Appendix F Seabed report

1. My full name is Holly May Bennett. I have been working in the consulting and research space as a Marine Ecologist at the Cawthron Institute since August 2017. I have been leading the Cawthron Environment and Aquaculture Interactions team since 2021.

2. I hold a PhD in Marine Science from Victoria University of Wellington, New Zealand, which I obtained in 2017. I also hold a Bachelor of Science with Honours in Marine Biology obtained from Victoria University of Wellington, New Zealand in 2012; and a Bachelor of Science in Marine Biology, Ecology and Biodiversity obtained from Victoria University of Wellington in 2011.

3. Prior to my role at Cawthron, my research focused on environmental stressors to benthic organisms, with a primary focus on climate change and sedimentation effects to sponges.

4. I have over 10 years of research experience related to the effects of human activities on the marine environment, including marine farming. My work at Cawthron centres around studying the interactions between aquaculture and the environment and is mainly focused on the benthic effects of salmon farming. I have either led or contributed to a number of commercial projects in this space, including site selection for potential aquaculture sites, monitoring of marine farms and environmental impact assessment work. I am also involved in a recently funded MPI project looking at the effects of open ocean aquaculture on seabed communities.

5. I have authored or co-authored 10 papers that have been published in high profile peer-reviewed international scientific journals, as well as >40 other technical reports including co-authoring the recent update to the Best management practice guidelines for salmon farms in the Marlborough Sounds Part 1: Benthic environmental quality standards and monitoring protocol (Version 1.2, MPI 2022).

CAWTHRON

REPORT NO. 3315B

ASSESSMENT OF SEABED EFFECTS ASSOCIATED WITH FARMING SALMON OFFSHORE OF NORTHERN STEWART ISLAND / RAKIURA

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EXECUTIVE SUMMARY

Ngāi Tahu Seafood Resources (Ngāi Tahu Seafood) wish to develop a c. 2,500 ha area for salmon farming 2 to 6 km offshore of northern Stewart Island / Rakiura, 13 km northwest of Oban (the Hananui proposal area). The proposed site will comprise four farms, each with up to two blocks of up to ten pens. This report characterises the seabed environment within the proposal area and considers the potential environmental effects from the proposed marine farming activity.

The existing environment
Water depths in the proposal area are 20 to 40 m and water current velocities are strong. Currents flow along a northwest / southeast axis. Sandy sediments, with varying amounts of gravel-sized particles (shell hash) and a small proportion of mud, dominate the substrate. The sediment is well oxygenated with low organic content. The sediment macrofaunal community (animals < 0.5 mm living on or in the seabed) has low abundance and moderate diversity.

The five dominant habitat types are 1) sand, 2) sandy shell hash, 3) coarse gravel shell and sand, 4) bushy bryozoan 'thickets' and 5) bryozoan-sponge reefs. The main habitat type across the proposal area is sand (c. 77% of the proposal area). Sand ripples, waves and large sand banks with some shell hash present were typical of this habitat type, and epifaunal assemblages were sparse. In areas with more shell hash (sandy shell hash, covering c. 11% of the proposal area) more epifauna were observed; these were mainly brittle stars. Habitat with shell hash, whole shell debris, gravel and some cobbles (defined as coarse gravel shell and sand) covered 2.7% of the proposal area. Brittle stars were fairly common across this habitat type and some isolated biogenic clumps, mainly bushy bryozoans, were observed. Bushy bryozoan thickets are areas of clown-hair-like bryozoans interspersed with calcareous tubeworms. These cover around 0.3% of the proposal area. These thickets have high epifaunal diversity and hold taxa of ecological importance such as erect bryozoans and sponges, brachiopods and large bivalve species. Bryozoan-sponge reefs are biodiverse habitats created by erect and encrusting bryozoans, sponges and tubeworms. These reefs cover approximately 9% of the proposal area.

Assessment of effects
Deposition of organic material (principally waste food and fish faeces) from finfish farming onto the seabed can be the ecological effect of most concern. In sites with low water flow, farm wastes fall to the seabed and remain largely near the farm, whereas in higher-flow environments, currents can spread wastes further afield. Modelling of salmon farm seabed enrichment has traditionally relied on primary deposition (one-way flux, i.e. straight to the seabed). However, with the move to farming in higher-flow environments, it becomes more important to consider the effects of resuspension and redeposition of farm wastes. We used two modelling approaches to predict the magnitude and extent of seabed deposition resulting from the proposed farms. The first depositional model predicted the 'worst-case' extent of seabed deposition without resuspension processes integrated (primary deposition, presented

as ‘kg solids $m^2 \cdot y^{-1}$’) at Stage 1 and Stage 4 of production (ranging from c. 10,000 to c. 25,000 tonnes of feed discharged per year). The second model took resuspension into account to estimate the spatial extent of dispersal and identify places in the environment where the accumulation of solids is likely (residual solids, presented as ‘g solids m^{2}’).

Ngāi Tahu Seafood propose to farm under a single year class regime whereby feed discharges will vary substantially throughout a production cycle. Under this regime, feed will increase prior to harvest, then decrease to zero following harvest, with sites laying fallow for at least three months between production cycles. Under this regime, peak feed inputs are of relatively short duration (less than a quarter of the production cycle at each farm) and production at each of the four farms will peak at different times (we refer to the cycling of peak production between the four farms as a ‘rolling peak’).

Depositional modelling[1] (without resuspension) indicated that at the Stage 1 production level (10,000 tonnes of feed discharged per year[2]), the maximum depositional flux would be up to 13.5 kg $m^{-2} \cdot yr^{-1}$ of solids (corresponding to very high enrichment). This level of enrichment is expected directly under the South farm block A pens during peak production. The main footprint of deposition (solids flux > 1 kg $m^{-2} \cdot yr^{-1}$) under the Stage 1 rolling peak scenarios ranges from 39 to 52 ha and the total footprint area (where the solids flux anywhere in the proposal area is < 1 kg $m^{-2} \cdot yr^{-1}$), ranges from 156 to 198 ha.

