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Exploring the use of spatial decision-support tools to identify trawl corridors in the Hauraki Gulf Marine Park

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EXECUTIVE SUMMARY

Bennion, M.[1]; Brough, T.[1]; Leunissen, E.[1]; Morrison, M.[1]; Hillman, J.[2]; Hewitt, J.E.[1]; Rowden, A.A.[1]; Lundquist, C.J.[1] (2023). Exploring the use of spatial decision-support tools to identify trawl corridors in the Hauraki Gulf Marine Park.

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The Hauraki Gulf / Tīkapa Moana / Te Moananui-ā-Toi is one of the most intensively used coastal area in Aotearoa New Zealand, with deep rooted historical importance for tangata whenua and a long history of commercial and recreational use. Decades of commercial fishing, increasing agricultural run-off, and industrialisation in the area have resulted in long-term degradation of benthic habitats in the gulf. In response, the Hauraki Gulf Marine Park (HGMP) was designated in 2000 under the Hauraki Gulf Marine Park Act (2000), followed by the development of the Sea Change – Tai Timu Tai Pari Hauraki Gulf Marine Spatial Plan (HGMSP) by a stakeholder working group. *Revitalising the Gulf: Government Action on the Sea Change Plan*, published in June 2021, builds on the aims of the HGMSP, particularly a management objective in the draft Hauraki Gulf Fisheries Plan to protect marine benthic habitats from any adverse effects of fishing. One approach to achieving this objective is through the identification of suitable locations for trawl corridors, areas where bottom trawling and Danish seining could continue while other areas are closed, to minimise impact to current biogenic habitats and to promote the recovery of biogenic habitats. Management of the impacts of scallop dredging was not within the scope of this project.

Here, we use the spatial decision-support tool, Zonation, to explore where trawl corridors could occur within the HGMP. An advisory group (the Hauraki Gulf Benthic Spatial Planning Advisory Group – HG-BSPAG) was convened, with members agreeing to terms of reference and contributing to five workshops to identify elements that should be considered in the identification of areas that are suitable or unsuitable for trawl corridors. Following a stocktake of available information on biogenic habitats and benthic biodiversity in the HGMP, available data for scenario development were extracted from national and international databases and digitised from historical reports and theses. In consultation with taxonomic experts, point records for biogenic structure-forming taxa were used to develop predictive layers of probability of occurrence for 20 biogenic habitat-forming functional groups (e.g., encrusting sponges, horse mussels). Other benthic biodiversity layers were compiled from recent work that developed national predictive models of benthic invertebrate species occurrence. These layers represent a significant increase in availability of data on benthic biodiversity and biogenic habitats compared to the limited layers available to inform the HGMSP which consisted of expert-derived polygons representing anecdotal biogenic habitats, and a layer from predictive modelling of potential biogenic habitat structure. The impacts of historical seafloor disturbance on biogenic habitats from trawl fishing gear was estimated by applying a fishing impact index, based on the historical trawl footprint, to the modelled probability of occurrence layers to provide an indication of the areas which may continue to support the different groups of benthic taxa. Areas of historical impact, which were predicted to support particular taxa in the absence of fishing, were identified as areas which could potentially support recovery if stressors were discontinued. A similar layer to evaluate the historical impacts of Danish seining was not available.

An independent workshop with fishing industry representatives identified metrics of fishing value to include in the exploratory scenarios, identifying four ‘fishery categories’ (Danish seine, trawl fishery vessels > 20 m, trawl fishery vessels < 20 m, precision seafood harvesting) and five stocks (snapper, *Chrysophrys auratus*; tarakihi, *Nemadactylus macropterus*; trevally, *Pseudocaranx dentex*; John dory, *Zeus faber*; red gurnard, *Chelidonichthys kumu*). Existing uses and spatial management were discussed across the HG-BSPAG workshops, and a final model area was selected that excluded scallop dredging

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open areas, aquaculture areas, and channel dredging zones, as these areas were likely to have seafloor disturbance even if bottom trawling was excluded. The deep area of the HGMP (> 200 m) was masked out from consideration in the exploratory scenarios as this area was primarily targeted by deepwater fisheries that were not represented in the advisory group membership. Inclusion of these areas in the prioritisations could also skew the model priorities toward protection of these deep habitats which are relatively rare in the HGMP and have a different benthic species composition that may not be adequately represented by the shallow subtidal biogenic habitat groups modelled for this project.

Four rounds of scenarios were presented at successive advisory group workshops, with scenario iterations designed to illustrate how the decision support tool could be used to identify areas that could be suitable as trawl corridors due to either low biogenic habitat value, low recovery potential, high fishery value, or combinations of these input layers. Analysis of overlapping value (i.e., post-accounting) for exploratory scenarios showed relative benefits of each scenario for protection of current modelled biogenic habitats and biogenic recovery potential, benthic biodiversity, and the Seafloor Community Classification, and costs. The scenarios identified within the advisory group can be used to inform management processes and provide input into considerations for management responses to the identification of trawl corridors in the HGMP. The advisory group also noted future opportunities to improve the data used in these exploratory prioritisations. The models of biogenic habitats developed for this project, and other modelled layers of benthic invertebrate biodiversity, represent a substantial improvement on data previously available. These models could be further improved through addressing gaps in spatial coverage to validate model predictions in areas with high model uncertainty, and collection of additional data on abundance to allow for development of robust abundance models. Development of layers representing stressors beyond trawl disturbance (e.g., Danish seining historical footprint, recreational and commercial scallop dredging footprints, spatial distribution of sediment inputs from land) could also inform locations of trawl corridors and areas of potential biogenic habitat recovery.

1. INTRODUCTION

1.1 Background of Sea Change – Tai Timu Tai Pari Hauraki Gulf Marine Spatial Plan

The Hauraki Gulf / Tīkapa Moana / Te Moananui-ā-Toi has been an important region for humans since the arrival of Māori to Aotearoa New Zealand. Today, the Hauraki Gulf is one of the most intensively used coastal spaces in New Zealand. The human population residing in and around the Hauraki Gulf is now greater than 1.7 million, with New Zealand's most densely populous area, Auckland (Tāmaki Makaurau) within this region (Hauraki Gulf Forum 2020). The coastal areas and moana of the Hauraki Gulf are of considerable importance for mana whenua, commercial stakeholders (e.g., fishing and aquaculture), and coastal communities in the Auckland and Waikato Regions. The Hauraki Gulf and its motu (e.g., Te Hauturu-o-Toi/Little Barrier Island and Aotea/Great Barrier Island) are of significant cultural, traditional, and spiritual importance to mana whenua. Coastal communities within the gulf's bounds, and beyond, rely on the moana and its resources for commercial, social, and recreational uses.

Like many coastal regions around the world, habitats in the Hauraki Gulf are under threat from a variety of anthropogenic activities (Lotze et al. 2006), including but not limited to, industrial and agricultural nutrients and contaminants, fishing, climate change, and sedimentation (Hauraki Gulf Forum 2014). Biogenic habitats are the foundation of healthy functioning ecosystems. For instance, kelp forests (Teagle et al. 2017) and shellfish beds (Carss et al. 2020) provide habitat for species assemblages which support the provision of ecosystem services (physical, chemical, and social). Habitat degradation and declines in several health indicators suggest a wide range of issues have contributed to the declining health of the gulf region (Hauraki Gulf Forum 2020). Declining health has implications for ecosystem service provision from a functional standpoint (e.g., nutrient cycling and pathogen/pollution removal) and socio-cultural implications like reduced abundance of kaimoana including taonga (treasured) species. Several recent studies have reported on the recovery potential of habitats in the Hauraki Gulf, with focus placed on biogenic habitats (Morrison 2021), the effect of the COVID-19 lockdown on the soundscape in the region (Pine et al. 2021), shellfish bed restoration projects (Sea et al. 2022), and recovery potential offered by non-biodiversity target protection areas, i.e., the Cable Protection Zone (CPZ) (Shears & Usmar 2006; Morrison et al. 2016).

In recognition of the degradation of the gulf and given the cultural value of the gulf as a taonga (treasure), the Hauraki Gulf Marine Park (HGMP) was established through the Hauraki Gulf Marine Park Act 2000 (hereafter referred to as 'the Act'). The HGMP covers an area of c.14 000 km^2 of coastal marine area on the east coast of the North Island (Te Ika-a-Māui). The overall purpose of the Act is to integrate the management of the historical, natural, and physical resources of the HGMP while recognising the historic, traditional, cultural, and spiritual relationship of tangata whenua with the Hauraki Gulf (moana) and its islands (motu) and catchments. Section 7 of the Act recognises the HGMP area as a region of national significance. Reasons include the interrelationship between the gulf (moana), its islands and catchments, and the 'life-supporting capacity' of the area. Furthermore, this life support provides for the historical, cultural, and spiritual relationship of mana whenua to the moana/whenua and brings capacity for social, economic, and recreational activities for coastal communities. Section 8 of the Act deals with the management of the designated HGMP area, namely the protection and where appropriate the enhancement of its life-supporting capacity and the natural, historical, and physical resources (including kaimoana / seafood) therein. The Act also mandates tri-annual state of the environment reports, with six reports delivered since the HGMP was established. Following the third State of the Environment (SoE) report (Hauraki Gulf Forum 2011), groundswell was initiated toward reversing trends of degradation in the HGMP through a stakeholder marine spatial planning process.

Consequently, the Sea Change – Tai Timu Tai Pari Hauraki Gulf Marine Spatial Plan (HGMSP) process was initiated in 2013 with the aim of developing a marine spatial plan for the HGMP. A stakeholder working group (SWG) of mana whenua and stakeholders from the region developed the HGMSP (Waikato Regional Council 2017). The 14-member SWG represented mana whenua, environmental groups and fishing, aquaculture, agriculture, infrastructure, and community sectors. The HGMSP is New

Zealand's first marine spatial plan and is a collaborative response to the threats and stressors responsible for the declining health of the Hauraki Gulf ecosystems. One of the goals of the SWG was to identify areas within the HGMP where new Marine Protected Areas (MPAs) could be established. The SWG proposed fifteen MPAs (six with two options), that varied in the level of protection offered: i.e., High Protected Areas (HPAs) and Seafloor Protection Areas (SPAs). At the time, limited information on the distribution of biogenic habitats in the HGMP was available to the SWG to inform this process. The primary spatial data comprised a modelled ecosystem services layer representing potential provisioning of biogenic habitat structure (Townsend et al. 2011; Townsend et al. 2014) and spatial layers representing six biogenic habitats, drawn based on expert interviews (Lundquist et al. 2020b). The HGMSP was released in 2017 (Waikato Regional Council 2017) and included several initiatives. For example, these included proposed protected areas, stabilising sediment, and connecting people to the environment to strengthen kaitiakitanga (guardianship), across five key topics: 1) mahinga kai—fish stocks and aquaculture; 2) biodiversity and habitat restoration; 3) a gulf sediment initiative, 4) ahu moana (kaitiakitanga by mana whenua and local communities), and 5) kaitiakitanga.

Central Government agencies were tasked with developing a Government Response Strategy to the HGMSP, detailing how respective agencies will implement Sea Change actions (Department of Conservation et al. 2021). In 2020, NIWA was contracted by the Department of Conservation (DOC) to evaluate the biodiversity protected by the proposed HPAs and SPAs (Lundquist et al. 2020b). The evaluation included an estimate of the protection of biodiversity features for six biogenic habitats (dog cockles, green-lipped mussels, mangrove, rhodolith, saltmarsh, and seagrass), 90 demersal fish species, a layer of 47 physical habitats (Jackson & Lundquist 2016), and biogenic ecosystem services. The assessment then estimated displacement of catch (commercial fisheries) for each of the protection scenarios. The evaluation made use of the decision-support tool Zonation to identify the relative benefits of different protection scenarios, and how they aligned with an optimal solution identified by Zonation with no spatial constraints in where protected areas could be located. The evaluation showed that the proposed protection scenarios do offer some protection to the biodiversity in the HGMP, however it was noted that for some species and habitats (importantly some biogenic habitats) the biodiversity protection offered by both MPA types fell short (Lundquist et al. 2020b). Additionally, the report highlighted the paucity of "robust and spatially comprehensive" datasets representing marine biodiversity in the Hauraki Gulf. The Ministerial response to the SWG proposals (Department of Conservation et al. 2021) provided slight variations on the SWG proposals with a total of 11 HPAs (and two Marine Reserve extensions) covering 5.5% of the HGMP, and 5 SPAs covering 5.4% of the HGMP (Figure 1B).

Since the completion of the previous evaluation, numerous datasets have become available which can be used to explore additional spatial management options for the HGMP. These include, but are not limited to, seafloor invertebrate species point records (which have been curated for other projects), species distribution models for macroalgae and seafloor invertebrates (Lundquist et al. 2020a), and a national seafloor community classification model (Stephenson et al. 2021b).

Government response to the Hauraki Gulf Marine Spatial Plan

Following the call to action made by the 2017 HGMSP, *Revitalising the Gulf: Government Action on the Sea Change Plan (*Revitalising the Gulf) was published in June 2021 (Department of Conservation et al. 2021). The strategy outlines the actions the Government will take to restore the "health and mauri" of the HGMP. Essentially, the strategy outlines two overarching outcomes: 1) effective kaitiakitanga and guardianship in the HGMP, and 2) healthy functioning ecosystems. To achieve these goals the Government has committed to several actions outlined in the strategy. They include but are not limited to: 1) increased marine protection to promote recovery of some of the most biodiverse regions in the HGMP; 2) increased kaimoana abundance; and 3) increased seabed habitat protection by restricting bottom trawling and Danish seining.

The strategy outlined in Revitalising the Gulf includes key actions covering eight elements: 1) fisheries management; 2) active habitat restoration; 3) aquaculture; 4) marine biosecurity; 5) marine protection; 6) protected species; 7) ahu moana; and 8) governance. Central to this project, under Management Objective 1.1 and Management Action 1.1.1, the draft Hauraki Gulf Fisheries Plan (released alongside

Revitalising the Gulf) proposes to "exclude bottom trawling and Danish seining from the Hauraki Gulf Marine Park (HGMP) except within defined areas or 'corridors'" (Department of Conservation et al. 2021). This proposed action drives the direction for aspects of this project, where a key aim is the development and evaluation of these 'trawl corridors', i.e., where bottom trawling and Danish seining could continue while the impact to biogenic habitats is minimised and the potential for biogenic habitat recovery (passively) is maximised. Importantly, the response notes the importance of monitoring closed areas to provide crucial data of benthic habitat change.

1.2 Existing marine protection in the Hauraki Gulf Marine Park

Several areas in the HGMP are already afforded protection via six no-take marine reserves (Figure 1A) which cover ~ 0.3% of the HGMP. The Cape Rodney-Okakari Point Marine Reserve (Goat Island) provides an example of a well-established and effective MPA. The marine reserve at Goat Island is recognised as the world's first and has been the subject of decades of research of MPA effectiveness (Cole et al. 1990; Allard et al. 2022). Other marine reserves within the bounds of the HGMP include Tāwharanui, Long Bay-Okura, Te Matuku, Whanganui a Hei (Cathedral Cove). Further de facto protection is provided by three Cable Protection Zones (CPZs), accounting for ~ 6% of the HGMP, within which most fisheries activities are prohibited (exceptions exist for commercial fisheries for pāūa and crayfish, and for small vessels that avoid bottom contact) (Figure 1A). However, analyses to date of fish and invertebrate assemblages suggest that cable zone status has 'negligible' effects on biodiversity in the area. (Shears & Usmar 2006) found no detectable effect of management type (i.e., inside or outside the cable zone), showing that area 'blocks' and depth explained more of the variability between sites than did protection status. (Morrison et al. 2016) compared fish and invertebrate species richness and abundance and demonstrated that the area assessed (therein 'block') and depth explained greater variability in the data than CPZ status.

Rāhui and scallop commercial fishery open areas

On Waitangi Day in February 2022, the Ngāti Manuhiri Settlement Trust placed a rāhui tapū (temporary ban/restrictions on an area or resource) on a portion of the HGMP with the aim of helping scallop (tipa, *Pecten novaezealandiae*) populations to regenerate. Rāhui tapū are a central tenet of kaitiakitanga (guardianship/stewardship) and are generally put in place when there is a marked decline in a resource or evident degradation of an area. The rāhui extends from Mangawhai Heads in the north to Takapuna in the South, and out to Aotea/Great Barrier Island, encompassing almost the entire northern half of the HGMP. The rāhui has been placed on scallops only and is anticipated to remain in place until scallop regeneration is 'evident' (Williams 2022). In March 2022, the Minister for Oceans and Fisheries announced further restrictions to the scallop fisheries in the HGMP, leaving two areas open to scallop dredging: one south of Te Hauturu-o-Toi/Little Barrier Island /Little Barrier Island, and another in the Colville Channel (Figure 1C).

Other spatial management measures

Other management measures that are in place within the HGMP may result in reductions in pressures on seafloor habitats. For instance, areas closed to commercial fishing offer another form of 'passive' protection, though the areas closed vary between fishing method (i.e., gear type) restrictions and/or vessel size (Figure 2). For instance, the area where Danish seining is permitted in the HGMP is greater than for bottom trawling (vessels > 20 m). Additionally, the area where bottom trawling (vessels under 20 m) is permitted is greater than where precision seafood harvesting[3] (PSH) and bottom trawling (vessels over 20 m) fishing methods are permitted.

Aquaculture areas and channel dredging zones are two additional areas where there may be impacts to seafloor habitats where bottom-contacting fishing does not occur (Figure 1C).

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[3] Precision seafood harvesting is a recently developed fish harvesting technology consisting of a Modular Harvesting System (MHS) which replaces the traditional mesh lengthener and cod-end of the trawl net, to improve the condition of fish and minimise bycatch of under-sized fish.

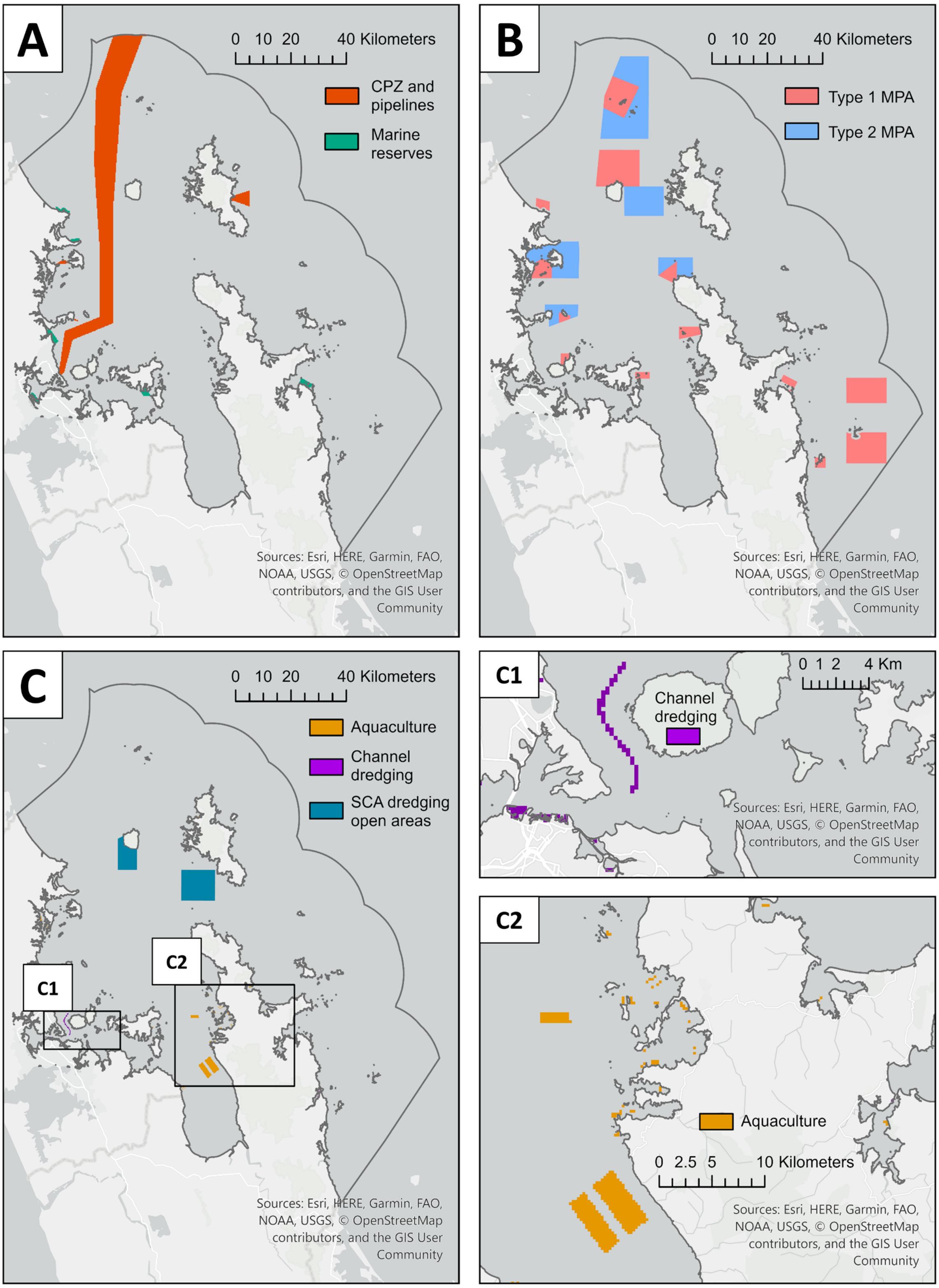

Figure 1: Hauraki Gulf Marine Park (bounded by the grey line) uses, protected areas, and model/study area. A) Cable way protection zone (CPZ), pipelines, and marine reserves. B) Sea Change – Tai Timu Tai Pari Government Strategy response proposed protected areas (Type 1, HPAs & Type 2, SPAs), noting these proposals exclude the Ōtata/Noises HPA. C) Model area with scallop dredging open areas (SCA in 2022) with inset C1) channel dredging in the Waitematā Harbour and inset C2) example of marine farms/aquaculture areas on the Coromandel Peninsula.

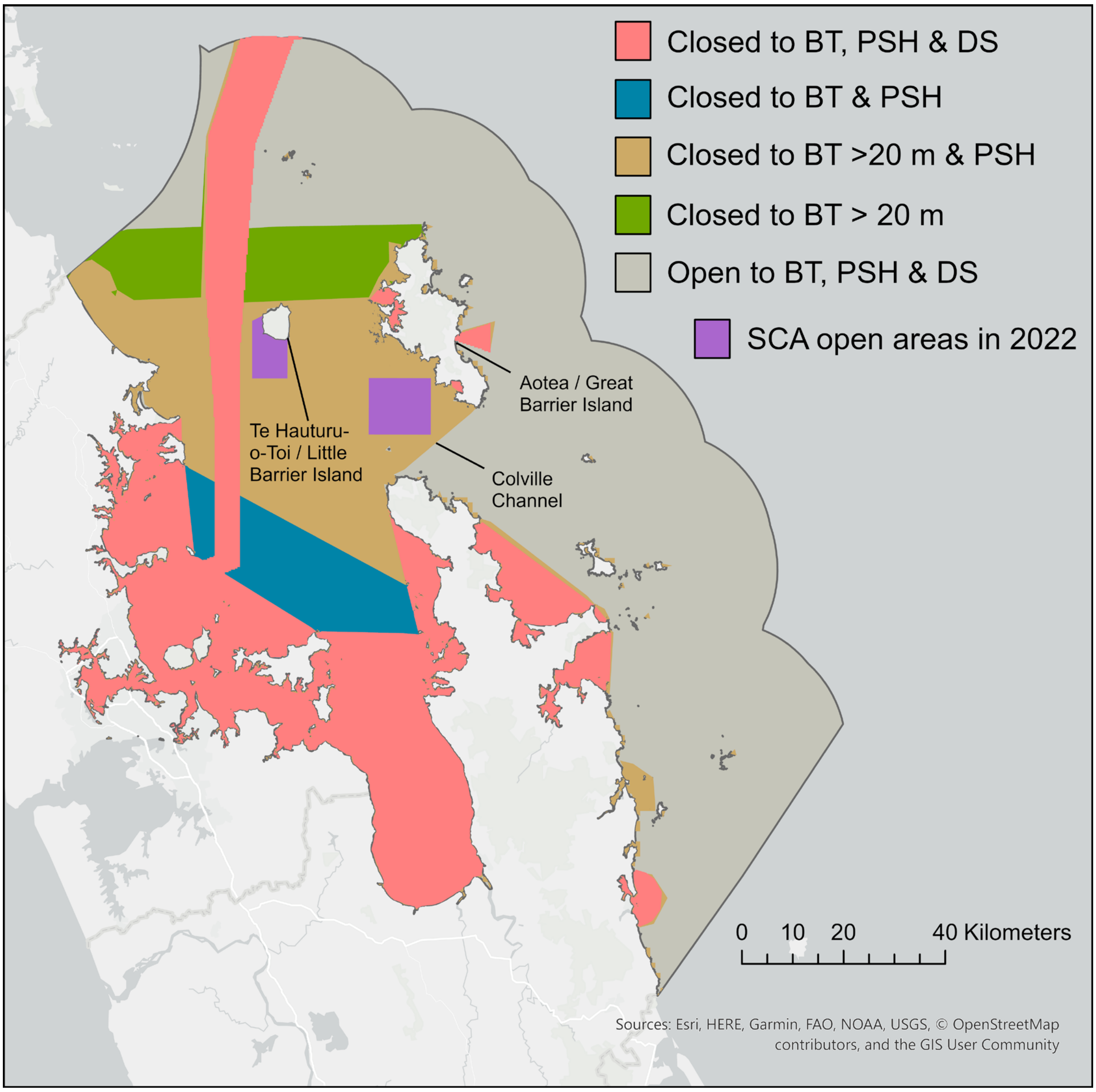

Figure 2: Areas open/closed to commercial fishing in the Hauraki Gulf Marine Park. Closed areas for Danish seine (DS), bottom trawling (BT, vessels > 20 m and < 20 m), and precision seafood harvesting (PSH) methods are shown. Areas open to commercial scallop dredging (Te Hauturu-o-Toi/Little Barrier Island and Colville Channel, as of June 2022) are also shown.

1.3 Biogenic habitats in the Hauraki Gulf Marine Park

Biogenic habitats are habitats created by plants and animals, that can form on both hard and soft substrate (e.g., canopy-forming macroalgae, calcium carbonate shellfish reefs, habitats created by tube-forming worms, ‘clumps’ created by encrusting species like bryozoans and sponges). Biogenic habitats provide physical structures which can provide habitat refugia for juvenile fish and invertebrates and provide suitable substrate for settlement (e.g., Teagle et al. 2017), and support associated species assemblages which contribute to ecosystem function through processes such as bioturbation by burrowing species (Lohrer et al. 2004).

The degradation of many biogenic habitats in the HGMP is well-recognised (Hauraki Gulf Forum 2020). However, the requirements to facilitate recovery of seafloor habitats in the gulf are unclear with a number of efforts having been undertaken, particularly with focus on restoring green-lipped mussel reefs (Alder et al. 2021; Alder et al. 2022; Sea et al. 2022). Morrison (2021) provided a comprehensive review of the habitats within the Hauraki Gulf and provided recommendations for both passive and active restoration. The review focused on 13 key biogenic habitat types including salt marsh, mangroves, seagrass, green-lipped mussels, scallops, horse mussels, infaunal bivalves, sponges, calcareous tubeworms (for example, *Galeolaria hystrix*), macroalgae, corals, sea pens (order: Pennatulacea), bryozoans, and oysters.

Spatial data on biogenic habitat distribution and abundance are surprisingly sparse and patchy. At the initiation of the HGMSP, information on biogenic habitats was available from an expert assessment process, provided as mapped polygons representing expert knowledge of the location and extent of biogenic habitats (Department of Conservation & Ministry of Fisheries 2011) (Figure 3). Three of these habitats were supplemented by ground-truthed coastal vegetation layers (mangrove forests, seagrass meadows, saltmarsh habitats; Lundquist et al. 2020b, Tablada et al. in press). These polygons represent areas of 'known' habitat, but an absence of polygons does not necessarily imply no biogenic habitats are present at that location. While these layers were the best available data at the time, the layers are not comprehensive, and few of these layers extend into areas that are fished with trawl gear (Figure 2). Thus, one of the research tasks in this project was to develop new layers to predict biogenic habitat distributions based on available point records of where biogenic habitat-forming species occur and modelled relationships to indicate where they could potentially recover if stressors were removed.

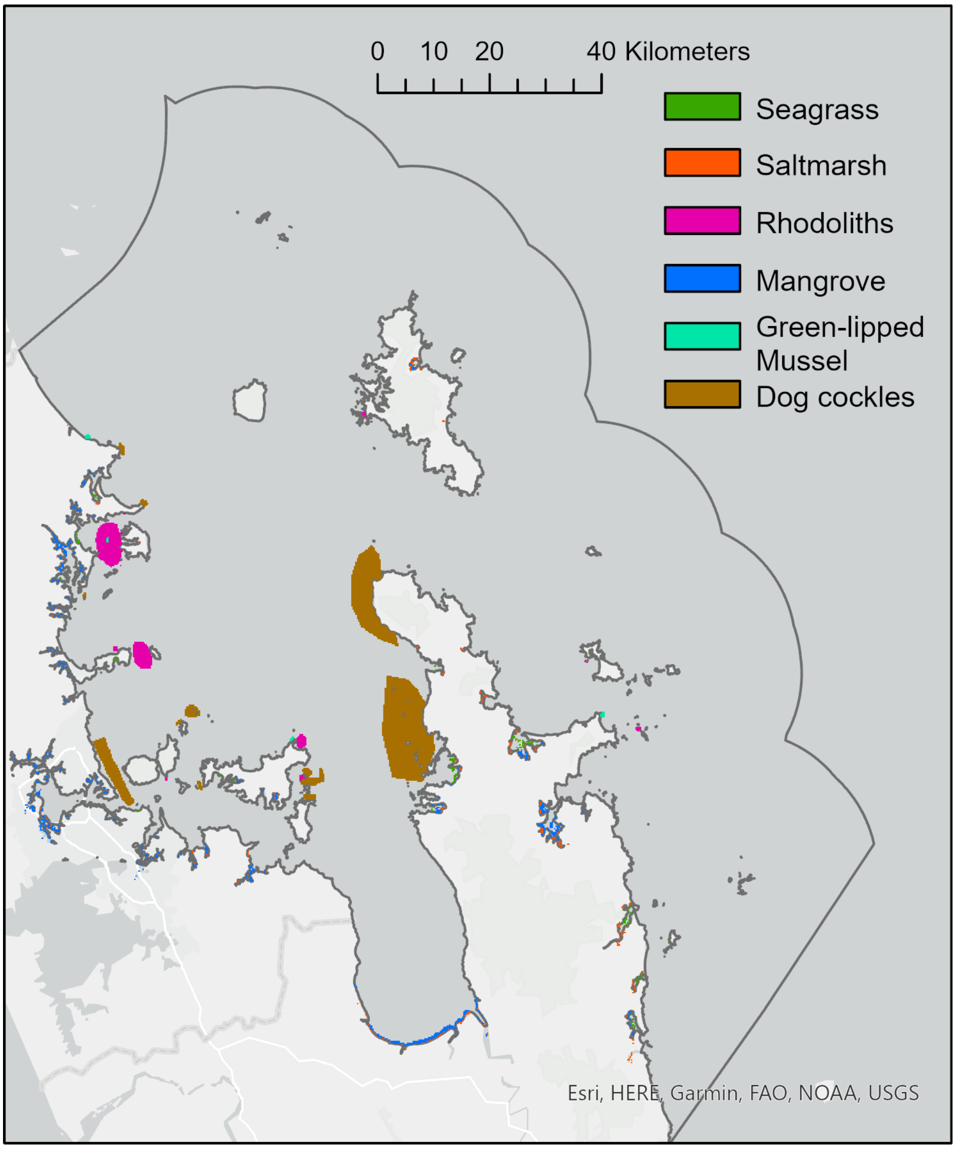

Figure 3: Mapped extent of six biogenic habitat types found in the Hauraki Gulf Marine Park. Layers available here: https://www.seasketch.org/#projecthomepage/52322dd05d3e2c665a00d119.

1.4 Objectives

This project (ZBD2020-06) was initially contracted in May 2021. Following the release of the Ministerial response to the Sea Change stakeholder working group proposals, project BEN2021-04 was merged into the project deliverables in October 2021, resulting in a change to the overall contract objective and an additional four specific objectives (Specific Objectives 3–6, as below) to support engagement with an advisory group.

Overall Contract Objective:
To assess spatial planning options to balance fishing activities (trawling and Danish seining) with the protection of benthic biodiversity and recovery of biogenic habitats within the Hauraki Gulf Marine Park.

Specific Contract Objectives:

1. Assess the potential for the recovery of habitats, offered by various spatial planning scenarios, taking into account meta-community dynamics, habitat condition, and ongoing stressors at local and regional scales and the interactive effects thereof.
2. Identify feasible strategies for the recovery and maintenance of habitats in the Hauraki Gulf Marine Park and suggest principles for future spatial planning processes to enhance recovery potential.
3. Identify areas that contain habitat types or biodiversity vulnerable to trawling and Danish seine fishing methods.
4. Quantify benthic impacts of bottom trawl fisheries and assess habitat naturalness using available fishing effort data and the outputs of project BEN2019-04.
5. Develop GIS layers representing value of fished areas to the fishing industry in conjunction with Fisheries New Zealand and the fishing industry.
6. Following a series of advisory group workshops, identify corridors that could be utilised for trawling and Danish seine fishing activities while allowing for the recovery of benthic habitats and the protection of benthic biodiversity within the Hauraki Gulf Marine Park.

1.5 Scope and limitations

This report details a scientific approach to inform spatial management in the Hauraki Gulf Marine Park. The scope of this report is to identify potential options for protecting biogenic habitat while providing for some bottom-impacting fishing activity. It is not the intention of this work to provide preferred management options to manage biogenic habitat recovery and protection in the HGMP. Instead, this work is intended to detail ways in which spatial management could be informed by the methods described herein. The key limitation of this work is the quality and resolution of data available and their distribution across the HGMP. Best available data have been used in this process to inform the development of layers where biogenic habitats are predicted to occur currently, or where their recovery may occur in the absence of fishing. This report details assumptions and caveats associated with modelling approaches, and limitations of the available data, particularly with respect to spatio-temporal and taxonomic biases in data availability. These assumptions and limitations should be considered carefully when adapting and using outputs of this work to guide future spatial management scenarios. Further, mana whenua and indigenous knowledge (mātauranga Māori) holders within the Hauraki Gulf possess comprehensive knowledge of past and present health indicators and status of habitats within their rohe. Inclusion of this knowledge was not within the scope of this work but could increase both the legitimacy and uptake of future co-developed (with iwi) spatial planning work in this area.

2. METHODS

2.1 Study area: Hauraki Gulf Marine Park

The Hauraki Gulf/Tīkapa Moana is a large coastal inlet in northern New Zealand. It is situated amongst the Auckland Region, Hauraki Plains, Coromandel Peninsula, and Aotea/Great Barrier Island. The HGMP covers an area of roughly 14 000 km^2, extending from Mangawhai Heads in the north (Auckland regional boundary) to Waihi Beach in the south (Waikato regional boundary). Within the HGMP boundary there are more than 50 islands. The outer region of the HGMP (east of the Coromandel Peninsula) is known as Te Moananui-ā-Toi. Hauraki is te reo Māori for the north wind, referring to the prevailing winds in the region. These winds generate mixing of the warm-temperate waters of the gulf which are replenished by cooler upwellings from the continental shelf. The HGMP hosts diverse flora and fauna, from kelp forests and sponge gardens (Blain & Shears 2019; Lohrer & Douglas 2019) to corals (Morrison 2021) and marine mammals (Dwyer et al. 2014; Stephenson et al. 2020), and unique biogenic habitats such as calcareous tubeworm mound fields (*Galeolaria hystrix*) (Morrison 2021). These waters and habitats also support a diversity of fishes and high abundance of important species (e.g., snapper, *Chrysophrys auratus)* (Compton et al. 2012). This highly productive region has provided a wealth of marine resources for centuries, yet information on the spatial distribution of biogenic habitats is relatively sparse (Morrison 2021). The region once hosted an estimated 500 km^2 of mussel reefs, analogous to the expansive oyster reefs once found in Chesapeake Bay, Virginia, USA (Schulte 2017). There was extensive commercial fishing of these green-lipped mussel beds from the 1910s to the 1960s, and some information on their historical distribution can be drawn from historical maps of bed distributions (Greenway 1969). Collecting all data available to describe biogenic habitat distributions in the region is central to the aims of this work.

To underpin the work in this report, best available information on biogenic habitats in the Hauraki Gulf Marine Park was required. Modelled layers of species distributions (abundance or probability of occurrence) provide a means to assess current and potential (recovery) habitat and can be used to inform spatial planning processes. Biogenic habitats in the HGMP were classified based on literature and expert advice (influenced by data availability for each potential group) into groups representing similar morphological categories for different biogenic habitat types. Predictive models were developed to represent probability of occurrence for each group of taxa. Following development of these layers, exploratory spatial prioritisations and scenarios, informed by an advisory group, were carried out. The report is divided into two primary sections:

1) biogenic habitat model development, including data compilation, characterisation of biogenic habitats in the HGMP, and model development; and
2) the iterative advisory group process, including spatial prioritisations, explorations, and trawl corridor development.

2.2 Biogenic habitat model development

Data compilation

To address objective 2, data on biogenic habitats (based on the definition “habitats created by plants and animals”) were sought and compiled. At this data compilation phase, data sought included point records and polygons representing presence and absence and abundance of individual species or biogenic habitats from published papers, central and regional government reports, and university theses. Modelled datasets were also compiled, including predictive models of individual species distributions, benthic biodiversity, and benthic species assemblages (species turnover).

To inform data collection, several key pieces of literature were reviewed to broadly inform what biogenic habitat types are present in the HGMP area and, therefore, where particular focus should be placed on data collection and retention. A list of marine biogenic habitat types present in Aotearoa New Zealand is shown in Table 1. For each habitat type, a description of the size or abundance of taxa required to constitute ‘biogenic habitat’ is provided. Of these groups, several biogenic habitats were expected to be present within the bounds of the HGMP, including kelp forests, macroalgae (meadows), beds of large bivalve molluscs, calcareous tubeworms, non-calcareous tubeworms, bryozoans (frame-building), rhodoliths, sponge gardens, stony corals, sea pens, brachiopod beds, and seagrass beds (MacDiarmid et al. 2013; Anderson et al. 2019).

Seagrass meadows are present in the HGMP (Figure 4) but given most seagrass meadows are intertidal in the HGMP, apart from known beds near Slipper Island/Whakahau (Clark & Crossett 2019) and Great Mercury Island/Ahuahu, this habitat was not a focus for this work. Similarly, intertidal mangrove forests (Figure 4) were not a focus for this project, as bottom-impacting trawling does not overlap with these habitats. Given the definition of biogenic habitat, highly mobile fauna (e.g., fish and large mobile crustaceans) were not considered as biogenic habitat formers in this project. Scallops (*Pecten* spp.) were discussed as a potential biogenic habitat, as the assemblages they form could constitute biogenic habitat, though these species are highly mobile. Nevertheless, these species were not reflected in the literature as biogenic habitat, rather the habitat with which they associate was considered to be included with the other biogenic information that was compiled. Additionally, invasive species records were intentionally not included as biogenic habitats in this project. Although some taxa are likely considered biogenic habitat-forming in their native ecoregions, non-indigenous flora and fauna are not representative of the natural state of the ecosystem and should not drive the prioritisation of areas for biodiversity protection.

Given the limited amount of data on biogenic habitat presence and extent available for this project, we used all available records, rather than limiting data retention based on a threshold abundance to delineate what constitutes biogenic habitat of certain groups (Table 1). Instead, all occurrence and abundance point records of biota that fell into the groups listed were retained for modelling. Several other biogenic habitat groups were identified during the literature review but were not deemed relevant for the current project given they are not known to occur in the HGMP, i.e., methane, cold-seep, and vent habitats (MacDiarmid et al. 2013; Anderson et al. 2019). For completeness, xenophyophores are included in the table below, but this biogenic habitat is not expected to occur within the HGMP given it is typically found at depths > 500 m, deeper than the maximum depth in the HGMP (Anderson et al. 2019).

