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Marine habitat mapping of green turtle (*Chelonia mydas*) foraging grounds in the Northern Territory, Australia

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ABSTRACT

Context. Green turtles (*Chelonia mydas*) are listed as vulnerable in Australia and are culturally significant to Indigenous Traditional Owners. However, their foraging habitats remain poorly understood, particularly in northern Australia. **Aims.** To map green turtle foraging habitats in the Northern Territory, through collaboration with Traditional Owners and ranger groups to support Sea Country management. **Methods.** Visual classifications of towed video transect data were used in a Support Vector Machine Learning Model to predict habitat across 379 km^2 of remotely sensed satellite imagery, encompassing two green turtle foraging grounds within jointly managed parks, namely, Trepang Bay (Garig Gunak Barlu Marine Park) and Field Island (Kakadu National Park). **Key results.** Foraging turtle habitat; algae and seagrass made up 30% of the Trepang Bay and 18.05% of the Field Island foraging areas. The classification accuracy of the model showed a high level of agreement at both sites (0.63 and 0.75 respectively). **Conclusion.** These habitats provide good foraging grounds for green turtles and support different age classes for various behaviours, including resting and predator avoidance. **Implications.** The simple and repeatable field methods used in this study allow for ongoing monitoring by ranger groups. The findings will support conservation planning and management in the Northern Territory.

Keywords: collaborative, ecology, feeding, management, rangers, remote sensing, seagrass, towed-video.

Introduction

The management of marine ecosystems has been shifting from a traditional single-species approach (Department of Agriculture, Water and the Environment 2022) towards an ecosystem-based management approach (Olsson *et al.* 2008; Fletcher *et al.* 2011; Smale *et al.* 2012; Smith *et al.* 2017). Ecosystem-based management aims to maintain the health and resilience of marine ecosystems by considering the interactions among species, habitats, and human activities. Habitat mapping is a crucial first step towards ecosystem-based and species management (Cogan *et al.* 2009; Guarinello *et al.* 2010).

Globally, many species of migratory marine megafauna are in decline, with their survival increasingly threatened by habitat loss and environmental changes (Bearzi *et al.* 2006; Sequeira *et al.* 2019; Lin *et al.* 2023). Sea turtles have suffered some of the most severe declines in abundance because of anthropogenic threats (Fuentes and Cinner 2010; Fuentes *et al.* 2023). However, global conservation efforts have led to an increase in sea turtle numbers in many populations (Hays *et al.* 2025). Providing adequate protection for these species requires an understanding of their habitat use, which is often provided by satellite telemetry studies (Schofield *et al.* 2013; Hays *et al.* 2018; Ferreira *et al.* 2021, 2023; Fossette *et al.* 2021; Peel *et al.* 2024). However, information on what constitutes the underlying habitat is largely lacking, presenting a significant challenge in generating evidence-based solutions.

Management and recovery plans for marine turtles tend to focus primarily on nesting grounds. However, marine turtles spend most of their lives at their foraging areas, only migrating to nesting grounds every 2–5 years on reaching maturity (30–50 years old) (Department of the Environment and Energy 2017). Turtles also display strong site fidelity to these foraging areas (Avens *et al.* 2003; González Carman *et al.* 2016; Shimada *et al.* 2016, 2020).

Green turtles (*Chelonia mydas*) are considered 'endangered' worldwide by the IUCN Red List (Seminoff 2023); however, there has been an increase in many local populations because of conservation efforts (Hays *et al.* 2025). Juvenile and adult green turtles are primarily herbivorous, foraging on algae, seagrass and occasionally mangroves (Mortimer 1981; Limpus and Limpus 2000; André *et al.* 2005; Holloway-Adkins and Dennis Hanisak 2017; Hays *et al.* 2018; Díaz-Abad *et al.* 2022). However, there is considerable variation in green turtle diets globally and within foraging grounds (Esteban *et al.* 2020). This diet means they depend on coastal habitats for their foraging grounds, often preferring to forage in shallow waters of ≤5 m (Mortimer 1981; André *et al.* 2005; Hazel *et al.* 2009; Reisser *et al.* 2013; Madeira *et al.* 2022).

In Australia, green turtles are listed as 'vulnerable' and 'migratory' under the Commonwealth *Environment Protection and Biodiversity Conservation Act* 1999 (EPBC 1999). However, their population status in the Northern Territory is unknown, and they are not listed under the *Territory Parks and Wildlife Conservation Act* 1976 (TPWC 1976). Green turtles are also a species of high cultural importance to coastal Traditional Owners throughout northern Australia. They appear as totems and in Dreamtime stories (often represented in Aboriginal art) (Butler *et al.* 2012; Department of the Environment and Energy 2017) and the meat of turtles and eggs from all species are an important food source (Kennett *et al.* 2004; Department of the Environment and Energy 2017; Delisle *et al.* 2018). Indigenous ranger groups are traditional custodians of the extensive Sea Country in the Northern Territory (Kennett *et al.* 2004; Rist *et al.* 2019). The term 'Sea Country' is used by Indigenous Australians to refer to any environment within their broader traditional estate that is associated with the sea or saltwater, including coastal areas, estuaries, beaches, marine areas, and islands (Ens *et al.* 2012; Dam Lam *et al.* 2019). Since 2008, Traditional Owners in the Northern Territory have been afforded legal rights to the intertidal zone of Aboriginal Land under the *Aboriginal Land Rights (Northern Territory) Act* 1976.

The northern coast of Australia presents a significant gap in our contemporary understanding of marine benthic habitats. Much of the coastline is very remote, and environmental factors such as high turbidity, very strong and variable tidal currents, and dangerous animals such as saltwater crocodiles (*Crocodylus porosus*) and box jellyfish (Cubozoa), have made marine research in this region difficult. In the Northern Territory, very little mapping has been undertaken outside of Darwin Harbour (Department of Environment and Natural Resources 2005; Geo Oceans 2011; Galaiduk *et al.* 2019; O2 Marine 2019). Given these restraints, remote sensing presents a valuable tool for mapping and monitoring the distribution of coastal marine habitats in the region (Monk *et al.* 2008; Wicaksono *et al.* 2019; Schill *et al.* 2021; Kuhwald *et al.* 2022; Wilson *et al.* 2022; AECOM, see www.aecom.com).

The integration of remote sensing with ground-truthed underwater video and photos is a widely used approach for identifying and mapping marine habitats (Hedley *et al.* 2012; Kuhwald *et al.* 2022; Wilson *et al.* 2022; AECOM, see www.aecom.com). Although remote sensing cannot provide the accuracy and level of detail that field surveys deliver, because it does not provide habitat classifications, it can be used to assess large-scale spatial patterns in habitat cover. Ground-truthing is used to provide that higher level of detail and is used to train a supervised image classification. The ground truth data can also then be used for determining the accuracy of the classification (Lyons *et al.* 2013; Komatsu *et al.* 2020; Kutser *et al.* 2020). This method is also invaluable for monitoring changes to marine habitats caused by climate change and other anthropogenic threats (Andréfouët *et al.* 2002; Hedley *et al.* 2012; Hovey and Fraser 2018).