At Stage 4 (c. 25,000 tonnes of feed discharged per year) the maximum depositional flux would be up to 21.1 kg solids $m^{-2} \cdot yr^{-1}$ (corresponding to very high enrichment) under the South farm pens during peak production, with very high enrichment predicted to occur across up to 4 ha of the seabed (c. 0.2% of the proposal area). At each site, during other (non-peak) times in the production cycle the feed discharge will be markedly lower or reduced to zero and a degree of seabed recovery is expected. The main footprint across the rolling peak scenarios for all farms at Stage 4 ranges from 89 to 127 ha and the total footprint (including solids < 1 kg $m^{-2} \cdot yr^{-1}$) ranges from 330 to 412 ha.

Based on depositional modelling *without* resuspension, very high enrichment of the seabed is predicted across up to 4 ha of the seabed (c. 0.2% of the proposal area) during periods of peak production at Stage 4. At these times, large reductions in community diversity and extreme abundances of opportunistic taxa such as nematodes and capitellid worms are likely. However, during other stages of the production cycle when feed discharge is low or zero at these sites, macrofaunal communities would be expected to show reduced effects from enrichment. High enrichment of the seabed is predicted across 24 to 33 ha of the seabed (up to 1.3% of the proposal area) and up to 350 m from the pen edges. Opportunistic taxa such as nematodes and capitellid worms are likely to dominate seabed sediment

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[1] Note that in a previous version of this report (issued in December 2019, see Bennett et al. 2019) *average* annual feed inputs were modelled. In contrast, in the present report we have modelled the *peak* feed inputs from the production cycle at each farm. This means that predicted effects are in some cases greater, but we recognise that these peak feed inputs are of relatively short duration (less than a quarter of the production cycle at each farm).

[2] Feed inputs are also changed from those in the previous version of this report.

communities; however, other taxa may persist. Moderate enrichment is predicted across up to 102 ha and under these conditions, opportunistic and tolerant species (e.g. capitellid and dorvilleid worms) are likely to dominate macrofaunal communities. Enrichment levels are predicted to reduce progressively to near-background conditions within 865 m of the pen edges.

However, the coarse sediments in the proposal area are non-cohesive and current speeds are strong, therefore significant resuspension of farm wastes is likely. The accumulation of organic material within the sediments under and near the pens is therefore likely to be less than that predicted by using the depositional model without resuspension. Conversely, high current speeds and non-cohesive coarse sediments also mean that while the footprint will be less intense, it will be more extensive than at a less dispersive site. Therefore, far-field effects on seabed communities are possible if redeposition is high, although the degree of impact is likely to be less.

The proposed farms have been placed so that primary organic deposition (where particles first fall from the farm to the seabed), and the associated effects, are unlikely to occur in areas of high-value habitats (high biogenic cover). The substratum within the boundaries of each farm block and associated depositional footprint is mainly sand with varying amounts of shell hash. Epibiota (organisms on the surface of the seabed) are patchy within this habitat type. Brittle stars are the most common taxon, while bryozoans, sponges, tubeworms, ascidians, hydroids, brachiopods and large bivalve species, including scallops, oysters, horse mussels and dog cockles, are scarce. Depositional modelling with resuspension indicates that the amount of waste accumulated within the primary depositional footprints (where particles first fall from the farm to the seabed) within the immediate area of the farms would be substantially lower than the solids accumulation predicted with no resuspension. Resuspension modelling also suggests that low levels of organic deposition are expected up to at least 10 km from the proposal area boundary. Outside the farms, areas of high biogenic cover with sensitive species are found. Many filter-feeding organisms are present within the biogenic habitat and low levels of increased organic matter in the environment may represent an enhanced food supply for these organisms. With the farm layout proposed by Ngāi Tahu Seafood, accumulation-spots of organic matter redeposition are not expected in areas where biogenic habitats and their associated communities are known to occur. Further to this, far-field deposition and accumulation into these areas are generally expected to occur only at low levels that may not be easily discernible.

However, in considering residual solids thresholds developed for the Marlborough Sounds (which suggest effects to biogenic habitats and their associated communities are unlikely at or below 9 g·m^{-2} of residual solids[3]), deposition of organic material from the proposed farm could affect up to 4.6% of the total surveyed area of bryozoan-sponge reef and 3.8% of the

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[3] Note that the sites for which these relationships were derived differ to the proposal area and the relationship between residual solids levels and “effects’ are likely to vary depending on site characteristics. Nevertheless, these relationships provide the best available information from which potential effects from residual solids can be explored.

total surveyed area of bushy bryozoan thickets in and around the proposed site. At Stage 1 of the proposed development, areas of biogenic habitat are outside of the predicted 9 $g{\cdot}m^{-2}$ residual solids footprint and during other stages of the production cycle deposition across these same areas is low (i.e. < 5 $g{\cdot}m^{-2}$) or zero.

As the exact nature of effects on these sensitive taxa, and the level of deposition at which they occur, are difficult to predict in the absence of targeted research monitoring of these communities is crucial to ensure undue adverse effects are not manifested.

Management and monitoring recommendations

The proposed Hananui farming operation may be the first of its kind and scale in New Zealand. Therefore, although seabed effects arising from salmon farming are well studied in soft-sediment environments with lower current speeds, the proposal area presents some challenges for monitoring design. So far, research into the effects of salmon farming on the seabed has focused mainly on the deposition of organic waste immediately under or next to salmon net pens (‘near-field effects’), while far-field deposition has received much less attention. Monitoring of effects at dispersive sites will need to consider the potential for wider ecological effects as well as local-scale effects near to the farms.