Table 1: Biogenic habitat descriptions (general agreement) from previous studies in Aotearoa New Zealand. (Continued on next page)

Biogenic habitat	Description and suggested threshold abundance to delineate biogenic habitat	Source
Kelp forests	Monospecific or mixed species stand of mature brown algae from the orders Laminariales and Fucales that form complete canopy cover with > 4 adult plants per m^2.	(Shears et al. 2004; Thrush et al. 2011; MacDiarmid et al. 2013; Anderson et al. 2019)
Macroalgae (meadow)	1) Greater than or equal to 35% cover over an area of ≥ 10 m^2 in seabed imagery (e.g., towed video), or 2) meadows may be indicated (although not verified) where key species contribute at least 30% of the volume of the catch from towed sample gear, or 3) occur in two successive samples collected by point sampling gear.	(Thrush et al. 2011; Anderson et al. 2019; Douglas 2019)
Beds of large bivalve molluscs	1) 30% or more of the seabed in a visual image (e.g., *Atrina*, *Perna*, *Mytilus* spp.), or 2) where catches contribute 30% or more by weight or volume in a single dredge tow or grab sample.	(Thrush et al. 2011; MacDiarmid et al. 2013; Anderson et al. 2019; Douglas 2019)
Calcareous tubeworms	1) One or more tube worm mounds are visible for each 250 m^2 of seabed covered during an imaging survey or, 2) two or more intertwined specimens of a mound forming species of tube worm are found in any point sample, or 3) tube worm species comprise 10% of the catch by weight or volume in towed samples.	(MacDiarmid et al. 2013; Anderson et al. 2019; Douglas 2019)

Biogenic habitat	Description and suggested threshold abundance to delineate biogenic habitat	Source
Non-calcareous tubeworms	1) Where tubeworms (and any attached epifauna) cover > 500 m^2 of seafloor, or 2) occupy 25% or more of the seabed in imaging surveys covering an area of 500 m^2, or 3) contribute at least 25% of the weight or volume of the catch from towed sample gear, or 4) occur in two successive samples collected by point sampling gear.	(Thrush et al. 2011; MacDiarmid et al. 2013; Anderson et al. 2019; Douglas 2019)
Bryozoan thickets	1) Colonies of large frame-building bryozoan species cover at least 50% of the seabed in visual imaging surveys over an area of 10–100 m^2, or 2) colonies of large frame-building bryozoan species cover at least 4% of the seabed in visual imaging surveys over an area that exceeds 10 km^2, or 3) one or more colonies of large frame-building bryozoan species occur per m^2 of seabed sampled using towed sampling gear, or 4) one or more large frame-building bryozoan species is found in successive point samples.	(Thrush et al. 2011; MacDiarmid et al. 2013; Wood et al. 2013; Anderson et al. 2019; Douglas 2019)
Rhodolith beds	1) More than 10% cover of living coralline thalli in a visual image, or 2) a single occurrence of a rhodolith species in a towed or point sample.	(Steller et al. 2003; Thrush et al. 2011; MacDiarmid et al. 2013; Anderson et al. 2019; Douglas 2019)
Sponge gardens	1) Greater than or equal to 25% cover over an area of 100 m^2, or 2) where sponge specimens contribute to ≥ 20% of the volume of the catch from towed sampling gear, or 3) ≥ 25% of the volume in a successive grab sample.	(Thrush et al. 2011; MacDiarmid et al. 2013; Anderson et al. 2019; Douglas 2019)
Stony corals	1) Live or dead colonies of structure-forming species cover 15% or more of the seabed in a visual imaging survey covering 100 m^2, or 2) one or more specimens of thicket-forming species are found in two successive point samples, or 3) one or more structure-forming species is found in a sample collected using towed gear.	(MacDiarmid et al. 2013; Anderson et al. 2019)
Sea pens	1) Two or more individuals per m^2 in seabed imaging surveys, or 2) one or more specimens of any species of sea pen is found in two successive samples collected using point sampling gear.	(Thrush et al. 2011; MacDiarmid et al. 2013; Anderson et al. 2019)
Xenophyophores	One or more individuals per m^2 using any sampling method. Typically found at depths > 500 m.	(MacDiarmid et al. 2013; Anderson et al. 2019)
Brachiopod beds	1) One live brachiopod occurs per m^2 of seabed sampled using towed gear, or 2) one or more live specimens occur in successive samples obtained using point sampling gear.	(MacDiarmid et al. 2013)
Seagrass beds	Greater than 60% plant cover, within an area of 10 000 m^2 or more. Areas smaller than this are referred to as seagrass patches.	(Thrush et al. 2011; Anderson et al. 2019; Douglas 2019)

Existing spatial datasets of biodiversity and species assemblages

Invertebrate species distribution models (SDMs) produced for a previous NIWA client report prepared for the Department of Conservation (Lundquist et al. 2020a) were used in this project. These layers were included to represent 'biodiversity' and were collated into several taxa groups for reporting: polychaetes, bivalves, bryozoans, corals, crustacea, echinoderms, gastropods, octopuses, sponges, and 'other epifauna' (198 modelled layers in total). Modelled layers (probability of occurrence and uncertainty layers) were clipped to the HGMP area and resampled (nearest neighbour) from a grid size of 1 km × 1 km to 250 m × 250 m. Other layers for reporting included mangrove and seagrass habitat layers (polygons) which provide a broad indication of habitat extents (Figure 4). For spatial analyses, these layers were converted into raster grids (250-m grid). Finally, scallop survey strata (dive and dredge) polygon spatial datasets were included to provide a broad indication of scallop habitat in the HGMP (Williams & Parkinson 2010; Williams et al. 2013). These layers represent the dredge and dive survey areas for 2021 (Figure 4). Broadly within these survey strata areas, estimated scallop catch-rate (density per square metre) between 1995 and 2021 was used to construct a layer for reporting. The density data available for this process were in point form (location data with density estimate). These points were converted to a raster grid (250 m); where multiple points occurred in the same grid cell, average density was used.

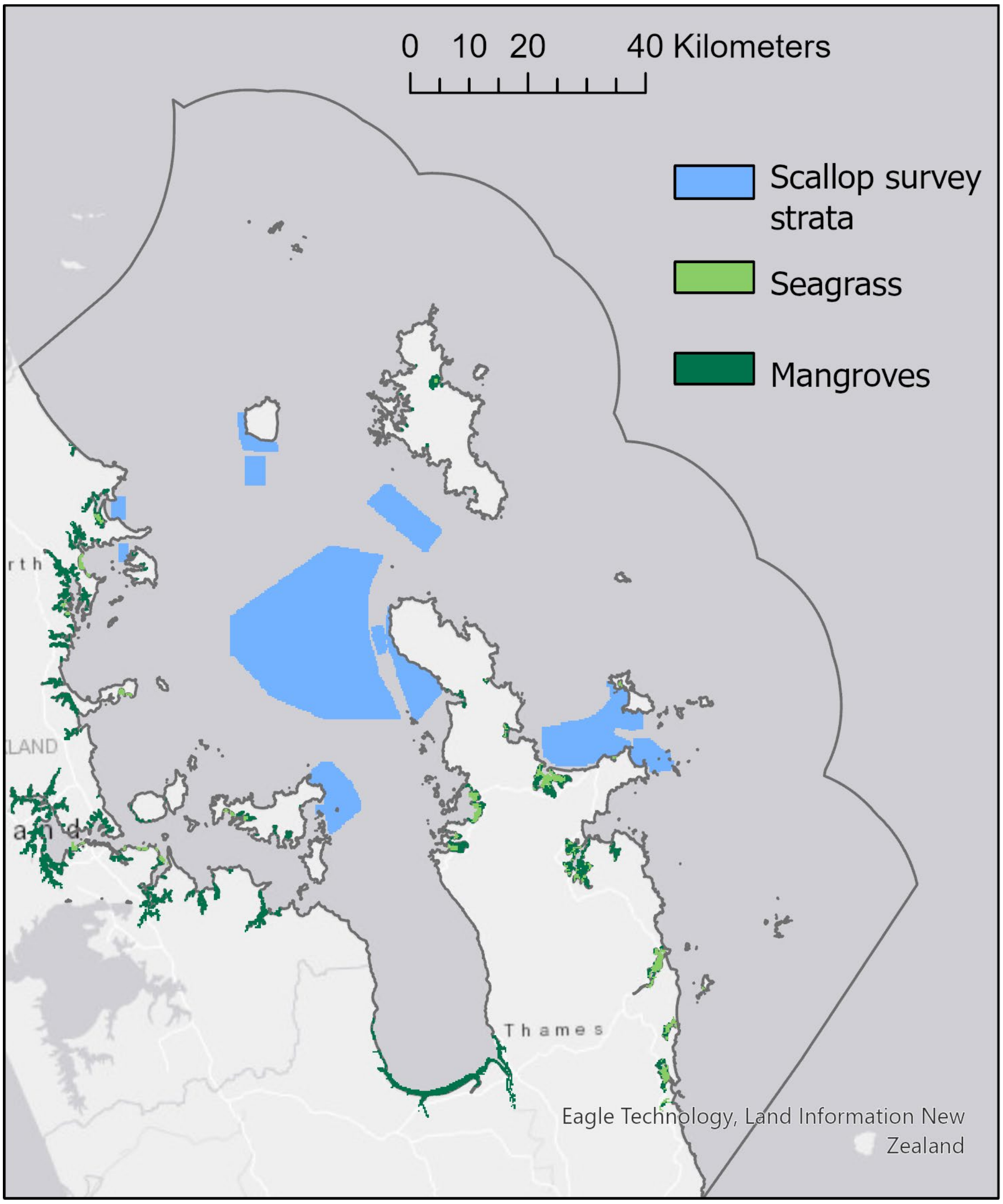

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Figure 4: Dive and dredge scallop survey (2021) strata locations and seagrass and mangrove habitat extent in the HGMP.

An additional NIWA client report (Stephenson et al. 2021b) involved the development of the 'seafloor community classification' (SCC), a 75-group classification of the seafloor environment. For this work, the SCC layer was clipped to the HGMP area. For reporting, each group was extracted from this resulting layer, producing individual layers for each SCC group represented in the HGMP (20 groups in total, Figure 5). To assess uniqueness of SCC groups within the HGMP, compared to the HGMP, the Territorial Sea, and whole EEZ areas, proportions of groups represented were calculated (Table 2).

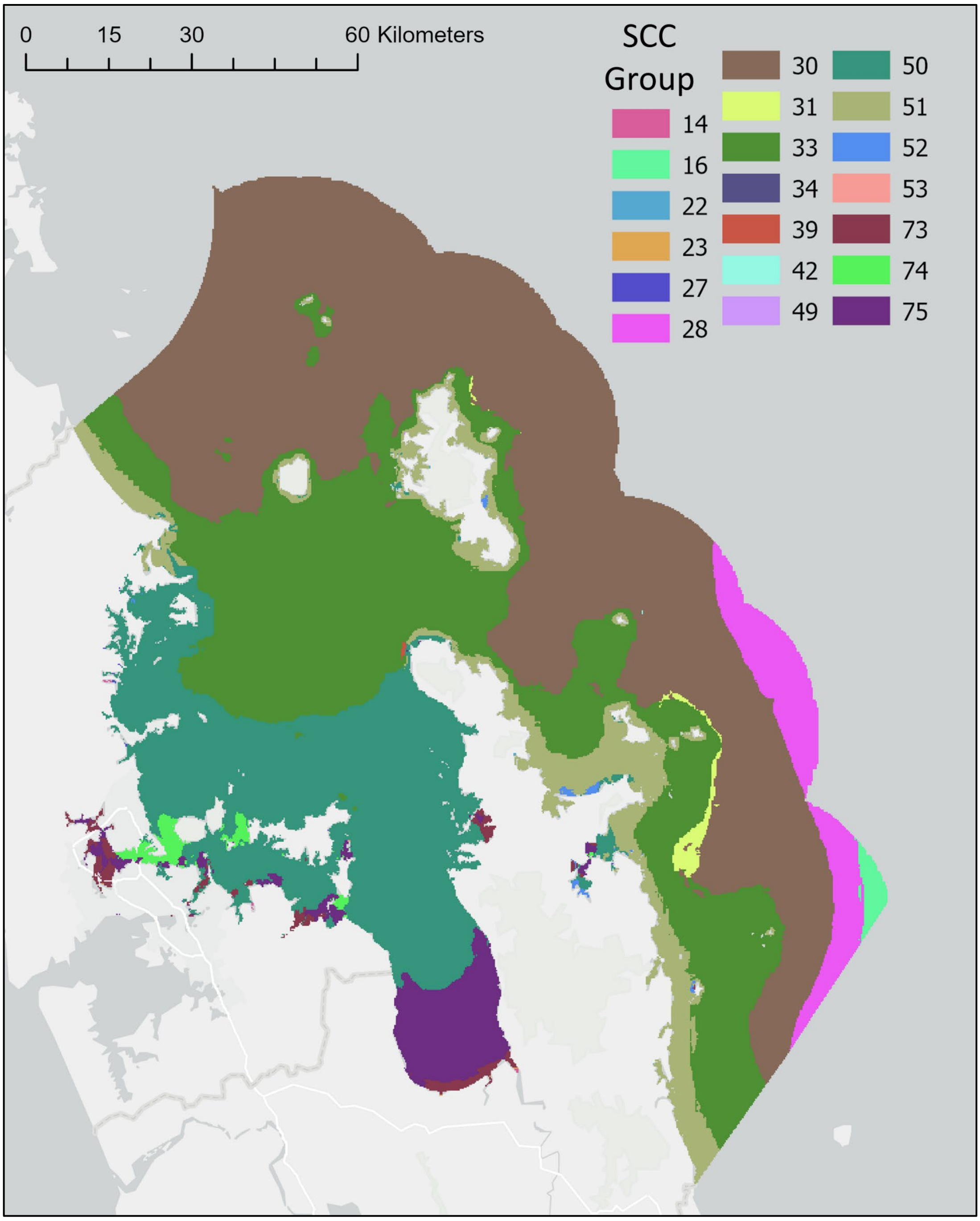


Figure 5: Seafloor community classification (SCC) groups in the HGMP. Proportions of groups represented in the HGMP are shown in Table 2.

Table 2: The percentage of each Seafloor Community Classification (SCC) group found in the Hauraki Gulf Marine Park (HGMP) is shown in the table below. The first column lists each SCC group found in the HGMP, the second shows the proportion of each group found in the HGMP as a percentage of the total HGMP area. Column three shows the percentage of each group as a proportion of the Territorial Sea (to 12 n. mile offshore), the final column shows the same, but for the entire Economic Exclusion Zone (EEZ). Groups highly represented in the HGMP (> 20% of EEZ) are highlighted. See SCC groups in Figure 5.

SCC group	Percentage (%) of SCC groups in HGMP (layer extent: HGMP)	Percentage (%) of SCC groups in HGMP (layer extent: Territorial Sea)	Percentage (%) of SCC groups in HGMP (layer extent: EEZ)
14	0.01	0.05	0.01
16	0.39	3.38	0.10
22	0.00	0.09	0.00
23	0.00	0.08	0.01
27	0.01	0.33	0.32
28	3.68	13.56	2.13
30	40.65	30.95	9.76
31	0.43	1.55	1.25
33	25.80	24.80	23.10
34	0.00	0.00	0.00
39	0.01	0.05	0.02
42	0.00	0.01	0.01
49	0.00	0.02	0.00
50	18.02	67.04	66.59
51	6.55	20.21	19.11
52	0.10	0.31	0.31
53	0.00	0.01	0.01
73	0.64	11.84	11.84
74	0.52	20.13	20.13
75	3.17	36.95	36.95

Point records for biogenic habitats and benthic biodiversity

Point records (species occurrence data) were sourced from several databases (e.g., Table 3, Figure 6). In the first instance, repository data provided the basis for many species records within the HGMP. These initial datasets provided the basis for further data compilation by providing a starting point to build on. These repositories include Ocean Biodiversity Information System (OBIS), *niwainvert*, *niwaalgae*, and TRAWL database (Fisheries New Zealand). These repositories host species occurrence data, with varying amounts of taxonomic and other metadata. Often, data hosted in these repositories is hosted on behalf of other organisations and institutions (e.g., Te Papa Museum and Auckland Museum), and permissions to use various databases were requested when required. Much of the species records compiled for this project were pooled for previous NIWA client reports for separate projects (Lundquist et al. 2014; Stephenson et al. 2018b; Lundquist et al. 2020a; Stephenson et al. 2021b). When compiling these data, emphasis was placed on biogenic habitat-forming species, i.e., reef-forming molluscs, sponges, bryozoans, macroalgae, and brachiopods.

Miscellaneous data sources

Point records were also sourced from various one-off projects and from individuals with datasets generated following years of research in the HGMP area. Examples from various sources include *Perna canaliculus* records compiled for the MBIE Moana project by Carolyn Lundquist (NIWA), rhodolith records compiled by Mark Morrison (NIWA), macroalgae records gathered by Nick Shears (funded by

Department of Conservation), and *Atrina zelandica* records compiled by Clinton Duffy (Department of Conservation). See Table 3 for a full list of data sources compiled for this project.

Table 3: Data sources, reference for data source, number of unique locations of species data within each data source, and number of presences and absences obtained from each data source. Note: absence data are heavily inflated here. For instance, with Compton et al. (2012), the large number of absences obtained is for every site and every taxon; where a presence and absence overlap, the presence is favoured. Therefore, the number of absences available for use in the models was significantly smaller.

Data source	No. of unique locations	Presences	Absences
NIWA Invertebrate Collection Specify database (*niwainvert*), including fisheries datasets for which taxonomic identification was performed	–	256	0
OBIS	–	124	0
Auckland Museum	–	542	0
Te Papa Tongarewa Museum of New Zealand	–	87	0
iNaturalist (GBIF Research grade)	–	10	0
Specify database (*niwaalgae*) (also includes records from Auckland Museum and Te Papa Tongarewa Museum of New Zealand)	–	8 674	0
Lundquist et al. (2014)	–	186	0
Chiaroni et al. (2008)	327	738	4 027
Chiaroni et al. (2010)	239	141	4 233
Thrush et al. (2001)	10	162	268
Thrush et al. (1998)	17	149	616
Hewitt et al. (2004)	122	322	0
Clinton Duffy horse mussel point records	87	87	0
Whitten (1979)	28	579	0
Wood (2014)	15	45	0
Morrison et al. (2016)	27	159	753
Morrison et al. (2000)	71	7	64
Compton et al. (2012); projects CO1X0506 and CO1X0907	2 371	1 610	164 433
Juvenile Bottlenecks Programme (M. Morrison, unpublished data); project CO1X1618	339	363	19 774
Morrison et al. (1999)	–	5	107
Lohrer & Douglas (2019)	56	97	1 302
UoA video surveys (J. Hillman, T, Evans, and S. Schenone, unpublished data)	159	99	1 333
M. Morrison (unpublished data); Dewas & O'Shea (2012); Morrison et al. (2009); Morrison et al. (2003); Morrison (1999)	–	12	0
Morrison et al. (2002)	43	34	670

NIWA client reports

Habitat surveys contracted to NIWA by Auckland Council (ARC07212 & ARC09212) offered another source of data for the HGMP (Table 3). These projects (Chiaroni et al. 2008; Chiaroni et al. 2010) used several different sampling methods, including video surveys; all of which provide additional data points within the HGMP, particularly within the Kawau Bay area. Many points extracted from associated datasets for this work consist of taxa in the classes Bivalvia and Polychaeta. Quality control of these data included removal of entries with incomplete taxonomic information or records which were not of interest (i.e., non-biogenic habitat forming like crustaceans) for the purposes of this work.

An acoustic and video survey of soft sediment habitats in the Whitford Embayment as part of a NIWA client report for Auckland Regional Council (2000, AK00083) provided another source of species occurrence records (Morrison et al. 2000). Similarly, a NIWA client report for Auckland Regional Council (1999, AK99087) using the same techniques (Morrison et al. 1999), provided another source of biogenic habitat presence (and importantly, absence). A further NIWA client report prepared for Department of Conservation in the Firth of Thames area (using video and acoustic survey methods) provided additional sources of biogenic habitat presence-absence (Morrison et al. 2002). These three reports, collectively, did not provide many unique locations representing biogenic habitat presences. However, due to the video survey technique used, considerable amounts of absence data could be inferred.

In the HGMP, the Cableway Protection Zone, extends from the inner Hauraki Gulf to the outer harbour and extends north (parallel to Aotea/Great Barrier Island and the Coromandel Peninsula, Figure 1A). A towed-camera survey was used to assess the protection offered by the CPZ ban on all fishing and anchoring for seafloor assemblages (Morrison et al. 2016). Species presence-absence data was therefore available for five blocks along the CPZ, wherein each block consisted of two transects (Figure 6).

Following, the creation of a biogenic ecosystem services layer for the Hauraki Gulf using the Ecosystem Principles Approach (Townsend et al. 2011), empirical validation of the modelled layer was carried out with ground-truthed data (Townsend & Lohrer 2019). The ground-truthing involved a video survey in the Hauraki Gulf at Motu Aotea (Great Barrier Island) in 2015 (Lohrer & Douglas 2019). Subsequently, these drop-camera surveys provide additional point records for a wide range of biogenic habitat forming species, predominantly for macroalgae and sponges.

Research

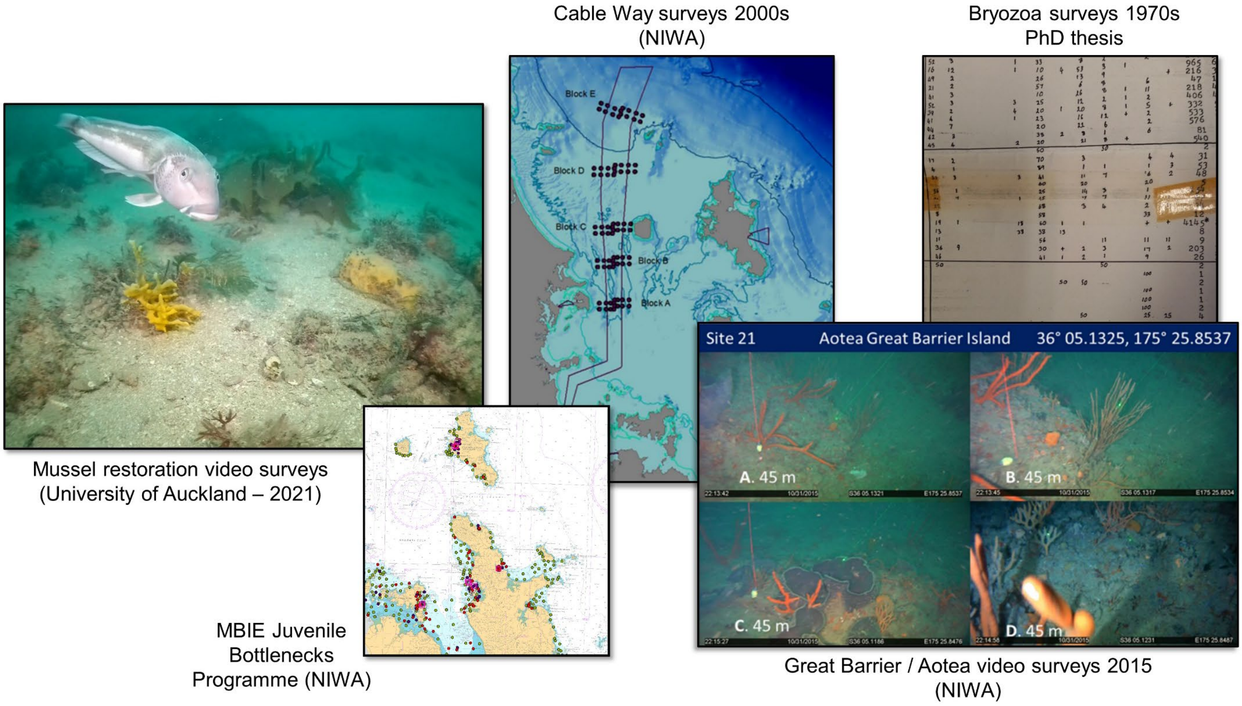
Research conducted by individuals, institutions (universities), and organisations provided another key source of biogenic habitat occurrence data. Academic papers published in the late 1990s and early 2000s provided a source of 100s of records of biogenic habitat forming species. These published works included studies focused on the impacts of commercial fishing on benthic habitats and species assemblages (Thrush et al. 1998; Thrush et al. 2001). Additionally, a specific study that mapped biogenic habitats (video and side-scan sonar surveys) provided a key source of data in the Kawau Bay area of the HGMP (Hewitt et al. 2004).

Grab samples collected by I. C. Thompson in 1973 and 1974, samples collected by the New Zealand Oceanographic Institute, and samples gathered by SCUBA in the late 1970s were the basis of a PhD thesis (Whitten 1979) on the "Systematics and Ecology of Northern Hauraki Gulf Bryozoa". The thesis collected, identified, and curated data representing 180 Bryozoa taxa at 109 sites within the Hauraki Gulf. Data were recorded as percentage occurrence of a given taxon in a sample. As the author also included the number of Bryozoa specimens in each 15-g sample taken at each site, it is also possible to calculate a proxy abundance of each taxon at each site by multiplying 'percentage of occurrence' by 'number of specimens in 15 g of sediment'. However, for this project, this dataset was reduced to presence-absence because it could not be confirmed whether taxa sampled by grab were alive or dead.

Bryozoa point records compiled for an additional PhD thesis (Wood 2014) were included in this project. This dataset was used to model the spatial distribution of several Bryozoa taxa in New Zealand (Wood et al. 2013). Of the records compiled within this dataset, only 15 were for unique locations within the HGMP.

Research from tertiary institutions provided a significant source of data for this work. Surveys carried out for a variety of projects focused on mussel (*Perna canaliculus*) restoration were compiled and provided by the University of Auckland (Figure 6). Video and image surveys conducted by students and researchers at the University of Auckland at Aotea/Great Barrier Island and Te Hauturu-o-Toi/Little Barrier Island, and Kawau Bay resulted in additional new point records of biogenic habitat presence-absence. Videos were examined, and presence-absence and abundance (where counts were available) of biogenic habitat-forming species were recorded. Unique location information was recorded via geotagged images/videos.

Two large research projects funded by the Ministry of Business, Innovation & Employment (MBIE) provided a source of systematically collected species occurrence records within the bounds of the HGMP. Both research projects place overarching focus on benthic habitats and associations with economically important fish species. The first (funded under CO1X0506 and CO1X0907), provided systematically gathered data (via video/camera surveys) in the inner Hauraki Gulf area (near the Waiheke, Rangitoto, and Motutapu islands) (Compton et al. 2012). The second, the Juvenile Bottlenecks Programme (CO1X1618) (M. Morrison, unpublished data), provided another set of systematically gathered species occurrence records, but over a much larger area of the HGMP (Figure 6) and focused on seafloor habitat and fish associations. Specifically, it provided species occurrence records gathered by beam trawl for the compiled dataset. Abundance data were also available from this dataset, in millilitres (derived by graduated bins on-deck). Within the HGMP, survey data available for this project were collected in 2017, with high coverage in the inner Hauraki Gulf, as well as the western sides of Aotea/Great Barrier Island and Te Hauturu-o-Toi/Little Barrier Island and east and west of the Coromandel Peninsula.



Cable Way surveys 2000s (NIWA)

Bryozoa surveys 1970s PhD thesis

Mussel restoration video surveys (University of Auckland – 2021)

MBIE Juvenile Bottlenecks Programme (NIWA)

Great Barrier / Aotea video surveys 2015 (NIWA)

Figure 6: Examples of data sources for modelling the spatial distribution of biogenic habitats in the HGMP. From left to right: University of Auckland video surveys, MBIE-funded Juvenile Bottlenecks Programme (CO1X1618, M. Morrison), Cableway Protection Zone (CPZ) surveys (Morrison et al. 2016), Aotea/Great Barrier Island video surveys (Lohrer & Douglas 2019) and Bryozoa surveys (grab and dive) (Whitten 1979).

Characterising biogenic habitats in the HGMP

Point records of biogenic habitat locations (i.e., biogenic habitat forming species occurrence) are generally not effective for spatial planning exercises in their raw format, due to sampling bias (location and target taxa) and subsequent uneven coverage across study/management area. To circumvent this issue, and meet objective 3 of this project, spatial distributions are often modelled using available point record information and a suite of environmental layers that can be used to train and predict species occurrence into unsampled space. Models using this approach have been implemented throughout Aotearoa New Zealand, at various scales, for various spatial planning tasks (Compton et al. 2012; Wood et al. 2013; Stephenson et al. 2021c). Probability of occurrence (providing a habitat suitability index, HSI) models are often used when data available for modelling is presence-only or presence-absence (Binomial). If species density information is available to modellers, several modelling approaches (e.g., density, hurdle-models) can be used to estimate species abundance (e.g., Gaussian or Poisson). For this project, abundance models were tested in early stages of model development, but due to limited available data on abundance, and subsequent performance, these models were not deemed to be sufficiently robust for use in the process, and instead all further analyses relied on the production of probability of occurrence models.

Taxa and groupings

There were not enough species occurrence records in the compiled dataset to allow for modelling at species or genus level (Figure 7). Thus, distinct biogenic habitat groups required definition for modelling. To maximise the limited number of point records for various biogenic habitat-forming taxa in the HGMP, taxa were classified into biogenic groups which best reflected their ecology and (or) morphology (Table 4). This process was case by case, for example 'horse mussels' were simply grouped by taxonomic classification (i.e., genus *Atrina*), but for Bryozoa and Porifera, the use of a coarse taxonomic classification was deemed to be less useful in the identification of particular types of biogenic habitats. For this reason, expert advice was sought from several taxonomic and ecological experts (see Acknowledgements section) to develop biogenic habitat groups that best reflected biogenic habitats and species assemblages with similar ecological functions in the HGMP.

Many of the selected groupings place emphasis on shared characteristics of suitable habitat, rather than separation into higher taxonomic levels. Under a similar guise, a baseline habitat mapping study was performed in the Hauraki Gulf (Aotea/Great Barrier Island) (Lee et al. 2015). The authors in this study combined certain taxa with substrate information to develop four 'biotopes': 1) shallow water macroalgae on rocky substrate; 2) diverse sponge and bryozoan epifauna on rocky substrate; 3) brittle stars and sea anemones on muddy sand; and 4) hydrozoans on mud. Here, we use a wider range of biogenic habitat groups for Cnidaria, Porifera, Bryozoa, Bivalvia, and Annelida. Taxonomic and expert advice was followed except in some instances where compromises had to be made due to data quality and availability, where the number of records were insufficient to model some suggested biogenic habitat groupings. Individual point records were assessed to determine if any protected species records were present in the HGMP. While no protected species taxa were specified for those taxa for which full identification had occurred, a large proportion of records were taxonomically unresolved (i.e., 'erect sponge'), thus there is potential that protected species were included within the modelled taxa.

The counts provided in Table 4 are based on the records used for modelling where records have been filtered to only allow one record representing the presence of a biogenic group per grid cell, though some cells were represented by multiple point records for the same biogenic habitat group. As an example, for erect/upright sponges, > 1000 point records representing presence of this biogenic group were available; however after removing duplicates in each grid cell, a total of 531 records were used for the model. Thus, counts represent the total number of unique cells with presence records for that biogenic habitat group, and not the total number of available records.

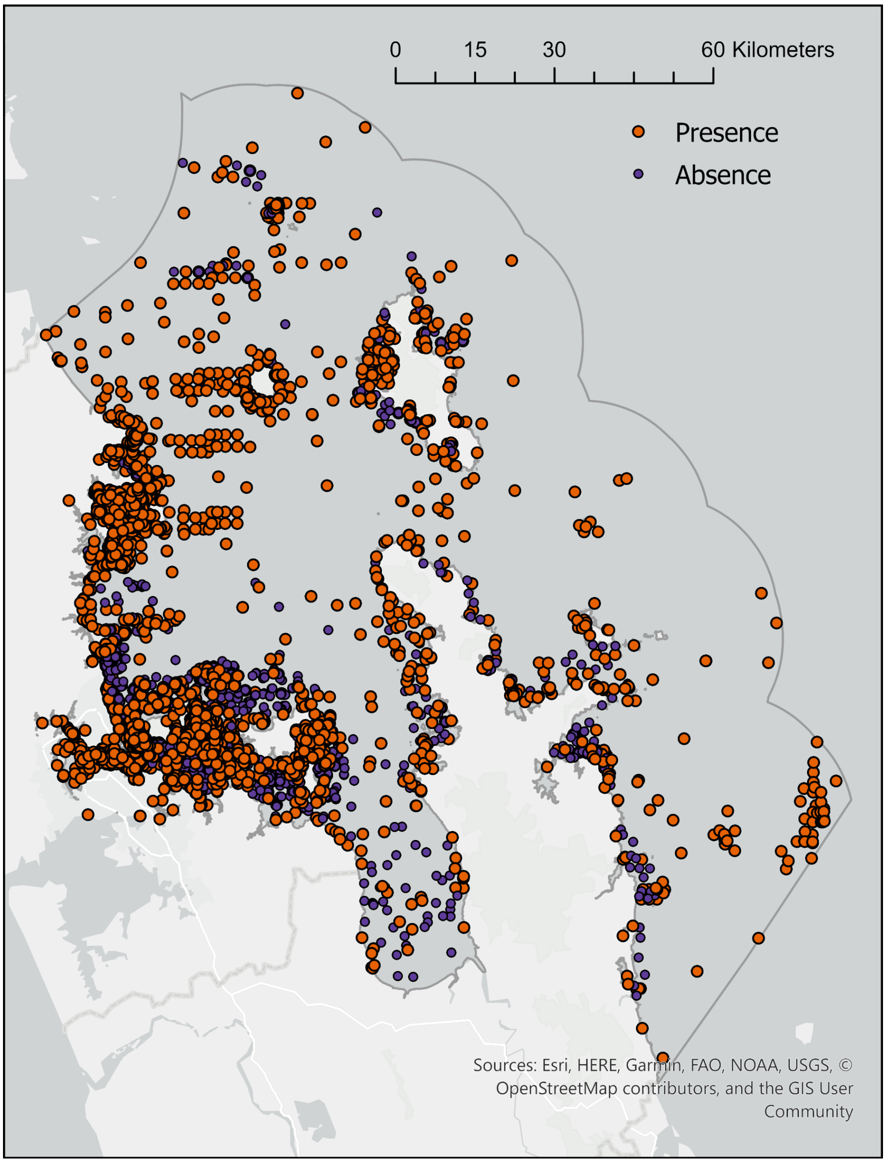


Figure 7: Presence (orange) and absence (purple) records of all biogenic habitats within the Hauraki Gulf Marine Park (thin line indicates HGMP boundary).

Cnidaria

Considering expert advice, point records for taxa in the phylum Cnidaria were grouped for modelling biogenic habitats. That is, specific 'ecotypes' were used to divide taxa instead of an arbitrary higher taxonomic classification grouping approach. This approach was considered superior as it was more morphologically and ecologically relevant. For instance, *Polycyathus* and *Caryophyllia* are two genera in the Family Caryophylliidae, but the morphology and ecology of these taxa are quite distinct (the former being colonial and the latter being solitary). Thus, these two genera were grouped separately for this study.

One consideration to note is the absence of certain species from our analyses, despite their known presence near the HGMP. An example of this is *Oculina* spp., where divers report their presence, for instance, at the Poor Knights Islands ~ 60 km north of the HGMP (Di Tracey, NIWA, pers. comm.). Though due to the attachment of *Oculina* spp. on the underside of shelves, individuals of this genera would not be readily obtained by typical sampling methods (like benthic trawls), hence their absence from point record datasets, despite their known abundance within the wider region.

Many Cnidaria taxa constitute biogenic habitat (e.g., Scleractinia & Alcyonacea). Experts advised that several groups could be developed from Anthozoa taxa records. When considering life histories, it was suggested that cup corals (e.g., *Flabellum* and *Monomyces*) be modelled independently due to their habitat/niche requirements compared to other suggested groupings. Given the large amount of data available, sea anemones were modelled as a separate group (i.e., Actiniaria). Next, Hydrozoa were split into a separate group for modelling. Several other groupings were suggested and/or discussed with experts including soft corals (Alcyonacea) and sea pens (Pennatulacea). However, given the low number of species records available, all remaining records were compiled into a higher-level taxa group 'Misc. Anthozoa' for modelling.

Bivalves (Mollusca) & Brachiopoda

Bivalve species were split into biogenic habitat groups based on life histories and data availability. Foremost, given the amount of data available, a group for horse mussels *Atrina zelandica* was developed. This is the only biogenic habitat group at the species level. Two other groups were developed based on reef-forming capacity and similar life histories, one for 'Mussels' (Mytilidae) and another for oysters.

During the expert consultation process, several decisions were made pertaining to bivalve species that constituted biogenic habitat-formers in the Hauraki Gulf, and whether they should be included in models and subsequent assessments of protection offered spatial planning exercises. It was decided that invasive and non-native species (e.g., Asian date mussel, *Arcuatula senhousia* and Pacific oyster, *Magallana gigas*) would not be included, given their potential negative impact to native flora and fauna in the HGMP. That is, they are not a target for protection and/or recovery. Further, the decision was made to not include infaunal bivalve species, i.e., those species which reside in the sediment beneath the surface of the seafloor, and rather to focus on epifaunal biogenic habitats that are more sensitive to fishing impacts. Finally, a further decision was made to exclude mobile bivalve species from the analysis, such as scallops (e.g., *Pecten novaezealandiae*). Although aggregations of scallops can form 'scallop beds', their mobility was deemed counter to the concept of 'biogenic habitat-forming' which, in the context of this report, is considered a stationary refugium. It was hoped that scallop-associated habitat would instead be captured in the 'multispecies aggregations' group described below, as dead shell records (included those of scallops) were included in this model group. Essentially, this left three key biogenic habitat forming bivalve groups: large mussels (> 60 mm in length), small mussels (< 60 mm in length), and oysters. Invasive bivalve species records were excluded.

A group was formed with all Brachiopoda records available (phylum level, similar life histories to bivalve molluscs). All the taxonomically identified Brachiopoda records were for genera in the family Terebratellidae.

Porifera

Sponges (Porifera) are dynamic taxa with diverse life histories. For instance, some taxa are delicate (Hexactinellida; glass sponges), while other, massive cup forming sponges like *Ecionemia alata* are more robust compared to the fragility of glass sponge morphologies. While discussing the potential groupings for sponge taxa records, several suggestions were made, including the concept of 'inner' and 'outer' Hauraki Gulf sponge ecotypes. To better inform spatial planning solutions (when considering fishing impact) and to better align niche requirements of grouped taxa for modelling, two groups for sponges were formulated. The two groups are 'encrusting' and 'erect/upright' sponges. Literature (Lee et al. 2015; Kelly & Herr 2018; Lohrer & Douglas 2019) and expert input informed taxonomic breakdown of groups. Additionally, many of the species records available for modelling were taxonomically unidentified records, e.g., descriptions from video surveys like "yellow finger sponge". In this case, this record would have been assigned to the erect/upright sponge group.

Bryozoa

As for the biogenic habitat groups/taxa above, Bryozoa taxa were grouped in an ecologically relevant way (for the Hauraki Gulf) to maximise the limited number of records available. Based on expert advice, it was decided that the best way to group taxon was instead largely by niche habitat requirements. This grouping approach matched the approach used for Cnidaria, Porifera, and Annelida. Three groups were used for the modelling, wherein point records of species presence were pooled. The first group contained bryozoan taxa which are typically found on hard/rocky substrates (frame-building Bryozoa). The other two groups comprised bryozoan taxa that are generally associated with less hard substrate, i.e., gravel and/or shell rubble (encrusting Bryozoa, erect and rooted Bryozoa). One of latter groups (encrusting Bryozoa) represented a significant challenge as they do not fit the typical definition of biogenic habitat-forming (i.e., frame-building) bryozoan species (Duncan 1957; Wood et al. 2012; Wood et al. 2013). However, expert advice suggested that omitting these taxa would exclude significant possible bryozoan biodiversity (D. Gordon, NIWA, pers. comm.), such that although not technically 'habitat-forming species', many of the taxa in this second group represent significant biogenic habitat-forming potential by contributing to multi-species aggregations/species assemblages that constitute biogenic habitat.

Annelida

Characterised during the literature review process (Table 1), two groups for Annelids or worms were developed, with one for calcareous tube-forming worms (i.e., Serpulidae) and another for non-calcareous tube forming worms (i.e., Sabellidae). The latter group is typically associated with hard substrates. After further consultation with ecologists, a third group named 'Miscellaneous annelid assemblages' was developed to contain a variety of other epibenthic annelids. This third group was created to capture biogenic habitats featuring diverse annelid assemblages which would not fit into two groups described above. Invasive annelid species records were excluded.

