The extent of kina barrens over time at Hauturu-o-Toi and the Noises Islands

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Abstract

Kelp forest habitats are the foundation for many species found on temperate rocky reefs. With fishing pressures decreasing populations of key urchin predators, the issues of urchin (kina) barrens and deforestation of kelp beds have become more prevalent. Satellite and aerial imagery were used to map the extent of kina barrens surrounding Hauturu-o-Toi and the Noises Islands in the Hauraki Gulf, northern New Zealand. GIS mapping software was used to digitise images from 1953, 1979 and 2019 for Hauturu-o-Toi, and for 1978 and 2019 for the Noises. This allowed a large-scale assessment of the current extent of kina barrens in each location and long-term changes in the extent of kina barrens at key locations.

Aerial imagery and historic descriptions indicate that kina barrens did not occur in either location in the 1950's but by the 1970's kina barrens were a major habitat on subtidal reefs: covering 11.6% of reef at Hauturu-o-Toi and 23.97% at the Noises. This progression is consistent with industrial scale removal of predators, such as the spiny rock lobster and snapper, in the middle of last century. The extent of barren found to cover the reef habitat at the Noises increased between 1979 (24.0%) and in 2019 (49.5%) demonstrating that kina barrens are now a major habitat on the inner gulf reefs. This is contrary to much of the previous literature which claimed that the inner gulf was not subject to the issue of kina barrens to the extent that outer gulf islands were.

Urchin barren covers 32.73% of reef habitat at Hauturu, dominating a shallow band around much of the island, but most extensive on the more wave exposed northern and eastern coasts. There was a positive relationship between the extent of kina barrens and wave exposure, with overall barren coverage and the lower depth of barrens increasing with exposure.

The accuracy of habitat maps produced ranged from 67.9% to 79.5%, falling within the range of accuracies found in studies using similar methods, scope and detail. These habitat maps provide a clear visualisation of both how barren extent has changed over time, and where barren is to be found at each site. With marine protected areas (MPA's) proposed for both locations, these habitat maps and the methods used provide an efficient and effective tool for monitoring future change in the extent of kina barrens and kelp forests on shallow reefs.

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1.0 Introduction

Macroalgae, or seaweeds, including brown algae or kelp, are dominant habitat forming species influencing the biodiversity of coastal ecosystems across around 25% of the world's coastlines (Wernberget al., 2019a). Kelp beds provide shelter, a food source, and a habitat for a range of fish and invertebrates (Perreault et al., 2014; Wernberg et al., 2019b). As well as directly impacting activities such as fishing and tourism, the health of macroalgal beds, or kelp forests, influences energy flows, carbon storage, and coastal protection against heavy weather events (Wernberg et al., 2019a).

Kelp beds have been found to significantly shelter the shore from wave action, as well as providing structural complexity and shelter for the reef itself (Estes & Palmisano, 1974; Choat & Ayling, 1987). Abundances of fish and crustacean species have been found to be higher within and around kelp forests, with more complex food webs stemming from a higher primary productivity, therefore reductions in kelp beds would have negative effects on the species who are part of these food webs (Filbee-Dexter & Scheibling, 2014; Choat & Ayling, 1987; Estes & Palmisano, 1974).

There are a variety of constraints on worldwide kelp distribution. In high latitudes light availability is the key constraint, with low latitudes facing constraints from nutrients and warm temperatures as well as other macroalgae (Steneck et al., 2002). Meanwhile in mid latitudes, such as around New Zealand, the biggest issue kelp forests face is that of herbivory, most often from sea urchins (Steneck et al., 2002). Areas where urchins have fully depleted kelp beds are referred to as urchin barrens (fig. 1), with these barren areas being hard to reverse once they form (Ling et al., 2015).

Urchins, or echinoids, are spiny, ground dwelling grazers of the Family Echinometridae (McRae, 1959; Andrew, 1988). There are a variety of urchin species found worldwide that each fill similar ecosystem functions and are key herbivores on rocky reefs. The dominant species in New Zealand is *Evechinus chloroticus,* an endemic species commonly known as kina (fig. 1) (McRae, 1959). Consequently, urchin barrens in New Zealand are commonly known as "kina barrens".

Figure 1 - Urchin (kina) barrens at Hauturu-o-Toi, north-eastern New Zealand. Photo: Paul Caiger

E. chloroticus are found on shallow rocky reefs throughout the New Zealand coastline and inshore islands, as well as the Three Kings, Chatham and Snares Islands (Andrew, 1988). Around the North Island they are found from the intertidal zone to beyond 15m, often forming a characteristic barren zone within the shallower extent of this range, while in the south kina are generally found only in patches (Schiel, 1990).

1.1 Global issues with urchin barrens

The formation of urchin barrens

When key urchin predators, such as sea otters, lobsters and large finfish, are removed from a system, often through over-harvesting, urchin populations can increase to a level where kelp beds are removed leaving barren areas in their place, devoid of the structurally complex canopies found in kelp beds (Mann, 1977, Coleman & Kennelly, 2019; Wernberg et al., 2019b; Shears & Babcock, 2002). The resulting barrens are instead encrusted with coralline and short turfing algae, which has a lower nutritional value compared to the fleshy kelp (Wernberg et al., 2019b).

Large reef fish of the size capable to remove urchins are less likely to feed outside of kelp stands, which only intensifies the issue of an overly high urchin population (Choat & Ayling, 1987). Continued grazing of urchins within the barrens prevents the kelp and other algae from re-establishing, and urchin populations remain high as settlement is generally higher in urchin barrens than in areas of kelp forest (Breen & Mann, 1976; Lang & Mann, 1976; Choat & Andrew, 1986). Each of these factors contributes to a positive feedback loop that encourages the maintenance and expansion of barrens (Wernberg et al., 2019b).

Global examples

The issue of over grazing by urchins and the resulting areas cleared of kelp has been noted across many areas worldwide, including the west coast of North America, Northern Chile, Nova Scotia and eastern Canada, the north-eastern coasts of the Atlantic including Norway and Russia, South Korea, and around the coasts of Victoria and Tasmania in Australia (Estes & Palmisano, 1974; Breen & Mann, 1976; Mann, 1977; Chapman & Johnson, 1990; Norderhaug & Christie, 2009; Jeon, Yang, & Kim, 2015; Layton et al., 2020; Perreault et al., 2014).

One of the most well recognised and studied relationships between urchin overpopulation and kelp loss is that from the west coast of North America, following the depletion of sea otter populations which were being trapped for their furs (Estes & Palmisano, 1974; Claisse et al., 2013).

An example of this being two island groups off the coast of Alaska, Rat Island group and Near Island group, both of a similar structure and distance to the mainland but one with a dense sea otter population and the other without (Estes & Palmisano, 1970). It was suggested that the differences in the two marine communities were due to the presence and absence of the sea otters, with the sea urchins *Strongylocentrotus sp.*, known for feeding on and depleting large areas of kelp, being an important food source for the otters (Estes and Palmisano, 1974). The island without sea otter presence had areas almost carpeted with urchins below the intertidal zone, while the other group had macroalgal cover to 20-25m, and little to no urchins found shallower than 10m (Estes & Palmisano, 1974). Estes & Palmisano (1974) suggest that a high number of sea otters in the area depletes the urchin population to a small number of smaller individuals, and this release from grazing pressure allowed for an increase in kelp beds.

1.2 Role of no-take marine reserves

By studying marine reserve areas where predator populations have recovered, we can understand the cause of urchin barrens. The establishment of marine reserves have shown increases in lobsters as well as known kina predator fish species, resulting in a recovery of kelp beds compared to nearby unprotected areas (Wernberg et al., 2019b). For example, in the Leigh Marine Reserve the main predators of kina, *Evechinus chloroticus*, are suggested to be large snapper and lobsters capable of crushing through the urchin shell (Babcock et al, 1999). Babcock et al. (1999) analysed gut content of snapper caught on coastal reefs around Leigh, Tawharanui and Kawau Island and found that kina did form a large portion of their diet.

The spiny lobster *Jasus edwardsii,* commonly known in New Zealand as crayfish are found to contribute to a large proportion of predation on large urchins, with smaller urchins predated on by both crayfish and *Pagrus auratus,* commonly known as snapper (Shears & Babcock, 2002).

Babcock et al. (1999) found abundances of legal sized snapper, *Pagrus auratus*, were at least 5.75 to 8.70 times higher inside reserves than outside, when comparing the Leigh and Tawharanui reserves to nearby non-reserve sites, as well as the fish being significantly larger inside the reserve. Densities of spiny lobster, *Jasus edwardsii*, were also over twice as high within reserves as compared to sites surveyed outside, as well as having an increase in mean size (Babcock et al., 1999). The same study found that the proportion of urchin barren habitat dominated by urchins at depths deeper than 10m was roughly three times higher outside of protected areas, 39 +/- 7% (95% CI) compared to 13 +/- 5.9% (95% CI) inside protected areas (Babcock et al., 1999). Of the 10 sites they had originally classified as urchin dominated rock flats in 1978, 8 of these were reclassified to either shallow mixed fucoid or kelp forest by 1996 as densities of *Ecklonia radiata* and/or other large algae increased (Babcock et al., 1999). After 40 years of the Leigh marine reserve being in place, there was an increase in overall biomass of fish, as well as an increase of kelp abundance noted (Allard et al., 2022).

1.3 Using remote sensing / GIS for mapping underwater habitats

Because of limitations around access to underwater sites, it is more difficult to monitor kelp / barren areas than it is to monitor terrestrial and intertidal habitats. One option is to SCUBA dive the sites and undertake surveys, but this is time and cost intensive to cover only small areas, whereas remote sensing can cover much larger areas, with field work cut down to obtaining imagery on a clear day and taking drop camera images for ground truthing (St-Pierre & Gagnon, 2020).

The difficulties with using remote sensing for underwater sites is that you are limited to mapping only what can be seen through the water (St-Pierre & Gagnon, 2020). With increased colour loss with depth, substrates that already look similar may become even more indistinguishable, and factors such as turbidity can decrease visibility further (St-Pierre & Gagnon, 2020). Wave action and glare may cause aerial or satellite imagery to be unusable with completely restricted visibility, but when images are collected in the right conditions this can be a very effective technique (St-Pierre & Gagnon, 2020; Claisse et al., 2013).

St-Pierre & Gagnon (2020) compared three classification methods using digital aerial and satellite images of an ~250ha area of seabed around 4 islands in the Mingan Archipelago, east of Quebec, Canada, to map kelp beds. Because the intent of their study was to compare classification techniques, instead of classifying each habitat category as we are, they simply categorized into ‘kelp’ and ‘not kelp’. They compared a software-led unsupervised classification, a software-led supervised classification and a visual classification, with the supervised and the visual classifications having the highest overall accuracies (St-Pierre & Gagnon, 2020). Their study was focusing on the 0-7m depth range, with gradual changes in depth, so adjusting for light attenuation in the water was not required (St-Pierre & Gagnon, 2020).

St-Pierre & Gagnon (2020) obtained their aerial images at low tide on days with low wind, and low wave action, following 4 days preceding with low wind. This ensured the lowest turbidity of the water, minimising glare and the allowing best ability to view the seabed clearly to a depth of ~8m (St-Pierre & Gagnon, 2020).

Claisse et al. (2013) used heads-up digitization to map sites in Santa Monica Bay, California, using 2011 satellite imagery from Google Earth, later refined further with the use of 2009 satellite imagery. They used GPS points from SCUBA surveys with information about densities of urchin and macroalgal cover as training points (Claisse et al., 2013).

These methods provide an opportunity to not only map the current distribution of urchin barrens and kelp forest but can be applied to historic imagery of varying types to document long-term changes.

Leleu et al. (2012) mapped within and outside the Leigh Marine Reserve to compare habitat extent from 1977, showing the area soon after the marine reserve was created, to the same area mapped in 2006. They used a variety of methods including aerial images, existing surveys, side-scan sonar, underwater video and diver tows to collect the data used to digitize the area (Leleu et al., 2012). The resulting maps showed that within the marine reserve there was a 50.2ha increase in *E. radiata* beds, from 28% to 60% coverage of reef, and a 40.2ha decrease in areas of urchin barren, 31% to 1% reef coverage (Leleu et al., 2012).

1.4 History of urchin barrens in New Zealand

Kina barrens in the Hauraki Gulf and their associated causes have been a topic of interest since the 1970's, after commercial fisheries expanded in the 1950's, and barren extents became notable in rocky reef surveys (Choat & Schiel, 1982). Predators such as spiny rock lobsters and fishes such as snapper work to control urchin populations, however, it is suggested that this pressure was higher before commercial fishing decreased the populations of these predators (Schiel, 1990). Commercial fisheries around New Zealand and in the Hauraki Gulf took off in the 1950's following the recommencement of trawling after the end of WWII (MacDiarmid et al., 2018). Exports of frozen lobster tails caught in Auckland and Whitianga boomed in the early 1950's, with reports at this time already suggesting that this level of catch rate may not be sustainable (MacDiarmid et al., 2018). As well as increased exports, the 1950's saw foreign fishing vessels entering New Zealand waters, adding extra pressure to fish stocks (Science Learning Hub – Pokapū Akoranga Pūtaiao, 2009).

It has been suggested that due to recreational and commercial fishing pressures, snapper stocks dropped to 10% of their original biomass by the end of the 20th century, as fishing methods became increasingly efficient from the 1950's (Ministry for Primary Industries, 2013; Parsons et al., 2009; Parsons et al., 2014). Since this point, some stocks have increased to 24% of the original biomass, with stock assessments as well as fisherman's diary logs of catch rates showing an increase in snapper stocks since the 1990's, before which stocks had been continuously depleting (Ministry for Primary Industries, 2013; Parsons et al., 2009).

New Zealand introduced the Individual Transferable Quota (ITQ) system to manage commercial fisheries in 1986 (Lock & Leslie, 2007). Over the years since this quota management system (QMS) has been adjusted, but it is generally deemed to have been successful in managing fisheries within New Zealand waters ensuring that practices remain sustainable (Lock & Leslie, 2007). Snapper was included in the QMS from its inception, while spiny rock lobsters and packhorse lobsters were introduced in 1989 (Lock & Leslie, 2007). In the 1986/1987 fishing year there was an overall 6% reduction in in catch, but this included a 54% reduction in catch for snapper, rig, school shark and hāpuku bass, as well as snapper receiving nearly half of the total funding from the introduced buy-back scheme (Lock & Leslie, 2007).

While the QMS has been successful in boosting snapper stocks, they remain less than a quarter of their original level. The QMS has been successful in preventing the decline and rebuilding the spiny rock lobster populations. A study published in 1997 in Gisborne found that the QMS alone had not slowed the decline in catch rates through to the 1993 season, and extra schemes needed to be put in place to increase the catch rates (Breen & Kendrick, 1997).

With the dramatic increase in fishing pressures in the mid-20th century for these important sea urchin predators, it can be expected that the extent of urchin barrens would expand with the loss of key predators, but become more stable when the QMS took hold from the late 1980's to the 1990's as snapper stocks started to bounce back. Because lobsters are an important urchin predator and these populations have not bounced back as significantly since the introduction of the QMS. However, as well as pressure from predators, site conditions such as wave exposure, turbidity and salinity are also suggested to influence the extent of urchin barrens.

A 1970 study found that high-density groups of *E. chloroticus* were not associated with barren areas in the highly exposed Kaikoura region, while in the Queen Charlotte Sound, a significantly more sheltered area, there were groups of *E. chloroticus* in high densities that were associated with larger cleared areas (Dix, 1970). They suggest that urchin activity is influenced by wave energy, with urchins in sheltered areas roaming and feeding from large areas of kelp, while urchins in areas of high wave action remain more stationary, feeding from drift material and only foraging in localised areas (Dix, 1970).

In the 1982 study by Choat & Schiel, the two sites that were studied where urchins were found to be rare and which also had unbroken kelp forest, were both exposed to high wave energy. Choat and Ayling (1987) found that in areas of moderate wave exposure urchins and mollusc grazers dominate the 4-10m zone, with continuous algal stands dominant beyond 10m. In areas with high wave exposure they found algal stands dominate this 4-10m zone, however, there were some observations showing that particularly sheltered areas also had this same result (Choat & Ayling, 1987).

Shears & Babcock (2004) found clear patterns in community structure around wave exposure and turbidity. They found that the species richness of macroalgae was highest at offshore islands, and lowest at the most sheltered sites, which in this study was Long Bay (Shears & Babcock, 2004). Urchin abundance was found to vary with depth and exposure, with increasing abundance at more exposed sites, where their grazing limit also moved deeper (Shears & Babcock, 2004). They found urchins to be rare at the inshore, sheltered sites, suggesting that barren areas were instead replaced by *Carpophyllum flexuosum* forests in these areas (Shears & Babcock, 2004).

Grace (1983) also suggest that in very sheltered areas, such as the inner Hauraki Gulf, *E. radiata* beds are replaced by *C. flexuosum,* and that urchin barren areas, referred to as ‘rock flats’, are absent south of Tiritiri Matangi Island, with kina being less common closer to Auckland (fig. 2). Grace noted that as you get further into the Gulf where wave exposure decreases and turbidity increases, substrate zones and their boundaries become progressively shallower (Grace, 1983). It is suggested that macroalgal zones move shallower in areas further within the gulf due to light restrictions from the increasing turbidity, and that reduced salinity at these sites may limit the extent of rock flat zones (Grace, 1983). Notably however, Grace did not include any inner Gulf islands in his study.

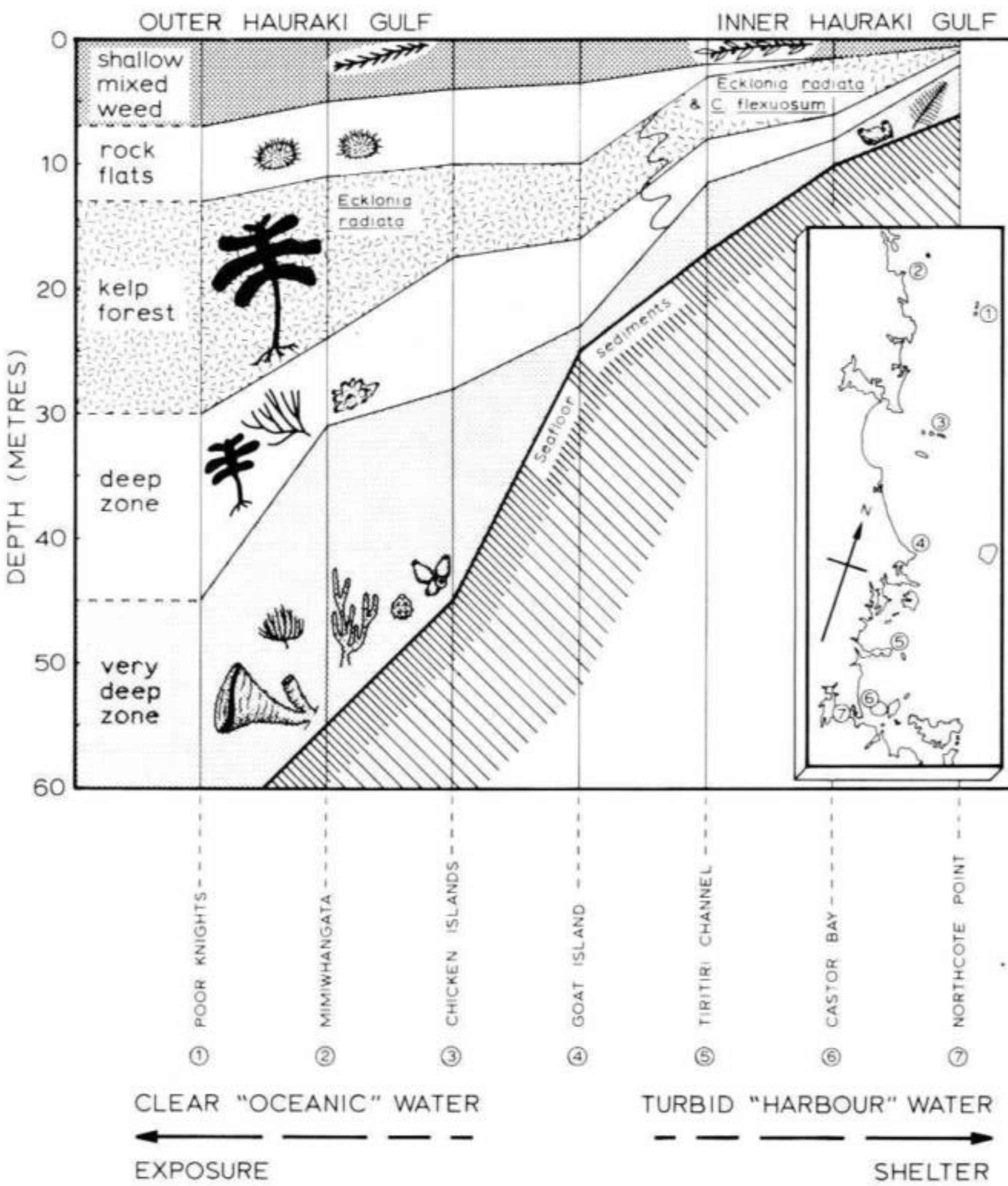


Figure 2 - Zonation map showing depths of zones as they vary with exposure and turbidity (Grace, 1983, page 107)

While there have been many studies across the wider north-eastern North Island area, particularly sites such as Leigh, there has been little study done looking specifically at the Noises Islands group and Hauturu-o-Toi (Little Barrier).