Ngāi Tahu Seafood propose a staged approach to development that will allow for monitoring and understanding of the response of the proposal area to deposition before development is increased. Effects-based management involves monitoring of potential effects of concern and adapting farming practices to ensure unacceptable effects do not eventuate as the activity progresses. We recommend that an effects-based management strategy is adopted as a mechanism for reducing and mitigating potential effects of the proposal to ensure the farm is managed within a level of allowable effect. Adaptive management actions to limit the effect of seabed deposition, should they emerge during active farming operations, could include site fallowing and rotation (as is planned under the single year class farming regime proposed by Ngāi Tahu Seafood), and reduction of planned farming intensity. Given the scale of the proposed operation, and uncertainty around potential far-field effects, an adaptive approach will also need to be taken with respect to monitoring design and assessment of environmental impacts. Monitoring recommendations are under development.

Concluding comments

Potential effects on the seabed environment have been partially avoided and mitigated from the outset by placing farms over soft-sediment habitats and away from areas with high biogenic cover.

From our assessment, the main effects expected are those caused by organic material and possibly other contaminants (e.g. metals) being deposited onto sediment communities. Low level deposition of resuspended organic material (and possibly other contaminants) could conceivably affect biogenic habitat including bushy bryozoan thickets and bryozoan-sponge reefs (and associated sensitive taxa).

Ultimately, effects-based management combined with a staged development approach (whereby the potential effects of concern can be monitored, and farming practices adapted to minimise risk of unacceptable effects occurring as the scale of the development progresses) will ensure the farms are managed within a level of allowable effect to these communities.

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1. INTRODUCTION

1.1. Background

Northern Stewart Island / Rakiura has suitable characteristics for open-coast finfish aquaculture (Vennell et al. 2018; Taylor & Jary 2018; Bennett et al. 2018). Ngāi Tahu Seafood Resources (Ngāi Tahu Seafood) wish to develop an area for salmon farming 2 to 6 km offshore of northern Stewart Island / Rakiura (the Hananui proposal area), 13 km northwest of Oban (Figure 1). This report characterises the seabed environment within the proposal area, considers the potential environmental effects on these habitats from the proposed farm and recommends appropriate mitigation measures.

This is the third iteration of this report. The first version (Bennett et al. 2019) was submitted as part of the Ngāi Tahu Seafood application (APP-20191561). The second version (Bennett et al. 2020) was submitted in response to a Section 92 request for further information and included revisions to the proposed farm layout and feed inputs. This current version has been updated to include a high resolution habitat map that was created following a seabed mapping exercise carried out across the proposal area as a part of a wider Land Information New Zealand (LINZ) survey in early 2022.

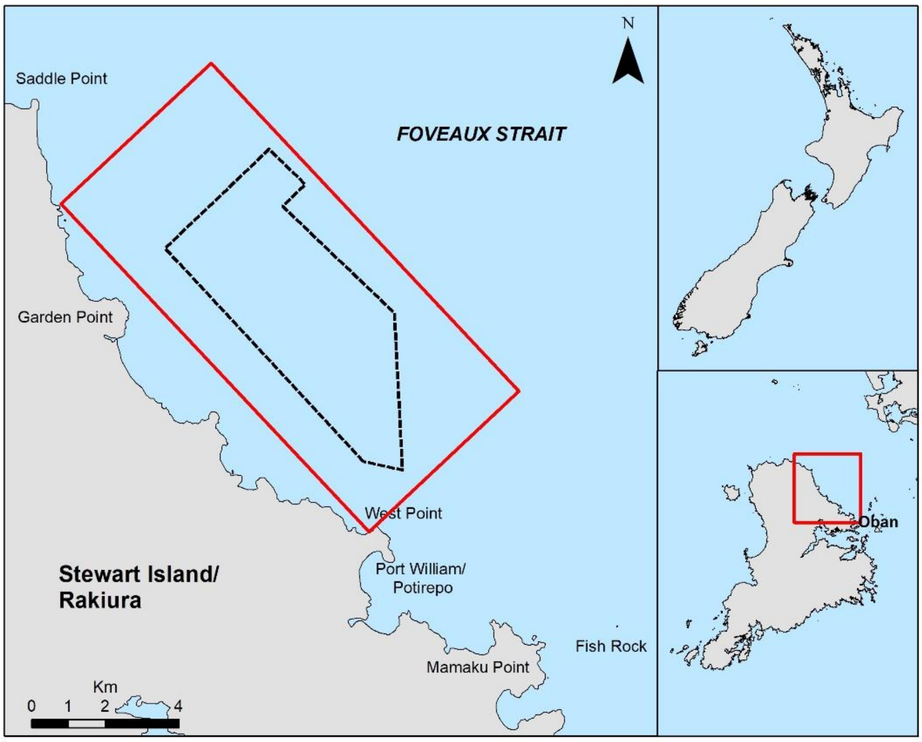

Figure 1. The Ngāi Tahu Seafood Resources Hananui proposal area (black dashed line). Information collected as a part of preliminary scoping investigations is also included in this assessment, forming a wider 'survey area' (red polygon in left panel).

1.2. Proposed activities at site

Ngāi Tahu Seafood propose developing a c. 2,500-ha area that would contain up to 80 pens to farm king salmon (*Oncorhynchus tshawytscha*). The proposed pen structures will likely be polar circle pens, 168 m in circumference (c. 25 m radius) and extending to 15 m depth at the centre of the fish net and 21 m at the centre of the predator net. Each pen will be individually moored using a combination of dual-shank anchors, chain and 5-tonne mooring blocks. Each farm will be serviced with an onsite barge that will be moored using this same system. The proposed farm layout at full production (up to an estimated 16,000 tonnes salmon per year) is shown in Figure 2.