Multi-species aggregations that support biogenic habitats

Soft sediments are not devoid of biogenic habitat forming species. A hard substrate lends itself towards habitat-forming species given 3-dimensional structure, which can offer shelter and predation protection and provide settlement surfaces for plants and animals. In soft sediment habitats, hard structures available for settlement and refuge are harder to come by. One notable exception comes in the form of dead shell accumulations. Piles of mollusc shell debris can be found scattered on the seabed, and through physical or biological processes, can become aggregated or accumulated in patches. These patches form a substrate for species to settle, and some of these species are biogenic reef forming, e.g., encrusting sponges and bryozoans, and tubeworms that settle on shell debris (Hewitt et al. 2004; Morrison et al. 2016). To capture these potential biogenic clumps/patches or multi-species aggregations that support biogenic habitats, all records for biogenic patches (Morrison et al. 2016) and dead mollusc shell records (from several previous studies) were compiled. While a specific model for scallops was not developed, scallops create habitats posthumously in the form of shell hash. The contribution of scallops to surface complexity, and ultimately biogenic habitat procurement, was therefore incorporated into this model via dead shell records. However, as few of the available dead shell records were taxonomically identified, it is therefore not possible to know the proportional contribution of different taxa to shell hash in this model group. As there were not enough dog cockle (*Tucetona laticostata*) records to develop a specific dog cockle model, these records were included in the multi-species aggregation model as dog cockle habitats are well recognised for the shell debris substrata that they create for biogenic habitat-forming species (Morrison et al. 2014).

Macroalgae

Large brown macroalgae (kelps) and canopy-forming algae are well recognised biogenic habitat-forming species in coastal areas (Teagle et al. 2017). Their three-dimensional structure offers refugia for species (e.g., juvenile fishes), their holdfasts, stipes, and blades provide substrate for flora and fauna, while their presence modulates conditions for understory assemblages (Teagle et al. 2017). Records for large brown algae were grouped into a 'canopy-forming macroalgae' group, i.e., large browns (Neill et al. 2016). Rhodolith records were extracted (e.g., *Lithothamnion* and *Sporolithon*) and modelled as a separate macroalgae group given their comparatively different life-history stages as crustose calcareous nodules opposed to blade-forming Fucales, for example. Many other macroalgae species provide habitat for species assemblages. To capture these taxa, all macroalgae species that did not fall into the first two groups were modelled as a third "Miscellaneous macroalgae" group. Invasive macroalgae species records were excluded.

Table 4: Modelled biogenic groups are shown as well as the respective sources of presence and absence data for each modelled group. Number of orders and genera represented by the model is shown as well as the total number of presence records used in each model. Finally, the number of records (of the total) which were of a low taxonomic resolution, i.e., could be "upright sponge" described from video surveys are shown. Due to low taxonomic resolution records, the total number of orders and genera represented in each model could be higher than the figures shown. (Continued on next page)

Modelled biogenic habitat group	Group	Group description	Orders	Genera	Total no. presence records used in models	No. of records observed via video – limited taxonomic resolution (incl. in total presence records)
ANTH	Miscellaneous Anthozoa	All Anthozoa records except for sea anemones, cup corals, and Hydrozoa	4	9	67	6
Biogen	Biogenic patches/lumps or multi-species aggregations that indicate biogenic habitat	Multi-species aggregations that indicate biogenic habitat. Models created with records for 'biogenic lumps', dog cockles, and dead shell debris	–	–	346	–
BRAC	Brachiopoda	All Brachiopoda records	1	4	53	20
CALC	Calcareous tubeworms	All calcareous tubeworm records, e.g., Serpulidae	2	7	26	
CANSW	Canopy-forming macroalgae	Large brown macroalgae, e.g., *Ecklonia* and *Carpophyllum*	4	9	308	67
CUP	Cup corals	All cup coral records, mostly *Monomyces* and *Flabellum*	1	4	44	1
ENCB	Encrusting Bryozoa	Encrusting bryozoan taxa, list created based on literature and expert advice	3	28	120	7
ENCSP	Encrusting sponges	Encrusting sponge taxa, list created based on literature and expert advice	13	19	245	92
ERCSP	Erect/upright sponges	Erect/upright sponge taxa, list created based on literature and expert advice	13	27	531	162
ERCT	Erect/structure-forming Bryozoa	Erect/frame-building bryozoan taxa, list created based on literature and expert advice	4	11	48	10
EROO	Erect and rooted Bryozoa (soft sediment associated)	Erect and rooted bryozoan taxa (soft sediment associated), list created based on literature and expert advice	4	6	24	1

Modelled biogenic habitat group	Group	Group description	Orders	Genera	Total no. presence records used in models	No. of records observed via video – limited taxonomic resolution (incl. in total presence records)
HSM	Horse mussels	All point records for *Atrina* spp.	1	1	477	–
HYD	Hydrozoa	All point records for taxa in the class Hydrozoa	2	5	30	30
MUS	Mussels	All point records for mussels, i.e., Mytilidae	2	9	101	6
OYS	Oysters	All point records for oysters	1	2	42	20
Rhodoliths	–	All rhodolith (*Lithothamnion*, *Sporolithon*) point records and observations (videos and M. Morrison, pers. obs.)	–	2	24	18
SEA	Sea anemones	All point records for sea anemone taxa	3	11	137	84
SURF	Miscellaneous annelid assemblages	Generally soft sediment associated taxa, some tube forming; mostly taxa in the orders Terebellida, Eunicida, and Spionida	3	45	209	32
SWIL	Miscellaneous macroalgae	All macroalgae taxa records remaining following the removal of canopy-forming macroalgae and rhodolith records	25	90	424	52
TUBE	Non-calcareous tubeworms	Generally hard substrate associated taxa; mainly Sabellidae	1	12	192	122

Data pre-processing

Once all available point records, environmental layers, and modelled layers (produced for previous projects) had been sourced for the HMGP area, several quality control and pre-processing steps were taken. First, only taxa which had been identified as biogenic habitat-forming taxa in the Hauraki Gulf were retained. In the first instance, a list of all taxa with point records available was collated for the Hauraki Gulf from multiple sources (e.g., Auckland Museum, NIWA invertebrate collection, and TRAWL). At this point, an initial 'trimming' of point records was employed. For this study, it was decided that invasive species (e.g., the Asian date mussel, *Arcuatula senhousia*) and infaunal species would not be assessed. While it is acknowledged that infaunal species can create significant biogenic habitats, without adequate information on abundance it was not possible to accurately assess when certain species might simply occur rather than when their abundance was high enough in the sediment to be deemed biogenic habitats. Additionally, mobile species were excluded from assessment, despite the 'habitat-forming' potential of some species, for instance scallop beds (*Pecten novaezelandiae*). The mobility was therefore a disqualifying characteristic as while habitats might be formed, they would be transient and thus not fit the definition of biogenic habitat-forming species employed here. Other disqualified species included mobile taxa of Gastropoda, Crustacea, and Echinodermata.

After expert evaluation, this list was further reduced. Retained taxa were only those deemed as 'biogenic habitat-formers' by a panel of experts. At the same time, an assessment was made of whether point records were realistic for certain taxa in the HGMP; those that were deemed inaccurate, improbable, or impossible were also removed at this stage.

The observation dates of species occurrence records retained for modelling spanned decades, furthermore some records did not possess date metadata, so the year of observation was unknown. For modelling, all records regardless of date, were retained to train models. While the initial goal was to retain only 'recent' point records that were indicative of current distributions, the sparsity of recent datasets (i.e., within 5 years) meant that a temporal cut-off would result in insufficient point records to support modelling of all identified biogenic habitat groups. Furthermore, dozens of gear types were used to collect the species/habitat observation data compiled for modelling. All records were retained for training models regardless of gear type used. Additionally, all abundance data was converted to presence data. For example, a count of erect sponges from a video survey in each area was converted into a single presence point for erect sponges in the corresponding grid cell. Abundance models are preferrable to the models used here; however, there was not enough data available to develop robust, well performing abundance models for this project.

Environmental layers

To contribute to objective 3, a broad range of environmental datasets were compiled for the development of spatial models under this project. A database of 30 different environmental predictors were sourced from a NIWA repository initially compiled for NIWA contracts to the Department of Conservation, in particular the development of the New Zealand seafloor community classification (Stephenson et al. 2021b) and mapping Key Ecological Areas (Stephenson et al. 2018b; Lundquist et al. 2020a). These national scale layers report a range of environmental characteristics of importance for New Zealand taxa including aspects of seafloor geomorphology (e.g., depth, slope, roughness, sediment characteristics), oceanographic settings (e.g., temperature, salinity, turbidity), and water column chemistry (e.g., nutrient concentration), among others. These national scale datasets were obtained at 250 m × 250 m grid cell resolution and included data across a range of temporal periods (Table 5). It is important to note that for some layers these temporal ranges do not match the collection dates of the point records used for model development. This temporal mismatch means that conditions represented by these environmental layers may not match the conditions present when point records were created, i.e., due to changes in sediment mud content over time, a habitat may no longer be suitable for a taxon that was found there a decade previously.

An additional, complementary source of environmental data was acquired from NIWA's 'Seas, Coasts, Estuaries New Zealand' (SCENZ) geoportal that provides environmental products derived from ocean-colour data from satellite remote sensing (NASA's MODIS-Aqua mission). For this project, we extracted six environmental layers from the SCENZ portal that reported sea surface temperature (SST), chlorophyll-a concentration (CHLa), particulate backscatter (BBP), detrital light absorption (DET), light incidence at the seabed (EBED), and photosynthetically active radiation (PAR). Average conditions for each predictor were calculated by averaging the annual conditions between 2002 and 2021. SCENZ datasets were extracted at a native resolution of 500 m × 500 m and were sub-sampled a 250 m × 250 m grid to match the national scale environmental predictors.

Two further environmental layers made available report the highest resolution information on bathymetry and substrate types within the HGMP. These layers were originally developed for Sea Change – Tai Timu Tai Pari. Layers were updated with additional data from stakeholders (e.g., government agencies, territorial authorities) including accurate bathymetric surveys (e.g., multi-beam echosounder surveys) and substrate sampling/monitoring programmes. The bathymetry layers report the depth of the seafloor below chart datum at 250 m × 250 m grid cell resolution (MetOcean Solutions Ltd. 2012). Substrate is a categorical variable representing the dominant habitat type coded by numeric values 1 (soft substrate; mud) to 6 (hard substrate; rocky reef), rasterised at 250 m × 250 m resolution (MetOcean Solutions Ltd. 2013).

Table 5: Environmental parameters used to model the spatial distribution of biogenic habitat groups in the Hauraki Gulf Marine Park. Many of the environmental layers used for this work were compiled as national scale datasets for other projects (Lundquist et al. 2020a; Stephenson et al. 2021b). These layers are complemented by extracts from the SCENZ geoportal and additional layers developed under the Sea Change spatial planning process. Layer names, descriptions, resolution, and units are given as well as reference and source information for each layer. All layers used in this project are in raster format at 250 m grid resolution. (Continued on next 2 pages)

Layer name	Full name	Temporal range	Description	Units	Reference/source
Bathy	Bathymetry	Static	Depth of the seafloor	m	SeaChange Tai Timu Tai Pari Marine Spatial Plan
BBP	Backscatter	2002 – 2021	Backscatter of particulates at 555 nm	m^{-1}	SCENZ (Pinkerton et al. 2022)
BedDist	Benthic sediment disturbance	2017 – 2018	One-year mean value of friction velocity from wave action	ms^{-1}	National scale dataset (Swart 1974); updated in 2019
BotNi	Bottom nitrate	Static	Annual average water nitrate concentration at the seafloor	umol l^{-1}	National scale dataset NIWA, unpublished
BotOxy	Dissolved oxygen at depth	Static	Annual average water oxygen concentration at the seafloor	ml l^{-1}	National scale dataset NIWA, unpublished
BotPhos	Bottom phosphate	Static	Annual average phosphate concentration at the seafloor	umol l^{-1}	National scale dataset NIWA, unpublished
BotSal	Salinity at depth	Static	Annual average salinity concentration at the seafloor	psu	National scale dataset NIWA, unpublished
BotSil	Bottom silicate	Static	Annual average silicate concentration at the seafloor	umol l^{-1}	National scale dataset NIWA, unpublished
BotTemp	Temperature at depth	Static	Annual average water temperature at the seafloor	°C km^{-1}	National scale dataset NIWA, unpublished
BPI_broad	BPI_broad	Static	Bathymetric position index (BPI) is a measure of where a referenced location is relative to the locations surrounding it. Terrain metrics were calculated using an inner annulus of 12 km and a radius of 62 km.	m	National scale dataset NIWA, unpublished
BPI_fine	BPI_fine	Static	Bathymetric position index (BPI) is a measure of where a referenced location is relative to the locations surrounding it. Terrain metrics were calculated using an inner annulus of 12 km and a radius of 62 km	m	National scale dataset NIWA, unpublished

Layer name	Full name	Temporal range	Description	Units	Reference/source
Carbonate	Percent carbonate	Static	Percent carbonate layer developed from >30 000 sediment core data	%	National scale dataset (Bostock et al. 2019)
CHLA	Chlorophyll-a concentration	2002 – 2021	A proxy for the biomass of phytoplankton present in the surface ocean (to ~30 m depth)	Mg m^{-3}	SCENZ (Pinkerton et al. 2022)
ChlAGrad	Chlorophyll-a concentration spatial gradient	2002 – 2019	Smoothed magnitude of the spatial gradient of annual mean Chl-a, derived from Chl-a described above	Mg m^{-3} km^{-1}	National scale dataset NIWA unpublished, updated in 2020
DET	Detrital absorption	2002 – 2021	Total detrital absorption coefficient at 443 nm, including due to coloured dissolved organic matter (CDOM) and particulate detrital absorption	m^{-1}	SCENZ (Pinkerton et al. 2022)
DynOc	Dynamic oceanography	1993 – 1999	Mean of the 1993 – 1999 period sea surface above geoid	M	National scale dataset NIWA, unpublished
EBED	Seabed incident irradiance	2002 – 2021	Broadband (400–700 nm) incident irradiance (E m^{-2} d^{-1}) at the seabed, averaged over a whole year	E m^{-2} d^{-1}	SCENZ (Pinkerton et al. 2022)
K_{PAR}	Diffuse downwelling attenuation	2002 – 2019	Vertical attenuation of diffuse, downwelling broadband irradiance (Photosynthetically Available Radiation, PAR, 400–700 nm)	m^{-1}	National scale dataset NIWA unpublished, updated in 2020
MLD	Mixed layer depth	2002 – 2019	The depth that separates the homogenized mixed water above from the denser stratified water below	m	National scale dataset NIWA unpublished, updated in 2020
PAR	Photosynthetically active radiation	2002 – 2021	Daily-integrated, broadband, incident irradiance at the sea-surface based on day length, solar elevation and measurements of cloud cover from ocean colour satellites (Frouin et al. 2002)	E m^{-2} d^{-1}	SCENZ (Pinkerton et al. 2022)
POCFlux	Downward vertical flux of particulate organic matter at the seabed	2002 – 2019	Net primary production in the surface mixed layer estimated as the VGPM model (see below in this table)	mgC m^{-2} d^{-1}	National scale dataset NIWA unpublished, updated in 2020
Rough	Roughness	Static	Roughness of the seafloor calculated as the variation in three-dimensional orientation of grid cells within a neighbourhood	m	National scale dataset NIWA, unpublished, updated in 2019

Layer name	Full name	Temporal range	Description	Units	Reference/source
SeasTDiff	Annual amplitude of sea floor temperature	Static	Smoothed difference in seafloor temperature between the three warmest and coldest months, providing a measure of temperature amplitude through the year	°C km^{-1}	National scale dataset NIWA, unpublished, updated in 2018
Slope	Slope	Static	Bathymetric slope was calculated from water depth and is the degree change from one depth value to the next	°	National scale dataset NIWA, unpublished, updated in 2019
SST	Sea surface temperature	1981 – 2018 (ocean); 2002 – 2018 (coastal)	Blended from OI-SST (Reynolds et al. 2002) ocean product and MODISAqua SST coastal product. Long term (2002 – 2021) average values at 250 m resolution	°C	SCENZ (Pinkerton et al. 2022)
SSTGrad	Sea surface temperature gradient	1981 – 2018 (ocean); 2002–2018 (coastal)	Smoothed magnitude of the spatial gradient of annual mean SST. This indicates locations in which frontal mixing of different water bodies is occurring (Leathwick et al. 2006)	°C km^{-1}	National scale dataset NIWA unpublished, updated in 2020
Substrate	Substrate type categories	Static	Categorical representation of dominant substrate types reported as numerical values between 1 (soft sediment) and 6 (rocky reef).	Substrate class (categorical)	SeaChange Tai Timu Tai Pari Marine Spatial Plan
TC	Tidal Current speed	2009 – 2020	Maximum depth-averaged (New Zealand bathymetry) flows from tidal currents calculated from a tidal model for New Zealand waters (Walters et al. 2001)	Ms^{-1}	National scale dataset NIWA unpublished, updated in 2020
TempRes	Temperature residuals	2017 – 2018	Residuals from a GLM relating temperature to depth using natural splines – highlights areas where average temperature is higher or lower than would be expected for any given depth	°C	National scale dataset (Leathwick et al. 2006)
VGPM	Net primary production by the vertically generalised production model	2002 – 2019	Daily production of organic matter by the growth of phytoplankton in the surface mixed layer, net of phytoplankton respiration	mgC m^{-2} d^{-1}	National scale dataset NIWA unpublished, updated in 2020

Development of biogenic habitat models

Biogenic habitat group models

Under objective 3, species distribution models (SDMs) were used to predict the spatial probability of occurrence of biogenic habitat groups at a regional scale, based on inputs of taxon presence-absence data and spatially explicit environmental variables (Bowden et al. 2019; Watson et al. 2022). Ensemble SDMs (i.e., the combination of predictions from more than one SDM method) were generated using outputs from two model types: Boosted regression tree (BRT) and random forests (RF). The ensemble approach reduces dependence on a single model type or structural assumption and enables a more robust characterisation of the predicted spatial variation and uncertainties (Robert et al. 2016). All statistical analyses were undertaken in R (R Core Team 2020). Key packages used include the *extendedForest* (Liaw & Wiener 2002), *dismo* (Hijmans et al. 2017), and *gbm* (Greenwell et al. 2020) packages.

Explanatory variable selection

An automated variable selection procedure was used to ensure models were parsimonious (i.e., used explanatory variables sparingly). Initially, an RF model was fitted to the taxa data with all 30 explanatory variables (Table 5) using conditional permutation of variable importance in the *extendedForest* package in R (Liaw & Wiener 2002). This method accounts for any co-linearity in explanatory variables when determining the relative importance of each variable in the model through the implementation of a conditional approach to calculation of variable importance (Ellis et al. 2012). Only explanatory variables with a relative influence greater than 3% were used for modelling (100 divided by the number of explanatory variables). This procedure allowed explanatory variables that may have important localised influence but low overall importance to be retained whilst removing variables with very low, or negative influence. The set of explanatory variables selected through this approach was used in the final RF and BRT models for each biogenic habitat model group.

Random Forest (RF) models

RF models (Breiman 2001) fit an ensemble of non-correlated classification tree (presence-absence data) models describing the relationship between the distribution of an individual taxon and some set of explanatory variables (Ellis et al. 2012). Individual trees are fit using 'bagging' (bootstrap aggregation with replacement) and feature randomness to introduce greater variation among tress at nodal splits (Breiman 2001). The RF algorithm can rapidly optimise a large set of non-correlated classification trees with greater diversity, often resulting in high predictive accuracy. Models were tuned with 1000 trees, a step factor of 1.5, and error relative improvement rate of 0.0001. RF models have previously been applied to predict the distribution of demersal fish and benthic invertebrates in New Zealand (Anderson et al. 2016; Stephenson et al. 2018a; Lundquist et al. 2020a; Stephenson et al. 2023).

Boosted Regression Tree (BRT) models

BRTs are the combination of two algorithms: 1) regression trees (models that relate a response to their predictors by recursive binary splits) and 2) boosting (an adaptive method for combining many simple models to give improved predictive performance) to form a single ensemble model (Elith et al. 2008). Detailed descriptions of the BRT method are given by Ridgeway (2006) and Elith et al. (2008). BRT models were fitted with a Bernoulli distribution, a bag fraction of 0.6, a tree complexity of 2 (moderate), and random 5-fold cross evaluation. Models were fitted using the *dismo* package in R (Hijmans et al. 2017). BRT models with decreasing learning rates were successively fitted (starting at a rate of 0.05) until a model with ≥ 1500 trees was fitted. BRT models have been extensively used in previous studies of fish and invertebrate distributions in New Zealand (Leathwick et al. 2006; Compton et al. 2013; Anderson et al. 2016; Bowden et al. 2019; Lundquist et al. 2020a; Stephenson et al. 2021c; Stephenson et al. 2023).

Uncertainty layers

To assess the relative confidence in predictions across the model extent, a bootstrap technique was used to produce spatially explicit uncertainty measures (Anderson et al. 2020). Bootstrapping involved the creation of 'training' and 'evaluation' samples. Random draws (with replacement) with a sample size equal to the number of presence-absence records constituted the training sample. Presence-absence records which were not randomly selected constituted the evaluation sample and this was used for independent assessment of model performance. This process was repeated 100 times for each model type (RF, BRT) and each taxon group. For each BRT and RF model iteration (bootstrap), geographic predictions were made using predictor variables to a 250 m × 250 m grid. Probability of occurrence and a spatially explicit measure of uncertainty (measured as the standard deviation (SD) of the mean probability of occurrence) were calculated for each grid cell using the 100 (bootstrapped) predicted layers for each biogenic habitat model.

Model fit and performance

Model performance was assessed at each bootstrap iteration for each of the BRT and RF models for each of the biogenic habitat groups. Models were evaluated using AUC (area under the Receiver Operating Characteristic curve) and TSS (True Skill Statistic). AUC is a measure of model performance and a threshold-independent measure of accuracy, whereas the TSS is a threshold-dependent measure of accuracy that is not sensitive to prevalence (Allouche et al. 2006; Komac et al. 2016). AUC scores range from 0 to 1, and model performance is considered better when scores approach 1. That is, a score of 0.5 indicates model performance is equal to random chance, a score > 0.7 indicates adequate performance, and a score > 0.8 indicates excellent model performance (Hosmer Jr et al. 2013). TSS is calculated as followed, sensitivity + specificity -1, resulting in an index ranging from -1 to +1, where +1 equals perfect agreement, -1 is equal to random, and a value > 0.6 is considered ‘useful’ (Allouche et al. 2006). AUC and TSS were calculated for each bootstrap using both the ‘training’ dataset and the ‘evaluation’ dataset. Using ‘evaluation’ datasets (i.e., iteratively withheld data) to evaluate model performance is considered a more robust and conservative method of model evaluation compared with using the same data with which the model was trained (Friedman et al. 2001).

Ensemble models

The ensemble model was produced using weighted averages of the predictions from each model (BRT and RF), using methods adapted from (Anderson et al. 2020). The two-part weighting procedure for each component of the ensemble model (BRT and RF) derives equal contributions from the overall model performance (AUC scores derived from ‘evaluation’ data) and the uncertainty measure (SD) in each 250 m × 250 m grid cell.

Spatial cross validation

It has been proposed that spatial sorting bias (i.e., autocorrelation) in presence and absence data may overestimate the performance of predictive spatial models, particularly when input data are highly clustered (Hijmans 2012; Valavi et al. 2018; Ploton et al. 2020). While the repeat-random cross-validation process used as an initial model performance assessment follows a routinely used method (Compton et al. 2013; Anderson et al. 2016; Stephenson et al. 2021c; Wadoux et al. 2021), an additional validation step was undertaken to ensure spatial autocorrelation in presence-absence data did not bias the evaluation metrics.

We used a spatial blocking method developed by Valavi et al. (2018) to partition the study area into eight blocks of equal size, with each containing a minimum quantity of presence and absence data sufficient to allow a robust validation within each block (see section 3.1). The size of the blocks was configured based on the median distance beyond which the inherent landscape scale autocorrelation of the environmental variables was reduced (ca. 70 km). Spatial cross validation was undertaken for the final ensemble prediction for each biogenic habitat model using a random selection of presence and absence points for each model in the R package *blockCV* (Valavi et al. 2018). The process provided AUC model fit metrics for each spatial block, for each model prediction, which were summarised as mean, minimum, and maximum values for each biogenic model. While the mean value is directly comparable with the AUC value derived from the repeat-random cross validation process, the minimum spatial CV value provides information on whether any spatial block fails the minimum standards (e.g., 0.7) for a useful model.

Expert evaluation

Modelled distributions were also evaluated by taxonomists and ecologists with substantial expertise in the distribution and abundance of the various taxonomic groupings. Evaluation criteria were identical to those used for previous spatial modelling projects (Lundquist et al. 2020a; Stephenson et al. 2023) The expert assessment focused on the congruence between predicted taxa distribution and expert view of expected distributions of biogenic habitat forming groups in the HGMP. Expert assessment included a category which reflected the expert's knowledge of a particular biogenic habitat-forming group. Two additional categories reflected both whether the point records matched expert understanding of where the taxa were likely to occur in the HGMP, and whether the model spatial predictions reflect the expected distributions based on expert knowledge of that taxa (Table 6). Scores for this final metric ranged from 1 (Very accurate – the predicted distribution reflects expert view of taxa distribution (> 80% overlap)) to 5 (Inaccurate – the predicted distribution does not match the expert's view of the taxa distribution (< 20% agreement)). Following this expert assessment process, three biogenic habitat groups were determined to be not robust, as experts felt patterns did not reflect ecological or taxonomic expectations of where that group was likely to be found in the HGMP. These three groups were retained for post-accounting analyses but not included as priorities for protection or restoration within Zonation scenarios (see next section).

Table 6: Evaluation criteria and descriptions presented to experts for input. Evaluation criteria and description developed by (Stephenson et al. 2023).

Evaluation score		Description
Assessment of expert knowledge		
1	Very high	Expert confidently knows the fine scale distribution of the species
2	High	Expert confidently knows the broad scale distribution of the species
3	Moderate	Expert has some knowledge of the likely distribution with some uncertainty
4	Low	Expert has little knowledge of likely distribution and with large uncertainty
Species records reflect expert knowledge of distribution		
1	Very accurate	Records of species reflect expert view of taxa distribution (> 80% agreement)
2	Accurate	Records of species reflect expert view of taxa distribution, but some areas do not (> 60% agreement)
3	Somewhat accurate	Records of species somewhat reflect expert's view of the taxa distribution but there are considerable inconsistencies (> 40% agreement) and/or moderate spatial bias in records
4	Inaccurate	Records of species do not match the expert's view of the taxa distribution (< 40% agreement) and/or high spatial bias in records
Spatial predictions reflect expert knowledge of species distributions		
1	Very accurate	Predicted distribution reflects expert view of taxa distribution (> 80% overlap)
2	Accurate	Predicted distribution reflects expert view of taxa distribution, but some areas may not be correct (> 60% overlap)
3	Somewhat accurate	Predicted distribution somewhat reflects expert view of the taxa distribution but there are considerable inconsistencies (> 40% agreement)
4	Largely inaccurate	Predicted distribution contains large inconsistencies with the expert's view of the taxa distribution (> 20% agreement)
5	Inaccurate	Predicted distribution does not match the expert's view of the taxa distribution (< 20% agreement)

2.3 Exploratory trawl corridor development through iterative advisory group workshops

Hauraki Gulf Benthic Spatial Advisory Group

An advisory group (HG-BSPAG – the Hauraki Gulf Benthic Spatial Advisory Group) was established to provide a means to collaborate with a group of advisors as part of the project. The role of the HG-BSPAG was to contribute through a series of workshops (March–July 2022) to:

1. the review of information inputs to be used in a spatial planning decision support tool (Zonation) to facilitate the identification of bottom fishing corridors;
2. the development and testing of different bottom fishing corridor scenarios that vary in the number, size, shape, and/or spatial arrangement of the corridors; and
3. the assessment of the relative costs and benefits for fisheries and biodiversity protection and recovery offered by the various scenarios.

All members of HG-BSPAG agreed to Terms of Reference and standards of participation which outlined their obligations. The Terms of Reference clarified that HG-BSPAG does not make management recommendations or decisions, rather this responsibility lies with Fisheries New Zealand and the Minister of Oceans and Fisheries. The group included a Chair from Fisheries New Zealand, and participants from Fisheries New Zealand science and fisheries management teams, research providers (NIWA), representatives of the Department of Conservation, Auckland Council, Waikato Regional Council, nominated parties representing industry and ENGOs (environmental non-government organisations), and other invited experts.

HG-BSPAG contributed to five advisory group workshops to identify elements that should be considered in evaluating areas to be left open to trawling and Danish seining. An independent workshop with industry identified metrics of industry value to include in the exploratory scenarios, identifying four ‘fishery categories’ (Danish seine, trawl vessels > 20 m, trawl vessels < 20 m, precision seafood harvesting) and five stocks (snapper, tarakihi, trevally, John dory, red gurnard). Existing uses and spatial management were discussed during the advisory group workshops, informing different iterations of the model area that were used for assessing each round of scenarios that was presented at the workshops. A final model area was selected by HG-BSPAG that excluded scallop dredging open areas, aquaculture areas, and channel dredging zones, as these areas are likely to have seafloor disturbance even if bottom trawling was excluded. The deep area of the HGMP (> 200 m) was masked from consideration in the final exploratory scenarios as this area was primarily targeted by deepwater fisheries that were not represented by the participants of the advisory group. Four suites of scenarios were presented at successive advisory group workshops (see Section 3.2), with scenario iterations designed to illustrate how the decision support tool could be used to identify spatial regions that could be trawl corridors due to either low biogenic habitat value, low recovery potential, high fishery value, or combinations of these input layers. Post-accounting for exploratory scenarios was presented at workshops, illustrating relative benefits of each scenario for protection of the current predicted distribution of habitat-forming taxa, areas which could potentially support recovery of biogenic habitats in the absence of fishing, benthic biodiversity groups, and the Seafloor Community Classification, and values based on the fishing industry layers suggested by industry.

Spatial decision-support tool (Zonation)

Objectives 1 and 2 required analyses to assess spatial planning options to enable the protection of the current biogenic habitats while also allowing for future recovery. We addressed these objectives by carrying out spatial prioritisations using the modelled distribution of biogenic habitats in the decision support tool Zonation (Moilanen et al. 2014). Zonation was developed to assist the identification of areas important for retaining habitat quality and connectivity. The power of Zonation comes from its ability to handle extensive complementary datasets rapidly (e.g., the large areas of the South Pacific at 1 km × 1 km resolution), allowing for scenario testing (Rowden et al. 2019). The hierarchical prioritisation algorithm of Zonation works by progressively removing cells of lower value until the minimum area, providing the maximum value (incorporating costs) remains (Moilanen et al. 2014). For example, 'value' in this study could be several modelled species distribution layers (probability of occurrence) where a higher likelihood of occurrence would be considered higher value.

The decision-support tool Zonation has been used extensively in New Zealand, for identifying spatial conservation priorities for vulnerable marine ecosystems (VMEs) in the high seas (Rowden et al. 2019), for identifying optimal areas for biodiversity conservation throughout the New Zealand EEZ (Lundquist et al. 2021) and to assess the protection of biodiversity offered by proposed Sea Change – Tai Timu Tai Pari marine protected areas in the Hauraki Gulf Marine Park (Lundquist et al. 2020b; Tablada et al. in press).

Layer preparation for Zonation

Clipping to the ROC threshold

Input biodiversity layers that have had a threshold applied are often used to represent locations with the highest likelihood of taxa/habitat occurrence in systematic marine spatial planning (Wilson et al. 2005; Guisan et al. 2013). For layers from species distribution models, threshold values are often used to convert the prediction of a continuous representation of probability of occurrence to binary values representing presence (1) or absence (0) (Liu et al. 2005; Wilson et al. 2005). A commonly used approach is to derive a value from the receiver operator characteristic (ROC) curve that maximises the ability of the model to distinguish true positives (sensitivity) from true negatives (specificity) (Liu et al. 2005). This threshold was calculated for the ensemble model of each biogenic habitat model with the *coords* function of package *pROC* in R using Youden's J statistic (Youden 1950).

While producing threshold layers from probability of occurrence models is commonly undertaken, utilising the full range of continuous probability of occurrence predictions while explicitly incorporating uncertainty also has some merit (Moilanen et al. 2004; Guisan et al. 2013). In this project, based on feedback from the advisory group and following similar examples with national (BEN2019-05) and international (South Pacific Regional Fisheries Management Organisation, SPRFMO) spatial planning processes (Rowden 2015; Rowden et al. 2019), we used a hybrid approach where all probability of occurrence values below the ROC threshold were set to 0 and those above the threshold retained their continuous distribution. This approach removes highly unsuitable habitat from the prioritisation and allows the analysis to distinguish between areas of moderate to high suitability while incorporating uncertainty.

Condition layers: current and recovery biogenic habitat distribution

To meet objectives 1, 2, and 3 of this project, we investigated potential locations for trawl corridors (or areas exempt from the ban on bottom trawling and Danish seining) to allow for utilisation to continue, whilst providing protection to areas that are likely to currently support habitat forming species or may in future support their recovery. Therefore, it was necessary to represent biogenic habitats in two different formats: current distribution and recovery potential. There is currently no quantitative information on how stressors other than trawling impact the distribution of biogenic habitat types. Thus, 'current' and 'recovery' distributions consider the impact of this single stressor only.

Objective 4 required the quantification of benthic impacts of fisheries and habitat naturalness. To develop layers which represent current (impacted) biogenic habitat and recovery biogenic habitat, we scaled each biogenic habitat layer by 'condition' layers that represent an estimate of the degree of removal of biogenic habitat types given a known quantity of bottom trawl fishing in each cell.

Condition layers were produced for a separate project (BEN2019-04) based on historical trawl footprint (area swept km^2) information (Rowden et al. in review). The degree to which a biogenic habitat can be considered natural versus altered depends on the amount of anthropogenic disturbance (in this case trawling effort) and on the type of habitat, broadly divided into two groups: large, erect, hard, and sessile (LEHS) and small, fragile, and encrusting (SFE). The LEHS condition layer was applied to erect/upright sponges, erect/frame-building Bryozoa, erect and rooted Bryozoa, horse mussels, mussels, and oysters, and 2) the SFE condition layer was applied to the Brachiopoda, tubeworms, cup corals, encrusting Bryozoa, encrusting sponges, Hydrozoa, rhodoliths, sea anemones, and misc. Anthozoa. While the

BEN2019-04 project explored a number of methods for quantifying condition, the MSRP method developed by Mormede et al. (2017) was used here (Rowden et al. in review). We note that recovery is not considered in the MSRP approach, thus the level of impact is likely to be an overestimate.

Layers representing the ‘current’ distribution are defined as the native probability of occurrence layers from each biogenic habitat model, multiplied by the relevant condition layer. This format has the effect of substantially reducing the probability of occurrence values in areas where trawl fishing intensity is high and retaining probability of occurrence values where intensity is low. Layers representing ‘recovery’ distribution are then defined as the difference between the native probability of occurrence layers and the ‘current’ distribution layers (e.g., an approximation of the areas most impacted by trawl fishing) (Figure 8). Thus, recovery potential layers for each biogenic habitat have a higher overlap with areas where fishing value is high.

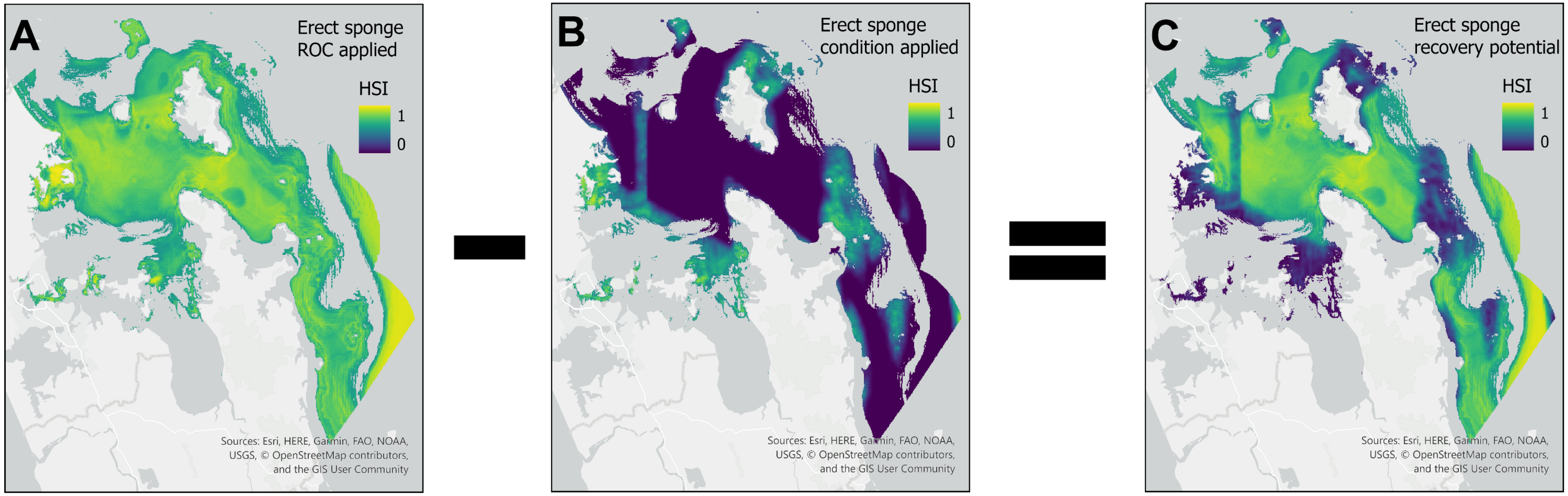
Like other non-fishing related stressors, there is no information on how the intensity of fishing methods, other than trawling, impact the distribution of biogenic habitats (for example, see reviews of trawling impacts in Collie et al. 2000; Thrush & Dayton 2002; Kaiser et al. 2006). In this project, additional bottom-contacting fisheries included Danish seining and precision seafood harvesting (PSH; an alternative form of bottom trawling) and these are considered within the spatial planning process, yet we have no available stressor impact layers (analogous to the MSRP method layers) to incorporate the impacts of these methods on current or potential recovery distribution. Further, the effects of additional practices such as dredging (for fisheries or navigation), seabed mining, and aquaculture are not considered with respect to the distribution of biogenic habitats. This exclusion is largely due to a lack of accurate data on the effects of these practices on biogenic habitat and spatially explicit information on their intensity within the HGMP.

To calculate the spatial extent of the predicted distributions of each taxa group, as well as the extent of the current and recovery potential distributions, the sum area was calculated for the ROC-threshold layers, the current distribution layer (condition applied) and the recovery potential layer (current distribution subtracted from the ROC cut-off layer) (Figure 8). Using area calculations from the ROC-threshold layer and the current distribution layer, proportion (%) of habitat remaining was calculated.

Fishing values

Objective 5 of this project required the generation of GIS layers representing the distribution of fishing value in the HGMP. Fishing value datasets were provided by Fisheries New Zealand as catch and effort raster layers at 1-km resolution (grid). An initial dataset provided by Fisheries New Zealand consisted of two Danish seine layers: area swept (km^2) and catch ($kg\ km^{-2}$) as annual averages over the 2007–2020 period, and 12 trawl layers. These trawl layers were for area swept (km^2) and catch ($kg\ km^{-2}$) for: all species combined (2), deepwater (in depths greater than 200 m) and inshore fisheries (4), and for snapper, tarakihi, and trevally (6), each as annual averages over the 2018–2020 period.

A second dataset provided by Fisheries New Zealand following subsequent advisory group input included catch and effort for two additional species (red gurnard and John dory), and trawling was split by vessel size, and precision seafood harvesting (PSH) was also included. This iteration consisted of 12 layers each for Danish seine, trawling with vessels under 20 m, and PSH. These layers were for area swept (km^2) and catch ($kg\ km^{-2}$) for: all species combined, red gurnard, John dory, snapper, tarakihi, and trevally, each as annual averages over the 2018–2020 period, except for Danish seine which was the annual average over the 2015–2020 period. Eight layers for bottom trawling vessels > 20 m were included for area swept (km^2) and catch ($kg\ km^{-2}$) for: all species combined, snapper, tarakihi, and trevally, each as annual averages over the 2018–2020 period. The third iteration had the same number and type of layers as the second iteration, except any contributions of deepwater fisheries were removed (i.e., hoki *Macruronus novaezelandiae* and scampi *Metanephrops challengeri*). This included the bottom trawling and PSH layers, whereas the Danish seine layers were unchanged as all effort is inshore.



HSI model ROC threshold applied
Model output with the cut-off derived from the ROC applied

Subtract condition applied layer
The HSI cut-off applied layer with condition (MRSP) subtracted. This is layer is then subtracted from the HSI cut-off applied layer

Recovery potential only
Output of the condition applied layer subtracted from the HSI cut-off applied layer

Figure 8: Processing of modelled layers (probability of occurrence) for use in Zonation prioritisation and post-accounting. A) Layer shown is the probability of occurrence model for erect sponges with the ROC threshold (cut-off) applied, representing suitable habitat for each group. B) The ROC threshold applied layer with the MSRP condition subtracted from it; the resulting layer is referred to as current distribution. C) The current distribution (B) subtracted from the ROC threshold applied probability of occurrence layer (A); the resulting layer is referred to as the recovery potential layer.

