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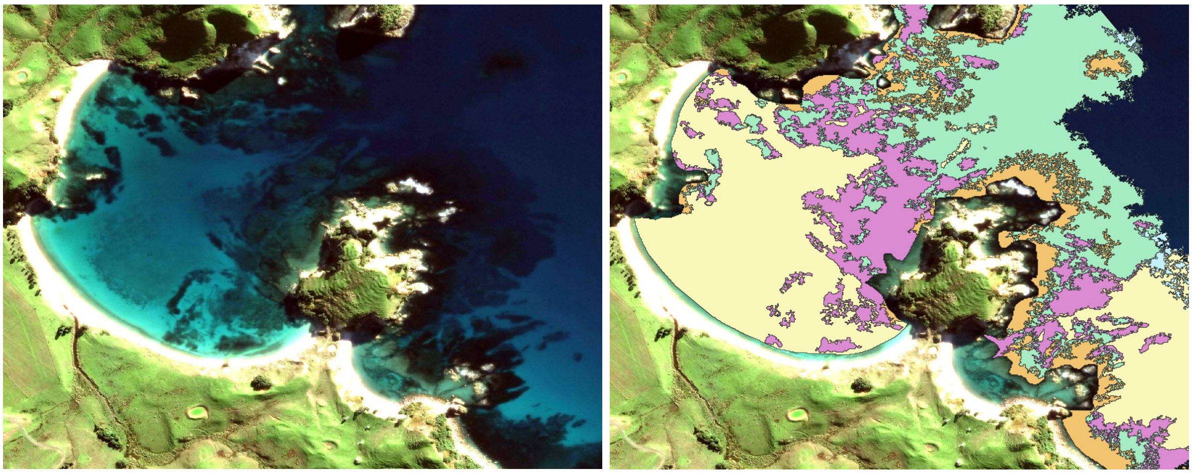

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Report prepared for Waikato Regional Council

Abstract

Mapping the broad-scale distribution and extent of marine habitats is critical to developing an ecosystem-based approach to managing the marine environment as well as monitoring large-scale changes in these habitats over time. Utilisation of existing satellite and aerial imagery of coastal regions can provide a cost-effective approach to mapping broad-scale habitat types in the shallow subtidal marine environment.

In this study, we use multi-spectral satellite imagery of the Mercury Islands, northeastern Aotearoa New Zealand, to map broad-scale marine habitats in shallow water (<15-20 m depth) around the island group. Supervised classification techniques were used to classify and map broad-scale reef and soft sediment habitat types. Georeferenced ground truth photos of shallow habitats were taken using drop camera and diver-based surveys across a range of sites in March 2022 and used to carry out accuracy assessment of resulting maps. Due to limited availability of concurrent satellite imagery with good weather and sea conditions across the entire island group, shallow water habitats around Ahuahu-Great Mercury Island and the eastern Mercury islands were mapped separately using satellite imagery from July 2020 and March 2016 respectively.

A total area of 1558 ha of shallow marine habitats were mapped around the island group. Habitats were mapped around Ahuahu-Great Mercury Island to a depth of ~20 m with an overall accuracy of 76%, whereas for the eastern Mercury Islands habitats were typically mapped to a depth of ~15 m with an overall accuracy of 67%. The mapped area around the entire island group was largely dominated by extensive reef systems (71% total mapped area) with soft-sediment habitats largely restricted to sheltered embayments on the western side of the main islands. This included two large areas of seagrass (total area 16 ha) in and adjacent to Huruhi Harbour on the western side of Ahuahu. The subtidal reef areas were dominated by kelp forest (77% of reef), urchin barren and turfing algae (12%) and shallow mixed algal forest (11%). Mapped areas of urchin barrens and turfing algae were most extensive in sheltered embayments on Ahuahu and on the more sheltered western and southwestern sides of the eastern Mercury islands.

Overall, the maps produced provide a good representation of the distribution of broad-scale habitat types in shallow water around the Mercury islands and based on comparison with other imagery these patterns appear stable over the last decade. However, mapping submerged habitats using satellite imagery is inherently difficult and the accuracy of the resulting maps was limited by factors relating to variable water quality and sea conditions, and acquisition artefacts in the available satellite imagery. The limitations and application of these methods are discussed, and recommendations are made for the future mapping and monitoring of marine habitats at the Mercury Islands.

Introduction

With increasing anthropogenic and environmental pressures on the marine environment there is a growing need for management agencies to understand the extent and distribution of coastal marine habitats and how they are changing over time. This information is crucial for local and governmental bodies to be able to make informed decisions in terms of resource management, fisheries and conservation policies and measures. Advancements in remote sensing techniques and greater availability and access to aerial and satellite imagery (Wang et al., 2010) provide increased opportunities to map broad-scale habitat types at large, management appropriate scales. Consequently, remote sensing approaches are increasingly being used to map broad-scale habitats as part of decision-making processes for marine spatial planning and marine protected area design (Douvere, 2008; Nguyen et al., 2016; Saarman et al., 2012) as well as for long-term monitoring of marine habitats (Leleu et al., 2012). Furthermore, recent studies in Aotearoa New Zealand have used satellite imagery to examine the effects of recent marine heatwaves on seagrass and giant kelp forests (e.g., Clemente et al., 2023; Tait et al., 2021).

Remote sensing approaches are well developed and commonly used for mapping non-submerged aquatic and marine habitats (Rowan et al., 2021). For example, surface canopies of giant kelp are easily distinguishable in freely available low resolution satellite imagery, lending themselves to automated classification techniques (Cavanaugh et al., 2021; Tait et al., 2021). In contrast, approaches to mapping submerged or subtidal habitats are less well developed, most likely due to the inherent difficulties in classifying habitats underneath water of varying depths and clarity (Kibele 2017; St-Pierre & Gagnon, 2020). This is particularly the case for mapping submerged kelp forests, which occur in cool-water temperate regions that have high coastal productivity and often low water clarity compared to tropical regions. A variety of methods have been used to map submerged kelp forests and other shallow reef habitats, such as urchin barrens, with satellite and aerial imagery ranging from highly complex optical remote sensing methods to simple manual methods. Optical remote sensing methods use water column correction processes to remove the effects of varying depth on the spectral signature on different habitats, and then use an automated classification on the resulting depth corrected image (e.g., Kibele 2017; Kibele and Shears 2018). In contrast, simple manual or visual methods involve a trained observer manually digitising polygons around visibly different habitats, usually with the aid of ground-truth information (Leleu et al., 2012; Kerr and Grace 2017; Dartnall 2022). Supervised classification provides an intermediate approach whereby a user identifies multiple areas representative of each benthic habitat and then a GIS mapping algorithm classifies the image (on a pixel-by-pixel basis) based on the spectral signature of the known areas. The supervised-classification approach can yield a similar degree of accuracy as more advanced optical methods but reduces potential bias or user-error and can potentially be applied over larger scales than manual methods (Lawrence 2019; St-Pierre & Gagnon 2020).

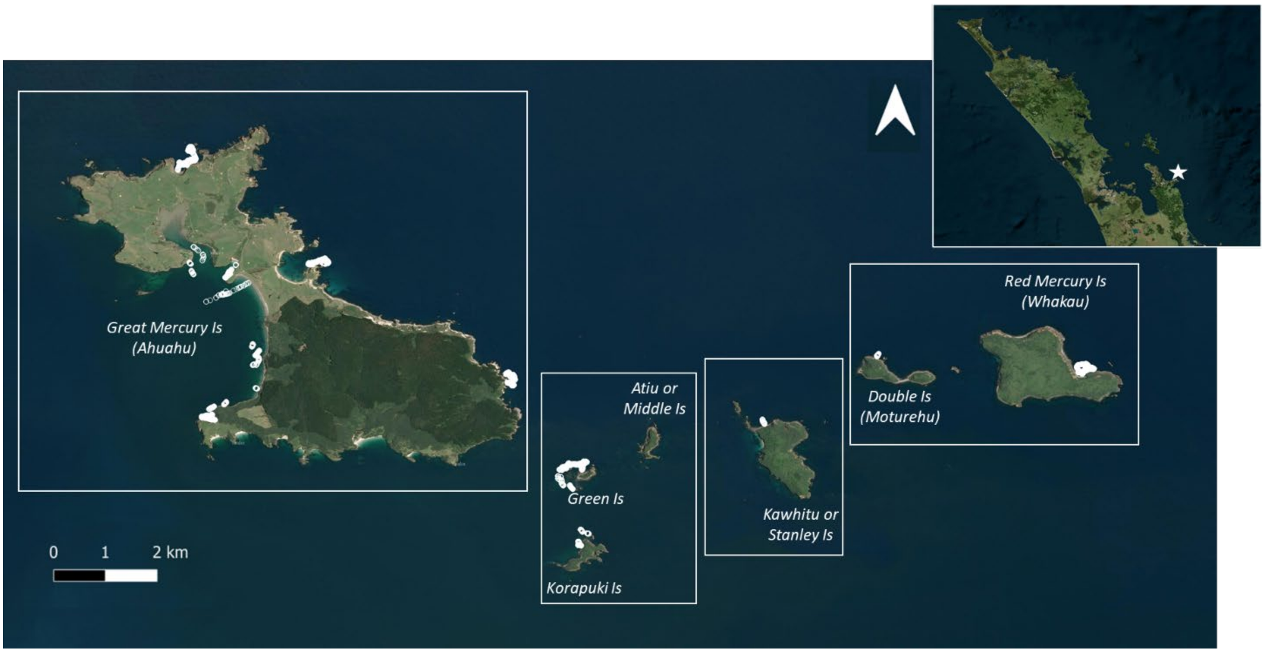
Shallow reef ecosystems in temperate regions of the world are historically dominated by kelp forests, which support high biodiversity and provide numerous ecosystem services (Eger et al. 2023). However, kelp forests are under increasing threat due to overfishing of sea urchin predators, sedimentation from land use change and catchment activities, and from the impacts of climate change (Blain et al., 2021; Ling, 2008; Steneck, 2020; Wernberg et al., 2019). For example, in Aotearoa New Zealand fishing of sea urchin predators (snapper and crayfish) over many decades has led to an increase in sea urchins (kina *Evechinus chloroticus*), with subsequent loss of kelp forest and formation of urchin (or kina) barrens (Shears & Babcock, 2003). Furthermore, recent warming trends in northern Aotearoa New Zealand have likely led to an increases in the subtropical sea urchin *Centrostephanus rodgersii* and further expansion in the extent of urchin barrens at offshore islands in northeastern Aotearoa New

Zealand (Balemi and Shears 2023). The loss of highly productive kelp forest to an “urchin barren” state results in reduced biodiversity and ecosystem services with potential negative impacts on local coastal economies (Ling, 2008; Wernberg et al., 2019). Understanding the extent of urchin barrens and kelp forests is therefore critical to marine managers in developing strategies to safeguard native biodiversity and manage the effects of fishing and catchment based pressures, and restore and conserve these important ecosystems. Remote sensing provides a valuable resource to provide this information, as kelp forests and urchin barrens on shallow reefs (<20 m depth) can be visually distinctive in aerial and satellite imagery in regions with good water clarity (St-Pierre & Gagnon 2020). In northeastern Aotearoa New Zealand, shallow reef habitats have been mapped in a number of studies using aerial and/or satellite imagery (e.g., Kerr & Grace 2005, 2017; Kibele 2017, Kibele and Shears 2018; Leleu et al., 2012; Lawrence 2019, Dartnall 2022, Kerr et al. 2024). In some cases, these have been used to detect large-scale shifts in habitat types associated with fishing and/or marine protection (Kerr and Grace 2005; Leleu et al., 2012).

The Mercury Islands, situated off the eastern coast of the Coromandel Peninsula northeastern Aotearoa New Zealand (Fig. 1), are of high cultural, recreational and commercial significance, yet limited documented information exists on the historic or current distribution and extent of key habitats. There are extensive reef systems around much of the Mercury Islands and these are characterised by reef habitats such as *Ecklonia radiata* forests and urchin (or kina) barrens that are typical of other open coast and offshore island locations in northeastern Aotearoa New Zealand (Caiger et al. 2023). Previous remote sensing studies as outlined above have successfully mapped these broad habitat types in northeastern Aotearoa New Zealand, including at Hahei on the nearby Coromandel Peninsula (Kibele & Shears, 2018). Seagrass *Zostera muelleri* beds have also been mapped over soft sediment areas at Ahuahu – Great Mercury Island (Clark and Crossett 2019). These studies highlight the potential and need for broad-scale habitat mapping at the Mercury Islands that can be used not only to understand it’s current state but also as a baseline for future monitoring and mapping, so that changes in broad-scale habitats can be assessed.

The overall aim of this study is to provide a baseline map of key shallow habitats around the Mercury Islands, that in conjunction with future mapping and monitoring of the region can inform marine environmental management. We use remote sensing methods to map broad-scale shallow water habitats around the Mercury Islands, northeastern Aotearoa New Zealand (Fig. 1). Shallow habitats are mapped using supervised classification of multispectral satellite imagery of the island group from 2016 and 2020, and ground truth imagery collected at the Mercury Is in 2022 (Caiger et al 2023) is used to complete an accuracy assessment of the resulting habitat maps, while recognising the difference in timing between satellite image and ground-truth data acquisition. The mapping approach and the broad-scale reef habitat types used are comparable with recent shallow subtidal mapping efforts in the Waikato Region (Kibele and Shears 2017) and other parts of northeastern Aotearoa New Zealand (Kerr and Grace 2017; Lawrence 2019, Dartnall 2022) and the resulting maps are discussed in this broader context. In addition, the extent of seagrass, which represents an ecologically important shallow soft-sediment habitat at the Mercury Islands, is mapped and its current distribution compared with earlier studies.

Fig. 1 Location map of Mercury Islands, Coromandel Peninsular, northeastern Aotearoa New Zealand. White boxes indicate the different mapping areas. Positions of ground-truth images indicated by white dots and white boxes indicate extent of the two areas where reef habitats are mapped in this study.



2. Methods

2.1 Study area

The Mercury Islands are a group of 7 main islands situated off the eastern coast of the Coromandel Peninsula, northeastern Aotearoa New Zealand (Fig. 1). The islands run east-west over ~18km with Ahuahu - Great Mercury Island, the largest in the west, and Whakau - Red Mercury in the east. Located between ~6 and 15 km offshore from the mainland, the islands are influenced to varying degrees by sediment runoff originating from the mainland. Caiger et al. (2023) provides a description of the subtidal reef habitats and associated biodiversity found across the islands. In general, shallow subtidal reef assemblages at the Mercury Islands are typical of those found at offshore Islands in northeastern Aotearoa New Zealand, being dominated by forests of large seaweeds (mainly the kelp *Ecklonia radiata* and fucoids *Carpopyhllum* spp.), and some areas of reef are dominated by the sea urchin or kina *Evechinus chloroticus,* which form urchin barrens. The depth extent of subtidal reefs varies with reefs being shallower (<10 m) in more sheltered areas such as on the eastern side of Ahuahu-Great Mercury Island but extend beyond 20 m on more exposed eastern and northern coasts. Reefs typically give way to coarse sandy habitat, and in sheltered areas such as Huruhi Harbour seagrass *Zostera muelleri* is known to form beds over soft sediment (Clark and Crossett 2019).

2.2 Satellite imagery of the Mercury Islands

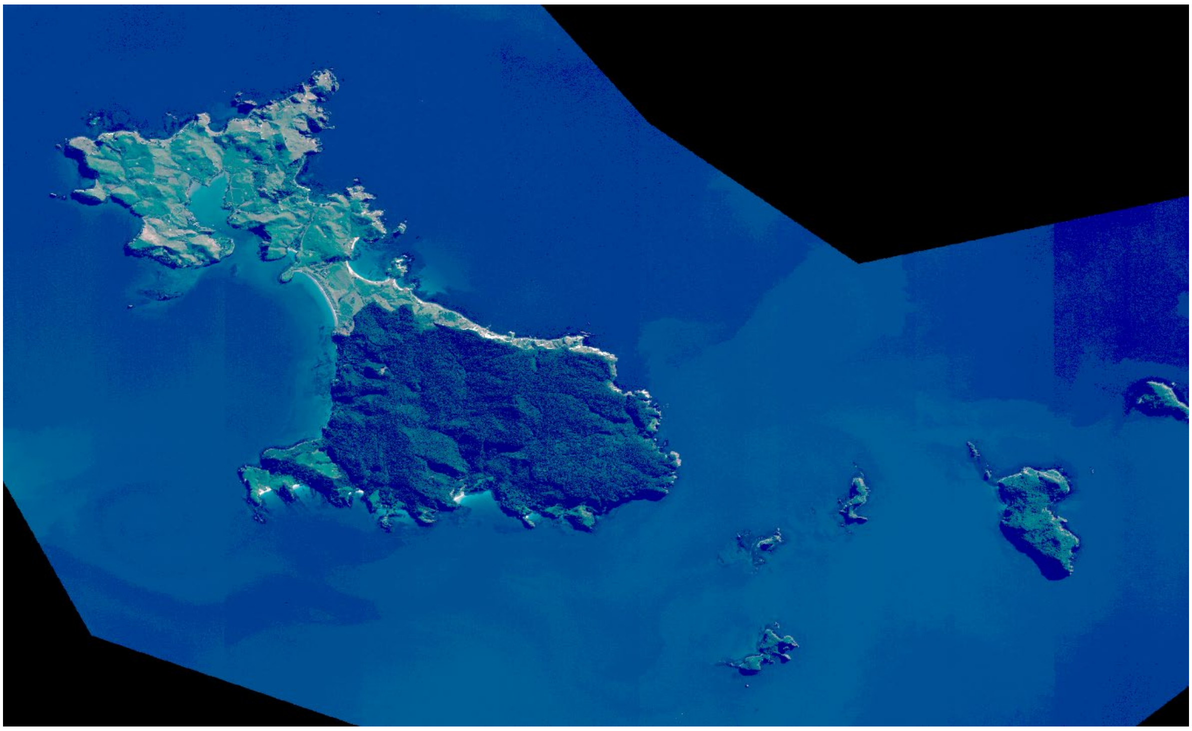
The Maxar online satellite imagery archive (https://discover.maxar.com/) was searched in 2021 for recent satellite imagery that was suitable for mapping shallow marine habitats across the Mercury Islands. The 8-band WorldView-2 or -3 imagery available in this archive is high resolution (2m pixels). This high resolution is necessary to map submerged and often patchy shallow water habitats (Kibele and Shears 2018, Lawrence 2019). At the time of this study free satellite imagery of this resolution was not available.

Mapping of submerged marine habitats requires optimal conditions in order to “see” through the water and delineate spectrally distinct habitats on the bottom. This therefore requires minimal cloud cover, high water clarity, and calm sea conditions with little glint. There was limited imagery available from recent years that met these criteria. The most recent and clearest available image of the Mercury Islands was WorldView-2 imagery from 9th July 2020 (Fig. 2A). While this image had good water clarity around Ahuahu-Great Mercury Island, there was a marked decline in water clarity in the eastern region of the islands. This image was therefore only used to map Ahuahu-Great Mercury Island. Very limited imagery of suitable quality was available for the smaller islands to the east including Korapuki Island, Green Island, Atiu (Middle Island) and Kawhitu (Stanley Island). The best available imagery of these islands was WorldView-2 imagery from 4th March 2016.

Maxar imagery was purchased by Waikato Regional Council through Eagle Technologies. The WorldView-2 multispectral satellite imagery was received from Maxar at the LV3D product level. No atmospheric correction was carried out.

Fig. 2. WorldView-2 satellite imagery of the Mercury islands from 9th July 2020 (A) and 4th March 2016 (B). Note the change in water clarity at eastern end of Great Mercuty Island in 2020 image – lighter blue colouration in offshore waters indicate lower clarity water, compared to darker blue/clearer water in western part of image.

A



B

2.3 Ground-truth imagery collection

Georeferenced images of the seafloor were collected across a range of sites across the island chain between the 14 and 17th March 2022 (Fig. 1). The location of sites was largely determined by weather conditions at the time of sampling, but an attempt was made to sample both exposed and sheltered sides of each of the main islands. Limited sites in the eastern islands were sampled due to poor weather conditions during multiple field trips.

The surveys were conducted for use with the Benthic Photo Survey (BPS) ground-truth system (Kibele, 2016) and are hereafter referred to as “BPS” images. This involved collection of images by drop-camera deployed from a boat or by divers. At each site an attempt was made to haphazardly take images down the depth gradient from the shallows (1-2 m depth) to the edge of the reef (or a maximum depth of ~20m). Downward facing photos were taken of the seafloor with a GoPro, fixed 1.1 m off the bottom and capturing an area of seafloor ~2.5 m^2. The depth of each image is recorded on a Sensus depth logger[1].