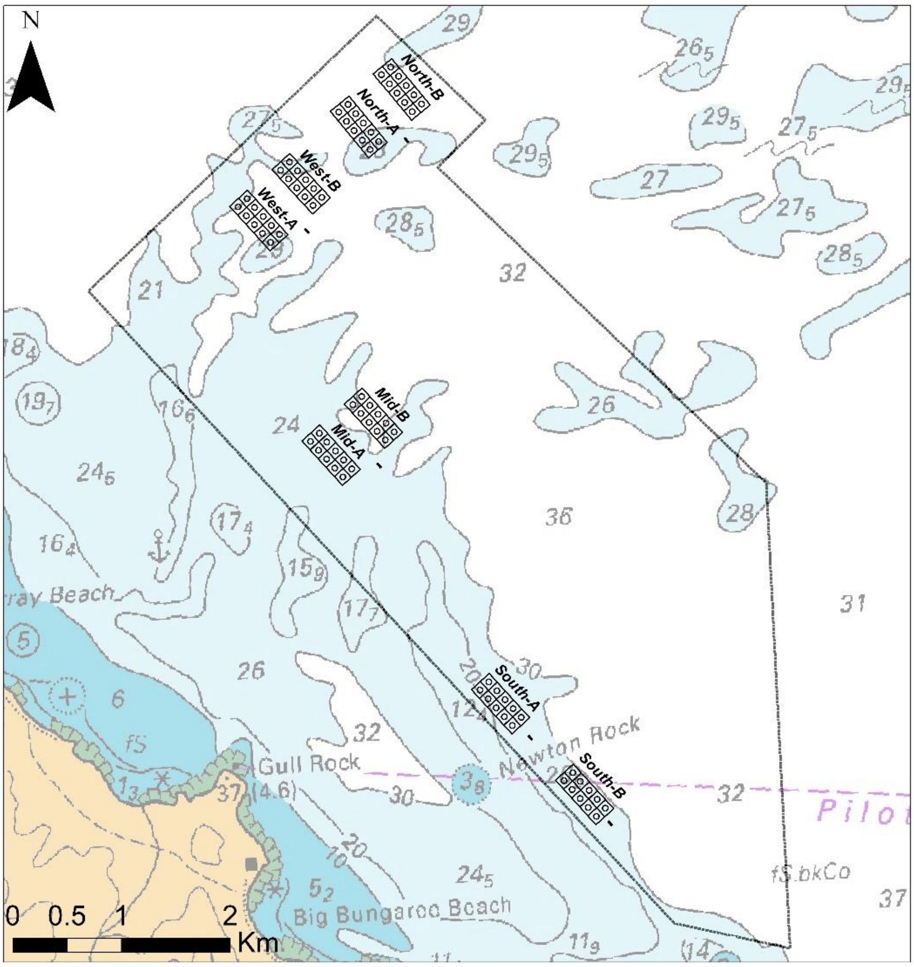

Figure 2. Proposed farm layout at the Ngāi Tahu Seafood Hananui proposal area (black outline). Background bathymetry source: Chart No. NZ681 Land Information New Zealand (LINZ) and licensed by LINZ for re-use under the Creative Commons Attribution 4.0 International licence).

1.3. Scope of report

This assessment forms one component of a wider assessment of environmental effects that has been conducted to inform Ngāi Tahu Seafood’s resource consent application to farm salmon in northern Stewart Island / Rakiura. This report characterises the seabed environment within the proposal and surrounding areas and considers the potential environmental effects on seabed habitats from the proposed operation. While the surveys undertaken as part of this assessment target the c. 2,500 ha proposal area, information collected during preliminary scoping investigations is also used (Vennell et al. 2018; Taylor & Jary 2018; Bennett et al. 2018, McGrath & Bennett 2019). The proposal area combined with additional area covered during scoping investigations is herein referred to as the ‘wider survey area’ (red polygon, Figure 1).

2. EXISTING KNOWLEDGE OF SEABED ENVIRONMENTS AROUND NORTHERN STEWART ISLAND

Foveaux Strait is a dynamic coastal region with strong, tidally-driven flows. The mean circulation of the region has water entering from the west and southeast, and discharging to the northeast above Ruapuke Island (Cranfield et al. 2003). Large fan-shaped subtidal dunes are known to extend from Garden Point to the northeast near the survey area, due to the convergence of those tidal currents (Figure 3).