1.5 History of kina barrens around Hauturu-o-Toi (Little Barrier)

Hauturu-o-Toi of Little Barrier Island (hereafter "Hauturu") is a critically important terrestrial conservation island, in 1894 becoming New Zealand's first nature reserve: a pest-free island, home to over 50 rare or endangered bird, reptile and bat species (Department of Conservation, 2012).

Trevarthen noted in 1953 that *E. radiata,* kelp, could be seen from the surface of the water around Hauturu, until depths where the kelp could be barely seen through the 'translucent' water. Trevarthen (1953) described aerial photographs of the island showing a patchwork of seaweed beds surrounding the island, with the only empty patches due to accumulations of sand. While they described multiple organisms living in the intertidal and upper sublittoral zones, including species of gastropods and crustaceans, there was no mention of urchins found (Trevarthen, 1953).

Bergquist (1960) studied the biotic communities around Hauturu, breaking the surface pattern zonation into categories based on depth, and noting various algal species in each of these zones. *E. radiata*, was noted in the upper sublittoral zone, and there was no mention of urchins in any zone (Bergquist, 1960).

In a 1964 study, Dromgoole analysed the coastline of Hauturu, and described the island as having much of the coastline consisting of boulder beaches, which in several places on the north and east coasts stretched well past the low tide line. Because the rocks tend to be well rounded, close packing doesn't really occur, so movement of the rocks happens frequently in littoral and sublittoral zones impacting the algae supported (Dromgoole, 1964). While they didn't note any areas of urchin barren, they did note that there was an absence of *E. chloroticus* (kina) at Te Titoki Point on the south western corner, likely due to the loose boulder substrate found there (Dromgoole, 1964).

Choat and Schiel (1982), with sampling undertaken in 1978, ran transects and quadrats at seven sites around the North Island of New Zealand, including two at Hauturu, on the northern and eastern coasts. As of that study, *E. chloroticus* were relatively rare at the sites studied around Hauturu, with the peak abundance found at 10m depth at the kelp forest line, although, there were still areas of less algal coverage, both fucoid and *E. radiata*, around the 6-8m mark which were attributed to urchins (Choat & Schiel, 1982).

Choat and Ayling (1987) compared reef fish densities between kelp forests and urchin dominated reefs. Hauturu was one of their study sites among others across the north-eastern coast of the North Island, with enough of a kina presence at this point in time for it to be included, contrasting Bergquist's 1960 study with no mention of kina (Choat & Ayling, 1987).

Although there have been these various separate studies since the 1950's, the full extent of barren and how it has varied over time is unknown.

1.6 History of kina barrens around the Noises

The Noises Islands are also important terrestrial conservation areas. Ruapuke / Maria Island of the Noises Island group was the first island in the world to be completely cleared of rodents after an eradication effort in 1964, inspiring other pest eradication programmes around the world (The Noises, 2021a). Motuhoropapa and Otata Islands have both also been rodent free since 2002, with Motuhoropapa Island being particularly distinct with its complete cover of indigenous plant life, one of the few islands in the Hauraki Gulf to remain relatively untouched (The Noises, 2021a).

Considering the extensive conservation efforts undertaken onshore there is a lack of study looking under the water. There is surprisingly little known about the marine life surrounding these islands, and while attempts for marine restoration are beginning at the Noises, more knowledge of the area and how it currently functions will be highly beneficial at ensuring this restoration is as effective (The Noises, 2021b).

Bergquist (1960) categorised species found around the Otata Island of the Noises and Shag Rock together, with again no mention of urchins in any zone, various algal species through all zones, and *E. radiata* dominating the lower sublittoral and localised dominance in the upper sublittoral.

Beyond this, there is very little literature noting the presence or extent of urchin barrens or the health of kelp forests around the Noises specifically.

Both Hauturu and the Noises have proposed marine protected areas (MPA's), making it important to understand the current distributions of key habitat to provide a baseline for moving forward. It is also beneficial to use available imagery to understand how habitats may have changed in the years leading up to now.

1.7 Aim

The aim of this study is to map broad-scale reef habitats at Hauturu and the Noises Islands, and where possible use available historic aerial imagery to examine long-term changes in both locations, to see how kina barrens and kelp beds have changed over time. Both areas were mapped using satellite and ground-truth imagery from 2019, and historic comparisons were made using aerial imagery from 1978 (Hauturu and Noises) and 1953 (Hauturu only). The ground-truth imagery was also used to examine how the extent and depth distribution of kina barrens around Hauturu relates to wave action. In addition, these maps will provide a baseline to detect long-term changes including inside and outside proposed MPA's, as well as for future study examining the role of kina removals in kelp forest reforestation.

2.0 Methodology

2.1 Location

Islands within the Hauraki Gulf, north-eastern New Zealand, are the main locations of interest through this study, specifically Hauturu (Te Hauturu-o-Toi / Little Barrier), and the Noises Island group. Hauturu is located 80km north of Auckland, and to the west of the larger Great Barrier Island / Aotea at coordinates 36˚11’57”S 175˚04’53”E (fig. 3a, 3b). The Noises Islands are closer within the Hauraki Gulf, only 24km to the north of Auckland at coordinates 36˚41’42”S 174˚58’30”E (fig. 3a, 3c, 4).

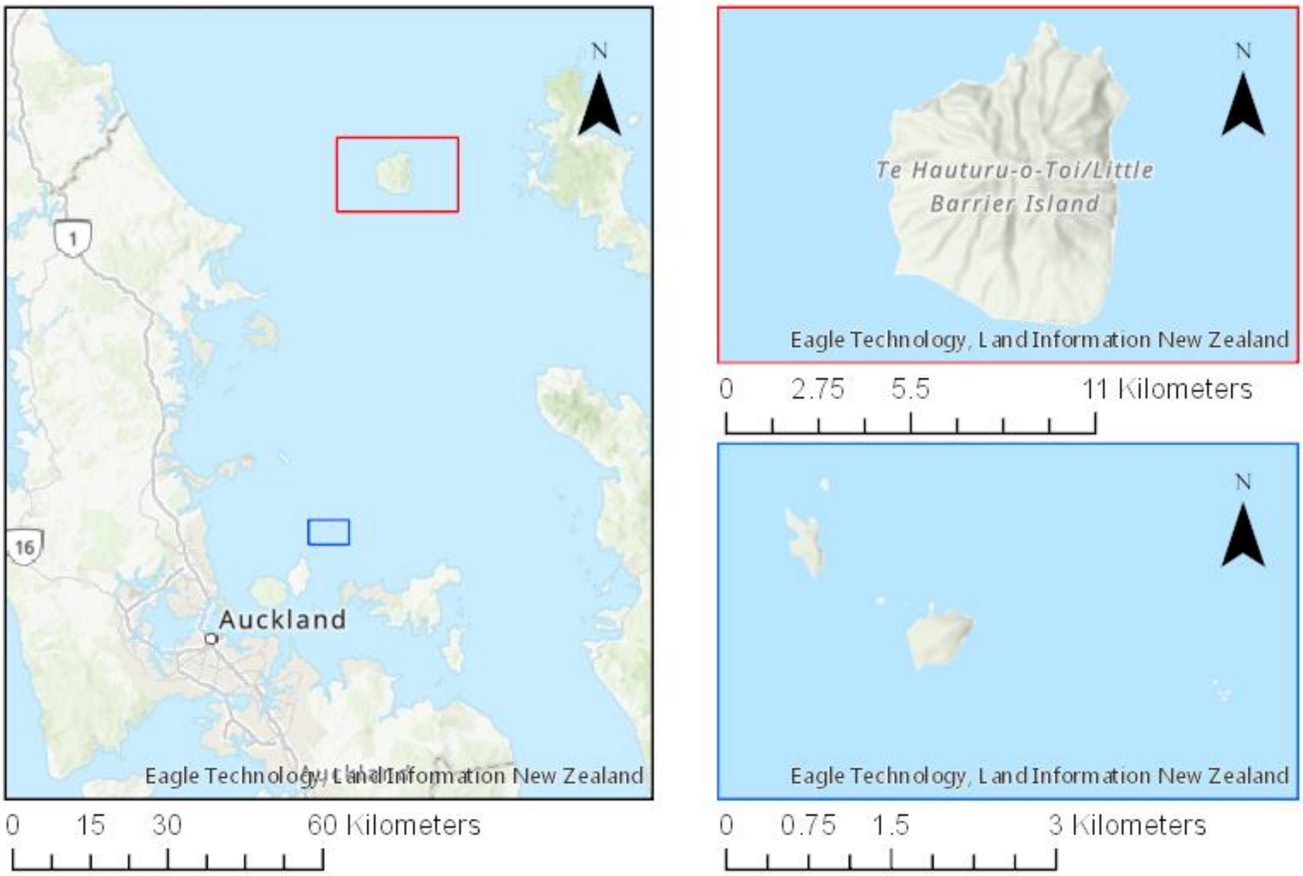


Figure 3 - Clockwise: a) Hauraki Gulf highlighting Hauturu-o-Toi (red) and the Noises Islands (blue), b) Hauturu-o-Toi, c) Noises Islands; left to right, Motuhoropapa Island, Otata Island, Maria / Ruapuke Island

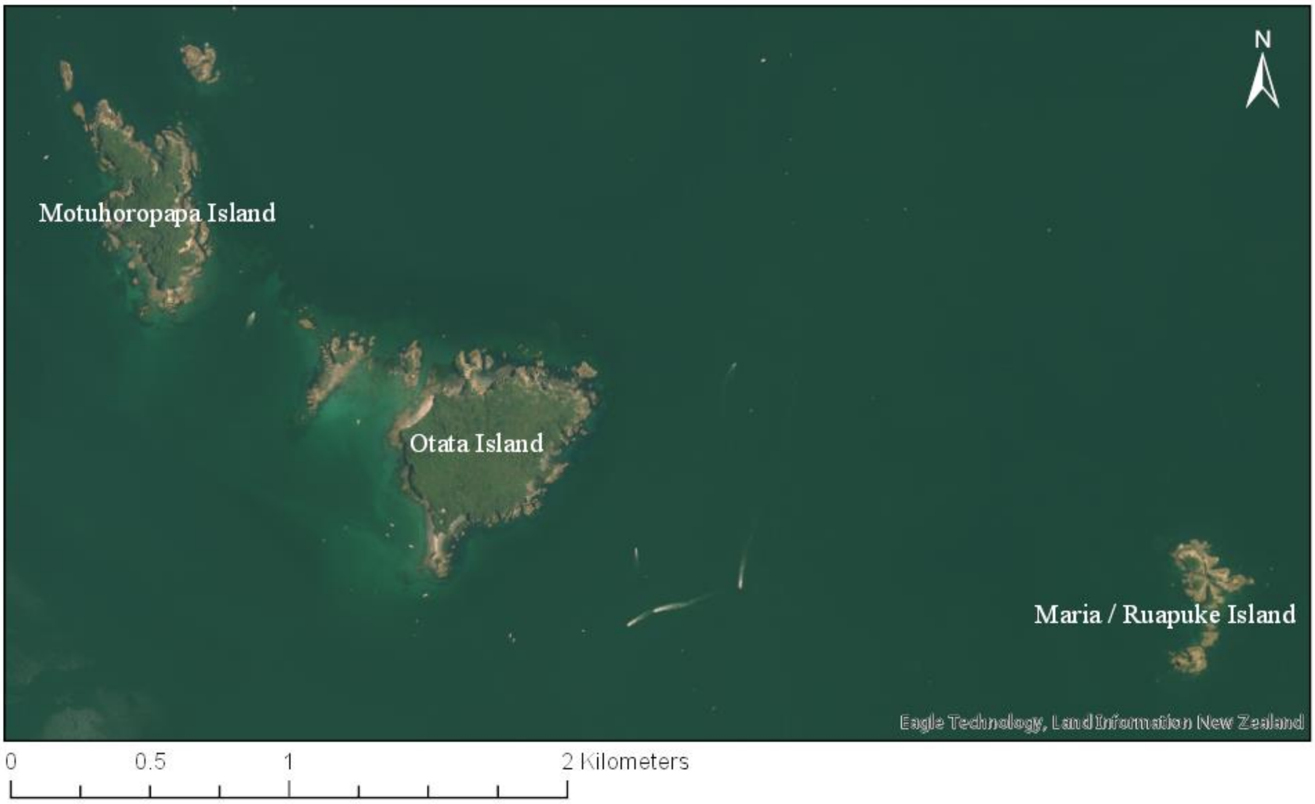


Figure 4 - 2012 LINZ aerial image of the Noises Islands, with Motuhoropapa Island, Otata Island and Maria / Ruapuke Island labelled

2.2 Data collection / image acquisition

2.2.1 Satellite and aerial imagery

Orthorectified aerial images used for locating low tide lines and geo-referencing our other images were downloaded from the LINZ (Land Information New Zealand) data service in the geographic coordinate system of New Zealand Transverse Mercator 2000 (NZGD2000). Reference images were used from the years 2010 to 2012. Historical images were downloaded from Retrolens (retrolens.co.nz), from the years 1953 and 1979 for Hauturu, and the year 1978 for the Noises.

The Retrolens images were georeferenced using 20 to 30 control points per image images, with the aim to have minimal total RMS errors. By sorting the attribute table by the margin of error, the points with the highest errors were either adjusted or deleted, until the overall errors were at an acceptable level. The corners of recognisable rocks were primarily used for control points, as well as any buildings that were found across the timescales. Occasionally recognisable trees were used to create control points, marking the centre of the tree in the historic image and the 2012 reference image. Because trees may not grow evenly, these were only used if there was no other clear reference point in that area, and only if it was clearly the same tree across the timescales.

The 23rd October 2018 and 17th June 2019 Hauturu satellite images, and the 23rd August 2018 and 13th March 2019 Noises satellite images were obtained from Digital Globe - Maxar. These images were georeferenced if necessary and mosaiced, to create one image covering the entire area. Images were adjusted using the stretch tool to increase contrast and colours, to more easily differentiate between substrates. Generally, the custom histogram option was selected, where colours could be specifically adjusted.

2.2.2 Ground truth imagery

Georeferenced drop camera images were used to ground truth the mapping. These were collected by drop camera around Hauturu and by divers at the Noises, with all images geo-referenced and depth tagged using Benthic Photo Survey (BPS) methods (Kibele, 2016).

Drop camera images were taken based on methods used by Kibele and Shears (2018). This involved using a Go-Pro which was dropped to the sea floor on a line from a University of Auckland boat, attached to a weighted, ~1.2m high camera stand, to capture images covering ~3m^2 of the seafloor. A float was attached to the top of the camera stand to keep it at an upright angle, while a Sensus ultra depth and temperature logger was attached to the base. A coaxial cable was run along the line to allow for Wi-Fi transmission to the Go-Pro, so that images could be taken remotely at the surface using the Go-Pro phone application. A Garmin GPS device was used at the surface to record the location at which each image was taken, worn around the neck of the person lowering the camera, to ensure the GPS location most accurately matched where the image was captured. The drop camera images at Hauturu were collected on the 11th June 2019 and 2nd September 2019, and at the start of each day the time of the Garmin GPS device was synchronised to the Go-Pro for accurate geo-tagging.

Geo-tagged diver images were taken using Go-Pros throughout the course of 8 dives around the Noises Islands on the 17th October 2017 and the 11th, 12th, 17th and 26th July 2018. For this method an underwater camera with a Sensus depth logger attached was operated manually by a diver. For GPS locations to be logged, the diver towed a GPS device in a waterproof box attached to a float at the surface (Kibele, 2016). To keep locations exact, the 20m bungee to the float was attached to the diver and kept taut throughout the dive to ensure it was directly overhead. The BPS software was used to geotag and depth tag the images, which was used to create shapefiles for each location that could be viewed in GIS.

The ground truth images were used to record habitat type, depth and temperature for each location. For Hauturu, a total of 627 photos were used from 28 transects located at approximately 400m intervals around the island at a perpendicular angle to the shore, with images ~5m apart along each transect from the shallow subtidal to beyond the reef edge. There were 1,652 geotagged diver images were provided for use as ground truth data around the Noises Islands, which were filtered by whether they overlaid the mapped area or not, leaving 854 relevant images. The diver images were also taken along transects perpendicular to the shoreline, at ~5m intervals, from depths of 1-15m.

Due to the nature of mapping substrates through the water column from satellite and aerial images, quite different biological habitats can appear visually similar, and are therefore indistinguishable. For this reason, only coarse habitat and substrate categories can be used and ground-truth imagery is essential in identifying these. Drop camera images were each individually classified, into one of the following biological habitat and substrate categories:

- **Intertidal (INT)** – intertidal rocks not connected to the landmass
- **Sand (SAND) -** >50% sand
    - **Caulerpa (CAU) -** >50% sand with *Caulerpa flexilis* present
- **Cobbles (COB)** - >50% loose cobble or small, loose rocks
- Reef
    - **Shallow mixed algae (SMA)** - >50% large seaweed of mixed species
    - **Kelp forest (ECK) -** >50% *Ecklonia radiata*
    - **Kina barren (KINA) -** <50% large seaweed with Kina present

- **Other (OTHER) -** <50% large seaweed with no Kina present, that doesn't fall under SAND or COB
- **Not classified (NC)** – undecided, generally due to image quality or indistinguishable classification

Figure 5 - Left to right; images of cobbles (COB), sand (SAND), shallow mixed algae (SMA), E. radiata (ECK), kina barren (KINA) and C. flexilis (CAU)

As well as including areas with less than 50% seaweed coverage but no kina present, the 'OTHER' category included areas of mussel bed, images of anemones, sponges, nudibranchs, sea squirts, paua, fan worms, crabs, octopus and triple fins.

There are studies undertaken in north-eastern New Zealand, such as Leleu et al., 2012; Ayling, 1978 and Kerr & Grace, 2005, that have also used similar coarse habitat types to what we have used here (table 1).

