications of these studies on marine protected areas (e.g. Potts et al., 2014; Geange et al., 2019) or marine planning of whole seas (e.g. Galparsoro et al., 2014; Depellegrin et al., 2017), modified habitats may not form a large proportion of the habitat types in these areas. In SE Asia, however, coastal environments such as those of the case study sites can contain large numbers of artificial structures such as fish cages, seaweed farms, pearl farms, jetties and seawalls (Chung et al., 2017; IPBES, 2018). Typically, these structures and associated activities are viewed as pressures on the marine environment (Holmer, 2010) but there is growing evidence that these structures act as fish aggregating devices (e.g. Oakes and Pondella II, 2009, Sudirman et al., 2009) and are likely to be rapidly colonised by marine organisms that can contribute to the provision of ecosystem services (Alleway et al., 2019).

The inclusion of artificial structures as modified habitats is not without challenge due to the three dimensional nature of the marine environment. Some artificial structures are found in the water column above coral reefs, seagrass beds or sedimentary habitats. It is not possible, given the evidence available, to entirely disentangle the contribution of the artificial structures to the provision of ecosystem service from the natural habitat below or the water column (pelagic habitat) itself. This introduces an additional layer of uncertainty into the modified habitat scores. Formal inclusion within the assessment of these modified habitats, which are increasingly dominating coastal seascapes in SE Asia, acknowledges their positive contribution to ecosystem services, in contrast to the negative impacts often associated with them (e.g. Macura et al., 2019). This negative impact, however, should not be overlooked. A subsequent stage in this ecosystem service assessment will add an additional layer into the GIS to illustrate how human pressures are influencing the ability of habitats to provide ecosystem services (section 4.2.1).

4.1.4. Interdependencies and overlaps between services

One of the biggest challenges when scoring the matrix arose from the interdependency and overlap between ecosystem services. Although the definition of each individual ecosystem service is designed to reduce overlap and avoid double counting (Fisher et al., 2009), some overlaps still exist, especially with cultural services. Cultural services are an accumulation of human experiences tied to the environment, many of which are location specific (Chan et al., 2012) and the overlap between provisioning and cultural services is particularly striking. While it is tempting, for ease, to remove cultural services from the matrix (e.g. Geange et al., 2019), Chan et al. (2012) explicitly recognise that cultural ecosystem services overlap with other services and suggest that, where valuation is not the end point, this overlap is not problematic. Understanding the cultural complexities associated with marine resource and ecosystem service use may be essential to the success of marine management measures (FAO, 2001). Where such measures are introduced, it may not be possible to trade cultural ecosystem services off against other services. Impacts need to be examined discursively alongside differential access of groups to these services (Chan et al., 2012; Fish et al., 2016).

These interdependencies are not unique to provisioning and cultural services. Regulating services (e.g. maintaining nursery habitats) are essential to the supply of provisioning services (e.g. food from demersal, pelagic and invertebrate species) and, in some cases should be considered as supporting services. Ecosystems are inherently complex with multiple species contributing to multiple functions supporting multiple services. While the matrix can provide an overview of the importance of different habitats to the provision of different services, management actions that build upon the matrix model need to take this complexity into consideration (Townsend et al., 2018).

4.2. Application of the matrix

4.2.1. Data visualisation

The next stage in the ecosystem service assessment presented here will involve further layering of the ecosystem service potential scores on to habitat maps (exemplified in Fig. 4), alongside information relating to the pressures resulting from human activity (e.g. aquaculture and fishing activities) and the sensitivity of the habitats to these pressures (cf. Hooper et al., 2017). Our example (Fig. 4) clearly shows the differences between service provision within the habitats even around a relatively small example area. Analysis can then be undertaken to identify how different management measures may impact ecosystem service delivery (cf. Langmead et al., 2015). While it is recognised that there may be questions over the accuracy of the baseline data used to create the matrix, and that detailed interpretation may not be possible (Jacobs et al., 2015), the purpose of the approach is to provide a rapid assessment for areas of policy or management importance, especially in data-poor regions. Ecosystem complexity is reduced into broadly understandable information (albeit with limited accuracy). When accompanied with additional data layers and analysis, the ensemble may indicate areas of disproportionately high ecosystem service provision, where further more in-depth assessments are needed, or where interventions or policies should be focused to reduce pressures (Burkhard et al., 2012, Burkhard et al., 2014, Gorn et al., 2018).