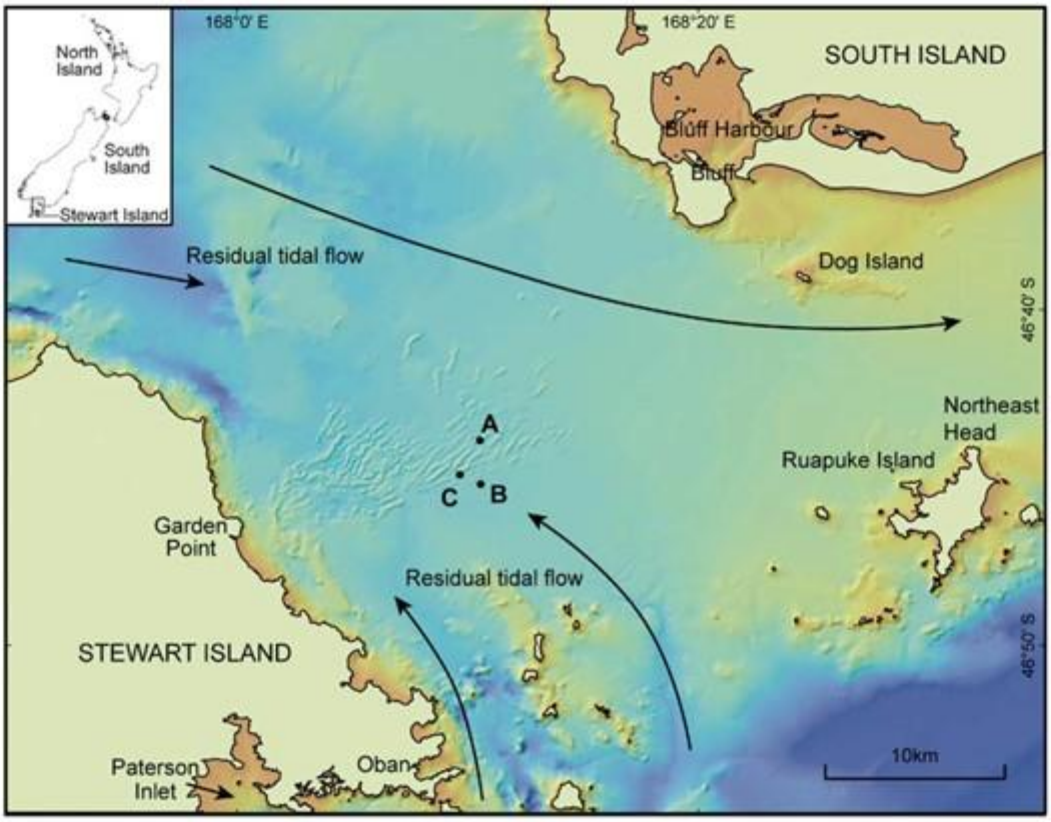

Figure 3. Subtidal features and patterns of mean tidal circulation in Foveaux Strait (from Cranfield et al. 2003, A to C indicate sediment grab sample locations in that study).

Historical records of bottom sediments show the general Foveaux Strait region to be a mixture of pebbly gravel, medium to fine sandy pebble gravel, and well- and poorly-sorted fine sand (Figure 4). A recent analysis of local knowledge of biogenic habitats reports a number of habitat types throughout Foveaux Strait and around Stewart Island, with patches of bryozoans, sponges, ‘coral’, large bivalve beds, tubeworms, sea tulips and complex reef identified (Figure 5, Jones et al. 2016). A rich variety of macroalgae are also reported for shallow rocky reefs in the Foveaux Strait region, while Foveaux Strait rock-wall communities have a very high diversity of encrusting invertebrates (Kettles et al. 2017).

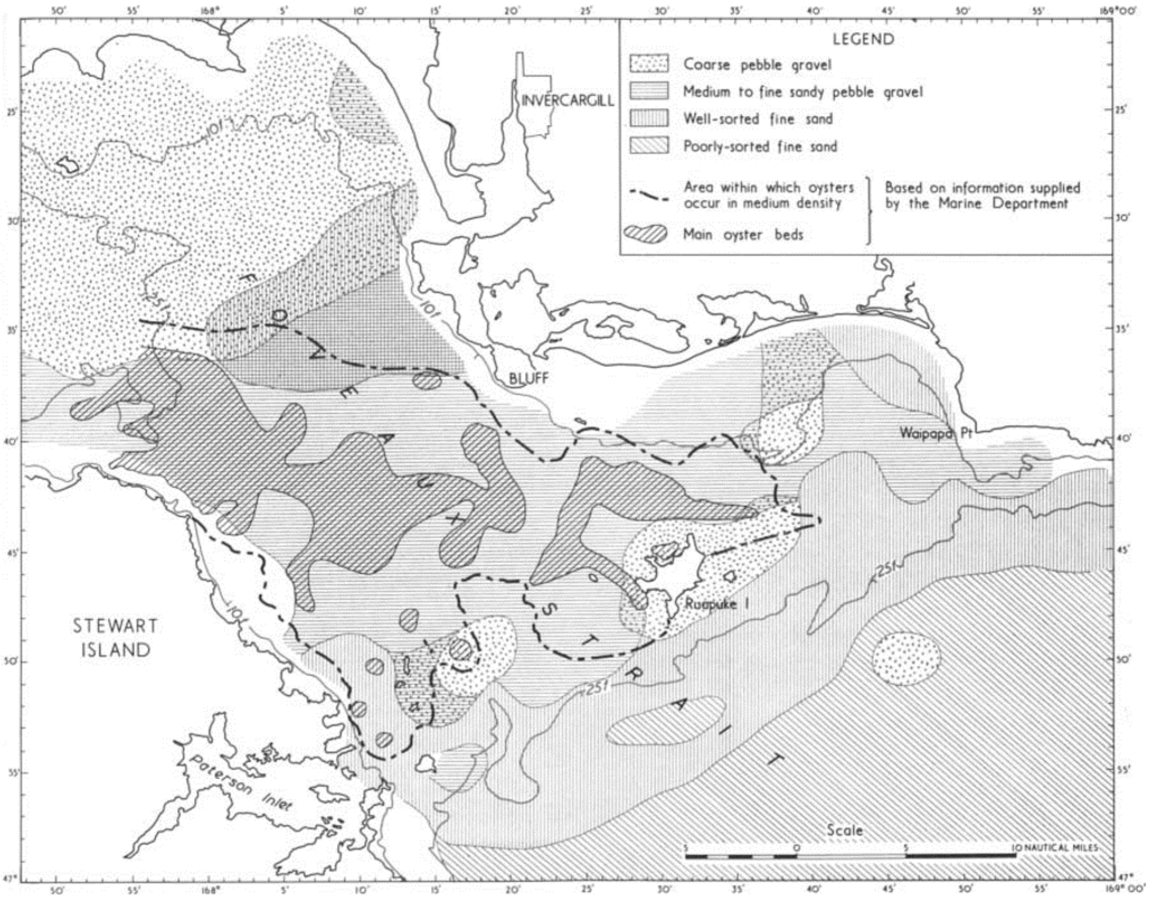

Figure 4. The distribution of bottom sediments in Foveaux Strait including the location of historic oyster beds (dark hash) (from Cullen 1962).