Many different classification schemes exist for analysing marine habitat data globally, such as the European Nature Information System (EUNIS) and the Coordination of Information on the Environment and the Barcelona Convention classification (Montefalcone *et al.* 2021). In Australia, local examples include the News South Wales National Intertidal–Subtidal Benthic Habitat Map (NISB) (Department of Climate Change, Energy, the Environment and Water 2023), and the Combined Biotope Classification Scheme (CBiCS) (Flynn 2018). A key feature of the CBiCS approach is that it enables the mapping and monitoring of benthic assemblages in conjunction with associated environmental and habitat features, which are classified as biotopes. This approach is commonly used internationally for marine habitats (Olenin and Ducrotoy 2006; Hooper *et al.* 2009; Monteiro *et al.* 2021). To support habitat classification from underwater imagery, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) published the Collaborative and Automated Tools for Analysis of Marine Imagery (CATAMI), a standardised vocabulary for annotating benthic characteristics (biota and substrata) that can then be used to classify benthic habitats (Althaus *et al.* 2015). CATAMI combines coarse-level taxonomy and morphology into a hierarchical classification.

The goal of this study was to enhance the understanding and management of green turtle foraging habitats in the Northern Territory through a collaborative partnership with Traditional Owners and ranger groups. The specific aims of the study were:

1. To identify and map the marine habitats at two remote green turtle foraging areas in the Northern Territory by using remote sensing and towed-video transects, and additionally, to investigate the similarities and differences in habitats between the two foraging areas and which benthic species are driving those differences. This detailed benthic habitat mapping can be used to inform ecosystem-based management plans that support the conservation of green turtles, a species that is both vulnerable in Australia and culturally significant.

2. To provide training and capacity building for Indigenous ranger groups, empowering them with the skills and knowledge necessary to collect, analyse, and utilise habitat data. This will enhance their ability to protect green turtles and their habitats and support Traditional Owner-led management.

Materials and methods

Study sites

The Northern Territory is characterised by a tropical monsoonal climate, with high temperatures, heavy seasonal rainfall and cyclones, alternated with extended rain-free periods. There are also complex tidal regimes, with two tides in some areas, one tide in other areas, huge tidal ranges (up to 8 m) in some areas and almost no tidal range in others (Department of Sustainability, Environment, Water, Population and Communities 2012). The Northern Territory has an average sea-surface temperature of 30.6°C in the wet season and 24.5°C in the dry season (URS 2008).

Garig Gunak Barlu Marine Park and Kakadu National Park are critical conservation areas in the Northern Territory, recognised for their ecological, cultural, and biodiversity significance (Dethmers *et al.* 2010; Northern Territory Government 2011; Groom *et al.* 2017; Department of Climate Change, Energy, the Environment and Water 2019). Within these parks, two green turtle foraging grounds were selected for this study (Fig. 1) on the basis of traditional knowledge, local knowledge, and existing scientific knowledge of foraging green turtles in the Northern Territory (Dethmers *et al.* 2010; Ferreira *et al.* 2021).

Trepang Bay (Fig. 1*a*), on the Cobourg Peninsula, is part of Garig Gunak Barlu Marine Park and is jointly managed by the Northern Territory Government and Traditional Owners. The area experiences minimal freshwater and sediment input (Department of Environment, Water, Heritage and the Arts 2007). The bay has a smaller tidal range than do many areas of the Northern Territory (2–2.5 m). Coral reefs have been recorded along the Cobourg Peninsula; the taxonomic similarities of these reefs are like those found in the Torres Strait (Veron 2004). A coral bleaching event recorded between November 2002 and January 2003 caused significant destruction to corals and surrounding habitats in Coral Bay, within Port Essington, and the area has not been surveyed since (Department of Environment, Water, Heritage and the Arts 2007).

Field Island (Fig. 1*b*), managed by (Commonwealth) Kakadu National Park, is located within the Van Diemen Gulf. The gulf is a semi-enclosed, poorly flushed embayment with significant input from the East and South Alligator, Adelaide and Mary rivers. These large catchments contribute significantly to the inflow of sediment, freshwater, and nutrients into the system during the Northern Territory's wet season. The area has a large tidal range (3–5 m), causing strong currents that scour the benthic habitats (Department of Environment, Water, Heritage and the Arts 2007).

The reefs surrounding Field Island are classified as a biologically important area (BIA) for foraging green turtles, although this delineation is predominantly based on expert opinion, rather than quantitative analysis of turtle data, and is currently being updated (Department of the Environment and Energy 2017). A marine benthic survey of the south-eastern Van Diemen Gulf in 2004 used a combination of aerial and vessel-based surveys, the latter including beam trawl, benthic grab, box dredge, gillnet and underwater video, to characterise the biota and substrates at each site (Russell and Smit 2007).

Of the areas surveyed, the intertidal habitats around Field Island had the most seagrass cover. *Halophila decipiens* was the dominant seagrass species and often occurred with *Halodule uninervis*, *Halophila minor* and *Syringodium isoetifolium*. Seagrass meadows studied were all intertidal, except for a small area just off the north-western tip of Field Island (Russell and Smit 2007). The extent of the seagrass meadows from 2004 is available from SeaMap Australia (see https://seamapaustralia.org/).

Data collection

Field surveys were supported by a Ranger Exchange Program facilitated by Larrakia Nation Rangers with six participating ranger groups. An additional exchange was conducted between the Garig Gunak Barlu National Park Rangers and the Garngi Rangers from Croker Island. In all, the Kakadu National Park Rangers, Garig Gunak Barlu National Park Rangers, Larrakia Nation Rangers, Gumurr-Marthakal Rangers, Kenbi Rangers, Garngi Rangers, Tiwi Rangers and Mardbalk Rangers all contributed to this data collection.

For each of the selected sites (Trepang Bay and Field Island), the extent of the turtle foraging grounds, and detailed mapping area were identified on the basis of the mean foraging turtle kernel utilisation density (KUD) from satellite-tracking data. This foraging movement data were collected from 13 green turtles (seven at Trepang Bay and six at Field Island) by Charles Darwin University between 2021 and 2023 (N. Robson, unpubl. data). The average tag duration was 117 days (range of 52–224 days). The mean 50% KUD was used to identify areas of high turtle use (Supplementary material Fig. S2*a*, *b*).

The habitat map of each green turtle foraging ground was created using a combination of remote-sensing tools. In this study, Sentinel-2 satellite imagery was used to create the habitat map; this imagery has been successfully used in marine habitat mapping worldwide (Kuhwald *et al.* 2022; Wilson *et al.* 2022). Sentinel-2 imagery is free to download through the Sentinel Australasia Regional Access (SARA) and is available at a spatial resolution of 10 m^2 (pixel size). On the basis of field observations (visibility of the camera), the late dry season had the best water clarity at both sites. Therefore, images from the dry season (August–September)