4.2.2. Alternative scoring systems

The matrix scoring exercise presented here was undertaken by members of the scientific community through interpretation of the evidence available in the literature. Campagne et al. (2017), however, recommend the use of carefully selected mixed stakeholder groups due to their different backgrounds and motivations (Jacobs et al., 2015). How the scores are then combined presents a challenge, but methods are available, such as the calculation of central values (Campagne et al., 2017) or weighting methods that have been applied to produce indices (e.g. Scottish natural capital asset index; McKenna et al., 2019). Presenting alternative representations of the matrix (e.g. those developed by community groups together with those from local resource managers) without combining scores could act as a useful communication tool. It could help identify areas of knowledge overlap and divergence and indicate how the introduction of management issues may need to be accompanied by careful discussion and communication. This should create an iterative loop that can improve the accuracy of the gathered data through stakeholder engagement (Luyet et al., 2012).

4.2.3. Score transferability

While the objective behind the creation of the ecosystem service potential matrix has been to support the management of the four GCRF Blue Communities case study sites, the general absence of data and the resulting creation of a more generic harmonised matrix and accompanying evidence review can provide a baseline for further assessments across the wider SE Asia marine region. There was particular commonality among scores allocated to habitats in Indonesia, Malaysia and the Philippines, with all case study areas in relative close proximity and populated by ethnically similar people. While the Vietnamese case study site is more distinct, both ecologically and culturally, harmonisation of scores was still largely possible aided by the broad scale at which habitats were classified and assessed. This suggests that it may be possible to transfer the matrix to other tropical marine locations. The appropriateness of this requires further investigation as no other tropical marine ecosystem service potential matrices are available for comparison. Such re-use of ecosystem service potential matrices, however, is already observed in terrestrial applications (Campagne et al., 2020).

While it is recognised that ecosystem services are not delivered uniformly across habitats and seascapes (Barbier et al., 2008; Townsend et al., 2018), application of the harmonised matrix will enable a comparative view of how ecosystem services are provided by different sites with similar habitat composition. Local differences, however, will be lost indicating the need for the matrix to be updated where specific case study data are available (e.g. more refined habitat classes and or detail of ecosystem service provision by habitat). The scores for places for ceremonial activities are a case in point. While this study developed harmonised scores for most services relevant to marine SE Asia, this was not possible for places for ceremonial activities due to the differences in local tradition and culture. When re-using this matrix, it will therefore be important to incorporate local knowledge and data, specific to the site of interest.

On a broader scale, the ecosystem service potential matrix may also provide data relevant to the assessment of natural capital. Natural capital is recognised as a large component of national wealth, especially in lower income countries, and is considered essential for economic performance and the well-being of people (Lange et al., 2018). Rapid economic growth in many SE Asian countries has occurred at the expense of natural capital and there are mounting calls for improved mechanisms for accounting for the contribution of natural capital to social and economic development (IPBES, 2018). An ASEAN Natural Capital road map is in preparation (ASEAN, 2019) and countries in SE Asia (e.g. Singapore and Philippines) are undertaking natural capital assessments (Natural Capital Singapore, 2018; Losada et al., 2017). The focus of natural capital accounts is often terrestrial, but a marine focused ecosystem service potential matrix can contribute to the development of marine natural capital asset registers and support the assessment of natural capital stocks and flows (Hooper et al., 2019).