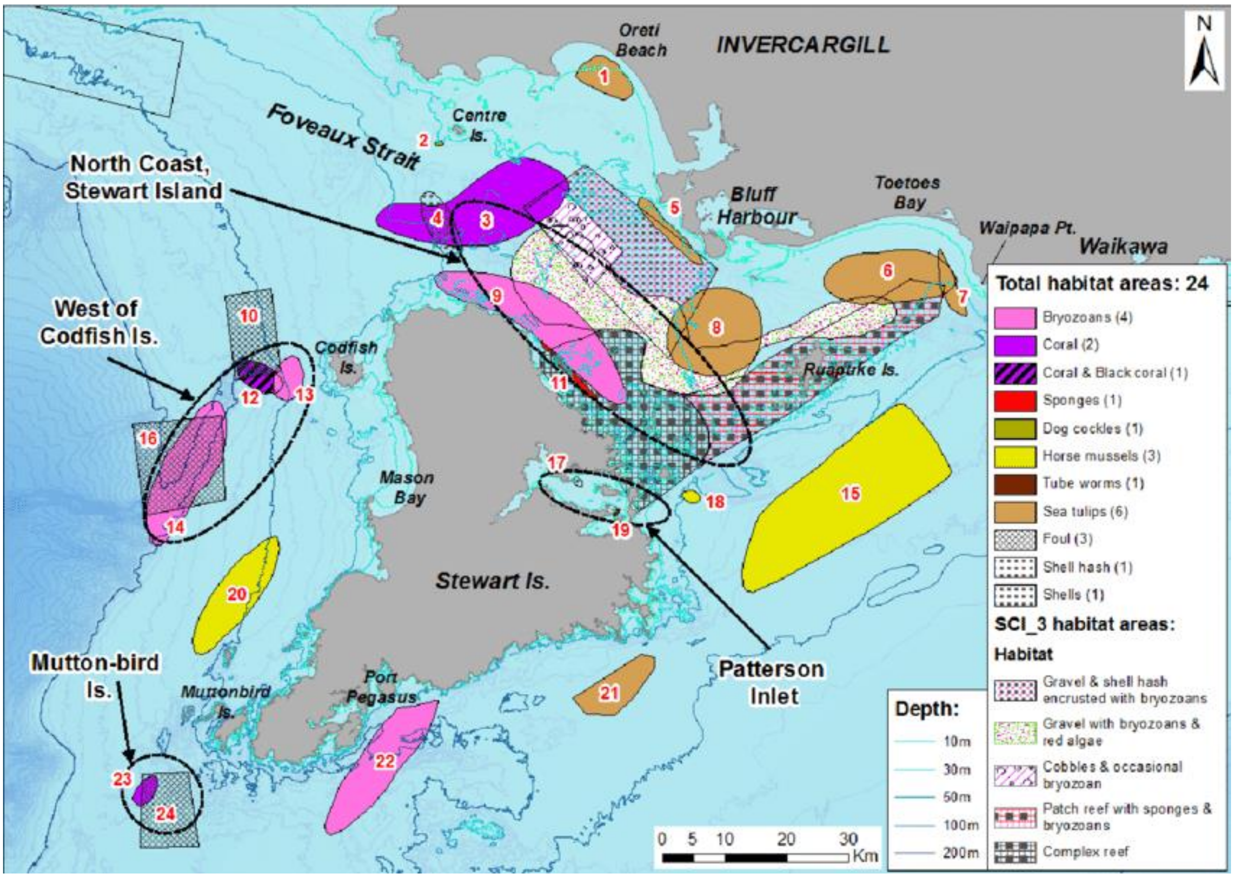

Figure 5. General overview of where different habitat types have been observed around Stewart Island, identified with local ecological knowledge. From Jones et al. 2016.

Dredge oysters (tio, *Ostrea chilensis*) have been dredged as part of the Foveaux Strait oyster fishery since 1867 (Figure 4 and Figure 6; Cranfield et al. 2003). Dredges were targeted traditionally at areas of complex biogenic reef habitat (commonly referred to as ‘mullock’), where oysters were known to be abundant. The principal reef component was the bryozoan *Cinctipora elegans*, together with other encrusting bryozoan species, ascidians, sponges and polychaete worms (Cranfield et al. 1999). Mullock reefs are typically found in areas of strong current flow and historically were hundreds of metres wide and kilometres long (Cranfield et al. 1999). Large bivalves were abundant on these reefs, especially dredge oysters and mussel species. However, after over 140 years of heavy dredging, many mullock reefs in Foveaux Strait have been destroyed, resulting in significant declines in oyster populations and widespread human-induced change in seabed habitats across the area (Cranfield et al. 2003; Hill et al. 2010). The dredge oysters also suffer from periodic mortality events associated with the haplosporidian parasite *Bonamia exitiosa*, which has resulted in further significant declines in oyster populations since 1906 (Michael et al. 2017).