The boat-based drop camera system used was the same as that described in Kibele and Shears (2018). For diver-based surveys, divers towed a float with GPS and took photos approximately every 5 seconds as they swam over the reef, ensuring the GPS float was directly above when taking each photo. Each photo was first geo-tagged based on the GPS track using GeoSetter software[2] and then depth tagged using the BPS software (Kibele 2016)[3]. Shape files of image locations were then created using the BPS software.

Once collected these images are assessed for quality and the main habitat category present within each image was classified according to habitat type categories outlined in Table 1 (based on Shears et al 2004). These images therefore provide a georeferenced point of a known habitat type that can then be used for accuracy assessment of the habitat map (Section 2.5).

2.4 Habitat mapping and classification

The 8-band imagery was processed in the NZTM coordinate system and was checked for orthorectification using LINZ aerial imagery for reference. Broad-scale habitats were classified using a supervised classification approach, which involves input from a trained and experienced analyst to select areas of known habitat types that are used to train the classification algorithm and classify pixels into categories based on their spectral signatures (Richards & Jia, 2006; Abburu and Golla, 2015). While a subset of ground-truth samples can be used to select these training areas, we had a limited availability of ground-truth samples, and these are often not located in optimal places for training. Instead, we identified areas of known habitat based on the authors knowledge of the reef ecosystems in the region from extensive diving observations and surveys at the Mercury Islands in 2021/2022 (e.g., Caiger et al 2023) and previous mapping exercises that used these same methods (Lawrence 2019). This approach meant that all ground-truth photos were used to provide an independent accuracy assessment of the resulting map (Section 2.5).

The mapping process was carried out for Great Mercury Island using the 2020 image and the eastern islands using the 2016. However, due to variation in water column characteristics and banding across

[1] https://reefnet.ca/products/sensus/
[2] https://geosetter.de/en/main-en/
[3] http://jkibele.github.io/benthic_photo_survey/

the 2016 image, the eastern islands were mapped separately in three groups: 1. Korapuki-Green-Atiu, 2. Kawhitu and 3. Moturehu-Whakau (Figure 1). This meant that different training inputs were used for each of the four mapped regions so that the classification process could better distinguish the habitat categories within each of the four areas given differing water column characteristics.

In each of the four mapping regions, between 5 and 10 training polygons were selected from known areas of each habitat type as well as optically deep areas which were assigned as "unclassified" (See Appendix 1 for positions and examples of training polygons). Each training polygon was assigned a macroclass ID (MC ID) and supervised classification was carried out using QGIS software (Version 3.22.16) and the Semi-Automatic Classification Plugin (SCP) with the spectral angle mapping algorithm (Congedo, 2021). This algorithm was found to be the best for mapping reef habitats using supervised classification approaches in QGIS (Lawrence 2019). Classification was isolated to subtidal habitats using a mask layer to exclude land and intertidal areas, and sections that could not be classified such as areas of white water or areas where shadow may block visibility through the water column.

Habitat mapping based on satellite imagery only allows for broad-scale categories to be mapped as the habitats must be able to be distinguished spectrally underwater (Kibele & Shears, 2018). Therefore, some of the finer-scale habitat categories identified in BPS images that are spectrally similar such as urchin barren and turfing algae were mapped as a single habitat (Barren/Turf). The same broad-scale reef habitats as Kibele & Shears (2018) were mapped (Table 1, Fig. 3). In addition, Seagrass habitat was also mapped, as this forms an important and visually distinctive subtidal soft-sediment habitat that can be readily mapped with aerial and satellite imagery (Clark and Crossett 2019; Clemente et al. 2023). However, seagrass was not included as a habitat in the supervised classification (i.e. sea grass training polygons were not included) due to its restricted spatial extent at the Mercury Is (Clark and Crossett 2019) and its spectral similarity to reef habitats (Lawrence 2019). Instead, areas of seagrass were mapped as part of post-processing (as outlined below).

Classification was carried out on individual pixels, which then requires a sieving procedure to reduce detailed pixelations that make the map difficult to read and interpret. Manual edits can then be carried out as part of post-processing to fix known errors and misclassifications. This was limited to visual observation and evaluation of the satellite imagery and knowledge of habitats that may be difficult to spectrally distinguish (e.g., habitats such as gravel or seagrass). Seagrass has a restricted distribution on shallow sandy habitats on the western side of Ahuahu and is easily distinguished visually by a trained analyst from reef habitats. The supervised classification generally classified seagrass areas as Barren/Turf and these were manually re-classified as seagrass. Ground truth imagery was not used to make any manual changes to the map, otherwise this would have discredited the accuracy assessment results.

2.5 Accuracy Assessment

Accuracy assessment of the habitat maps of Ahuahu-Great Mercury Is (2020) and eastern Mercury islands (2016) was conducted using the BPS images following methods in Kibele and Shears (2018). BPS images that had been both geotagged and depth tagged were used to confirm the accuracy of the mapping classification using a radiused approach (<3m), such that if a pixel with a matching classification to the BPS image occurs within 3 m of the image position this is deemed a successful classification. Accuracy of the map was reported as producer accuracy (percentage or ground truth data points classified correctly), user accuracy (percentage of mapped area of a habitat category that was shown to be accurate by the ground truth data) and overall accuracy (percentage of total ground truth points mapped correctly).

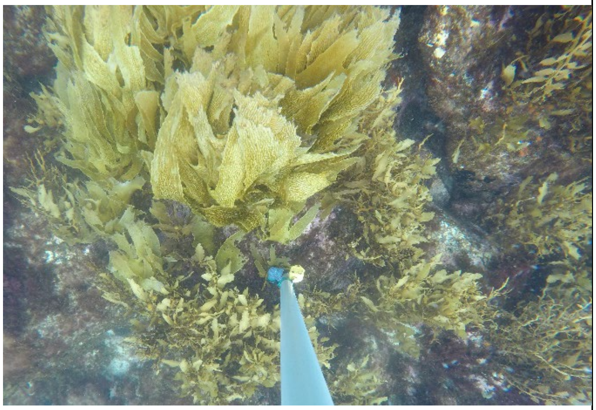
Table 2. Mapped habitat types used to classify the reef soft sediment habitats in this study (reef habitats based on Shears et al. 2004). Note canopy cover is used to allow assessment of habitat type from photos.

Mapped habitat	**Related Habitat type in Shears et. al. (2004)**	**Description**
Shallow mixed algal forest	Shallow *Carpophyllum forest*	Dominated by high abundances (>20 adult plants m^{-2}) of *Carpophyllum maschalocarpum, C. plumosum, C. angustifolium* and in some cases *Xiphophora chondrophylla. Ecklonia radiata, Sargassum sinclairii* and the red algae *Pterocladia lucida, Osmundaria colensoi,* and *Melanthalia abscissa* also common. Sea urchin *Evechinus chloroticus* occurs in low numbers and usually occupies crevices.
	Mixed algal forest	Mixture of large brown algal species including *Lessonia variegata*. No clear dominance of one particular species, with >50% canopy cover (typically >4 adult plants m^{-2}) and urchins may also occur at low numbers (<2 exposed urchins m^{-2}).
Barren/Turf	Urchin barrens	Low numbers of large brown algae present (<50% cover), substratum typically dominated by crustose coralline algae and urchins present. Usually associated with grazing activity of *Evechinus* (>2 exposed urchins m^{-2}), which leaves the substratum relatively devoid of macroalgae. *C. flexuosum* and *Sargassum sinclairii* may occur.
	Turfing algae	Substratum predominantly covered by turfing algae (e.g., articulated corallines and other red turfing algae) (>50% cover). Low numbers of large brown algae (<50% cover) and urchins may be common.
Kelp forest	*Ecklonia* forest	Generally monospecific stands of mature *Ecklonia* with >50% canopy cover (typically >4 adult plants m^{-2}), occasional *C. flexuosum* plants. Urchins at low numbers and usually occupy crevices.
	Carpophyllum flexuosum forest	*C. flexuosum* plants dominate (>4 adult plants m^{-2}), on sheltered reefs plants are large and associated with high levels of sediment. On more exposed reefs plants are short and generally associated with *Evechinus.*
Seagrass	NA	Presence of patches of seagrass *Zostera muelleri* on soft sediment habitat
Sand	Sand and gravel	Soft sediment habitat.
Not mapped	Deep reef	Deep reef with sparse *Ecklonia* (<4 adult plants m^{-2}) and sponges visually dominant, high cover of sediment. Usually occurs on the reef-sand interface in deep water (>15 m) and therefore cannot be mapped with satellite imagery.
Not mapped	Encrusting invertebrates	Usually vertical walls, substratum predominantly covered by community of encrusting ascidians, sponges, hydroids, and bryozoans. Large brown algae are rare. Vertical walls cannot be mapped with satellite imagery.
Not mapped	*Caulerpa flexilis* mats**	Mats of *Caulerpa flexilis* over the substratum (>40%). Usually occurs on the reef-sand interface. Urchins and large brown algae rare. Indistinguishable in satellite imagery from kelp forest on reef or seagrass on sand.

* The invasive *Caulerpa* species were not observed during the ground-truth photo surveys in March 2022.

Fig. 3. Ground-truth (BPS) images showing broad habitat categories that were mapped with satellite imagery.

Shallow mixed algal forest (*Ecklonia radiata and Carpophyllum maschalocarpum*



Kelp forest (*Ecklonia radiata*)

Barren/Turf (Typical kina barren with kina, crustose coralline algae and filamentous algae)

Barren/Turf (Turfing algal (*Corallina officinalis*) dominated reef with cryptic kina)

Seagrass (*Zostera muelleri)*

Sand

3. Results

3.1 Ahuahu - Great Mercury Island habitat map

A total area of 842 ha of shallow subtidal habitats were mapped around Ahuahu - Great Mercury Island using the 2020 satellite image to depths up to 20 m (Table 3, Fig. 4A, Appendix 2.1). The majority of the mapped area was reef (62%), with the remaining soft sediment areas (38%) classified as Sand or Seagrass (Table 3). The northern and eastern sides of the island are dominated by rocky reef habitats, which typically extend beyond the mapped depths, with shallower sandy habitats restricted to the shallow embayment's at Cathedral Rocks and Coralie Bay (Fig. 4B). The more sheltered western and southern sides of Ahuahu have a greater dominance of sandy habitats with reefs typically resticted to depths <15 m (Fig. 4D). This shallowing of the reef and sand border is evident around the northwestern (Fig. 4C) and southwestern (Fig. 4E) corners of Ahuahu.

Table 3. Total area (ha) of mapped habitats at Ahuahu – Great Mercury Island (2020) and the eastern Mercury islands (2016) (A) and the relative cover of dominant reef habitats (B). Note this excludes areas that were unclassified.

(A) Total area (ha) Habitat	Ahuahu - Great Mercury Is	Atiu-Green Is - Korapuki	Kawhitu	Moturehu - Whakau	Total
Shallow Mixed	65.8	17.9	8.4	24.5	116.5
Barren/Turf	80.6	29.4	12.5	12.9	135.5
Kelp Forest	373.8	217.9	76.7	184.7	853.1
Sand	306.1	48.5	38.9	42.8	436.3
Seagrass	16.1	0.0	0.0	0.0	16.1
Total area mapped	*842.4*	*313.8*	*136.5*	*264.8*	*1557.5*
(B) Cover of reef habitat types (%)					
Shallow Mixed	12.6	6.7	8.6	11.0	10.5
Barren/Turf	15.5	11.1	12.8	5.8	12.3
Kelp Forest	71.9	82.2	78.5	83.2	77.1

The overall area of mapped reef at Ahuahu was dominated by kelp forest (72%), followed by Barren/Turf (16%) and then Shallow Mixed algal forest (13%) (Table 3). There is a shallow margin (~<2 m) of Shallow Mixed algal forest around much of the island, Barren/Turf is most prevalent but patchy at intermediate depths (~2-8 m), and Kelp Forest generally dominates the reef from below the Shallow Mixed zone to either the edge of the reef or edge of the mapped extent (Fig.4A-E). On the western and southern sides of Ahuahu the lower edge of Kelp Forest was mapped where reef transitioned onto sand, but on the northern and eastern side of the island the Kelp Forest and reef generally extended beyond the mapped extent and the reef-sand border was not optically evident.

Along the northwestern section of Ahuahu (Fig. 4C) and parts of the central eastern side of the island (Fig. 4B) Barren/Turf formed a distinctive band between the Shallow Mixed and Kelp Forest. However, there were also large areas of shallow low lying patch reef (<5 m depth) that were mapped as Barren/Turf, e.g., northern side of Sister Rocks and offshore from Paritu Point (Fig 4D).

Subtidal seagrass beds represented a distinctive soft sediment habitat that could be mapped from the satellite imagery. Areas of seagrass were only present on the western side of the island in the entrance of Huruhi Harbour and around Matakawau Pt (Fig. 4D).

Accuracy assessment of the Ahuahu map based on ground-truth images revealed an overall accuracy of 76% (Table 4A). Kelp forest, Barren/Turf, Sand and Seagrass had the highest producer accuracy (ground-truth images correctly classified), with Shallow Mixed having the lowest (45%). Kelp forest images were most commonly mis-classified as Shallow Mixed, but this generally occurred when Kelp Forest occurred in shallow water (<2 m; e.g. Appendix 2.2).

Ground-truth images of Shallow Mixed were most commonly misclassified as Kelp Forest (27%) and Barren/Turf (27%). When Shallow Mixed algae occurred in deeper areas it tended to get classified as Kelp forest (Appendix 2.2). There were also numerous occasions where images of Shallow Mixed were mapped as Barren/Turf, which in some cases likely indicates changes on the reef since the satellite image was taken (Appendix 2.3). The classification accuracy of Barren/Turf was moderate (77%), being most commonly classified as Kelp (19% of Barren/Turf images). Examples of known barren areas being mapped as kelp occurred in Cathedral Rocks, which is likely due to shading (Appendix 2.2). Seagrass had a moderate Producer Accuracy with 79% of Seagrass ground-truth images successfully classified, and most often mis-classified as Sand.

Table 4. Accuracy assessment of Ahuahu – Great Mercury Island based on 2020 satellite image (A) and the eastern Mercury Islands based on the 2016 satellite image (B).

A	**Ground Truth Image**							
Habitat	Kelp Forest	Barren/ Turf	Shallow Mixed	Sand	Seagrass	Other	*Totals*	**User Acc.**
Kelp Forest	<u>584</u>	85	61	21	0	3	*754*	**77%**
Barren/Turf	32	<u>350</u>	61	28	1	0	*472*	**74%**
Shallow Mixed	34	5	<u>102</u>	0	0	0	*141*	**72%**
Sand	12	12	4	<u>131</u>	7	3	*169*	**78%**
Seagrass	0	1	0	0	<u>30</u>	0	*31*	**97%**
Totals	*662*	*453*	*228*	*180*	*38*	*6*	*1567*	**-**
Producer Acc.	**88%**	**77%**	**45%**	**73%**	**79%**	**-**	**-**	**76%**

B	**Ground Truth Image**					
Habitat	Kelp Forest	Barren/Turf	Shallow Mixed	Sand	*Totals*	**User Acc.**
Kelp Forest	<u>342</u>	72	88	18	*520*	**66%**
Barren/Turf	3	<u>135</u>	20	4	*162*	**83%**
Shallow Mixed	12	55	<u>64</u>	8	*139*	**46%**
Sand	7	0	0	<u>48</u>	*55*	**87%**
Totals	*364*	*262*	*172*	*78*	*876*	**-**
Producer Acc.	**94%**	**52%**	**37%**	**62%**	**-**	**67%**

Fig. 4A Map of shallow marine habitats (<20 m depth) at Ahuahu - Great Mercury Island based on 2020 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/). Inset boxes show locations of Fig 4B-E.

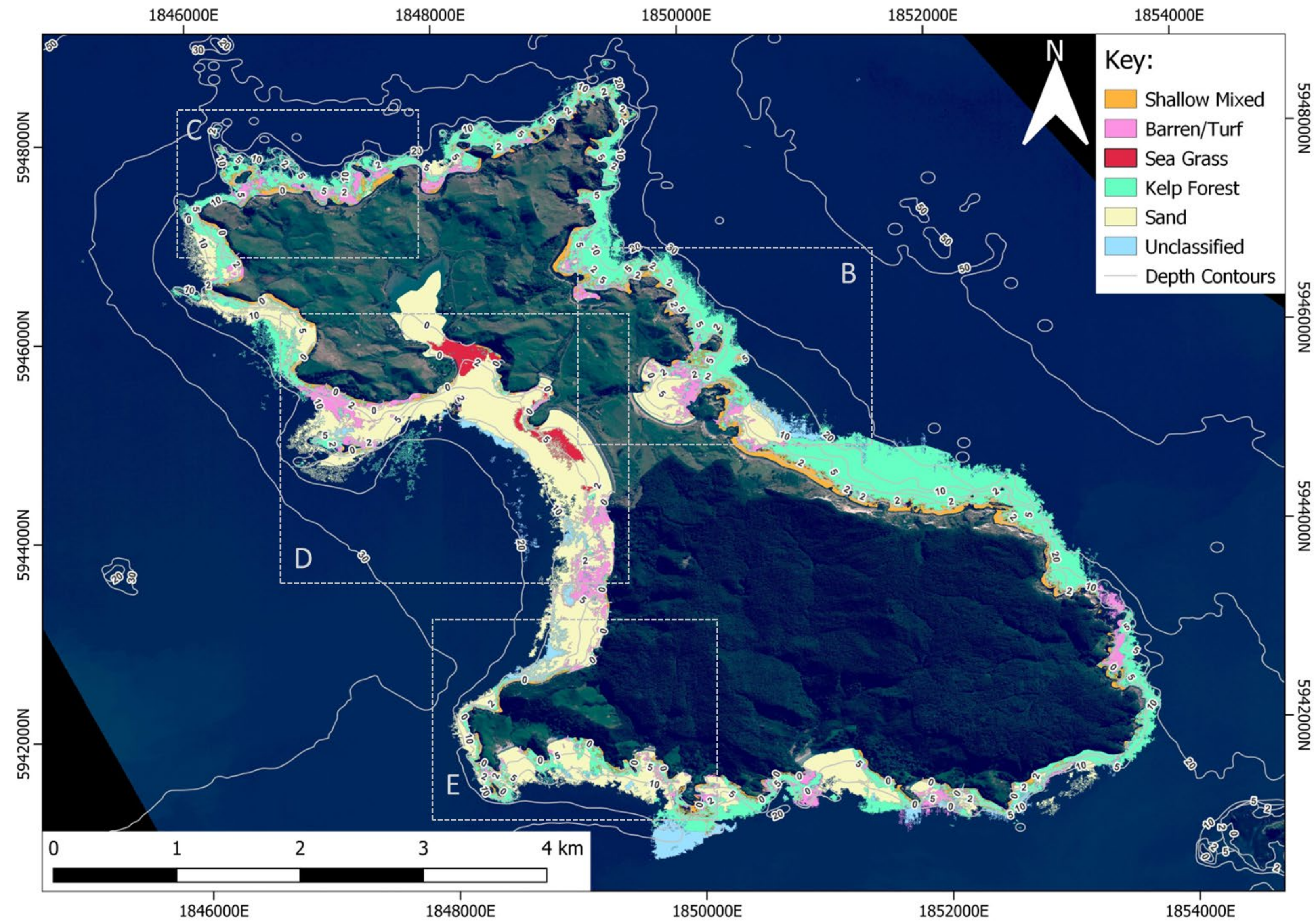


Fig. 4B Shallow marine habitats (<~20 m depth) of the Coralie Bay area, Ahuahu - Great Mercury Island based on 2020 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/).