All processing was undertaken in R (R-Core-Team 2022) using the package *raster* (Hijmans et al. 2022). All layers (Table 7) were matched to the extent and cell alignment of the HGMP template (250 m × 250 m grid configured using an Albers Equal Area spatial projection for the full extent of the HGMP). Grid cell values were resampled with nearest neighbour interpolation and scaled by 1/16 to account for the effect of downscaling 1 km × 1 km cells to 250 m × 250 m cells.

Table 7: Spatial layers included in spatial prioritisations and post-accounting. Group describes overall reporting group. Class indicates whether layers are biogenic habitat, misc. biodiversity, or fishing value. Taxa/layers shows details of layers included. Where multiple layers are grouped e.g., 'crustacean' the number of layers grouped is shown in brackets.

Group	Class	Taxa/Layers
Modelled biogenic habitat layers		
Small, fragile, encrusting	Biogenic	Anthozoa, Brachiopoda, calcareous tubeworms, cup corals, encrusting Bryozoa, encrusting sponges, Hydrozoa, multi-species aggregations (biogenic clumps), misc. annelid assemblages, rhodoliths, sea anemones, tubeworms.
Large, sessile, erect	Biogenic	Erect Bryozoa, erect rooted Bryozoa, erect sponges, horse mussels, mussels, oysters.
Macroalgae	Biogenic	Canopy-forming macroalgae, miscellaneous seaweed.
Other layers		
Biodiversity	Biodiversity	National species occurrence models for: bivalves (n = 8), bryozoans (n = 11), cnidarians (n = 24), crustaceans (n = 42), echinoderms (n = 61), gastropods (n = 13), octopus (n = 4), other epifauna (n = 9), polychaetes (n = 9), and sponges (n = 17).
Trawl value (vessels under 20 m)	Fishing value	All inshore species combined (catch-kg and catch-effort from 2018/19–2020/21), catch-kg and catch-effort from 2018/19–2020/21 by species (red gurnard, John dory, snapper, tarakihi, trevally).
Trawl value (vessels over 20 m)	Fishing value	All inshore species combined (catch-kg and catch-effort from 2018/19–2020/21), catch-kg and catch-effort from 2018/19–2020/21 by species (snapper, tarakihi, trevally).
Danish seine value	Fishing value	All inshore species combined (catch-kg and catch-effort from the 5 most recent years, 2015–2020), catch-kg and catch-effort from 5 most recent years (2015–2020) by species (red gurnard, John dory, snapper, tarakihi, trevally).
PSH value	Fishing value	All inshore species combined (catch-kg and catch-effort from 2018/19–2020/21), catch-kg and catch-effort from 2018/19–2020/21 by species (gurnard, John dory, snapper, tarakihi, trevally).
Inshore (totals)	Fishing value	Bottom trawling (vessels over 20 m) catch-kg and catch-effort, bottom trawling (vessels under 20 m) catch-kg and catch-effort, Danish seine catch-kg and catch-effort, PSH catch- kg and catch-effort.

Scenario iterations and trawl corridor development

Scenarios were developed either through use of Zonation or other geospatial analyses to identify biodiversity or fishing priorities, or through drawing of individual boxes that could represent trawl corridor locations. Each scenario consisted of all areas of the HGMP identified as either open (i.e., trawl corridors) or closed to fishing. Each scenario was specified using a raster layer, with the value of cells in the area closed to fishing set to '1' and those in the open area set to '0'. This layer was used in the post accounting process for each scenario. The model area template was generated for the full extent of the HGMP (with different areas masked out, where applicable), and a 250 m × 250 m grid was configured using an Albers Equal Area spatial projection.

The closure layer was constructed depending on the type of scenario. For scenarios based on existing data layers (such as current/proposed closures or fishing footprints, see Section 3.2), the closure layer was created by formatting the existing datasets to ensure consistent cell alignment, extent, and resolution. All existing raster datasets were matched to the template, with grid-cell values being resampled with bilinear interpolation or nearest neighbour interpolation (to preserve edges) when changes in resolution were required. Polygon datasets were rasterised to match the template. All processing was undertaken in R (R-Core-Team 2022) using the package *raster* (Hijmans et al. 2022). The cell values were then set to '1' for closed and '0' for open. Some scenarios were based on the top percentage of catch value (kilograms). The areas that were contained in this top percentage were determined using the zonation ranking process. The cells that were above the top percentage value were set to '0' (as these would be in the areas open to fishing) and those below were set to '1'. For example, to create a scenario representing trawl corridors that include only areas of Danish seine top 25% catch value (Scenario 3a 25% in round 2; see Section 3.2), the cells that were ranked to be in the top 25% of fishing value (as determined by the Zonation process) were set to '0', and the remaining set to '1'. Similarly, for scenarios based on the top percentage of biodiversity value (based on the modelled probability of occurrence), the areas that were contained in the top percentage were determined using Zonation. The cells that were above the top percentage value were set to '1' (as these would be in the areas closed to fishing) and those below were set to '0'. For example, to create a scenario that represented closed areas for the top 90% of current biogenic habitat distribution (scenario 2b in round 1, see Section 3.2), the cells that were ranked to be in the top 90% of probability of occurrence value (as determined by the Zonation process) were set to '1', and the remaining set to '0'. For scenarios based on a combination of the above scenario types, closure layers were combined, and any non-zero cell was set to '1'.

Zonation prioritisations

For this project over 30 Zonation prioritisations were run. Generally, the settings used were: *core area cell removal* (see below for detail), *warp factor* (defines how many cells removed each iteration) set to 1000, *edge removal* set to 1—Zonation gives lower priority to cells from the edges of remaining landscape, and *z* (the exponent of the species area curve (S = cAz), used to calculate the extinction risk of taxa as their distribution decreases) set to 0.25 (default setting). *Mask missing areas* was used (set to 1) with the relevant model area as the 'area mask file', which results in any excluded areas (i.e., dredge zone, aquaculture areas) being excluded or masked from the analysis. *Use info-gap* weights was used (set to 1) to allow for the inclusion of modelled uncertainty for the species occurrence probability of occurrence layers, with uncertainty layers produced for each biodiversity (n = 198) and biogenic habitat (n = 20). *Info-gap proportional* was set to 0 (errors in species occurrences were assumed to be uniform) and the uncertainty weighting parameter α was set to 0.2, following iterations to determine a weighting that included, but did not overweight, uncertainty within the solution (see e.g., Rowden et al. 2019; Lundquist et al. 2021). Default settings for other Zonation options were set to 0 (i.e., not used).

To incorporate a trade-off with fishing value (catch-kg), some prioritisations were run with fishing value layers as negative biodiversity layers; that is, these layers were used as weighted feature layers in the Zonation prioritisation but were given a negative value such that Zonation tried to avoid including these layers in priority solutions. The negative value weighting was selected such that the combined weight of the fishing value balanced (i.e., was equal to) the combined weight of the biodiversity value.

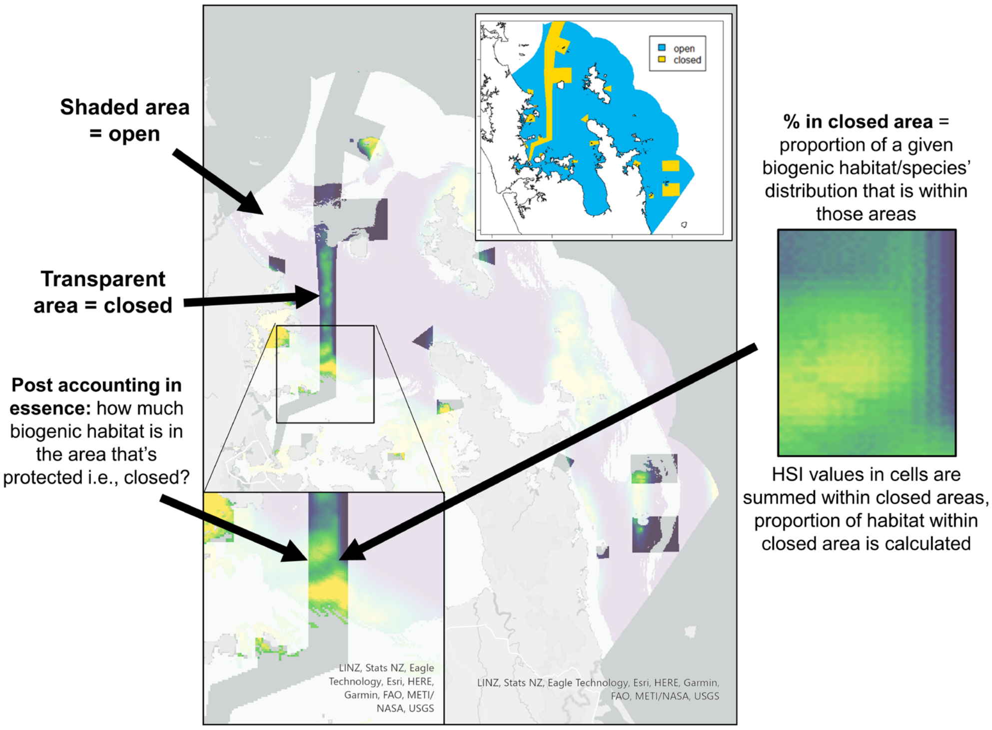
For all Zonation prioritisation scenarios carried out for this project, the core-area Zonation cell removal algorithm was used. In this algorithm, cell removal minimises biological loss by picking cell *i* that has the lowest occurrence for the most valuable feature over all biodiversity features in the cell. Therefore, if even one species has a high proportion of its relative occurrence found there, the cell gets a high value. Removal is then carried out by calculating a removal index δ_i for each of the cells using the following equation:

$$\delta_i = \max_j \frac{q_{ij} w_j}{c_i},$$

where w_j is the weight of species j and c_i is the cost of adding cell i to the reserve network. When running the analysis, the programme analyses all cells and calculates a δ_i value for each cell based on the feature that has the highest weighted proportion of distribution remaining in that specific cell. The cell which has the lowest δ_i value will then be removed. Zonation peer-reviewed literature provides more details on model equations and model options (Moilanen 2005; Moilanen 2007; Moilanen et al. 2014).

Post-accounting

To facilitate comparison of scenarios for developing spatial management options, summary statistics were generated for each scenario using the 'closure' layers. The proportion of suitable habitat cells for each biogenic habitat layer (current biogenic habitat, n = 20 layers; recovery potential, n = 20 layers) and biodiversity (current distribution, n = 198 layers; recovery potential, n = 198 layers) (see Table 7) within the sum of closed areas was calculated (i.e., % in closed area) (Figure 9). At the same time, the proportion of fishing value (effort and catch, n = 44 layers) within closed areas was also calculated, based on the value (area swept or catch-kg) within each cell. The same calculations were carried out for other biodiversity (i.e., layers resulting from national scale species distribution models at the genus level) and habitat layers (mangrove and seagrass). For modelled layers, discounting of value due to uncertainty was included in summary statistic calculations (0.2 weighting).



Shaded area = open

Transparent area = closed

Post accounting in essence: how much biogenic habitat is in the area that's protected i.e., closed?

% in closed area = proportion of a given biogenic habitat/species' distribution that is within those areas

HSI values in cells are summed within closed areas, proportion of habitat within closed area is calculated

Figure 9: Example of the post-accounting process employed here. In the insert map, open (blue) and closed (yellow) areas are shown. In the main map, open (shaded) and closed (transparent) areas are shown, with an example of a modelled biogenic habitat layer underneath. The post-accounting process is illustrated where probability of occurrence values (HSI) in unshaded (closed) areas are summed and the proportion of habitat inside and outside of these closed areas are calculated for each input layer i.e., biogenic habitat, biodiversity, and fishing value (effort and catch-kg).

3. RESULTS

3.1 Biogenic habitat modelled layers

Model performance (fit)

From a model fit standpoint, all but one of the ensemble models were useful to predict the occurrence of biogenic habitat groups as assessed by the withheld evaluation data (AUC > 0.7) (Table 8). The highest performing probability of occurrence models were encrusting Bryozoa (AUC: 0.95 and TSS 0.84), canopy-forming macroalgae (AUC: 0.91–0.92 and TSS: 0.70–0.73), miscellaneous macroalgae AUC: 0.91 and TSS: 0.69–0.70), and oysters (AUC: 0.90–0.91 and TSS: 0.78–0.80). The lowest performing probability of occurrence models were calcareous tubeworms (AUC: 0.58–0.66 and TSS 0.34–0.44) and Brachiopoda (AUC: 0.71–0.72 and TSS: 0.45–0.47).

The use of spatial cross validation as an additional model performance assessment revealed there were some areas within the study area where certain biogenic models perform poorly (Figure 10). The average spatial cross validation AUC score was above 0.7 for all but two models (Table 9). However, the minimum AUC score was below 0.7 for encrusting bryozoans, erect and rooted bryozoans, miscellaneous annelids, and tube worms. Thus, these models perform poorly in at least some part of the study area. Presently, these models have been retained in subsequent analyses as they hold some useful information for the study area and are thus a significant improvement on the previous state of knowledge for these habitats. Decision rules around the exclusion of models were based on the area-wide cross-validation scores and the expert review of model outputs with the spatial cross validation being used to identify priority taxa for future sampling effort.

The models were also assessed by a panel of experts with knowledge of each biogenic habitat group. Experts provided scores for several criteria (Table 10), including the spatial predictions. For the assessment of spatial predictions, any models that received a score ≥ 4 (largely inaccurate) was deemed not to be useful. The highest scoring model was canopy-forming macroalgae (1, very accurate). Most of the models scored a 2 (accurate) or 3 (somewhat accurate) (Table 10). The lowest performing models were given a score of 4 (deemed not to be useful). Three models obtained this score: calcareous tubeworms, Brachiopoda, and mussels. For the misc. macroalgae and Rhodolith modelled layers, some pre-processing was suggested by the consulted expert. For misc. macroalgae, the expert suggested that following application of the 'ROC threshold' (described above), that all values in the modelled layer be changed to 1 denoting high probability of occurrence. This is because the spatial distribution was considered appropriate, but the probability of occurrence values (between the ROC cut-off and 1) were lower than expected. For Rhodoliths, given the known depth limits of Rhodolith taxa, the consulted expert recommended that the modelled layer was clipped to depths < 200 m, removing predicted distribution in areas deeper than 200 m.

Environmental variable contributions

The most commonly selected environmental variables for the biogenic models were downward vertical flux of particulate organic matter at the seabed (POCFlux) and temperature at depth (BotTemp), which were selected in 15 of 20 models (Table 11). In contrast, mixed layer depth (MLD) and temperature residuals (TempRes) were not selected for any of the models. Generally, the selected environmental variables were similar between model groups that fall under the same higher taxonomic classification. For example, downward vertical flux of particulate organic matter at the seabed (POCFlux) was selected for all cnidarian models (misc. Anthozoa, cup corals, Hydrozoa, and sea anemones) accounting for 9–14% of influence in these models. Similarly, for sponges (Porifera), tidal current speed (TC) was selected for both the encrusting and erect/upright sponge models, accounting for 10.9% and 15.5% influence, respectively. For macroalgae, slope, bathymetry (Bathy200), and light incidence at the seabed (EBED) were selected for the misc. macroalgae and canopy-forming macroalgae models accounting for ~ 50–60% combined influence for each model (Table 11). The smallest number of variables were selected for the cup coral model (6), whereas the greatest number of environmental variables selected for a model was 20, for the horse mussel model.

Spatial predictions

Maps showing the spatial predictions (probability of occurrence) and model uncertainty (SD) estimates are shown for all 20 biogenic habitat ensemble models in Appendix 1 (Figures 1.1–1.20). In each of these figures, the four plots show probability of occurrence layers (model output), ROC cut-off applied layers, uncertainty (SD), and point records (presence-absence) used to train the model. An example is provided in text using the erect sponge model, where the probability of occurrence layer (Figure 11) and model uncertainty estimates (Figure 12) are shown in greater detail.

Broadly, for several biogenic habitat groups, high probability of occurrence is predicted in Kawau Bay, the area east of Kawau Island (e.g., non-calcareous tubeworms, multi-species aggregations, encrusting and erect sponges and oysters). The Colville Channel, between the Coromandel Peninsula and Aotea/Great Barrier Island hosts high probability of occurrence index values for encrusting and erect sponges and erect and rooted Bryozoa. In the deeper areas of the HGMP (> 200 m), high probability of occurrence is predicted for sea anemones, erect sponges (e.g., Figure 11), and misc. Anthozoa. For almost all the 20 modelled biogenic habitat groups, probability of occurrence predicted in the Firth of Thames area was very low (probability of occurrence < 0.4), therefore for most layers, this entire area was removed following application of the ROC cut-off (see Appendix 1). Uncertainty estimates varied considerably between models, though for several model groups including erect sponges, non-calcareous tubeworms, encrusting sponges, canopy-forming macroalgae, Brachiopoda, multi-species aggregations, and misc. Anthozoa, uncertainty estimates were relatively high (SD: ~ 0.2–0.3) on the western side of the HGMP, west of the Coromandel Peninsula and Aotea/Great Barrier Island (e.g., Figure 12).

Areal coverage (km^2) calculations are shown in Table 12 for each of the biogenic habitat model layers. Areal statistics are shown for the model prediction (ROC cut-off applied), current (condition applied), and recovery potential layers. The models with the greatest extent of predicted distribution in the HGMP include encrusting Bryozoa, Hydrozoa, misc. annelid assemblages, erect Bryozoa, and Brachiopoda (> 10 000 km^2). In contrast, the lowest extents are for the misc. macroalgae, canopy-forming macroalgae, and horse mussel models (< 1500 km^2). In terms of area remaining (%), canopy-forming macroalgae and horse mussels are estimated to have the greatest area remaining following application of the MSRP condition layer (44–53%). Biogenic habitat groups that are estimated to have less than 10% area (distribution extent) remaining include non-calcareous tubeworms, Rhodoliths, erect and rooted Bryozoa, and mussels (Table 12).

Table 8: Model fit metrics for the random forest (RF) and boosted regression trees (BRT) biogenic habitat groups in Table 4. Area under curve (AUC) and true skill statistic (TSS) scores are based on training and evaluation data. Mean and standard deviation (SD) based on 100 bootstraps.

		Training data				Evaluation data			
Biogenic habitat model	Fit metric	RF mean	RF SD	BRT mean	BRT SD	RF mean	RF SD	BRT mean	BRT SD
ANTH	AUC	0.92	0.02	0.89	0.03	0.83	0.05	0.83	0.05
	TSS	0.76	0.05	0.84	0.06	0.60	0.09	0.60	0.09
Biogen	AUC	0.92	0.01	0.87	0.02	0.79	0.02	0.78	0.03
	TSS	0.74	0.02	0.87	0.06	0.47	0.05	0.47	0.05
BRAC	AUC	0.89	0.03	0.83	0.05	0.72	0.09	0.71	0.09
	TSS	0.71	0.07	0.77	0.12	0.47	0.14	0.45	0.13
CALC	AUC	0.86	0.04	0.69	0.09	0.66	0.20	0.58	0.06
	TSS	0.73	0.04	0.65	0.08	0.44	0.19	0.34	0.06
CANSW	AUC	0.97	0.01	0.93	0.01	0.92	0.02	0.91	0.02
	TSS	0.84	0.02	0.86	0.07	0.73	0.04	0.70	0.04
CUP	AUC	0.93	0.03	0.87	0.06	0.87	0.07	0.80	0.10
	TSS	0.82	0.06	0.85	0.12	0.71	0.13	0.64	0.13
ENCB	AUC	0.99	0.00	0.98	0.01	0.95	0.04	0.95	0.04
	TSS	0.95	0.01	0.97	0.02	0.84	0.09	0.84	0.09
ENCSP	AUC	0.91	0.01	0.84	0.03	0.77	0.03	0.76	0.03
	TSS	0.69	0.03	0.81	0.09	0.45	0.05	0.43	0.05
ERCSP	AUC	0.94	0.01	0.89	0.01	0.82	0.02	0.81	0.03
	TSS	0.76	0.02	0.89	0.05	0.52	0.04	0.50	0.05
ERCT	AUC	0.93	0.03	0.86	0.05	0.81	0.08	0.77	0.08
	TSS	0.77	0.06	0.88	0.09	0.57	0.13	0.51	0.13
EROO	AUC	0.94	0.04	0.91	0.06	0.87	0.10	0.86	0.09
	TSS	0.81	0.09	0.89	0.08	0.73	0.15	0.71	0.15
HSM	AUC	0.93	0.01	0.88	0.02	0.79	0.02	0.78	0.02
	TSS	0.73	0.02	0.91	0.04	0.45	0.04	0.44	0.04
HYD	AUC	0.94	0.03	0.91	0.04	0.88	0.06	0.85	0.07
	TSS	0.82	0.06	0.87	0.08	0.71	0.10	0.70	0.11
MUS	AUC	0.92	0.02	0.84	0.03	0.81	0.05	0.80	0.05
	TSS	0.72	0.05	0.71	0.08	0.56	0.07	0.54	0.08
OYS	AUC	0.96	0.02	0.95	0.03	0.91	0.06	0.90	0.06
	TSS	0.89	0.04	0.95	0.05	0.80	0.10	0.78	0.11
Rhodolith	AUC	0.92	0.04	0.86	0.08	0.81	0.10	0.77	0.11
	TSS	0.77	0.08	0.86	0.10	0.63	0.16	0.60	0.16
SEA	AUC	0.89	0.02	0.77	0.05	0.72	0.05	0.70	0.06
	TSS	0.68	0.04	0.61	0.13	0.40	0.09	0.37	0.09
SURF	AUC	0.96	0.01	0.92	0.02	0.78	0.04	0.77	0.04
	TSS	0.79	0.02	0.97	0.03	0.44	0.07	0.44	0.07
SWIL	AUC	0.97	0.00	0.94	0.01	0.91	0.01	0.91	0.01
	TSS	0.84	0.02	0.85	0.05	0.70	0.03	0.69	0.04
TUBE	AUC	0.95	0.01	0.90	0.02	0.90	0.03	0.88	0.03
	TSS	0.80	0.03	0.73	0.04	0.67	0.06	0.66	0.06

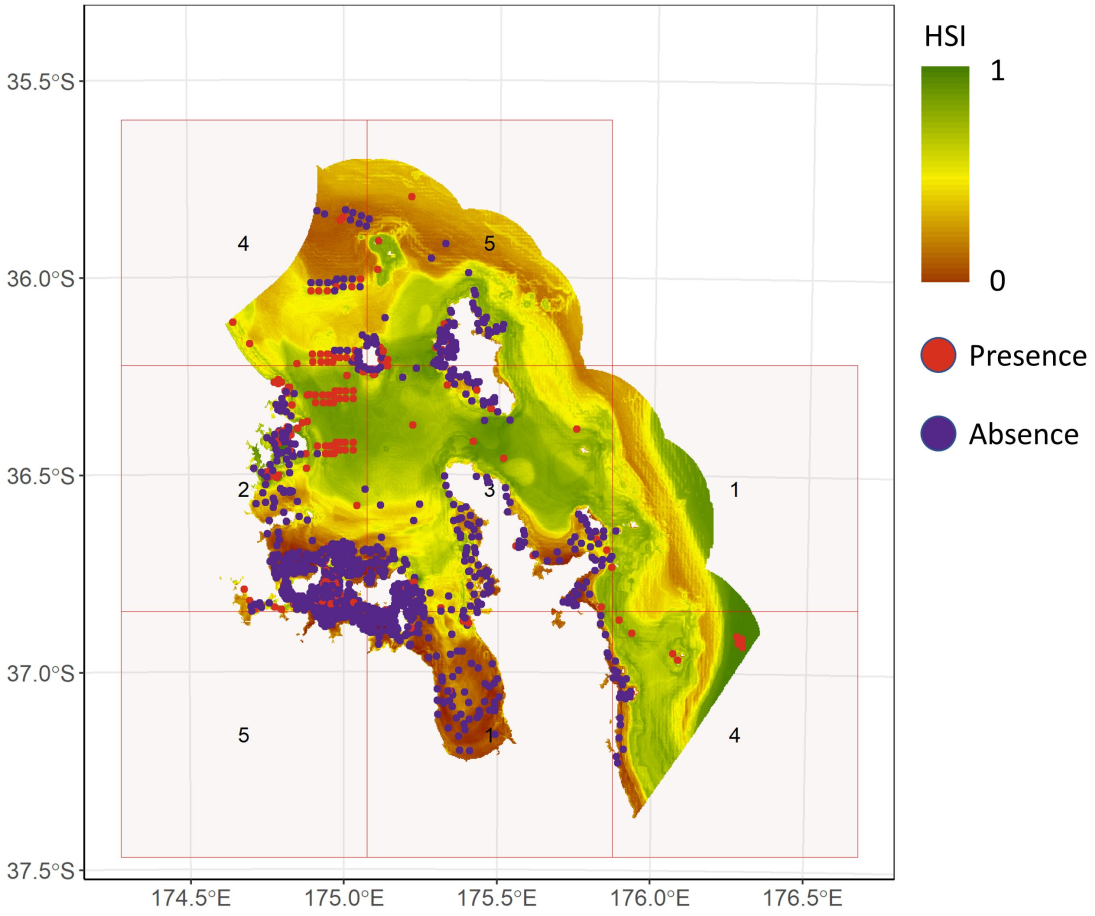


Figure 10: Spatial blocking example with the probability of occurrence model (HSI) for the erect/upright sponge group using the *blockCV* package in R. Spatial block size set to 70 000 m, k folds = 5.

Table 9: AUC spatial cross validation scores for the invertebrate biogenic habitat models developed in this study. Scores < 0.7 indicate a model with limited transferability (i.e., extrapolation of environmental relationships) between different areas in the study area. * indicates biogenic habitats that were assessed by experts as having low confidence in model outputs.

Model	Min spatial AUC	Mean spatial AUC
ANTH	0.89	0.96
BRAC*	0.89	0.93
CALC*	0.78	0.90
CUP	0.83	0.94
ENCB	0.61	0.66
ENCSP	0.91	0.94
ERCSP	0.75	0.82
ERCT	0.94	0.97
EROO	0.69	0.86
HSM	0.86	0.92
HYD	0.98	0.99
MUS*	0.84	0.94
OYS	0.98	1.00
SEA	0.86	0.94
SURF	0.58	0.65
TUBE	0.39	0.84

Table 10: Expert evaluation scores. Experts provided scores for 1) self-assessment of their knowledge of biogenic habitat group in the HGMP, 2) the distribution of point records used to train models, and 3) the predicted spatial distributions of biogenic habitat.

Group description	Code	Assessment of expert knowledge	Distribution of records	Predicted distributions
Misc. Anthozoa	ANTH	1	2	3
Multi-species aggregations that indicate biogenic habitat	Biogen	2	3	3
Brachiopoda	BRAC	3	3	4
Calcareous tubeworms	CALC	3	2	4
Canopy-forming macroalgae	CANSW	1	2	1
Cup corals	CUP	1	2	2
Encrusting Bryozoa	ENCB	2	2	2/3
Encrusting sponges	ENCSP	2	3	2/3
Erect/upright sponges	ERCSP	2	2	2/3
Erect/frame-building Bryozoa	ERCT	2	2	2/3
Erect and rooted Bryozoa	EROO	2	2	2/3
Horse mussels	HSM	1	1	2
Hydrozoa	HYD	3	2	2
Mussels	MUS	2/3	2	4
Oysters	OYS	2	2	2
Rhodoliths	Rhodoliths	1	3	3
Sea anemones	SEA	2	2	2/3
Misc. annelid assemblages	SURF	2	2	3
Misc. macroalgae	SWIL	1	3	2/3
Non-calcareous tubeworms	TUBE	2	1	2

Table 11: Environmental variable influence (percentage contribution) to each biogenic habitat ensemble model. Environmental variables are detailed in Table 5.

	Biogenic habitat model group																			
Env. variable	ANTH	Biogen	BRAC	CALC	CANSW	CUP	ENCB	ENCSP	ERCSP	ERCT	EROO	HSM	HYD	MUS	OYS	Rhodolith	SEA	SURF	SWIL	TUBE
Bathy200	–	8.5	8.0	4.3	27.1	–	–	–	8.7	5.7	–	4.7	3.9	25.8	8.3	8.0	7.6	–	18.8	–
BBP	–	–	13.3	–	6.6	–	–	–	–	–	–	4.3	–	8.4	–	4.8	–	7.4	4.5	–
BedDist	5.2	–	5.0	–	14.4	8.6	–	–	–	–	6.8	–	–	4.9	12.9	–	4.3	–	–	–
BotNi	3.1	7.9	–	6.0	–	–	6.6	–	7.7	–	–	3.6	6.3	–	–	–	–	5.3	5.3	7.1
BotOxy	2.9	–	–	11.8	–	–	–	4.8	–	–	–	4.7	2.6	4.8	14.8	–	4.1	7.7	5.5	–
BotPhos	3.9	7.4	–	14.5	–	–	16.4	–	–	13.5	9.3	3.7	5.4	–	–	7.9	–	5.2	6.3	–
BotOxySat	3.7	–	–	–	–	–	–	7.1	7.9	–	–	5.6	2.7	–	6.0	–	6.2	–	6.2	–
BotSal	3.7	–	7.0	–	–	13.5	–	6.8	8.8	–	–	5.5	4.3	–	–	4.9	12.3	–	–	6.0
BotSil	9.2	7.1	7.3	5.8	–	–	–	–	–	6.7	–	3.6	3.2	–	–	4.1	–	6.7	5.0	–
BotTemp	5.5	13.3	–	4.4	9.3	–	4.7	8.8	12.0	12.7	9.7	4.7	31.8	–	–	–	8.9	6.2	13.8	20.4
BPI_broad	12.3	7.8	–	–	–	41.2	7.8	6.9	–	–	9.8	–	–	–	–	8.1	–	11.0	–	14.2
BPI_fine	–	–	4.2	3.7	8.2	–	4.1	–	–	–	–	–	–	4.7	–	28.2	–	6.2	–	–
Carbonate	–	–	12.6	10.2	–	–	19.3	–	–	9.0	19.7	–	–	–	5.4	–	–	7.9	–	–
CHLA	5.5	–	9.4	–	–	–	–	5.1	–	–	–	5.2	–	7.1	–	–	5.6	–	–	5.7
ChlAGrad	–	–	–	–	–	–	5.0	–	–	–	–	–	9.2	–	–	–	5.8	6.3	–	–
DET	5.7	–	–	–	–	–	–	5.5	–	7.2	–	4.2	–	–	–	5.1	–	–	–	–
DynOc	7.9	–	–	–	–	8.4	–	–	–	–	–	–	–	–	3.5	–	–	–	–	–
EBED	5.9	–	9.7	4.7	14.5	–	–	–	7.7	4.6	–	–	4.5	6.5	–	8.7	–	–	17.1	–
KPAR	7.8	–	5.8	4.1	–	16.6	10.8	–	–	–	17.6	5.4	–	12.3	7.9	–	12.3	6.9	–	–
MLD	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
PAR	–	–	–	2.9	–	–	–	–	–	4.9	5.0	6.1	2.4	–	–	–	–	–	–	4.2
POCFlux	12.4	11.9	6.3	7.9	–	11.8	–	6.7	7.5	7.6	8.3	4.9	8.6	–	–	–	13.6	5.5	4.8	19.0
Rough	–	–	–	–	–	–	16.4	6.3	–	–	–	5.0	–	4.6	13.6	–	–	–	–	5.6
SeasTDiff	–	–	5.8	9.4	–	–	–	–	6.4	6.9	3.7	5.4	4.9	–	10.6	–	–	–	–	5.7
Slope	–	8.3	–	–	19.9	–	–	10.5	9.4	8.7	–	–	–	14.9	–	12.0	–	–	12.7	–
SST	–	–	–	–	–	–	–	6.6	–	–	–	5.0	–	5.9	–	–	6.3	6.6	–	–
SSTGrad	–	8.3	5.8	10.2	–	–	–	5.3	–	7.9	3.1	6.0	3.3	–	–	–	–	6.2	–	–
SubstrateAEA	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	8.3	–	–	–	–
TC	–	11.2	–	–	–	–	–	10.9	15.5	–	–	7.1	–	–	17.1	–	6.4	–	–	–
TempRes	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
VGPM	5.3	8.3	–	–	–	–	9.0	8.6	8.4	4.6	7.0	5.4	7.1	–	–	–	6.5	4.7	–	12.0

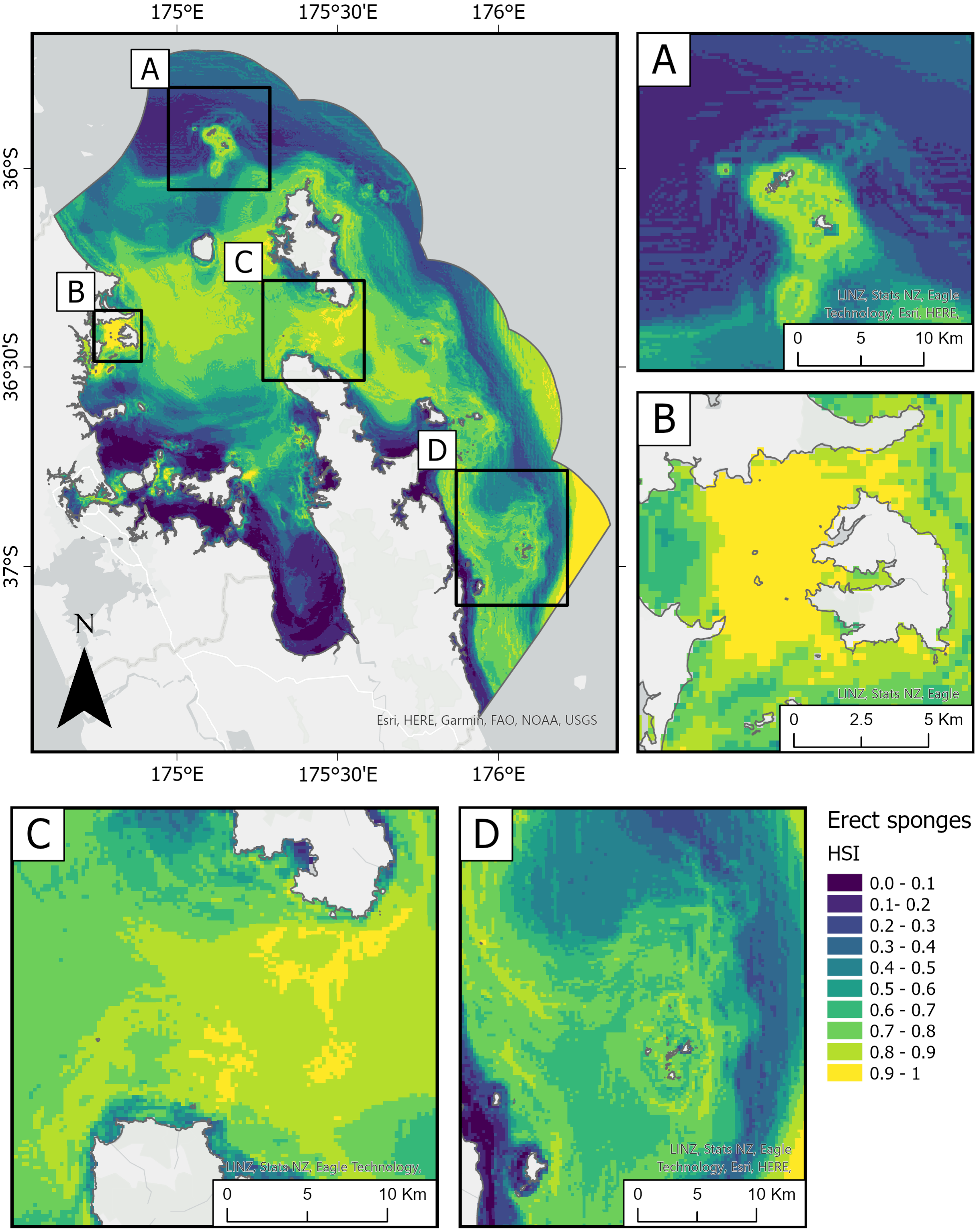


Figure 11: **Probability of occurrence (represented as HSI) modelled layer for erect sponges (mean based on 100 bootstraps). Layer shown is an ensemble model, i.e., combined spatial predictions from random forest (RF) and boosted regression tree (BRT) models. A) Mokohinau Islands, B) Kawau Bay, C) Colville Channel, and D) Alderman Islands.**

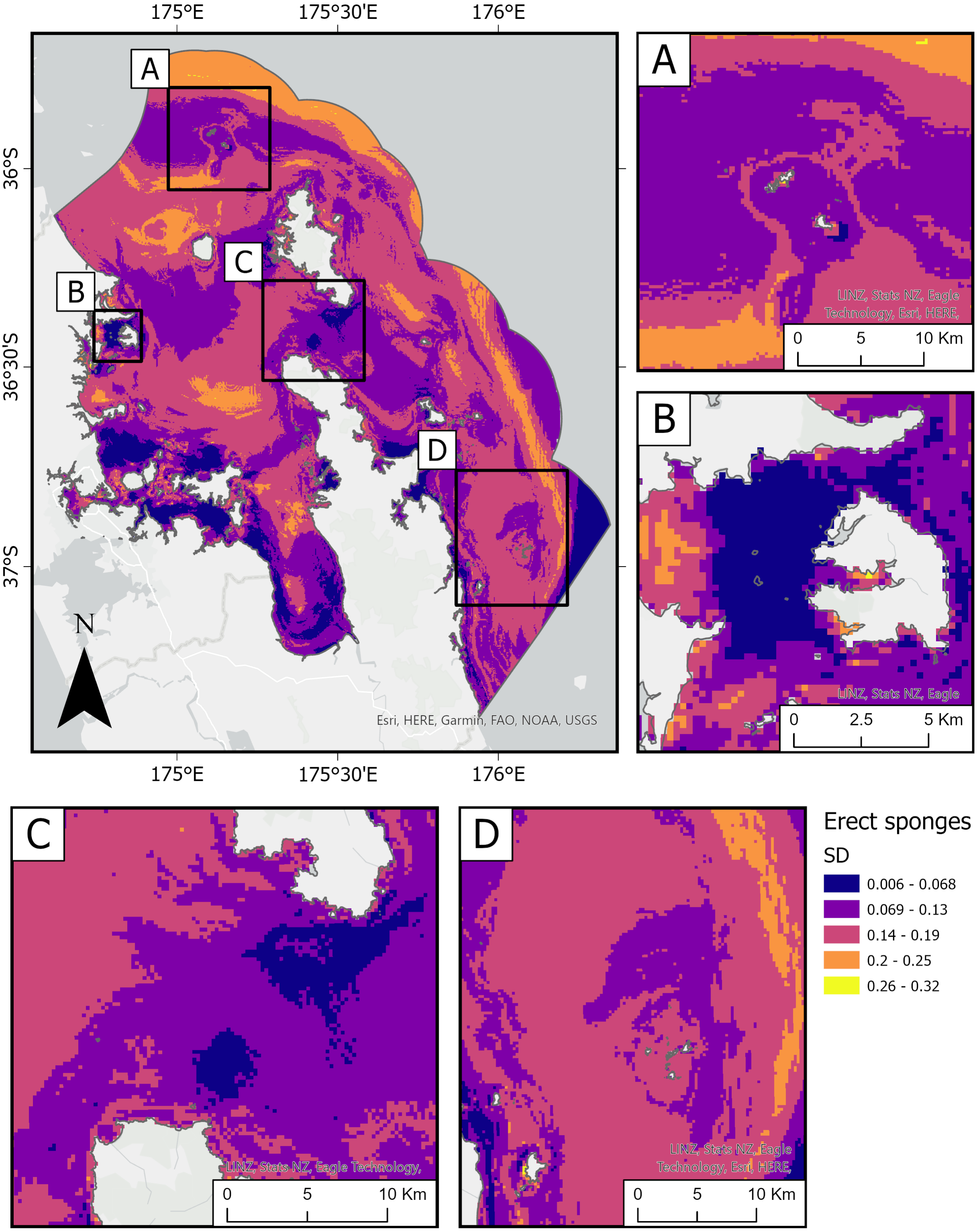


Figure 12: Uncertainty layer (standard deviation) for erect sponges (SD based on 100 bootstraps). Layer shown is an ensemble model, i.e., combined spatial predictions from random forest (RF) and boosted regression tree (BRT) models. A) Mokohinau Islands, B) Kawau Bay, C) Colville Channel, and D) Alderman Islands.