Table 1 - Compilation of different habitat classes used in previous studies

	Leleu et al., 2012	**Ayling, 1978**	**Kerr & Grace, 2005**
Habitat category			
Cobble (COB)	Drifts of small boulders and cobbles, <0.5m diameter	Sand or gravel mixed with smal1 boulders or cobbles 5-15crn in diameter	Gravel / cobble
Ecklonia radiata (ECK)	Almost entirely mature *E. radiata*, from 50% coverage, urchins are rare but can be dense on the edges	Urchins almost completely absent, *E. radiata* sparser at 10-18m depth and denser in shallow water	*Ecklonia* forest

Kina (KINA)	Absence of large brown algae, average urchin density >$2m^{-2}$, rocks covered by crustose coralline algae	Urchins have removed all large brown algae, bare rock accounts for 5-20% of surface	Kina barrens
Sand (SAND)	Coarse sand and shell hash	Soft substrates	Sand / mud, coarse gravelly sand
Shallow mixed algae (SMA)	Mixture of large brown algae, no clear dominance of one species, urchins in low abundance	Presence of large, brown fucoid algae, 0-6m depth, urchins found in depressions or cracks	Shallow mixed weed
Caulerpa flexilis (CAU)	N/A	Green algae, usually *Caulerpa flexilis*, urchins and large brown algae rare	N/A

Some of these studies, such as Leleu et al. (2012) used a larger number of smaller categories, such as separating 'shallow *Carpophyllum*' and 'mixed algae' or separating 'sediment' and 'sand and shell covered flat rock', where here we combined these into the broader categories of shallow mixed algae and sand. This assisted ease of classification, and because the main aim here is to compare urchin barren extents, it wasn't necessary for different sand or sediment types, or shallow mixed algal species to be classed in distinct groups as this would not have added extra value to the analysis. Shears et al. (2004) used similar categories as Ayling (1978), including having a category for *Caulerpa flexilis*, and found these to be both biologically distinct and meaningful, and that these habitat types can be reliably visually distinguished for the purposes and techniques used here to classify ground truth imagery.

The associated coordinates for each image in the form of a point shapefile was overlaid on their corresponding satellite image for each location, with each point colour coded by habitat type (fig. 6, fig. 7).

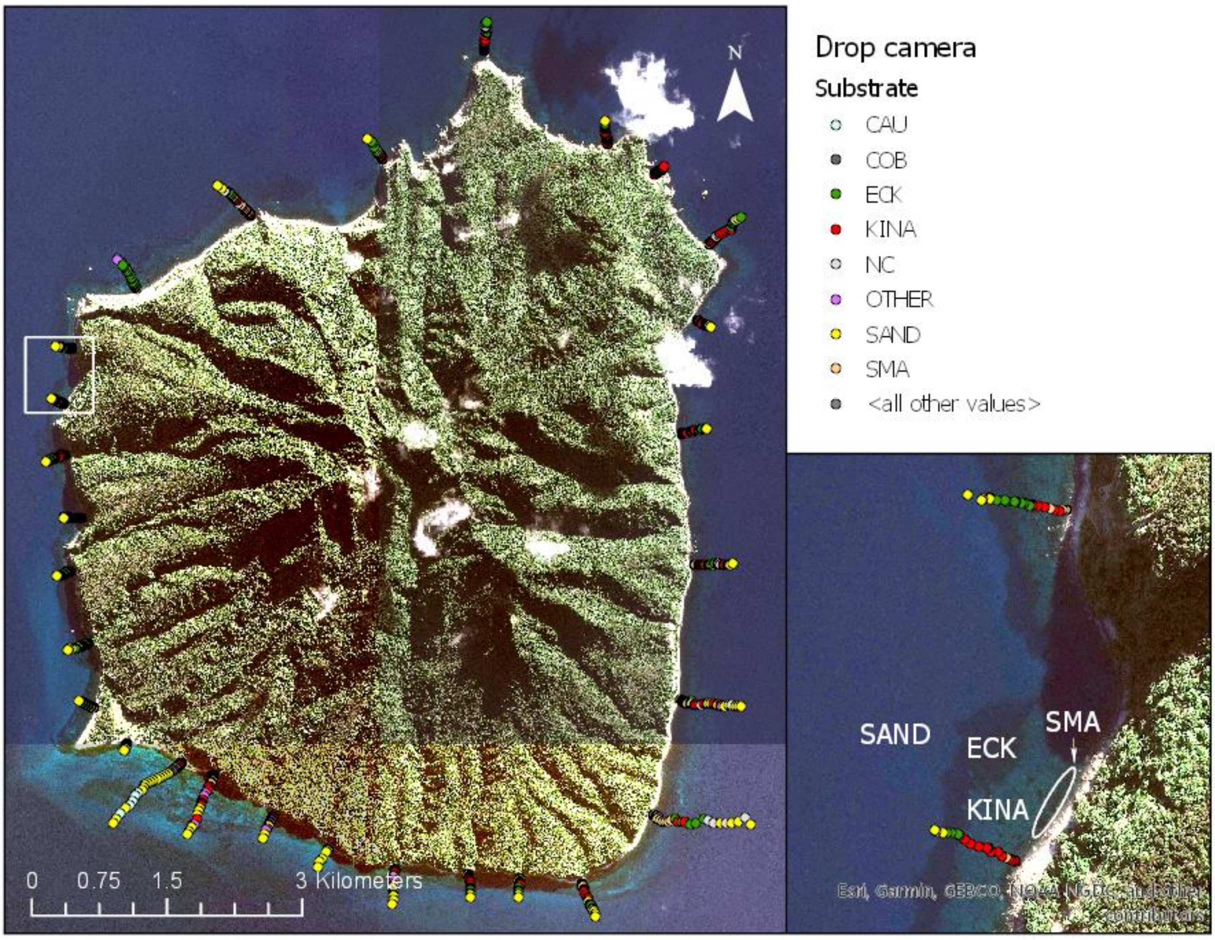


Figure 6 – Satellite image (2019) showing the location of drop camera images at Hauturu-o-Toi, colour coded for the substrate they represent. Inset shows zoomed in section of coast with subtidal habitats evident; sand, E. radiata, kina, and shallow mixed algae

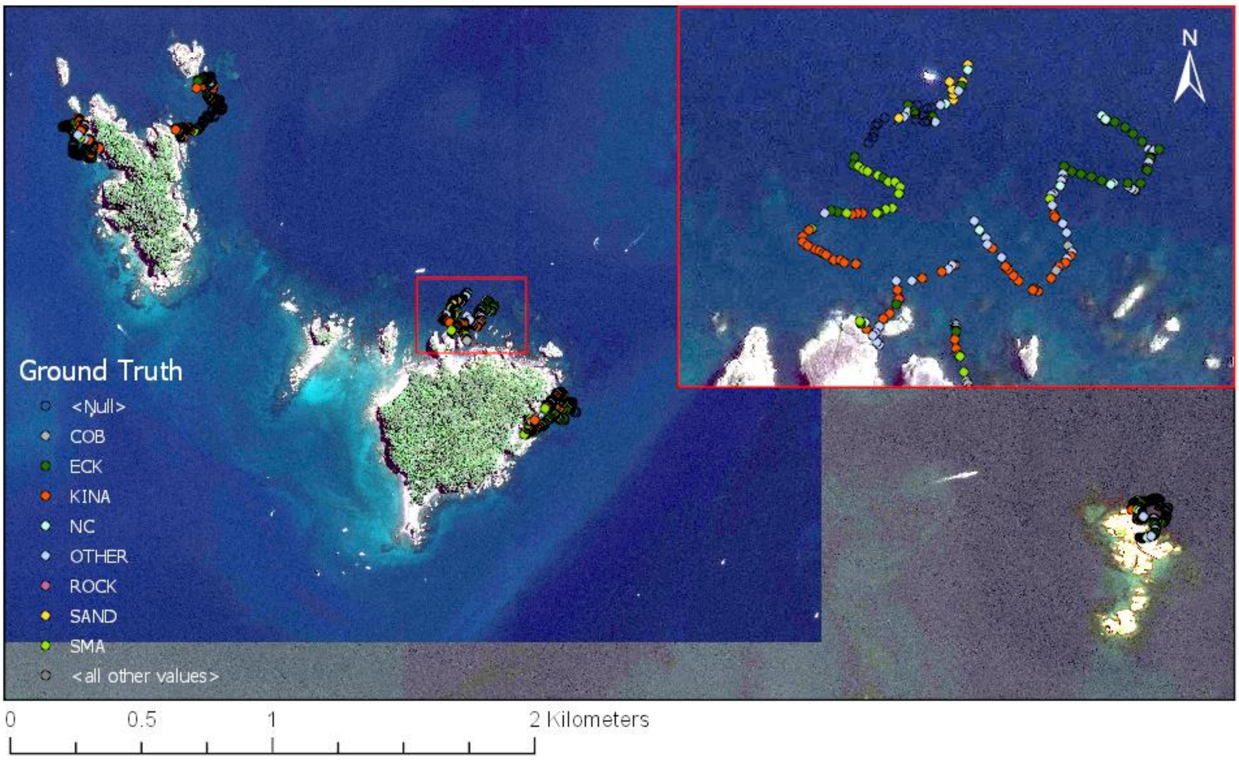


Figure 7 – Location of drop camera images at the Noises Islands, colour coded for the habitat type and substrate they represent, overlaid on 2019 (left) and 2018 (right) satellite imagery

2.3 Mapping

ArcGIS Pro was used to create each map, creating shapefiles to represent each aerial or satellite image and individually digitizing these to form the habitat maps. Based on previous studies there are four broad habitats that can be reliably mapped, including sand, *E. radiata*, barren and shallow mixed algae (Shears et al., 2004; Kibele, 2017)

However, ground truth imagery revealed other habitat types, so the substrates of cobble and *Caulerpa flexilis* were also included. *C. flexilis* was only included in the Hauturu maps, as it was only seen in ground truth photos from around this island.

Substratum and habitat classes used for classification included:

- **Intertidal (INT)** – bare rock or sandy beach in the intertidal zone
- **Cobble (COB)** – loose small boulders and cobbles, generally shallow
- ***Ecklonia radiata* (ECK) -** <50% *E. radiata,* distinguishable from SMA due to being slightly deeper and a darker green colour when the images were stretched
- **Kina (KINA) -** <50% macroalgae, kina present. Appears to have more texture in the aerial imagery than areas of sand
- **Land (LAND)** – mainland or protruding offshore rocks above the high tide line
- **Sand (SAND)** – sand, minimal macroalgae present, appeared less textured and generally deeper or in more sheltered areas than kina
- **Shallow mixed algae (SMA)** – mixed macroalgal species, ~0-5m depth, appears more of a brown / lighter green when images are stretched
- ***Caulerpa flexilis* (CAU)** – *C. flexilis* present, typically in areas with sand nearby, similar colouring to other macroalgal species

Ground truth images were used as an initial guide to gauge what each substrate looked like in the 2019 aerial images for both sites. Not all the drop camera or geo-tagged diver images were referred to for every site across all locations, to allow mapping to be based off the primarily from the aerial photos and so the ground truth images could be comfortably used in the accuracy assessment and results would not be skewed.

Aerial images were adjusted using the stretch tools to increase contrast and define the substrates. With the substrates defined, classes were mapped in sections moving around the location, to result in the full extent of the islands being digitised. The polygon and autocomplete polygon tools were used to digitise the habitat maps, with vertices adjusted as necessary. Images were zoomed in to the source resolution, and substrates were mapped to a scale as fine as possible. Any areas disrupted by shading, glare or where it was otherwise difficult to define the substrate were moved past initially, to return to after the area was completed and there was more of an idea of what substrate would be expected to be there. For these areas reference was made to secondary images of the same site, for example switching to the 2018 Hauturu and Noises satellite images, or extra historic imagery that overlapped the site but may have not been used as the primary image for other quality reasons.

Once the shoreline was mapped in the first image, this was exported to the next shapefile to be used as the shoreline for the images that followed. If any rocks or sections of the land did not line up with the initial shoreline, the ‘adjust vertices’ or the ‘move feature’ tools were used to align these to the next image. The clearest imagery for each site was used to map the outer edge of the reef where the sand started, and this ‘reef extent’ ring was used to match up the outer extents of *E. radiata* or kina barren for the following years. After the completion of each map, small and separated neighbouring polygons of the same substrate were merged to create one larger polygon.

2.3.1 Hauturu

The 2018 and 2019 satellite images were georeferenced to the 2010/2012 LINZ images to ensure they were aligned. The 2019 images were used for the mapping process, except for areas where cloud coverage or shading from cliffs was an issue, in which case the 2018 images were used in substitute. The 2019 data was prioritised as this was closer to the dates the drop camera images were collected. Images were digitally balanced, enhancing contrast between classes and allowing for easier recognition of bottom types at depth.

Reef (shallow mixed algae (SMA), *E. radiata* or kina barren) was mapped to where the edge meets sand or deep reef, or to the point where the water became optically deep and it was no longer clear which substrate covered the bottom, so could not be defined if it was reef or sand. This marked the edge of the 'mapped reef' with the depths defining the border of this taken from the drop camera images recordings.

Specific sections of the historic images were selected to map, focusing on where there was the least impact from glare on the water, allowing for accurate mapping, with attention to relevant points of particularly high or low noticeable change.

2.3.2 Noises

The 2019 and 2018 satellite images were georeferenced to the 2012 LINZ image to ensure they were aligned and that they would match the geotagged diver images. Of the two images the 2019 image was of higher quality, but the extent only covered Motuhoropapa and Otata Islands, not Maria Island. Therefore, the 2019 image was used primarily for mapping Motuhoropapa and Otata Islands, but because the extent of the 2019 image did not reach Maria Island, the 2018 image was solely used here instead. Reference was made to the 2018 image around Motuhoropapa and Otata Islands for any areas where shadows or glare on the water was an issue.

2.3.3 Historical imagery and mapping

Historic aerial images were downloaded from Retrolens with the NZGD 2000 New Zealand Transverse Mercator spatial reference. The images used for the Noises were taken 02/01/1978, and for Hauturu the images were taken on 24/10/1953 and 24/10/1979. These were georeferenced to the 2012 images downloaded from LINZ, also with the NZGD 2000 New Zealand Transverse Mercator spatial reference.

The years 1953 and 1979 were chosen for comparison to the 2019 imagery because as well as being the highest quality historic images available, they were spaced across time in relatively even intervals through to present day. By having 1953 imagery as a baseline before the launch of commercial fisheries in the Hauraki Gulf, and imagery from 1979 to contrast soon afterwards this point, this provides a good idea of what impacts increased fisheries may have had on urchin barren extent.

Because the historic images for both 1953 and 1979 were not of adequate quality to map the entirety of Hauturu, a section was chosen where both years were of consistent quality and where the deep reef edge could be clearly identified, allowing for comparison with the current imagery. The area selected that fit this criteria was the western coast, where there was minimal glare or shadowing from the land, and clear water clarity.

The 1978 Noises imagery was of adequate quality to map around the entirety of Motuhoropapa, Otata and Maria / Ruapuke Islands. As with the 2019/2018 islands, the northern extent was mapped to the edge of the reef extent, or where the water became too dark to satisfactorily classify the substrates.

Historic maps were created with the same methods and habitat classes as the current day maps, with the relevant substrates manually digitised where they were found. The reef extent from the clearest images was used across each of the following maps. A difficulty found with mapping historic imagery is the lack of ground truth data for the sites, beyond what is stated in past literature. This means that as well as accuracy assessments not being able to be run, drop camera or diver imagery could not be used as an initial reference while mapping. However, based on previous descriptions the broad reef habitat seems to be comparable and can therefore assumed to represent the same broad habitat types.

2.4 Statistics

2.4.1 Accuracy assessment

The categorised drop camera and geotagged diver images were used as ground truth points to perform an accuracy assessment of each of the digitised 2019 maps from Hauturu and the Noises (fig. 6, fig. 7). Ground truth points classified as ‘OTHER’ or ‘NC’ were not included in the accuracy assessment process, neither were points overlapping what was classified as ‘LAND’ or ‘INT’. A strict accuracy assessment was run, which compares the classified substrate to the ground truth data at the exact GPS coordinates of the ground truth image. This assessment style does not account for any error in the GPS tagging of the ground truth data as a radiused approach would, where the point is deemed accurate if the corresponding substrate is within a close vicinity. Therefore, any georeferencing or geo-tagging issues will have an influence on the accuracy.

2.4.2 Area of mapped habitat types

For each of the maps produced, four for Hauturu (1953 comparison area (CA), 1979 CA, 2019 CA, 2019 full extent) and two for the Noises (1978 full extent, 2019 full extent), the shapefile data was exported to an excel sheet. Here the area mapped for each substrate was combined, giving us the total area mapped around the site of that substrate. The shallow mixed algae (SMA), *E. radiata* (ECK) and kina barren (KINA) classes were combined to give a total area of mapped reef, so the overall percentage of kina barren could be calculated. This encompasses the areas where there is the potential for seaweed to grow, or for kina barrens to form, while excluding sand or cobble areas. This percentage of barrens on reef was used to compare the extents of barrens over time.

2.4.3 Extent of urchin barrens vs wave exposure

Wind fetch is the distance across water that wind can blow, which we used here as a proxy for wave exposure. For each transect being analysed the individual fetches from the north, east, south and west were used to calculate the average fetch for the site, using the fetchR package in the statistics programme R (Seers, 2020).

Using drop camera images from around Hauturu the extent (%) of each reef habitat type was calculated for each of the 28 transects, and this was plotted against the average fetch of the transect. A linear regression analysis was completed for each of these comparisons to assess if the relationships were significant.

The maximum and minimum depth of kina barrens was also recorded along each transect, and this plotted against the average fetch. A linear regression analysis was completed for the relationship between wave exposure and the upper (shallower) extent of barren, and a second linear regression analysis was completed for the relationship between wave exposure and the lower (deeper) extent of barren.

3.0 Results

3.1 Hauturu

3.1.1 Hauturu in 2019

A total area of 20.85km^2 of seafloor was mapped around Hauturu, to an estimated depth of ~20m. This included 9.02km^2 of reef. In 2019, kina barrens covered 32.73% of the reef, with the remaining reef split between 50.34% of *E. radiata* and 16.93% of shallow mixed algae (fig 8).

