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Original Article

Marine habitat mapping to support the use of conservation and anti-trawl structures in Kep Province, Cambodia

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The marine habitats within the Kep Archipelago, Cambodia, support species of conservation importance and commercial value. Despite the area being designated a Marine Fisheries Management Area (equivalent to a Marine Protected Area locally), illegal trawling has continued to damage vulnerable habitats within the region. To augment the protection of the designated area, Conservation and Anti Trawl Structures (CATS) have been deployed locally. These structures can snare the nets of illegal trawlers and provide a hard substratum for coral colonization. A sidescan sonar survey and ground truthing campaign was used to precisely locate the 40 CATS deployed and produce maps of the important benthic habitats in the area. Due to the challenging coastal environment and minimal available infrastructure, this study used small, rechargeable or low-power (12 V), and low-cost habitat mapping equipment to map the approximate extent of several benthic habitats of conservation interest. The area and type of habitat protected by CATS has been estimated by combining the marine habitat map with the precise locations of the deployed CATS. It is hoped that this information will help inform local management decisions, such as optimizing the placement of future CATS.

Keywords: anti-trawl devices, Cambodia, marine habitat mapping, seabed defence, seagrass.

Introduction

The marine habitats surrounding the islands of Kep Province, Cambodia, support species of conservation importance and commercial value (both in terms of fisheries and tourism), as well as multiple coastal habitats providing ecosystem services that underpin the country's growing coastal economy, food security, and the resilience of coastal communities (Teoh *et al.*, 2020). Historically, the area of seagrass in Kep was one of the most extensive in SE Asia (United Nations Environment Programme, 2007) and contains a small but locally important area of coral reef. However, these marine habitats are exposed to a high degree of anthropogenic pressures such as destructive and exploitative fishing, habitat degradation, and coastal pollution (Teoh *et al.*, 2020, and references within). Of particular concern within Kep Province is the influence of broad-scale, intensive, and unmanaged trawling activities, both from national and transnational sources. Despite the prohibition of trawling in 2006 in areas shallower than 20 m (The Cambodian Law on Fisheries, Article 49), which encompasses most of the provincial waters of Kep, bottom trawling and electric trawling remain a prevalent and pervasive threat within the Kep Archipelago.

Based on the national and international value of the marine habitats in Kep, a Marine Fisheries Management Area (MFMA—equivalent to a marine protected area), was created by Cambodia's Ministry of Agriculture, Forestry, and Fisheries and the Kep Municipality in April 2018 to manage human pressures and preserve coastal marine habitats (Figure 1). Trawling and other types of intensive fishing have been banned within the MFMA, while small-scale commercial and subsistence fishing is permitted within selected areas of the MFMA. The network of protected areas in Kep also includes two "no-take" zones surrounding the islands of Koh Ach Seh and Koh Angkrong as well as a seasonally closed refugia

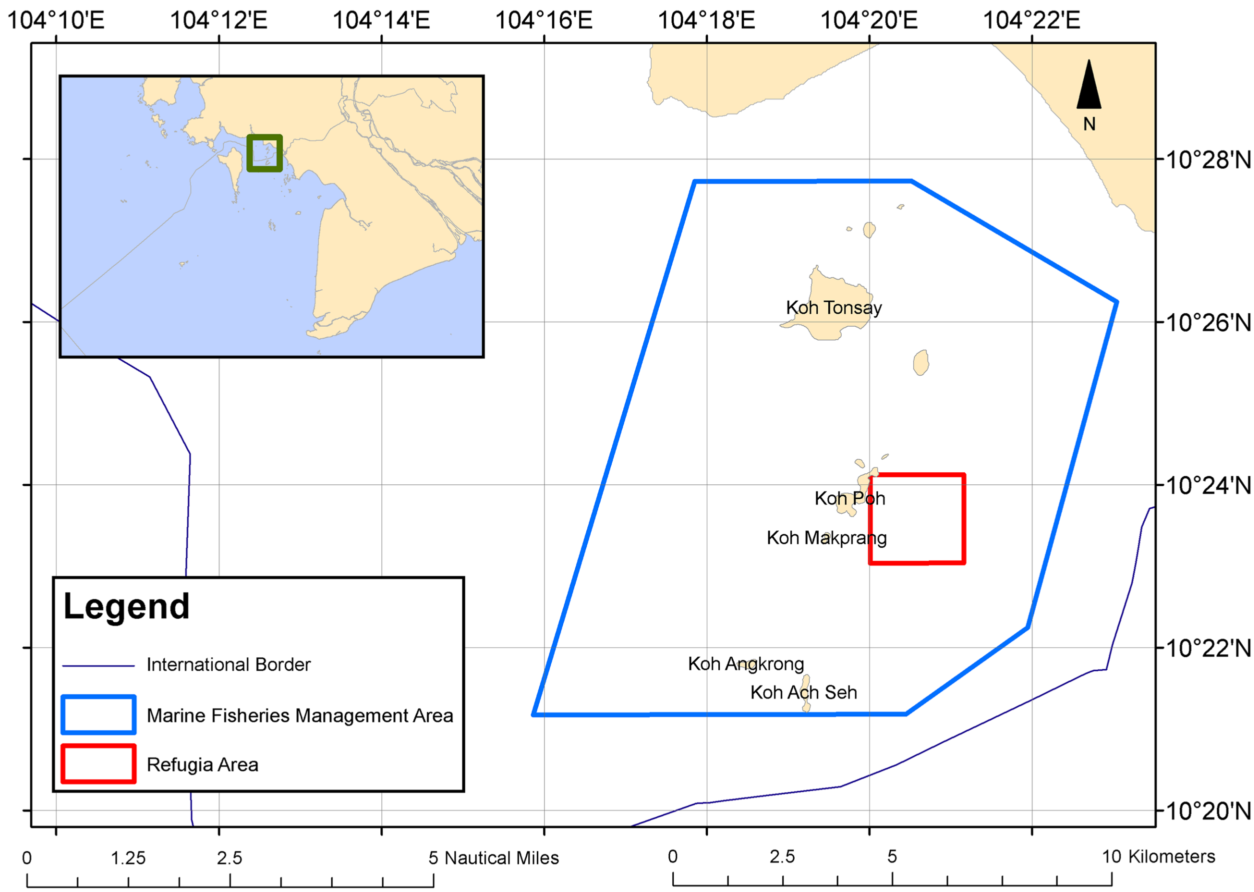

Figure 1. Location of the islands off Kep Province Cambodia. The green square within the inset map shows the location of the main figure. The international border is between Cambodia (to the north) and Vietnam (to the south).

area near Koh Poh (Figure 1). By providing the required level of protection, these efforts have made a substantial contribution by Cambodia to two of the goals set by the United Nations Sustainable Development Group, namely "Ensure sustainable consumption and production patterns" (SDG12) and "Conserve and sustainably use the oceans, seas and marine resources for sustainable development" (SDG14; General Assembly of the United Nations, 2015).

Local marine conservation efforts have been bolstered by the work of Marine Conservation Cambodia (MCC), which operates from Koh Ach Seh (Figure 1). Their primary objectives include: (i) the monitoring of coastal habitats (both protected areas and the wider environment); (ii) monitoring endangered and valuable species (including Irrawaddy dolphins, seahorses, and commercial fishes); (iii) supporting marine protection *via* assisting in patrols with local authorities and the deployment of "Conservation and Anti-Trawling Structures" (CATS); (iv) advocacy work that contributes to provincial and national marine policy; and (v) capacity building for marine scientists and conservationists locally. MCC has also been delegated responsibility by the Ministry of Agriculture, Forestry, and Fisheries, for the management and protection of Koh Ach Seh and 12 other island reefs in the area as well as approximately 30 km^2 of seagrass beds within Kep Province.