Table 12: Areal extent of modelled biogenic habitats in the HGMP. Unimpacted (probability of occurrence with ROC threshold applied) and current (MSRP condition applied) and recovery (unimpacted minus current) area are shown (square kilometres). Percentage (%) area remaining is also shown; i.e., current extent as a proportion of the unimpacted extent. Calculations are based on model area for Round 3.

Group description	Unimpacted (probability of occurrence ROC threshold applied) extent (km^2)	Current extent (km^2)	Recovery extent (km^2)	Area remaining (%)
Misc. Anthozoa	9 794.4	3 170.7	6 623.7	32.4
Multi-species aggregations	4 997.3	965.7	4 031.6	19.3
Brachiopoda	10 657.8	2 740.6	7 917.2	25.7
Calcareous tubeworms	7 542.1	1 076.3	6 465.8	14.3
Canopy-forming macroalgae	1 157.4	609.3	548.1	52.6
Cup corals	8 643.3	3 339.3	5 304.0	38.6
Encrusting Bryozoa	12 228.3	4 439.3	7 789.0	36.3
Encrusting sponges	6 550.0	924.6	5 625.4	14.1
Erect/upright sponges	7 305.9	806.8	6 499.1	11.0
Erect/frame-building Bryozoa	10 770.3	1 893.1	8 877.2	17.6
Erect and rooted Bryozoa	9 009.8	676.8	8 333.0	7.5
Horse mussels	758.7	334.9	423.8	44.1
Hydrozoa	11 337.9	4 123.7	7 214.2	36.4
Mussels	5 265.9	427.7	4 838.2	8.1
Oysters	5 187.3	1 339.4	3 847.9	25.8
Rhodoliths	3 221.1	223.9	2 997.2	7.0
Sea anemones	9 083.2	920.1	8 163.1	10.1
Misc. annelid assemblages	10 973.4	3 185.1	7 788.3	29.0
Misc. macroalgae	1 361.8	357.8	1 004.0	26.3
Non-calcareous tubeworms	5 827.9	409.1	5 418.8	7.0

2.1 Exploratory trawl corridor scenarios and spatial prioritisations

Model area

Over the course of the advisory group process, the model area (i.e., the area of the HGMP that was included in or masked out of the spatial prioritisation and post-accounting analyses) changed with different scenario iterations (Table 13, Figure 13). This change in model area was in response to requests from the working group and Fisheries New Zealand. Some areas were masked out and then reintroduced for subsequent rounds, based on developing discussions. In Round 1, the whole HGMP area was used, though exclusion of the CPZ and current and proposed protected areas was discussed. Ultimately, these areas were retained in the model area, noting that trawling may not occur in these areas. In Round 2, military zones, sand extraction areas, channel dredging, and aquaculture sites were all removed from the model area. Removal of these areas was attributed to the unknown impact of these activities and the exclusion of trawling from some of these areas (channel dredging and aquaculture sites). In Round 3, aquaculture and channel dredging sites were still excluded from the model area, but sand extraction and military zones were reintroduced because it was acknowledged that trawling can still occur in these areas. In the final round, Round 4, aquaculture sites and channel dredging areas remained excluded, but areas deeper than 200 m and scallop dredging open areas (in 2022) were also excluded. Deeper areas were excluded because this area was recognised as comparatively unique in terms of benthic habitat and fisheries (offshore fishery), and spatial management of this area would need to be discussed in a separate management process. The scallop dredging open areas were removed as it is not possible to account for the impact of dredging in these areas at present. Therefore, it was decided that biodiversity 'gains' should not be reported for these areas. The influence of the selected model area and boundary with respect to stressor impacts for which fishery footprints have or have not been quantified, can influence the estimate of how much biodiversity is protected, and the uncertainty reflected in decisions with respect to model boundaries is further considered in the discussion.

Table 13: Model area iterations throughout the advisory group process and rationale for each modification.

Round	Label in Figure 13	Description of change to model area	Rationale
1	A	Full HGMP: CPZ/HPAs/SPAs exclusion discussed	Trawling (potentially) not permitted, calculate biodiversity gains but do not overlap with corridors
2	B	Military zones and sand extraction excluded	Areas are already impacted therefore do not provide protection
		Aquaculture/channel dredging removed	Cannot trawl in these areas – impact on biogenic habitat unknown
3	C	Military zones and sand extraction reinstated	Trawling can still occur in these areas
4	D	Scallop dredging open areas (in 2022) removed	Cannot account for the impact of scallop dredging at present
		Areas deeper than 200 m removed	Deep area hosts comparatively unique biogenic habitats and fishery here is distinct (offshore fishery). Assessment of this area requires bespoke process.

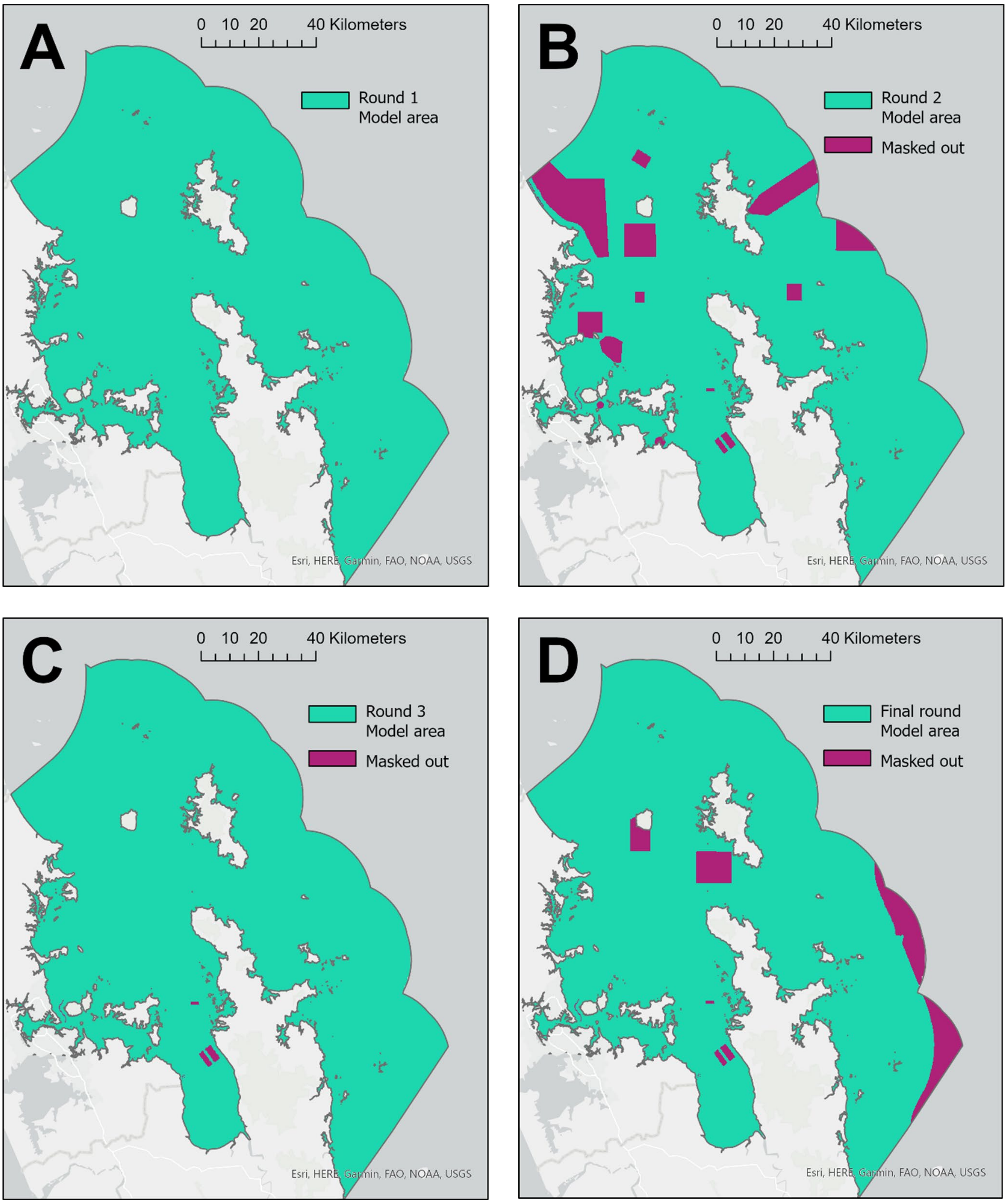


Figure 13: Model area iterations throughout the advisory group process and scenario iterations. A) Full HGMP area, B) Sand extraction, military, channel dredging, and aquaculture sites excluded from model area, C) Aquaculture sites excluded from model area, D) Aquaculture sites, depth > 200 m, and current commercial scallop dredging open areas (2022) excluded from model area.

Scenario iterations

Over 60 separate spatial prioritisation and post-accounting scenarios were developed for this project. A complete list is shown in Table 14. These scenario iterations are spread over four rounds, where each HG-BSPAG (working group meeting) was followed by a round of scenarios. The first round of scenarios was largely exploratory, with a wide range of options developed and reported on. These scenarios explored high biogenic habitat protection (Table 14, Scenarios 3a & 3b), as well as several options that explored 'freezing' trawl footprints (Table 14, Scenarios 5a & 5b). Importantly, biodiversity and biogenic habitat protection afforded by current and proposed protected areas was a key focus for this first round.

In the second round, a larger focus was placed on fishing and, in particular, exploring closures based on footprints of different fishing methods. For example, scenario 2 in Round 2 considered current and proposed closed areas separately for each fishing method. Scenario 3 in Round 2 included the scenario 2 exploratory closed areas but included the 'frozen' fishing footprint approach, i.e., all areas not included in the current fishing footprint were placed into closed areas. The final scenario for Round 2 explored initial Zonation-based spatial prioritisations where biogenic habitat protection was traded-off with fishing value (catch-kg). In response to advisory group feedback, several exploratory scenarios were conducted in this round to quantify biodiversity values in mangrove and seagrass habitat, and in deeper areas (> 200 m).

In Round 3, greater focus was placed on identifying areas of high value for different fishing methods (Table 14, 3a–3e). Round 3 prioritisations placed focus on current and recovery potential of biogenic habitats, with and without fishing value trade-off. Here, trade-off scenarios were repeated for each fishing method independently. Two scenarios in this round involved evaluating the effectiveness of two trawl corridor configurations for protection of biogenic habitat and benthic biodiversity, and their recovery potential. These manually configured scenarios, provided by Fisheries New Zealand, and informed by previous spatial prioritisation maps, were developed as test cases to provide the working group with examples for trawl corridor development for the final round of scenarios. At this stage, dozens of spatial prioritisation maps, maps of biogenic habitat predicted distributions, and fishing value maps were provided to the HG-BSPAG to inform trawl corridor placement for the final round.

Trawl corridors

The final round comprised > 10 trawl corridor configurations (Table 14) provided (i.e., manually configured or described) by members of the HG-BSPAG and Fisheries New Zealand. These scenarios included further exploration of the trawl corridor configurations from the previous round (Table 14, 1 and 2). Scenario 3 was provided by HG-BSPAG members, informed by maps that had been provided throughout the advisory group process. Scenarios 4 and 5 explored different levels of biogenic habitat protection, whereas the final five scenarios explored corridor placement in areas of high fishing value (for different fishing methods). The area of each trawl corridor configuration (square kilometres) and the proportion of the HGMP (based on the model area for the final round) within each configuration is shown in Table 15. The smallest trawl corridor configurations explored were scenarios 1, 2, and 8 (845–1271 km^2), accounting for less than 10% of the HGMP. The largest trawl corridor configurations were scenarios 5 and 10 (> 3000 km^2), accounting for 23.2% and 27.6% of the HGMP (Table 15).

All were informed by closure explorations (Figures 14, 15, and 16) and Zonation prioritisations (Figure 17 and Figure 18; also see Appendix 2) yet trawl corridor 'boxes' in these examples were constructed in different ways. Scenario 3 corridors were provided by members of the HG-BSPAG, scenarios 4 and 5 were based on target thresholds for areas encompassing current and recovery biogenic habitat distributions (e.g., areas encompassing 20% current biogenic habitat). For Scenario 10, an area was identified to encompass 75% of fishing value (catch-kg) for all methods and target species combined (Figure 16D). A selection of trawl corridor configurations explored in the final round are shown herein (Figure 19). These four trawl corridor configurations represent different scenario development methods.

Table 14: All scenarios for each of the four rounds of the stakeholder working group process.

Scenario	Description of closed area
Round 1	
1	Current and proposed closed areas
2a	100% of current biogenic habitat distribution
2b	90% of current biogenic habitat distribution
3a	100% of current biogenic habitat distribution + top 90% of areas for biogenic recovery
3b	100% of current biogenic habitat distribution + top 80% of areas for biogenic recovery
3c	100% of current biogenic habitat distribution + top 70% of areas for biogenic recovery
4	Trawl footprint + current/proposed protection
5a 70%	Recovery potential (top 70% with trawl trade-off) + trawl footprint + current/proposed protection + 100% of current distribution of biogenic habitat.
5a 80%	Recovery potential (top 80% with trawl trade-off) + trawl footprint + current/proposed protection + 100% of current distribution of biogenic habitat.
5a 90%	Recovery potential (top 90% with trawl trade-off) + trawl footprint + current/proposed protection + 100% of current distribution of biogenic habitat.
5b 70%	Recovery potential (top 70% with Danish seine trade-off) + trawl footprint + current/proposed protection + 100% of current distribution of biogenic habitat.
5b 80%	Recovery potential (top 80% with Danish seine trade-off) + trawl footprint + current/proposed protection + 100% of current distribution of biogenic habitat.
5b 90%	Recovery potential (top 90% with Danish seine trade-off) + trawl footprint + current/proposed protection + 100% of current distribution of biogenic habitat.
6	Current + proposed protection areas and 100% of the current distribution of biogenic habitats
Round 2	
1	Proportions of biogenic habitats in the model area
2a BT	Areas currently closed to bottom trawling
2a DS	Areas currently closed to Danish seine
2a PSH	Areas currently closed to PSH
2b BT	Areas currently closed to bottom trawling + proposed HPAs and SPAs
2b DS	Areas currently closed to Danish seine + proposed HPAs and SPAs
2b PSH	Areas currently closed to PSH + proposed HPAs and SPAs
2c BT	Areas currently closed to bottom trawling + proposed HPAs and SPAs + area outside bottom trawling footprint
2c DS	Areas currently closed to Danish seine + proposed HPAs and SPAs + area outside Danish seine footprint
2c PSH	Areas currently closed to PSH + proposed HPAs and SPAs + area outside PSH footprint
3a 25%	Area outside Danish seine top 25% catch value
3a 50%	Area outside Danish seine top 50% catch value
3a 75%	Area outside Danish seine top 75% catch value
3b 25%	Area outside bottom trawling (vessels under 20m) top 25% catch value
3b 50%	Area outside bottom trawling (vessels under 20m) top 50% catch value
3b 75%	Area outside bottom trawling (vessels under 20m) top 75% catch value
3c 25%	Area outside bottom trawling (vessels over 20m) top 25% catch value
3c 50%	Area outside bottom trawling (vessels over 20m) top 50% catch value
3c 75%	Area outside bottom trawling (vessels over 20m) top 75% catch value
3d 25%	Area outside PSH top 25% catch value
3d 50%	Area outside PSH top 50% catch value

Scenario	Description of closed area
3d 75%	Area outside PSH top 75% catch value
3e 25%	Area outside Danish seine, bottom trawling (under 20m vessels) and PSH top 25% catch value
3e 50%	Area outside Danish seine, bottom trawling (under 20m vessels) and PSH top 50% catch value
3e 75%	Area outside Danish seine, bottom trawling (under 20m vessels) and PSH top 75% catch value
Round 2 Zonation prioritisation scenarios	
4a	Trade-off between protection of current biogenic habitats and fishing value
4b	Trade-off between protection of areas for biogenic habitat recovery and fishing value
Round 2 Additional post-accounting scenarios	
-	Exploring the ‘deep’ area (>200 m) in the Hauraki Gulf Marine Park
-	Mangroves and seagrass: Current closed areas
-	Mangroves and seagrass: Current closed areas and HPAs and SPAs
Round 3	
1	Proportions of biogenic habitat in the model area
2a	Current closures (all fishing methods combined)
2b	Current closures (all fishing methods combined) + proposed protected areas HPAs and SPAs
2c	Current closures (all fishing methods combined) + proposed protected areas HPAs and SPAs + all areas outside of fishing footprint (all methods combined)
3a	Close areas outside top 25, 50, and 75% catch value for bottom trawling with vessels over 20 m
3b	Close areas outside top 25, 50, and 75% catch value for bottom trawling with vessels under 20 m
3c	Close areas outside top 25, 50 and 75% catch value for Danish seine
3d	Close areas outside top 25, 50 and 75% catch value for PSH
3e	Close areas outside top 25, 50 and 75% catch value for all fishing methods combined
Round 3 Zonation prioritisation scenarios	
4a	Zonation prioritisation of current biogenic habitat, no trade-off with fishing
4b	Zonation prioritisation of biogenic habitat recovery, no trade-off with fishing
4c	Zonation prioritisation of current biogenic habitat, trade-off with fishing (split into 5 scenarios: 1 for each of the 4 fishing methods plus 1 for combined, equally weighted value)
4d	Zonation prioritisation of biogenic habitat recovery, trade-off with fishing (split into 5 scenarios: 1 for each of the 4 fishing methods plus 1 for combined, equally weighted value)
Round 3 Exploratory trawl corridors	
1	Trawl corridor configuration 1
2	Trawl corridor configuration 2
Final Round	
1	“Trawl corridor configuration 1” 10% larger
1a	“Trawl corridor configuration 1” 10% larger with 500 m buffer
2	“Trawl corridor configuration 1” 15% larger
3	Trawl corridor drawn by working group members
4	Area encompassing bottom 20% current biogenic habitat and bottom 5% recovery potential habitat
5	Area encompassing bottom 10% current biogenic habitat and bottom 75% recovery potential distribution
6	Area encompassing top 75% of catch for Danish seine
7	Area encompassing top 75% of catch for bottom trawling (vessels under 20 m)
8	Area encompassing top 75% of catch for bottom trawling (vessels over 20 m)
9	Area encompassing top 75% of catch for PSH
10	Area encompassing top 75% of catch for all fishing methods combined

Table 15: Area (km^2) of each scenario designated as trawl corridors (i.e., open to fishing) in the final round and its percentage of the HGMP excluding the deep area (deeper than 200 m).

Area/Scenario	Area (km^2)	Proportion (%) of HGMP < 200 m depth
Total HGMP	14 009	–
HGMP > 200 m depth	457	–
Scenario 1	1 215	9.0
Scenario 1a	1 377	10.2
Scenario 2	1 271	9.4
Scenario 3	2 253	16.6
Scenario 4	2 569	19.0
Scenario 5	3 141	23.2
Scenario 6	1 930	14.2
Scenario 7	1 611	11.9
Scenario 8	845	6.2
Scenario 9	1 360	10.0
Scenario 10	3 746	27.6

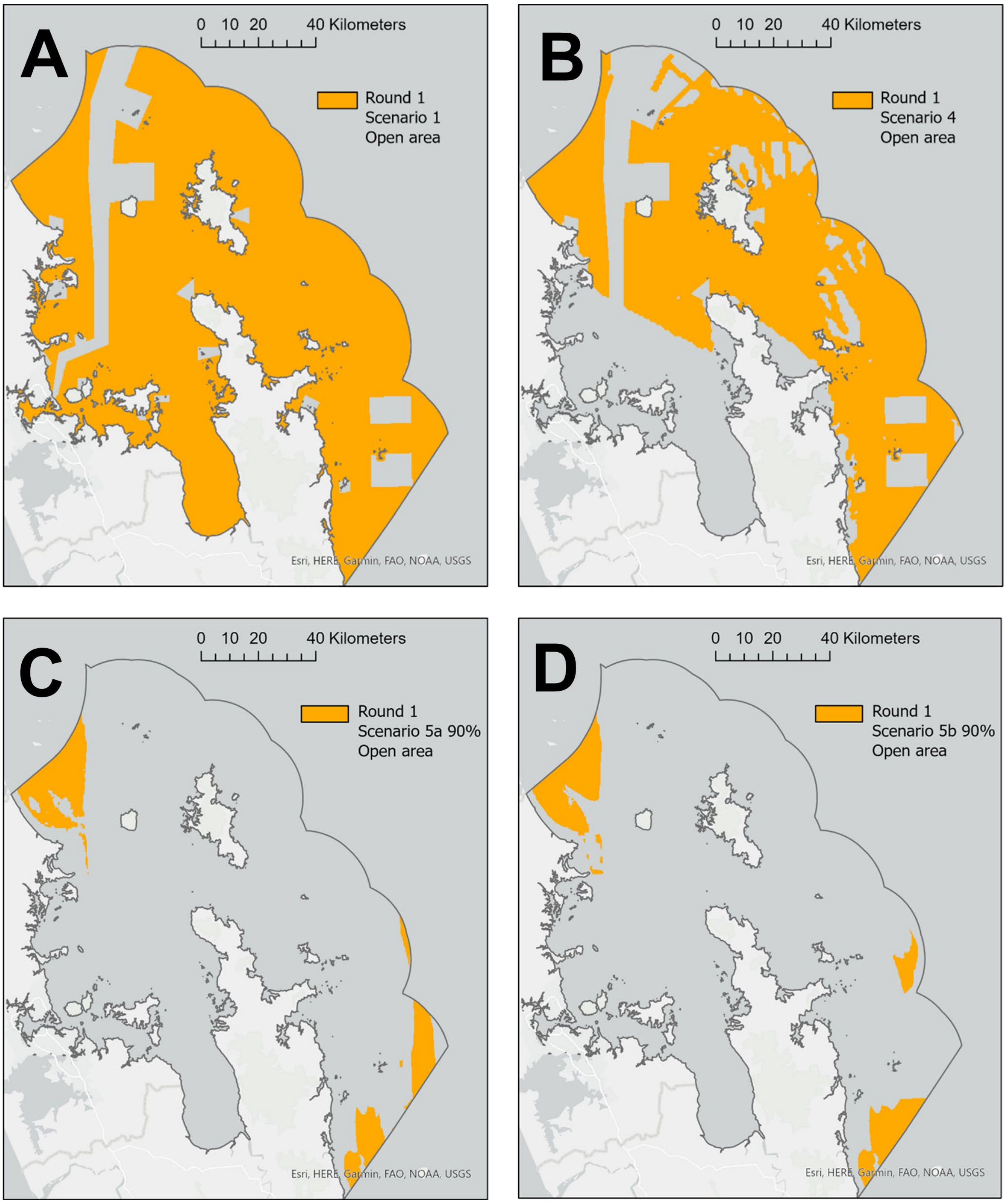


Figure 14: Examples of scenarios in Round 1 of explorations. A) Current and proposed protected areas in the HGMP, B) Current and proposed protected areas and areas within the trawl fishing footprint extent (2018/19–2020/21), C) 90% of recovery potential habitat and current trawl footprint & current/proposed protected areas and 100% of current distribution of biogenic habitat (minimising impacts on trawl fishery), D) 90% of recovery potential habitat and current trawl footprint & current/proposed protected areas and 100% of current distribution of biogenic habitat (minimising impacts on Danish seine fishery).

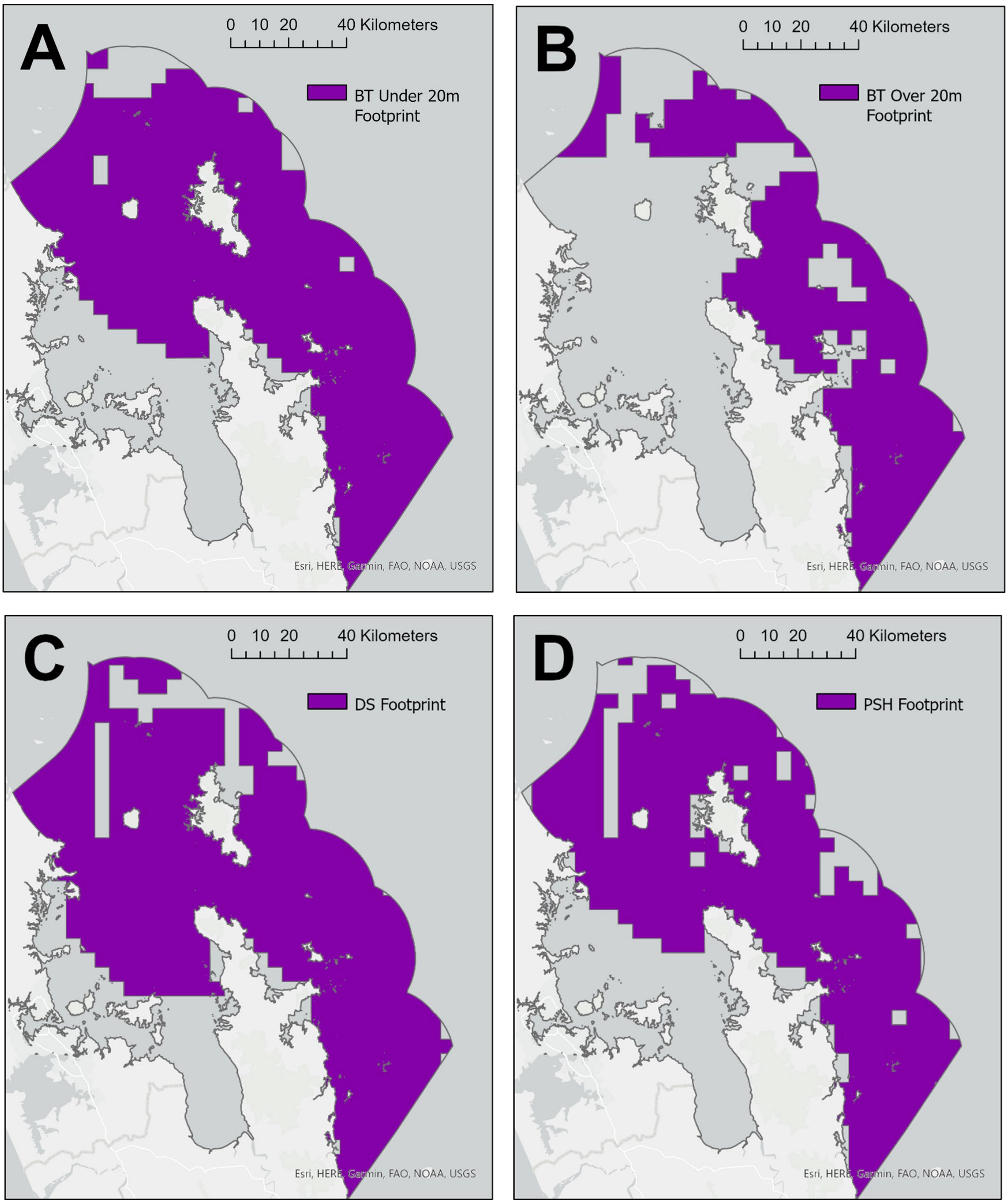


Figure 15: Extent of fishing footprints of different fishing methods in the HGMP. A) Bottom trawling (vessels under 20 m) fishing footprint, B) Bottom trawling (vessels over 20 m) fishing footprint, C) Danish seine fishing footprint, D) Precision seafood harvesting (PSH) fishing footprint (note that the fishing footprint represents the historical PSH footprint, and not the current spatial regulations for PSH as shown in Figure 2). Resolution reprojected at 3 n.mile grid to protect industry data.

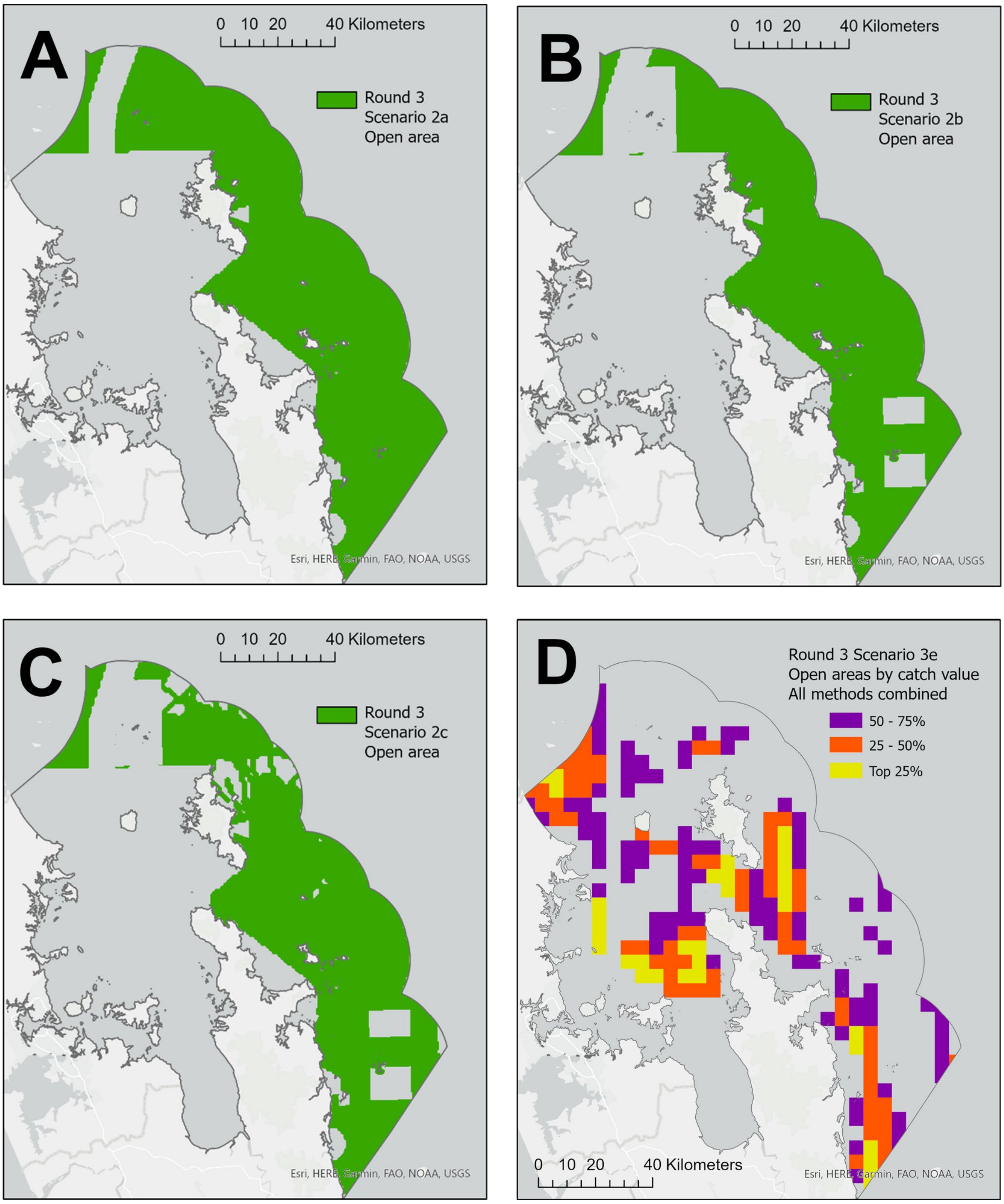


Figure 16: Examples of scenarios in Round 3 of scenario explorations. A) Current closures for all fishing methods combined, B) Current closures for all fishing methods combined, including proposed protected areas, C) Current closures for all fishing methods combined, including proposed protected areas and all area outside of fishing footprint (all fishing methods combined), D) Areas of high catch value for all fishing methods combined (bottom trawling, PSH, and Danish seine). Resolution reprojected at 3 n.mile grid to protect industry data.

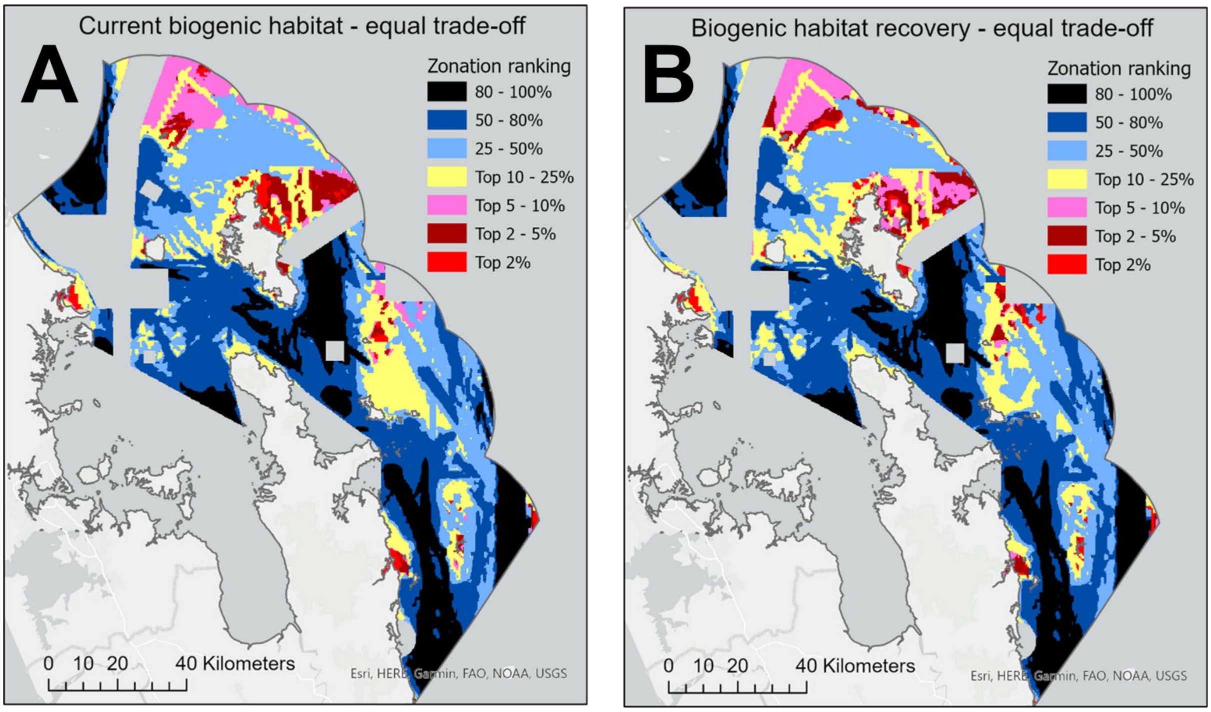


Figure 17: Zonation prioritisations from Round 2. A) Zonation prioritisation with 17 layers representing current distribution of biogenic habitat (equal value trade off with fishing value, catch-kg), B) Zonation prioritisation with 17 layers representing recovery potential biogenic habitat (equal value trade off with fishing value, catch-kg).

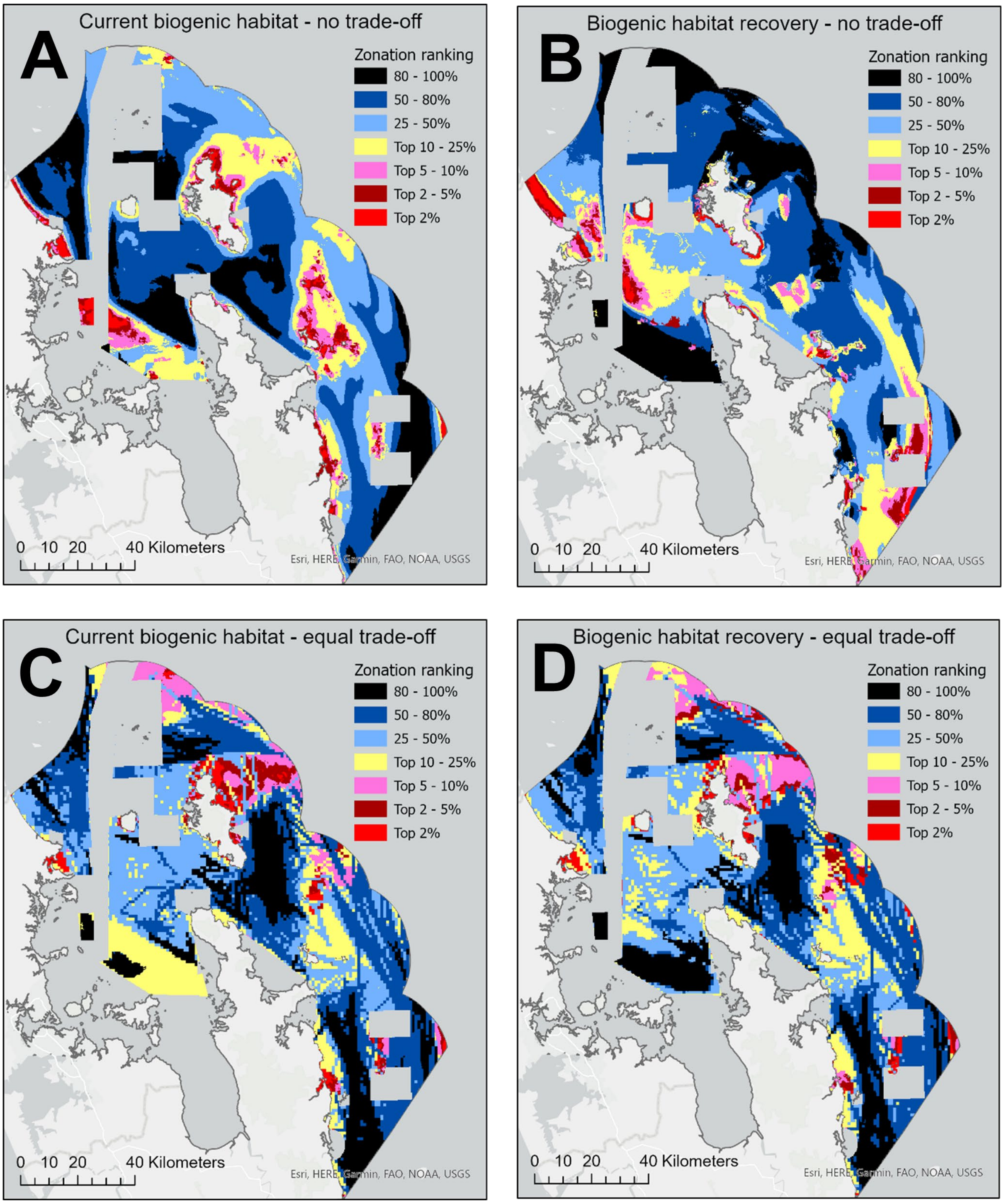


Figure 18: Zonation prioritisations from Round 3. A) Zonation prioritisation with 17 layers representing current distribution of biogenic habitat (no trade-off with fishing value, catch-kg), B) Zonation prioritisation with 17 layers representing recovery potential biogenic habitat (no trade-off with fishing value, catch-kg), C) Zonation prioritisation with 17 layers representing current distribution of biogenic habitat (equal value with fishing value, catch-kg), D) Zonation prioritisation with 17 layers representing recovery potential biogenic habitat (equal value trade-off with fishing value, catch-kg).