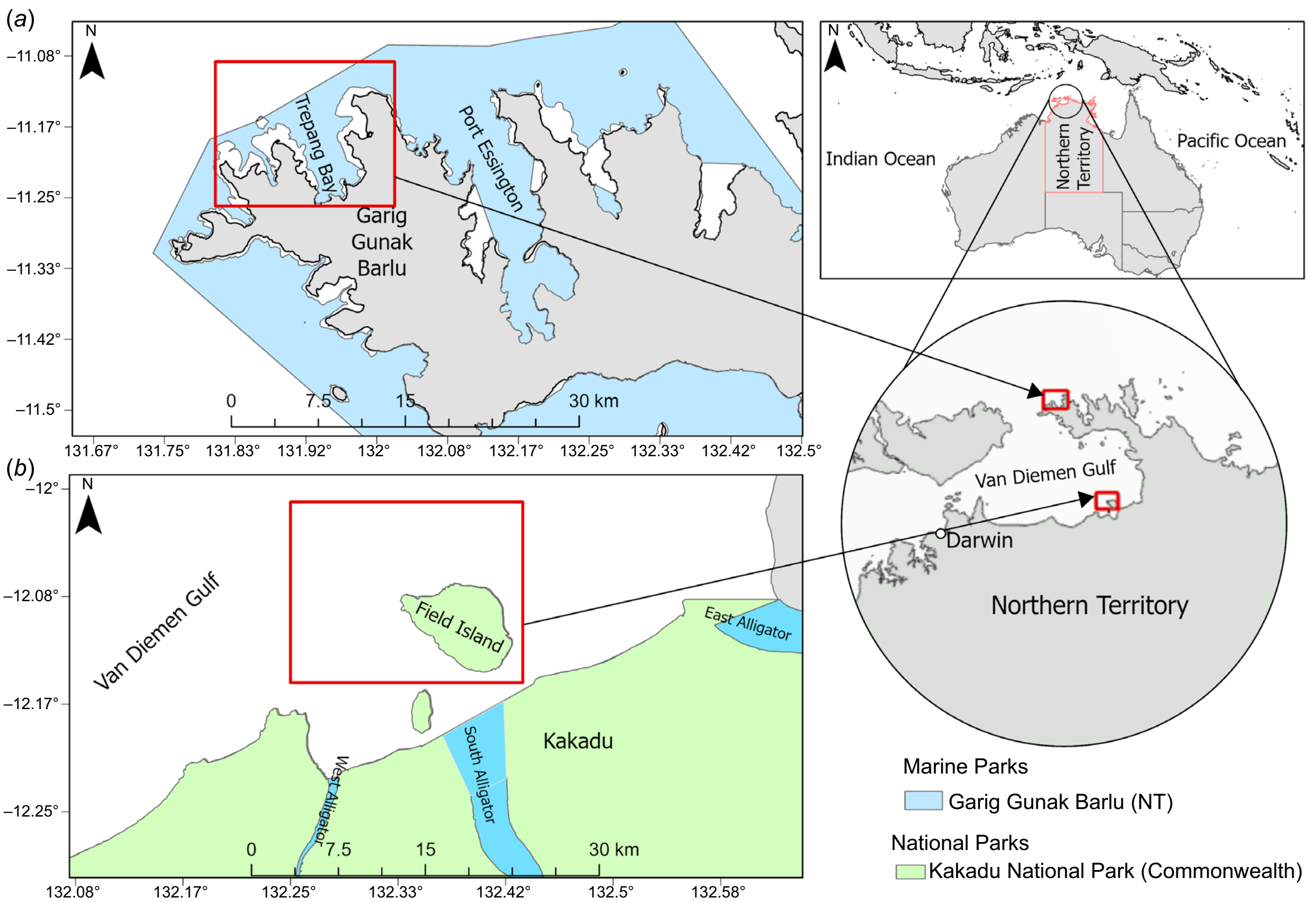

Fig. 1. A map of the two study sites, (*a*) Trepang Bay and (*b*) Field Island, in the Northern Territory, Australia, with right-hand side maps showing spatial context.

were selected for analysis on the basis of cloud cover (0%) and water clarity.

To create an accurate habitat map, it is important to 'ground truth' the remote-sensing mapping area and characterise benthic habitat types and associated assemblages. For this study, the ground-truthing was undertaken by running transects using a towed-video system during neap tides to optimise the quality of the seabed imagery (Carroll *et al.* 2020; Foster *et al.* 2020). The subsea video system used was a high-definition GoPro Hero 10 (set to 'wide' view, with a field of view of 122°) mounted onto a bespoke lightweight ballasted PVC pipe frame (Fig. S1). A wide-angle dive torch was attached to the frame above the camera, such that the light from the torch would illuminate the seabed at an oblique angle to the angle of view of the GoPro to mitigate backscatter. A hand-held Garmin GPSMap 64 (accuracy of <5 m) created a tracklog of each transect. The start and end depths were recorded using the vessel depth sounder. This system was chosen because of its compact nature and ease of use. Rangers participating in the survey were trained on the use of this video system, with the aim that it could be readily used for future habitat monitoring.

The number of transects at each site was defined on the basis of the relative size of the foraging ground and the complexity of the habitat (identified from bathymetry and satellite imagery). The location of each transect was chosen using a spatially balanced design (Foster *et al.* 2020). Spatially balanced designs are more efficient than other randomised designs because they tend to increase the balance on many environmental variables (in this case, depth). The *R* package *MBHdesign* (ver. 2.3.15, see https://cran.r-project.org/package=MBHdesign; Foster 2021) was used to create the survey design at each site, specially balanced by depth (using GEBCO_2021 bathymetry) (Foster *et al.* 2020). The survey points were added to *ArcGIS Pro* (see https://esriaustralia.com.au/products/arcgis-pro) to view any gaps and remove points, falling in waters too murky for accurate video transects. Additional points were manually added or adjusted using the Sentinal-2 imagery as a guide to ensure that each potential habitat type had been ground-truthed (Fig. 1, S2*a*, *b*). The camera system was deployed from the side of the vessel and towed for 5 min. The distance and direction of each transect were determined by the tides. The average transect distance was 81.11 m ± 51.20 at Trepang Bay and 151.80 m ± 76.50 at Field Island.

Eighty transects were undertaken at Trepang Bay, with two surveys per year (July and October in 2022 and May and November in 2023). Transect depths during the survey ranged from 0.5 to 17 m. Four surveys were also conducted at Field Island over those 2 years (April and August in 2022, and July and November in 2023), with 42 transects undertaken there. Most Field Island transects were conducted close to low tide. The depth of these transects during the survey ranged from 0.4 to 6.9 m.

Data analysis

Underwater image analysis

The video files associated with the towed-video system were viewed in *SMPlayer* (ver. 24.5.0, see https://www.smplayer.info/). Screenshots were used to extract images throughout the video when the image met the acceptable criteria, such as being well-lit, having good visibility of features, and being within sufficient distance of the seafloor to obtain clear imagery of seabed features. A random selection of at least five images was selected from these screenshots from each video. If a distinct habitat change was observed along the transect (i.e. bare sand to coral reef), the transect was split and renamed (i.e. K04 and K04-1), and an additional five images were extracted from the new habitat type. The timing of this habitat change was then recorded on the tracklog.

Images were analysed in the GNU Image Manipulation Program, *GIMP* (ver. 2.10.6, see https://www.gimp.org/). Each image was overlayed with a 10 × 10 square grid and then analysed for percentage cover of biota and substrate types. Any sessile organism or substrate (sand, shell, mud, pebbles and rock) taking up over half of a grid square (≥0.5%) was identified and the percentage cover was recorded. Organisms taking up less than half of one grid square were identified and recorded as 'present'. Motile organisms, such as fish, were identified and counted as individuals. The relative profile of each habitat (low, medium, or high) was also recorded. For consistency and comparability, the classification vocabulary followed the Collaborative and Automated Tools for Analysis of Marine Imagery (CATAMI) (Althaus *et al*. 2015). Each transect was classified by its depth range as either 'Intertidal' (<3 m) or 'Subtidal' (3–20 m), on the basis of the depth recorded on the vessel depth sounder and the tide at the time of the survey.