Despite the designation of refugia, no-take zones and a protected area in Kep Province, illegal fishing continues to occur (Reid *et al.*, 2019). Illegal fishing has both negative environmental and socio-economic consequences (Liddick, 2014). The local habitat damage compromises the: (i) abundance and diversity of the species they support; (ii) resilience of the ecosystem; and (iii) fisheries landings and commercial opportunities for local fishers, ultimately leading to social conflict (Long *et al.*, 2020).

To deter illegal trawling and protect critical habitats within the marine protected area, MCC have started to deploy CATS on the seabed. The primary objective of the CATS is to snare and entangle nets, and thereby dissuade illegal fishing within protected areas. The secondary design function of the CATS is to provide artificial reef blocks and thereby provide hard substrata for encrusting epifauna (corals and bivalves) and encourage the aggregation of fish and invertebrates.

The placement of artificial reefs to protect and restore existing vulnerable habitats, particularly seagrass meadows, in areas where trawling is banned has occurred throughout Europe from the late 1970s (Jensen, 2002). A priority in the deployment of these reefs has been to reduce or eliminate illegal trawling and this has been observed in many of the artificial reef areas, although recovery of already damaged habitats did not always occur (Relini and Orsi Relini, 1989; Guillén *et al.*, 1994; Jensen, 2002; Giakoumi *et al.*, 2015). Many of the reefs have also been monitored to assess their influence on species richness and abundance, with some areas showing increases in both, with the hard substrate often acting as a settlement site (Jensen, 2002).

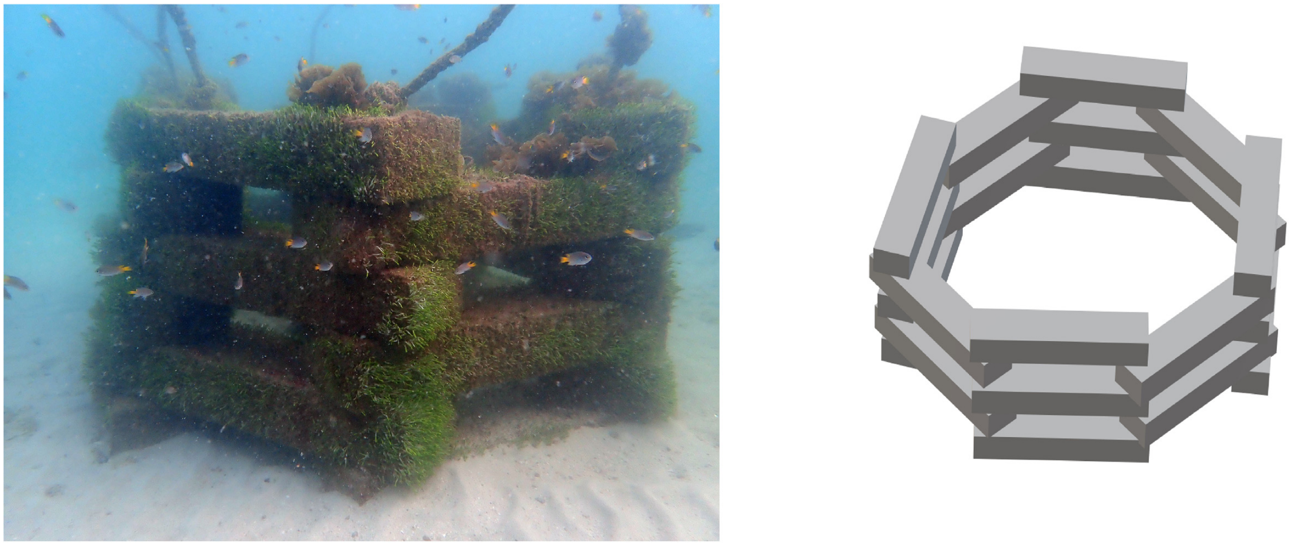

Figure 2. Deployed CATS in shallow water and a model demonstrating the constructed CATS (images courtesy of MCC).

The rationale, design, construction, and placement of conservation and anti-trawl structures

The CATS are constructed from cast concrete blocks. Blocks are lowered to the seabed from a deployment vessel. Once on the seabed, scuba divers manoeuvre and pin each block into the configuration shown in Figure 2. Once assembled underwater, a CATS is 2.5 m wide and, built from four to five layers with four blocks per layer, has a total weight of between 1.9 and 2.5 tonnes. This weight causes a portion of the first tier of blocks to sink into softer sediments and acts to anchor the entire CATS on the seabed. The number of layers and the weight of the blocks can be adapted according to the depth and intensity of fishing. The CATS are specifically designed and constructed to provide structural stability to maintain their form and position when ensnaring trawling nets. They also provide structural complexity and optimal surface area for encrusting organisms, as well as protected habitat for fish and invertebrates.

The materials, construction, and deployment of one CATS costs MCC approximately $500 USD. The CATS were deliberately designed to: (i) be cheap to manufacture; (ii) only require simple construction (e.g. cranes not required) and deployment equipment (e.g. large or specialized vessels not required); and (iii) not require specialized construction skills. As such, it is hoped that other coastal communities will be able to implement similar strategies, and thereby reduce the need for fisheries patrols and interactions with illegal fishers.

The placement of the CATS within the MFMA was determined by: (i) the likely location of undamaged habitats (based on diver surveys conducted by MCC) and areas with the greatest potential for recovery; (ii) the increased effectiveness of clustering CATS (based on 5 years of surveillance and patrols); and (iii) proximity to Koh Ach Seh (the location of the MCC station in the area). The triangle created between Koh Ach Seh, Koh Angkrong, and Koh Makprang was identified as being a suitable deployment area as it contained coral outcrops, seagrass, and experiences high levels of illegal fishing. Beginning with Koh Ach Seh, the CATS were deployed approximately 350 m apart, a balance between preventing trawling between the structures and increasing the size of the area protected. It is apparent from local observations that as the illegal fishers began to experience difficulties trawling in this area, they have generally avoided the area and additional CATS have not been necessary (A. Haïssoune, pers. comm. 22nd July).

Objectives

As of July 2019, 40 CATS had been deployed around Koh Ach Seh and Koh Angkrong. Due to difficulties of remaining on-station during the deployment of CATS and georeferencing structures underwater, the location of the CATS is known to within $\pm$ 50 m. This level of geo-referencing uncertainty makes it difficult for divers to revisit CATS for assessments of condition and to establish the proximity to benthic habitats of interest. Furthermore, the spatial distribution of important habitats, such as seagrass and reef mounds are not known in detail, i.e. point observations of habitat type are available but fine-scale multi-habitat maps, produced using modern full coverage acoustic techniques, are not available. The objectives for this study were to: (i) map the seabed habitats (coral reefs and seagrass surrounding Koh Ach Seh, Koh Angkrong, and Koh Poh and (ii) locate and georeference the anti-trawl structures placed locally by MCC. This information will be used to calculate the type and area of seabed protected. The spatial data will also facilitate the strategic placement of additional CATS to maximize the protection of high-value habitats.