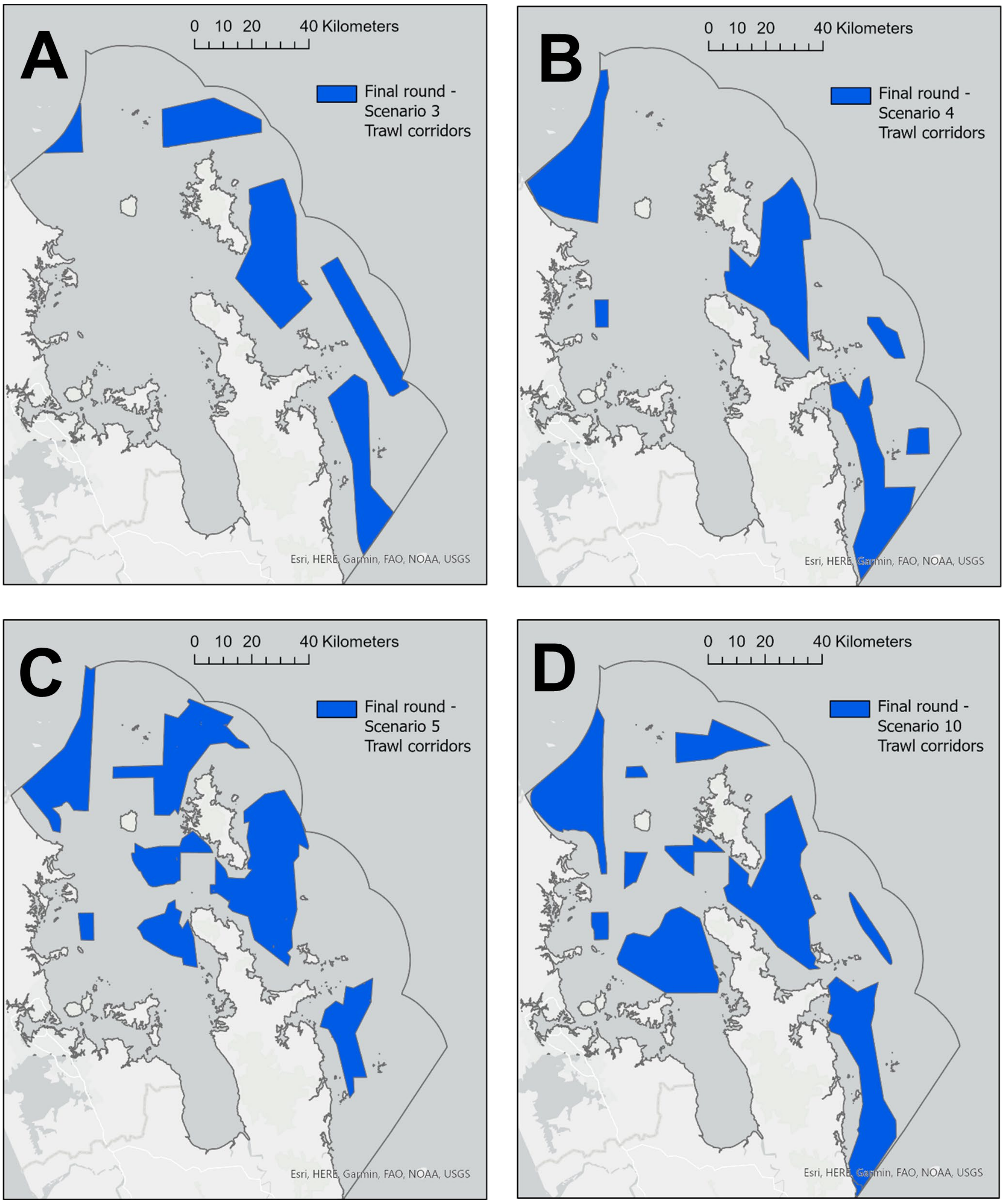


Figure 19: Examples of trawl corridor scenarios from the Final Round of scenarios explored. A) Scenario 3: Drawn corridors provided by working group members (informed by Zonation prioritisations from previous rounds), B) Scenario 4: Area encompassing bottom 20% of current biogenic habitat distribution and bottom 5% recovery potential habitat (Zonation prioritisation), C) Scenario 5: Area encompassing bottom 10% current biogenic habitat and bottom 75% recovery potential distribution (Zonation prioritisation), D) Scenario 10: Area encompassing top 75% of catch-kg for all fishing methods combined.

Post-accounting

For the final round of scenarios, the results of the post-accounting step for four scenarios that showcase different aspects of potential elements for the design of trawl corridors are provided in Table 16. All results in the table show the percentage (%) of each corresponding biogenic habitat, biodiversity, or fishing value layer within the sum of closed area for each scenario. Scenarios 3 and 4 explore trawl corridors that would close > 80% of the model area to bottom trawling and Danish seining. Scenarios 5 and 10 explore corridors that would result in 72–77% of the model area being closed. Broadly, these scenarios would result in ~ 93% of current biogenic and biodiversity distribution to be included within closed areas and ~ 72% of recovery distribution to be included within closed areas. For all scenarios, 100% of seagrass and mangrove habitat is within closed areas. Generally, there is a greater spread of the proportion in closed areas for the biodiversity layers (Figure 20), given these biodiversity layers (198) comprise a diverse group of taxa from octopuses to crustaceans (Table 16).

For the seafloor community classification groups, two groups (14 and 16) had no value within the HGMP following application of the model area mask (Figure 5 and Figure 13). For most other SCC groups, 100% of the distribution was within closed areas for each of the final round scenarios. The SCC groups 30, 31, and 33 have the least proportion of distribution in closed areas across the four scenarios, ranging from 26.9–86.4% (average: 57%). This is unsurprising given the overlap between the four scenario trawl corridors (Figure 19) and the SCC groups 30 and 33 (Figure 5), in particular (see Petersen et al. 2020 for descriptions of characteristics of each SCC group).

Fishing value layers (effort and catch-kg) were included in post-accounting analyses. In Table 16, fishing value (catch-kg) is shown for illustrative purposes (also see Figure 20). As for the biodiversity and habitat layers, the proportion of fishing value within closed areas for each scenario are reported. The proportion of total fishing value (all species combined) within closed areas varied between scenarios for different fishing methods. For bottom trawl vessels under 20 m, the proportion of value in closed areas ranged from 28.6% to 74.4%, and, for vessels over 20 m, the range was 16.2% to 57.6%. For Danish seining, the proportion of value in closed areas ranged from 22.7% to 82.3%. For precision seafood harvesting (PSH), the proportion of value in closed areas did not vary greatly between the four scenarios, ranging from 16.4% to 28.6%. When the fishing value is split for target species for each fishing method, the range between scenarios is much greater. For example, for red gurnard catch by bottom trawl vessels under 20 m in length, the proportion of value in closed areas ranges from 0% (Scenario 10) to 100% (Scenario 3). Furthermore, for some target taxa and fishing methods, the proportion of value is consistently higher or lower than the method total across scenarios. For example, for Danish seining targeting trevally, on average 90.2% of catch-kg is within closed areas. Whereas, for PSH targeting snapper, 18% of catch-kg is within closed areas (Table 16).

Table 16: Post-accounting results for a subset of scenarios run for this project. Scenarios are shown in Figure 19. Percentage (%) of distribution in closed areas is shown for the model area, current and recovery biogenic habitat and biodiversity distribution, fishing value (catch-kg), benthic community turnover (SCC) groups, and several other habitat layers. BT: bottom trawling, PSH: precision seafood harvesting, GUR: red gurnard, JDO: John dory, SNA: snapper, TAR: tarakihi, TRE: trevally. (Continued on next 2 pages)

Class	Input layer	No. of layers	Scen. 3	Scen. 4	Scen. 5	Scen. 10
Area of HGMP	Model area (Figure 13D)	1	83.4	81.0	76.8	72.4
Current (biogenic habitat and biodiversity)	Biogenic habitat modelled probability of occurrence					
	Misc. Anthozoa	1	90.2	96.8	93.5	93.8
	Canopy-forming macroalgae	1	99.8	98.7	99.9	97.1
	Cup corals	1	89.0	96.9	93.5	92.9
	Encrusting Bryozoa	1	92.2	96.6	93.6	87.5
	Encrusting sponges	1	91.9	96.1	95.8	91.6
	Erect Bryozoa	1	94.6	98.0	96.4	91.4
	Erect and rooted Bryozoa	1	93.8	99.0	97.6	96.8
	Erect/upright sponges	1	96.6	98.0	97.8	85.7
	Horse mussels	1	100.0	99.4	99.8	99.1
	Hydrozoa	1	91.1	96.2	92.9	88.7
	Misc. macroalgae	1	100.0	99.1	99.8	97.4
	Multi-species aggregations	1	97.5	95.1	93.4	77.2
	Oysters	1	97.3	99.2	99.2	95.7
	Misc. annelid assemblages	1	92.0	97.3	94.9	90.8
	Rhodoliths	1	88.8	97.9	99.0	95.5
	Sea anemones	1	90.0	97.3	93.9	94.3
	Non-calcareous tubeworms	1	92.6	96.4	93.6	91.0
	Biodiversity layers					
	Bivalve	8	86.7	85.7	84.6	77.3
	Bryozoan	11	95.5	98.9	98.9	95.5
	Coral	24	89.7	99.1	98.7	98.9
	Crustacean	42	89.3	80.2	92.2	91.8
	Echinoderm	61	90.8	88.3	92.0	89.7
	Gastropod	13	86.0	83.8	86.0	79.1
	Octopus	4	67.0	70.9	78.5	71.1
	Other epifauna	9	94.4	99.1	97.1	95.8
	Polychaete	9	82.7	86.9	84.2	82.3
	Sponge	17	92.5	97.3	97.0	87.6
Recovery (biogenic habitat and biodiversity)	Biogenic habitat modelled probability of occurrence					
	Misc. Anthozoa	1	63.6	60.3	58.2	57.1
	Canopy-forming macroalgae	1	99.8	98.7	99.9	97.1
	Cup corals	1	57.6	59.2	57.2	55.4
	Encrusting Bryozoa	1	70.5	63.4	58.3	55.1
	Encrusting sponges	1	76.7	61.2	57.2	52.0
	Erect Bryozoa	1	71.4	67.3	61.4	60.0
	Erect and rooted Bryozoa	1	68.2	64.3	61.7	58.7
	Erect/upright sponges	1	77.0	65.8	62.5	55.5
	Horse mussels	1	100.0	70.0	93.5	61.4
	Hydrozoa	1	70.7	63.1	57.6	55.0
	Misc. macroalgae	1	100.0	99.1	99.8	97.4
	Multi-species aggregations	1	87.7	68.1	54.7	53.2
	Oysters	1	63.9	54.3	69.1	49.4

Class	Input layer	No. of layers	Scen. 3	Scen. 4	Scen. 5	Scen. 10
	Misc. annelid assemblages	1	67.8	59.9	60.1	53.9
	Rhodoliths	1	58.3	66.9	88.7	75.2
	Sea anemones	1	64.9	61.3	58.1	56.2
	Non-calcareous tubeworms	1	78.2	69.3	54.3	55.7
	Biodiversity layers					
	Bivalve	8	77.5	65.5	63.1	56.2
	Bryozoan	11	86.1	82.6	83.7	82.6
	Coral	24	71.0	86.1	92.0	92.0
	Crustacean	42	87.7	80.0	89.8	89.3
	Echinoderm	61	87.7	85.3	88.8	84.9
	Gastropod	13	85.5	83.3	85.6	78.0
	Octopus	4	67.0	70.9	78.5	71.1
	Other epifauna	9	71.5	76.7	69.6	75.0
	Polychaete	9	71.6	69.4	73.0	66.7
	Sponge	17	79.0	77.5	73.4	73.6
Fishing value (catch-kg)	BT (over 20 m) total	1	52.1	17.6	57.6	16.2
	BT (under 20 m) total	1	74.4	44.5	43.1	28.6
	BT (over 20 m) SNA	1	46.3	23.6	39.6	19.3
	BT (over 20 m) TAR	1	64.9	59.3	82.1	79.1
	BT (over 20 m) TRE	1	56.4	5.8	73.5	4.7
	BT (under 20 m) GUR	1	100.0	15.2	12.7	0.0
	BT (under 20 m) JDO	1	84.1	45.8	32.6	39.0
	BT (under 20 m) SNA	1	84.5	54.0	42.7	28.2
	BT (under 20 m) TAR	1	66.6	68.8	90.6	87.5
	BT (under 20 m) TRE	1	58.9	28.9	41.5	19.9
	Danish seine total	1	82.3	59.1	57.8	22.7
	Danish seine GUR	1	52.1	27.8	34.1	22.2
	Danish seine JDO	1	81.4	68.0	54.1	30.5
	Danish seine SNA	1	87.7	63.4	61.1	20.8
	Danish seine TAR	1	53.5	63.4	97.6	81.9
	Danish seine TRE	1	96.6	86.0	96.0	82.1
	PSH total	1	21.9	26.9	28.6	16.4
	PSH GUR	1	2.4	47.8	32.7	19.2
	PSH JDO	1	50.7	44.8	36.2	36.1
	PSH SNA	1	16.2	23.6	20.6	11.7
	PSH TAR	1	69.2	71.1	97.2	85.5
	PSH TRE	1	36.6	27.9	57.9	19.9
Seafloor Community Classification	SCC group 14	1	–	–	–	–
	SCC group 16	1	–	–	–	–
	SCC group 22	1	100.0	100.0	100.0	100.0
	SCC group 23	1	100.0	100.0	100.0	100.0
	SCC group 27	1	100.0	100.0	100.0	100.0
	SCC group 28	1	92.9	98.1	100.0	100.0
	SCC group 30	1	69.3	73.8	65.6	71.7
	SCC group 31	1	32.6	30.8	26.9	27.5
	SCC group 33	1	86.4	72.6	70.6	58.2
	SCC group 34	1	100.0	100.0	100.0	100.0
	SCC group 39	1	100.0	100.0	100.0	100.0
	SCC group 42	1	100.0	100.0	100.0	100.0
	SCC group 49	1	100.0	100.0	100.0	100.0
	SCC group 50	1	100.0	100.0	95.4	79.3
	SCC group 51	1	100.0	90.1	99.3	83.3
	SCC group 52	1	100.0	100.0	100.0	100.0

Class	Input layer	No. of layers	Scen. 3	Scen. 4	Scen. 5	Scen. 10
	SCC group 53	1	100.0	100.0	100.0	100.0
	SCC group 73	1	100.0	100.0	100.0	100.0
	SCC group 74	1	100.0	100.0	100.0	100.0
	SCC group 75	1	100.0	100.0	100.0	100.0
Other habitat layers	Mangrove habitat	1	100.0	100.0	100.0	100.0
	Seagrass habitat	1	100.0	100.0	100.0	100.0
	Scallop abundance (m^2) 1995–2021 in survey strata	1	100.0	96.1	97.5	81.3
	Scallop survey strata 2021	1	100.0	99.3	74.6	56.8

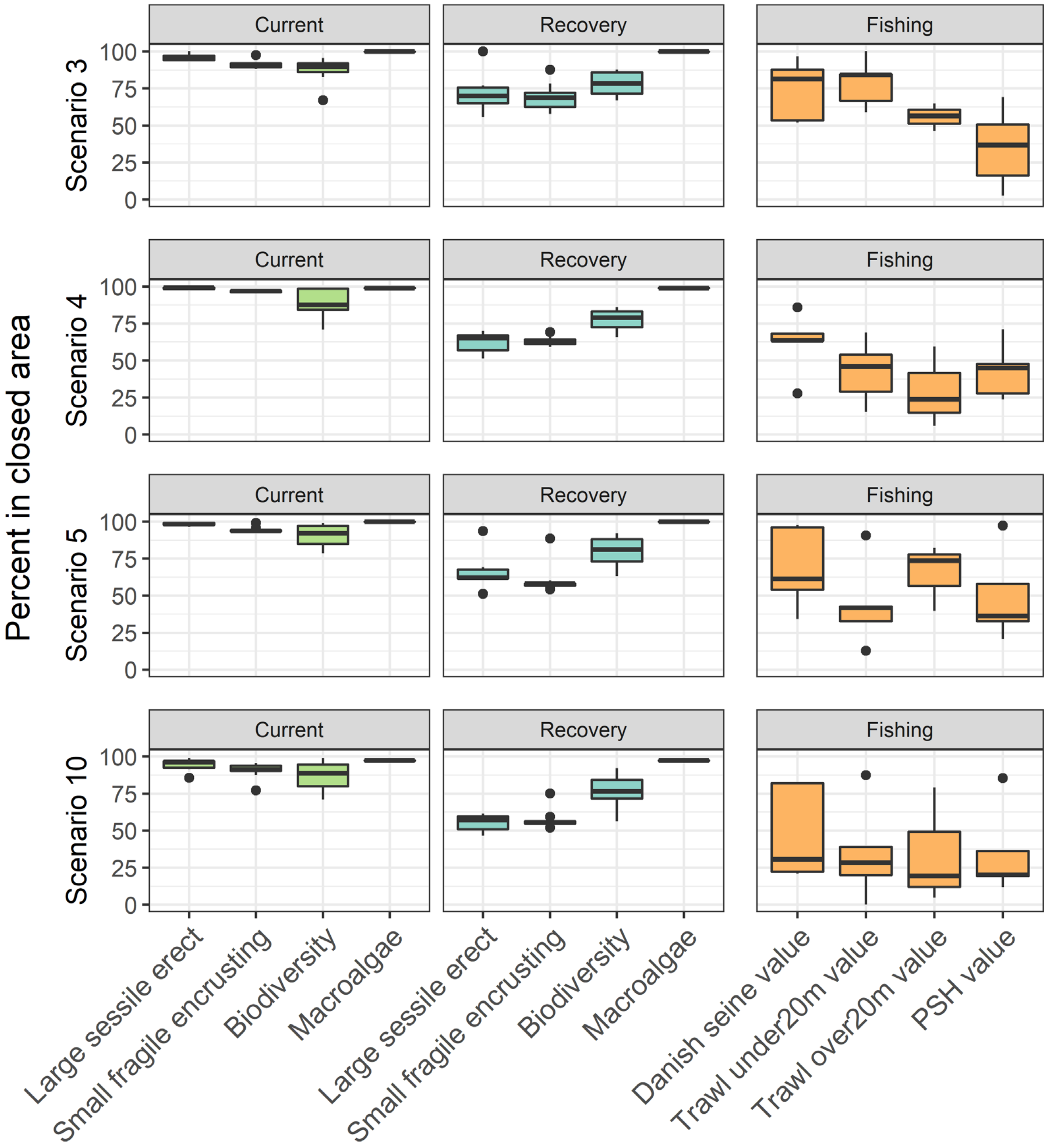


Figure 20: Post-accounting results for a subset of scenarios run for this project. Scenarios are shown in Figure 19. Percentage (%) of distribution/value in closed areas is shown for the impacted and recovery biogenic habitat and biodiversity, and fishing value (catch-kg).

3. DISCUSSION

Biogenic habitat distribution

The aim of this work was to explore the use of spatial decision-support tools to identify corridors where bottom trawling and Danish seining could continue, while minimising (overall objective) the impact to current and passively recovering biogenic habitats. In total, 20 biogenic habitat layers were produced using a compiled database of point records on biogenic habitat-forming species and probability of occurrence modelling. Seventeen of these layers were assessed as adequate representations of expected spatial distributions within an expert evaluation process. Current and recovery biogenic habitat spatial distributions were created using probability of occurrence modelling and condition layers of historical trawling impact (specific objectives 1, 3, & 4). This information, together with fishing value layers and human-use layers in the HGMP, was used to explore the size and potential placement of trawl and Danish seine corridors (specific objectives 5 & 6). Spatial prioritisations using the decision-support tool Zonation and a post-accounting process were used to develop and report on scenarios explored. More than 60 scenarios were explored over four development rounds responding to input and feedback from the HG-BSPAG. The types of scenarios (and their goals) differed between the rounds. Nevertheless, the 10 trawl corridor scenarios that were explored in the final round, with different layers used to prioritise trawl corridors, showed general alignment of corridor placement (Figure 19).

The modelled layers of biogenic habitat produced for this work were informed by taxonomic and ecological experts, with specific knowledge of benthic habitats and biota in the HGMP. In this way, these models are an improvement on higher taxonomic level models that often conflate morphologies, life histories, and niche requirements. Due to limitations in data availability for some taxonomic groups (e.g., 'misc. Anthozoa'), some higher groupings were inevitably used. Nevertheless, these modelled layers are a significant improvement on the six expert-drawn, presence-only polygons representing biogenic habitats (Figure 3) that were available for previous spatial planning assessments in the HGMP (Lundquist et al. 2020b). An ecosystem principles-based approach layer of biogenic habitat provision (Townsend et al. 2014) was also previously used to inform spatial planning exercises in the HGMP (Lundquist et al. 2020b), and while the performance of this layer was fair when independently evaluated in a small region of the Hauraki Gulf (Townsend & Lohrer 2019), it is not specific to a particular biogenic habitat category and provides only a ranking of low to high likelihood of the provision of biogenic habitat. In contrast, the model development presented here covers the whole extent of HGMP and includes seventeen distinct biogenic habitat groups. Differences in spatial priorities between the modelled biogenic habitat layers and the biogenic habitat models produced here could be further explored, particularly with respect to differences in areas of biogenic habitat identified in the Colville Channel and offshore from Aotea/Great Barrier Island.

Species distribution models are often used to inform spatial management as they 'fill gaps' where there is data paucity, by allowing extrapolation of species-environment relationships into unsampled space (Robinson et al. 2017). In essence, the reason why they are used is also why caution should be placed on interpretation of their outputs. Often management decisions need to be made about unsampled space, and, in these instances, species distribution models offer a solution, where species observations and best available environmental data can be used to predict into unsampled space. Validation with independent data is a crucial step towards ensuring predicted spatial distributions are accurate (Lee-Yaw et al. 2022). Occasionally, when data are limited, all available data are used to train and evaluate models. However, without a model validation step, often predicted distributions do not perform well when evaluated with independent data (Lee-Yaw et al. 2022). Evaluating SDMs using independent data (i.e., separating data into training and evaluation data) is key to ensure spatial predictions are accurate. However, in this case such evaluation with independent data has not been undertaken, so the results of our model-based analysis need to be treated with caution. Models developed with the same methods as those described here have previously performed well when evaluated with independent data (Stephenson et al. 2021c).

Plans to monitor biogenic habitat recovery in the HGMP are underway (Fisheries New Zealand project: BEN2022-06). Data collected could be used to independently evaluate spatial predictions developed here. The data gathered from the proposed BEN2022-06 project will provide data crucial for assessing the recovery of biogenic habitats following the implementation of spatial management actions in the gulf. The datasets gathered will provide a means to test the performance of the models used here, but also provide data which could be used to increase their utility through updating the presence-absence models used in model development and rerunning models, or preferably, to develop abundance models. See (Stephenson et al. 2021a) for examples of methodologies which could be applied.

Identifying trawl corridors using a decision-support tool

The strength of decision-support tools like Zonation comes from their ability to integrate datasets of biodiversity and value to identify priority areas for management (Rowden et al. 2019). The aims of this project evolved over its timeline, responding to wider management decisions for the gulf region (Department of Conservation et al. 2021). The use of Zonation was crucial for the development of the potential trawl corridors identified here. Each of the scenarios from the final round were informed by the Zonation prioritisations and post-accounting scenarios of former rounds. This iterative process allowed advisory group members the opportunity to raise concerns and provide their knowledge of fisheries, biodiversity/habitats, and uses in the HGMP to ultimately shape the scenarios explored (specific objective 6). This process can be seen in Figures 14 to 19, beginning with basic explorations of current and proposed protection and ending with identification of potential trawl corridors.

Closure layers and model areas are the basis of each scenario. The HG-BSPAG drove the creation of these layers by requesting prioritisations and explorations of closures that maximised biogenic habitat protection and recovery potential and/or minimised impact to fishing. The advisory group was comprised of industry, environmental non-governmental organisations (eNGOs), and government representatives, who potentially had different spatial management objectives. Often, perspectives on ‘protection’ may differ between government agencies, stakeholders, and individual organisations. For example, spatial planning in Denmark highlights that the gap between aspirations for the proportion of area that should be protected can differ by ~ 20% (Vrooman et al. 2022). Often, the fishing industry interprets areas that cannot be fished as protected, in contrast to governments and eNGOs which may only consider formally designated marine protected areas as biodiversity conservation zones (Vrooman et al. 2022). It should be noted, however, that the scope of this study was to identify areas where bottom-impacting fishing methods could be excluded—the analysis did not consider implications for other fishing methods. During the advisory group process used in this study, representatives of the fishing industry noted that much of the inner HGMP is already closed to bottom-impacting fishing methods (Figure 2), although it could be fished by other methods including the substantial recreational fishing effort. Other smaller areas of the HGMP are not fishable for a variety of reasons (e.g., aquaculture sites, Figure 1). On the other hand, eNGOs highlighted the need to exclude bottom-damaging fishing activities from most, if not all, of the HGMP to protect and restore marine benthic habitats. This misalignment in perspectives is evidenced by the iterations of model areas used in this work, responding to advisory group input (Table 13, Figure 13). While the advisory group terms of reference clearly stated the goals of the process, many of the stakeholder groups that were represented had differing opinions on what the goals of the larger trawl corridor process should be, and these opinions influenced dialogue with respect to the scenario selection. Advisory group discussions regularly reiterated the purpose of the advisory group process which was not to achieve consensus on spatial management designs or to develop management proposals, but rather to explore how decision-support tools could be used to inform the process of identifying potential trawl corridors for the protection and recovery of biogenic habitats and benthic biodiversity.

Long-term recommendations

This final section highlights the limitations of the approach used here, but also suggests principles for future spatial planning processes to enhance habitat recovery in the Hauraki Gulf Marine Park (specific objective 2). The models developed here were presence-absence models of biogenic habitat-forming species or groups. Each cell contains a value of probability of occurrence for a given taxa or multiple species, and a key assumption is that species occurrence is directly correlated with species abundance. Abundance models are more likely to represent the patchiness of biogenic habitat that are likely to provide realistic roles in ecosystem function such as the provisioning of habitat refugia. Abundance models were trialled in this project. However, insufficient point records that included abundance were available to develop robust models of abundance of biogenic habitats. However, abundance models were preferred and are better aligned with definitions of biogenic habitats provided in Table 1 that also include density or abundance thresholds. As the models used here do not predict abundance, it was not possible to infer where biogenic habitats occur aligned to the definitions given in Table 1. Two key approaches could improve our knowledge of biogenic habitats in the HGMP: 1) the creation of abundance models from systematically collected datasets; and 2) delineating biogenic habitat distribution (and biomass) using seafloor mapping technologies (e.g., multibeam echosounder). For example, abundance models can predict densities of species in a similar manner to presence-absence models (Rullens et al. 2021; Stephenson et al. 2021a) and ground-truthed multi-beam echosounder data (e.g., backscatter) can be used to estimate taxon/habitat biomass, for example for kelp (Bennion et al. 2019; Schimel et al. 2020).

The only stressor layer included in this project accounted for historical commercial fishing effort, noting that information on the trawl footprint itself is limited for inshore fisheries. Several other stressors are known to impact benthic habitats and biodiversity in the gulf including, but not limited to, sedimentation, recreational fishing, agricultural run-off, marine invasions, and climate change (Pinkerton et al. 2015; Hauraki Gulf Forum 2020). For example, climate change is having profound impacts on distribution of biogenic habitat forming species, for example range shifts (Yesson et al. 2015). Incorporating current and future stressors in spatial planning exercises will increase their utility and future-proof management actions (Wilson et al. 2020). Furthermore, although layers of commercial fishing impact were used here, they did not include impacts of historical fishing effort by scallop dredging (commercial and recreational) or by Danish seine. In fact, the lack of information on scallop dredging, and recent voluntary scallop closures, influenced the model area that was considered. Other potential stressors (military zones, channel dredging) were also used to inform model area boundaries based on where information was available or not available on other stressors to seafloor habitats that would not be mitigated outside trawl corridors. Integration of datasets of these other stressors would provide a more ‘complete’ picture of mobile bottom-impacting fishing in the gulf. The relative impact of fishing gear has also likely changed over recent decades, including major changes such as the use of precision seafood harvesting bottom trawl technology (for which the relative impacts on benthic habitats compared with traditional bottom trawl have yet to be measured). Additional gear changes implemented by industry include varying weight and size of trawl doors, weights, and other changes to ground gear that are designed to reduce bycatch, reduce drag, or otherwise increase trawl efficiency.

All fisheries management decisions have implications for industry as well as the marine environment. Here, the impact of different scenarios to the fishing industry was estimated using fishing value layers (catch-kg) using a particular set of years of data, selected by industry representatives for these exploratory analyses. This proxy measurement is one potential representation of industry value; however it is not in monetary form and does not integrate broader economic impacts of scenarios. For example, if potential trawl corridors move areas open to fishing farther from port, fuel costs have not been considered (Stevenson et al. 2013). It is possible to include broader economic impact in spatial scenarios, both in terms of economics impacts on fishing and on the marine environment; but layers that include this information require further development. Further, members of the HG-BSPAG raised the issue of displacement of fisheries on several occasions. Displacement can have a broader economic impact on communities (e.g., if catch is landed at a different port), but can also have implications for biodiversity if effort intensifies in areas outside the new management zone (Hiddink et al. 2006; Greenstreet et al. 2009). Displacement is challenging to pre-emptively incorporate into analyses, but holistic fisheries management should make efforts to consider the downstream impacts of displacement. For example, Fisheries New Zealand should consider implications of Hauraki Gulf fishers being displaced outside the gulf, noting that quota is allocated at the broader Fishery Management Area scale. Finally, industry expressed concern that any decisions resulting in closures are unlikely to be reopened, even if new data suggested changes in areas designated as trawl corridors, and that additional areas might be suitable. Understanding the timeline for decision-making and any future opportunities to validate models are important for understanding the long-term implications of trawl corridor implementation in the HGMP. Analyses of fishing impacts could be explored for different years, to determine consistency of historical, current, and future fishing priorities, and how robust trawl corridors are to temporal variations in distributions of fishing effort. Examples of temporal variation in fishing effort could be due to changes in wave and wind climatology that may influence access to particular fishing grounds, for example between El Niño and La Niña years.

The deeper area of the HGMP (> 200 m) was included in some of the earlier analyses for this project (Figure 13) but removed from the study area for the final round (Figure 19). It was decided that the comparatively different fisheries that operate here necessitate a separate process to explore spatial planning for this 457-km^2 area. For similar spatial prioritisations of the HGMP, similar decisions were made to remove this area from spatial planning exercises in the HGMP due to the atypical habitats and species present in this deep area compared to the rest of the HGMP (Lundquist et al. 2020b; Tablada et al. in press). While these slope habitats are unique for the HGMP, they are common and widespread habitats outside the HGMP. For example, this area is classified as SCC groups 16 and 28, accounting for 0.01% and 2.13% of the extent of these groups in the EEZ. Given this deep area accounts for ~ 4% of the HGMP, bespoke assessments for fisheries operating in this area should be complemented by investigations of biogenic habitats present. For example, the only records for sea pens (Pennatulacea) in the study area were situated in this deeper area.

Other elements could be considered in marine spatial planning for trawl corridors in the HGMP. For example, on soft sediments bottom-impacting trawling can not only displace sediment and associated species, but also suspend sediment into the water column. Plumes of suspended sediment within the turbulent wake of trawl gear can take days to settle and may be significant, relative to natural levels of suspension in areas with little seabed disturbance by currents or waves (Durrieu de Madron et al. 2005). There is a risk that bottom trawling on soft sediments near rocky reef systems could lead to suspended sediment deposition onto sensitive benthic species affecting their abundance, or health and condition. Additionally, detailed information on organic carbon content in surface sediments is not currently available at the resolution required for inclusion in spatial scenarios. If developed (e.g., Sabine et al. 2004; Sabine & Tanhua 2010), this information could be incorporated into spatial scenarios using Zonation through the inclusion of a carbon storage value layer. For example, carbon sequestration and storage could be used as an additional layer to inform trawl corridor identification, based on new information suggesting the potential of bottom trawling in resuspending seafloor carbon stores. Information on seabed carbon stocks could be used to identify priority areas (with highest carbon values) (Epstein & Roberts 2022) and incorporated into scenarios using the decision-support tool Zonation. Spatial planning would need to consider the displacement of fishing to lower priority areas, and the impact for carbon stores. At the same time, the societal and economic gains of climate change mitigation should be incorporated when considering carbon stores (blue carbon).

Finally, assessment of recovery potential here was based on past commercial bottom trawling effort only. The assumption being that if bottom trawling ceased in areas with historically high bottom-impacting trawling, habitats could recover (hence ‘potential’). This assumption does not consider the ability of biogenic habitat-forming taxa to recolonise areas where environmental conditions may have changed considerably over time, or where other stressors remain active. It is likely that for some biogenic habitats, recovery will not be possible in certain areas without the cessation of additional stressors (e.g., sedimentation or dredging) or active restorative effort.

4. MANAGEMENT IMPLICATIONS

1. This project developed new layers representing predicted species occurrence of seventeen biogenic habitats in the HGMP. These layers are a substantial improvement compared to previously available data on biogenic habitats in the Hauraki Gulf. Several improvements to the predictive models could include addressing gaps in spatial coverage to validate model predictions in areas with high uncertainty and collection of data on abundance to allow for development of robust abundance models.

2. These biogenic habitat models were supplemented by national scale species distribution models of 198 invertebrate genera. These national scale models could also be improved; for example through inclusion of updated environmental layers. Some activities to further validate environmental layers could include improving sediment layers through addition of new grain size information and inclusion of new deep reef information that is being collated for DOC. Other environmental layers that could be validated and updated include layers derived from models, for example those predicting seafloor metrics based on extrapolations from surface environmental layers.

3. One condition layer was applied, that of bottom trawling impact, to discount biodiversity and biogenic habitat layers based on historical trawl impacts. No layer exists for Danish seine impacts, although these are anticipated to be on the order of 10–20% of the impact of bottom trawls based on the smaller area of impact as well as the reduced disturbance intensity (Williams et al. 2011). Data representing spatial distributions of commercial and recreational scallop fisheries at the level of individual dredges are not available at spatial resolutions required to determine the spatial footprint of these fisheries to inform trawl corridor explorations. Other impact layers, such as the historical rate and spatial distribution of sediment inputs from land, were not accounted for directly in the model, though these sediment layers will have resulted in changes to seafloor sediment grain size that has been accounted for in the models and is likely responsible for much of the low priority allocated to the Firth of Thames which has a high expected sediment input from the Wairoa, Waihou, and Piako rivers.

4. The biodiversity and biogenic habitat layers, complemented by layers representing fishing industry catch by different gear types and different fisheries, were used in the decision-support tool Zonation to explore the application of the tool for designing trawl corridors. The layers were associated with the multiple objectives of trawl corridors: protecting existing biodiversity and biogenic habitats; protecting areas where passive restoration is likely to be successful; and examining where fisheries value through both the fisheries footprints and catch (in kilograms) were highest within the gulf. The general alignment of different scenarios that involved one or more of these different priorities suggests that the approach will be useful in bringing together extensive datasets to inform a multi-objective prioritisation of areas that are suitable for designation as trawl corridors.

5. The iterative approach, supporting the HG-BSPAG process and using advisory group input to further expand on model scenarios, proved useful to identify key data layers for consideration and identification of the assumptions of the different modelling approaches. The approach could be used to support a further management decision-making process, as suggested within the Ministerial response. It is anticipated that the approach will be used to inform both the Hauraki Gulf Fisheries Plan Advisory Group process, as well as a separate process to identify objectives for management of the deepwater area of the HGMP.

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APPENDIX 1

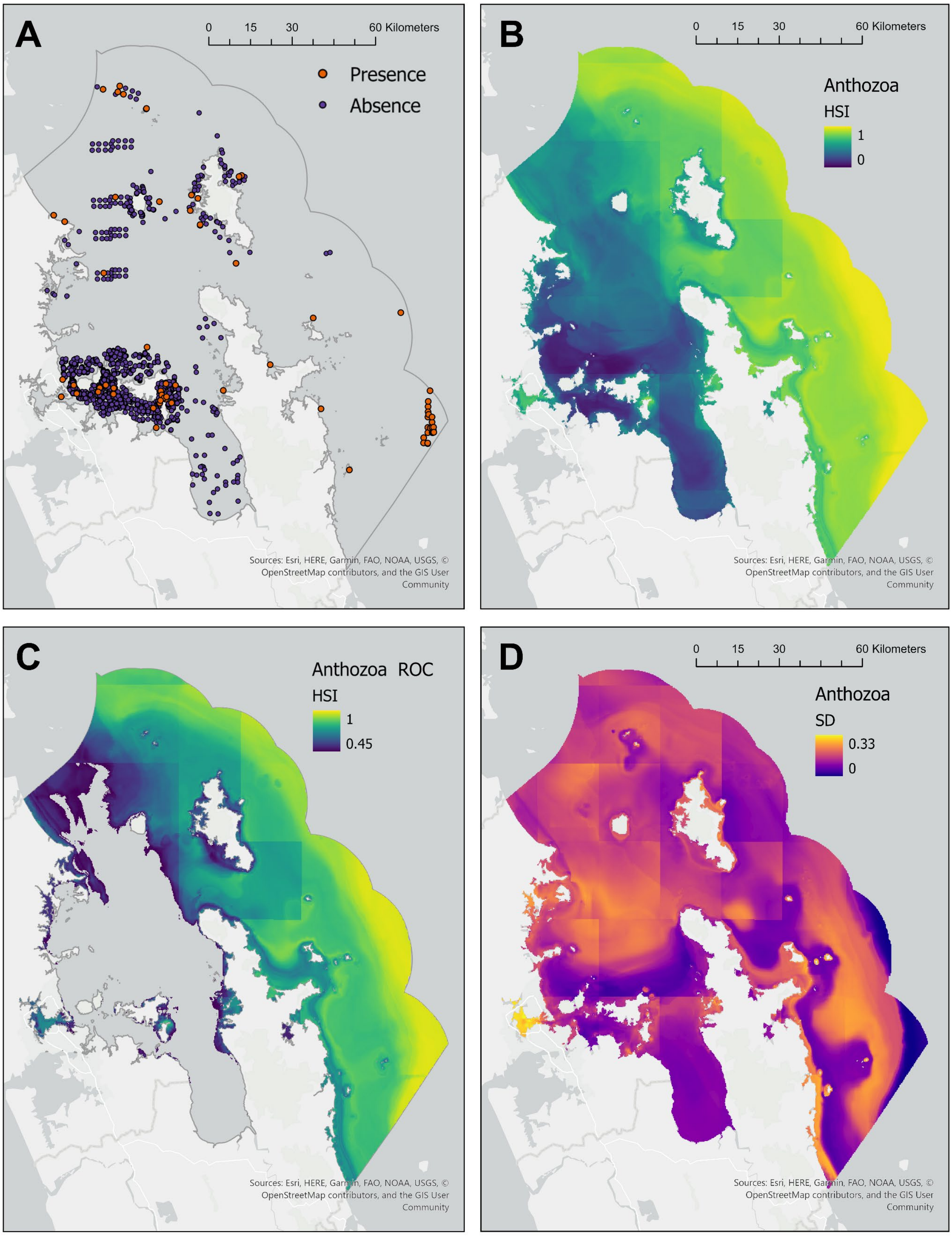

Figure 1.1: Anthozoa. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

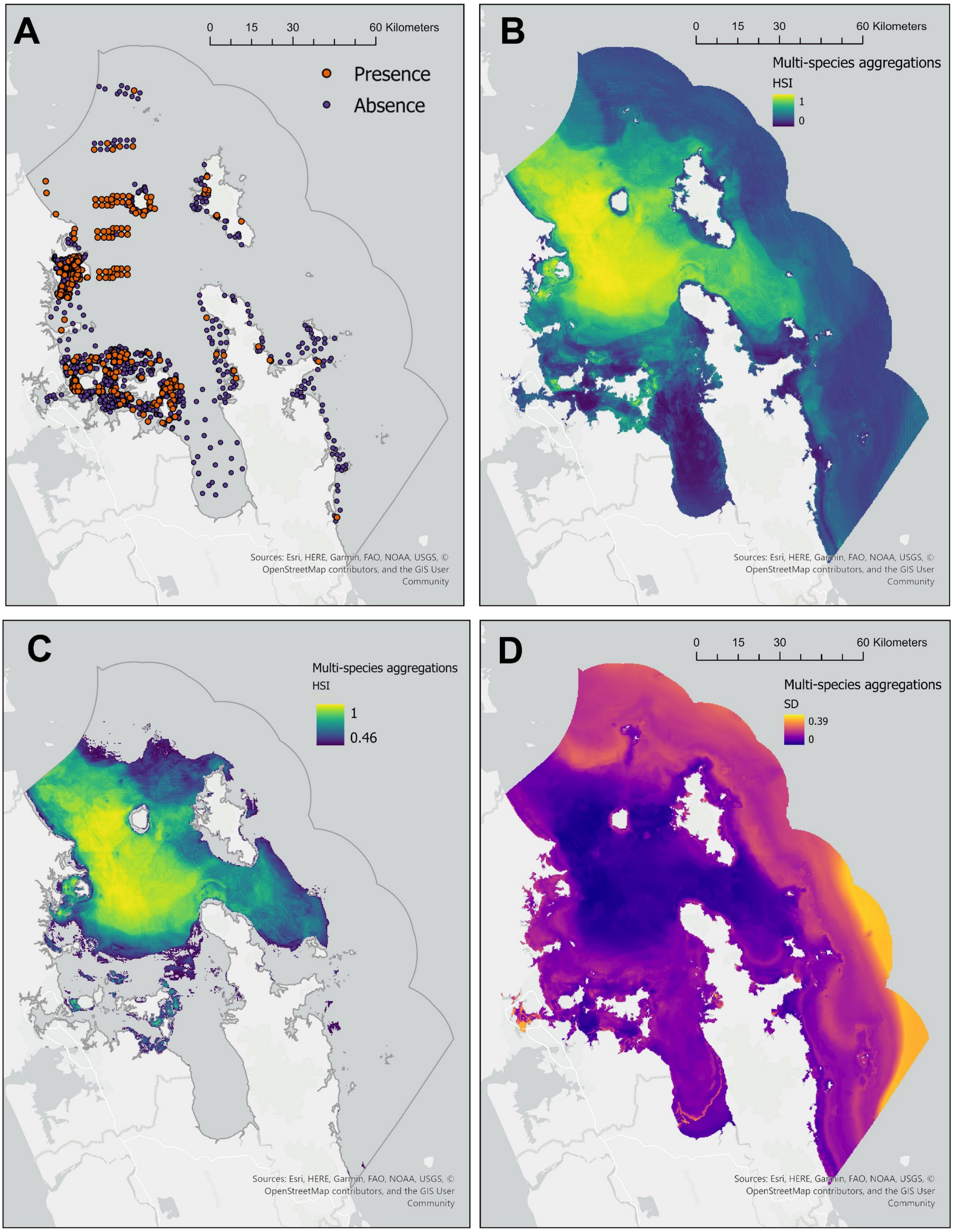

Figure 1.2: Multi-species aggregations (biogenic patches). A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