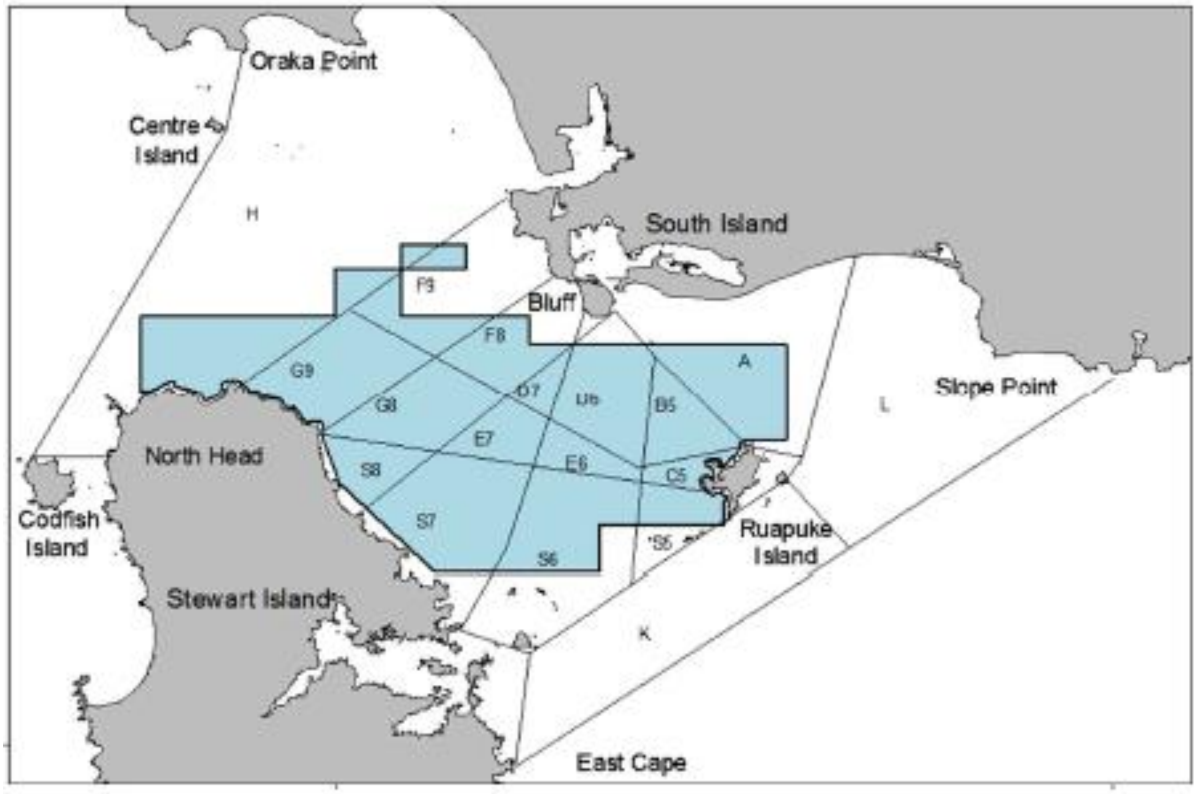

Figure 6. Approximate extent of the Foveaux Strait dredge oyster fishery (2007 stock boundary and oyster fishery statistical reporting areas from Michael [2019]).

Foveaux Strait also supports one of New Zealand's largest blue cod (*Parapercis colias*) fisheries (Annala et al. 2002 in Carbines et al. 2004, Beentjes et al. 2019). Blue cod are commonly found in abundance on mullock reefs (Cranfield et al. 2001) and densities are reported to decline in areas where oyster dredging occurs (Cranfield et al. 2001).

3. SEABED CHARACTERISTICS OF THE PROPOSAL AREA

3.1. Methods for assessing seabed characteristics

Seabed surveys were carried out across the proposal area between October 2018 and July 2019. Data collected during preliminary scoping investigations from the wider survey area (Taylor & Jary 2018; Bennett et al. 2018) are also included in this assessment.

3.1.1. Sonar imagery and bathymetry

Sonar mapping was carried out from the vessel *Takaroa II*. A Lowrance StructureScan HD® system with down and side-scanning sonar (455 kHz and 800 kHz frequencies) was used to map the seabed (Section 3.3). The sonar system was towed at 5–6 knots and had a swathe width of 200 m (100 m either side). Sonar mapping was conducted along predetermined parallel transects running both east to west and north to south throughout the survey area (Figure 7). Sonar imagery was processed using the Reefmaster 2.0 software package to convert the sonar files to geo-referenced .kml files. These were imported into ArcMap where outlines of benthic features (i.e. sand, shell debris, biogenic habitat) were traced to create a coarse map of habitats. This map was used to identify potential farming areas least likely to impact ecologically valuable habitats within the wider survey area.

Depth sounding data were collected concurrently with sonar imagery. Tidally-corrected depth data (using lowest astronomical tide) from all surveys as well as sounding points from LINZ (where available) were processed in ArcMap v10.4.1 to create a bathymetric map (see Section 3.2).