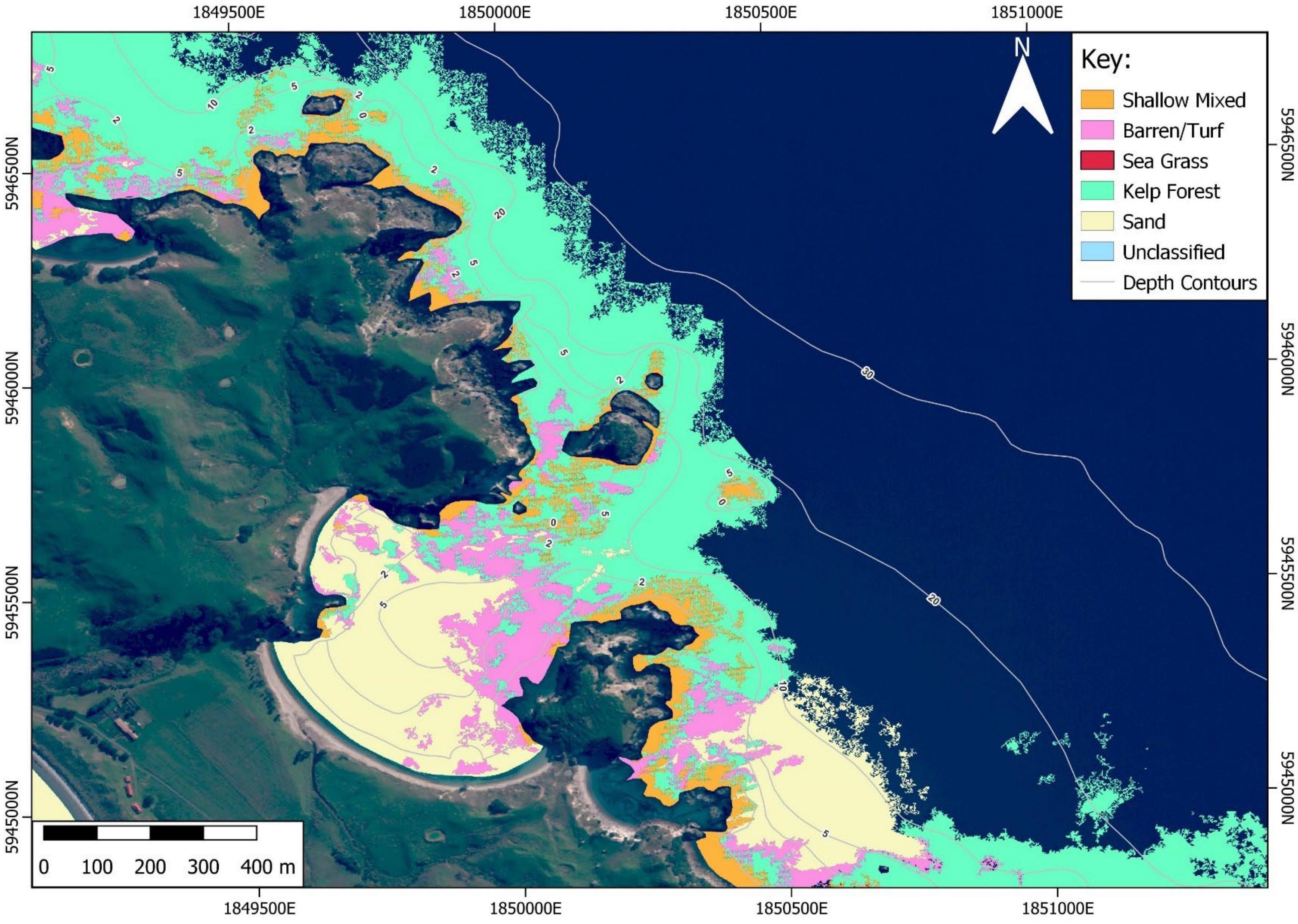


Fig. 4C Shallow marine habitats (<~20 m depth) of the northestern corner of Ahuahu - Great Mercury Island based on 2020 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/).

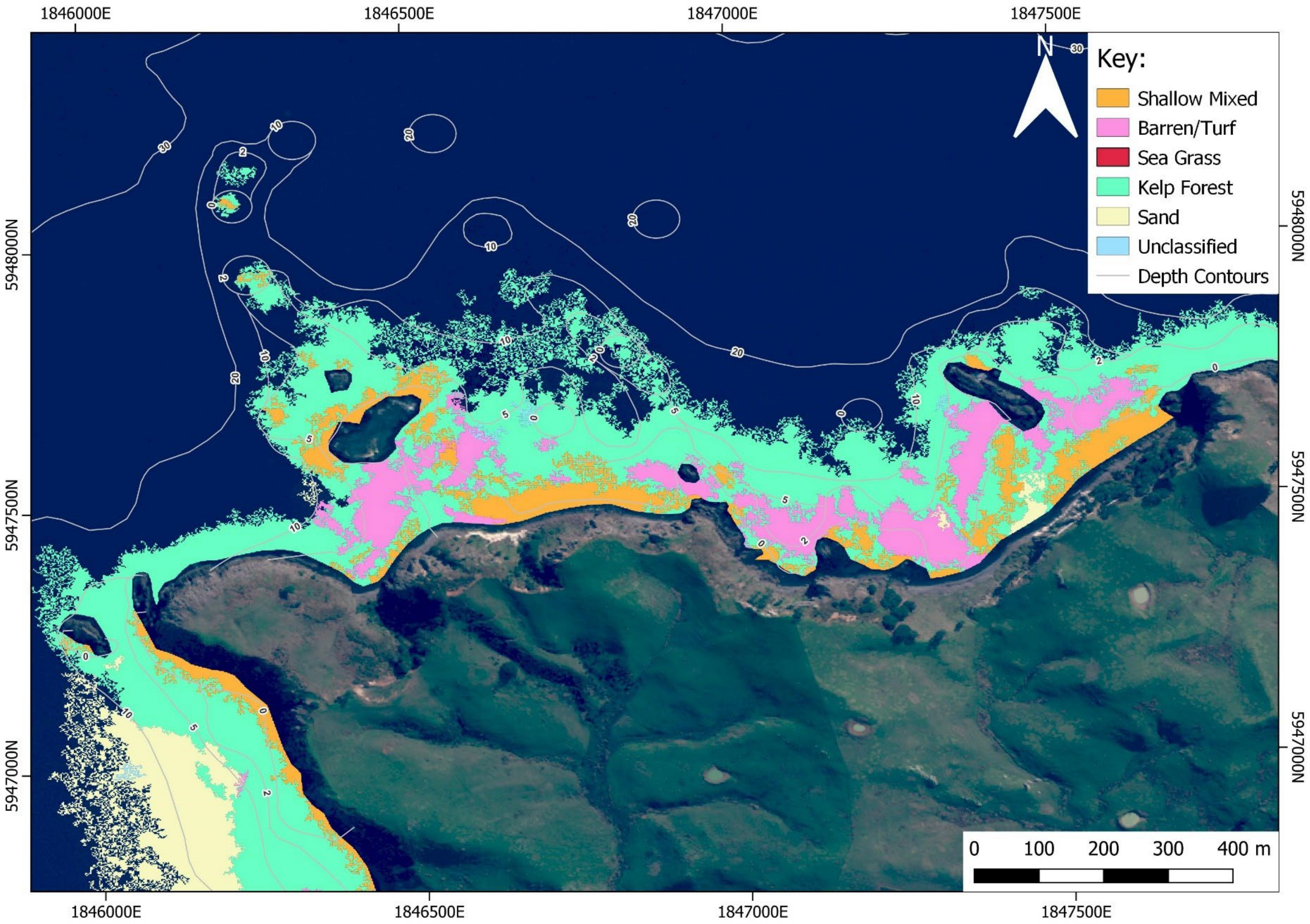


Fig. 4D Shallow marine habitats (<~20 m depth) of Huruhi Harbour and "western bay" of Ahuahu - Great Mercury Island based on 2020 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/).

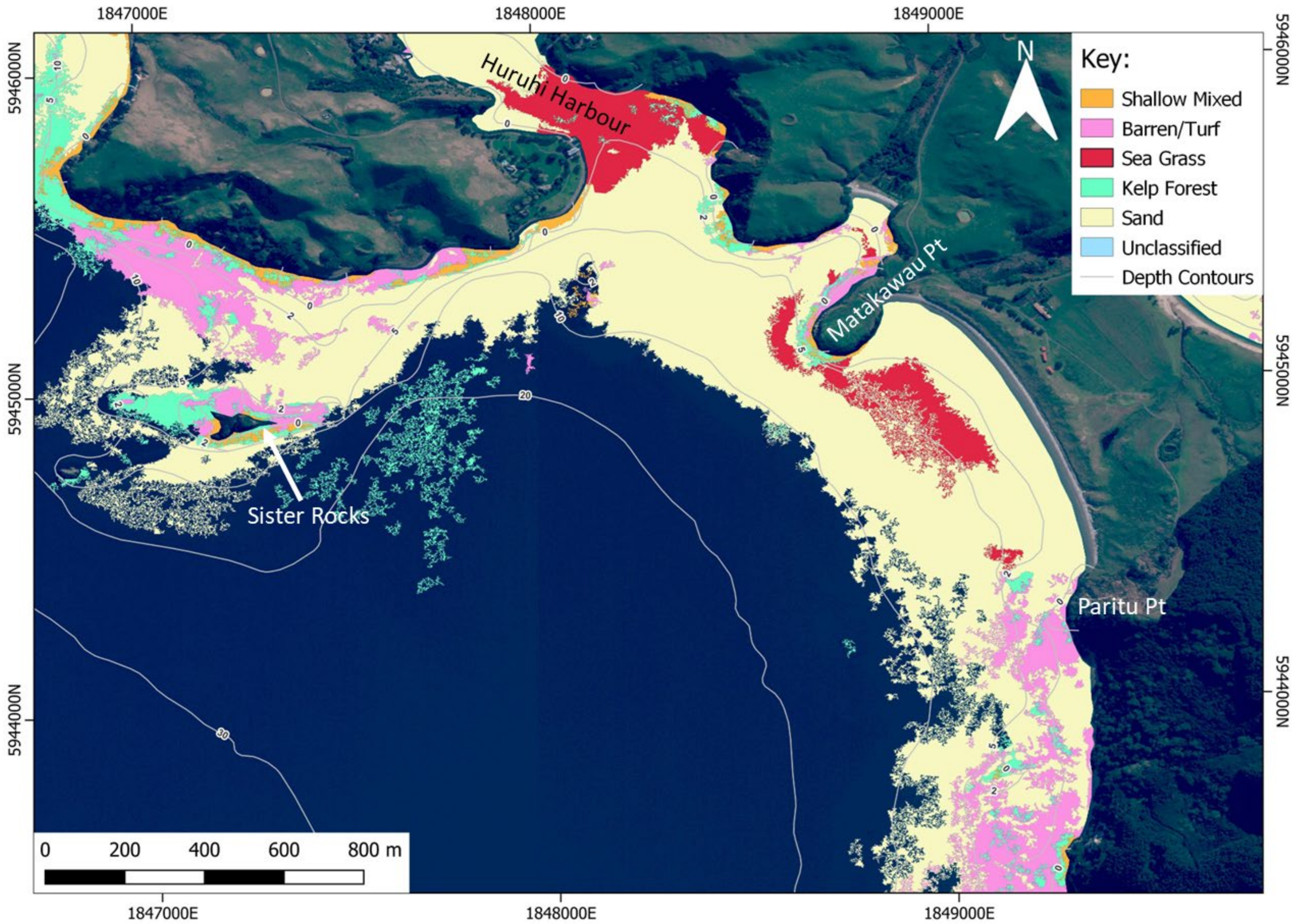
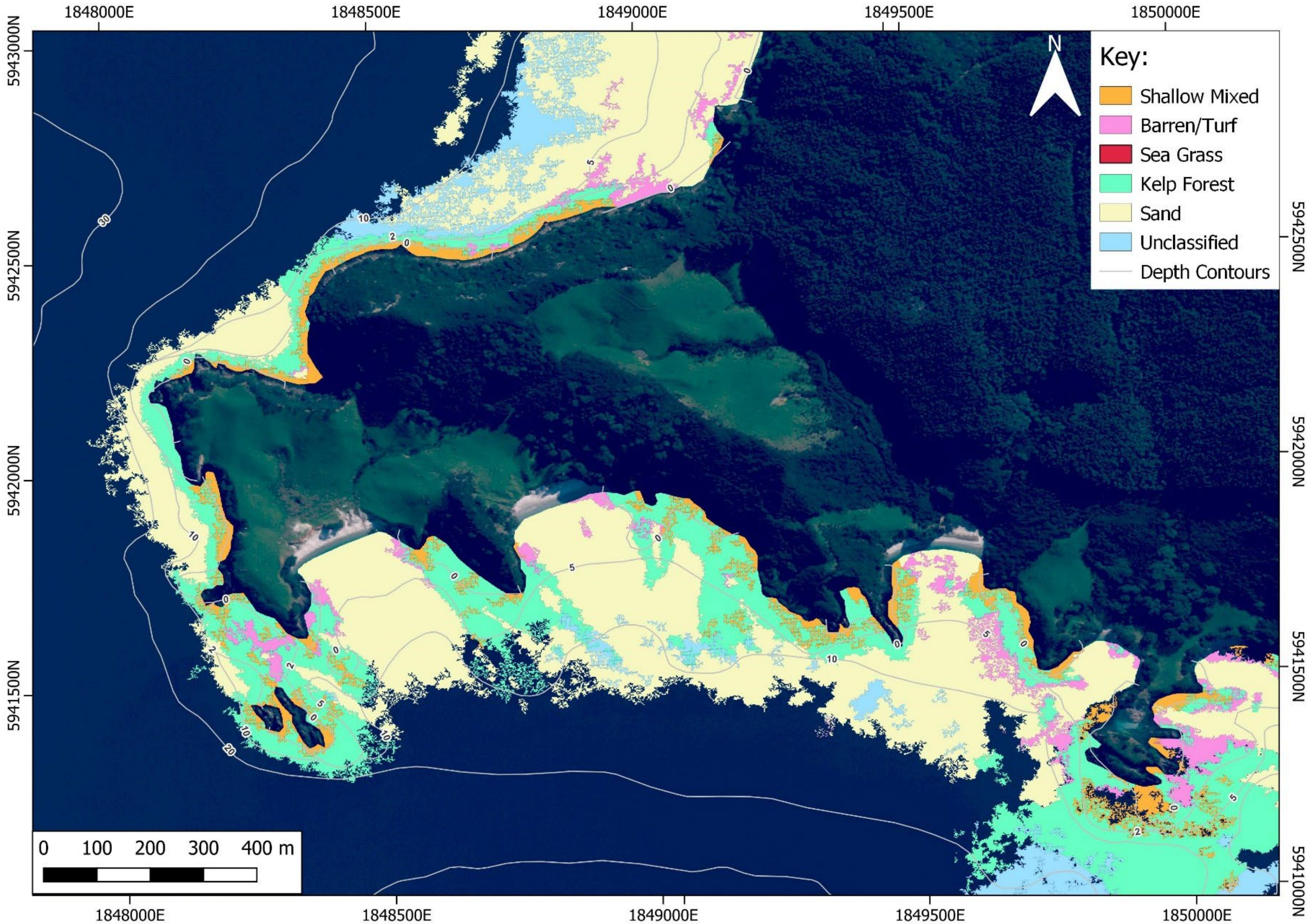


Fig. 4E Shallow marine habitats (<~20 m depth) of the northestern corner of Ahuahu - Great Mercury Island based on 2020 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/).



3.2 Eastern Mercury Islands 2016

The eastern Mercury Islands were mapped separately as three groups due to variation in water clarity and banding across the 2016 satellite image (Table 3B). Resulting habitat maps for each island are shown in Fig. 5 (A-E). Based on ground-truth imagery, habitats across these islands were mapped to depths of ~15 m (e.g., Appendix 2.4). The total area mapped around the eastern Mercury Islands was 715 ha (Table 3B).

Atiu, Green and Korapuki Islands are all relatively small islands, but with extensive interconnecting shallow reef systems interspersed with areas of coarse sand (Fig. 5A and B). The mapped reefs were dominated by Kelp Forest (82%), with areas of Barren/Turf (11%) and Shallow Mixed algal forest (7%) in shallow water (<8 m). Barren/Turf was most prevalent on the southwest and southeast parts of Green Island and Atiu, and around Korapuki (Fig. 5A and B).

There was a similar distribution of habitats at Kawhitu-Stanley Island (Fig. 5C) as Atiu, with Kelp Forest dominating (79%), but with large areas of Barren/Turf (13%) on the southeastern side of the island and in the bay on the eastern side. Barren/Turf was not present along the exposed northern coast.

Moturehu and Whakau-Red Mercury Islands are surrounded by extensive subtidal reef systems that extend well beyond the mapped extent (Fig. 5D and E). Only comparatively small areas of shallow sand habitat were mapped on the western side of Whakau. The vast majority of mapped reef is dominated by Kelp Forest (83%). However, the extent of Kelp Forest on the northern side of Whakau may have been overestimated in some areas (e.g. Appendix 2.6). There is a near continous band of Shallow Mixed algal forest around both islands (11%) and Barrens only covered 6% of the mapped reef. Barren/Turf was patchy on the northern side of Moturehu, but some large areas of barrens were present on the southern side of both islands. Ground-truth photos indicate deep areas of barrens (8-18 m) in Von Luckner's Cove, Whakau-Red Mercury Island but these were not evident in imagery.

There were insufficient ground-truth points across each island to carry out an island-specific accuracy assessment of each map. Across all the eastern islands, the maps had an overall accuracy of 67% (Table 4B). Kelp Forest ground truth points had highest classification success (94%), but Barren/Turf and Shallow Mixed had comparatively low accuracy (52% and 37% respectively). Barren/Turf images were most commonly mis-classified as Kelp Forest (27%) and Shallow Mixed (21%), whereas Shallow Mixed were predominatly misclassified as Kelp Forest (51%). In most cases where Shallow Mixed photos were mapped as Kelp forest, these tended to occur in deeper water, e.g. nothern side of Green Island and Von Luckner's Cove, Whakau-Red Mercury Island (Appendix 2.5 and 1.6 respectively). Urchin barrens were also patchy on northern side of Green Island and frequently mis-classified and mapped as kelp (Appendix 2.5), likely indicates changes in the habitats since satellite image aquisition. In a few instances, areas of sand identified in BPS images were mapped as Barrens/Turf, and conversely deeper areas of Barrens/Turf based on BPS images were not mapped (e.g. Appendix 2.5).

Fig. 5A Map of shallow marine habitats (<15 m depth) at the estern Mercury Island's based on 2016 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/). Inset boxes show locations of Fig 5B-F. Note vertical banding in satellite image.

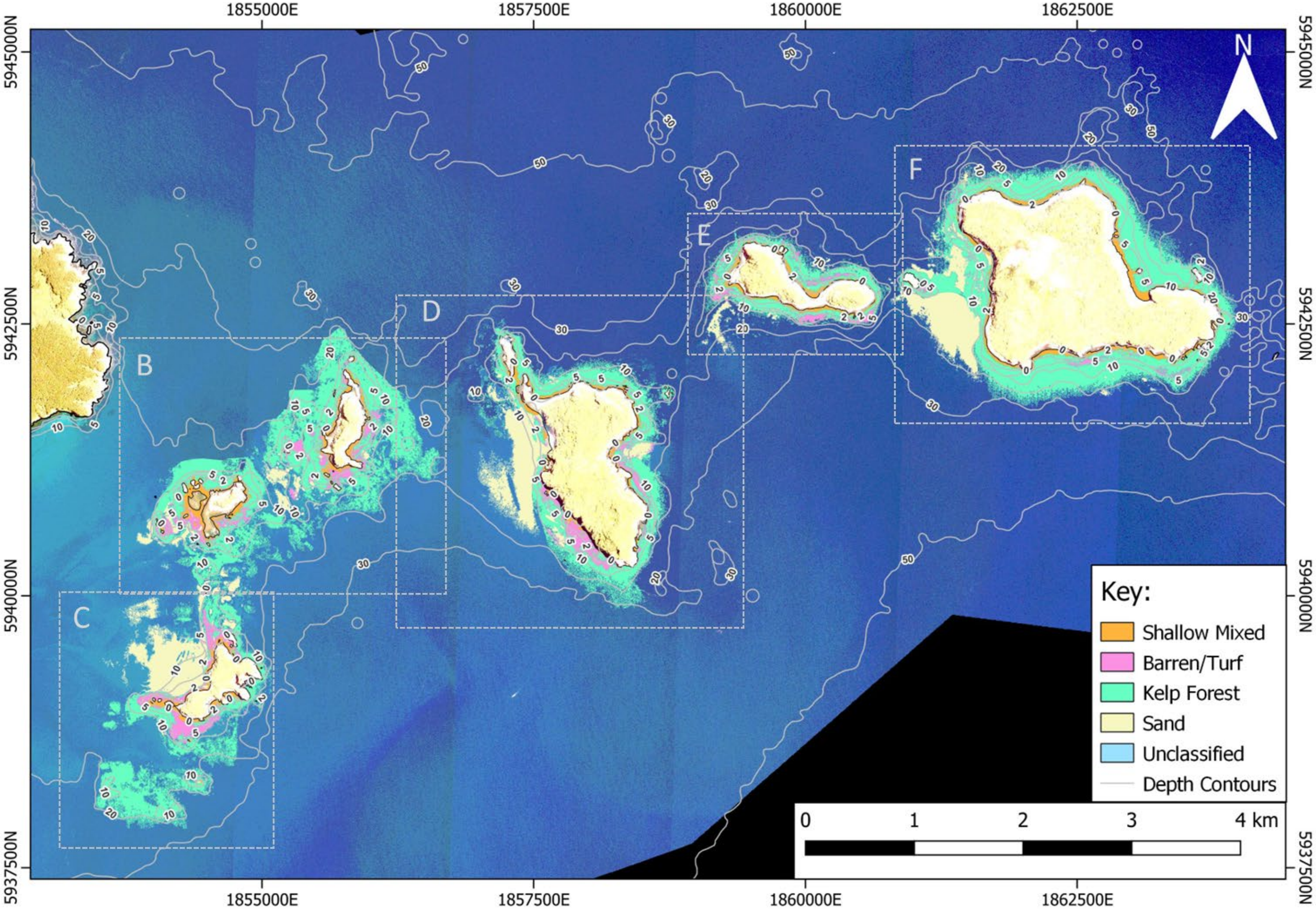


Fig. 5B Map of shallow marine habitats (<20 m depth) at Green Island and Atiu based on 2016 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/).