5. Conclusions

Ecosystem service assessments require a need for pragmatism, especially in the context of limited data and resources. The ecosystem service potential matrix model offers one such pragmatic approach allowing the incorporation of different types of data alongside expert judgement. It has proved particularly useful in the context of the development of a tropical marine ecosystem service assessment, where data on most aspects of the marine ecosystem are scarce. While the matrix has been developed to support the assessment of ecosystem services in four case study sites, the scarcity of data has led to the development of a generic, harmonised matrix that, together with the accompanying evidence base, can be applicable to sites across SE Asia. Such applications need to incorporate local evidence where available.

The evidence base used to create the matrix is derived from an extensive literature review combined with expert judgement. The justification for each ecosystem service potential score is clearly presented alongside an assessment of confidence in this score. While the matrix and evidence base has been validated through cross-checking and peer review, it is important to recognise the uncertainties generated from the absence of data and limited understanding of the complexity of the marine environment. The assessment of the evidence base indicates areas for future research that may help to reduce these uncertainties and close knowledge gaps. This includes a need for more extensive habitat mapping with an emphasis on micro-habitats within macro biogenic habitats, as well as sedimentary habitats. This should be accompanied by further investigation into cultural ecosystem services as relatively little is documented about how marine and coastal ecosystems support local culture in SE Asia beyond their contribution to recreation. Furthermore, the overlaps between cultural services and other ecosystem services should be better recognised as well as how other service types contribute to culture. This needs to be combined with mechanisms to capture the spatial and temporal dimensions of marine ecosystems.

The assessment presented here represents a significant advancement for marine tropical ecosystems. When mapped spatially and combined with other relevant data on human activities and pressures within the marine environment, the matrix could be a useful tool for local resource managers and national decision-makers alike. Capable of communicating the complexity of the marine environment in a readily understandable way, the matrix can be used as a basis for decision-making that better captures the importance of the marine environment to local and national prosperity and well-being.

CRediT authorship contribution statement

Caroline Hattam: Funding acquisition, Project administration, Investigation, Writing - original draft, Writing - review & editing. **Stefanie Broszeit:** Investigation, Data curation, Writing - original draft, Writing - review & editing. **Olivia Langmead:** Project administration, Investigation, Writing - original draft, Writing - review & editing. **Radisti A. Praptiwi:** Investigation, Data curation, Writing - original draft, Writing - review & editing. **Voon Ching Lim:** Investigation, Data curation, Writing - review & editing. **Lota A. Creencia:** Funding acquisition, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Tran Duc Hau:** Investigation, Data curation, Writing - original draft, Writing - review & editing. **Carya Maharja:** Investigation, Data curation, Writing - original draft, Writing - review & editing. **Tatang Mitra Setia:** Investigation, Writing - review & editing. **Prawesti Wulandari:** Investigation, Data curation, Writing - review & editing. **Jito Sugardjito:** Funding acquisition, Writing - review & editing. **Jonson Javier:** Writing - review & editing. **Edgar Jose:** Writing - review & editing. **Lea Janine Gajardo:** Writing - review & editing. **Amy Yee-Hui Then:** Writing - review & editing. **Affendi Yang Amri:** Funding acquisition, Writing - review & editing. **Sofia Johari:** Writing - review & editing. **Eva Vivian Justine:** Writing - review & editing. **Muhammad Ali Syed Hussein:** Writing - review & editing. **Hong Ching Goh:** Funding acquisition, Writing - review & editing. **Nguyen Phuc Hung:** Writing - review & editing. **Nguyen Van Quyen:** Writing - review & editing. **Le Ngoc Thao:** Writing - review & editing. **Nguyen Hoang Tri:** Writing - review & editing. **Andrew Edwards-Jones:** Writing - review & editing. **Daniel Clewley:** Data curation, Writing - review & editing. **Melanie Austen:** Funding acquisition, Project administration, Writing - review & editing.

Declaration of Competing 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2021.101346.

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