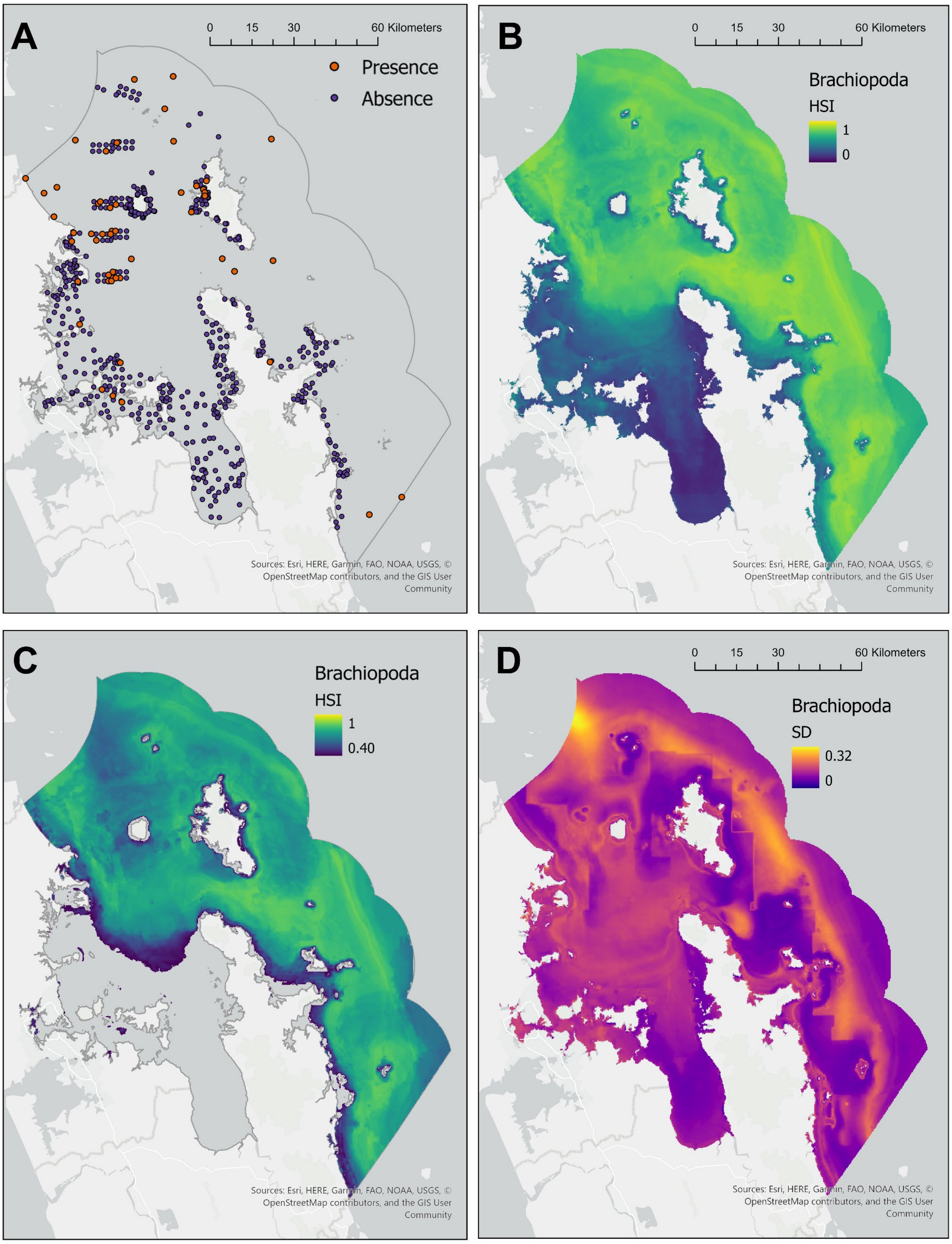

Figure 1.3: Brachiopoda. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

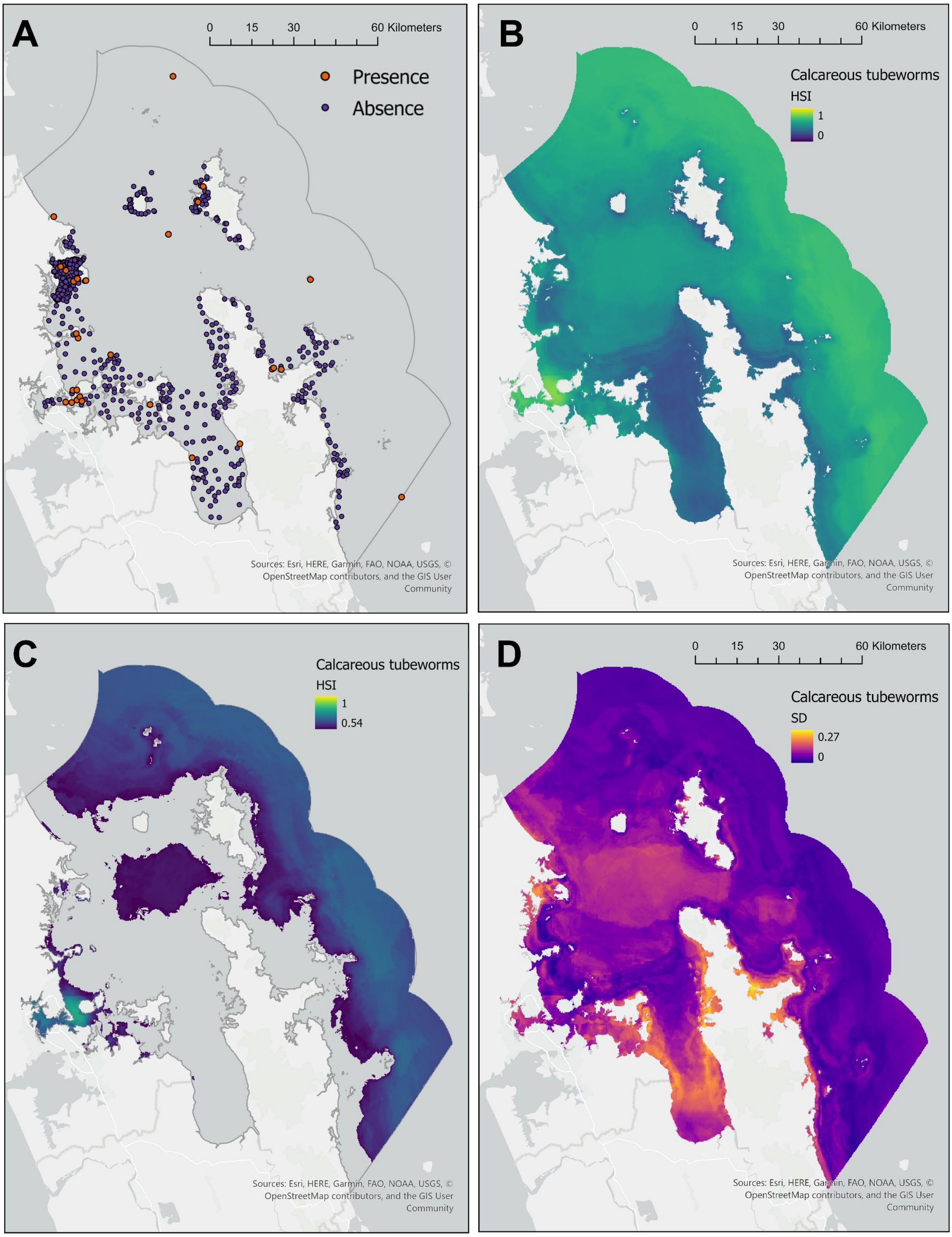

Figure 1.4: Calcareous tubeworms. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

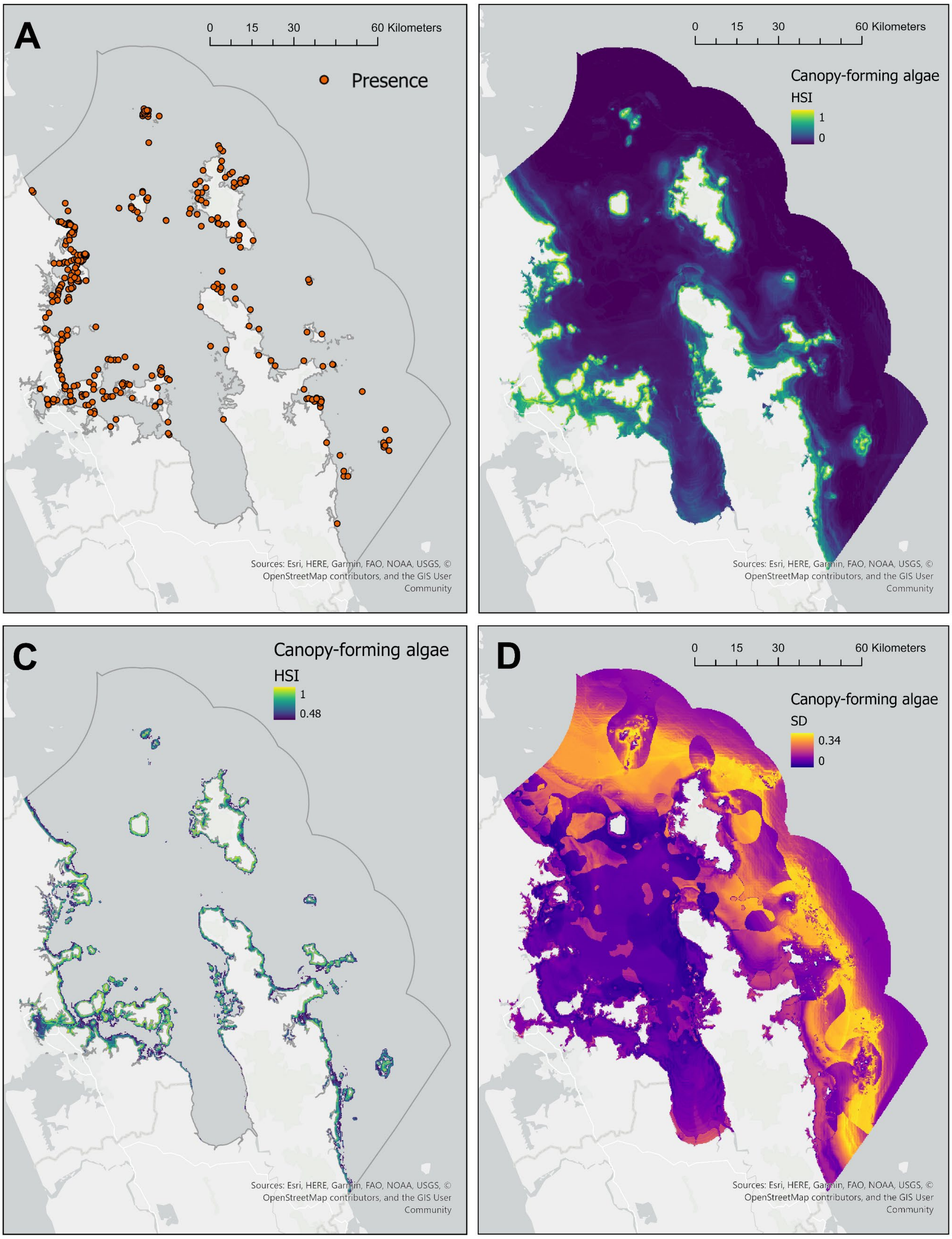

Figure 1.5: Canopy-forming algae. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

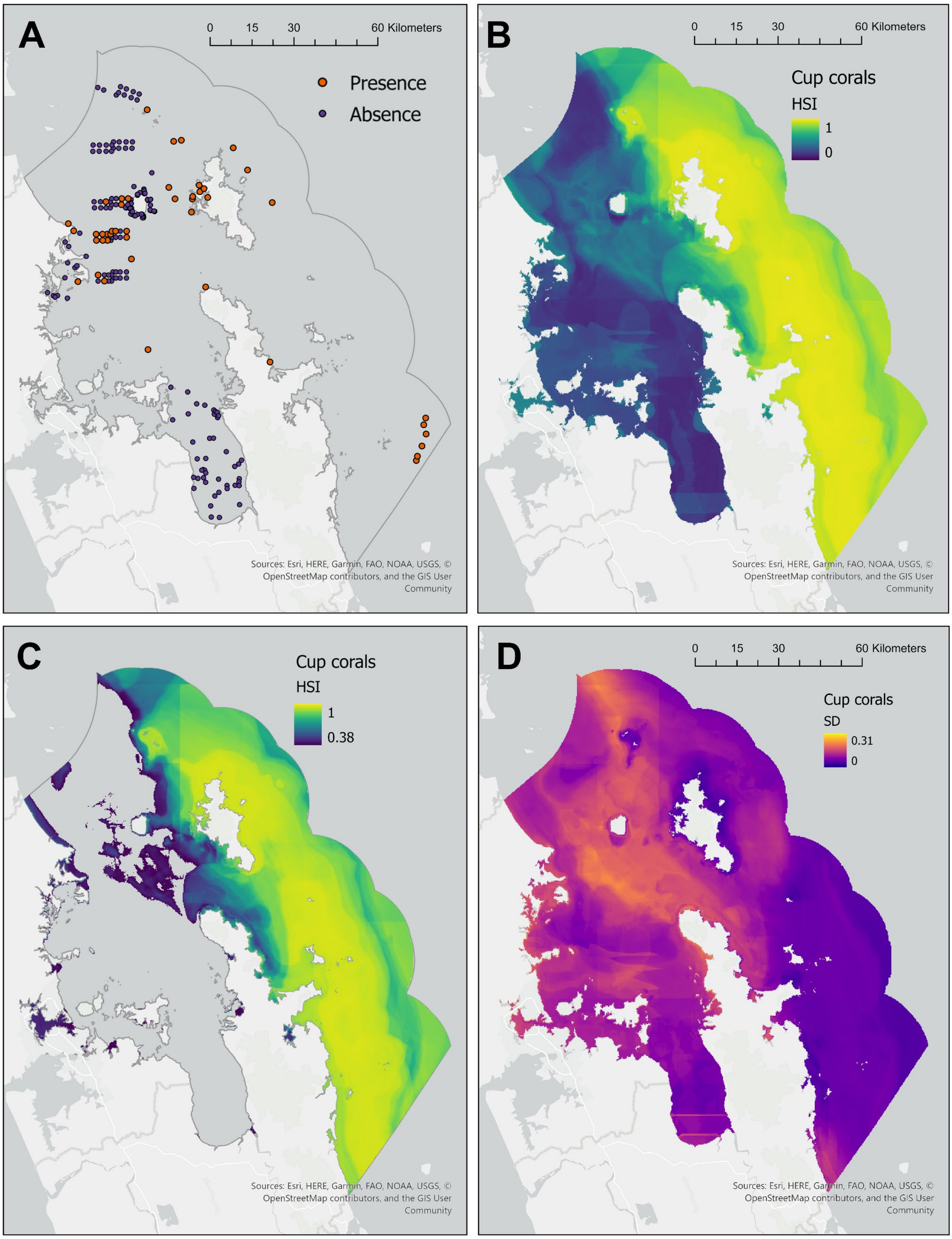

Figure 1.6: Cup corals. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

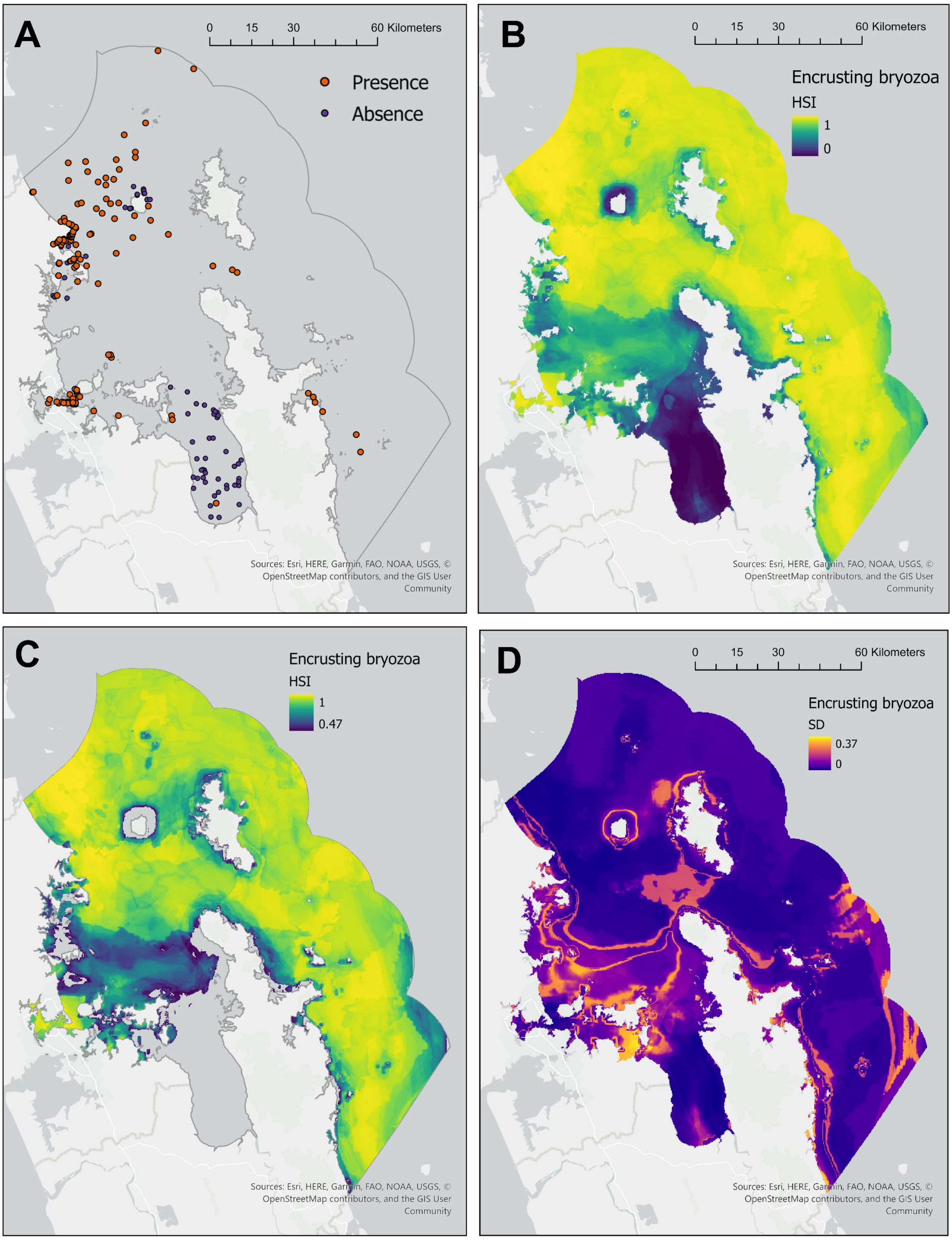

Figure 1.7: Encrusting Bryozoa. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

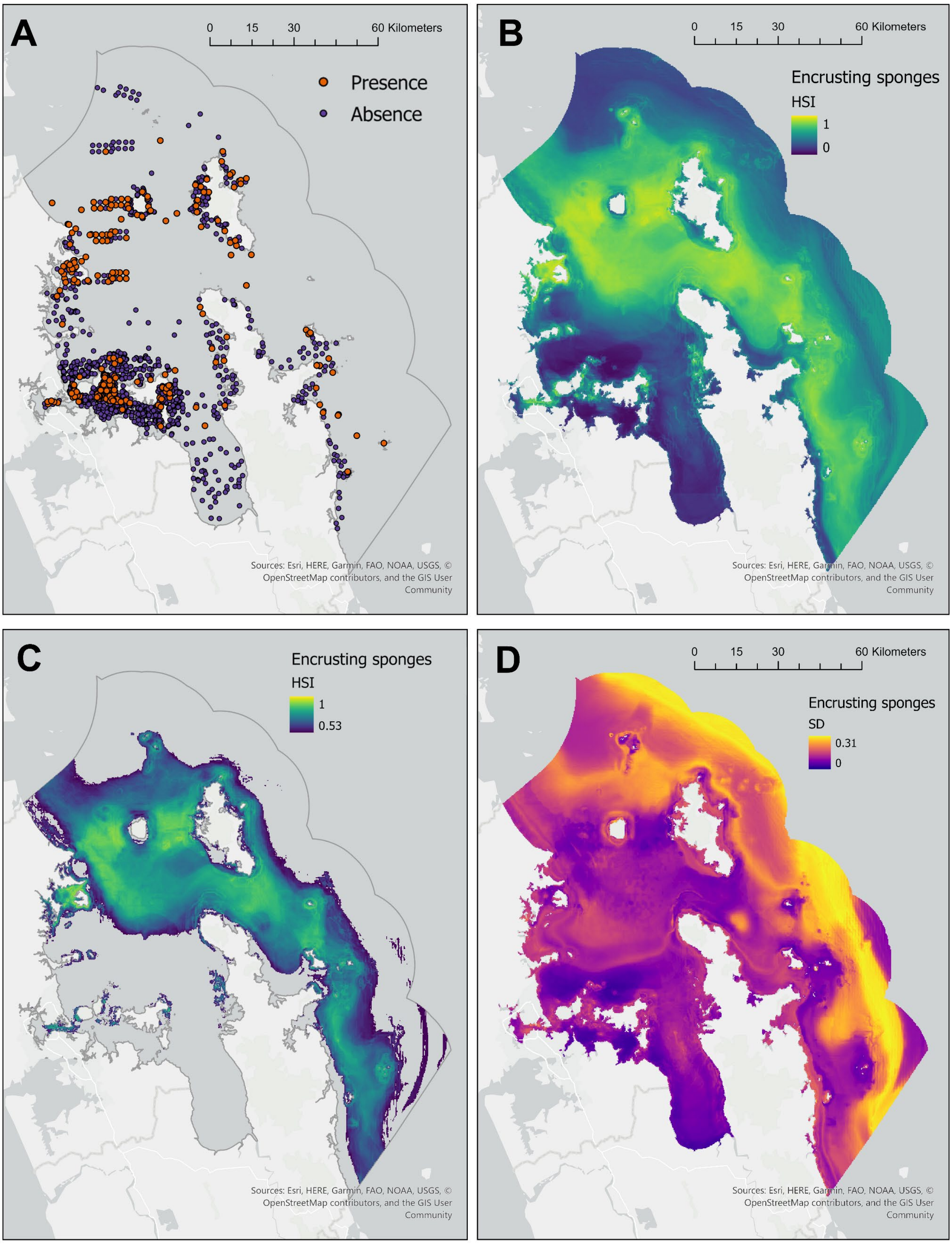

Figure 1.8: Encrusting sponges. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

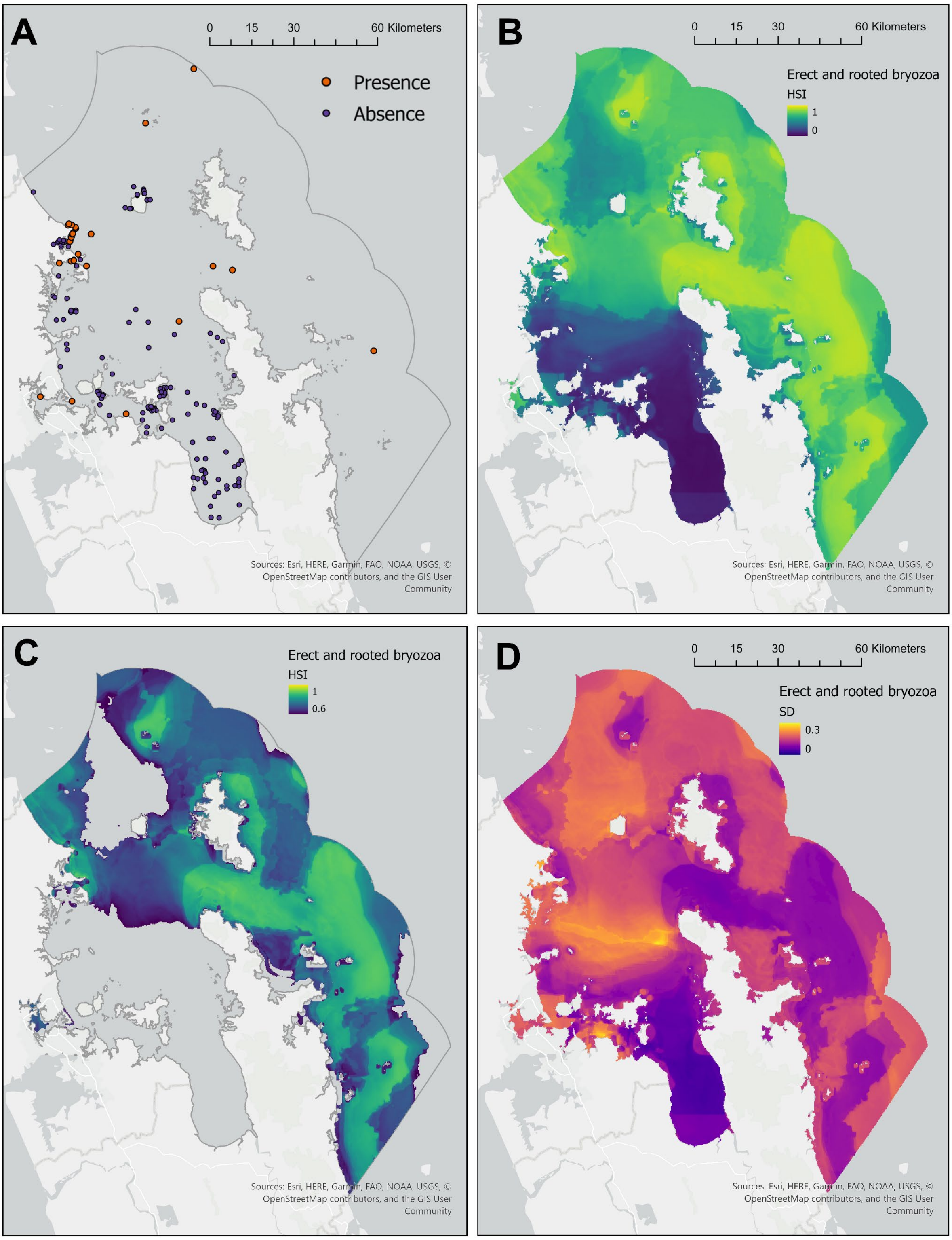

Figure 1.9: Erect and rooted Bryozoa. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

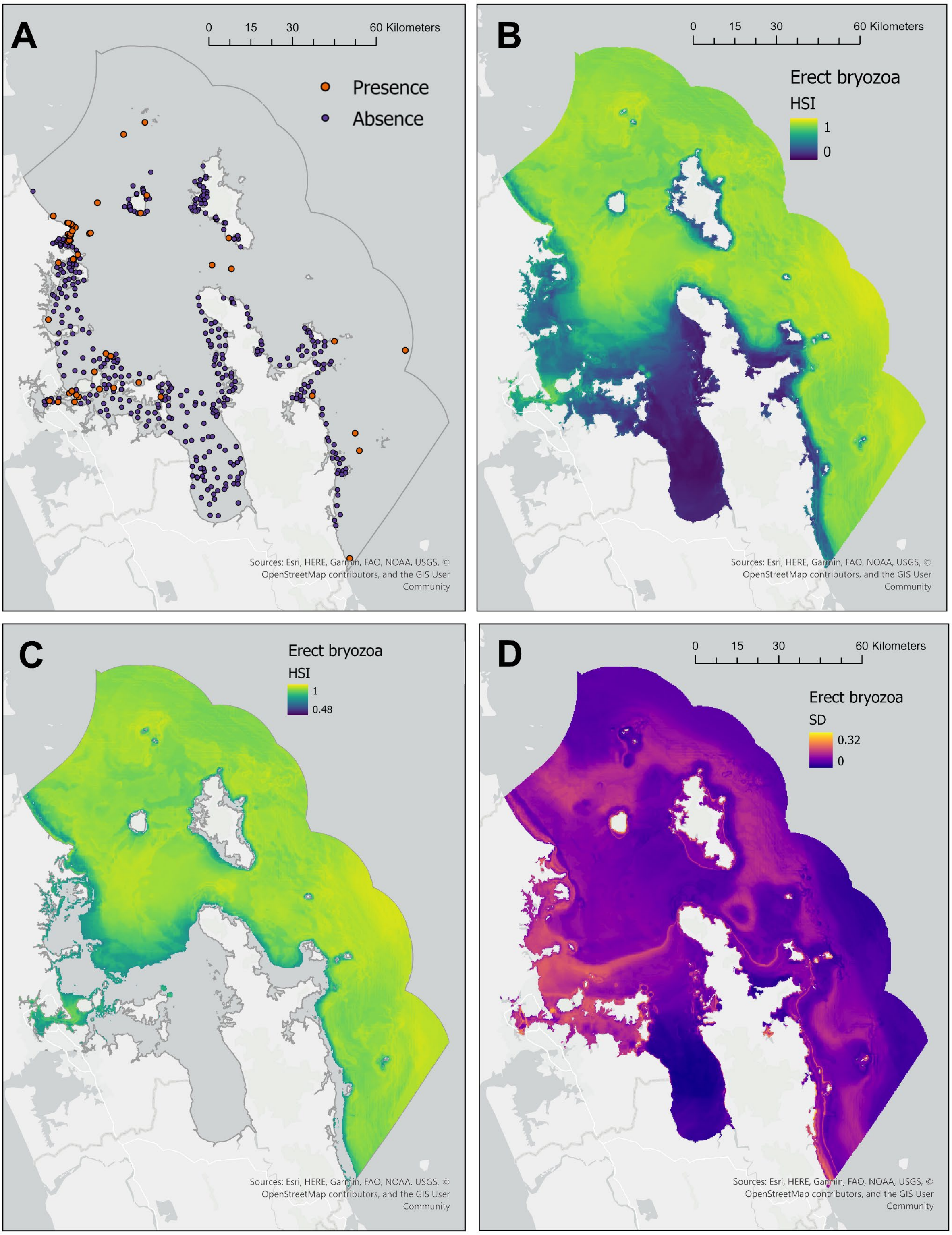

Figure 1.10: Erect Bryozoa. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

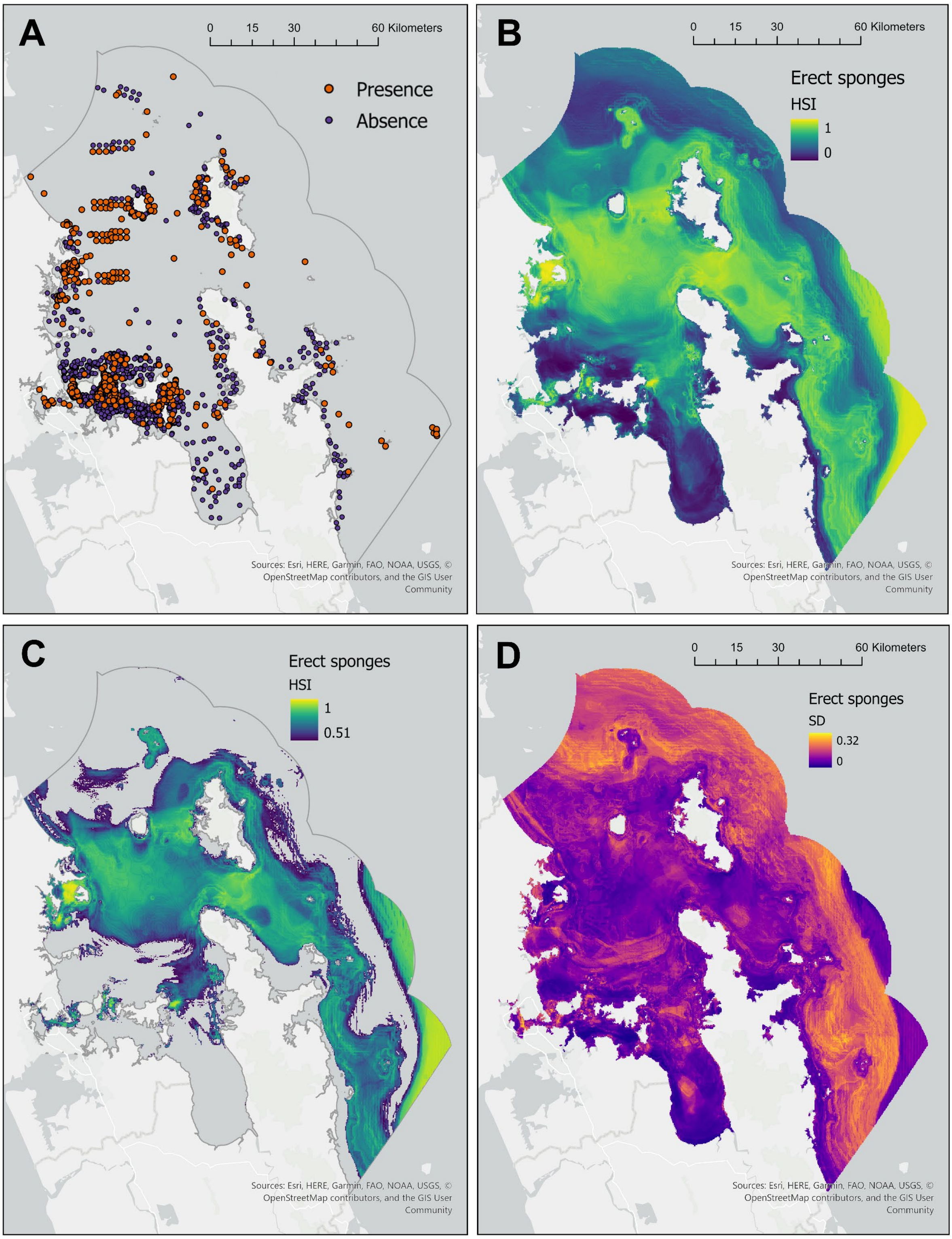

Figure 1.11: Erect sponges. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

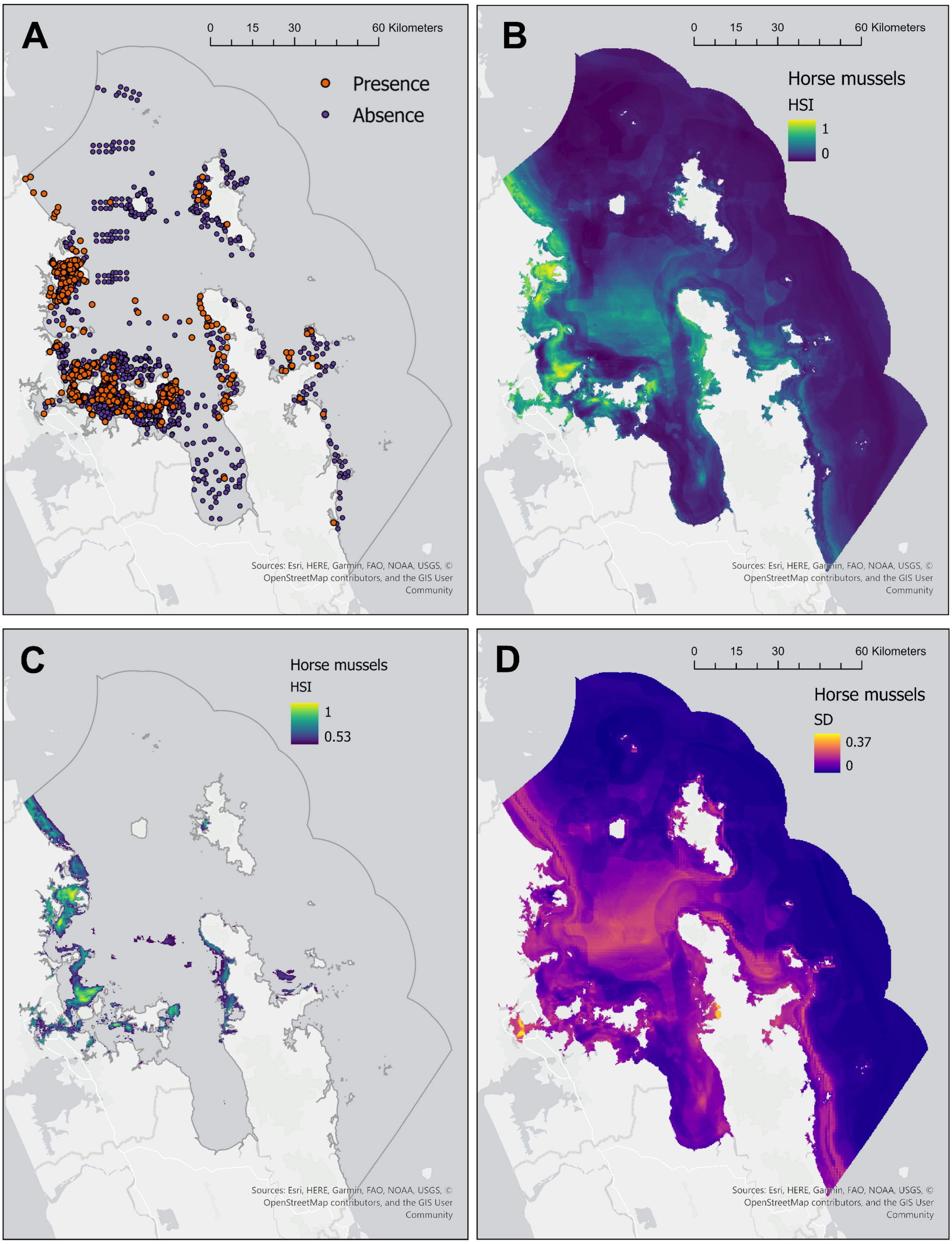

Figure 1.12: Horse mussels (*Atrina*). A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