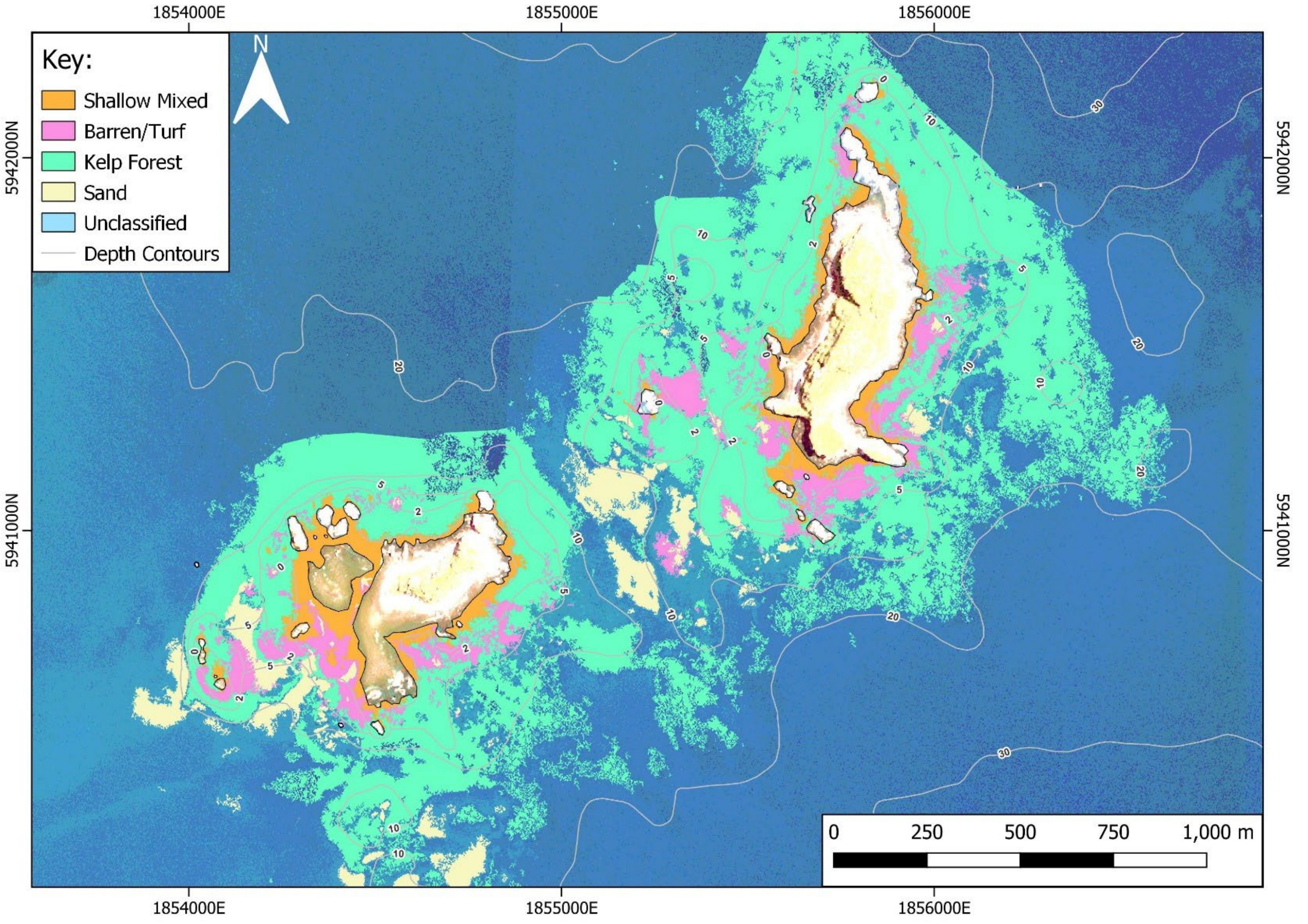


Fig. 5C Map of shallow marine habitats (<15 m depth) at Korapuki Island based on 2016 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/).

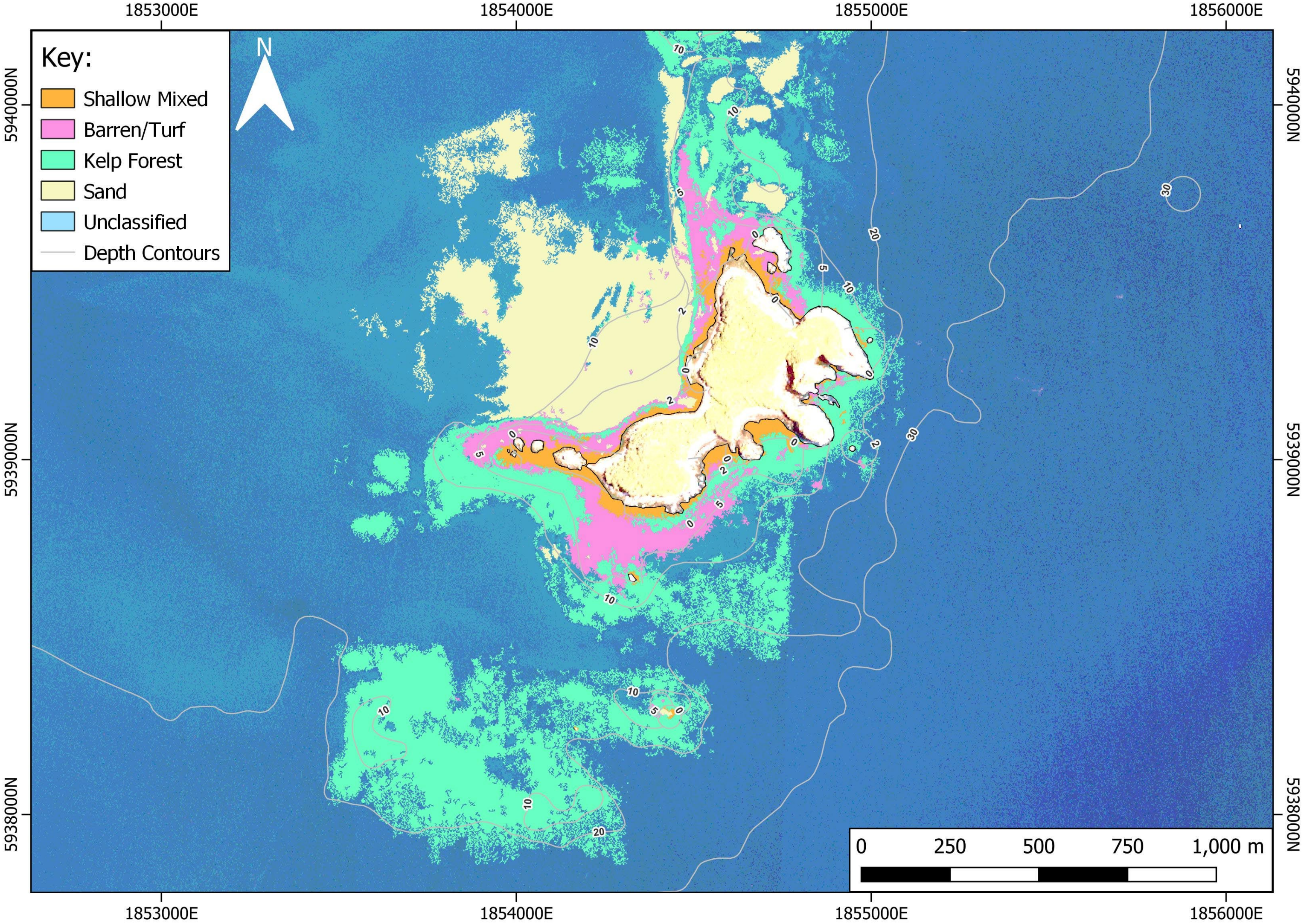


Fig. 5D Map of shallow marine habitats (<15 m depth) at Kawhitu-Stanley Is based on 2016 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/).

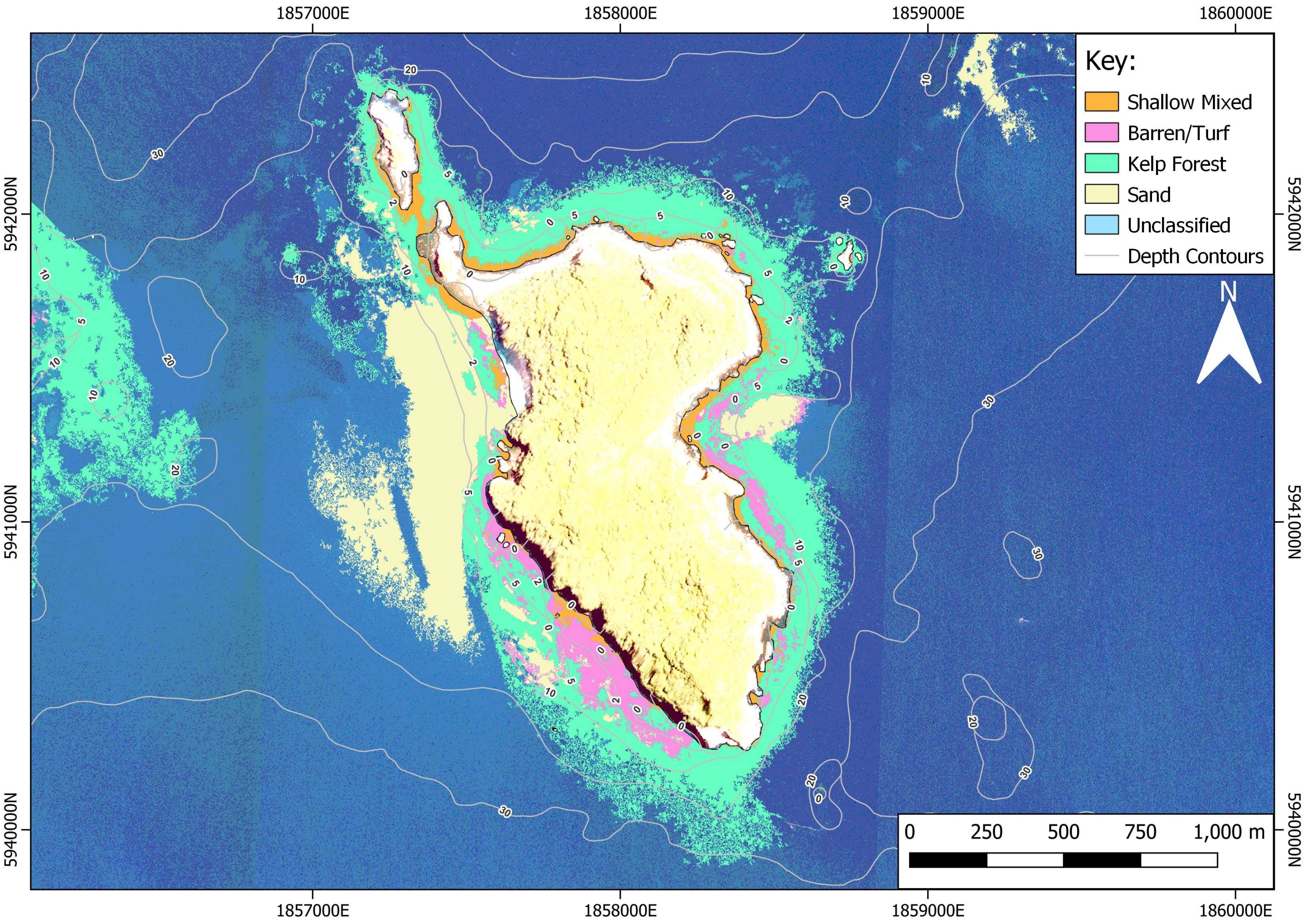


Fig. 5E Map of shallow marine habitats (<15 m depth) at Moturehu Island based on 2016 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/).

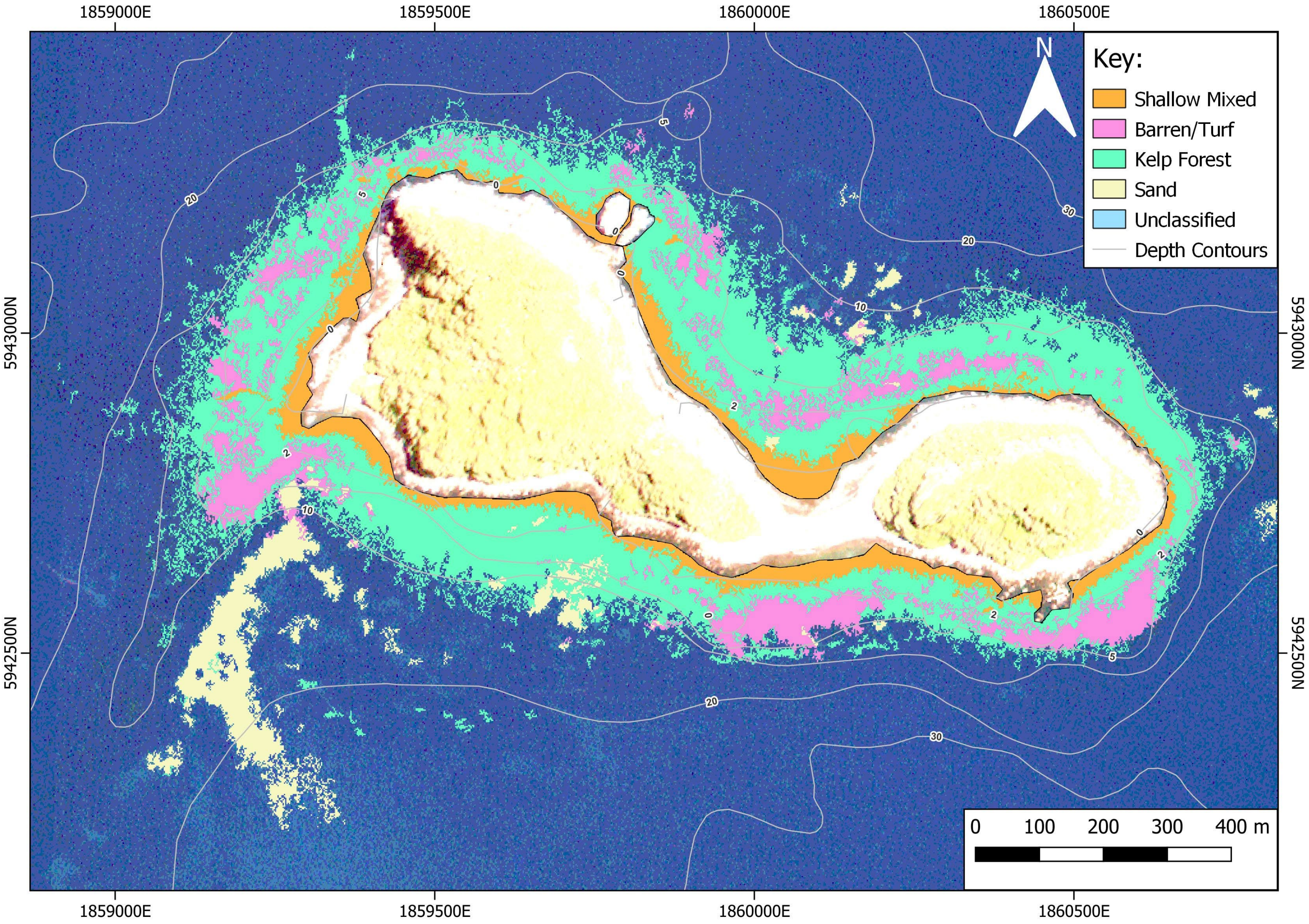
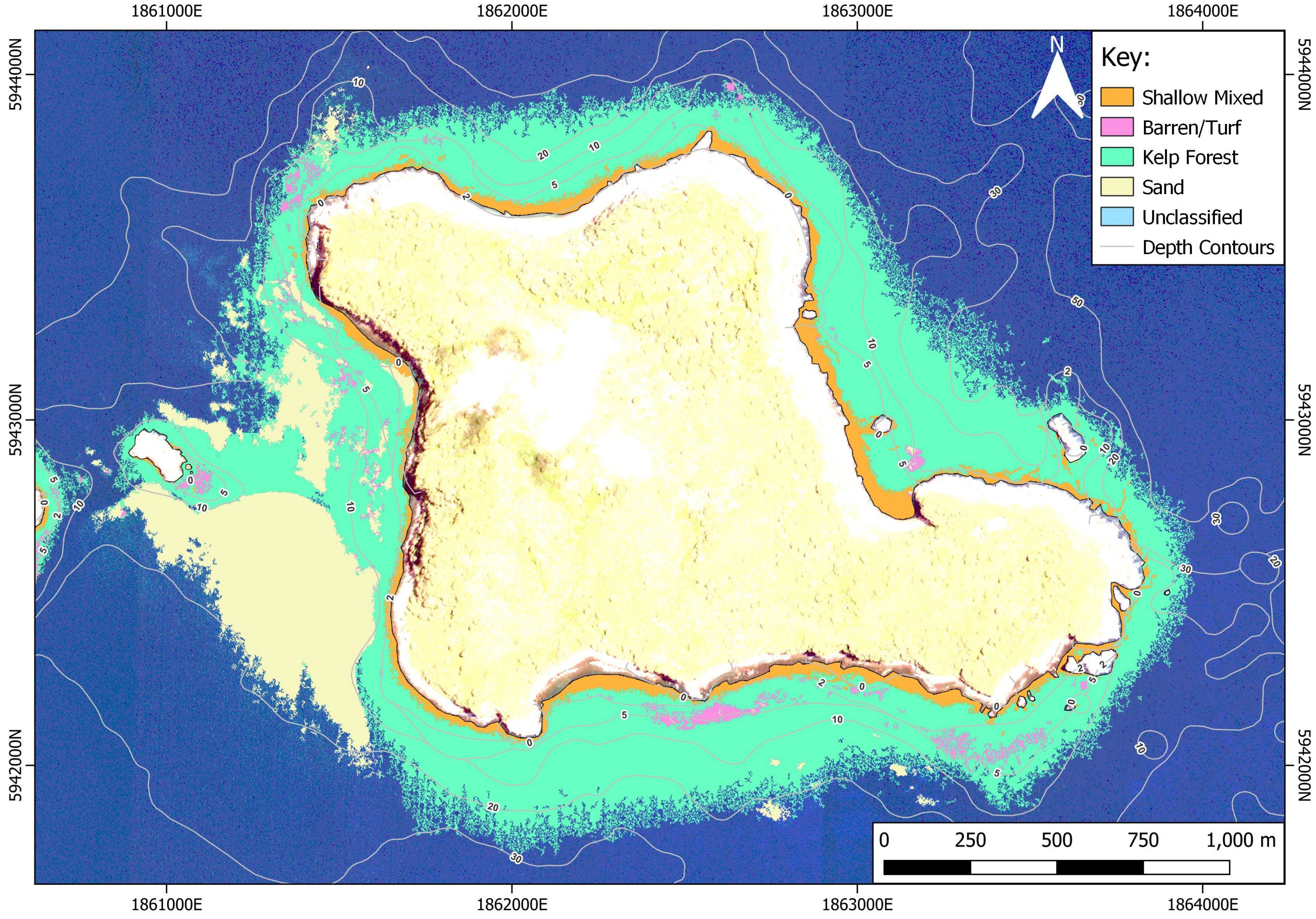


Fig. 5F Map of shallow marine habitats (<15 m depth) at Whakau – Red Mercury Island based on 2016 satellite image. Depth contours are indicative only (Source: https://data.linz.govt.nz/layer/50672-depth-contour-polyline-hydro-14k-122k/).