Material and methods

Study site

Koh Ach Seh island is in the southern part of Kep Province (Figure 1). The town of Kep is the closest populated area of the mainland to the island (separated by approximately 13 km) and the island is the furthest Cambodian island from the mainland and the closest island to the Vietnamese border. The island is uninhabited except for a small marine police station and the MCC conservation and research base.

The seabed around Koh Ach Seh, and the wider area, is between 1.5 and 4.5 m deep. The coastal waters of Kep are also very turbid due to freshwater input from two of the Mekong tributaries: Kampot river and Giang river. The high turbidity precludes the use of remote, optical mapping methods such as aerial or satellite imagery, and meant that subtidal mapping required an in-water, acoustic mapping method. Additionally, Koh Ach Seh and the vessels available in the local area lacked power supplies; hence, all survey equipment had to be powered from rechargeable internal batteries or from 12 v batteries that were recharged by generator overnight. The combination of high turbidity, shallow waters, and reduced infrastructure greatly reduced the survey equipment options and extent of the survey area.

Apparatus and survey design

Acoustic remote sensing with a sidescan sonar

The Blueprint 452F StarFish system is a lightweight and compact sidescan sonar that can be powered using an external 12 V battery. An inverter was used to power a laptop computer that controlled the sidescan sonar and merged GPS positioning (accuracy $\pm$ 5 m). It was selected for the acoustic survey due to: (i) the shallow waters within the survey area; (ii) the difficult logistics in getting equipment to and from the island; and (iii) the survey team were limited to the use of small boats lacking in-built power supplies (12, 110, or 240 V). The StarFish 452F operates at 450 kHz and includes CHIRP technology (i.e. CHIRP: Compressed High Intensity Radar Pulse) techniques substitute a single frequency for an acoustic burst that cycles through several frequencies during transmission, which can significantly improve the range resolution and target discrimination). The sonar is able to generate a 200 m ensonified swathe through these frequencies (beam angles 0.8° horizontal and 60° vertical).

Acoustic data were processed using SonarWiz, which was used to: (i) track the bottom of the seabed; (ii) apply layback offsets; (iii) apply an empirical gain normalization to all of the tracks; (iv) apply a de-stripe filter to remove heavy weather artefacts; and (v) export a 15 cm GeoTIFF of the survey area on completion. Subsequent analysis was undertaken in ArcMap and R Studio. As the survey site was very shallow, the tow used for the sidescan sonar was very short (set to 4 m behind the vessel). This length of tow remained unchanged throughout the survey and maintained the sonar directly behind the towing vessel.

Ground truthing using a micro remotely operated vehicle

The acoustic information was processed at the end the sidescan survey (approximately 5 d of acquisition). Ground truthing stations, sufficient to fill the remaining 4 d on site, were selected using expert judgement from the final acoustic surface. Care was taken to: (i) spread the stations between obvious acoustic differences; (ii) ensure a minimum number of observations were collected in each acoustic signature; and (iii) ensure stations were spread randomly within regions and separated by a minimum distance of 100 m. The lack of a usable power supply on the survey vessel meant that the survey team was restricted to the use of battery powered ground-truthing equipment only. A battery powered DeepTrekker 4 Remotely Operated Vehicle (ROV) was used to collect video and still photography of the seabed. The ROV was also fitted with a GoPro Hero 4 HD camera to provide additional imagery from the ROV.

To maintain the best georeferencing possible from a "leaving surface" GPS position, the ROV was driven to the seabed with a steep descent angle and facing the prevailing current. Having reached the seabed, the stationary ROV was used to film the seabed looking in one direction for about 20 s and then the process repeated at plus 90, 180, and 270°. Processing of the imagery estimated the percentage cover of substrata and the dominant species in each of the four replicates from each station. Species were identified to lowest taxonomic level.

Data analysis

Examination of the sidescan sonar data and ground-truthing video suggested the presence of four seabed features, namely, (i) CATS deployed by MCC; (ii) hard substrata, corals, and a large seagrass species (*Enhalus acoroides*) associated with a high acoustic reflectance (promptly established during the first ground-truthing stations and existing diver observation provided by MCC); (iii) two sedimentary substrata (namely a silty sand and a silty sand with coarse material; and (iv) an area occupied by two shorter species of seagrass (a mixture of species including *Thalassia hemprichii* and *Halophila ovalis* ranging in cover from sparse (~20%) to moderate (~80%) with a low above-ground biomass). A different analysis method was required for the mapping of each feature. The ground truthing data collected by the ROV was analysed by an experienced marine ecologist to extract the following:

1. Substratum (based four classes based on a varying quantity of sand, silty sand/mud, and coarse material).
2. Seagrass species and cover (estimated to nearest 20th percentile)—not reported here.
3. Common epifaunal species (e.g. corals, sponges, and bivalves).
4. Seabed morphology (flat, rippled, or bioturbated).
5. Evidence of human activity (litter, lost nets, overturned sponge clumps).

The four replicate observations (images from the four quarters) from each station were averaged to provide average values or majority classes.

Conservation and anti-trawl structures

The CATS were clearly defined in the acoustic data and could be manually labelled in ArcMap. The positions of the CATS obtained from the survey data were compared with the approximate positions held by MCC to confirm that all of the structures had been found. To estimate the area of seabed protected by the CATS, the typical dimensions for trawling gear were obtained from the Southeast Asian Fisheries Development Centre (SEAFDEC, 2021). The typical headline width for the trawling gear used by fishers in the region (example provided by a Vietnamese paired trawl) is between 26 and 40 m (SEAFDEC, 2021). Allowing for an estimated 20 m gap between trawls, the total trawl width of the average trawler is estimated to be between 72 and 100 m. To assess the area protected by CATS, each unit was buffered by both 72 and 100 m.

*Hard substrata, corals, and tall stands of seagrass (*E. acoroides*)*

A Random Forest Classifier approach (a supervised machine learning approach) was selected as the most suitable method for delineating the composite habitat characterized by a high acoustic reflectance class (i.e. coral rubble, hard coral, and the tall seagrass *E. acoroides*) within the sidescan sonar data.

An initial attempt to train a classification model using the 66 ground-truthing stations did not provide sufficient replication within modelled classes (i.e. substrata, coral, or tall seagrass) to produce separate classes and produce accurate maps. The composite class was considered a particularly important source of heterogeneity locally and a likely refugia for juvenile fish. As such, the composite class was delineated as is rather than disregarding it because it could not be accurately subdivided and mapped.

As the high reflectance areas were clearly discernible in the sonar data, it was possible to use expert labelling to manually place shapefile points ("presence" points) in the middle of approximately 250 areas of rubble/coral/seagrass using ArcMap GIS. Using expert labelling to create a training dataset is considered acceptable when the feature of interest can be unambiguously observed in the acoustic imagery (e.g. Jarna *et al.*, 2019). To generate an absence dataset, each point was buffered by 5 m and the ArcMap "create random points" was used to randomly distribute another 250 "absence" points in unbuffered areas.