Assigning habitat classifications

The species percentage cover data were analysed in *PRIMER* with PERMANOVA+ (ver. 7, see https://www.primer-e.com/). The initial analysis looked at these data for each image to assess the within-transect similarities in biological assemblage. A fourth-root transformation was used to downweigh the influence of more abundant habitat components (e.g. sand). A permutational ANOVA (PERMANOVA+) test was then used to test the null hypothesis (H_0) that there is no difference in the benthic assemblages among transects and survey sites. A similarity percentages (SIMPER) breakdown procedure was undertaken to assess the average percentage similarity within transects and to calculate the contribution of each species (%) to the similarity within each transect.

To compare biological assemblages among transects, the raw percentage cover data from both sites were averaged by transect and a fourth-root transformation, and Bray–Curtis resemblance was then applied. A cluster analysis using similarity profiles (SIMPROF) was then undertaken on the habitat data. SIMPROF is a series of permutation tests run on biotic data that looks for statistically significant evidence of genuine clusters of sites that are *a priori* unstructured (Clarke *et al*. 2008). A two-dimensional non-metric multi-dimensional scaling (MDS) ordinations plot was created from a resemblance matrix based on Bray–Curtis similarity, with a minimum stress of 0.01 and the Kruskal fit scheme 1 (Primer 2024). A PERMANOVA+ test was then used to compare the groups identified by the cluster analysis and identify any significance amog groupings, with the null hypothesis that there is no difference among SIMPROF groupings. A SIMPER breakdown procedure was undertaken to assess the average percentage contribution of individual variables (biota and substrate) to the dissimilarity among objects in a Bray–Curtis dissimilarity matrix (Clarke 1993) to calculate the contribution of each species (%) to the dissimilarity between each SIMPROF group. The data for both study sites (Trepang Bay and Field Island) were combined, and the same set of analyses was performed among sites to identify any significant differences and similarities in the benthic assemblages of the two sites. These analyses were used to assign a biotope habitat classification to each video transect. The cluster with SIMPROF defined the transects representing a particular biotope, and the outcomes of the SIMPER analysis subsequently defined the biotope characteristics.

Satellite imagery pre-processing and habitat classification

The Sentinel-2 imagery comes with 13 spectral bands (varying by wavelength and bandwidth). However, for identifying marine habitats we worked with only four bands with the best resolution (10 m^2), including Band 2 (blue, central wavelength of 490 nm), Band 3 (green, central wavelength of 560 nm), Band 4 (red, central wavelength of 665 nm) and Band 8 (near infrared (NIR), central wavelength of 832.8 nm). The proportions of each band within a pixel can indicate different habitat types.

Geometric corrections (resampling and subsetting) of the Sentinel-2 imagery for both sites were undertaken in the Sentinel Application Platform (*SNAP*) (Fig. 2). The Sen2Coral plug-in was then used to de-glint (remove sun glare) and remove any white caps (Serco Italia SPA 2019).

A depth mask was applied to the imagery by using 2021 GEBCO bathymetry (GEBCO Compilation Group 2021) in *R*, by using the *raster* package (ver. 3.6-32, see https://cran.r-project.org/package=raster). The GEBCO bathymetry was originally compared with the depths recorded on the vessel

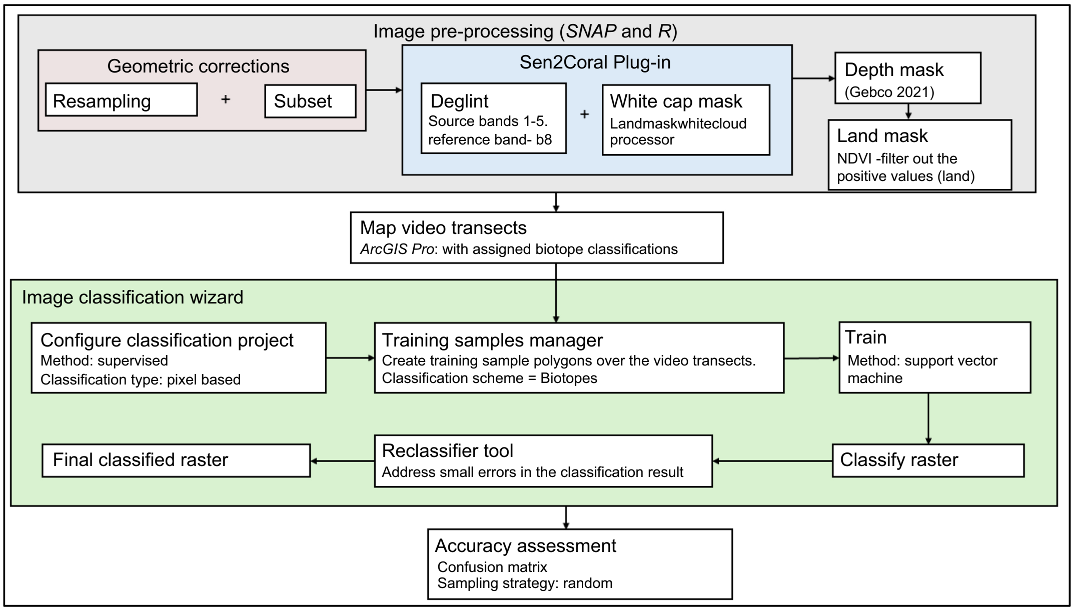

Fig. 2. A flow chart explaining the satellite image pre-processing and classification methods.

depth sounder. However, the tidal charts for these two sites are not accurate (varying from the closest tide gauge), and the depths could not be accurately adjusted for the tides. This filtered out any habitats too deep to be picked up by remote sensing, generally waters deeper than 20 m, but this can depend on water clarity, turbidity etc. (Kutser *et al.* 2020). The depth mask differed among sites on the basis of the water clarity and the green turtle foraging areas (18 m for Trepang Bay and 6 m for Field Island) (Fig. 2, S2*a*, *b*).

The normalised difference vegetation index (NDVI) was then calculated using the raster band data by the following formula (Blaschke *et al.* 2014):

$$\mathrm{NDVI} = ((\mathrm{NIR} – \mathrm{Red}) \div (\mathrm{NIR} + \mathrm{Red}))$$

The NDVI always ranges between −1 and 0, with zero usually representing bare habitat and negative values indicating water. Raster cell statistics were used to filter out the positive values (land) from the NDVI raster, which created a land mask. The resulting image contained only pixels that could be used for the marine habitat classification.