4. Discussion

4.1 Overview

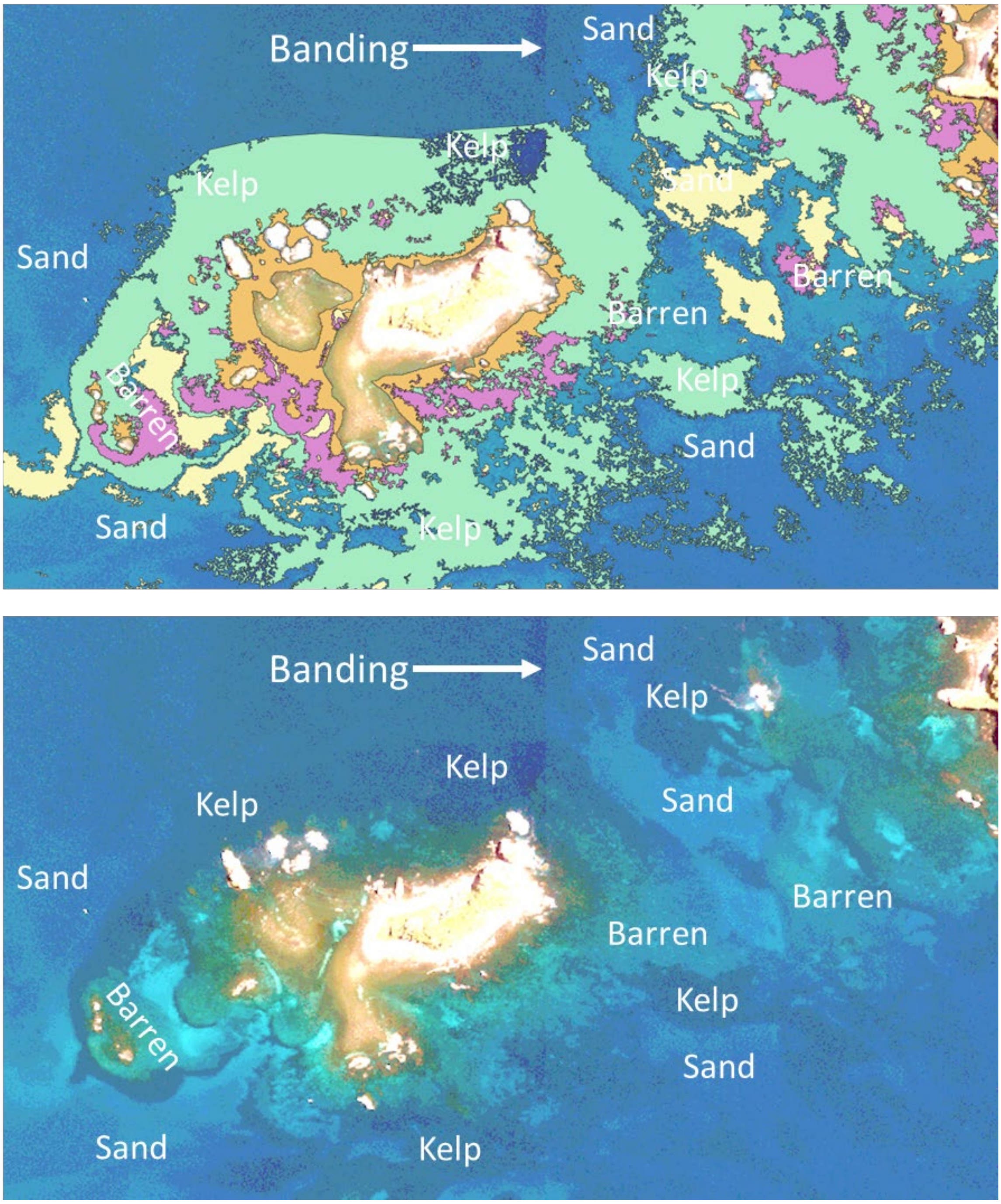
In this study, supervised classification techniques were used to map broad-scale marine habitats across the Mercury Islands based on the best available satellite imagery at the time. Using a satellite image from 2020, broad-scale habitats were mapped around Ahuahu-Great Mercury Island to a depth of ~20 m with an overall accuracy of 76%. The eastern Mercury Islands were mapped using a satellite image from 2016 to a depth of ~15 m and with an overall accuracy of 67%. Overall, this study demonstrates the utility of using supervised classification techniques to produce thematic habitat maps of broad-scale subtidal habitat types. The maps produced provide a broad-scale representation of the distribution of reef and soft sediment habitat types, including subtidal seagrass, across the Mercury Island's to depths of approximately 15 to 20 m. The distribution of broad-scale habitats around the Mercury Islands is broadly consistent with that reported from biodiversity surveys that were also carried out as part of this study (Caiger et al. 2023). However, there are inherent difficulties in trying to map and classify submerged habitats, and the accuracy of the maps produced was limited to some extent by variability in water column characteristics and image quality. The value, limitations and potential of mapping subtidal habitats with satellite and aerial imagery using the methods employed in this study are discussed and recommendations for future mapping at the Mercury Islands are provided below.

4.2 Accuracy and limitations of habitat maps

Overall, the level of accuracy of the habitat maps (67-76%) was within a range that would be considered suitable for marine spatial planning, but the maps would likely have limited application in terms of detecting small-scale changes in habitats over time. Nevertheless, the overall accuracy is encouraging given the large area mapped, the complexity of the island group and difference in timing between collection of ground-truth imagery (March 2022) and date of satellite image acquisition (2016 and 2020). The level of accuracy was similar to other subtidal mapping studies in northeastern Aotearoa New Zealand (e.g., Lawrence 2019 (62-82%), including those that have used more complex remote sensing methods (e.g., Kibele 2017 (79-85%), Kibele & Shears, 2018 (42-78%)). As seen in these other studies, map accuracy varies greatly with image quality, and with variation in water quality across an image. In both the 2016 and 2020 satellite images used in the present study there was large variation in water quality and image acquisition artefacts that likely reduced accuracy and limited our ability to map the entire island group. In the 2020 image there was evidence of a sediment plume with increased turbidity in the eastern islands compared to around Ahuahu (Fig. 2A). Initial mapping efforts using this image in the eastern Mercury Islands revealed that habitats could only be mapped to 8-9 m depth, and consequently the 2016 image was used to map these islands. Water quality also varied among the eastern islands in the 2016 image and there were also problems with banding in the image (Fig. 6). While we attempted to minimise the effect of this by mapping the eastern islands in three separate groups, the spectral signatures of habitats varied within bands which consequently affected accuracy.

It is also important to note that the accuracy assessment of the eastern Mercury Islands is only based on a low number of sites due to technical difficulties with the camera set up and poor weather conditions during ground-truth camera surveys. Nevertheless, the overall mapping accuracy in the eastern Mercury islands is more likely limited by satellite image quality than a lack of ground-truth information. If more ground-truth images were available a subset of these could have been used to objectively identify and select known areas of habitat, which would remove any potential for analyst error and bias (Richards & Jia, 2006; Abburu and Golla, 2015; St-Pierre & Gagnon 2020). Given our familiarity with the reefs at the Mercury Is and experience undertaking mapping from aerial and satellite imagery in northern Aotearoa New Zealand, we are confident in the selection of areas of known habitat and it is unlikely that this provided a source of error in the mapping process.

Fig. 6. Habitat map and satellite image of Green Is and reefs off southwestern corner of Atiu showing banding artefact and subsequent difficulties classifying habitats.



The complex topography of the Mercury Islands both above and below the water also increases the difficulty in mapping reef habitats using satellite imagery and likely reduced the overall accuracy. Steep cliffs above water can lead to shading of the nearshore waters, such as at Cathedral Rocks where a large area of urchin barrens was shaded and classified as kelp forest (Appendix 2.3). Steep drop-offs underwater are not accurately mapped as habitats on steep sloping reefs are not visible in a two-dimensional image (e.g., areas on the eastern side of Whakau, Appendix 2.6). Kibele and Shears (2018) noted similar difficulties mapping the areas of the Hahei coast and adjacent islands, which contributed to lower overall map accuracy compared to habitat maps of the Leigh area which have more gradual sloping reefs (Kibele 2017).

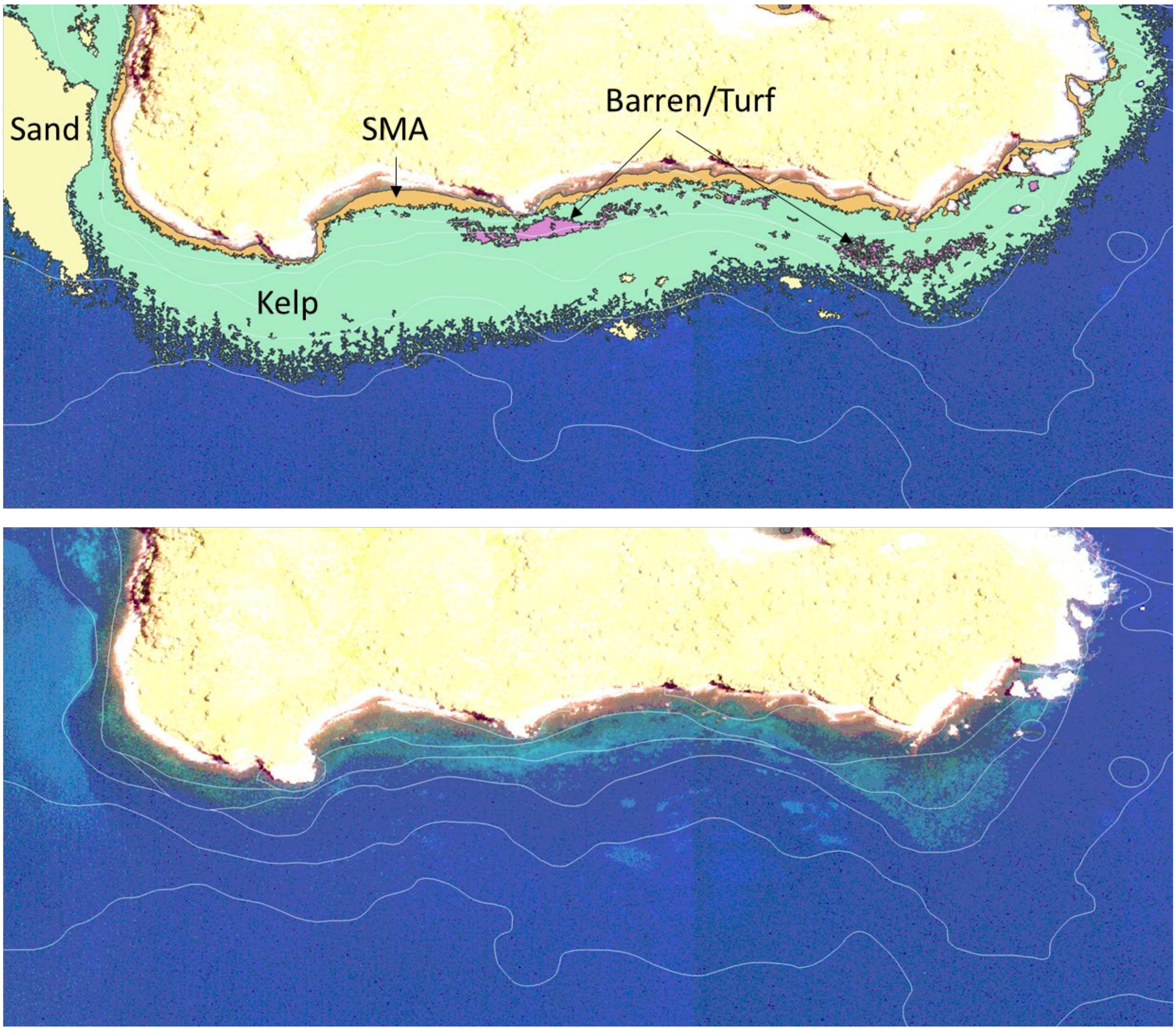
Another source of error with the supervised classification approach is the changing spectral signature of habitats with depth. While training points for a given habitat can be selected across a depth gradient in some cases, spectral signatures of different habitats will be the same at different depths. This was the case with Shallow Mixed algal forest ground truth points being commonly misclassified as kelp forest when they were in deep water, and vice versa shallow kelp forest ground truth points were commonly mis-classified as Shallow Mixed (Appendix 2.2). While optical remote sensing methods that employ a water column correction (WCC) procedure may help better distinguish these habitats across depths, the fact both habitats are characterised by large brown seaweeds means they are likely very similar spectrally. There were similar classification issues with distinguishing between Barren/Turf and Sand in deeper water (e.g., Appendix 2.6). Again, more complex WCC methods may help resolve these, but the complexity of these methods does limit their application (St-Pierre and Gagnon 2020). Alternatively, a manual approach could be used whereby a trained user reassigns incorrect habitat types on habitat maps generated using supervised classification methods.

There were also difficulties and inconsistencies in mapping the depth extent of kelp forest and/or the reef edge. In some cases, deeper kelp was visually evident but classified as optically deep (Fig. 6 and 7), whereas in others large areas of deep water were classified as kelp forest (e.g., Appendix 2.6). This highlights the inherent difficulty in mapping kelp in deep water due to its “dark” signature and blending into deep water. In some areas, generally less than 15 m depth, the sand-reef border is very distinct and therefore the edge of the kelp and reef can be mapped easily, but where the reef extends beyond 15 m it becomes difficult to distinguish the reef and kelp edge from water that is optically deep (this contrast is evident in Fig. 7 and across the bay at Cathedral Rocks, Appendix 2.3). Similarly, several deeper areas of sand were clearly evident in the eastern islands that were not classified and mapped (Fig 6). This is likely due to uncertainty and overlap in the spectral signatures of different habitats due to the banding in imagery and variable water quality.

While mapping accuracy could be improved by greater image quality, future mapping efforts that use satellite or other aerial imagery would benefit greatly from having multibeam bathymetry data as it would allow a clear delineation between reef and sand habitats (e.g., Kibele 2017). This would provide information on the wider extent of reef habitats and also help greatly with mapping and classifying vegetated soft sediment habitats such as seagrass and *Caulerpa* mats. For example, in this study seagrass was mapped during post-processing due to its spectral similarity with reef habitats. Delimiting the reef and soft sediment habitats would allow for a separate supervised classification process to be carried out for reef and soft sediment habitat types, which would avoid issues with spectrally similar reef and soft sediment habitats and increase overall map accuracy.

Finally, in some cases changes in habitats between satellite image acquisition and ground truth data collection may have impacted the results of the accuracy assessment and resulted in an underestimate of the accuracy of the maps. This was particularly the case in the eastern islands where the image was from 2016. One clear example was at Green Island (Appendix 2.5) where ground truth photos were classified as Shallow Mixed but the satellite image was classified as Barren/Turf. This likely indicates an increase in macroalgae (predominantly *C. flexuosum*) in an area that was formerly urchin barren, which was also noted in Caiger et al. (2023; see their Fig. 7 for an example). Nevertheless, the overall patterns and consistency between satellite and ground-truth images indicate a degree of stability at least over the last decade (as discussed below).

Fig. 7. Habitat map and satellite image of the southern side of Whakau – Red Mercury Is highlighting difficulty in mapping deep kelp forest and reef edge. Kelp extends much deeper and patches of sand are visually evident in deeper water. Areas of barren in shallow water also appear to be underestimated in the map.

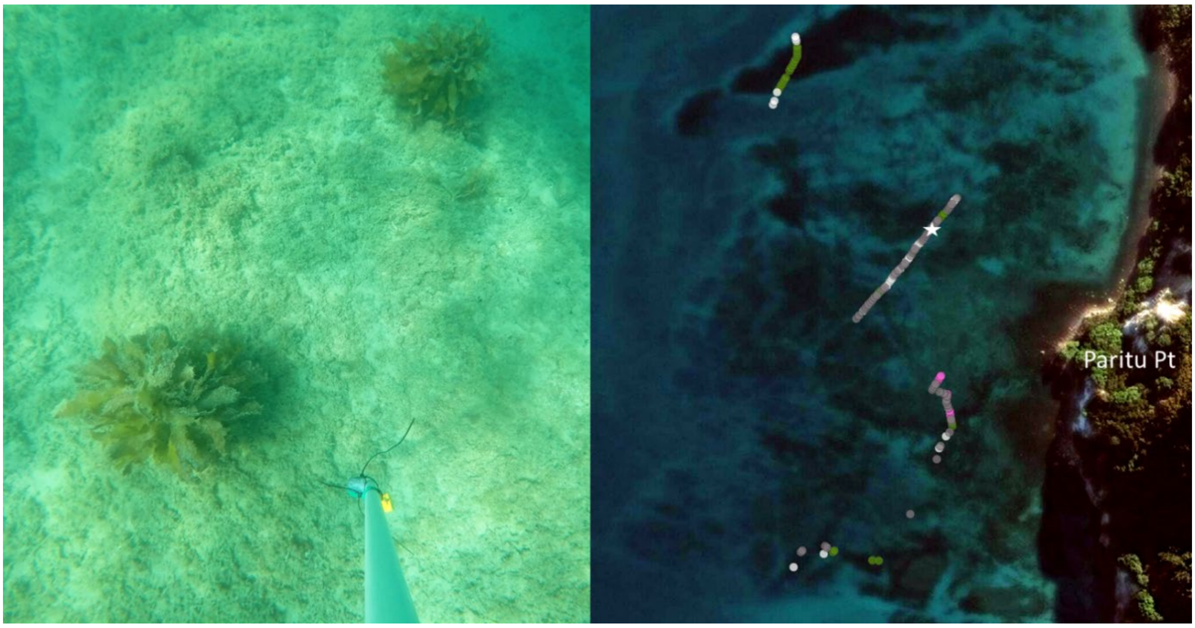


4.3 Ecological interpretation and implications

Overall, the habitat maps produced for the Mercury Islands are comparable to habitat maps of other open rocky coasts and offshore island locations in northeastern Aotearoa New Zealand that are open to fishing (e.g., Kerr & Grace 2005, 2017; Kibele 2017, Kibele and Shears 2018; Lawrence 2019, Dartnall 2022). The mapped reefs (<15-20 m) are largely dominated by kelp forests, but there is a clear zonation of habitats, with shallow depths (<~3 m) dominated by Shallow Mixed algal forest, intermediate depths (~3-10 m) comprised of a mosaic of kelp forest and Barren/Turf, and deeper reef dominated by kelp forest. The overall extent of Barren/Turf varied across the islands being highest at Great Mercury Island (16%) and lowest at Moturehu-Whakau (6%). This is substantially lower than islands in the Hauraki Gulf such as Mokohinau Is (2019: 26%; Lawrence 2019), Hauturu-o-Toi (2019: 33%; Dartnall 2022) and Noises (2019: 50%; Dartnall 2022). On the nearby Hahei coast Barren/Turf represented 20% of the reef mapped on the fished coast, but only 5% of the reef mapped in the Whanganui A Hei (Cathedral Cove) Marine Reserve (Kibele and Shears 2018).

The Barren/Turf habitat category combines both urchin barrens and turfing algae as these are not spectrally distinguishable from imagery (Kibele 2017). Ecologically, they both represent a reef habitat that is lacking a canopy of forest forming macroalgae. Urchin barrens are areas where sea urchins maintain the reef clear of large brown algae and the reef is generally dominated by encrusting algae, whereas turfing algal reef habitat is dominated by a short carpet (<5 cm) of turfing algae (Peleg et al 2023). On some northern Aotearoa New Zealand reefs such as on low-lying sand inundated reefs, articulated coralline turfs (e.g., *Corallina officinalis*) can form a persistent and stable reef habitat type (Ayling et al., 1981; Kulins 2021). However, turfing algae can also represent a transition phase between urchin barrens and macroalgal forest (Peleg et al 2023). Based on ground-truth images both types of turfing algae were present at the Mercury Islands. Coralline turf dominated large areas of low-lying and sand inundated patch reef off Paritu Pt, on the western side of Ahuahu (Fig. 8). In contrast, patches of turfing algae were interspersed within wider areas of urchin barrens in areas like Coralie Bay (Appendix 2.1) and Cathedral Rocks (Appendix 2.3).

Fig. 8. Example of shallow (<5m depth), low lying patch reef off Paritu Pt, Ahuahu, dominated by articulated coralline turf (*Corallina officinalis*). Note presence of sparse *Ecklonia radiata*. Satellite image on right shows ground truth points and white star indicates location of photo on left. Habitat colours for ground-truth points: grey = Turfing algae; pink = urchin barrens; green = kelp forest; white = sand.