The statistical platform R Studio was used to train a Random Forest (randomForest package—Liaw and Wiener 2002) model to classify seabed areas into coral/hard substrata and tall seagrass *E. acoroides* presence or absence (1000 trees). The predictor variables used for the Random Forest were: (i) the raw acoustic data smoothed using ArcMap's "Focal Statistics" tool with a search radius of 5 pixels (60 cm); and (ii) the variance of the raw acoustic information again produced using Focal Statistics with a search radius of 5 pixels (60 cm), which could be seen by eye to be of value to defining the patches of coral and hard substrata. All variables (both response and predictor variables) were checked for normality (normal Q–Q plot to assess if variables need to be transformed), and independence between predictor variables (Pearson correlation matrix to assess whether specific predictor variables are redundant). Model selection (i.e. the final selection of predictor variables to be used in each model) aimed to maximize the variance or deviance explained (i.e. model performance) while keeping the complexity of the model minimal (*via* reductions in the Akaike Information Criterion). The prevalence of spatial autocorrelation (Moran's I test) was assessed within the response variable to check whether the observations needed to be spatially thinned. The Out-Of-Bag estimate of error and class specific error rates were extracted from the bootstrapped confusion matrix provided by the Random Forest output.

*Sedimentary substrata and seagrass (*T. hemprichii *and* H. ovalis*) beds*

Interpretation of the ground-truthing videos indicated the presence of two distinct substrata: (i) seabed dominated by a homogeneous, and occasionally rippled, silty sand; and (ii) more heterogeneous areas with silty sand and a significant amount of surficial coarse material (rock and coral rubble). A Random Forest classifier, trained using the ground-truthing observations of the two sediment classes, was used to classify the sidescan sonar layers. However, the error estimates from the out-of-bag confusion matrix highlighted an inability of the model to accurately classify the data. Survey artefacts apparent in the acoustic data may have also contributed to the poor discrimination between sediment classes. Unsupervised k-means clustering was also trialled and again found that the two clusters could not discriminate the sediment class from the coarse material. Given the low accuracy values of both techniques, the entire seabed of the study site has been classified as a single silty sand class.

The density and size of the seagrass seen in the ROV images were extremely low. Equally, coarse material seen in the videos was as a sparse topping of material on a predominately silty sand background. As such, it is likely the backscatter intensity and standard deviation data lacks a consistent and sizeable change in values when collected in areas of sparse seagrass or coarse material. Despite the inability to classify the three classes seen in the ground-truthing, the approximate distribution of the seagrass (a composite of two shorter seagrass species, *T. hemprichii* and *H. ovalis*, with a low above-ground biomass) is likely to be of significant value locally. ArcMap was used to fit Thiessen polygons around the ground-truthing observations to provide an estimate of the extent of the seagrass. The resulting Thiessen polygons of the same class were merged using ArcMap's "Dissolve" tool and subsequently smoothed using the "Smooth Polygons" tool.

Results

Sidescan sonar data were collected from approximately 15.5 km^2 of seabed surrounding Koh Ach Seh, Koh Angkrong, and Koh Poh (Figure 3). To support the acoustic observations, 66 ground-truthing videos were collected across the ensonified area (Figure 3)—example images are shown in Figure 4. The ground-truthing stations indicated the survey area was dominated by silty sand with distinct areas of sand with coarser material (lower density) or with seagrass (low density). Large burrows were common in the footage, probably produced by shrimp and/or gobies. Epifaunal species included numerous pencil urchins (*Eucidaris tribuloides*) and occasional starfish (*Protoreaster nodosus*). Emergent infaunal species included *Pinna* sp. and a sedimentary sponge. Many of the sponges had been pulled from the sediment and overturned. Equally, the majority of the *Pinna* bivalves observed were dead.

Hard substrata, corals, and tall stands of seagrass (*E. acoroides*)

The Random Forest delineated approximately 1700 patches of habitat with a high acoustic reflectance. The high reflectance was generated by areas of seabed with a mixture of coral rubble, hard corals, and the seagrass *E. acoroides* (a significantly taller and denser seagrass species when compared to many of the other species of local seagrass). Ground-truthing suggests that most of the patches identified were dominated by discrete patches of *E. acoroides.* The total area of these acoustically similar habitats was 56500 m^2 from the area east of Koh Poh (Figures 5a and 5b). The mean area of each patch was 34 m^2 (standard deviation 51.6). The acoustic similarity of the coral rubble, hard corals, and discrete patches of dense seagrass meant it was not possible to separate these three classes within the final map. Discriminating these classes was especially difficult given their close spatial association as a fine-scale mosaic of mixed classes on the seabed and the lack of sufficient ground-truthing to adequately train a model to generate accurate predictions.

The error rates of commission and omission were all below 20% (Table 1). The overall accuracy, which reflects the proportion of out-of-bag observations that were classified correctly. The Kappa statistic, which takes into account random chance within the classification, was 0.82 and indicates a high performing classifier based on internal (out-of-bag) validation.

Sedimentary substrata and seagrass (*T. hemprichii* and *H. ovalis*) beds

Attempts to use supervised and unsupervised techniques to predict the distribution of the two substrata classes (i.e. silty sand and