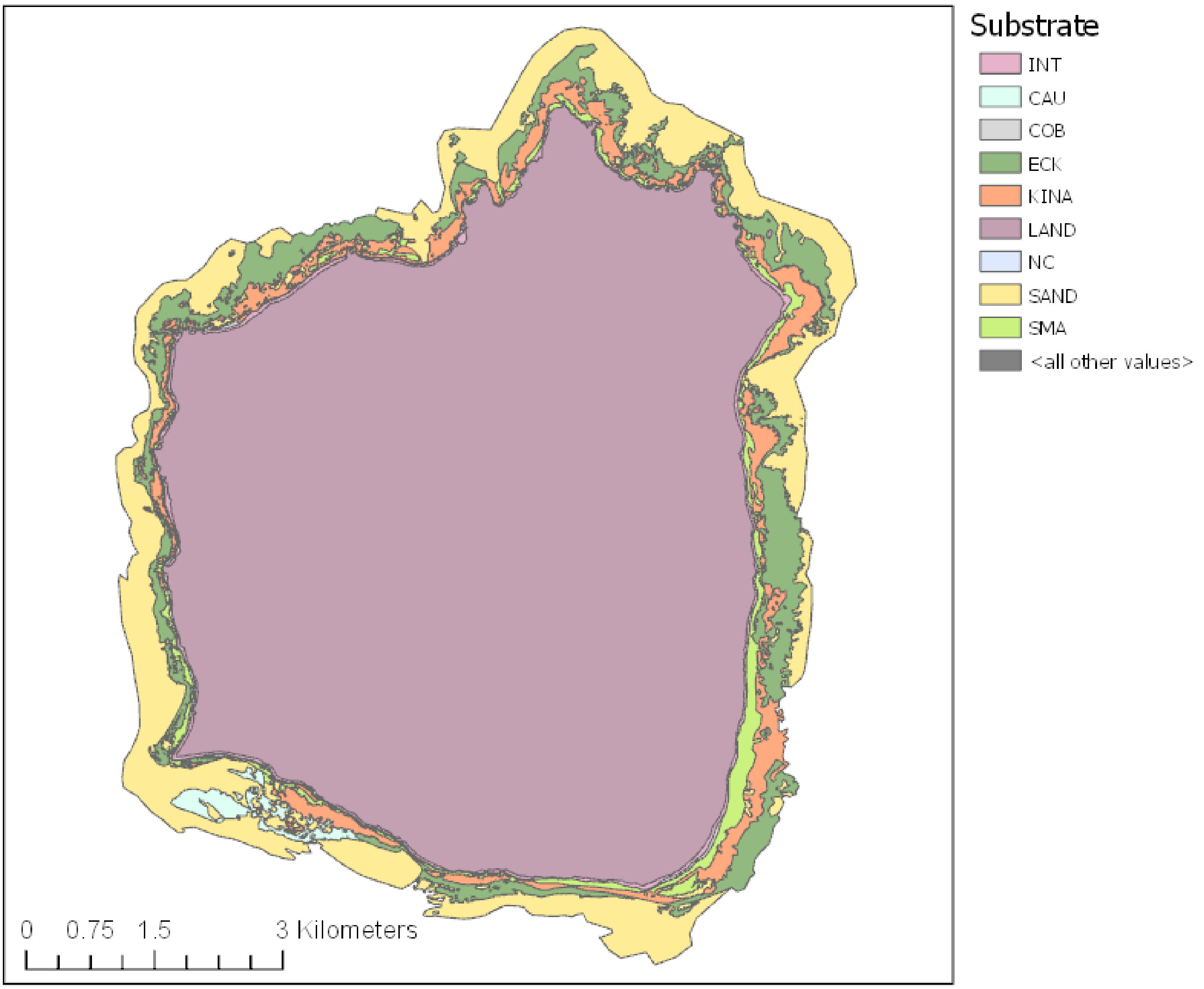


Figure 8 – Hauturu-o-Toi, showing the substrates mapped around the coastline using 2019 imagery

In general, urchin barren was found mainly between 3 and 7m depth, with some areas extending down to 14m. The largest barren areas were found around the northern and eastern coasts, mostly from depths of 3 to 7.5m, with some barren points reaching 14m to 23m depth. There is less barren extent on the western coast, mostly covering from 3 to 6m depth, with the deepest barren areas reaching up to 8m.

However, because the reef does not extend as far out from the coastline on the western and southern coasts, up to ~200m offshore, when compared to the eastern and northern coasts, up to ~500m offshore, this results in the largest stretches of kelp bed also being found on the northern and eastern sides.

The lower limit of *E. radiata* was determined by the reef edge and was typically found between 5 and 12m depth, while some points saw this extend to 20m, such as on the north eastern corner. On the western and southern coast, we see *E. radiata* mostly between 4.5 and 9.5m depth, with some points reaching up to 16m on south-eastern end. The northern and eastern coast however saw *E. radiata* mostly from 8 to 15m, with some points reaching 20m on the northern end.

SMA was typically found down to a depth of 5m, mostly between 1.5m and 3m but with some areas reaching 6.5m depth. This was fairly consistent around the island, if a slightly deeper extent on the more exposed eastern coast, mostly between 1.5 and 2.5m on the western coast, with the occasional points to 4-6m, and mostly between 1.5 and 3m on the eastern coast, with more points reaching the 5.5 – 6.5m mark.

Much of the island had cobble immediately off the beach, followed by an area of shallow mixed algae (SMA), which then either led to *E. radiata* (ECK) or into kina barren (KINA). Kina barren was either followed by a stretch of *E. radiata* or led straight to sand. *Caulerpa flexilis* beds were found off the south western point of the island, where there is a large sandy expanse.

3.1.2 Comparison over time at Hauturu

Adequate aerial imagery was only available for the long-term comparisons along the west coast and a section of the southern coast of Hauturu. Two analyses were run, one including the southern side of Te Titoki Point, and a second only including the coastline north of this point, due to potential unreliability of the southern area.

When looking at the entire area, the 1953 Hauturu analysis showed a dominance of kelp and absence of barrens, which were estimated to cover 0.4% across 1.65km^2 of the reef (KINA + ECK + SMA). For 1979 this increased to 11.6% across 1.71km^2 of mapped reef with a distinctive band of kina barrens evident along the western coast. This increased again to 32.3% of kina barren across 1.32km^2 of mapped reef in 2019, within the comparison area (fig. 9, fig. 10).

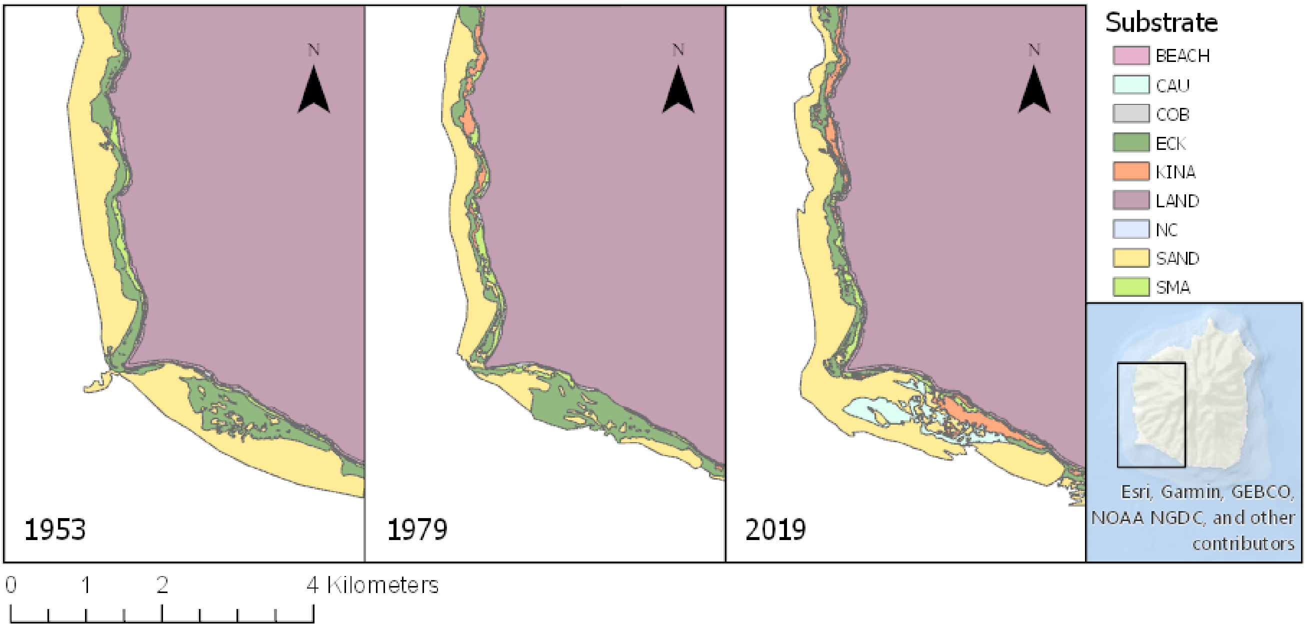


Figure 9 - Substrates within the comparison area, showing 1953, 1979 and 2019 from left to right. See appendix for enlarged version.

Figure 10 - Changing ratios of ECK: SMA: KINA between 1953, 1979 and 2019, for the western and partial southern coasts of Hauturu-o-Toi

A noticeable area of *E. radiata* loss is along the southern coast, where we can see a reduction in the kelp bed, and instead of areas dominated instead by *C. flexilis*, (fig. 11).

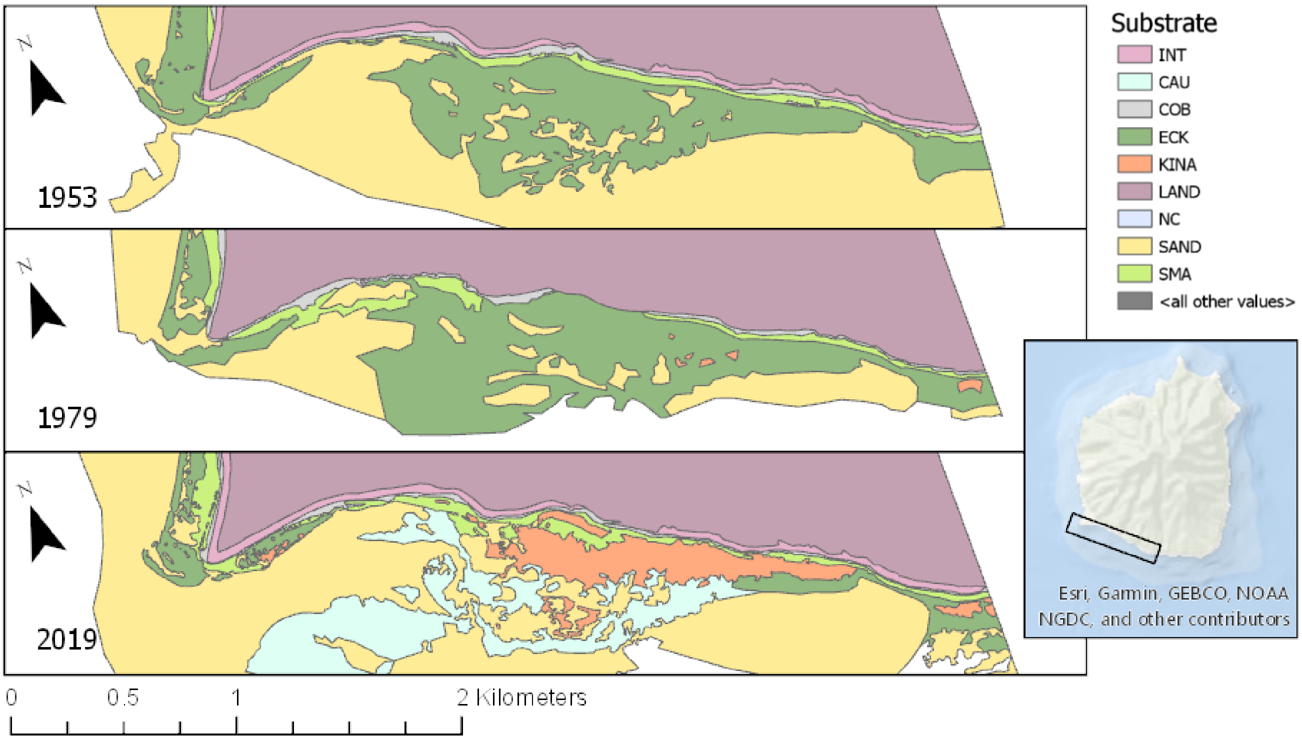


Figure 11 - South-western coast of Hauturu-o-Toi, comparing substrates in 1953, 1979 and 2019. See appendix for enlarged version.

There was shift at the northern extent of the target area, particularly between 1953 and 1979 where barren sections replaced *E. radiata*, which remained more stable between 1979 and 2019 (fig. 12). When we isolate the western coast and leave out the southern corner, taking the coastline from Te Titoki Point and upwards, we see this jump in barren extent between 1953 and 1979 more clearly (fig. 13, fig. 14).

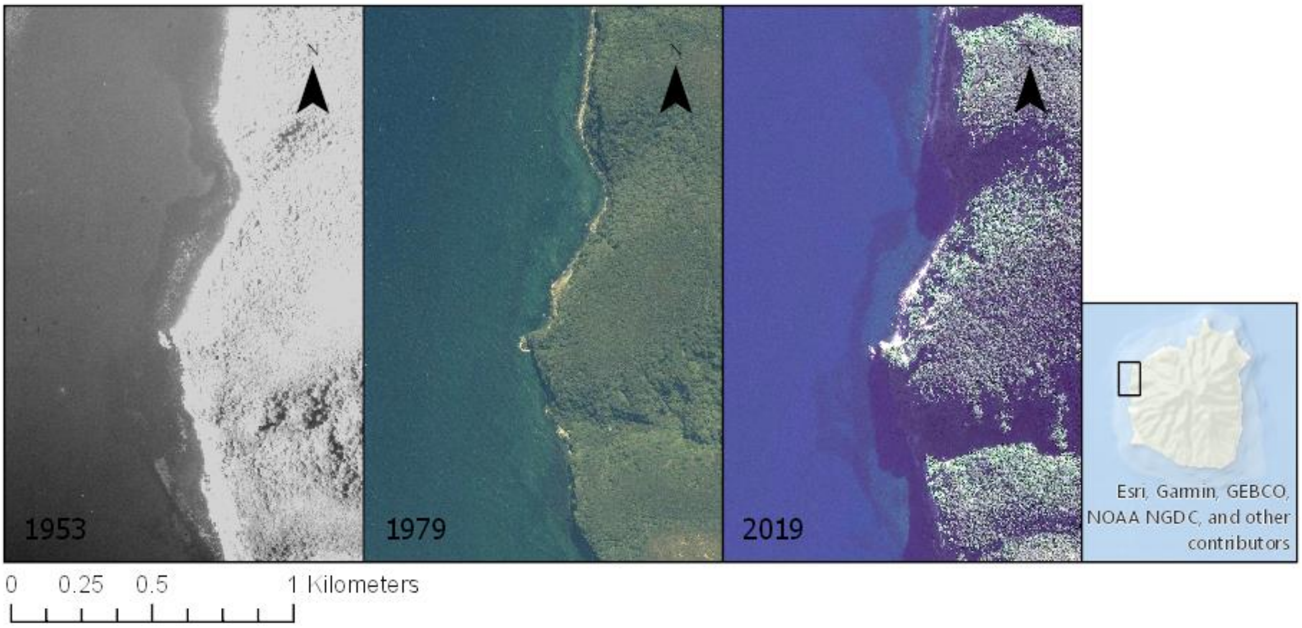


Figure 12 - Aerial images of the northern end of the west coast of Hauturu-o-Toi, with 1953 left, 1979 centre, 2019 right

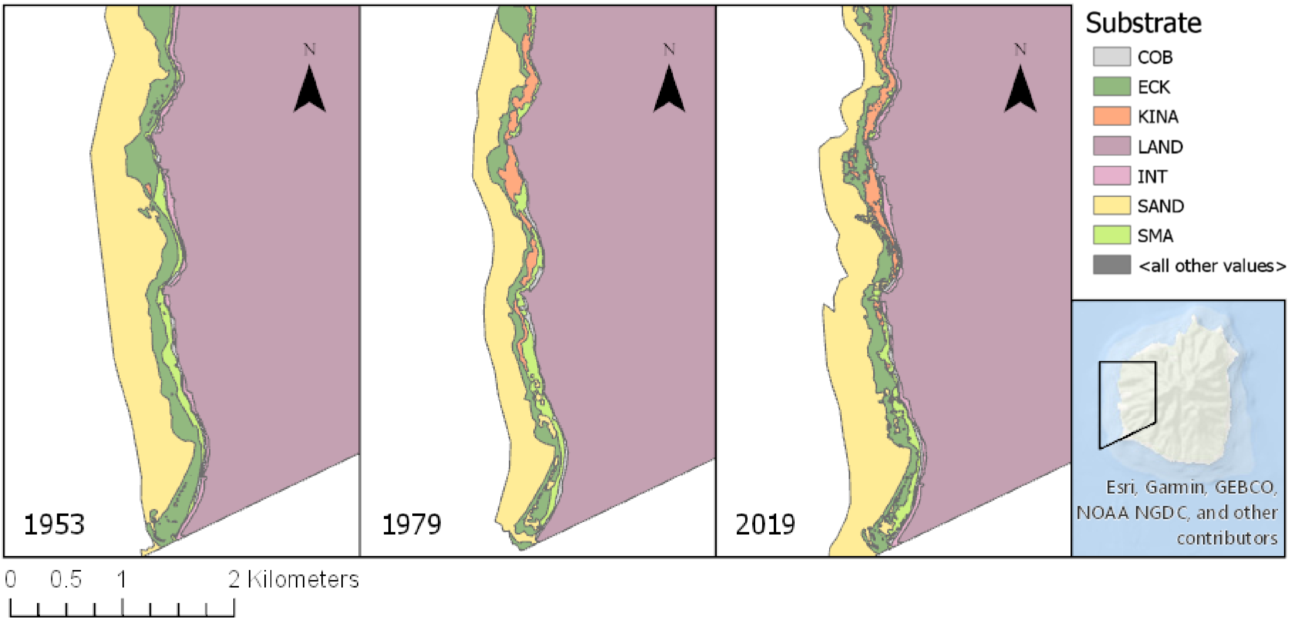


Figure 13 - Western coast of Hauturu-o-Toi, from Te Titoki Point upwards, comparing substrates in 1953, 1979 and 2019. See appendix for enlarged version.

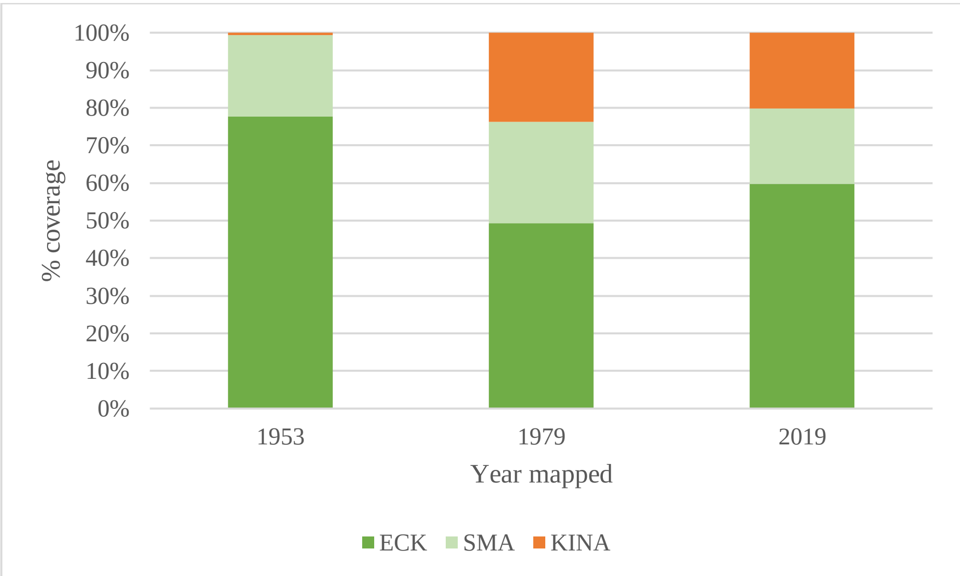


Figure 14 - Changing ratios of ECK: SMA: KINA between 1953, 1979 and 2019, for the western coast of Hauturu-o-Toi

In 1953 there was only 0.72% coverage of urchin barren over the mapped reef along the western coast, with 77.7% of the remaining reef covered with *E. radiata*. In 1979 this increases to 23.7% coverage of urchin barren, and only 49.4% *E. radiata*. However, in 2019, barren extent decreased to 20.1%, and *E. radiata* increased over 10% to a total of 59.7% coverage (fig. 14).

3.1.3 Accuracy assessment

Using 581 ground truth points, an accuracy assessment run on the 2019 Hauturu map gave a result of 79.5%.

Specific classification accuracies ranged from 53% to 87% (table 2). We can see that what was classified as *C. flexilis* was only correct 53% of the time, with the ground truth of these areas being most often sand, at 20%. This contrasts to the most accurate classification being sand, with this correct 87% of the time, while only 9% of the time was this shown with ground truth data to be *E. radiata*. *E. radiata* classifications were correct 79% of the time, and while 13% of the time this was shown to be sand, most notably was that 7% of the time this was shown with ground truth data to be missed kina barren. Kina classifications were correct 80% of the time, with most of the error coming from the ground truth being SMA.