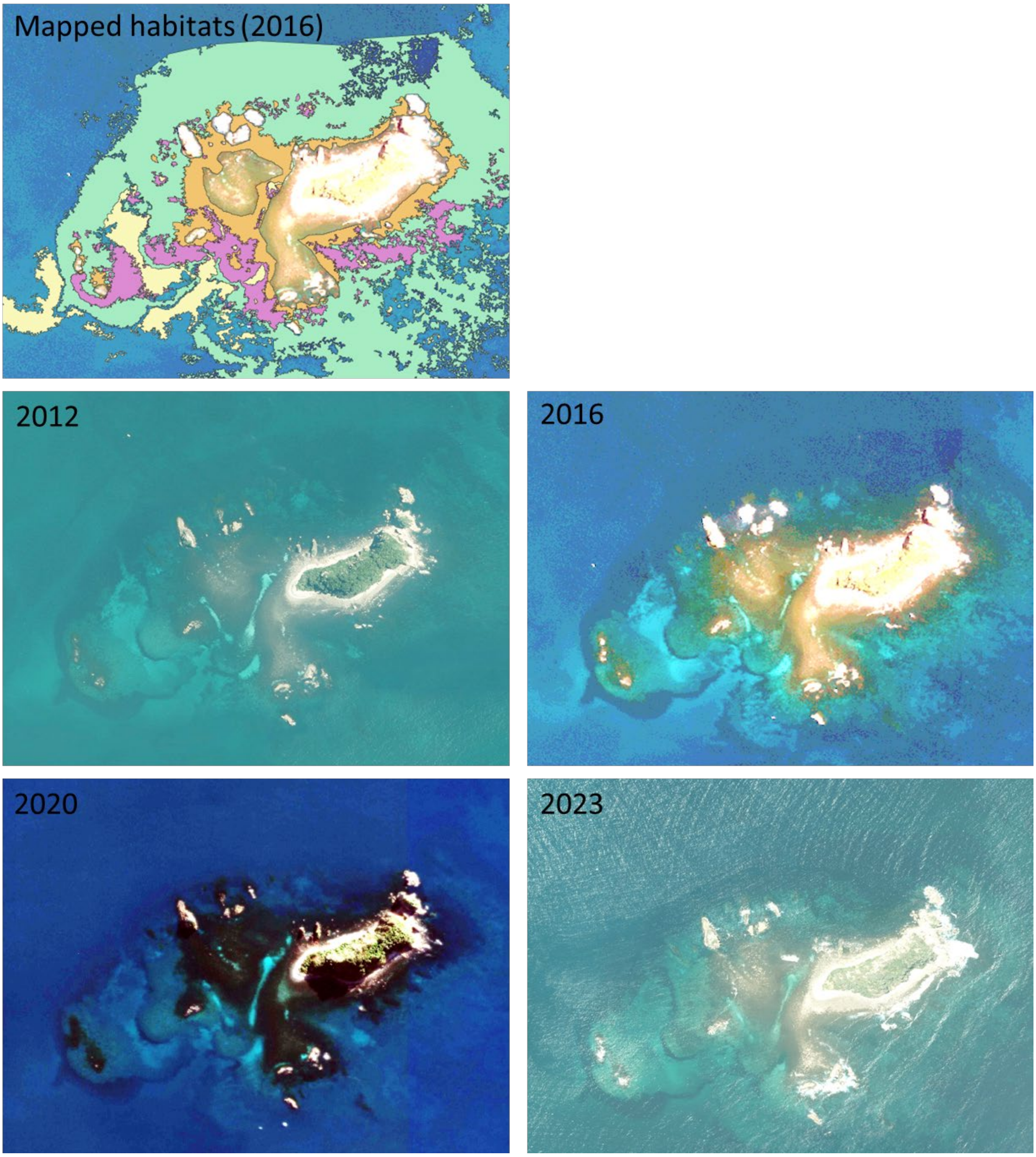


Previous studies have demonstrated that the presence of urchin barrens is an ecosystem-level effect of fishing sea urchin predators that has led to loss of kelp forest (Eger & Baum, 2020; Estes & Duggins, 1995; Shears & Babcock, 2003). However, due to the nature of the mapping methods and the inability to distinguish between urchin barrens and turfing algae, the overall coverage of Barren/Turf is likely an overestimate of the extent of urchin barrens on shallow reefs. However, there are limitations in the ability to map the extent of urchin barrens on steep reefs and in deep water based on imagery, which likely underestimates the overall extent of barrens in these habitats . For example, the urchin barrens that dominated from 8-18 m on the steep walls in Von Luckner's Cove (Appendix 2.6) were not visible in satellite imagery and therefore not mapped. Given urchin barrens also predominantly occur in shallow water, the relative proportion of urchin barrens in a 2-dimensional map will depend on the relative extent of shallow reef in the mapped area (Kerr et al. 2024). This was evident across the islands mapped in this study with the relative contribution of Barren/Turf being highest around Ahuahu (16%), where there was more gradual sloping reefs and a greater proportion of shallow reef visible in imagery, and lowest around Moturehu-Whakau where reefs dropped more steeply into deeper water (6%). In general, the urchin barrens were less evident on the more exposed northern and eastern shores, which is consistent with them occurring in deeper water on exposed coasts (Shears and Babcock 2004). In contrast barrens were more apparent on the more sheltered reefs on the western and southern side of the islands. This variability in the depth extent of urchin around the islands is broadly consistent with expectations based on how the depth distribution of urchin barrens varies with wave exposure in northeastern Aotearoa New Zealand (Shears and Babcock 2004).

The general distribution of the mapped reef habitats from the 2016 and 2020 satellite images were broadly consistent with ground-truth photos collected in this study and the benthic surveys carried out in 2022 (Caiger et al 2023). This suggests a general level of stability over recent years in the distribution of the dominant habitats. Comparison of aerial imagery of the Mercury islands from 2012 and 2013 with the satellite images further supports this (Fig. 9) and highlights the potential utility of good quality satellite and aerial imagery in mapping long-term changes in broad-scale reef habitat types. This stability in the extent of urchin barrens over recent decades is consistent with other fished locations in northeastern Aotearoa New Zealand including offshore islands (Balemi and Shears 2023; Peleg et al., 2023). However, recent evidence demonstrates that the sea urchin *Centrostephanus rodgersii* and barrens associated with this species is increasing in northeastern Aotearoa New Zealand, likely in response to recent warming (Balemi and Shears 2023). This species typically forms barrens at greater depths than kina but was observed in relatively low numbers in ground-truth photos in this study and associated benthic surveys (Caiger et al. 2023) at the Mercury Islands. However, *C. rodgersii* and associated barrens may be expected to increase in the future at the Mercury Islands as wider populations grow and ocean temperatures continue to increase.

Mapping from satellite imagery generally provides limited information on subtidal soft-sediment habitats, except for those that are visually conspicuous such as seagrass. In this study large areas of seagrass were mapped on the western side of Ahuahu, and these beds extended to depths of 8 m. In general, the extent and distribution of seagrass beds was similar to that previously mapped in Huruhi Harbour (9 ha; Clark and Crossett (2019), but we mapped an additional 7 ha of seagrass around Matakawau Pt and in the main bay of Ahuahu (Fig. 4D). Our study highlights the potential value of existing satellite and aerial imagery for mapping and understanding the spatial and temporal dynamics of subtidal seagrass at the Mercury Islands and more broadly. Furthermore, given recent marine heatwaves and extreme weather events, future monitoring of seagrass beds with aerial imagery would be pertinent.

Fig. 9. Mapped habitats (2016) and recent imagery of Green Island. Aerial imagery from 2012 and 2023 sourced through https://data.linz.govt.nz/ (Waikato 0.5m Rural Aerial Photos (2012-2013) and Waikato 0.3m Rural Aerial Photos (2021-2023)). 2016 and 2020 images are satellite images used in current study.



4.4 Recommendations for future mapping

Image acquisition

Our study highlights the need for high quality imagery with good water clarity and sea conditions in order to accurately map reefs to suitable depths. Ideally image acquisition should be at low tide with optimal sea conditions (i.e., low wind and waves, high water clarity) to minimise the number of suspended particles in the water column and surface reflection (glint). Under these conditions we would expect to see the seabed clearly to depths of up to 20 m. While commercially available satellite imagery has the benefit of providing large-scale coverage of an area, only occasionally images are available that meet these criteria. This may become less of a limitation in the future with an increasing number of satellite remote-sensing products available and an increased frequency of image acquisition. Importantly, satellite imagery needs to be of sufficient resolution (at least 2m pixels) during optimal condition for effective mapping of different submerged shallow reef habitats (Kibele 2017).

Aerial imagery collected from aircraft has been used successfully in the past as this allows image acquisition during appropriate sea and weather conditions for image collection flights (Kerr and Grace 2005; Leleu et al. 2012). Similarly, unmanned aerial vehicle's (UAV's) or drones are increasingly being used as a low cost and flexible approach to collecting imagery to map and monitor shallow water benthic habitats (Nababan et al., 2021). Collecting imagery during optimal conditions is key to successful mapping, particularly of submerged habitats, and therefore the use of drones would provide a versatile and cost-effective method for mapping and monitoring habitats at the Mercury Islands in the future. While drones would be particularly useful for repeat mapping and monitoring of key sites at smaller spatial scales, e.g., sea grass beds on the western side of Ahuahu, advances in drone technology and battery power mean that mapping areas as large as the Mercury Islands is increasingly possible. For example, new consumer grade drones with mapping capabilities (e.g., DJI Mavic 3E) have 40 min flight time and can map ~75 ha in a 30 min flight (this would encompass an area approximately the size of Green Is and its surrounding reefs). It would therefore require ~21 flights to map the entire area mapped in the current study (1551 ha), which could be carried out over 3-4 days of optimal weather conditions. Larger commercial drones and operators are likely to be able to cover larger areas in a single flight but will also be limited by weather and sea conditions.

The seasonal timing of image acquisition is also an important consideration as the spectral signatures of some reef habitats may vary seasonally. This is most likely an issue in urchin barrens, which can have a high cover of filamentous and foliose algae in late spring and summer, as seen during collection of ground-truth images at the Mercury Islands in March 2022 (Caiger et al. 2023). This can give a darker appearance to the reef in aerial imagery and potentially make it difficult to distinguish between urchin barrens and macroalgal dominated habitats. For these reasons it would be best to avoid image acquisition in spring and early summer. The cover of these seasonal algae, in particular filamentous algae, also need to be taken into account when classifying ground-truth photos.

Scale and application of habitat maps

The use of satellite imagery has the benefit of providing information across large-scales, which is invaluable when sea conditions and water column characteristics are favourable. However, as seen in this study and others using satellite imagery (Kibele 2017; Kibele and Shears 2019), applying an image classification over large areas is challenging (e.g. Ahuahu) and subsequently better results are achieved by applying the mapping process to subsections of the image to account for variability in conditions across an image. Therefore, while large-scale analysis of satellite imagery can provide a broad-scale picture of the distribution of habitat types, smaller-scale approaches to mapping are needed for monitoring changes in the distribution of habitats over time. This could be achieved by restricting finer-scale analysis to satellite imagery in focal monitoring areas where image quality and water column characteristics are favourable, or with targeted drone flights to obtain imagery of focal areas during favourable conditions. Available aerial imagery (linz.govt.nz) collected over large scales also has potential value for mapping changes at fine-scales but these are subject to variable conditions (Fig. 9). Understanding changes in key habitats in focal areas could use a combination of available imagery but obtaining high resolution drone imagery in the future is recommended.

Classification approach

A variety of mapping approaches are available of widely varying complexity, and we demonstrated that the supervised-classification approach used in this study produced maps of a similar accuracy to more complex optical remote sensing methods that use water column correction (WCC). The greatest impacts on accuracy appear to relate to image quality rather than the classification method. In shallow kelp-dominated systems (<8 m) where there is little variation in spectra across the depth gradient both supervised classification and manual methods of mapping yielded high accuracy (~90%; St-Pierre and Gagnon 2020). In our study, there were errors associated with depth-associated variation in spectral signatures of habitats that were visually evident when inspecting imagery and resulting maps (discussed above). Consequently, trained observers are likely to have a greater inherent ability in interpreting changes in spectra with depth and delineating between reef edge and areas that are optically deep. Therefore, a manual approach to mapping could provide a more accurate approach than the supervised classification used here. An alternate and potentially more efficient approach at larger scales would be to use a supervised classification to generate an initial map and then use a trained observer to manually edit and correct known inaccuracies. Further improvements to the supervised classification methods could be achieved by using a multi-stage classification process aimed at first delineating reef from soft sediment habitats and identifying areas optically deep. The supervised classification process could then be applied to the reef and soft sediment habitats separately. Exploring different classification algorithms and also adding the results of a texture analysis of the image to the classification layers could improve map accuracy (e.g. Mishra et al. 2019).

A major limitation with mapping submerged habitats from imagery is a lack of accurate information on depth and the extent of key physical habitats such as reef and soft sediment substratum (see Section 4.2). High-resolution multibeam or Lidar bathymetry data would therefore help greatly in improving map accuracy and facilitate mapping to be constrained to reef and or soft sediment habitats depending on the application and question. Accurate bathymetry data would also allow areas that are too deep to be classified to be masked as 'Unclassified' in addition to masking areas on land (above low tide). To increase the efficiency and accuracy of any future imagery-based mapping and monitoring projects we would strongly recommend the initial acquisition of multibeam data over the entire area to be mapped, particularly shallow water areas (<5 m).

Ground-truth photos

In this study, ground truth photos are primarily used to evaluate map accuracy, but these can be used in more advanced mapping procedures (Kibele 2017). Taking ground-truth photos down the reef profile at a range of sites also provides a valuable geo-referenced data source on the distribution of key habitats and species with depth at a given time. The BPS methods used in this study provide a simple and cost-effective approach to collecting ground truth imagery that is highly recommended for future mapping studies (Kibele 2016). However, in our study the distribution of ground-truth photos was limited by a combination of technical difficulties with the camera system (faulty cables) and poor weather conditions during field trips. This meant that only a few sites were sampled in the eastern most Mercury islands. Future mapping efforts would benefit from greater coverage of ground-truth photos, particularly in the eastern islands, using the methods described in Kibele (2016). In addition, it would also be beneficial to use a subset of ground-truth photos to identify known areas of different habitats to train the habitat classification algorithm. We do not believe this would have affected the mapping results in this study, but it would remove any subjectivity and also provide greater confidence when mapping new areas or regions where analysts have less experience.

4.5 Conclusions

The maps of shallow reefs produced for Ahuahu-Great Mercury Island (based on 2020 imagery) and the eastern Mercury Island's (based on 2016 imagery) provide the first broad-scale assessment of the distribution of key shallow water habitats. Despite limited availability of suitable quality satellite imagery, and variation in water column characteristics and image acquisition artefacts in the satellite images analysed, we were able to map broad-scale habitats with moderate accuracy to depths of 15-20 m. The mapped habitats exhibited a typical distribution for subtidal reefs in northeastern Aotearoa New Zealand and large seagrass beds were also successfully mapped. While there are a number of limitations and inherent difficulties in mapping submerged habitats from satellite imagery, the maps produced provide a snapshot that can be used for marine spatial planning purposes and a baseline for monitoring broad-scale changes in these key habitats in response to future management actions and/or environmental change or disturbance.

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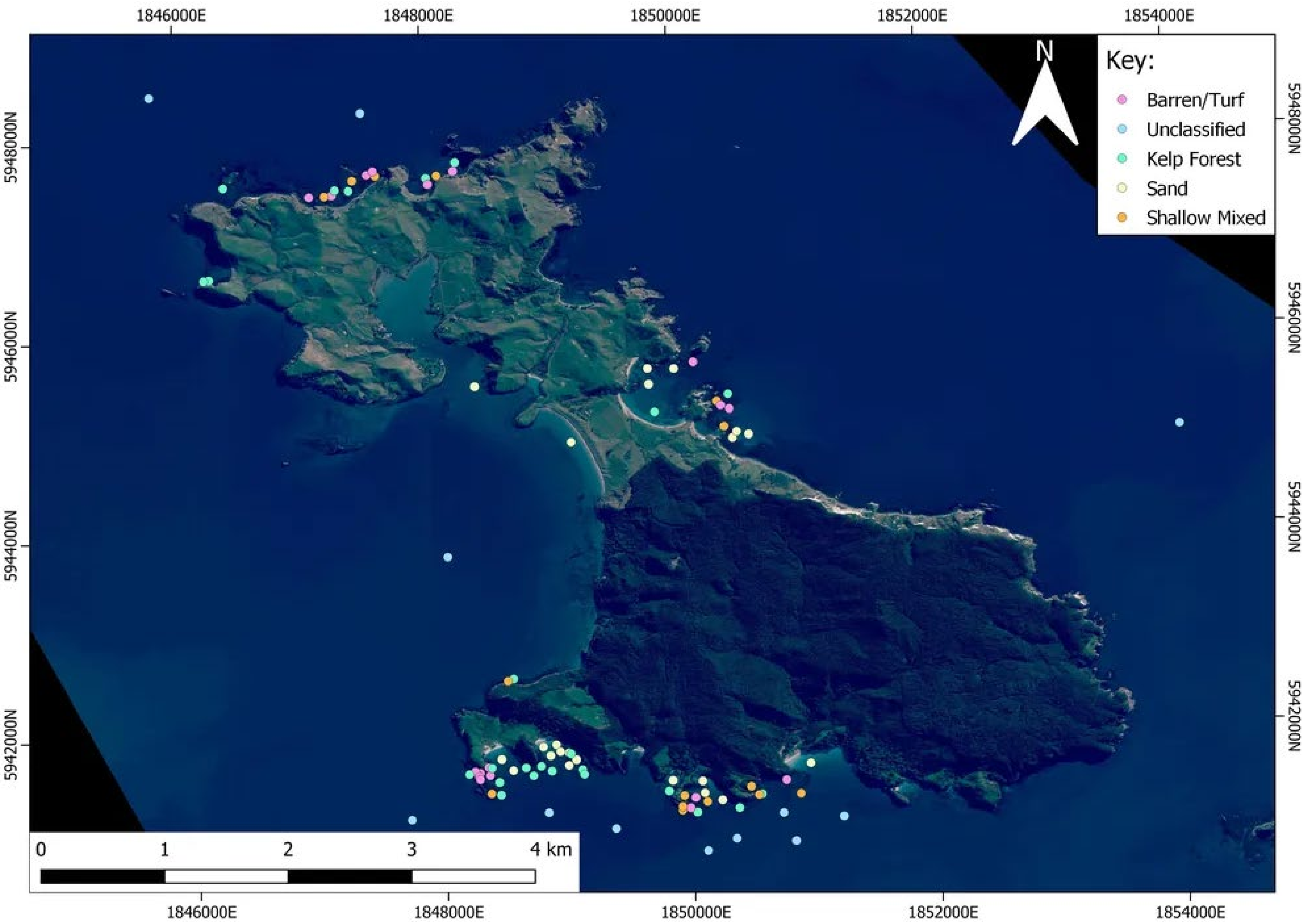
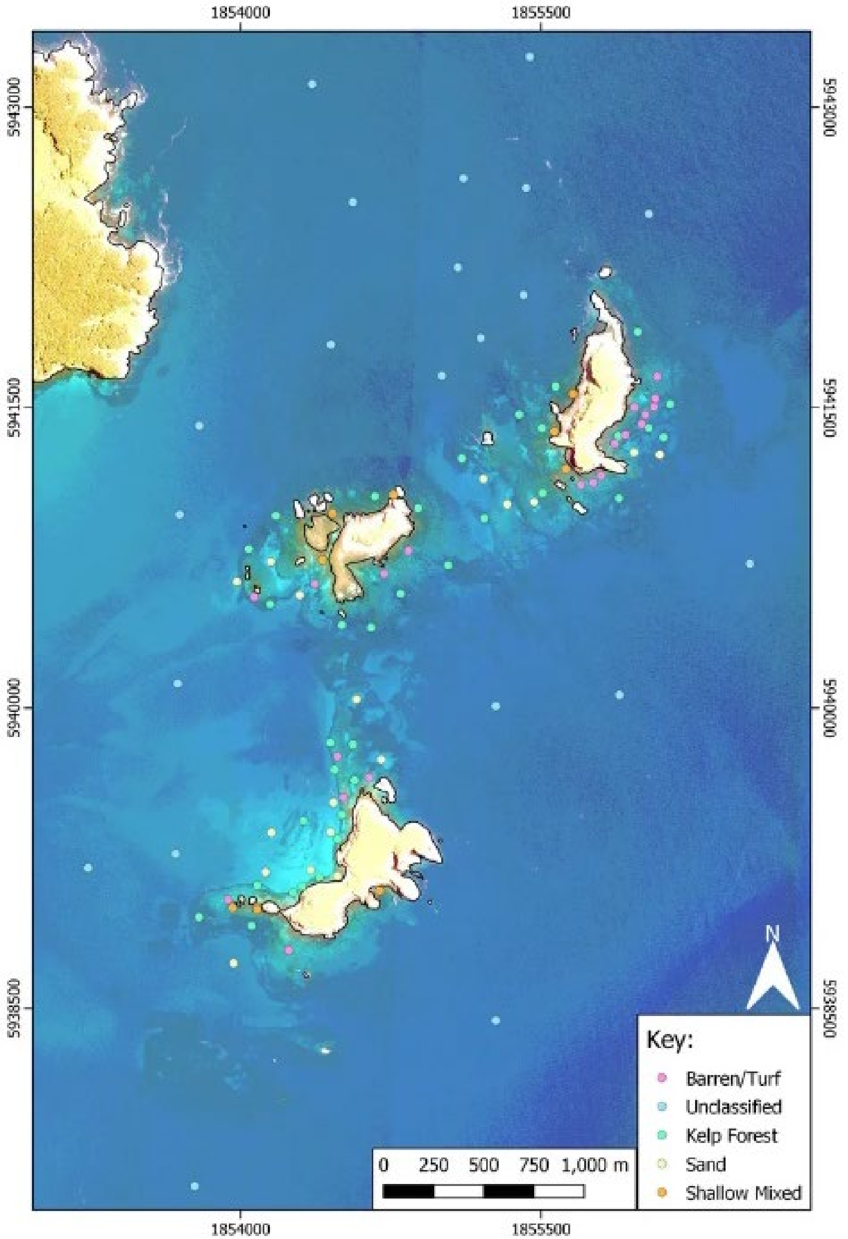
Appendix 1 – Positions (1.1) and examples (1.2) of habitat training polygons used for supervised classification of satellite image

Appendix 1.1 – Positions of training polygons of known habitats used at Ahuahu-Great Mercury Island (a), Korapuki-Green Is-Atiu (b), Kawhitu (c) and Moturehu-Whakau (d).