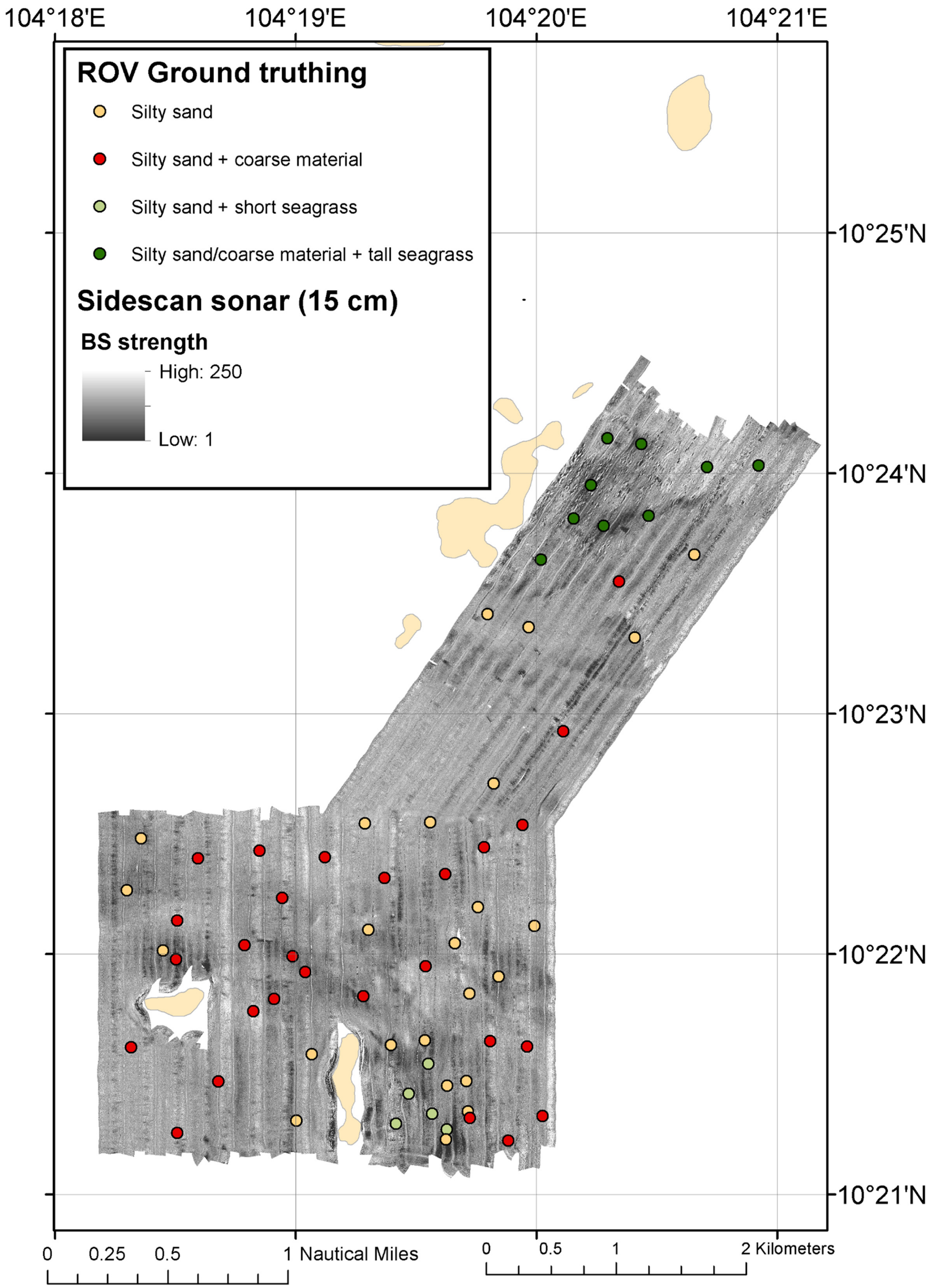

Figure 3. Sidescan sonar backscatter (BS) strength for the seabed surrounding Koh Ach Seh island with the ROV stations classified into one of three seabed classes. Banding within the image is the product of survey artefacts (engine wash travelling under the sidescan sonar and heavy seas).

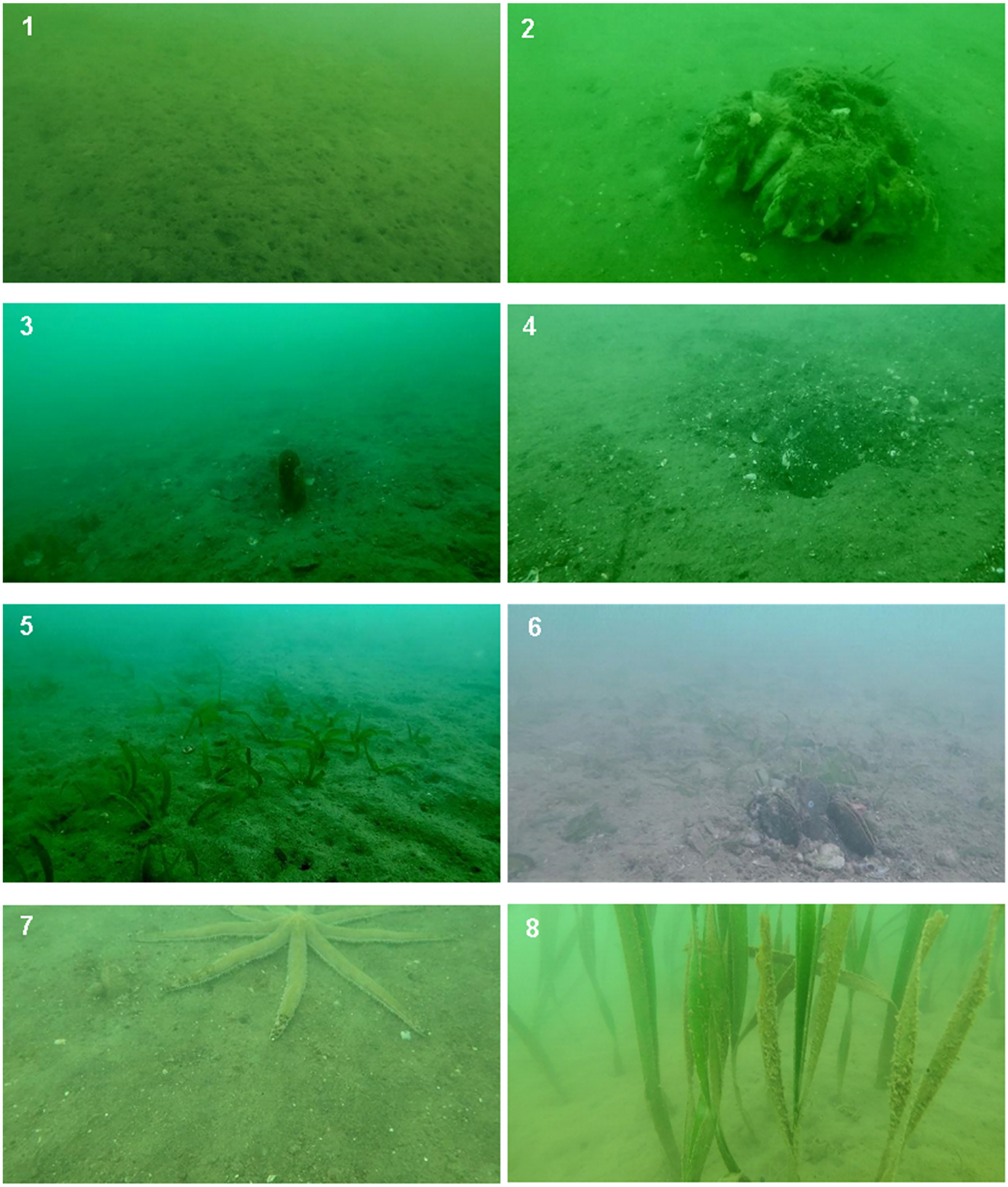

Figure 4. Example images from the ground-truthing footage collected with a Remotely Operated Vehicle. Images include: (1) heavily burrowed ground; (2) up-turned sponge clump; (3) dead Pinna shell on sand; (4) large burrow entrance; (5) bed of short seagrass, probably *T. hemprichii*; (6) clump of live *Pinna* bivalves; (7) ripple sand with sunstar; and (8) tall seabed patch (*E. acoroides*).

silty sand with coarse material) were unsuccessful, due to: (i) the inability to distinguish the two very similar sedimentary classes based on their acoustic return; and (ii) the poor acoustic reflection provided by the short and low above-ground biomass of the most commonly found seagrasses *T. hemprichii* and *H. ovalis*. A Thiessen polygon provides an approximation of the area likely to contain the two shorter seagrass species (*T. hemprichii* and *H. ovalis*; Figure 6).