The biotope classifications we identified from the analysis of each transect were mapped over the pre-processed Sentinel-2 imagery in *ArcGIS Pro* (Fig. 2), by using the GPS positions generated by the tracklog from each transect. To obtain the training data (training sample file) for the habitat classification model, we delineated a group of pixels from the satellite image underlying the biotope classification GPS point into a polygon representing features or potential habitats, such as a seagrass meadow or coral bommie, described from the image. This was undertaken using supervised pixel-based classification in the Training Samples Manager tool in *ArcGIS Pro*. All the pixels in the image were then statistically compared by their colour, with the pixels defined by the training samples by using a Support Vector Machine Learning (SVML) model. The SVML model was chosen as it is less susceptible to noise, correlated bands, and an unbalanced number or size of training sites within each class (ESRI 2022). Once trained, this model predicted the class membership (biotope) of each pixel across the whole mapping area (ESRI 2022). The output of this tool was a classified raster of the habitats (biotopes) in the mapping area (Fig. 2).

The accuracy of habitat classification models (such as SVML) decreases with depth and water clarity. An uncertainty layer was therefore added to the final habitat map for depths greater than 5 m in Trepang Bay and for 4 m at Field Island. Finally, a confusion matrix was run in *ArcGIS Pro* (using the Image Analyst toolbox) to look at the accuracy between the classified map and the ground-truth data points (ESRI 2023). The assessment included calculating user accuracy, producer accuracy, and the kappa index of agreement. These accuracy metrics range between 0 and 1, where 1 represents 100% accuracy. The Kappa index of agreement can be interpreted as follows: values of ≤0 as indicating no agreement, 0.01–0.20 as none to slight, 0.21–0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as substantial and 0.81–1.00 as almost perfect agreement (Landis and Koch 1977).

Ethics

Ethics was not required for this study. However, Animal Ethics and Human Ethics were obtained from Charles Darwin University for the broader Marine Megafauna Project.

Results

Analysis of biological data

A significant difference in the benthic assemblages among the transects at Trepang Bay was found from the PERMANOVA run on the detailed transect data ($P = 0.001$). The average similarity in the benthic assemblage within each transect ranged from 42.95 to 100%. The three transects with 100% average similarity all contained 100% mud and silt. The transect with the lowest average similarity had a mixed benthic assemblage, with the highest contributions coming from rock (38.85%), coarse sand (31.10%) and encrusting sponges (11.35%).

The cluster analysis identified 10 groupings (SIMPROF groups labelled a–j) for the averaged Trepang Bay transects, with the majority of transects falling into either group 'j' or 'h' (Fig. 3, S3*a*). A significant ($P = 0.001$) difference was found among the 10 SIMPROF groups. A two-dimensional, non-metric MDS ordination illustrates the differences among transects, with transects displayed as closer together being more similar in their benthic characteristics (Fig. 3).

The average similarity within the two biggest SIMPROF groups (in terms of number of transects per group) was 57.81 and 44.17% for groups 'h' and 'j' respectively. This similarity within group 'h' was characterised by the presence of coral rubble, stony corals (massive and submassive) and coarse sand. The average similarity within group 'j' was characterised by the presence of coarse sand, biogenic material (coral rubble and shells) and brown algae (laminate and erect-fine branching). The highest recorded within-group similarity was 92.43% for group 'd', with this similarity being driven by the presence of mud and silt (Fig. 3).

A significant difference was found between intertidal and subtidal assemblages at Trepang Bay, on the basis of the PERMANOVA ($P = 0.001$). Plotting SIMPROF clusters by depth better clarified the groupings and was used to divide some of the SIMPROF groups into subgroups when assigning biotopes.

A significant difference in the benthic assemblages among the transects at Field Island was found from the PERMANOVA run on the detailed transect data ($P = 0.001$). The average similarity in the benthic assemblage within each transect ranged from 24.74 to 100%. The two transects with 100% average similarity both contained 100% coarse sand. The transect with the lowest average similarity was dominated by mud and silt (73.54% contribution), but also had a few scattered coral bommies, which accounts for the low average similarity.

The cluster analysis identified seven SIMPROF groupings for the averaged Field Island transects, with the majority of transects falling into groups 'c' or 'd' (Fig. 3, S3c). A significant ($P = 0.001$) difference was found among the seven groups, on the basis of PERMANOVA. A two-dimensional non-metric MDS ordination displays the distance between transects as Bray–Curtis similarity, with transects being displayed as closer together having a closer similarity in the benthic assemblage (Fig. 3). The Field Island MDS ordination had a high stress of 0.23, which meant that the plot did not adequately represent the dissimilarities in two-dimensional space (Fig. 3).

The average similarity within the two largest SIMPROF groups was 53.92 and 42.40% for groups 'c' and 'd' respectively. This similarity within group 'c' was characterised by the consistency in coverage of coarse sand. The average similarity within group 'd' was characterised by the consistent occurrence of coarse sand, biogenic material (coral rubble), brown algae (filamentous) and encrusting sponges and stony corals. The highest within-group similarity group 'g' (77.18%), which was found to be characterised by the contribution of mud and silt, seagrass (strap-like and elliptical leaves), biogenic material (coral rubble and shells) and pebbles (Fig. 3). A significant difference was found between intertidal and subtidal assemblages at Field Island, on the basis of the PERMANOVA ($P = 0.001$). Plotting the SIMPROF clusters by depth better clarified the groupings and was used to divide some of the SIMPROF further when assigning biotopes.

Running a SIMPROF cluster analysis for the data from both sites showed that some transects from Trepang Bay and Field Island were more similar to each other than to other transects within their respective sites. However, there was still a significant ($P = 0.001$) difference between the benthic assemblages at Trepang Bay and Field Island. Whereas the two-dimensional non-metric MDS ordination had a high stress (two-dimensional stress of 0.21, indicating poor representation), visualisation on a three-dimensional non-metric MDS ordination exhibited a clear divide among sites, although strong similarities between many transects from Trepang Bay and Field Island were still evident (a relevant perspective of the three-dimensional ordination is presented in Fig. 4). A SIMPER analysis of the SIMPROF groups showed that the biggest mixed site group (group 'k') had an average similarity of 51.66%, with this similarity being driven by the presence of coarse sand.

Biotope classification

Biotope classifications were characterised on the basis of SIMPER analysis of SIMPROF groups and considering depth ranges (intertidal vs subtidal). Some SIMPROF groups were combined into the same biotope for mapping simplicity or split into two groups on the basis of depth and species presence. For example, the Field Island Transect K030 was assigned SIMPROF group 'c' and was classified as 'Subtidal coarse sand', whereas Transect K010, also in SIMPROF group 'c', was classified as 'Intertidal coarse sand and seagrass' (Fig. S3). This additional aspect was undertaken with the consideration that statistical significance does not necessarily directly translate into biotope classifications. For example, depauperate and abundant examples of the same basic biotope may be separated by statistical analysis but may still display the