Table 2 - Accuracy of the classifications, with percentages showing the ground truth for points were the classification was incorrect

		Ground truth					
Classified	**Accuracy**	CAU	COB	ECK	KINA	SAND	SMA
CAU	53%		13%	0%	13%	20%	0%
COB	50%	0%		0%	8%	0%	42%
ECK	79%	0%	0%		7%	13%	1%
KINA	80%	0%	1%	3%		2%	14%
SAND	87%	0%	0%	9%	3%		1%
SMA	82%	0%	5%	4%	9%	0%	

Conversely, when we look at how often ground truth data was accurately identified, we get a range of 59% to 100% (table 3). Any areas of *C. flexilis* were identified 100% of the time, while areas of cobble were only identified 59% of the time, often being miscategorised as SMA. Areas of SMA were accurately identified 74% of the time, and while it could be expected that any misclassifications would have been classed as *E. radiata* due to them both including macroalgae, SMA was miscategorised as kina barren 16% of the time. Kina barren areas were identified 85% of the time, with these being categorised as *E. radiata* and SMA 6% and 7% of the time respectively. *E. radiata* was identified 85% of the time, occasionally being misclassified as kina, sand or SMA.

Table 3 - Accuracy of identifying a substrate, with percentages showing what the true ground cover was misclassified as

		Classified					
Ground truth	**Accuracy**	CAU	COB	ECK	KINA	SAND	SMA
CAU	100%		0%	0%	0%	0%	0%
COB	59%	9%		0%	5%	0%	27%
ECK	85%	0%	0%		4%	7%	4%
KINA	82%	1%	1%	6%		2%	7%
SAND	79%	2%	0%	13%	3%		0%
SMA	74%	0%	8%	1%	16%	1%	

3.2 Noises

3.2.1 Noises in 2019

Of the 1.1km^2 of total substrate mapped around the Noises Islands to a depth of ~15m, 0.49km^2 of this was mapped reef (SMA + ECK + KINA). In 2019 there was 49.5% of kina barren coverage, with the remaining reef split between 40.7% of *E. radiata* and 9.8% of shallow mixed algae (fig. 15). Substrates were mapped to the edge of the reef line on the northern extents of the islands, at ~12-14m, but the area beyond was not classified as with glare and the optical drop off with depth, the substrates could not be accurately identified.

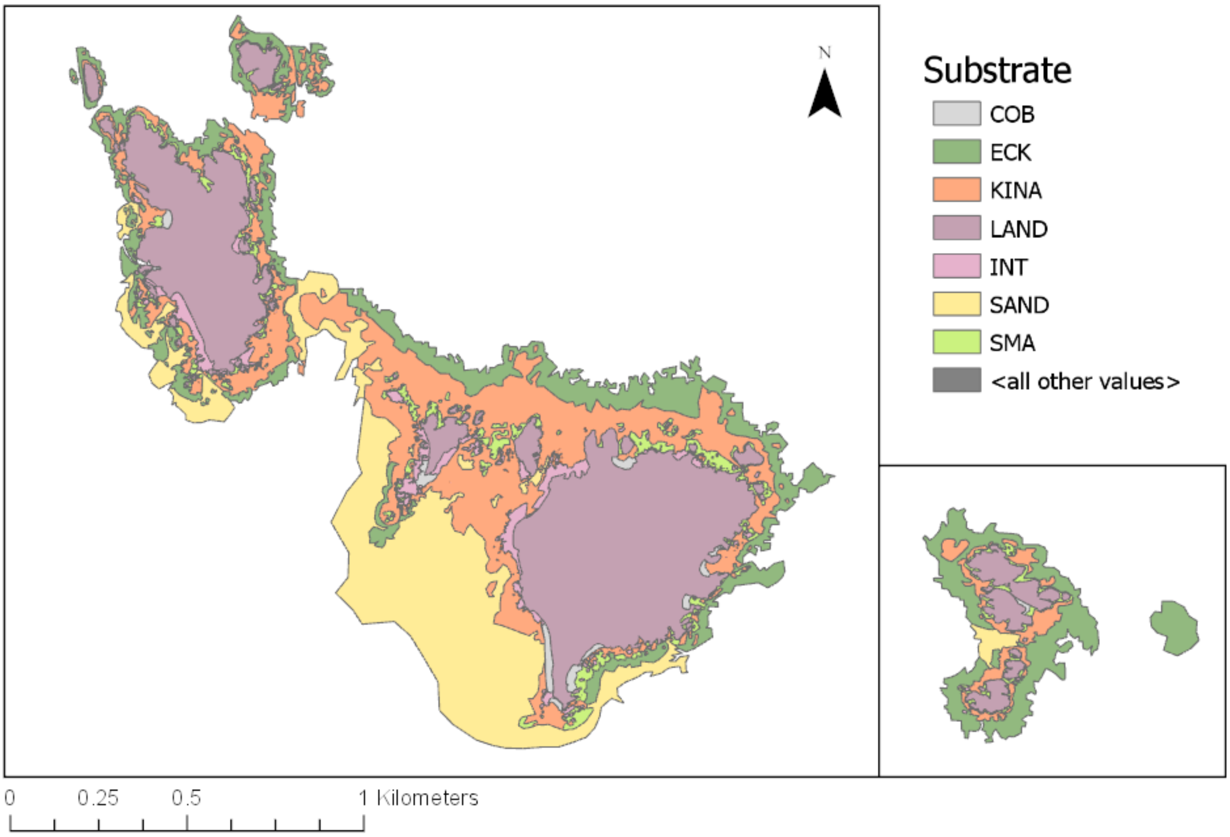


Figure 15 - Motuhoropapa Island, Otata Island and Maria / Ruapuke Island with 2019 mapped substrates

While the barren areas are found around all sides of each island, they are found most extensive and extend deeper on the northern facing coastlines, to ~7m depth. Reefs were less extensive and shallower, to ~2-4m, on the more sheltered southern facing sides with large sandy areas, where the northern and eastern sides had less sand but more *E. radiata.* Reef extended to 10-15m on the more exposed coasts, while reef extended to only ~5m depth where sand then filled in on the more sheltered southern / western facing coasts.

E. radiata was typically found between 2 and 8.5m depth, with some points reaching past 14m. Urchin barren was typically found between 1.5 and 4.5m depth, with some areas as deep as 7.5m. SMA was found down to a depth of 5.5m, although mostly between 0.5 and 3m.

3.2.2 Comparison across time

The areas being compared from the Noises Island group encompassed the main islands Motuhoropapa Island and Otata Island, as well as Maria / Ruapuke Island to the south-east. In 1978 there was a coverage of 23.97% of kina barren across 0.48km^2 of mapped reef, expanding to 49.52% of 0.49km^2 in 2019 (fig. 16 - 19).

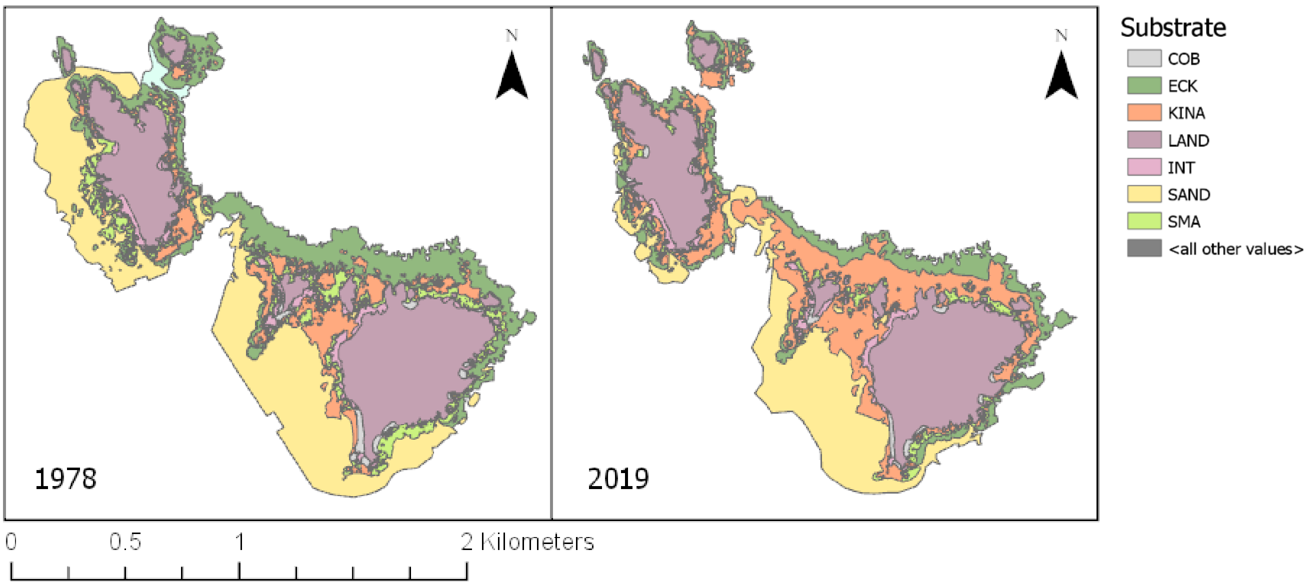


Figure 16 - Coverage of each substrate around Motuhoropapa Island (left) and Otata Island (right), from 1978 to 2019

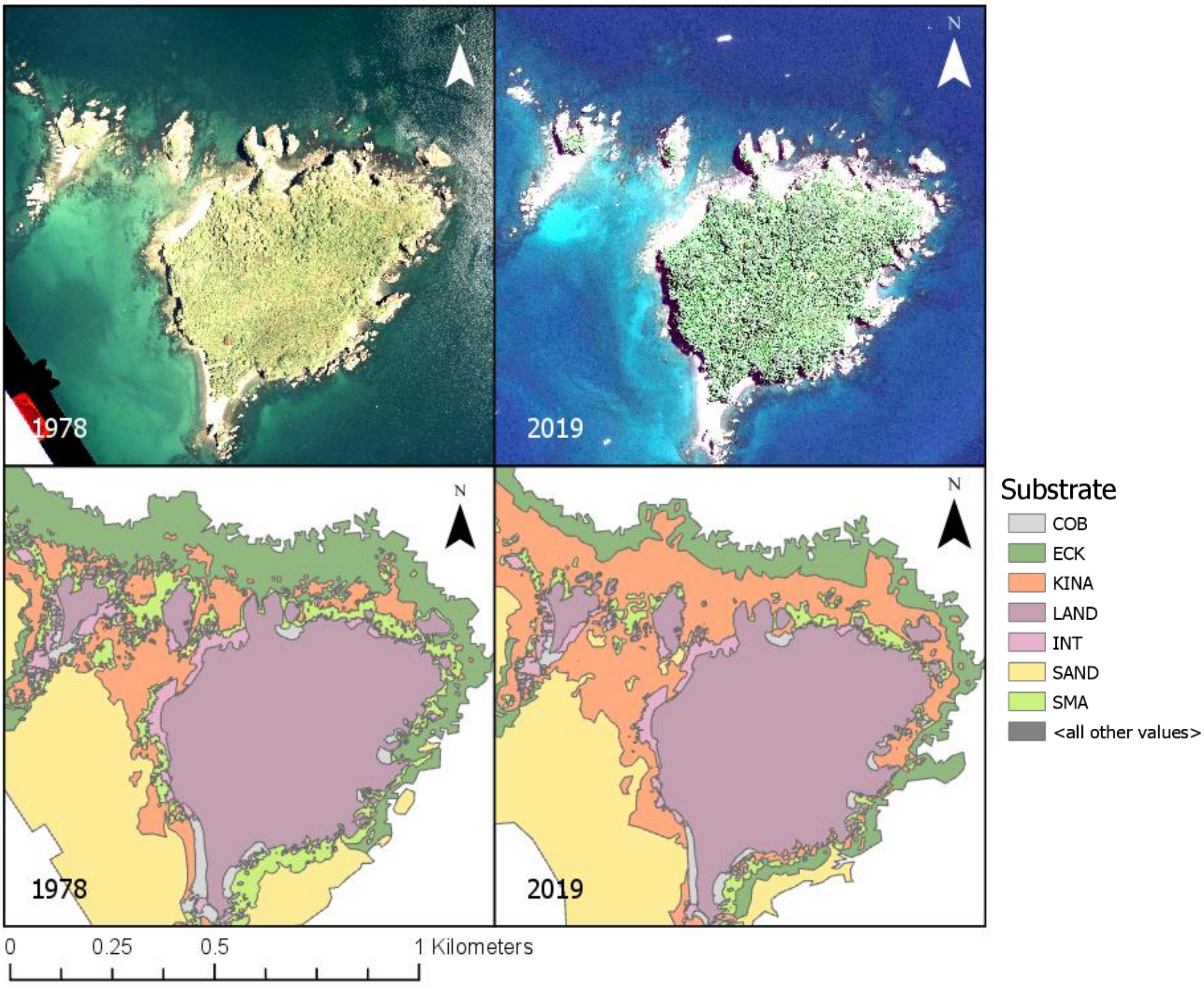


Figure 17 - Otata Island, corresponding aerial images (1978, 2019) shown above the resulting map

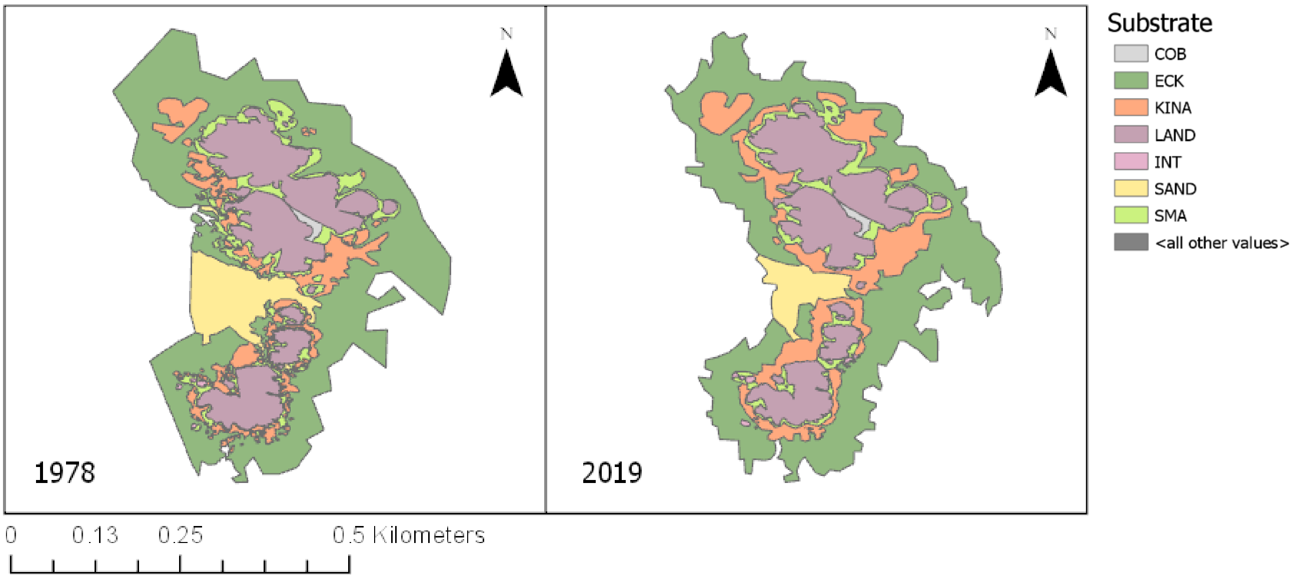


Figure 18 - Coverage of each substrate around Ruapuke / Maria Island, from 1978 to 2019

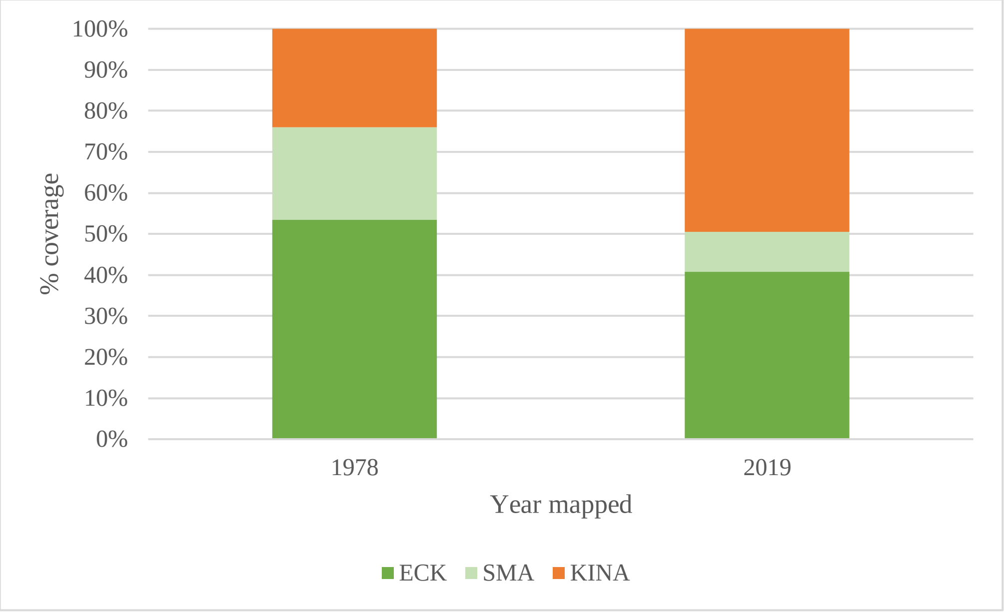


Figure 19 - Changing % of ECK: SMA: KINA between 1978 and 2019

There is a sizeable increase in the extent of barren on the northern side of Otata Island, with less extreme but still sizeable expansion of barren on the northern and eastern sides of Motuhoropapa Island. Where in 1978 the northern side of Otata Island only saw barrens along the shallow edge of the reef, by 2019 this had expanded to over halfway across the northern extent of the reef. Areas in the shallow, central section of Otata Island consistently remained urchin barren across the comparison. Where the eastern side saw very little urchin barren in 1978, we can see barren areas starting to appear in the shallows, particularly on the northern end of the east coast. Maria Island saw the barrens on the western side and in the centre remain relatively steady from 1978 to 2019. However, the barren areas particularly on the north-eastern side had notably expanded or switched completely from areas that were previously fully kelp.

3.2.3 Accuracy assessment

632 ground truth points were used for the accuracy assessment run on the 2019 Noises classification, with a resulting 67.9% accuracy, with individual accuracies for *E. radiata*, kina and SMA sitting at 62%, 75% and 54% respectively.

Because none of the ground truth points fell over areas that had been mapped as sand (SAND) or cobble (COB), there is no individual accuracy included for the classification of these substrates (table 4). Intertidal areas (INT) were also excluded from the accuracy assessment. We can see that SMA had

54% accuracy, with most of the misclassification being areas of kina, at 30% of the area mapped as SMA. 13% of what was classified as SMA was *E. radiata*, with the final 3% being cobble. Areas of mapped *E. radiata* were 62% accurate, with 25% of incorrect areas being SMA. While it could be expected that most error in SMA and *E. radiata* would be for the other, as they both are macroalgal substrates, it is interesting to note that while this is the case for the *E. radiata* classifications, misclassified SMA was more than double as likely to be kina than *E. radiata*. Kina was the most accurate classification at 75%, with equally 11% of area being *E. radiata* and 11% SMA.

Table 4 - Accuracy of each classification, with percentages showing the ground truth for points where the classification was incorrect

		Ground truth				
Classified	**Accuracy**	COB	ECK	KINA	SAND	SMA
ECK	62%	0%		10%	4%	25%
KINA	75%	3%	11%		0%	11%
SMA	54%	3%	13%	30%	0%	

Conversely, when looking at how accurately the ground truth areas were identified, we can see that accuracies range from 0% through to 75% (table 5). Areas of cobble were not correctly mapped for any of the ground truth points, with the majority, 82%, being classed as kina. Areas of *E. radiata* were correctly identified at 75% of ground truth points, with 21% being classed as kina. Ground truth points classified as kina were correctly identified 68% of the time, with 25% of the points being incorrectly classified as *E. radiata*. Sand and SMA ground truth points were both frequently incorrectly classified as *E. radiata*, at 90% and 46% respectively, while 32% of SMA was also incorrectly classified as kina.