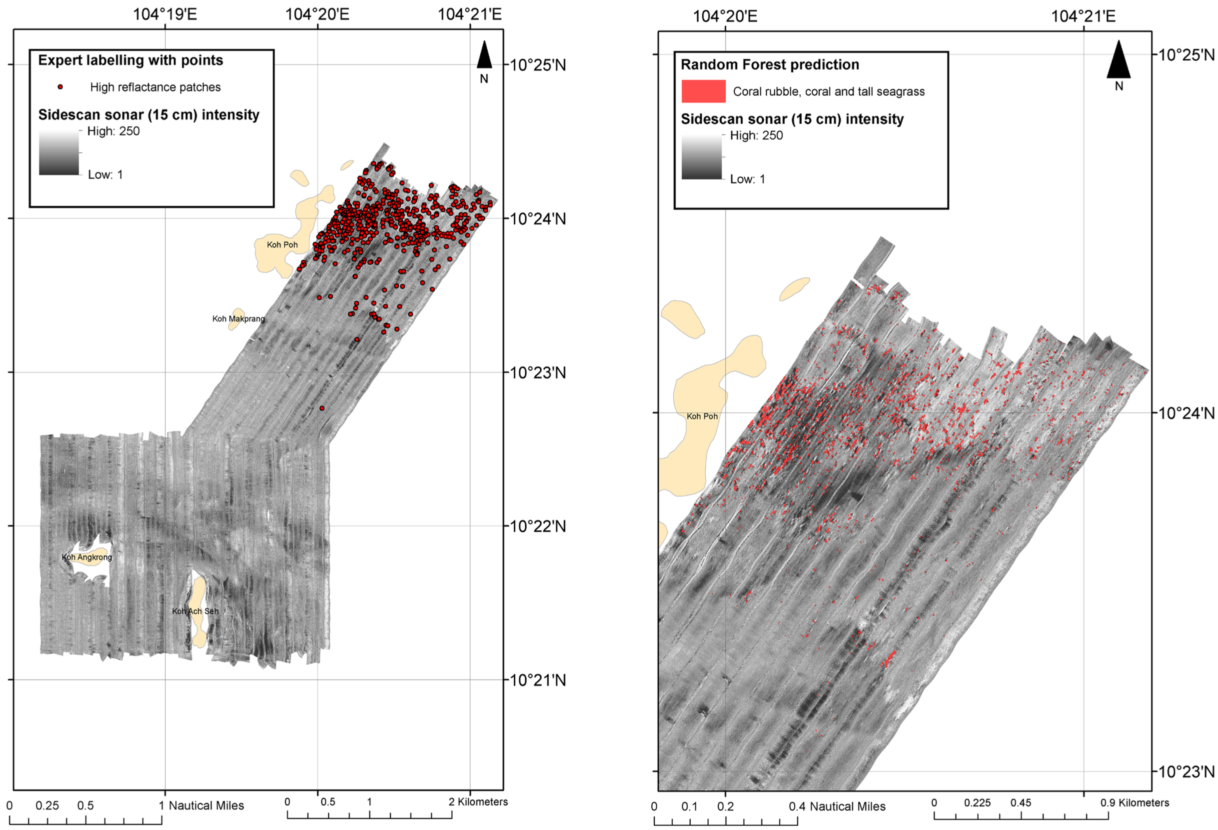

Figure 5. 5a (left): expert labelling of the mid-point of individual patches of high acoustic reflectance (a mosaic of coral rubble, hard corals, and the tall seagrass, *E. acoroides*) identified from the sidescan sonar image. 5b (right): the outline of each patch of high acoustic reflectance (a mosaic of coral rubble, hard corals, and the tall seagrass, *E. acoroides*) as delineated by a Random Forest model.

Table 1. Estimates of error rates, overall accuracy, and Kappa for the Random Forest model used to predict the presence/absence of the composite coral rubble, hard corals, and the tall seagrass (*E. acoroides*) habitat. The validation values have been sourced from the internal confusion matrix (Out-Of-Bag values) generated by the bootstrapping process.

	Errors of commission (%)	Errors of omission (%)	Producer accuracy (%)	User accuracy (%)
Presence	18.0	12.4	87.6	82.0
Absence	13.2	19.1	80.9	86.8
Observed accuracy (%)		84.2		
Kappa (0–1)		0.82		

Anti-trawl structures

The location of 40 anti-trawl structures was identified manually using the processed sidescan sonar surface (Figure 6). The high elevation and distinctive, hollow shape of the CATS allowed them to be identified easily in the acoustic imagery (Figure 7). Based on the accuracy of the dGPS and the highly certain layback correction from the short tow used for the sidescan sonar, the accuracy for the new positions for the CATS has been estimated to be $\pm$ 6 m. The minimum area of seabed protected by the CATS is significant (approximately 31400 m^2 based on 40 CATS) assuming that fishers know of, and avoid, the anti-trawling structures. The aversion of fishers to losing fishing gear on CATS may well extend the protected area further due to their uncertainty of the location of CATS.

Discussion

Mapping of benthic habitats and the conservation and anti-trawl structures

The mapping techniques used here are standard methods utilized in many marine habitat mapping studies. However, the limited facilities (both ashore and afloat), the small size of the survey vessel and the extremely shallow and rugose seabed precluded the use of more commonly used ground-truthing and acoustic equipment. The use of small, rechargeable, low power, or low cost (the combined cost of the sidescan sonar and the ROV was less than \$15000 USD) systems allowed an extensive area of sidescan sonar data and 66 ROV ground-truthing stations to be collected routinely in challenging conditions (rough seas on a daily basis). These data, paired with informed decisions concerning what can be classified within