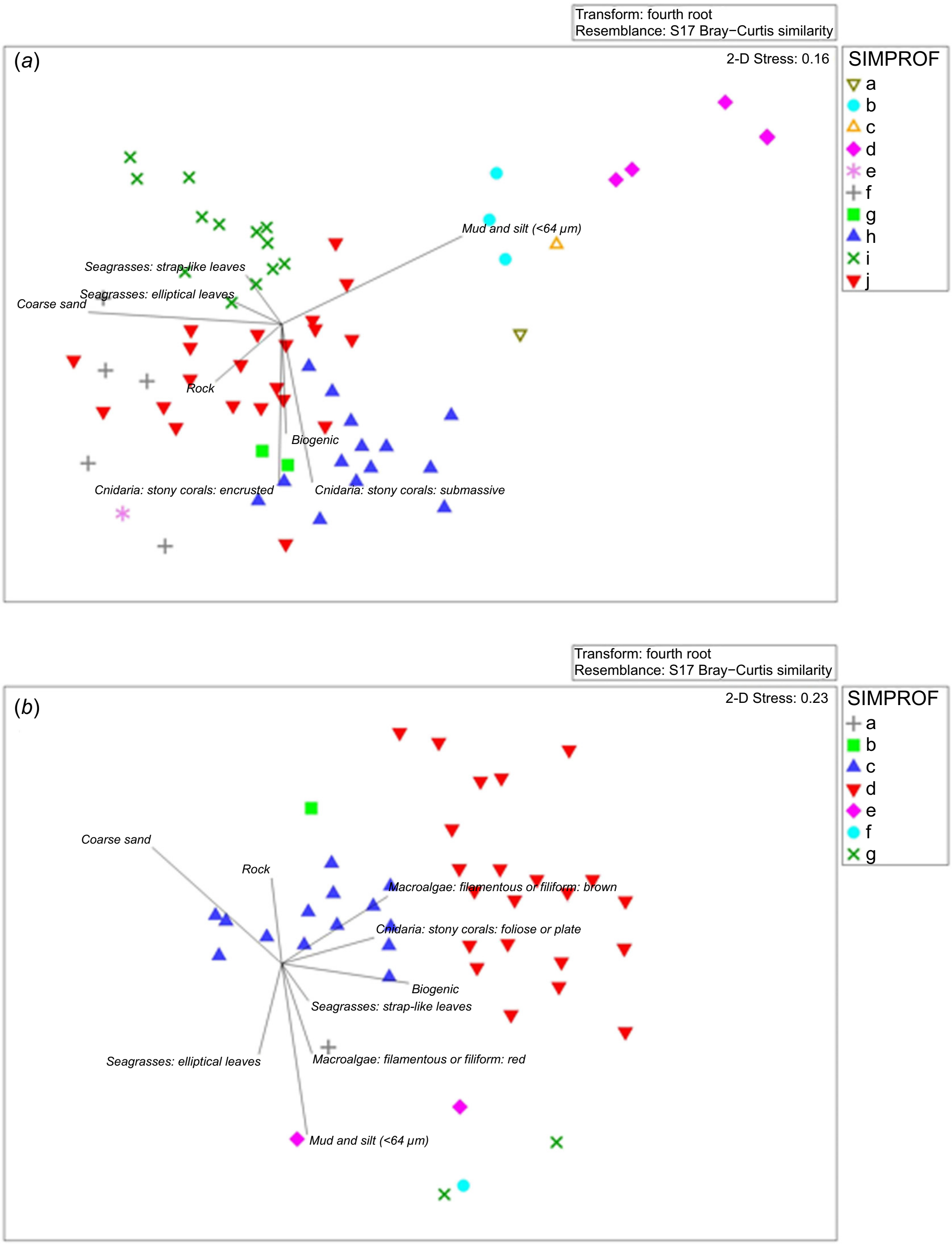

Fig. 3. Two-dimensional non-metric multi-dimensional scaling (MDS) ordinations of all transects within each site for (*a*) Trepang Bay and (*b*) Field Island, Northern Territory, Australia. The colours and symbols represent SIMPROF groups.

same basic characteristics and fulfil similar ecological functions and services to a lesser or greater degree. The Trepang Bay analysis results (SIMPROF groups, depth range, SIMPER) indicated that eight different biotopes occurred along the transects at this site, whereas seven biotopes were characterised from Field Island transects (Table 1).

Habitat mapping

Using the Support Vector Machine Learning Model, the total area for which habitat was predicted at Trepang Bay was 246.3 km^2, with the largest percentage of this area classified as 'Subtidal mud and silt' (40.44%) (Fig. 5). The habitat

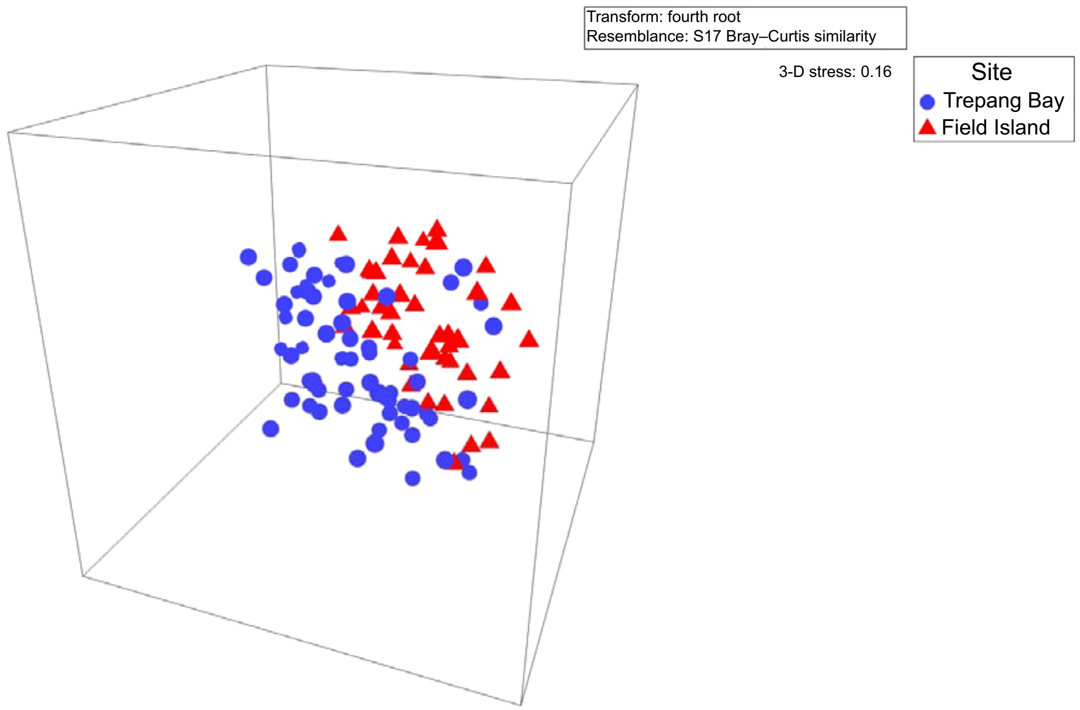

Fig. 4. A three-dimensional non-metric multi-dimensional scaling (MDS) ordination of all transects across both sites.

Table 1. Biotope classifications from Trepang Bay and Field Island.