Table 5 - Accuracy of identifying a substrate, with percentages showing what the true ground cover was misclassified as

		Classified			
Ground truth	**Accuracy**	ROCK	ECK	KINA	SMA
COB	0%	0%	0%	82%	18%
ECK	75%	0%		21%	4%
KINA	68%	1%	25%		6%
SAND	0%	0%	90%	10%	0%
SMA	20%	2%	46%	32%	

3.3 Relationship between kina barrens and wave action effect

Percentage coverage of each reef habitat was compared between each of the Hauturu drop camera transects, to assess whether exposure to wave action influenced the extent of kina barrens (fig. 20, fig.

21, fig. 22). Transects 16 to 28 on the north and east coast were the most exposed, with transects 1 to 15 on the west and south coasts being more sheltered.

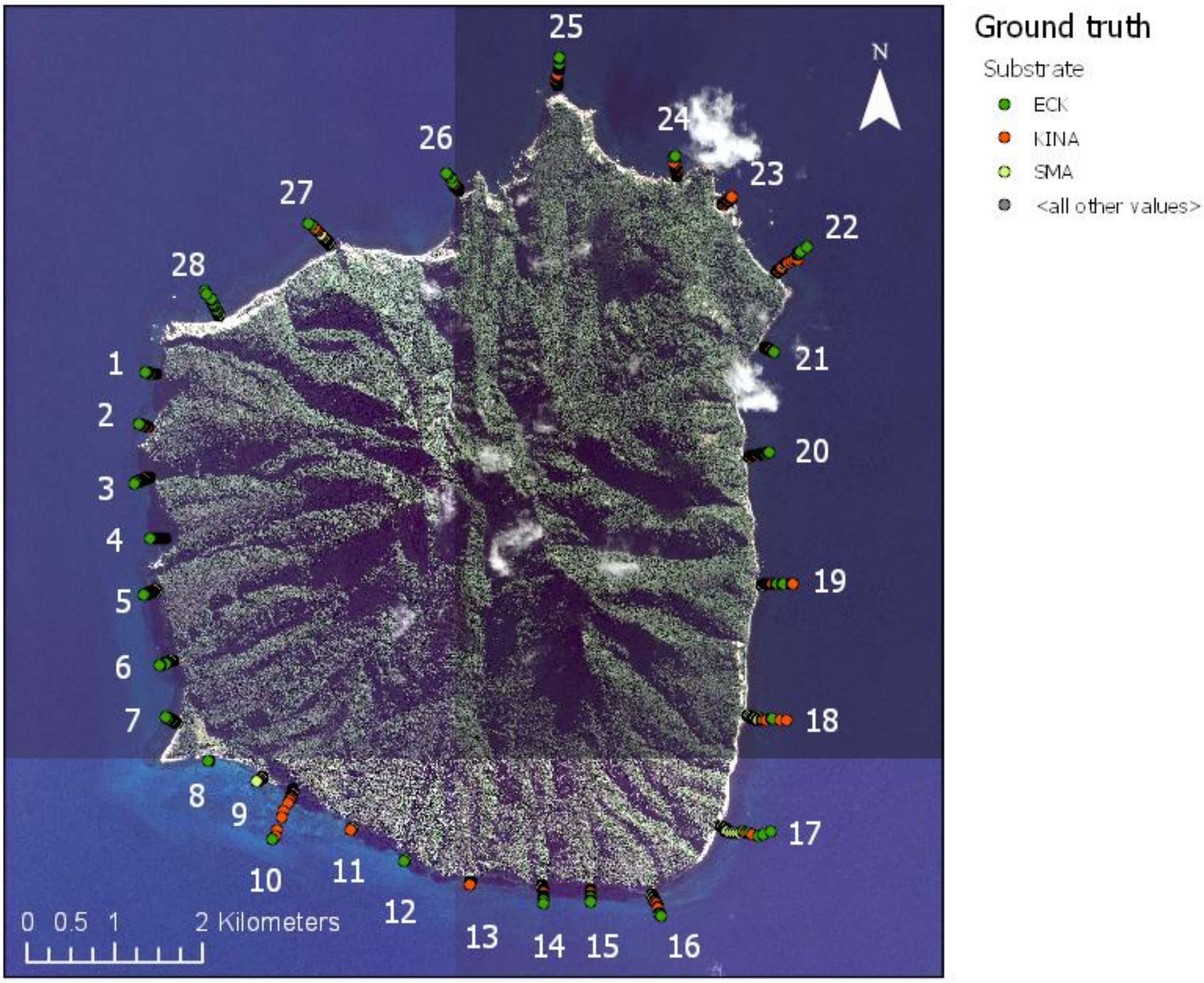


Figure 20 - Labelled transects around Hauturu-o-Toi, points colour coded to show kina barren, E. radiata and SMA

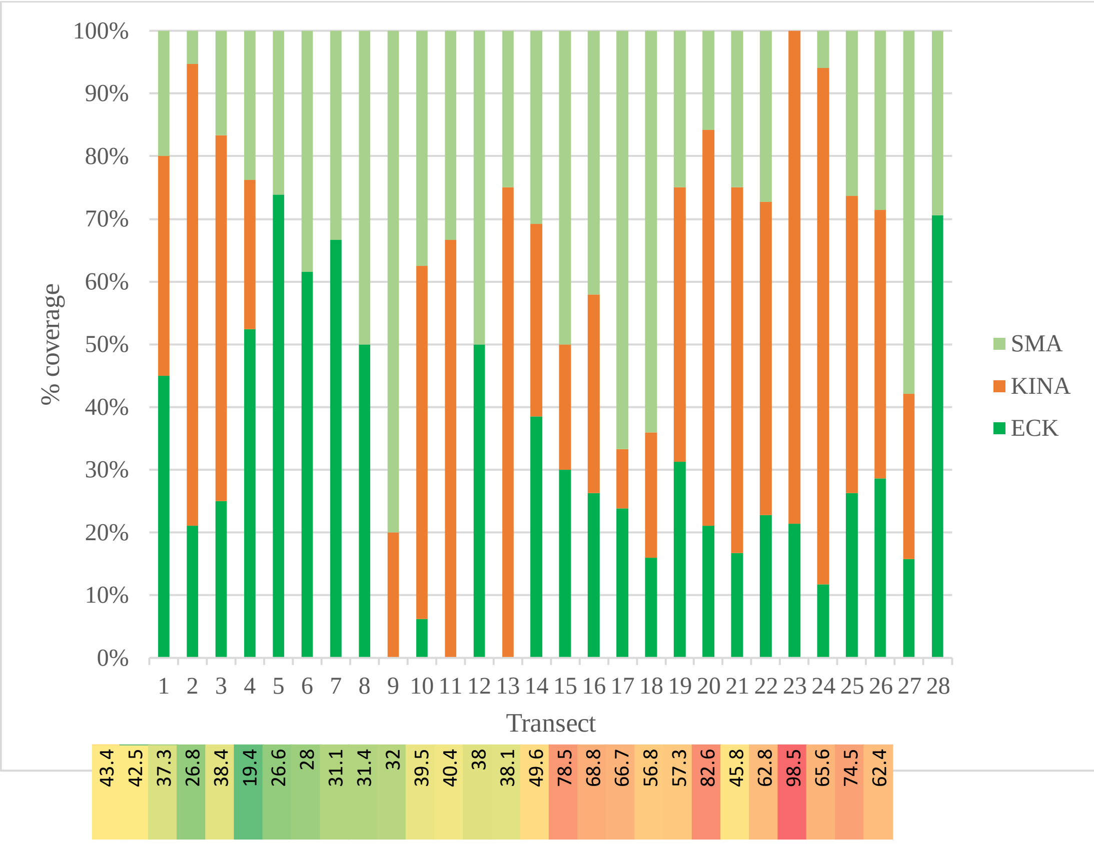


Figure 21 - % coverage of SMA, kina barren and E. radiata across each of the 28 transects taken around Hauturu-o-Toi. Bar underneath shows the average fetch for each transect, colour coded with green for most sheltered and red for most exposed

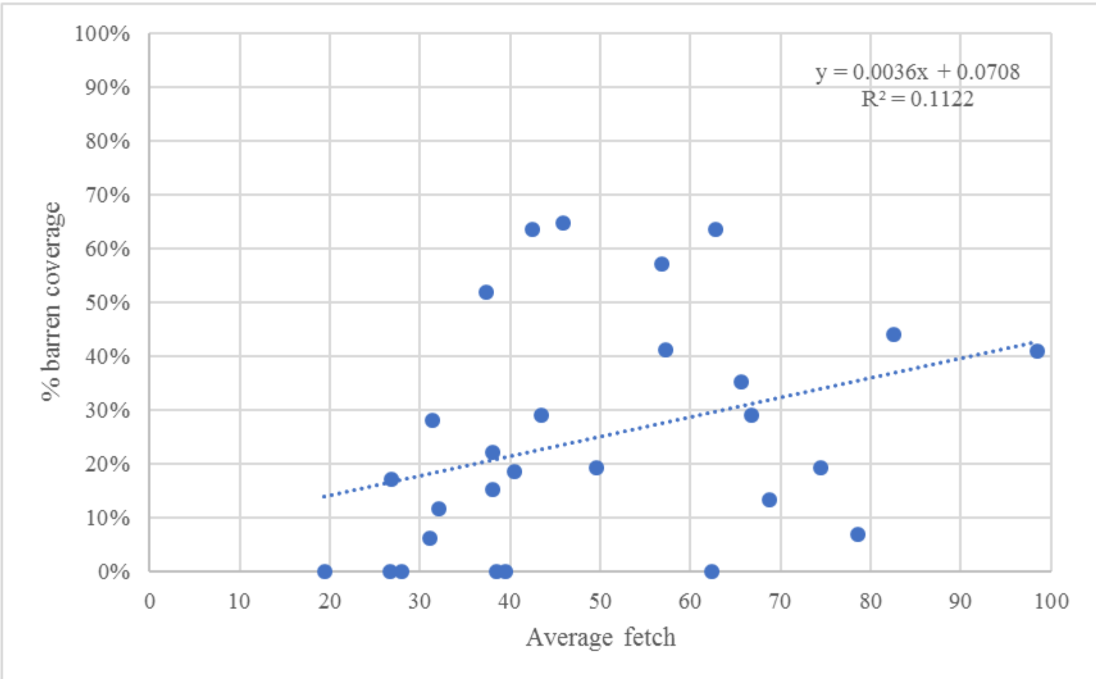


Figure 22 - Average fetch against % coverage of kina barren along each of the 28 transects

The % coverage of barren along each transect was highly variable but it was positively related to fetch. This gives an R^2 value of 0.1122, with some variability seen in the spread between the points. The p-value is 0.082, which is not <0.05 so we cannot reject the null hypothesis that there is no relationship between the average fetch and % barren coverage.

The upper (shallower) and lower (deeper) extents of barren plotted against the average fetch of the transect shows a pattern of increasing extent as exposure increases, as well as barren shifting overall deeper (fig. 23). The upper extent can be seen to get deeper slightly as exposure increases, with a gradient of 0.027 and an R^2 value of 0.0693, while the lower extent is also getting deeper but with a steeper gradient of 0.115 and an R^2 value of 0.1907. The p-value for the upper extent of barren depth is 0.237, which not <0.05 so we cannot reject the null hypothesis that there is no relationship between the average fetch and the upper depth of barrens. The p-value for the lower extent of barren depth is 0.042, so we can reject the null hypothesis that there is no relationship between the average fetch and the lower depth of barrens.

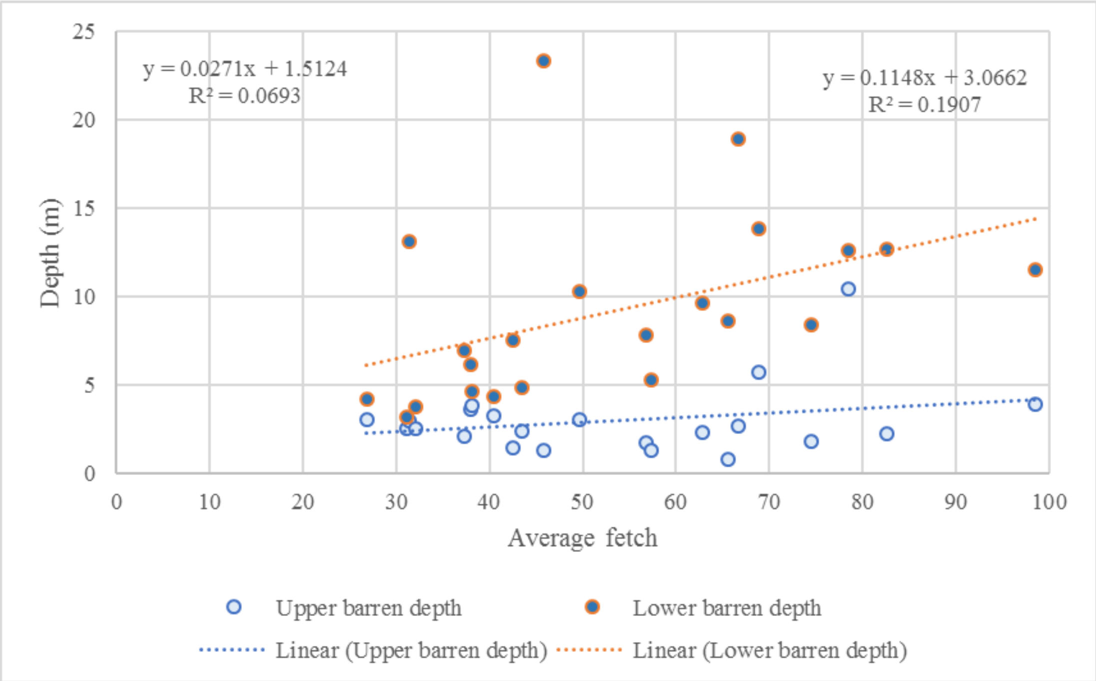


Figure 23 - Upper and lower extents of urchin barren against average fetch for sites where barren occurred

4.0 Discussion

The mapping undertaken in this study indicated that kina barrens are now extensive at both locations, furthermore, from the maps produced, we can see that in the 1950's urchin barrens were practically non-existent at Hauturu, which is consistent with other areas where long term comparisons of aerial imagery have been made, such as at Mimiwhangata and the Bay of Islands.

Mimiwhangata, an area halfway between Whangarei and Cape Brett had been previously mapped in 1973 and 1981, and Kerr & Grace (2005) built on these to produce updated maps as a result of investigations between 2001 and 2004 and images sources from the years 1993 and 2003. These were then compared to an image series from 1950, 1951, 1959 and 1961 of the same sites (Kerr & Grace, 2005). Like what we have seen in the Hauturu images, they saw nearly full macroalgal cover in the 1950's, and a continuous decline in *E. radiata* in the years since (Kerr & Grace, 2005). Kerr & Grace (2005) found that urchin barren had been extending shallower into areas of shallow mixed algae, and deeper into areas of *E. radiata*, the same pattern we have witnessed.

Various historic images were used to visually assess the disappearance of *E. radiata* around the Bay of Islands, with the conclusion that there is no valid explanation other than overfishing leading to increased urchin abundance, which have since eaten through the kelp beds (Booth, 2015). Images showed dense kelp across reefs in the 1940's and 1950's, receding kelp from the 1970's and onwards, and only fringing kelp remaining in the years since up until present day (Booth, 2015). This further backs the patterns we have seen at Hauturu and the Noises Islands.

These maps produced for Hauturu and the Noises Islands also go to show that by the 70's urchin barrens were common in areas of north-eastern New Zealand. This is supported by the first quantitative descriptions of rocky reefs produced around this time (Choat & Schiel, 1982). Since the 1970's the extent of urchin barrens has remained relatively consistent at Hauturu and expanded at the Noises Islands.

4.1 Accuracy

The overall accuracies of our maps were 79.5% for Hauturu, and 67.9% for the Noises Islands. We can compare this to studies that have done habitat classifications of similar scopes and detail using aerial and satellite imagery to assess whether our accuracies fall within an acceptable range.

In the 2020 study by St-Pierre & Gagnon, the accuracy of their visual classification was 90%. However, because they only had the classes of 'kelp' and 'not kelp', we can expect their accuracy to be higher than what we would have with more detailed substrate groups.

In their coarse habitat maps, Mumby & Edwards (2002) had overall accuracies between 67% and 75%, with their medium level habitat maps around 64% overall accuracy. Their coarse level analysis included 4 habitats: coral, macroalgae, seagrass and sand, with their medium level analysis including 8 categories (Mumby & Edwards, 2002). Our substrate maps included 6 main categories, so it could be expected that our accuracies would fall in the middle of their range. They also used 3-band imagery, looking at a similar depth range of up to 20m, however the water clarity at their sites in the Turks and Caicos Islands was significantly clearer than what is found in the Hauraki Gulf, with a horizontal Secchi distance greater than 50m (Mumby & Edwards, 2002). This would make it significantly easier to determine substrates through the water.

Leleu et al. (2012) mapped their sites at Leigh with similar substrate classes to our own, therefore if successful, we can expect our accuracies to align with these. The methods they used for accuracy assessments were slightly different, using a 10m radiused approach to mark a point as correct if the substrate was within 10m distance, which resulted in an overall accuracy of 86.6%. As our methods were stricter, the lower accuracies we have seen are likely still acceptable.

Previous studies looking at substrate classifications of a similar coarseness suggested anything over 70% accuracy is acceptable, which is promising for the accuracies we see here, with overall accuracies at 79.5% for Hauturu and 67.9% at the Noises Islands (Mumby & Edwards, 2002). As our accuracies fit within the ranges seen in similar studies, it would suggest that the accuracies of our maps are acceptable. This suggests that the mapping techniques used here have proved both efficient and effective, covering a far wider area than would be possible from in-water sampling alone. Using Hauturu as an example, ground truth data collection was completed over only 2 days for the whole island, while it would be near impossible to manually dive and map the whole coastline.

4.1.1 Accuracy of Hauturu map

With an overall accuracy of 79.5%, there are bound to be fluctuations in this value at different sites around the island. Some notable areas with low accuracy such as on the southern side of Te Titoki point, we see a decrease in areas mapped as reef substrates due to a reduction in what was classed as *E. radiata* for the 1959 and 1979 maps, replaced with *C. flexilis* in the 2019 map. Because there is such a large area of change, and that the change isn't between two reef substrates but instead one species that generally lives on a reef substrate (*E. radiata*) and one that lives in sandy areas (*C. flexilis*), this suggests that the discrepancy is likely an issue with the mapping. One reason could be that there was an underestimation of *C. flexilis* for the two historic images, or an overestimation for the 2019 image. Because of limitations around fine scale definition with the historic images, it is not unlikely that the two species could have been grouped together, as they appear visually similar from above as compared to sand or barren. Our accuracy assessments showed that while 100% of ground truth points known to be *C. flexilis* were mapped as such, the overall area mapped as *C. flexilis* was only 53% accurate, suggesting that there was an overestimation of *C. flexilis* extent. With the uncertainty around the *C. flexilis* classifications, it was for this reason that the historic comparisons looked only from Te Titoki Point and northward up the western coast.

As well as the lack of confidence around *C. flexilis* in this area west of Te Titoki Point, there is a higher rate of barren being classified than would be expected. This area is one of the most sheltered around the island, with the three transects across the section being 3/6 of the lowest fetch scores of all sites. It would therefore be expected that was this area to fit the pattern of wave exposure and barren extent we saw around the rest of the island, there would be very minimal barren here, and any found would be shallow and of marginal extent. This however is not the case and suggests that perhaps there is another factor involved such as a recent storm or dieback event that removed *E. radiata* from deeper areas of reef at this location.