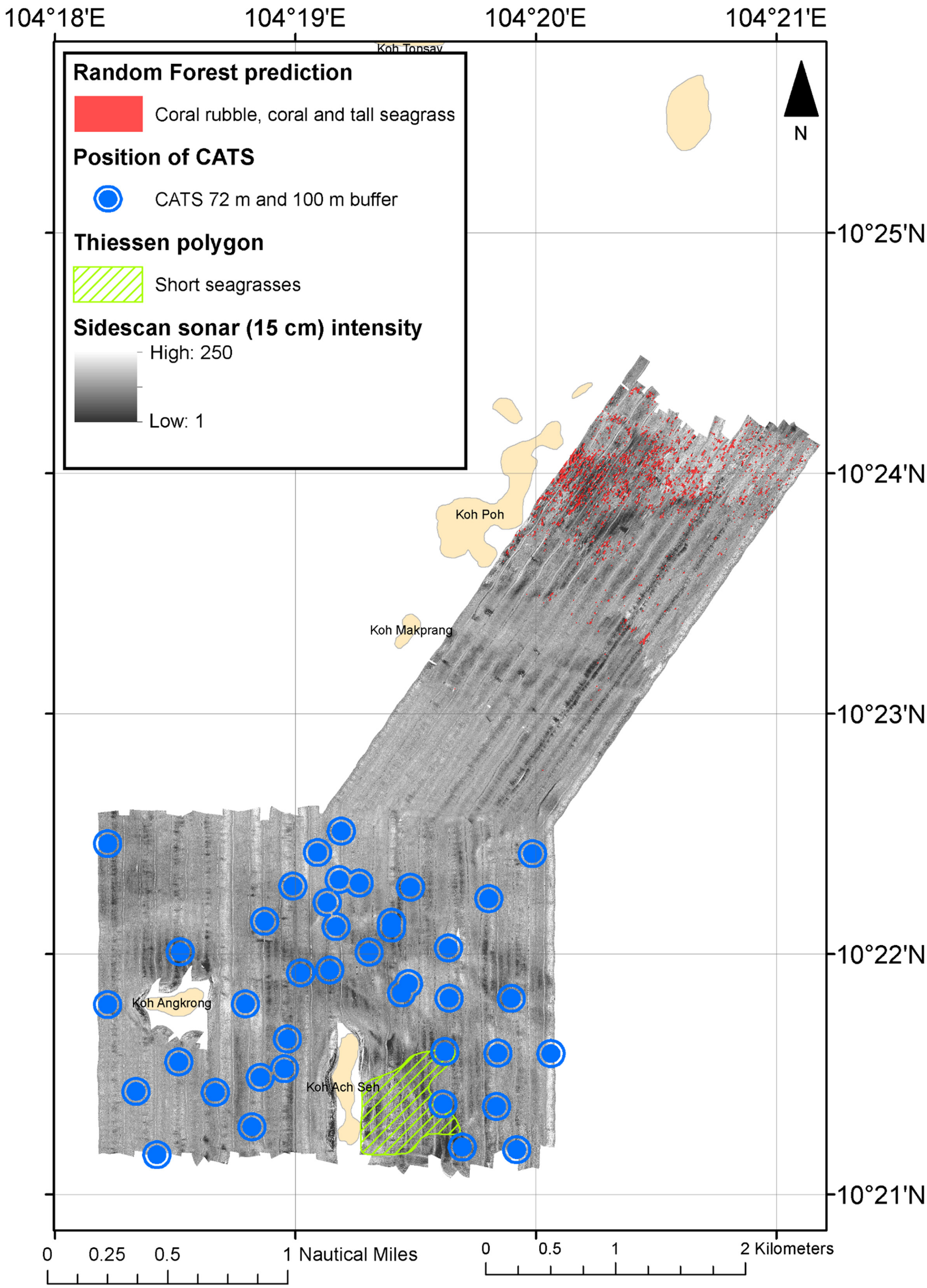

Figure 6. Map showing: (i) Thiessen polygon for the bed of short seagrass (*T. hemprichii*and *H. ovalis*) as derived from the video ground-truthing; (ii) high acoustic reflectance (a mosaic of coral rubble, hard corals, and the tall seagrass, *E. acoroides*) distribution provided by the Random Forest; and (iii) location of the MCC CATS in the survey area (left) and buffering to estimate the area of seabed protected from trawling based on the average dimensions of a typical local trawler.

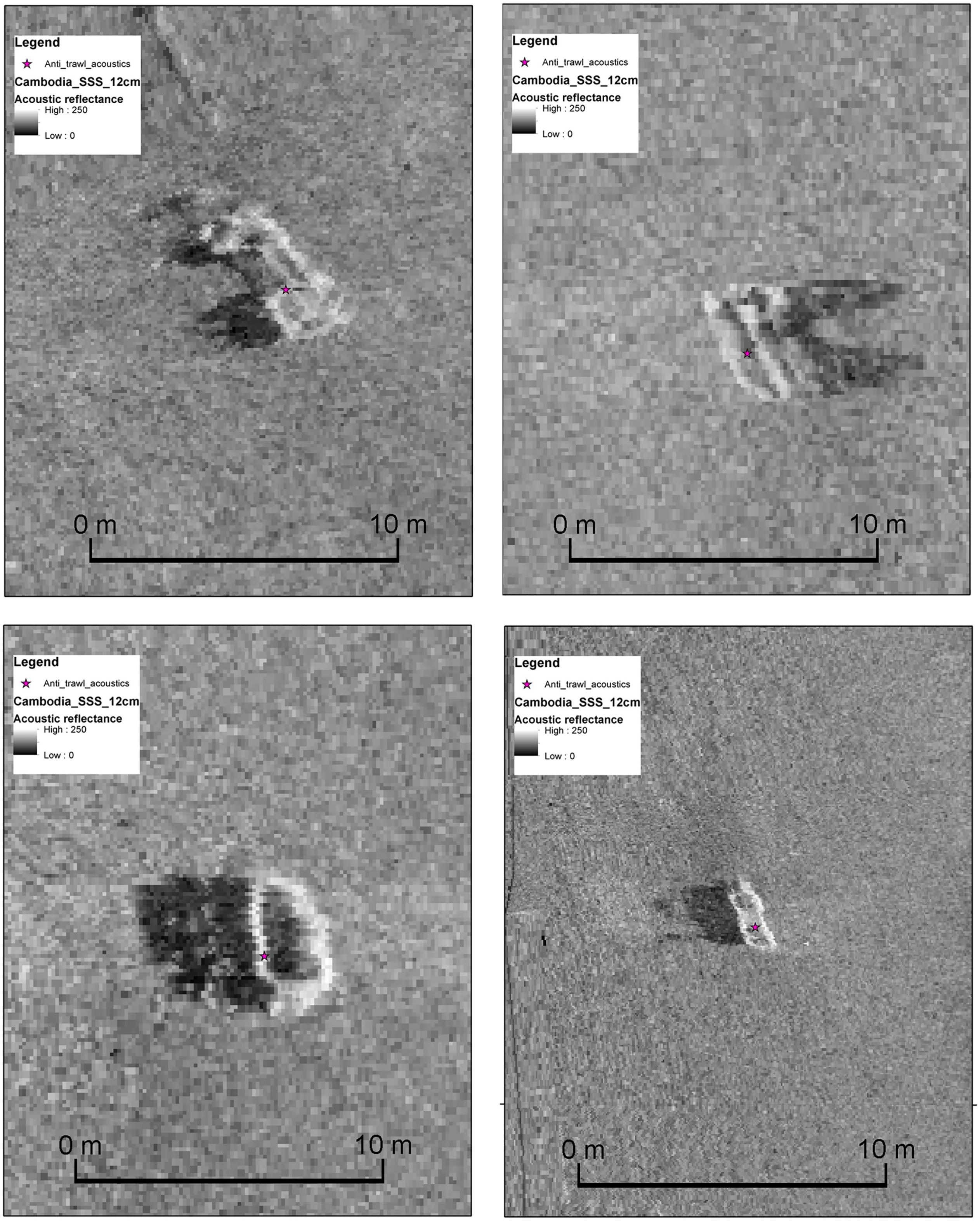

Figure 7. Example images of the CATS as seen in the acoustic sidescan sonar data.

the data, has produced high-confidence maps of coral mounds and tall seagrass (*E. acoroides*) and larger areas covered by shorter seagrass species (*T. hemprichii* and *H. ovalis*) in the area, as well as the exact position of the CATS. These features are the priority habitats and structures in the area.

These achievements demonstrate that valuable and informative mapping studies can be undertaken in challenging coastal environments with minimal infrastructure. The ability to work in such environments is important as these isolated areas are often exposed to some of the most challenging and intense issues present in the coastal environment. Interactions between illegal fishers and management/conservation bodies in the area have led to physical attacks and damaged infrastructure, wide-scale habitat degradation and a significant loss of livelihood for local people. Gathering key environmental information on the distribution of locally important habitats is likely to stimulate significant improvements to regional management, and hopefully lead to substantial developments for local communities and the marine habitat on which they rely. Repeated mapping exercises in the area also provides an opportunity to monitor changes in habitat extent and assess longer-term trajectories of spatial change and recovery at the site.

A total of 66 ROV ground-truthing stations allowed the detailed characterization of emergent infaunal and epifaunal species that characterize the fauna associated with the predominant substratum. It is likely that some of the emergent species, such as the broken or dead *Pinna* shells and over-turned sponge clumps seen in the ROV imagery, are useful indicator species for trawling activity. The two sediment types were indiscernible in the acoustic data and required the ground-truthing videos. This highlights that differences seen in ground-truthing are not always discernible when classification methods are applied to acoustic data. In these cases, good judgement must be used when classification errors are large so as not to produce inaccurate maps that may impact effective management in the area.

The supervised and unsupervised classifications of both the acoustic data and the ground-truthing imagery were able to broadly identify the main zones and features present across the survey site. Further work is required to optimize these models by assessing the performance of the maps produced using an independent validation dataset rather than relying on internal assessments of accuracy derived from the bootstrapping process and the Out-of-Bag statistics. MCC are currently expanding their diver survey to provide the additional validation data required.

The survey equipment and design proved effective for identifying coral mounds and tall seagrass *E. acoroides* in this small study. Based on the ability of sidescan sonars to image large areas of seabed in a relatively short time, expanding this method to map coral and seagrass in the entire MFMA is feasible. It is also likely that with the collection of a greater number of ground-truthing samples, it should be possible to generate maps of a greater thematic resolution, e.g. broad ground types. Distinguishing smaller or sparser seagrass on acoustic images is often unreliable, however, local knowledge of coral reef and seagrass coverage could direct ground-truthing survey efforts and subsequent targeted CATS deployment. Equally, incorporating additional sources of spatial data that are known to be important drivers of seagrass presence, such as modelled products or remotely sensed variables, will improve the prediction accuracy.