Site	SIMPROF group	Description and similarities	Biotope name
Trepang Bay	h, e, a	Coral rubble, massive, submassive, and encrusting hard coral structures, coarse sand, and brown algae (laminate and erect fine branching)	Intertidal mixed coral reef habitat
	j	Coarse sand, coral rubble and brown algae (laminate and erect fine branching)	Intertidal algal reef
	j2, i2	Coarse sand, green algae and seagrass (mostly *Halodule uninervis*, but areas mixed with *Halophila ovalis*)	Intertidal mixed algae and seagrass
	g	Coral rubble, coarse sand, encrusting, submassive, foliose and corymbose hard coral structures	Subtidal mixed coral reef habitat and algal reef
	b, d2	Mud and silt and brown filamentous algae (red and brown)	Intertidal mud and silt and algae
	f	Coarse sand, hydroids, rock, encrusting sponges, soft whip corals, seasonal seagrass (*Halophila ovalis*)	Deeper subtidal mixed soft coral reef and seasonal seagrass
	i	Coarse sand	Intertidal coarse sand
	c, d	Mud and silt and brown erect branching red algae, with high levels of bioturbation	Subtidal mud and silt
Field Island	c	Coarse sand	Subtidal coarse sand
	c2, a	Coarse sand and seagrass (mixed *Halophila ovalis, Thalassia hemprichii, Syringodium Isoetifolium* and *Halodule uninervis*)	Intertidal coarse sand and seagrass
	c3	Coarse sand – mobile sandbanks	Intertidal coarse sand
	d	Coarse sand, coral rubble, filamentous brown algae, encrusting sponges, and hard corals (encrusting) with patchy seagrass (*Halodule uninervis*)	Intertidal mixed coral reef habitat and algal reef
	d2	Coarse sand, coral rubble, filamentous brown algae, encrusting sponges, hard (foliose) and soft corals (branching and whip)	Subtidal mixed coral reef habitat and algal reef
	b, e	Mud and silt, some red algae	Subtidal mud and silt
	f, g	Mud and silt, seagrass (mixed *Halophila ovalis* and *Thalassia hemprichii*) and pebbles	Intertidal mud and silt and seagrass

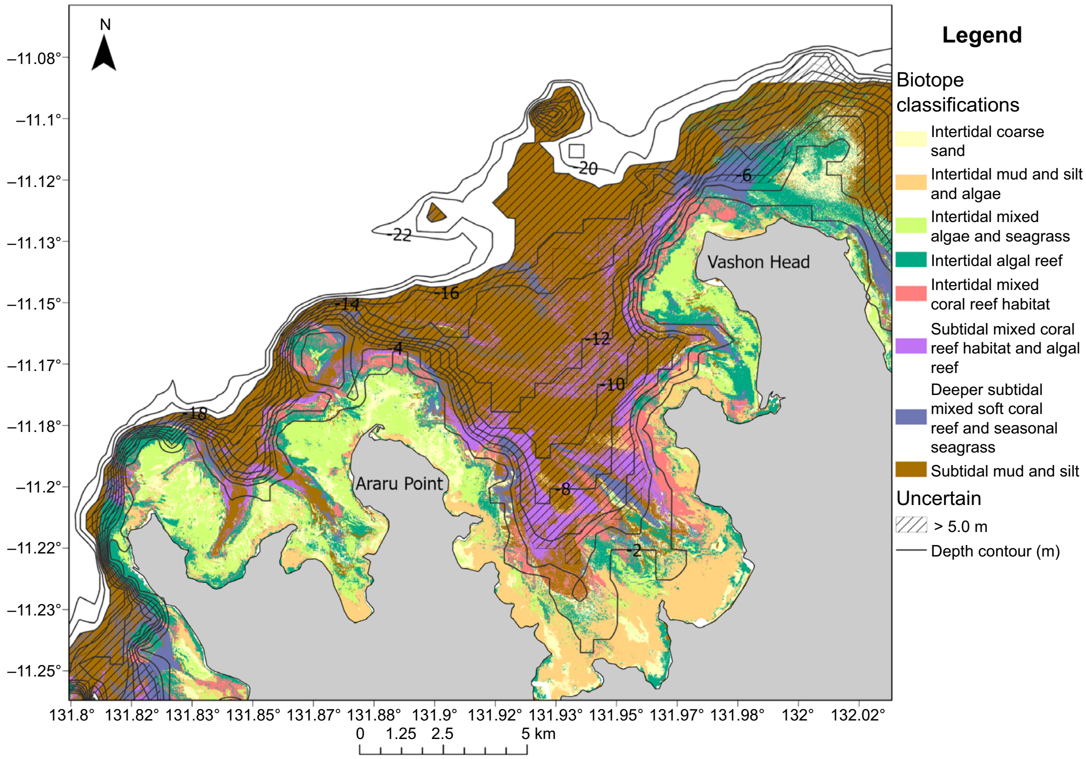

Fig. 5. Habitat map of Trepang Bay with the predicted biotope classifications from the Support Vector Machine Learning model trained using towed-video survey data. Depth contours are noted on the map and areas that are too deep for accurate remote sensing have been marked as 'Uncertain'.

'Intertidal algal reef' was the second most predicted biotope at 12.99%, followed by 'Intertidal mud and silt' (9.55%), 'Intertidal mixed algae and seagrass' (9.15%), 'Intertidal coarse sand' (8.12%), 'Deeper subtidal mixed coral reef and season seagrass' (7.92%), 'Subtidal mixed coral reef habitat and algal reef' (5.93%) and 'Intertidal mixed coral reef habitat' (5.88%).

The total area for which habitat was predicted at Field Island was 132.3 km^2; similar to Trepang Bay, the largest percentage of this area was classified as 'Subtidal mud and silt' (54.45%) (Fig. 6). The habitat 'Intertidal coarse sand' was the second-most predicted biotope at Field Island at 16.05%, followed by 'Subtidal coarse sand' (11.52%), 'Intertidal coarse sand and seagrass' (5.60%), 'Intertidal mixed coral reef habitat and algal reef' (5.33%), 'Subtidal mixed coral reef habitat and algal reef' (4.47%) and 'Intertidal mud and silt and seagrass' (2.65%).

The results of the accuracy assessment found that the kappa *index* for Trepang Bay was 0.63, indicating a substantial level of agreement between predicted and observed habitat classifications. The biotope 'Subtidal mud and silt' exhibited the highest user accuracy at 0.98 (almost perfect agreement), indicating the reliability of the classification for this habitat type. The lowest accuracy (0.28) was found for the more complex deeper habitat, 'Subtidal mixed coral reef habitat and algal reef', meaning that there was minimal agreement between observed and predicted for this habitat.

Similarly, for Field Island, the kappa index was found to be 0.75, signifying a higher, but still substantial, level of agreement between predicted and observed classifications. The biotope 'Intertidal coarse sand' demonstrated the highest user accuracy at 0.96 (almost perfect agreement). The lowest accuracy, of 0.53 (moderate agreement), was found for the habitat 'subtidal coarse sand', with this habitat type having the fewest ground-truthed transects.