The accuracy assessments also showed that 16% of ground truth images identified as shallow mixed algae were classified as kina. This could come down to problems with georeferencing, or patchiness of substrates in shallow water. Beyond this, the accuracies of the kina, *E. radiata* and SMA classifications were 80%, 79% and 82% respectively.

4.1.2 Accuracy of Noises Islands map

The overall accuracy for the Noises Islands map was 67.9%, 11.6% lower than that of the Hauturu assessment. A key reason for this is due to the water clarity at the Noises Islands, with increased turbidity making it more difficult to distinguish habitats and substrates, as well as not allowing reefs to be mapped as deep as they were at Hauturu. We can see this in that Hauturu maps reached ~20m in depth, whereas the Noises Islands maps only reached ~15m. Another factor is because we used ground truth data from 2017 and 2018 and images used for mapping from 2019, there is a chance of changes in the extent of barren or kelp beds in this time period, which could influence accuracy.

Through the accuracy assessment we can see that accuracies for *E. radiata* and for kina are similar, with 10% of incorrectly classified *E. radiata* being shown through ground truth data as kina, and 11% of incorrectly classified kina showing as *E. radiata* with the ground truth data. The biggest difference comes with 30% of the area being classified as SMA shown with ground truth data to be kina, and only 13% of the incorrect area being *E. radiata.* This is surprising in that it would be expected for most error to come from interchanging classification of *E. radiata* and SMA, as they appear similar visually with both being macroalgae. Because of this, it is possible that the 2019 map produced is underestimating the current extent of barren areas around the Noises.

Some error arose from an imperfect alignment of the GPS data from ground truth images and that from the imagery used for mapping. This can be seen in that some of the diver images appear to be taken on rocks or over land, and the depth or classification for the point does not match this, which would likely be due to issues with georeferencing of the aerial imagery (fig. 24, fig. 25).

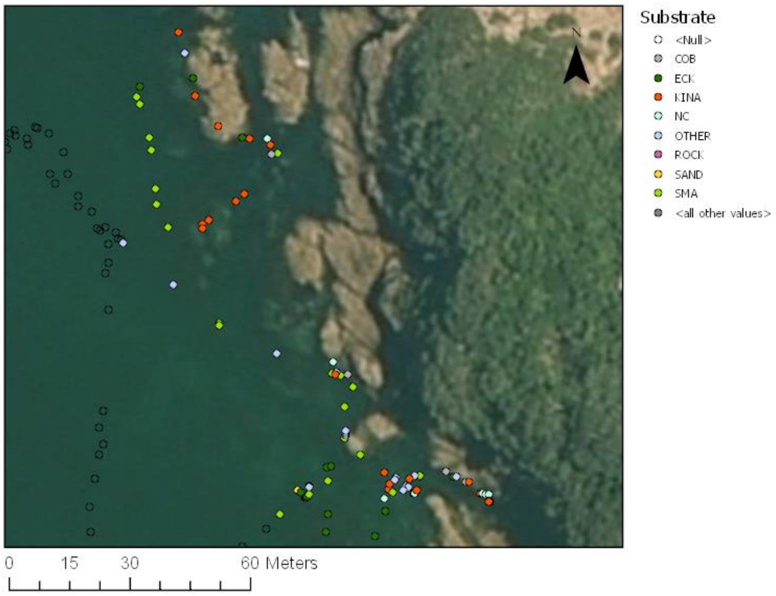


Figure 24 - Location of colour coded, geotagged diver photos used for ground truthing, overlaid on 2010 LINZ satelite imagery of the eastern side of Motuhoropapa Island

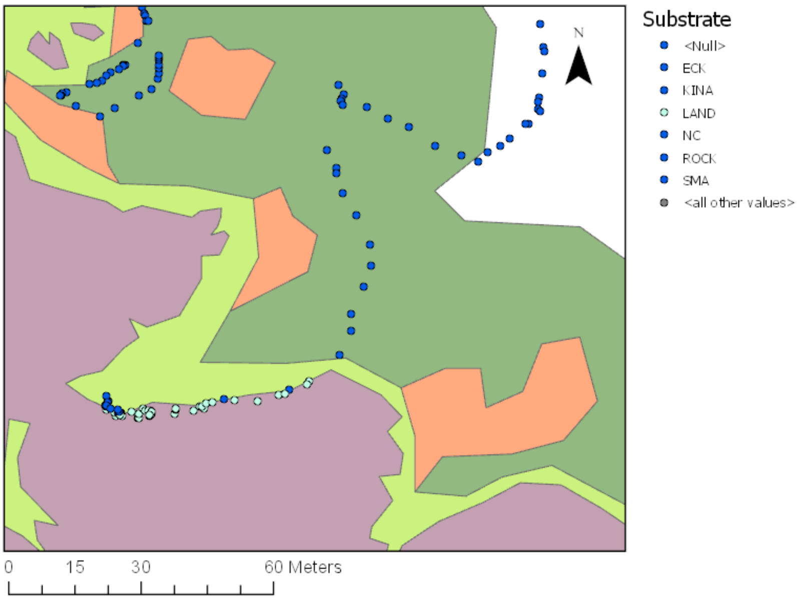


Figure 25 - Location of geotagged diver reference photos overlaid on the 2019 map of the north eastern side of Ruapuke / Maria Island, with points overlapping areas classified as 'LAND' highlighted

Differences in accuracy between Motuhoropapa and Otata Islands compared to Maria / Ruapuke Island could be due to Otata and Motuhoropapa Islands following the 2019 aerial image, while Maria / Ruapuke Island was following the 2018 aerial image which may have not been as accurately geo-referenced.

This is however only a minor shift, and the overall impression of the diver images still gives a good idea of substrate patterns to be used as a guide while digitising.

4.2 Kina Barrens in the Hauraki Gulf

Previous studies analysing kelp extent and substrates found in the Hauraki Gulf have not focused to a great extent on Hauturu or the Noises Islands. The 1983 Roger Grace study where he formed the zonation map showing the changes moving from the outer Hauraki Gulf with "clear 'oceanic' water" through to the inner Hauraki Gulf with "turbid 'harbour' water" doesn't include Hauturu or the Noises at all, instead using Castor Bay and Northcote Point as the inner gulf sites. Castor Bay sees similar environmental conditions to the Noises, however as it is on the mainland the area is more sheltered from some conditions, as well as reefs only reaching ~5m in depth (Grace, 1983). Grace (1983) claims the 'rock flats zone', which we refer to as urchin barren, is absent from the inner gulf, however this could be due to the sites chosen in this study not being physically suited for 'reef' habitat, rather than urchin barrens not existing at all across inshore sites.

Shears & Babcock (2004) also looked at the community composition of subtidal reefs, with their study area covering north-eastern New Zealand with sites from Cape Reinga to Hahei. Long Bay was used as their inner gulf sampling location, and as with Grace (1983) they found that there was low richness of algal species as well as low macroinvertebrate species richness at the inshore site (Shears & Babcock, 2004). The reef at Long Bay is a shallow, flat, sandstone reef which only extended to a maximum of 5m depth, at some points only 2m, and if this was being used to represent all inshore reef areas it is excluding many sites with a more solid, rockier reef that does extend beyond this depth, as we see at the Noises (Shears & Babcock, 2004).

From our study we can see that there is extensive barren at the Noises Islands, and therefore sites such as Long Bay as well as Castor Bay and Northcote Point are not representative of the wider inshore communities.

The main reasoning both Grace (1983) and Shears & Babcock (2004) used to explain their suggested lack of urchin barrens and kelp extent in the inner gulf is that of higher sediment and turbidity in the water, and less wave action due to being further inshore. It is possible that the Noises being an offshore island, and therefore being more exposed than these coastal locations, could prompt the growth of urchin populations and urchin barrens. Hauturu is a very useful site in this instance, because the water clarity is broadly consistent around the entire island, so we can isolate the variable of wave action and compare the effect this has itself on barren extent (see section 4.3 below).

With fishing pressures increasing dramatically for spiny rock lobster and snapper in the 1950's after the initiation of industrial fishing, there was a large decline in each of their populations in the decades following (MacDiarmid et al., 2018). This would account for the large decrease in kelp extent that we see between 1953 and 1979, with urchin barren expanding from 0.72% to 23.7% at Hauturu.

Following the introduction of the QMS in 1986, snapper populations started to bounce back, which could account for why the extent of kelp has not appeared to continue to decline in this area between 1979 and 2019 (Ministry for Primary Industries, 2013; Parsons et al., 2009; Lock & Leslie, 2007). An alternative explanation is that because urchin barrens tend to occupy a consistent depth zone that varies with wave exposure, they had already expanded into this region by the 1970's and could therefore extend no further (Choat & Ayling, 1987; Grace, 1983; Shears & Babcock, 2004). We saw 23.7% of urchin barren coverage in 1979, which remained steady, even decreasing slightly to 20.1% across the same area in 2019.

There are a variety of reasons why we could be seeing a higher overall coverage of urchin barrens across the reef at the Noises Islands than we see at Hauturu, 49.5% compared to 32.73%, despite being located further into the Hauraki Gulf than Hauturu. This is likely due to mapping not extending as deep around the Noises as around Hauturu, meaning that while barrens which occupy shallow bands were covered, areas of deeper kelp forest were missed at the Noises. This would skew the percentages in favour of barrens at this more turbid site. Alternative explanations couple include higher fishing pressures, particularly from recreational fisheries, more consistent wave exposure across the range due to the islands being smaller, and due to the presence of large, shallow areas.

Because there is no suitable imagery to use for mapping substrates from before the 1970's, we must rely on literature to understand the extent of barrens before when we could map them. While there is very little literature specifically discussing the Noises, Bergquist (1960) briefly described the algal ecology and key animal species at Otata Island and notes the presence of *E. radiata* in the upper and lower sublittoral zones, with no mention of *E. chloroticus*. This suggests a lack of barren at Otata as of 1959, and considering in 1978 and 2019 we see the most barren at Otata of the three islands mapped, we can assume that there was little to no barren across the Noises Islands as a whole at this time.

Urchin barrens covered 24% of reef in 1978, expanding to 49.5% in 2019. Although the Noises Islands were also subject to relieved fishing pressure commercially with the introduction of the QMS, because of their location central to Auckland City they are a very popular recreational fishing destination. With snapper being one of, if not the most popular recreationally fished species in New Zealand, it is to be expected the snapper population at the Noises Islands has taken a hit (Holdsworth, Rea, & Southwick, 2016). With ease of access to this location, and the popularity of recreational fishing in Auckland, it is unsurprising that we continue to see expansion of urchin barren around all islands in the Noises group.

Bergquist (1960) describes Otata Island to be subject to 'moderate to fairly severe wave action', as compared to the description of Hauturu as subject to 'vigorous wave action'. This fits the pattern of wave exposure that you would expect with the Noises Islands being further into the gulf and therefore comparatively more sheltered, but still exposed to significant wave action due to the small size of the islands and their location off the mainland.

4.3 Wave action effect

Hauturu is an ideal location to perform analysis on the effects of wave action, due to consistent and high water clarity negating the effect of turbidity, near consistent fishing pressure around the coastline, and the shape of the island providing data for a wide range of wave action and levels of shelter. Past literature regarding the effect of wave action on urchin barren extent has mixed opinions, with some concluding that more sheltered areas are more prone to urchin barrens, and others concluding the opposite, that sheltered areas have less or very minimal barren areas.

Dix (1970) suggested that in more sheltered areas urchins roamed and foraged more freely, resulting in larger barren extents, while they were more stationary in areas of higher wave action. Similarly, the findings from Choat & Ayling (1978), where the sites they studied that had the least urchin individuals and barren extent were those exposed to the highest wave energy. Choat & Ayling (1978) found that sites with moderate wave energy had the most urchin barren, however, there were some observations that very sheltered sites did not follow this pattern, instead the highly sheltered sites were more aligned with the exposed sites in having less barren. If the Noises Islands are to be classed as moderately exposed rather than used as an example of a sheltered site, this could be further explanation for why we see extensive barrens at this site.

Grace (1983) and Shears & Babcock (2004) however both concluded that sheltered sites such as the inner Hauraki Gulf were not subject to urchin barrens, instead that more exposed sites are of higher susceptibility. While this does not align with the comparison in extents between Hauturu and the Noises (32.73% vs 49.5%), it does fit the pattern we see in the wave action effect assessment completed using Hauturu drop camera analysis.

The patterns that emerged from comparing percentage of barren with fetch, showed higher urchin barren extent at more exposed sites, and lesser extent at sites that were more sheltered. This was only a weakly positive correlation (p-value 0.082) but does still appear to align with the findings of Grace (1983) and Shears & Babcock (2004).

There was however a significant relationship between wave action and the depth of urchin barrens. The shallow limit of barrens did not vary with wave exposure, but the lower limit of the barren was positively related to wave exposure.

This matches the findings of Grace (1983) and Shears & Babcock (2004), where they also found barrens to stretch deeper with increasing wave action. Both studies also found that barren extent tended to creep further up into the shallow mixed algal zone with increasing wave exposure, but as the upper extent of urchin barrens was already fairly shallow around Hauturu, this is perhaps why we did not find a significant relationship of these moving shallower still (Grace, 1983; Shears & Babcock, 2004).

4.4 Limitations

When using aerial and satellite imagery to create habitat maps, there is a lot of reliance on consistent image quality over time and across the area, which unfortunately isn't always the case. As seen with the Hauturu habitat maps, the historic images, both the 1959 and 1979, were only of a high enough quality to map the western coast, with glare being a major factor in not being able to identify habitats around the rest of the island.

As well as consistent quality of images taken at a single period, an issue faced with comparisons over time is the differences in image quality between the years being analysed. For example, the 1950's Hauturu imagery was clear enough to show borders of more coarse scale areas, and could clearly identify macroalgae, sand, and note the lack of barren areas. However, being black and white and lower definition, it was harder to get details for more fine scale substrate differentiations, such as between *E. radiata* and shallow mixed algae, and for identifying any potential areas of *C. flexilis* on the southern side of Te Titoki Point.

As with the 1950's, the 1970's Hauturu imagery was also detailed enough to define the substrates being assessed, but still resulted in a coarser substrate map than was produced with the 2018/2019 imagery (fig. 27).

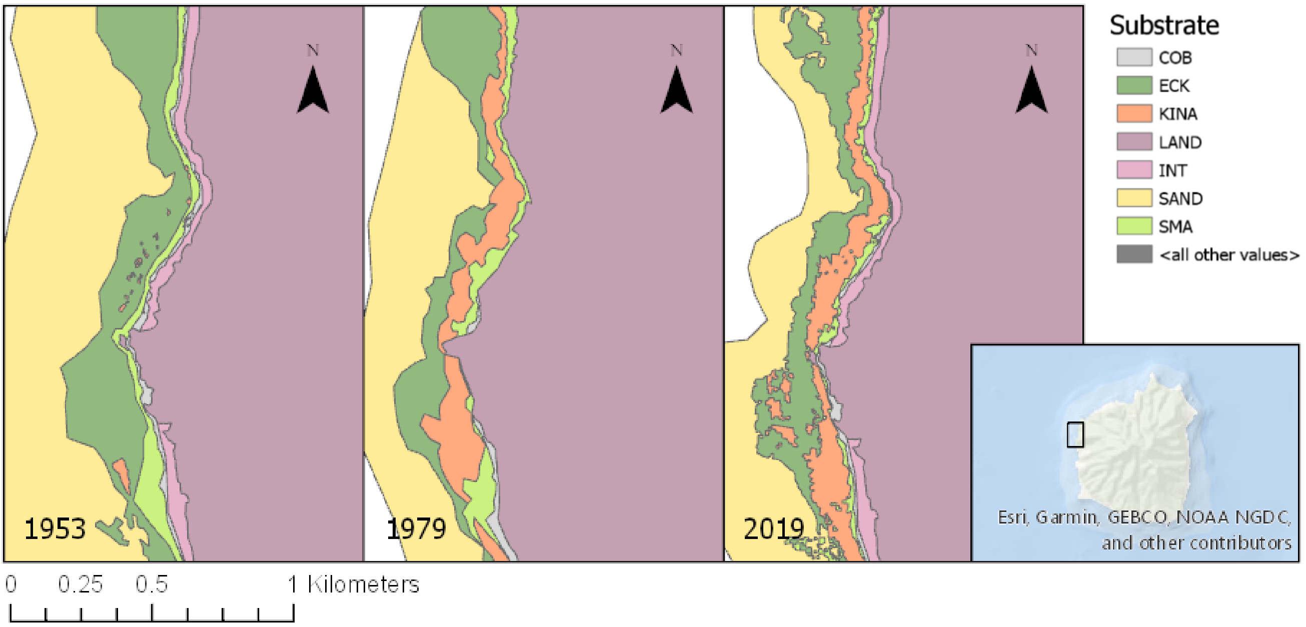


Figure 26 - Northern extent of the comparison area on the west coast of Hauturu-o-Toi, showing the differences in fine scale definition between the 3 years classified

Decreasing clarity with depth was noted at all sites, where eventually an optical drop off point was reached, at which substrates could not be confidently classified. As suggested by Kerr & Grace, (2005), this is less of an issue as major substrate fluctuations tend to happen in shallower water where clarity is still sufficient for mapping, and urchin barrens, the areas of note in this study, typically occur in shallow water (<15m) which we were able to map to (Shears & Babcock, 2002). This is notable when comparing Hauturu directly to the Noises Islands, where mapping was unable to extend as deep due to turbidity, meaning that areas of deeper kelp forest may have been missed. By constraining both maps to a depth of 10m, a fairer comparison could be made between % of barren from reef habitat at both sites.

More data is always beneficial in improving the strength of an analysis, and the strength of the wave action effect analysis could perhaps be improved with the addition of more transects and having transects of more even lengths. Some transects, 4 of 28, only consisted of 2-4 data points when specifying only ground truth images that were of reef habitats (*E. radiata*, shallow mixed algae, kina), which could have both skewed the data, or could have resulted in missing areas of reef that did exist in the space surrounding the transect line. With all substrates included, only 2 transects fell short of 10 data points.

4.5 Into the future

With both Hauturu and the Noises Islands subject to proposed marine protected areas (MPA’s), it is highly beneficial to have baseline maps of the current distributions of key habitats, to compare to when moving forward (Department of Conservation, Fisheries New Zealand, & Ministry for Primary Industries, 2021). As well as having an idea of the current distributions, knowing how the areas have changed from the past through to present day can give an idea of what changes could be expected if the protection of key urchin predators in these areas is increased.

In these reserves we could expect to see a rebound in the populations of key urchin predators such as snapper and the spiny rock lobster, as has been seen in the years since the implementation of the Leigh Marine Reserve (Leleu et al., 2012). With this we could expect a decrease in urchin populations, and a resulting decrease in barren extents, to be replaced with a regeneration of kelp forest.