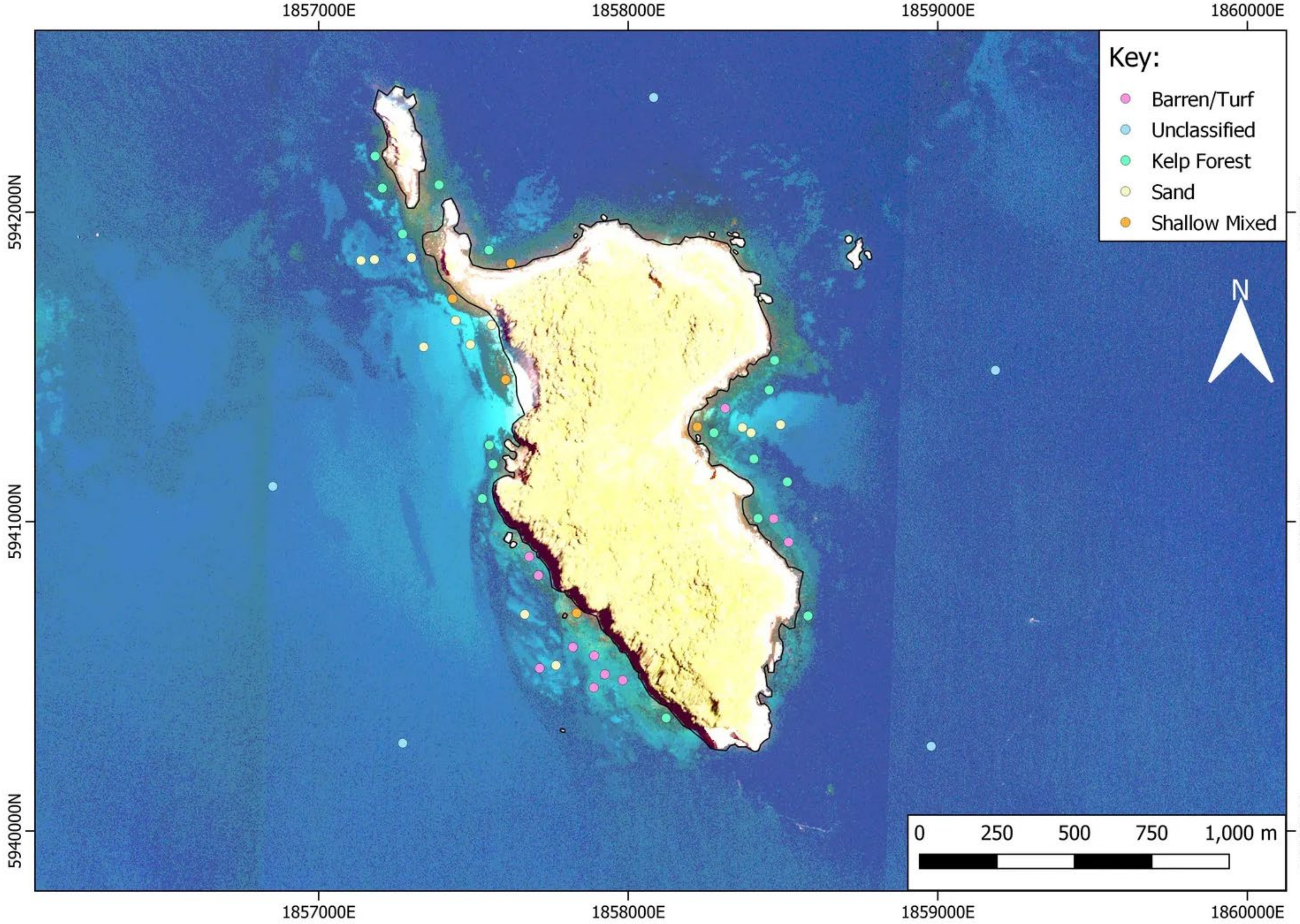
(a)



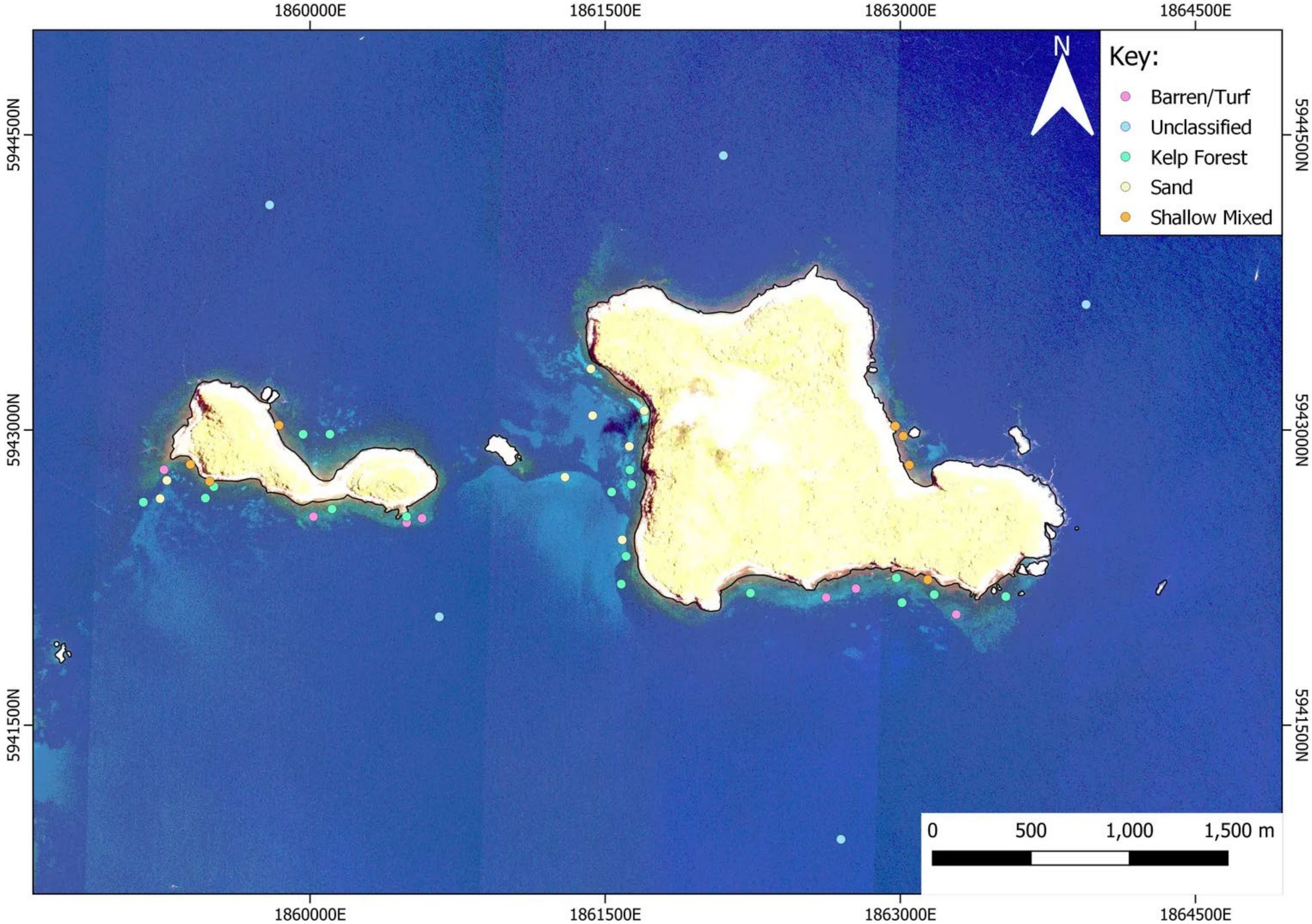
(b)


1854000
1855500
5943000
5941500
5940000
5938500
N
Key:
Barren/Turf
Unclassified
Kelp Forest
Sand
Shallow Mixed
0 250 500 750 1,000 m

(c)

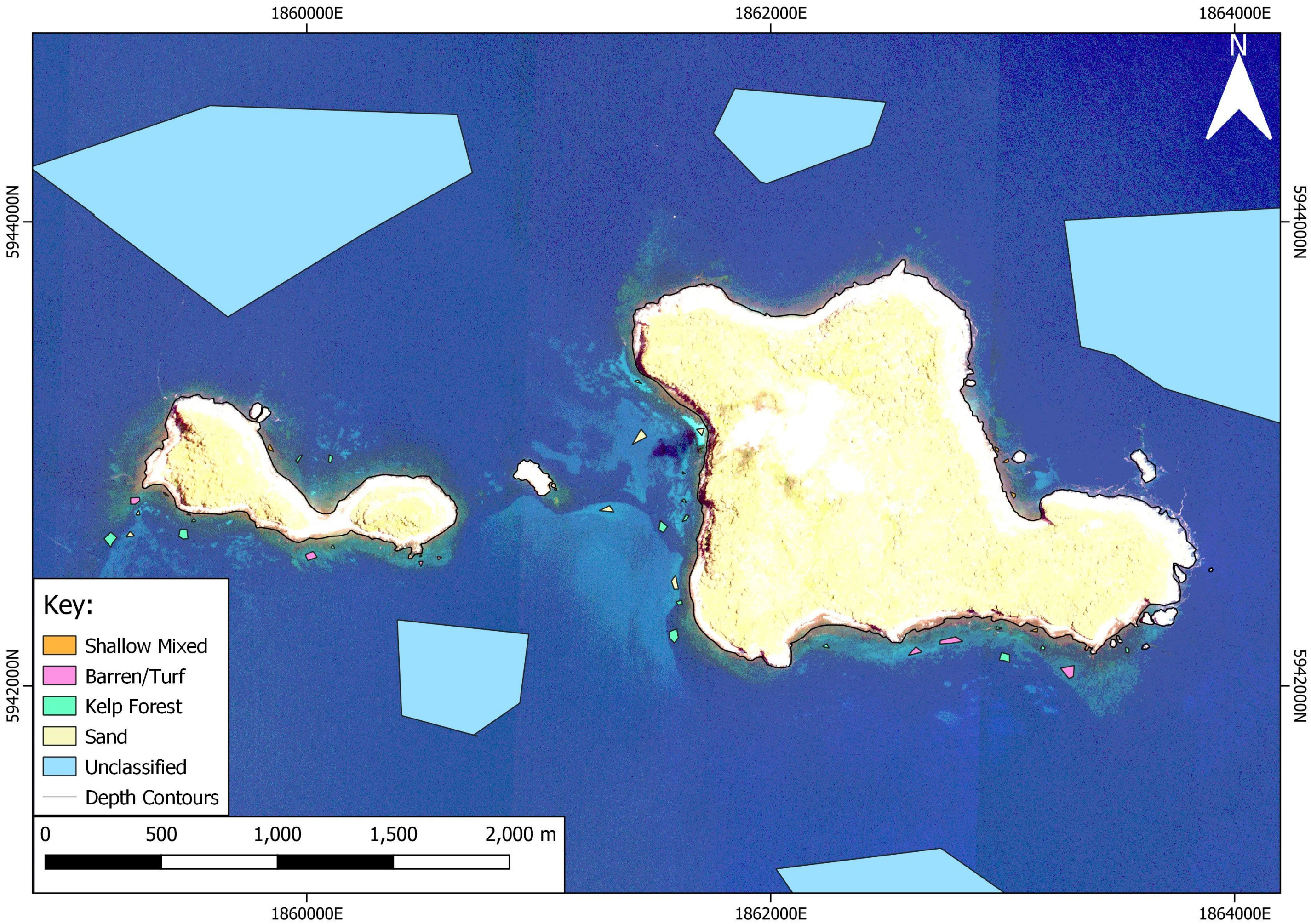

1857000E
1858000E
1859000E
1860000E
5942000N
5941000N
5940000N
Key:
Barren/Turf
Unclassified
Kelp Forest
Sand
Shallow Mixed
N
0
250
500
750
1,000 m

(d)

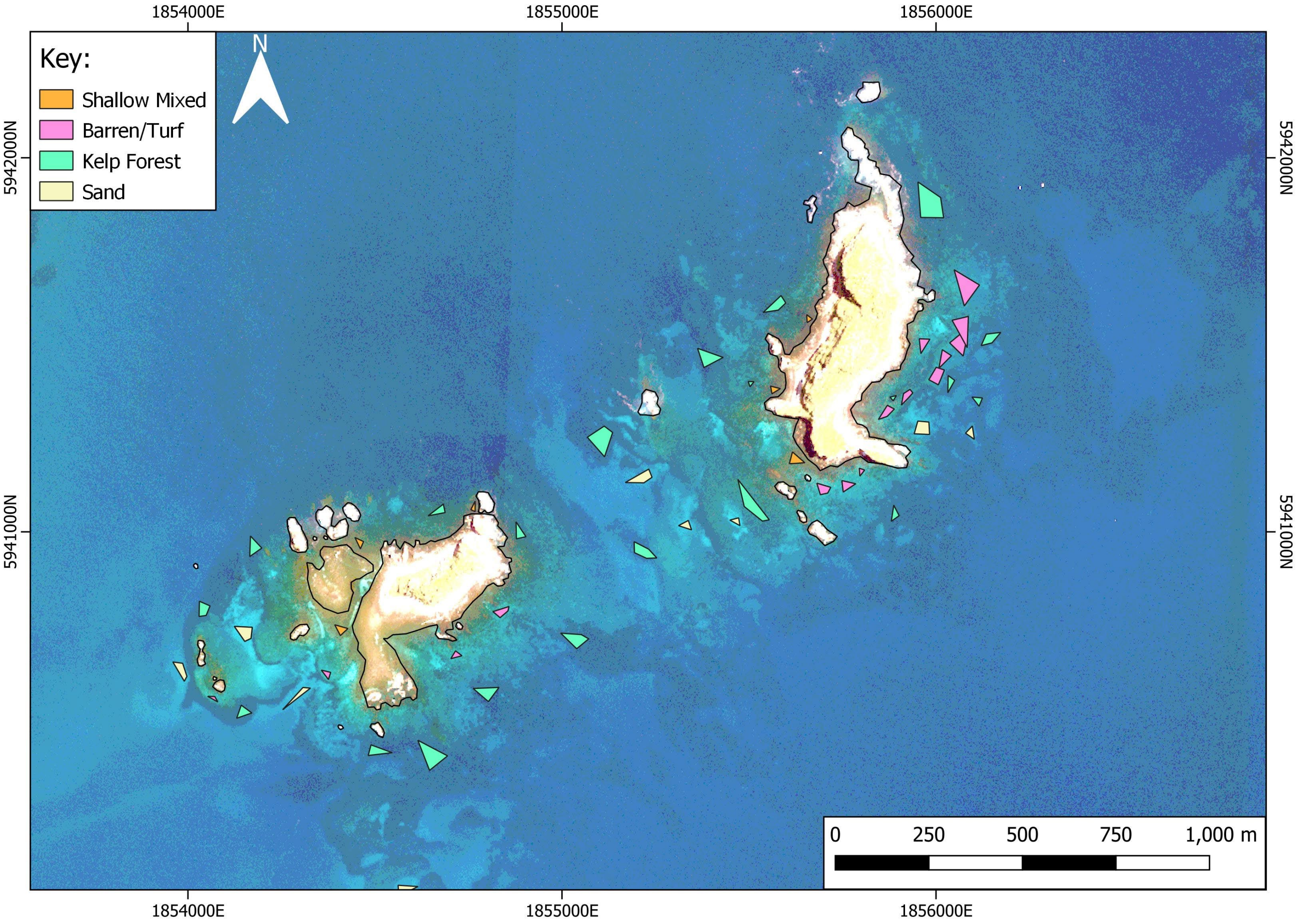

1860000E
1861500E
1863000E
1864500E
5944500N
5943000N
5941500N
N
Key:
Barren/Turf
Unclassified
Kelp Forest
Sand
Shallow Mixed
0
500
1,000
1,500 m

Appendix 1.2 – Examples of training polygons of known habitats used at Moturehu and Whakau (a) and Atiu-Green Island (b). Note large polygons used to identify optically deep areas as "Unclassified", relative to small polygons used to identify other habitats.

(a)



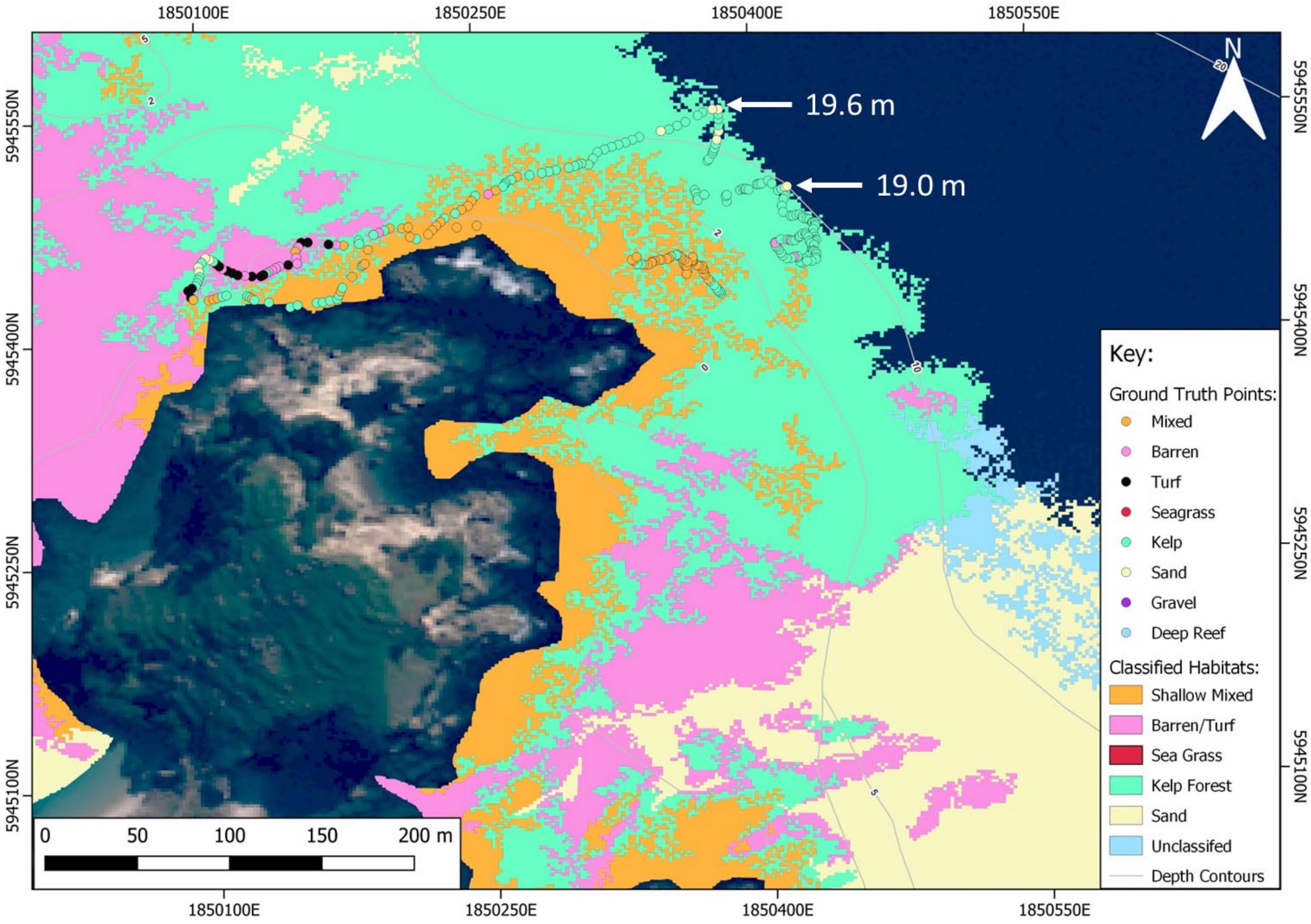
(b)



1854000E
1855000E
1856000E
5942000N
5941000N
Key:
Shallow Mixed
Barren/Turf
Kelp Forest
Sand
N
0
250
500
750
1,000 m