Discussion

Through a collaborative partnership with Traditional Owners and ranger groups, progress has been made in enhancing the understanding and management of green turtle foraging habitats in the Northern Territory. This collaboration was essential in creating these habitat maps, as the expertise and knowledge of Traditional Owners and ranger groups provided valuable insights into the local marine ecosystems. This study marks the first application of ground-truthed remote-sensing techniques for mapping subtidal habitats in the Northern Territory. Sentinel-2 imagery was used to detect habitats such as seagrass meadows, coral reefs and algal reefs, as well as distinguishing among mud, coarse sand and rocky habitats with a high level of agreement at both sites (0.63 for Trepang Bay and 0.75 for Field Island). The successful

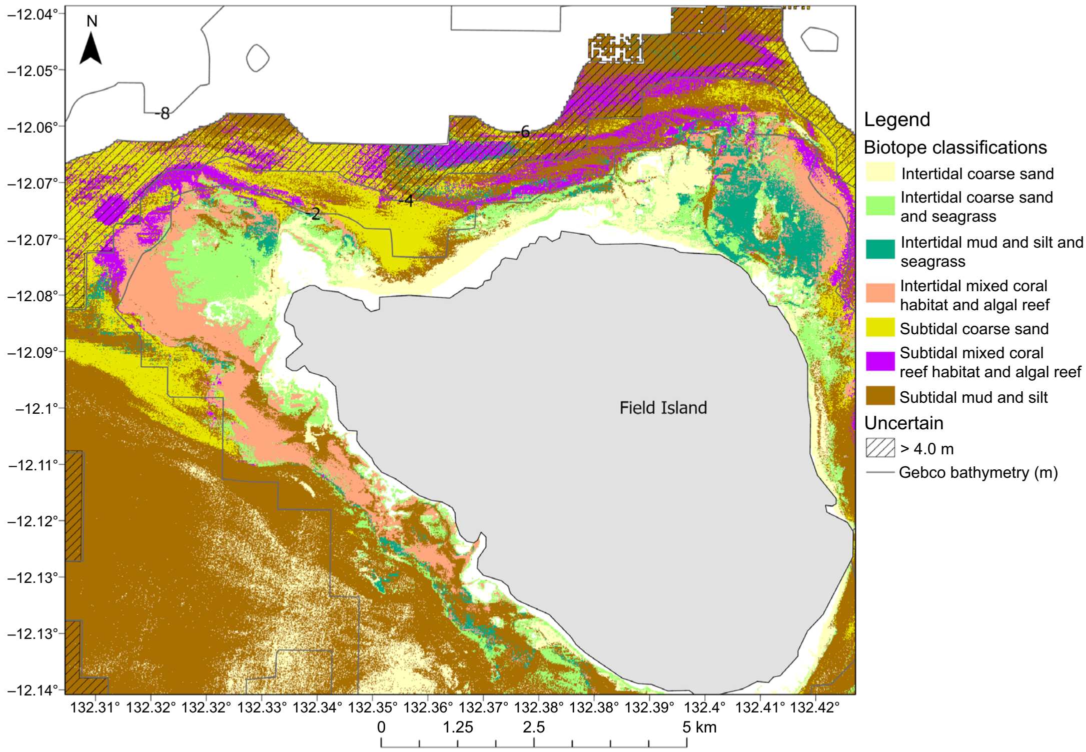

Fig. 6. Habitat map of the waters around Field Island with the predicted biotope classifications from the Support Vector Machine Learning model trained using towed-video survey data. Depth contours are noted on the map and areas that are too deep for accurate remote sensing have been marked as 'Uncertain'.

utilisation of Sentinel-2 imagery has demonstrated the potential of remote sensing, when paired with ground-truthed transects, as a valuable tool for assessing and monitoring marine habitats in remote and challenging environments. Even with the environmental challenges of low water clarity and high tidal range (Kuhwald *et al.* 2022), this study has shown that remote sensing can be effectively applied to the Northern Territory's shallow coastal waters. However, further research is required into both the seasonal and long-term changes in benthic assemblage, spatial extent and habitat health at these sites (Hedley *et al.* 2012; Lyons *et al.* 2013; Hovey and Fraser 2018; Krause *et al.* 2021).

The habitat classification model generally had a lower accuracy rating for deeper and more complex habitat types. Fine-scale habitat changes are more difficult to detect from satellite imagery with an increasing depth, and complex habitats can be difficult to distinguish at the spatial scale of 10 m^2. However, this lower accuracy can be mitigated by increased ground-truthing (Hedley *et al.* 2012; Wilson *et al.* 2022).

The significant differences between the benthic assemblages at Trepang Bay and Field Island could be attributed to varying levels of freshwater input. Trepang Bay, characterised by smaller rivers and catchments, experiences less freshwater and sediment input than does Field Island, which is located within Van Diemen's Gulf. The Gulf receives significant inflow from large river systems during the wet season (Department of Environment, Water, Heritage and the Arts 2007). This difference in hydrological dynamics, and associated differences in, for example, levels of sedimentation and turbidity, are likely to influence habitat composition and distribution, highlighting the importance of considering local environmental factors in habitat mapping and management efforts.

Although juvenile and adult green turtles are primarily herbivorous, foraging on algae, seagrass and occasionally mangroves (Mortimer 1981; André *et al.* 2005; Díaz-Abad *et al.* 2022), considerable variability in green turtle diet exists around the world, both among and within foraging grounds (Limpus and Limpus 2000; Palmer *et al.* 2021; Clyde-Brockway *et al.* 2022). The benthic assemblage results from Trepang Bay and Field Island both showed a diverse array of marine habitats, including mixed coral reef habitats, algal reefs and seagrass meadows. Algae and seagrass habitats made up a combined 30% of the mapped habitats in Trepang Bay and 18.05% at Field Island. The seagrass species found at Field Island during this study were similar to those found in 2004, with the new addition of *Thalassia hemprichii* (Russell and Smit 2007). These seagrass and algae habitats provide good foraging grounds for green turtles, with the diversity of marine habitats allowing for a range of different age classes of green turtles to forage at both sites. The more complex coral reef habitats also provide areas for rest and predator avoidance. This diversity of habitats also plays a crucial role in supporting other marine species such as hawksbill turtles (coral reef) and dugongs (seagrass) (André *et al*. 2005; Clyde-Brockway *et al*. 2022).

The collaborative partnership between ranger groups and scientists in field surveys not only facilitated the collection of ground-truthing data in very remote areas, but also demonstrated the potential for repeatability and effectiveness of these field methods for habitat monitoring. The towed-video system developed was highly cost-efficient, and lightweight, allowing it to be hand-haulable from small, open survey vessels and is easily constructed from materials that are commonly available in hardware stores. Although a live video feed was not used for this project', this camera set-up allows for a wifi extender cable to connect personnel on the vessel to the live video feed at an extra cost. A live video feed would allow for more control of the camera system (distance from the bottom, avoiding collision with large rocks), particularly at deeper or low-visibility sites. This approach has demonstrated the potential value to ranger groups for increasing opportunities for data collection in remote areas where other systems were either too bulky or failed.

A future goal for the collaborative partnership is to continue the capability building of ranger groups and community members to collect long-term marine habitat data, such as tracking coral bleaching and seagrass extent. By training ranger groups in field data collection and data storage methods, a ranger database can be created for towed-video data, which can then be used by Indigenous natural and cultural resource management agencies to support their decision-making on Country. The collaborative approach used in this study highlights the possibility for future seasonal and annual monitoring of marine habitats by remote ranger groups, as well as increasing the amount of available ground-truthing data. Combining these data with information on the species that these habitats support, including green turtles, is extremely useful for management planning, including the development of marine turtle management plans and Indigenous protected areas in the Northern Territory (Parks and Wildlife Service of the Northern Territory 2011; Department of the Environment and Energy 2017). By combining remote-sensing technologies with field observations, we have gained valuable knowledge about the availability, diversity and quality of the marine habitats used by foraging green turtles in the Northern Territory.

Supplementary material

Supplementary material is available online.

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Data availability. The habitat maps will be made available at https://seamapaustralia.org/.

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