5. Conclusions

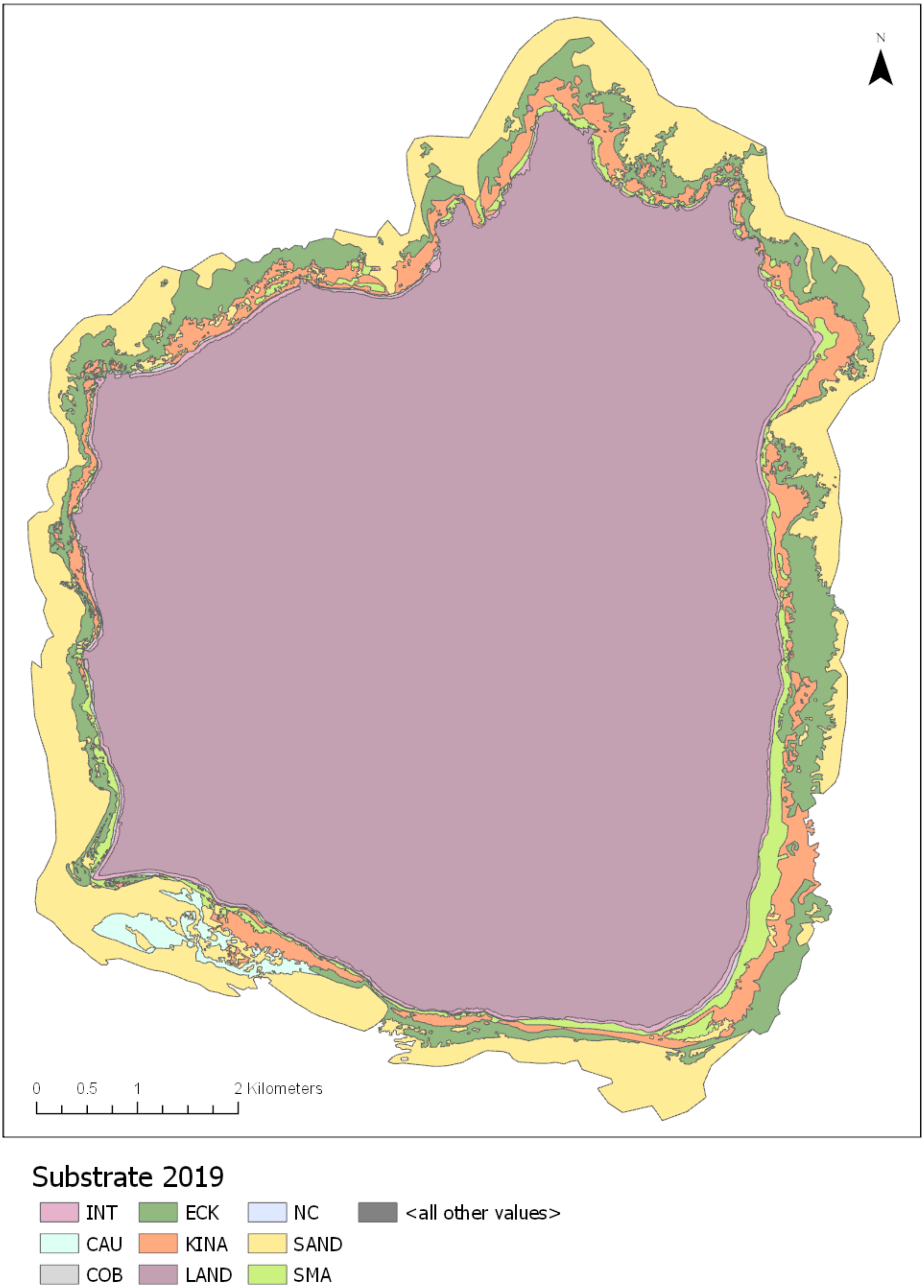
Overall, the maps produced in this study found that while urchin barrens were practically non-existent in the 1950's, from the 1970's onwards they have been a dominant habitat particularly on shallow reefs. Around Hauturu, barren extent is broadly consistent between the 1970's and current day, however, the extent of barrens has increased greatly in the waters surrounding the Noises Islands over the same time period. Results from 2019 imagery showed Hauturu to have 32.73% urchin barren coverage of the surrounding reef, and the Noises Islands having a coverage of 49.5%, noticeably more for the island group located further within the Hauraki Gulf. In both islands, urchin barrens were dominating shallow reefs (<10m), and the greater overall cover at the Noises is likely related to reefs only being mapped to a shallower depth than at Hauturu.

Comparing 28 transects from around Hauturu, a relationship between wave action effect and the extent of urchin barrens could be seen. This showed more exposed sites generally having larger extents of barren with barrens stretching increasingly deeper as wave action increased, matching the findings of Grace (1983) and Shears and Babcock (2004).

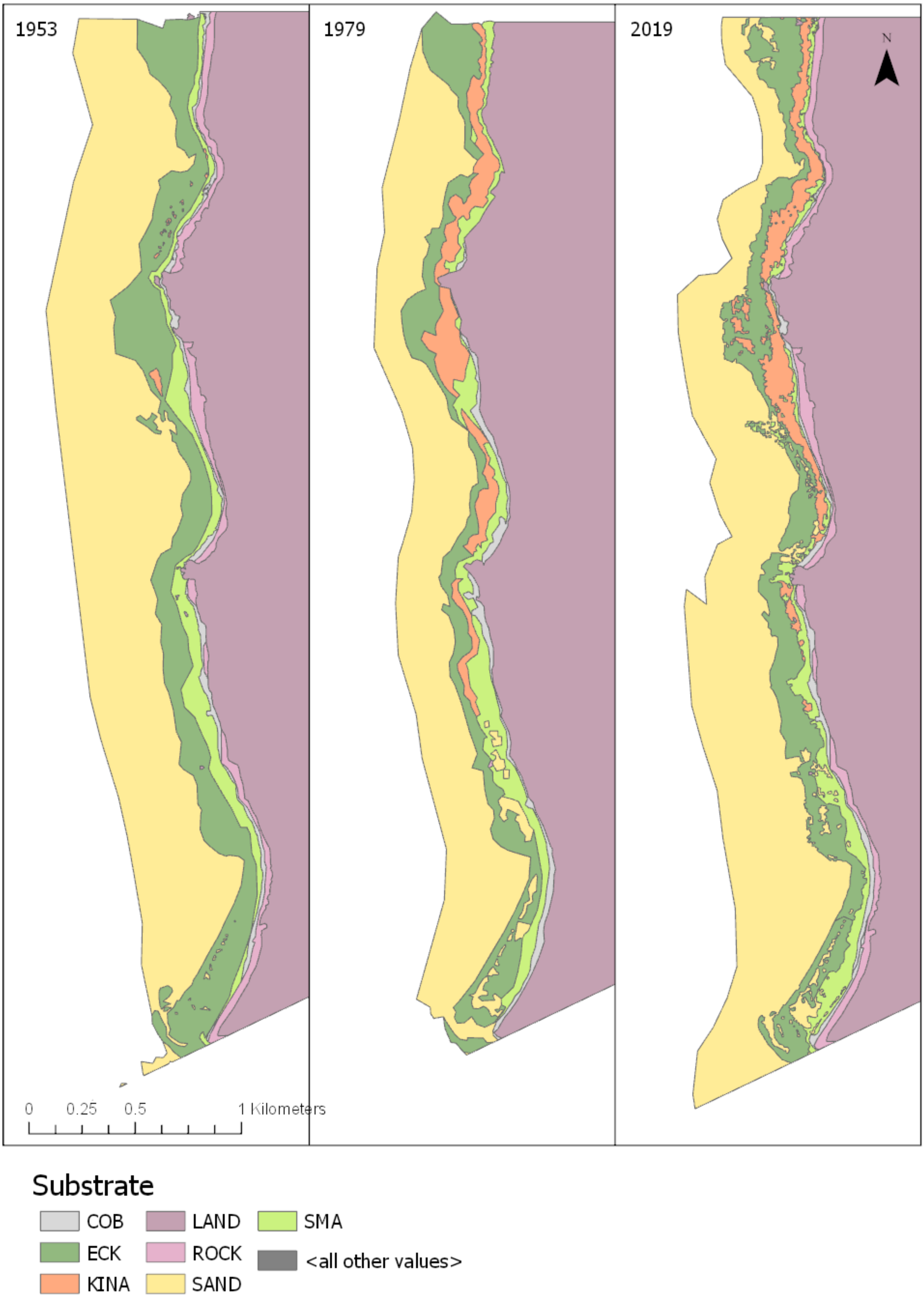
The digitisation methods used to map these locations showed accuracies that aligned with previous mapping studies of similar scopes and detail. This suggests that these maps can comfortably be used as a baseline for further study in these areas, with proposed MPA's in place for both sites.

Appendix

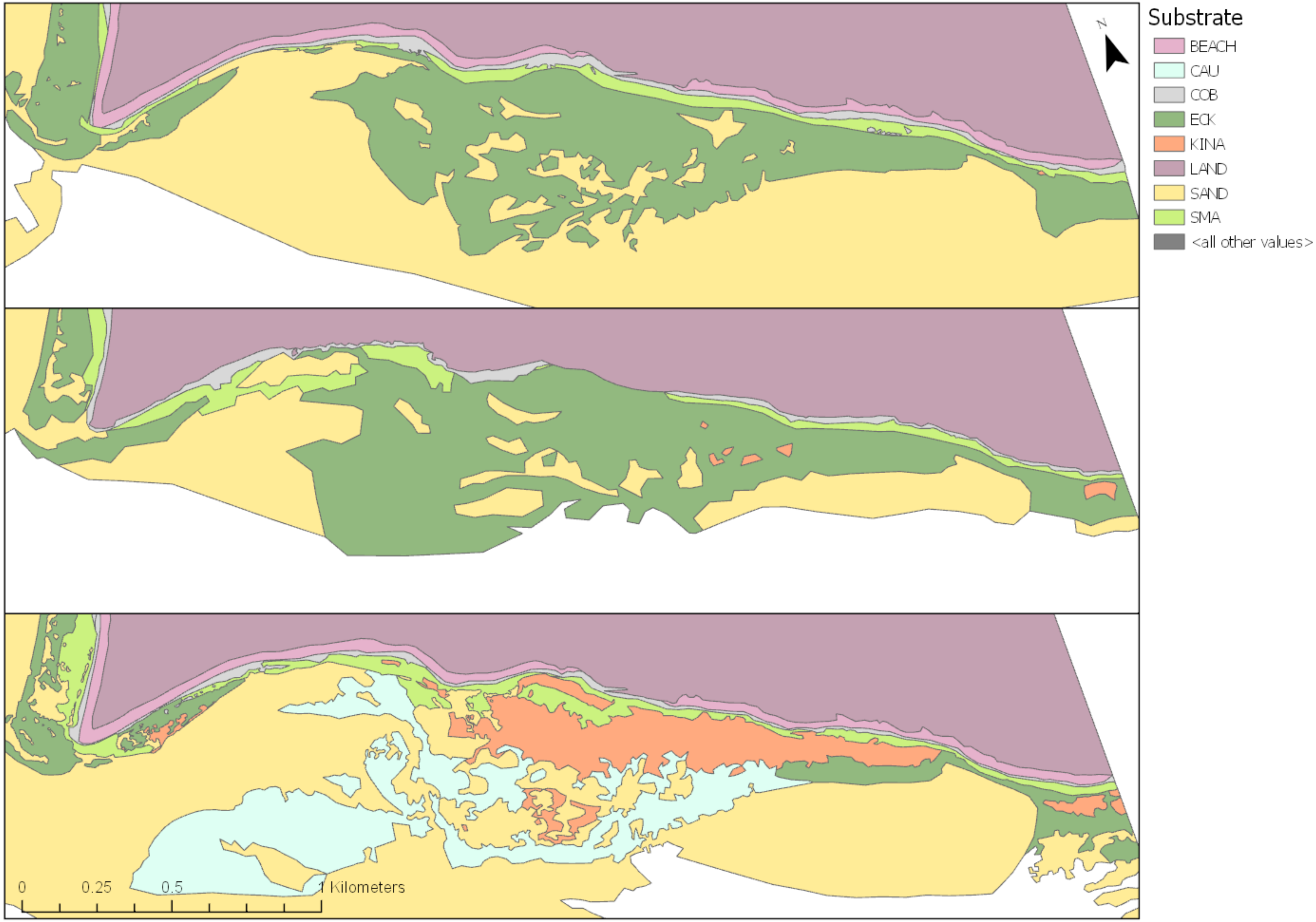
The following appendix includes detailed large-scale versions of the habitat maps produced for this study, including the 2019 Hauturu-o-Toi habitat map, the 1953 / 1979 / 2019 Hauturu-o-Toi comparisons (partial west coast and partial southern coast), the 2019 Noises Islands habitat map, and the 1978 Noises habitat map (figures 8, 11, 13, 15, 28).



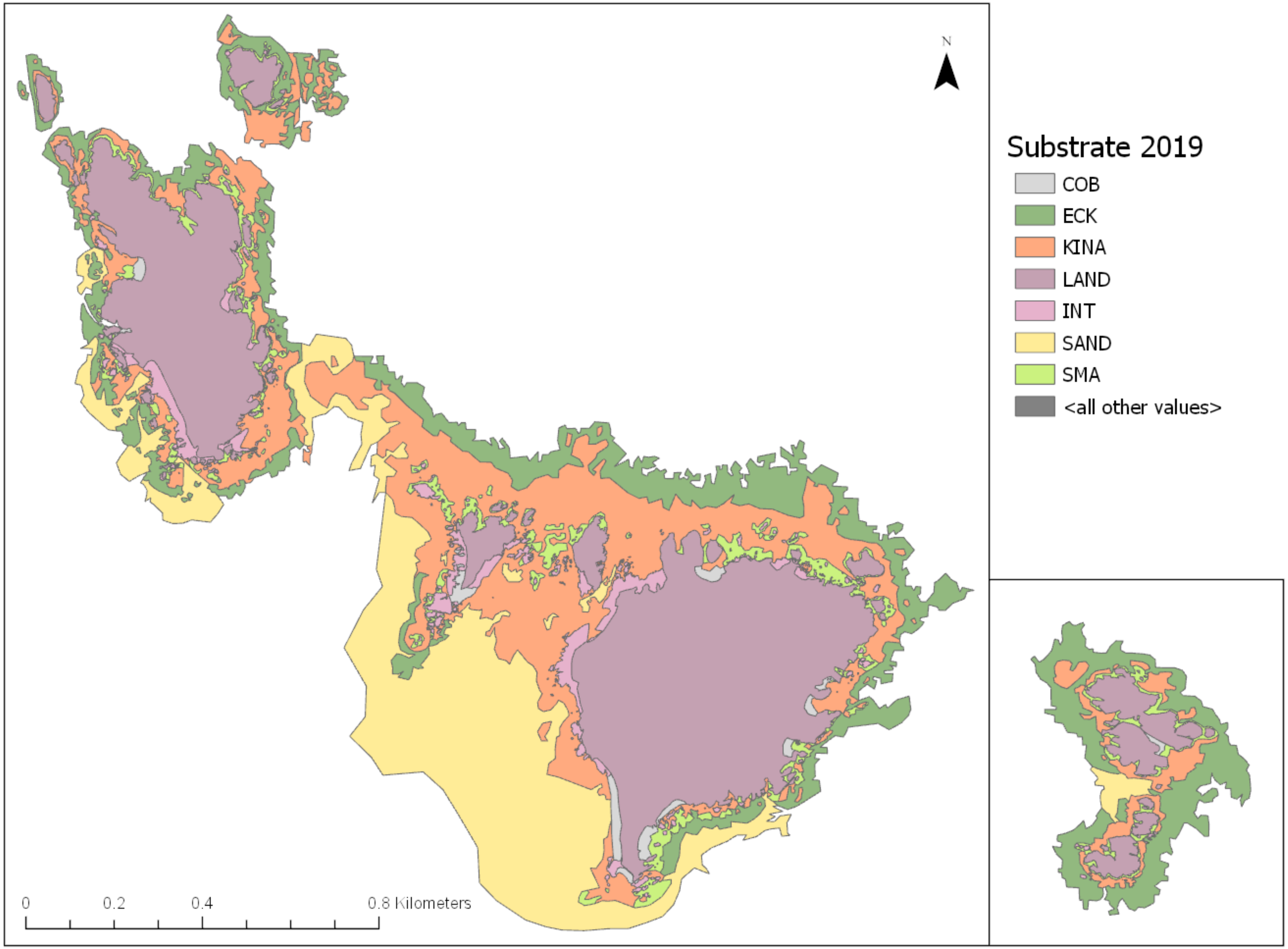
Habitat map of Hauturu-o-Toi (2019)



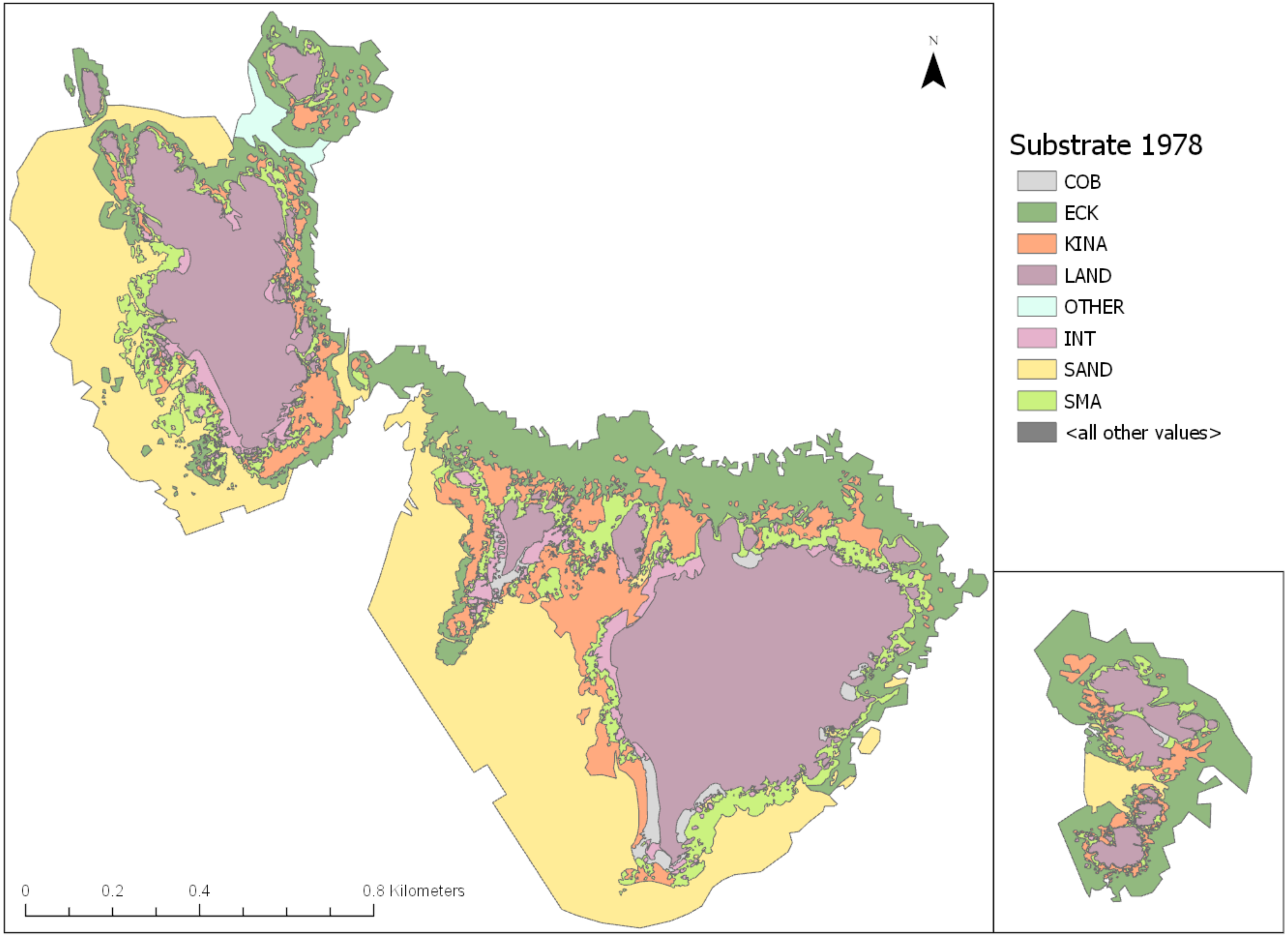
Habitat comparison for the western coast of Hauturu-o-Toi (1953 / 1979 / 2019)



Habitat comparison for the southern coast of Hauturu-o-Toi (1953 / 1979 / 2019)



Habitat map of Noises Islands (2019)



Habitat map of Noises Islands (1978)

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