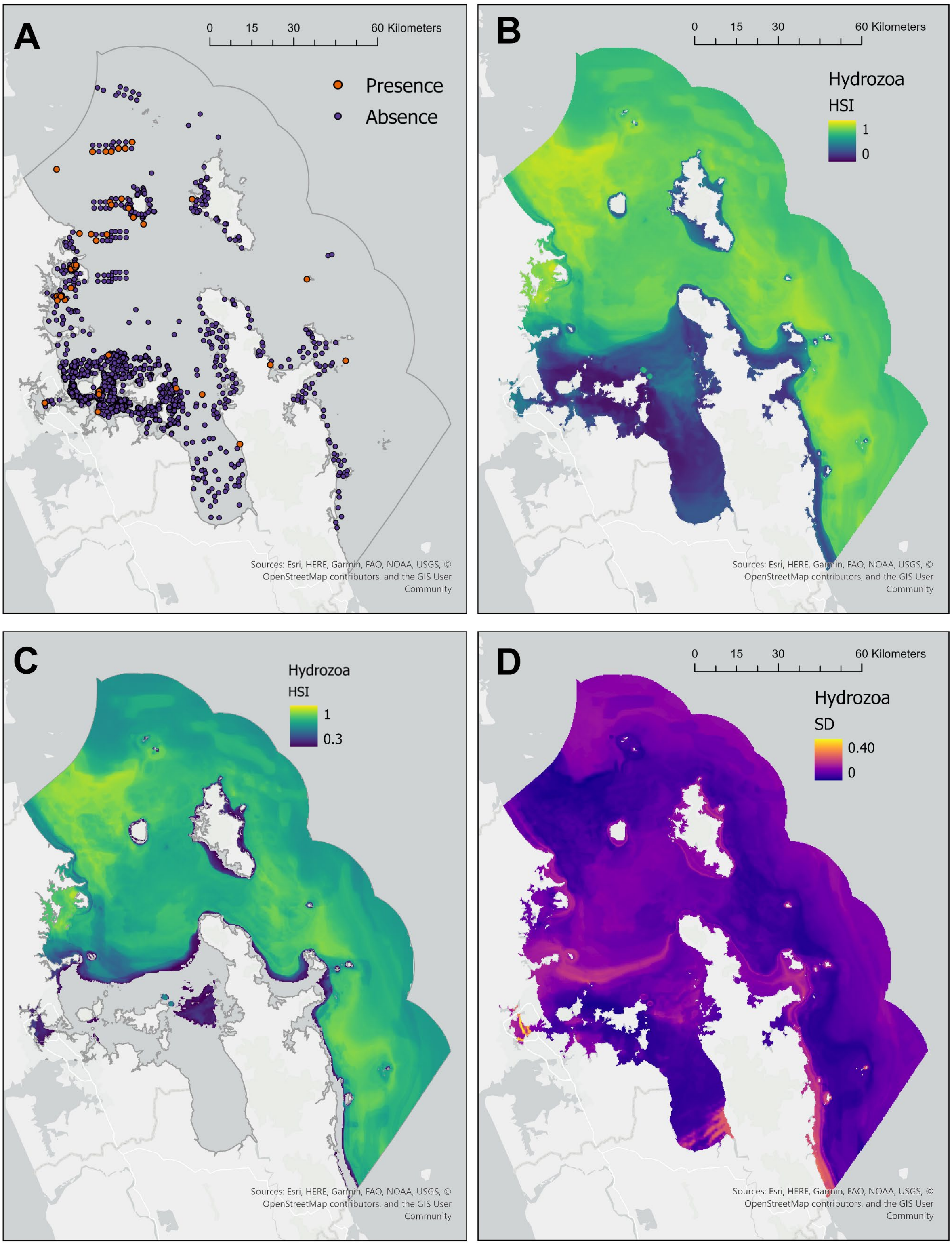

Figure 1.13: Hydrozoa. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

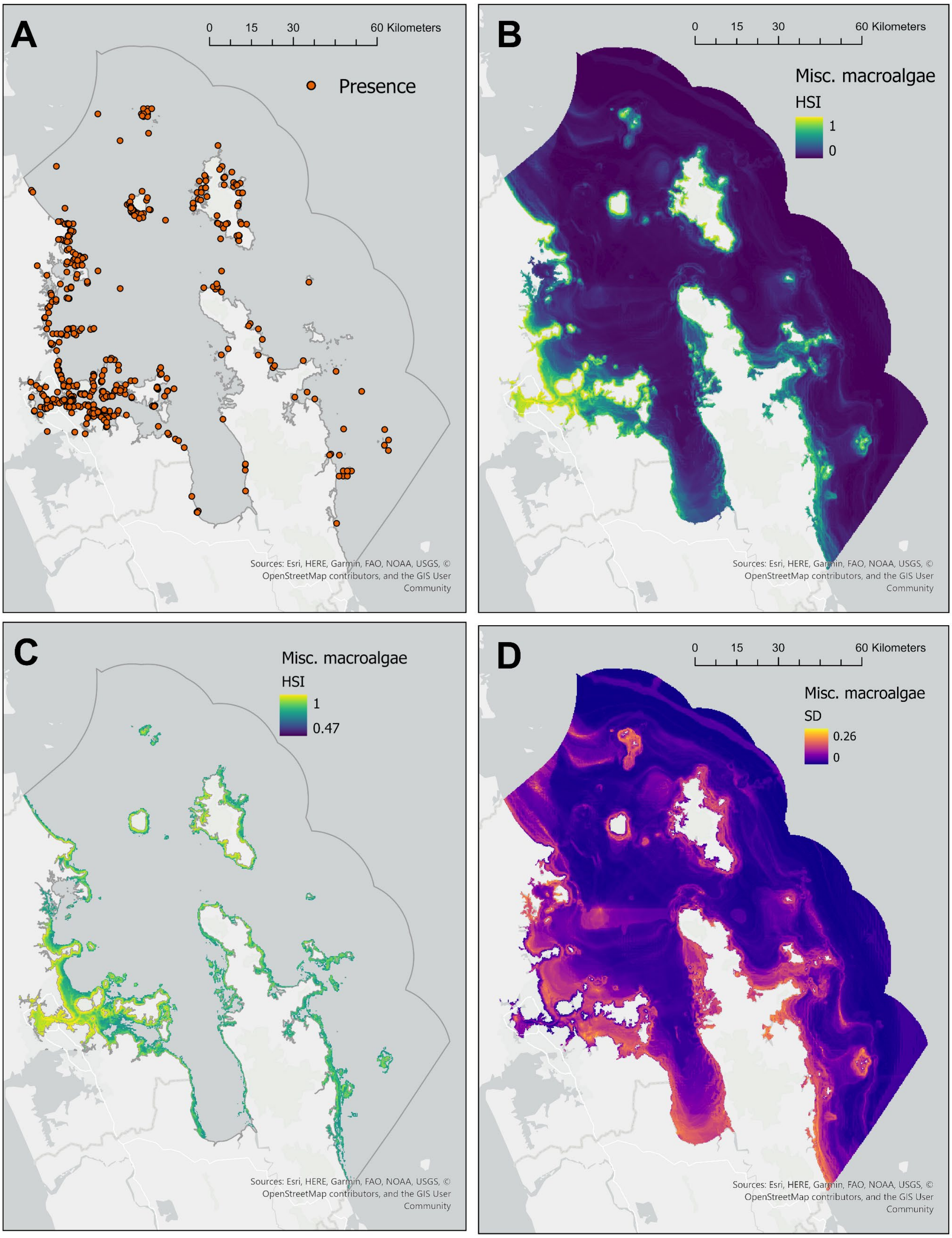

Figure 1.14: Miscellaneous macroalgae. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

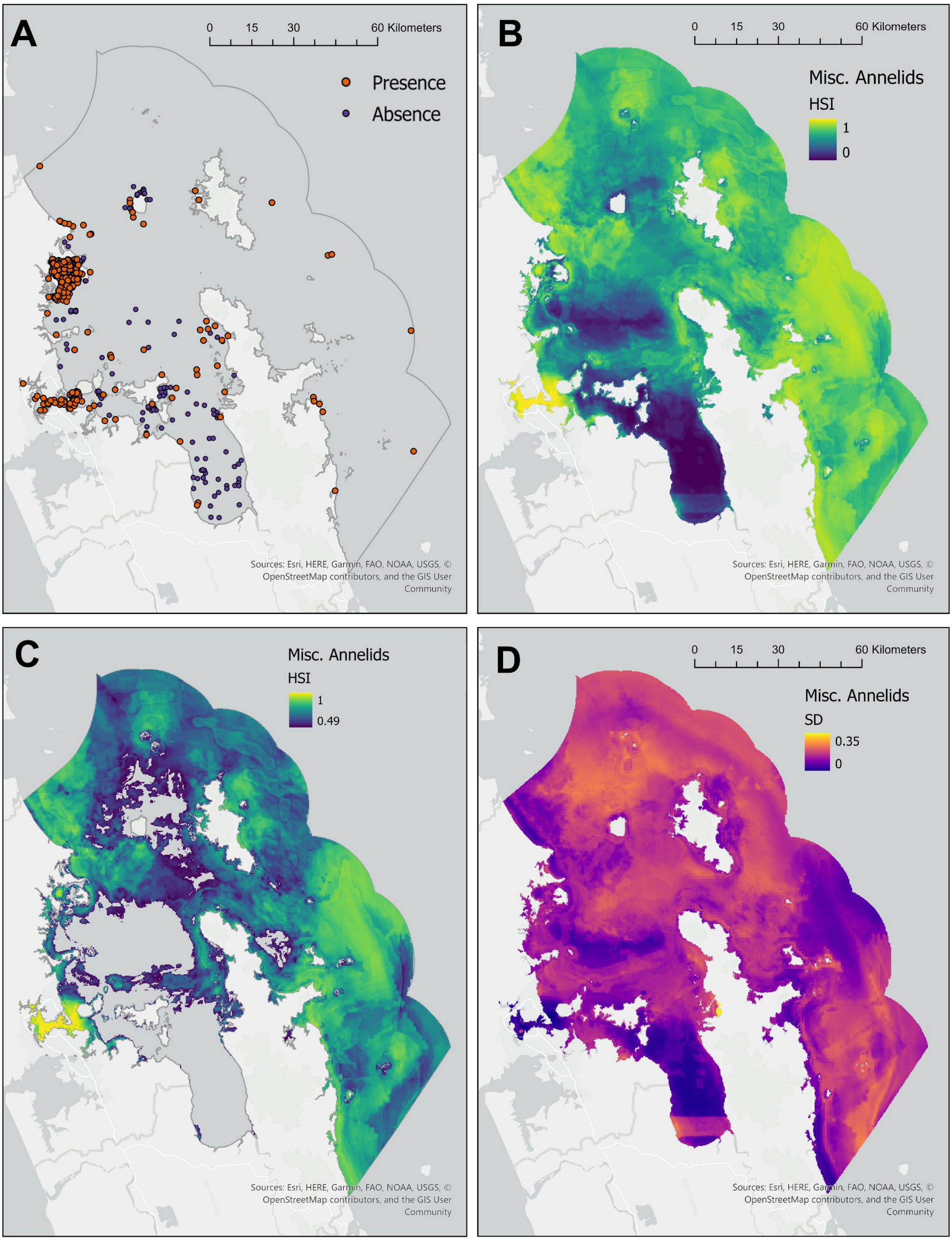

Figure 1.15: Miscellaneous Annelida assemblages. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

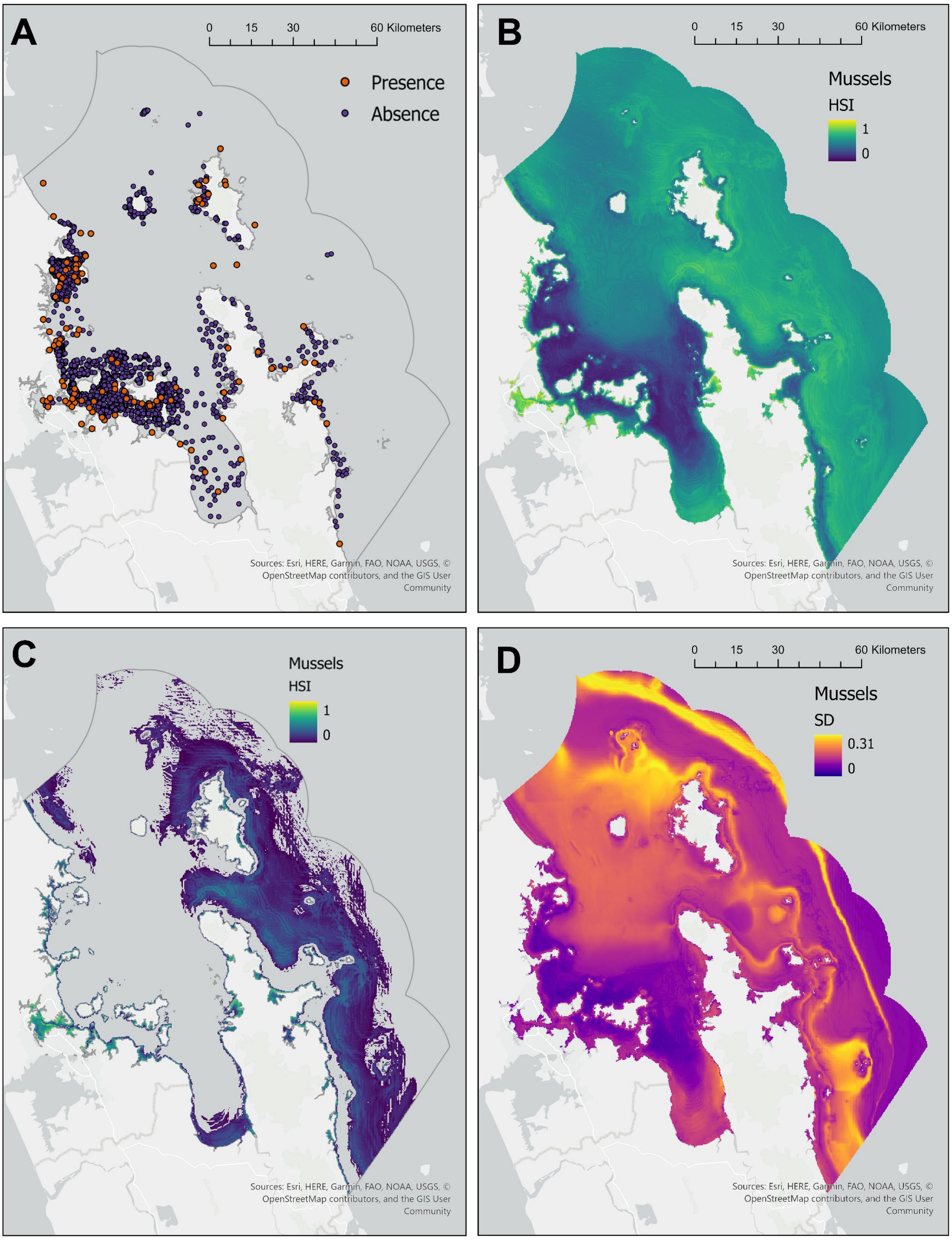

Figure 1.16: Mussels. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

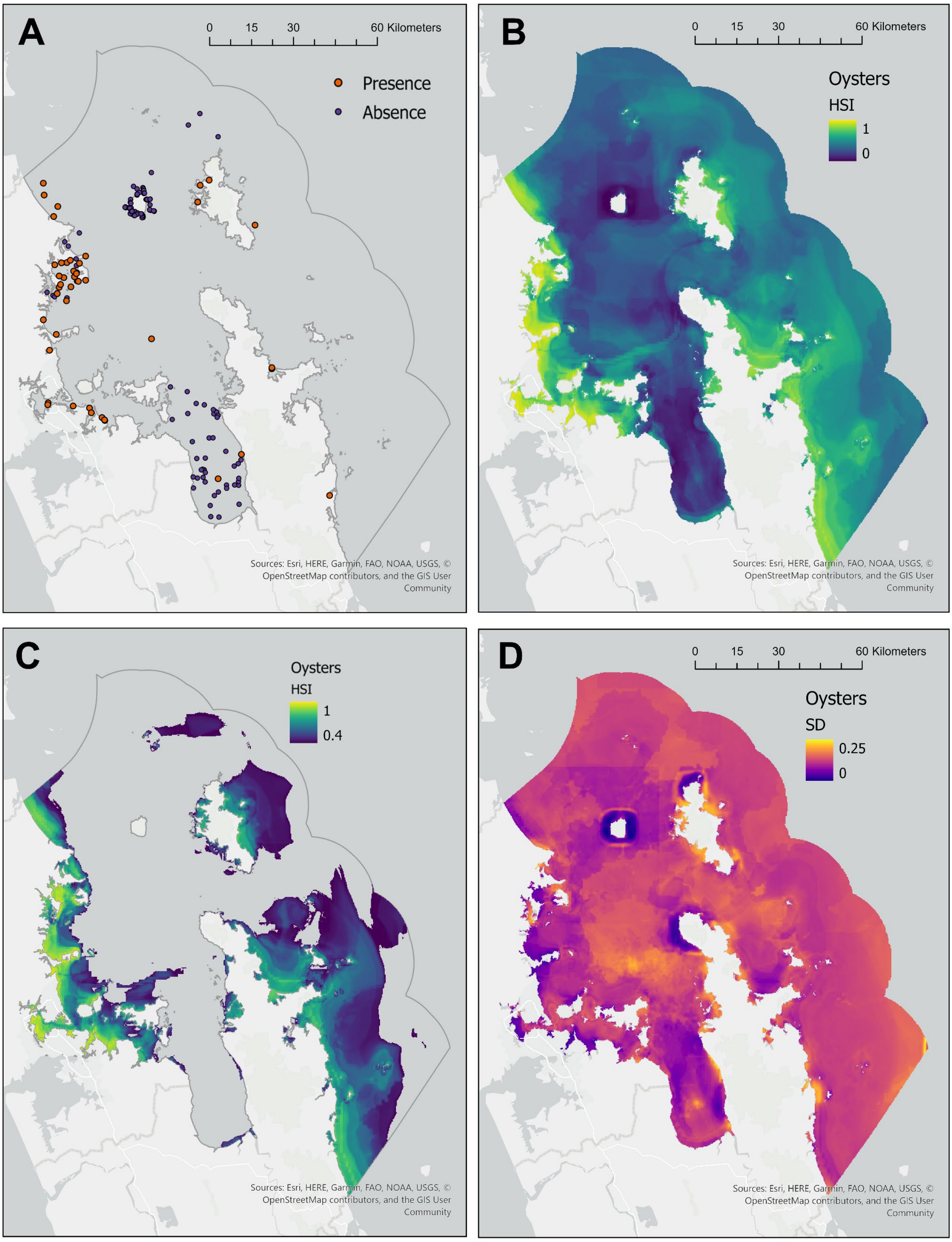

Figure 1.17: Oysters. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

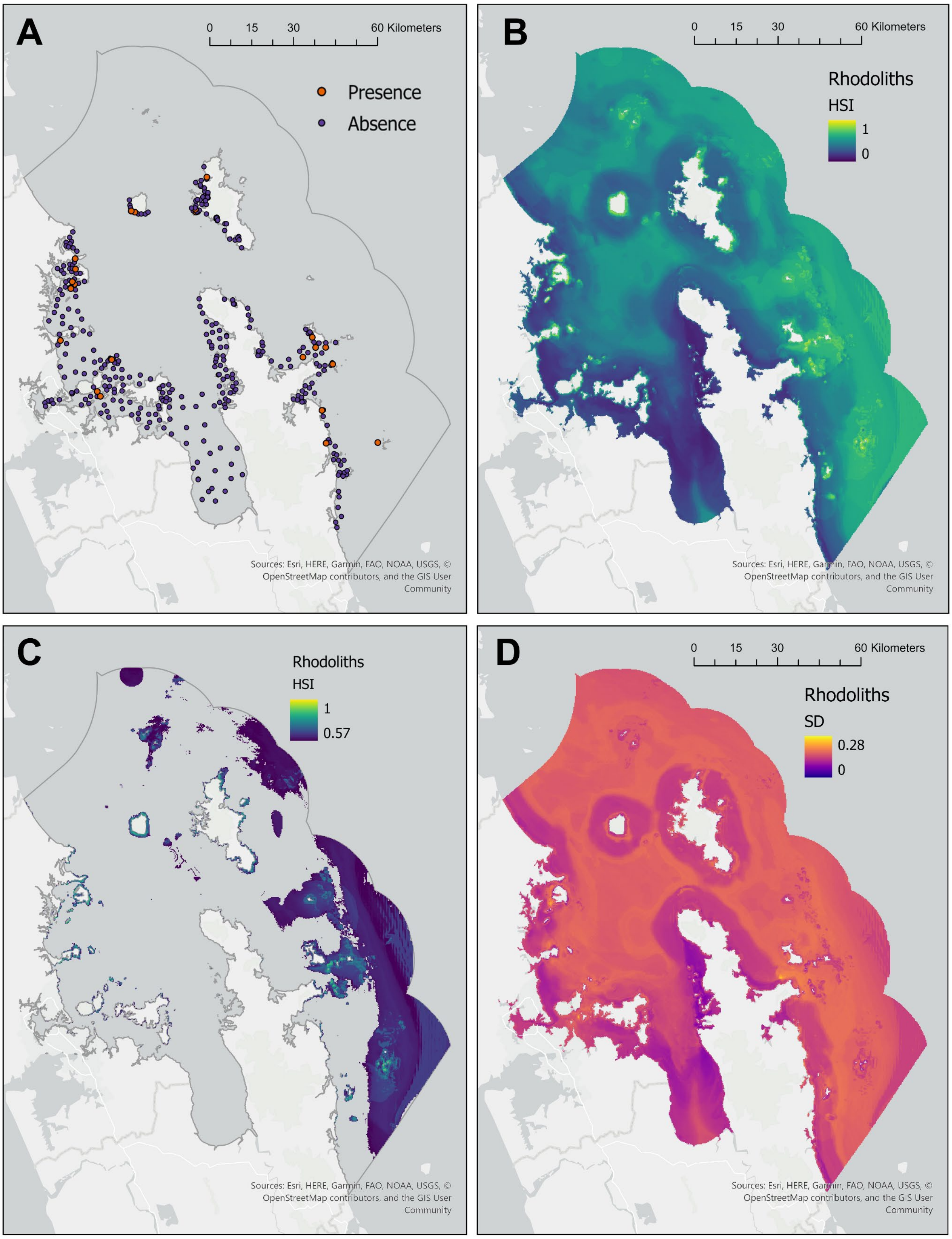

Figure 1.18: Rhodoliths. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation). For spatial prioritisations, the rhodolith layer was clipped to a maximum depth of 200 m.

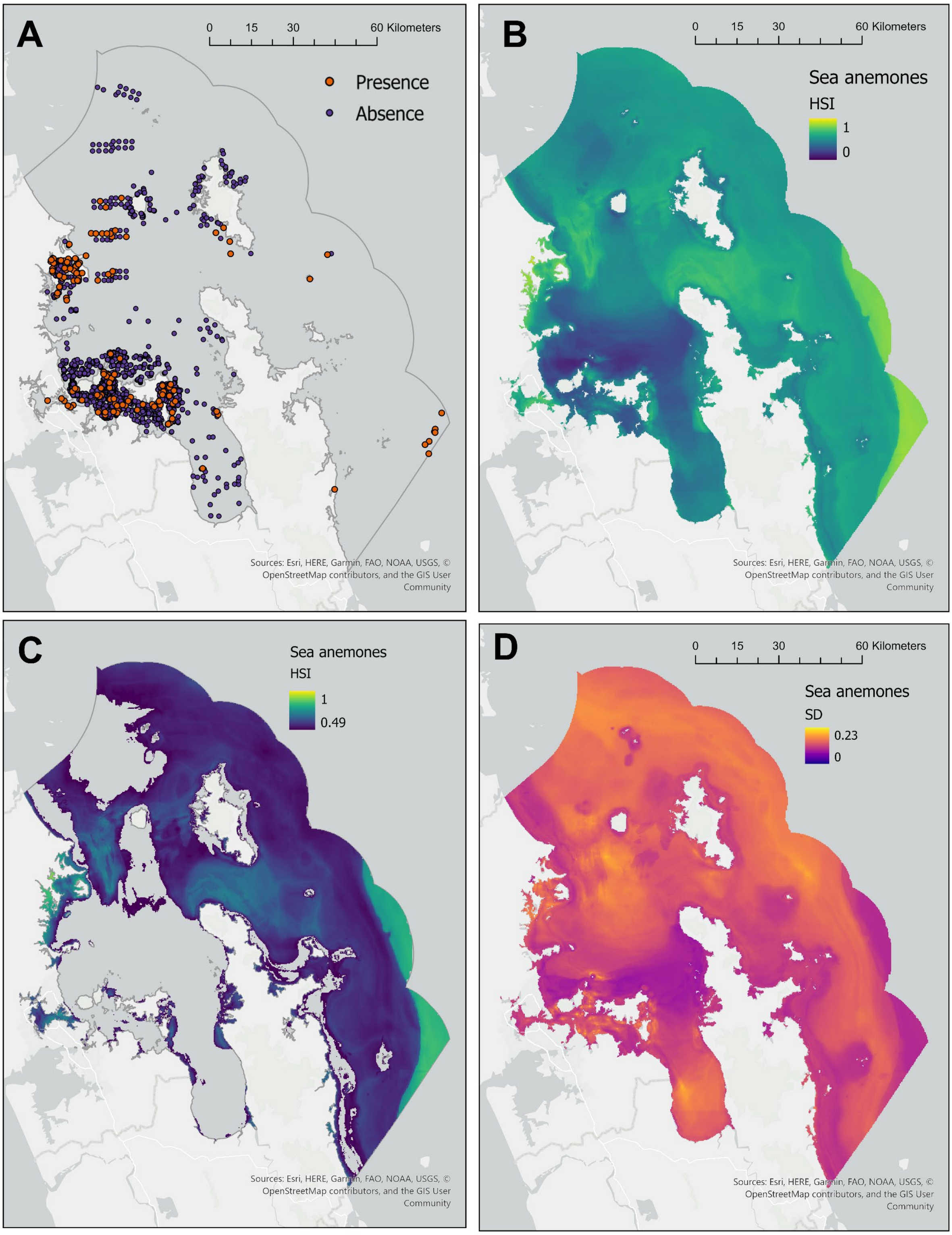

Figure 1.19: Sea anemones. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

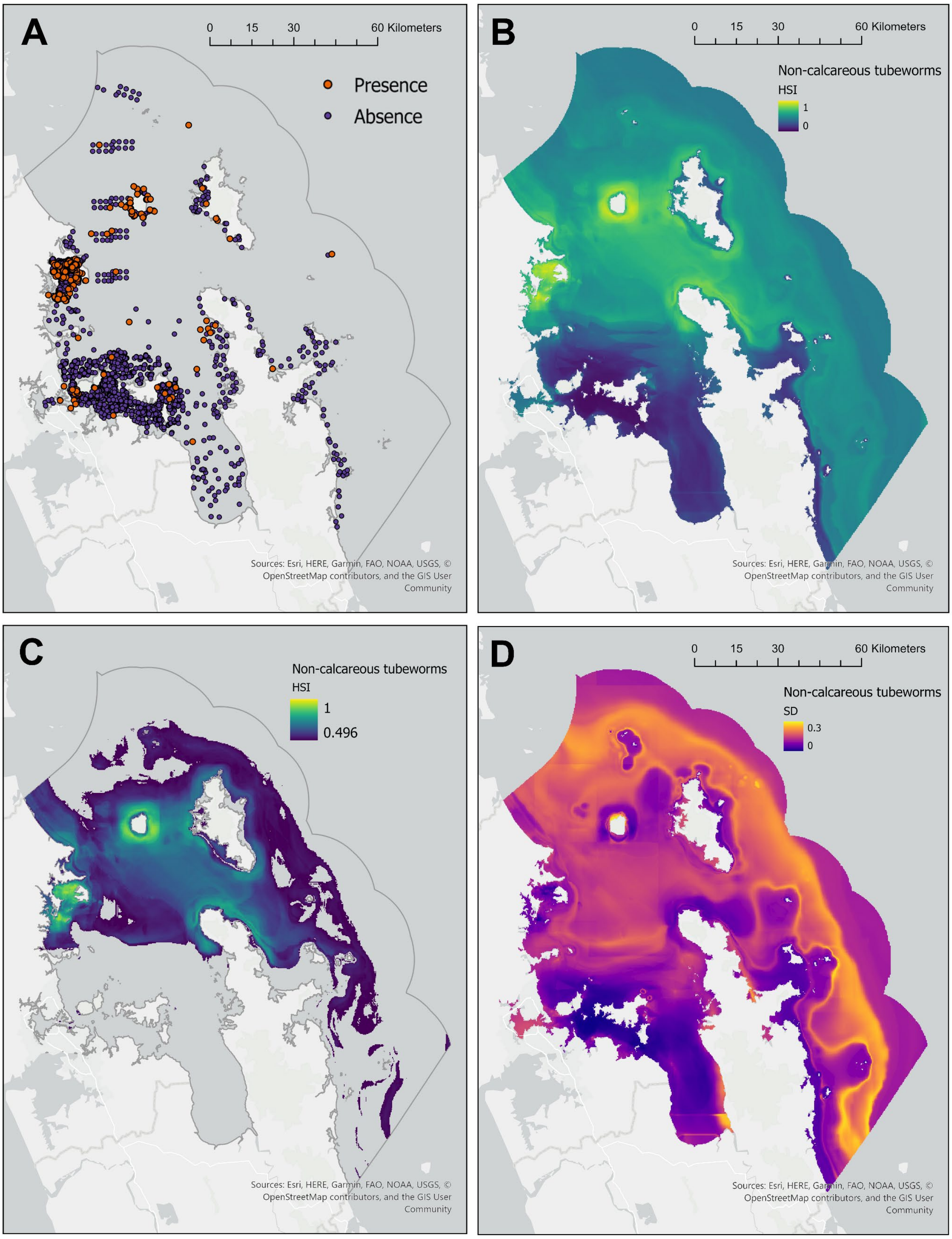

Figure 1.20: Non-calcareous tubeworms. A) Presence and absence point records, B) Ensemble probability of occurrence modelled layer, C) ROC threshold applied to probability of occurrence layer, D) Ensemble uncertainty layer (standard deviation).

APPENDIX 2

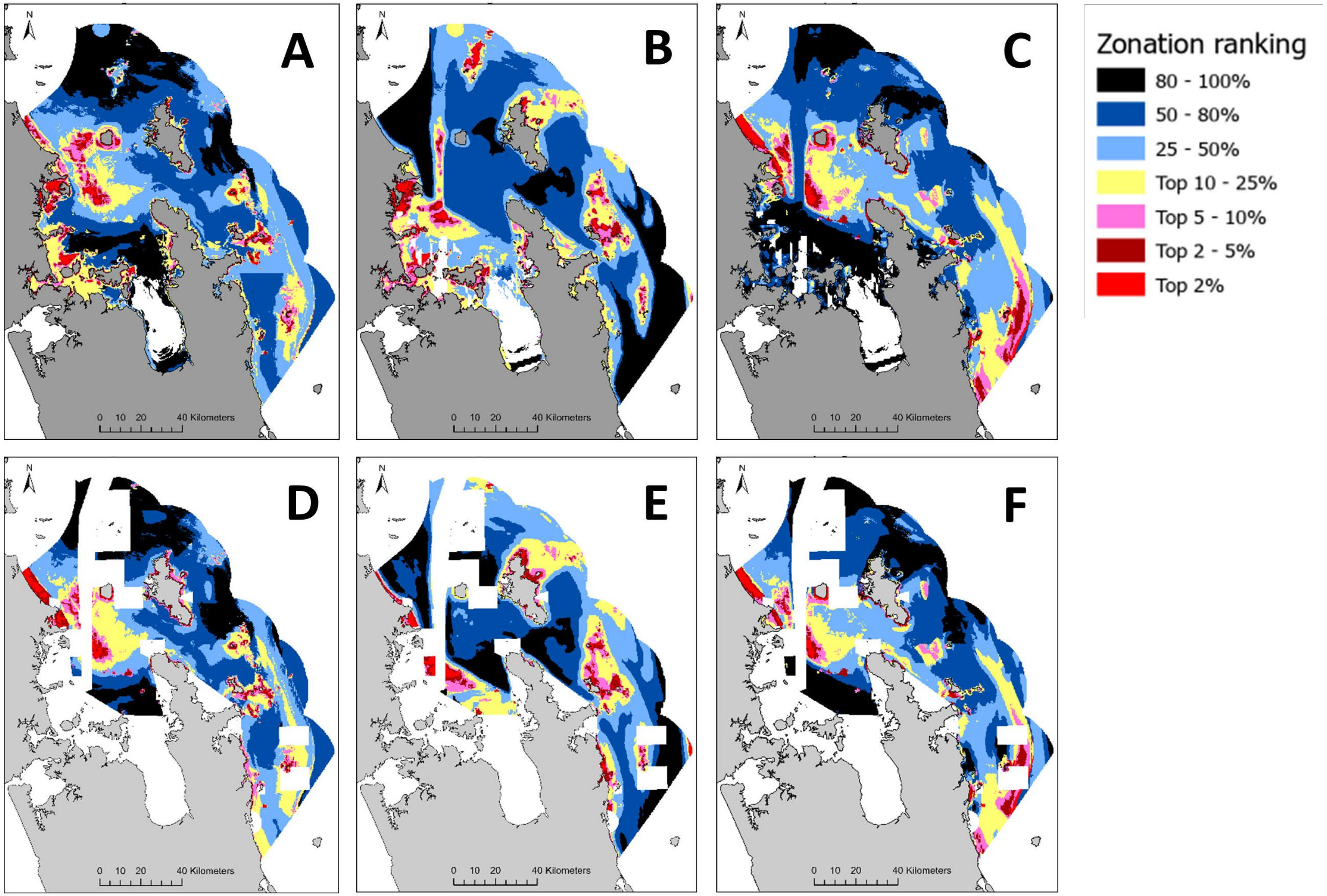

Figure 2.1: Zonation prioritisation of the 17 biogenic habitat groups based on A) probability of occurrence models, clipped to the full HGMP extent (no masking), B) the impacted model layers, clipped to the full HGMP extent (no masking), C) the recovery model layers (probability of occurrence minus impacted), clipped to the full HGMP extent (no masking), D) probability of occurrence models, with areas closed to all fishing methods and proposed HPAs and SPAs masked out, E) the impacted model layers, with areas closed to all fishing methods and proposed HPAs and SPAs masked out, F) the recovery model layers, with areas closed to all fishing methods and proposed HPAs and SPAs masked out.

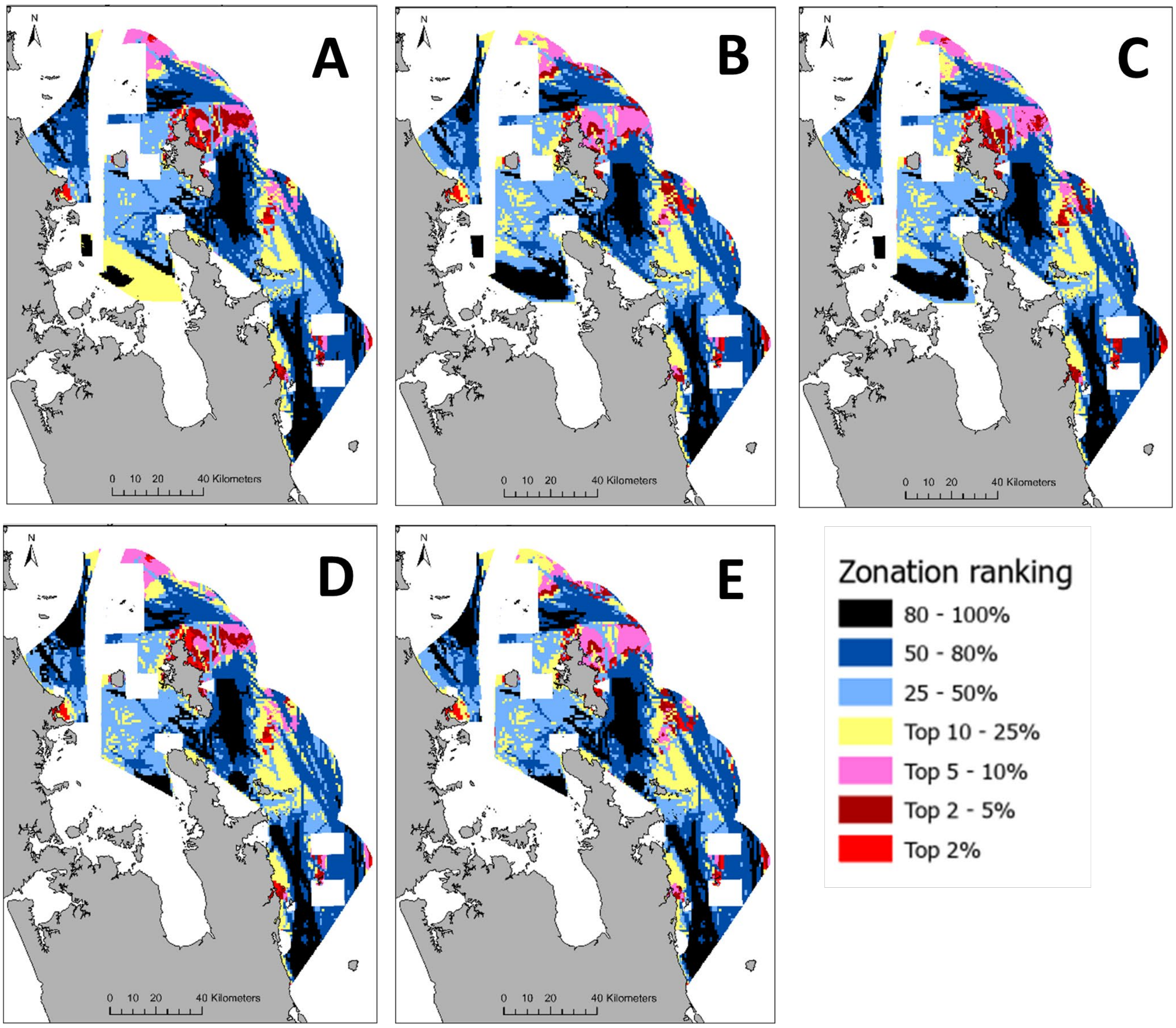

Figure 2.2: Zonation prioritisation of biogenic habitat, the 17 biogenic habitat groups used, and negatively weighted fishing value layers (equally weighted) to generate a trade-off between biodiversity and fishing value, based on A) the impacted model layers, with areas closed to all bottom trawling methods and proposed HPAs and SPAs masked out, B) the recovery model layers, with areas closed to all bottom trawling methods and proposed HPAs and SPAs masked out, C) probability of occurrence models, with areas closed to all bottom trawling methods and proposed HPAs and SPAs masked out, D) the impacted model layers, with areas closed to Danish seining and proposed HPAs and SPAs masked out, E) the recovery model layers, with areas closed to Danish seining and proposed HPAs and SPAs masked out.

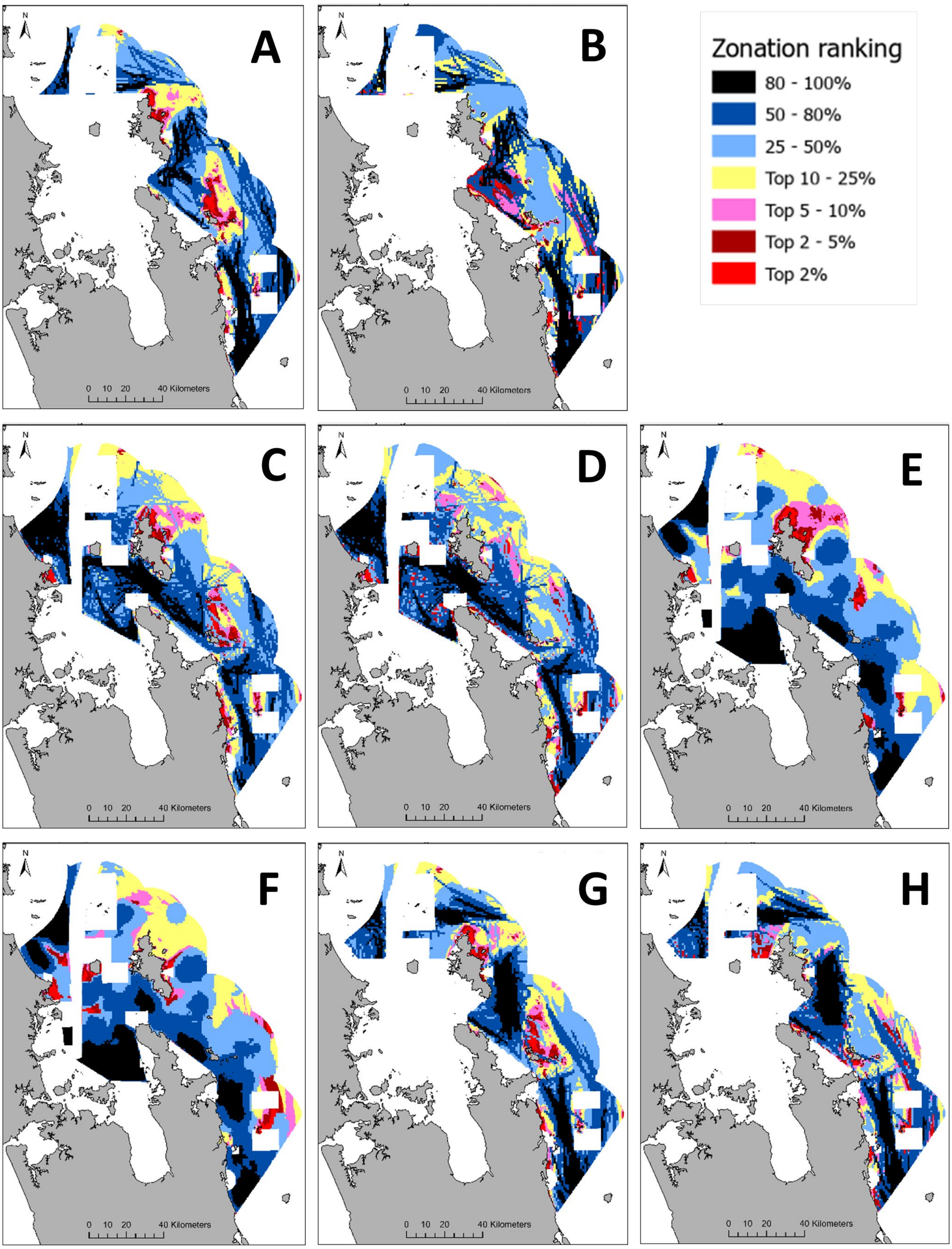

Figure 2.3: **Zonation prioritisation of biogenic habitat, based on the 17 biodiversity groups, and negatively weighted fishing value layer to generate a trade-off between biodiversity and fishing value based on A) impacted model layers and value of bottom trawling using vessels over 20 m, B) recovery model layers and value of bottom trawling using vessels over 20 m, C) impacted model layers and value of bottom trawling using vessels under 20 m, D) recovery model layers and value of bottom trawling using vessels under 20 m, E) impacted model layers and value of Danish seining, F) recovery model layers and value of Danish Seining, G) impacted model layers and value of PSH, H) recovery model layers and value of PSH. All prioritisations had proposed HPAs and SPAs and respective fishing restrictions for each method masked out.**