Appendix 2 - Examples of mapped areas with ground-truth points coloured according to fine-scale habitats (Table 1)

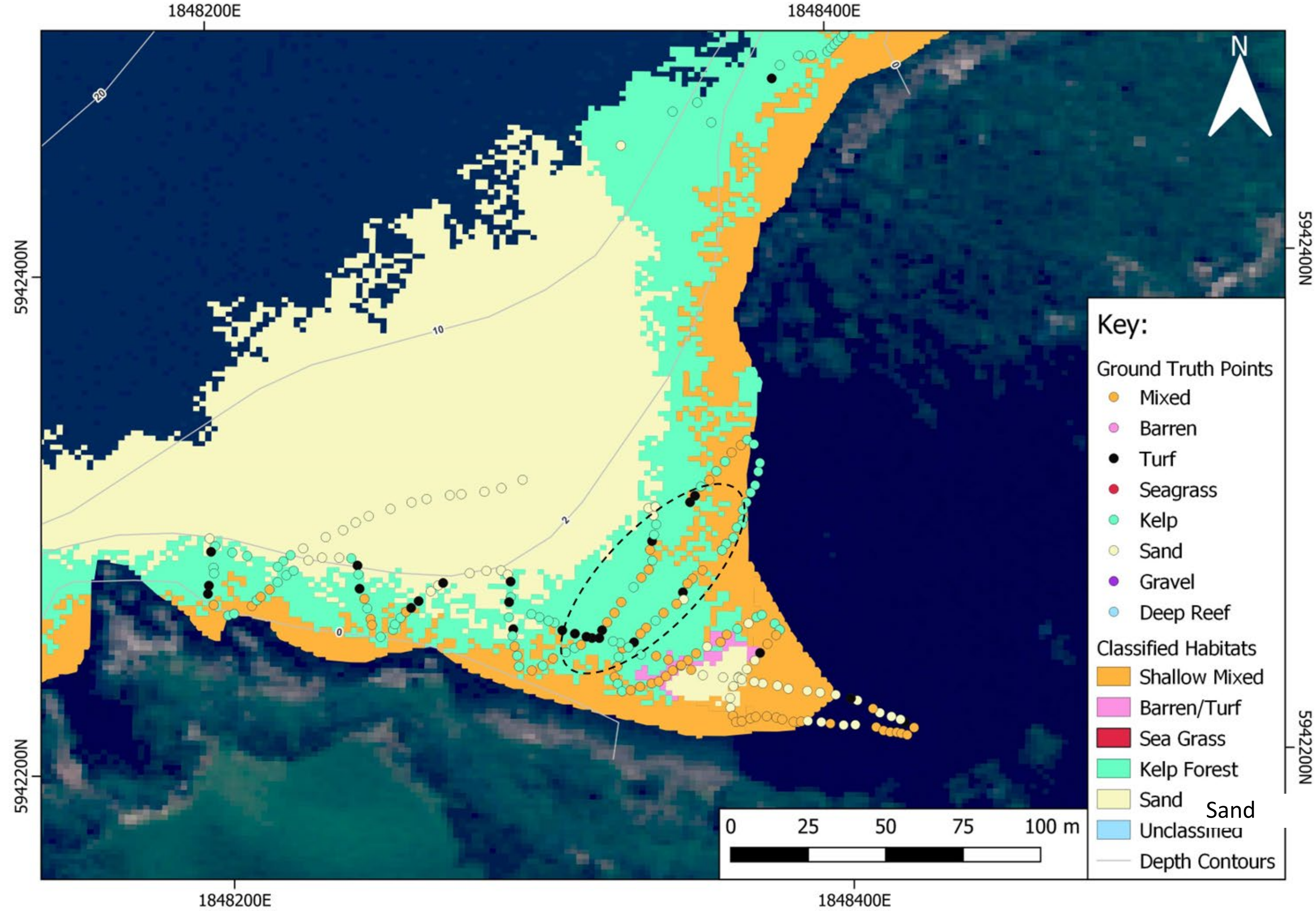
Appendix 2.1 Point between Coralie and Te Koru Bay, eastern side Ahuahu.



Key points:

- Mapped area and ground-truth points extend out to the edge of the reef at ~20m depth. Depths shown are based on BPS photos and highlight inaccuracy of available contours.
- Generally high concordance between mapped habitats and ground-truth (BPS) images
- BPS images in Barren/Turf habitat include an even mix of urchin barrens and turfing algae

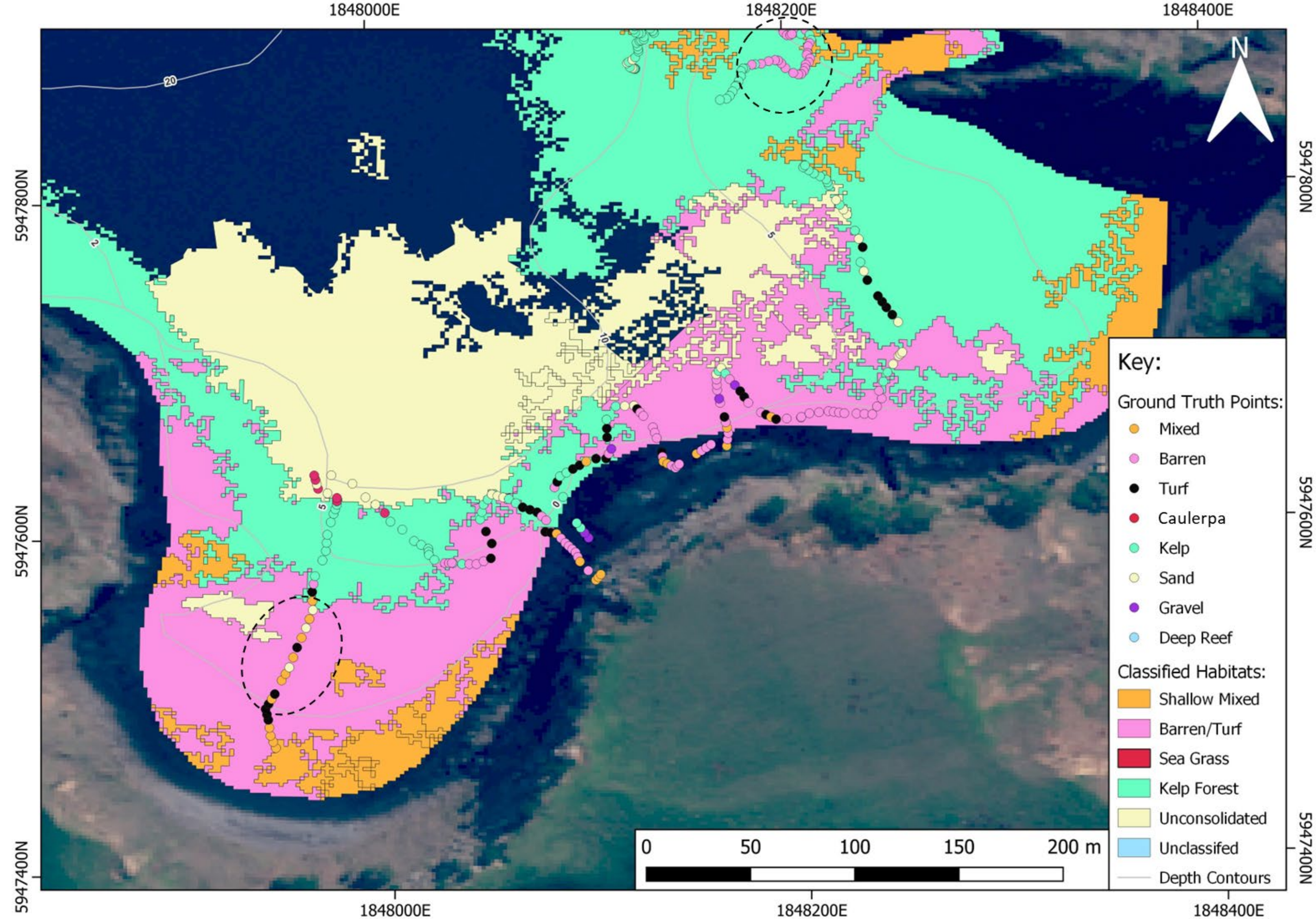
Appendix 2.2 Bay north of Ahikopua Pt, western side Ahuahu-Great Mercury Island



Key points:

- Dotted circle highlights an area where Shallow Mixed ground truth points are misclassified as Kelp Forest
- Also note shallower area on right mapped as Shallow Mixed but ground truth points are classified as Kelp forest

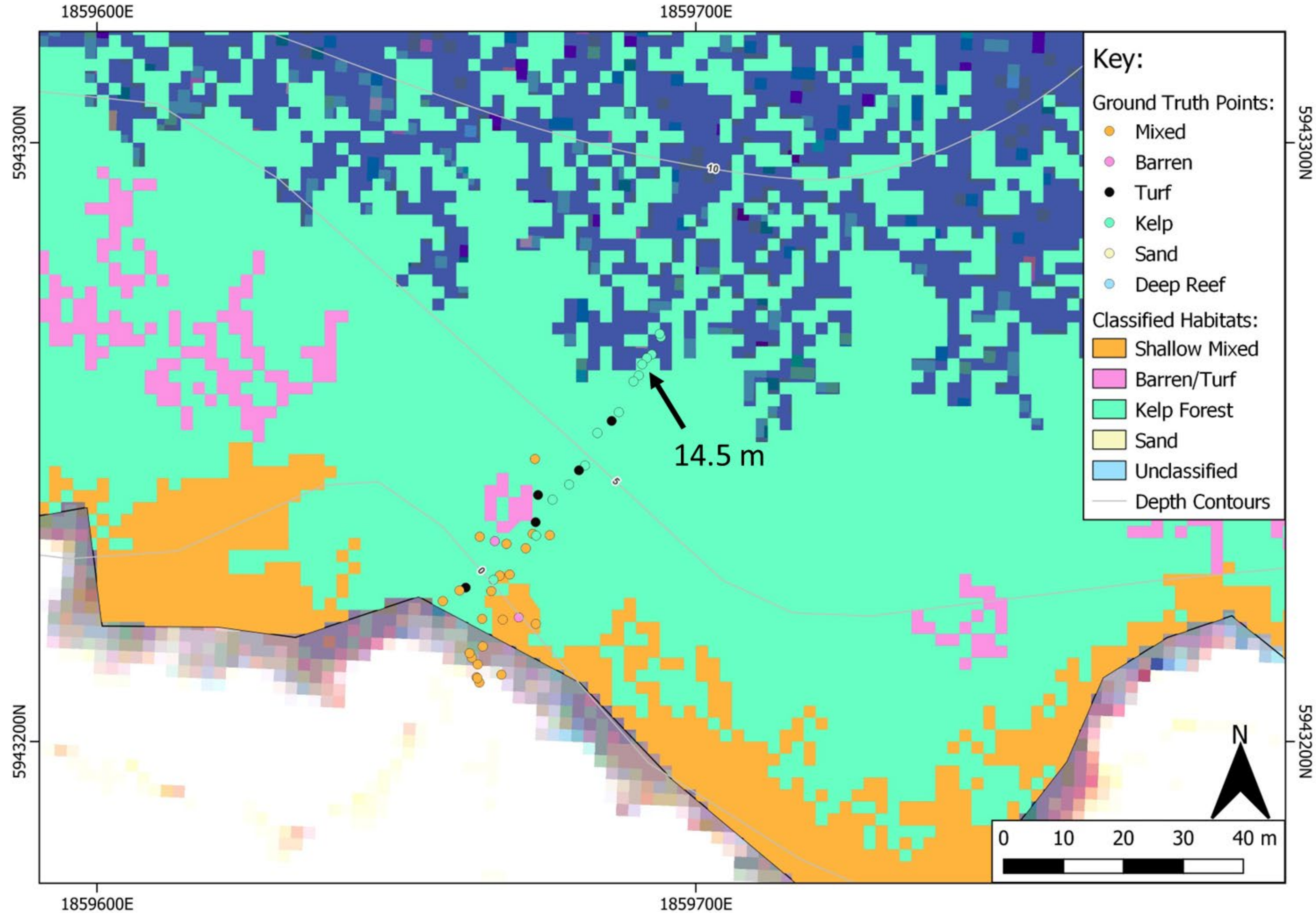
Appendix 2.3 Cathedral Rocks area, northern side Ahuahu-Great Mercury Is.



Key points:

- Top circle area of barrens but mapped as Kelp due to shading in image. Lower circle: area mapped as barrens but photos classified as SMA, likely due to changes since the satellite image was taken
- Occurrence of *Caulerpa flexilis* on reef edge

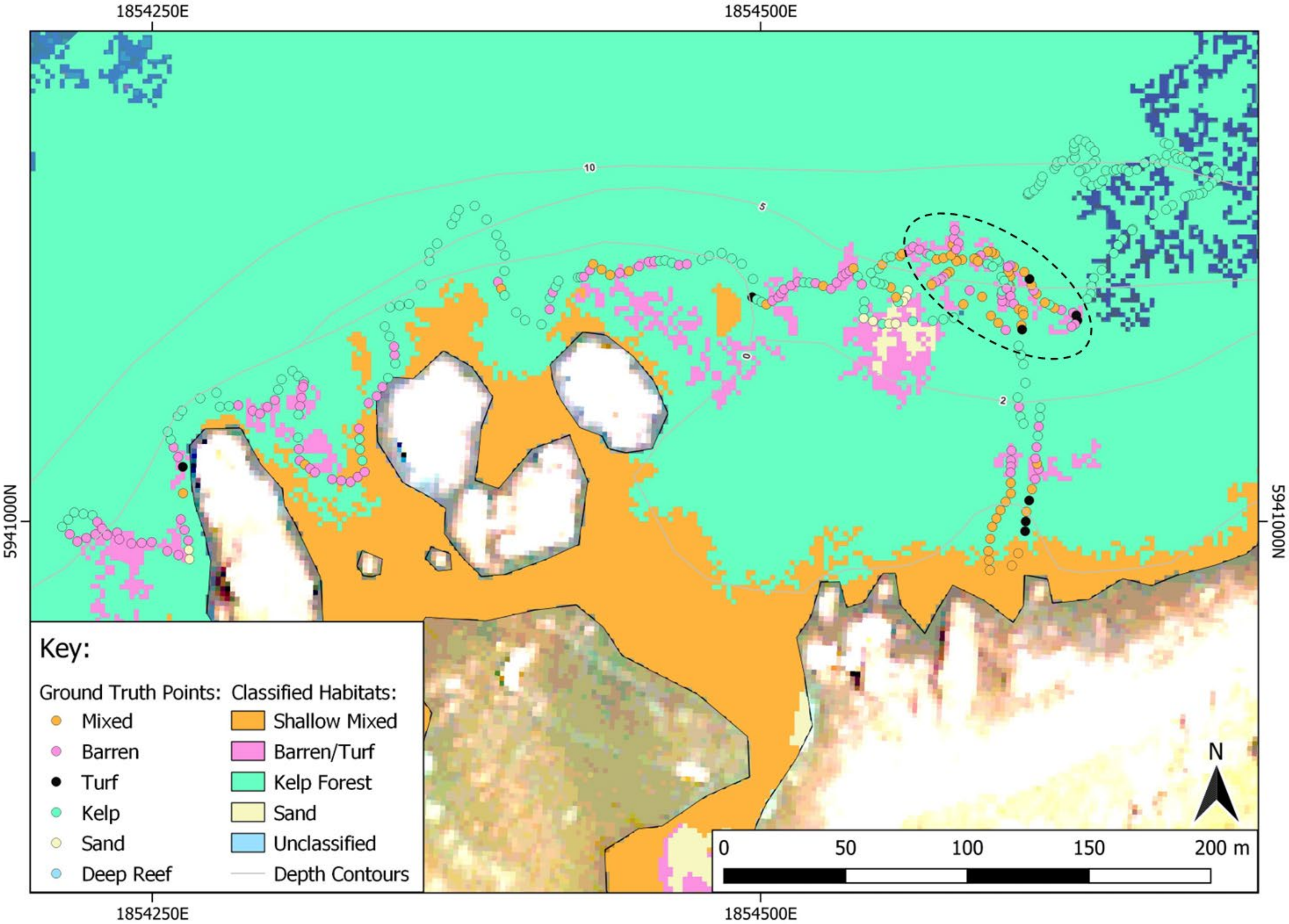
Appendix 2.4. Northern side of Moturehu Is



Key points:

- High concordance between BPS and mapped habitats to a depth of 14.5 m

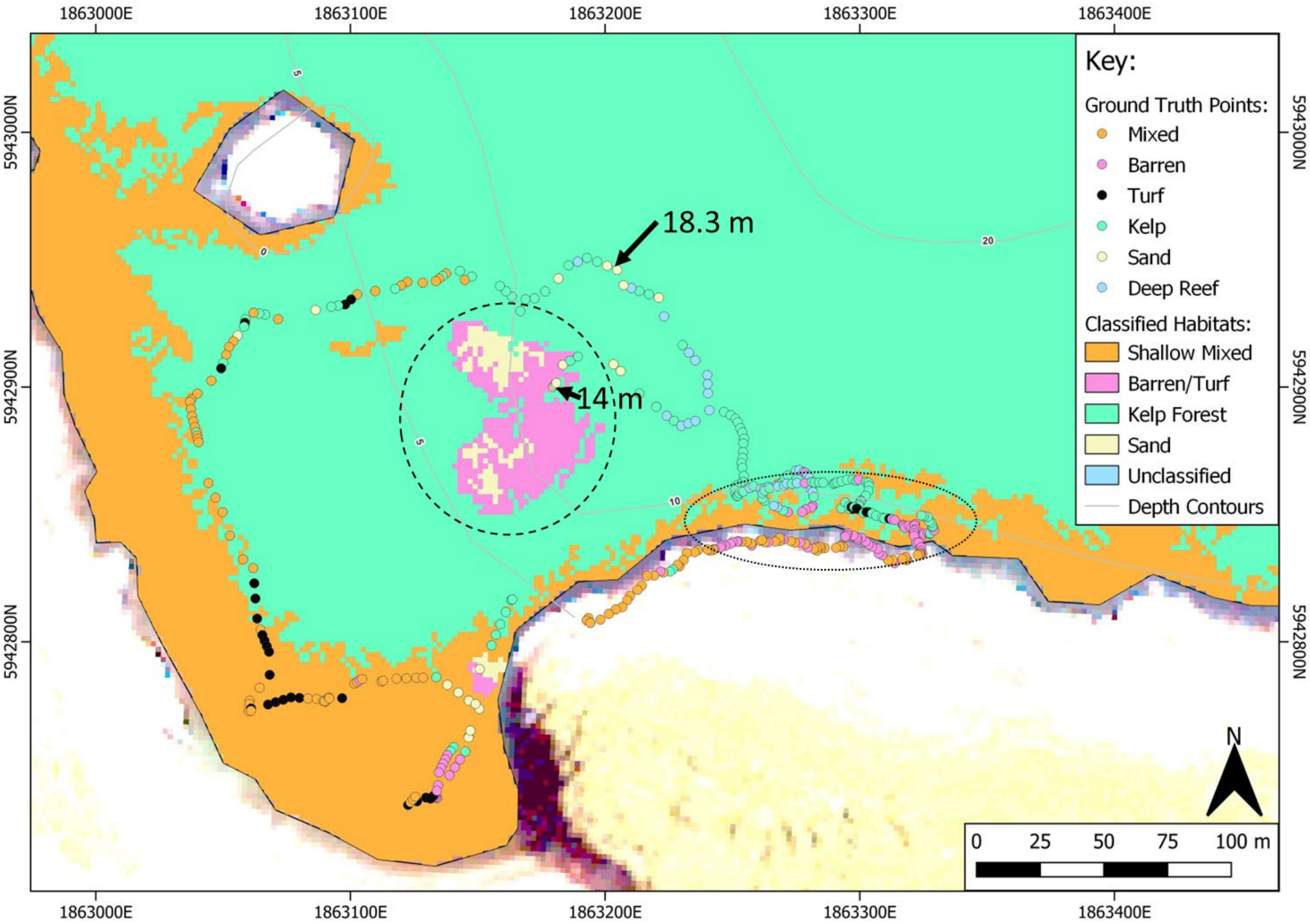
Appendix 2.5 – North side of Green Island



Key points:

- Circled area of patchy barrens but photos classified as SMA, likely due to changes since the satellite image was taken
- Many Barren/Turf areas are mapped as kelp, also suggesting changes

Appendix 2.6 – Von Luckner's Cove, Whakau-Red Mercury Island



Key points:

- Patches of sand at 18 m were not detected in mapping process. Suggests these areas are optically deep and not accurately mapped.
- Dashed circled is a patch of sand at 14 m that was mapped as barrens
- Dotted ellipse is a steep reef area where urchin barrens (8-18 m depth) were not detectable on the satellite image
- Also note presence of barrens in shallow that were not mapped