Conservation and anti-trawl structures

Despite efforts by the local authority, the current level of enforcement within Kep's MFMA, and other MFMAs (Endroyono, 2017; Roig-Boixeda *et al.*, 2018; Reid *et al.*, 2019), is unable to totally eliminate illegal fishing within designated areas. This is understandable considering the extent of the coastal domain around Cambodia, the available resources for marine management and the abundance of small vessels operating near an international border. The drive to reduce illegal fishing is further hampered as many offenders, especially those with larger vessels, are from outside Cambodia, which limits the effectiveness of educational outreach on the value of MPAs and the ability to impose sanctions for illegal activities. Providing sufficient enforcement to fulfil conservation objectives and maintain the ecological management effectiveness within MPAs is a consistent problem, not just around small islands or developing states (e.g. Maliao *et al.*, 2004; Mangubhai *et al.*, 2011; Arias *et al.*, 2016) but also in developed countries (e.g. Guidetti *et al.*, 2008; Rife *et al.*, 2013; Clark and Humphreys, 2020).

Within months of the deployment of the CATS, MCC observed decreased trawling activity in the protected area and is continuing with CATS deployment to extend the protection surrounding Koh Poh. MCC consider the CATS to be more effective at preventing illegal fishing than the previous method of patrolling, which required overnight observation and possibly dangerous interactions with the illegal fishers. They have also observed reduced illegal activity in areas of sparse CATS coverage, supporting the belief that the area is being avoided due to uncertainty in CATS density. This avoidance behaviour expands the protected region without increasing the cost, in materials or labour, to MCC. If MCC then monitor areas in which the illegal fishers continue to trawl, they can prioritize these habitats for future deployments. The increased size of the protected region will improve the connectivity between habitats, and hopefully the health and resilience of the region. Furthermore, the reduced presence of trawling in the area has made it safer for local communities to deploy static fishing gear. This increase in small-scale fishing methods, such as longlines, following reductions in bottom trawling activity has been observed in other countries e.g. Venezuela and Qatar (Al-Abdulrazzak, 2013; McConnaughey *et al.*, 2020).

An estimated area of 31400 m^2 is protected by approximately 40 CATS, excluding the areas avoided by trawlers due to their uncertainty in CATS placement. This equates to a cost of \$20000 USD (\$0.64 USD per m^2), not including MCC equipment, vessels, and labour. The CATS present a one-off investment with an estimated 50-year lifespan. Alongside the short-term physical protection provided by the CATS, it is also hoped that the later colonization of the structures by biogenic species will sustain their physical presence beyond the anticipated lifespan of the CATS. When investing in CATS, it must be considered whether this money could be more strategically spent on implementing designations, greater enforcement, fleet decommission, or providing subsidies for diversification. However, estimates of the lifetime expenditure of such actions are likely to exceed the deployment cost of a moderate number of CATS and the time delay to implement less immediate measures could result in irrecoverable harm to the vulnerable habitats. Long-term, it is likely that a combined strategy of defence, protection and enforcement are likely to provide the most effective outcomes for the marine habitats locally.

Based on the efficiency and low ongoing cost of CATS, the preference of the Cambodian Government is, in collaboration with MCC, to extend the number of CATS within the MFMA to 400 over the next 3–5 years (as of July 2021, MCC have now placed 185 CATS within the MFMA). The long-term goal, if the CATS continue to prove effective at limiting illegal fishing, is to spread these structures throughout shallow coastal areas of Cambodia. One important consequence of physically preventing fishing activity in the protected areas around Koh Ach Seh has been to displace fishing activity elsewhere and has presumably led to an intensification of fishing in areas already damaged by these activities.

The focus of MCC was to protect areas showing the highest recovery potential for recovery. It is assumed that the protection provided may have reduced the resuspension and sedimentation caused by trawling, as well as physical abrasion of the seabed. Ongoing monitoring of the area by MCC has observed colonization of the seagrass *Halophilia* spp. in previously denuded sites (A. Haïssoune, pers. comm. 22nd July). It is also hoped that the CATS provide hard substrata for important filter-feeding species (such as oysters; *Crassostrea belcheri*, mussels; *Perna viridis*, sponges, algae, and barnacles), which may over time help improve water quality locally and promote the subsequent settlement of hard corals. The eventual colonization of these structures by coral species is likely to improve habitat connectivity within the area and facilitate the long-term recovery of coral habitat.

Recognized best practices that reduce the impact of trawling require a change in societal perspective within fishing communities, as well as resources for the implementation of operational change and an overarching management plan that includes education and alternative livelihoods are required (McConnaughey *et al.*, 2020). Other effective measures such as the monitoring of fishing activity *via* vessel tracking and monitoring landings, requires both significant investment and a greater enforcement presence at sea and at landing sites (Hilborn, 2018).

Anecdotal reports from the region indicates that illegal fishers actively avoid the areas with CATS and that the hard surfaces of the CATS also continue to be colonized by epifaunal species (A. Haïssoune, pers. comm.). As such, the CATS also contribute to the biodiversity of the area and, with time, the connectivity of other assemblages fragmented by fishing damage and environmental change. Further work, in the form of continued monitoring and surveys of the seagrass and coral reef habitats, as well as the density and diversity of commercially important fish and shellfish in the area has been established by MCC and is necessary to measure the efficacy of the CATS in promoting ecosystem recovery and preventing habitat destruction. Once the efficiency of the CATS has been firmly established, socio-economic cost-benefit analyses can determine the likely short- and long-term return provided by a network of CATS when compared with other forms of education, enforcement, and enticement. Additional monitoring of changes in fishing activity as the CATS are deployed may also provide an indication of the deployment strategy to produce the greatest reduction in fishing pressure for the smallest input of CATS.

Future work is also needed to use the habitat map, provided here, for the placement of any remaining CATS. Based on the information provided here, future CATS deployments can be strategically placed to: (i) protect sensitive habitats; (ii) protect areas that provide ecosystem services in for local communities (e.g. essential fish habitats and those moderating climate change multihazards); and (iii) maximize connectivity between coral habitats. Ultimately, the habitat mapping needs to be extended beyond the area of deployed CATS to cover the entire MFMA.

As marine enforcement efforts within Cambodia are unable to eradicate illegal fishing, the use of passive structures that provide continuous protection within protected areas presents several advantages. In the absence of strict enforcement, the passive, yet robust, protection provided by the CATS is likely to be an effective mechanism for bolstering the efficacy of the protected area and delivering tangible benefits for local communities. Furthermore, one of the most effective mechanisms for delivering the UN's sustainable development goals in the marine environment is through the establishment of a network of MPAs. Given the limited local enforcement (Reid *et al.*, 2019), it is likely that MPAs that are reinforced with passive protection, as provided by measures such as CATS, are likely to make a tangible difference to coastal communities and their environment. Furthermore, this study has proven that specialized (small, low-power, or rechargeable units) but affordable survey equipment can be used in isolated conditions to produce valuable maps. These maps will help inform management decisions regarding the protected area and hopefully benefit the local community. Continued mapping following the deployment of the CATS can be used to assess the response and possible recovery of the marine environment in the Kep Archipelago.

Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

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