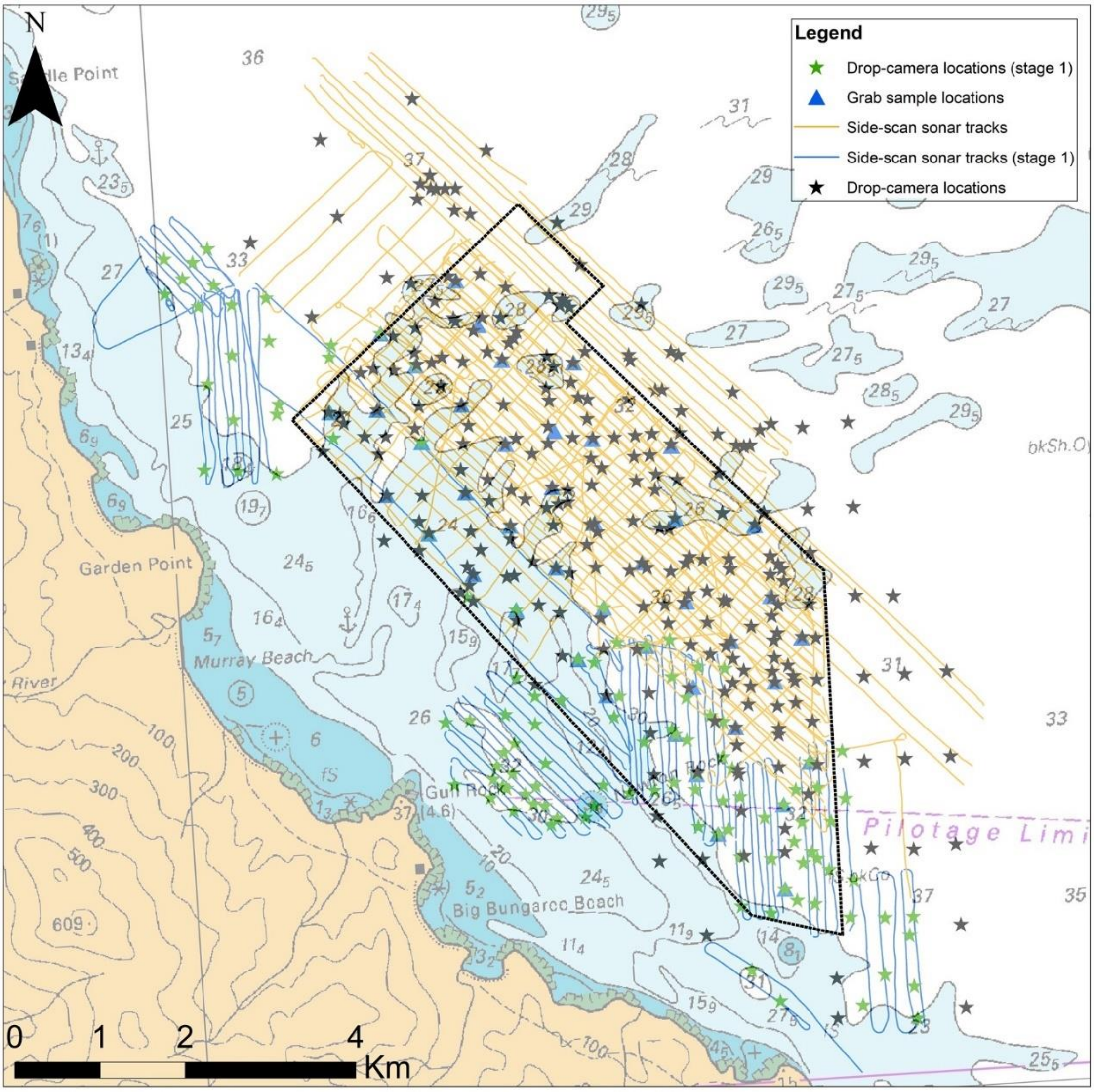

Figure 7. Side-scan sonar transects (including data collected during initial scoping investigations - Stage 1) and the locations of drop-camera and grab sampling stations used to characterise seabed habitats and communities within the Hananui proposal area (black line). Background bathymetry source: Chart No. NZ681 Land Information New Zealand (LINZ) and licensed by LINZ for re-use under the Creative Commons Attribution 4.0 International licence).

3.1.2. Video assessments

Video was used to ground-truth features identified with sonar. A high-definition surface data-feed video (with lights) was deployed at targeted drop-camera sites throughout the survey area (Figure 7). Drop-camera sites were selected to characterise different seabed communities that had been identified through sonar mapping (i.e. differences in texture seen in the sonar image). Additional images were collected in a grid (500 m x 500 m) across the entire survey area to ascertain seabed characteristics (primarily epifaunal[4] communities) not evident in the sonar imaging survey (Figure 7).

At each site, the drop-camera was lowered over the side of the vessel until the seabed was visible. At least 30 seconds of video was captured as the vessel (and camera) drifted down-current. The footage was viewed live on the surface, and notes on habitat type (i.e. sand, biogenic habitat), significant features and conspicuous epifauna were recorded. Video files were later analysed for specific habitat type classifications and identification of epifaunal taxa. Relative abundance scores were assigned for notable taxa, based on qualitative density estimates at each site: absent = not observed; sparse = isolated individuals; patchy = 2–3 individuals in close proximity; moderate = several individuals in close proximity; and abundant = dense aggregations (see Section 3.4.1).

3.1.3. Sediment characterisation

Sediment cores were collected using a van Veen grab sampler at 31[5] sites across the proposal area for determination of physico-chemical properties (Figure 7). Each grab sample was examined for sediment colour, odour and texture. Redox potential (Eh_{NHE}, mV) was measured in triplicate directly from the grab using a probe at a depth of 1 cm. Transparent acrylic corers were used to collect two sediment cores (6.3 cm internal diameter) from each grab sample and photographed. The top 3 cm of sediment cores was retained; one was sent for analysis of organic content (as % ash-free dry weight; AFDW), the other for particle size distribution (using a seven-fraction grain-size analysis). Brief method descriptions for the physical and chemical analyses are provided in Appendix 1.

A separate core (10 cm deep and 113 cm^2 surface area) was collected from each grab to describe the macrofaunal[6] community assemblages. Core contents were sieved to 0.5 mm and preserved in a solution of 95% ethanol and 5% glyoxal. Animals were identified and counted by specialists at the Cawthron taxonomy laboratory. Total abundance and total number of taxa (taxa diversity) were calculated, as well as a range of biotic indices (Appendix 2). Macrofaunal assemblages in each sample were

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[4] Organisms living on the seabed.

[5] Attempts were made to grab sample at 42 sites, however due to the presence of biogenic habitat and / or large shell hash it was not possible to obtain a sample at 11 of these sites.

[6] Macrofauna includes both epifauna (animals living on the sediment surface) and infauna (animals living within the sediment) measuring < 0.5 mm long.

then compared using non-metric multi-dimensional scaling (nMDS) and cluster diagrams based on Bray-Curtis similarities (Clarke & Warwick 1994). Abundance data were fourth-root transformed to de-emphasise the influence of the dominant species. The major taxa contributing to the similarities between samples grouped by area were identified using similarity percentage analysis (SIMPER; Clarke 1993). All multivariate analyses were performed using PRIMER v7 software (Clarke & Gorley 2015).

3.2. Site bathymetry

Bathymetry within the proposal area ranges from 20 to 25 m inshore to up to 40 m offshore (Figure 8). Large sand banks are evident in the bathymetric map, particularly in the north-western end.

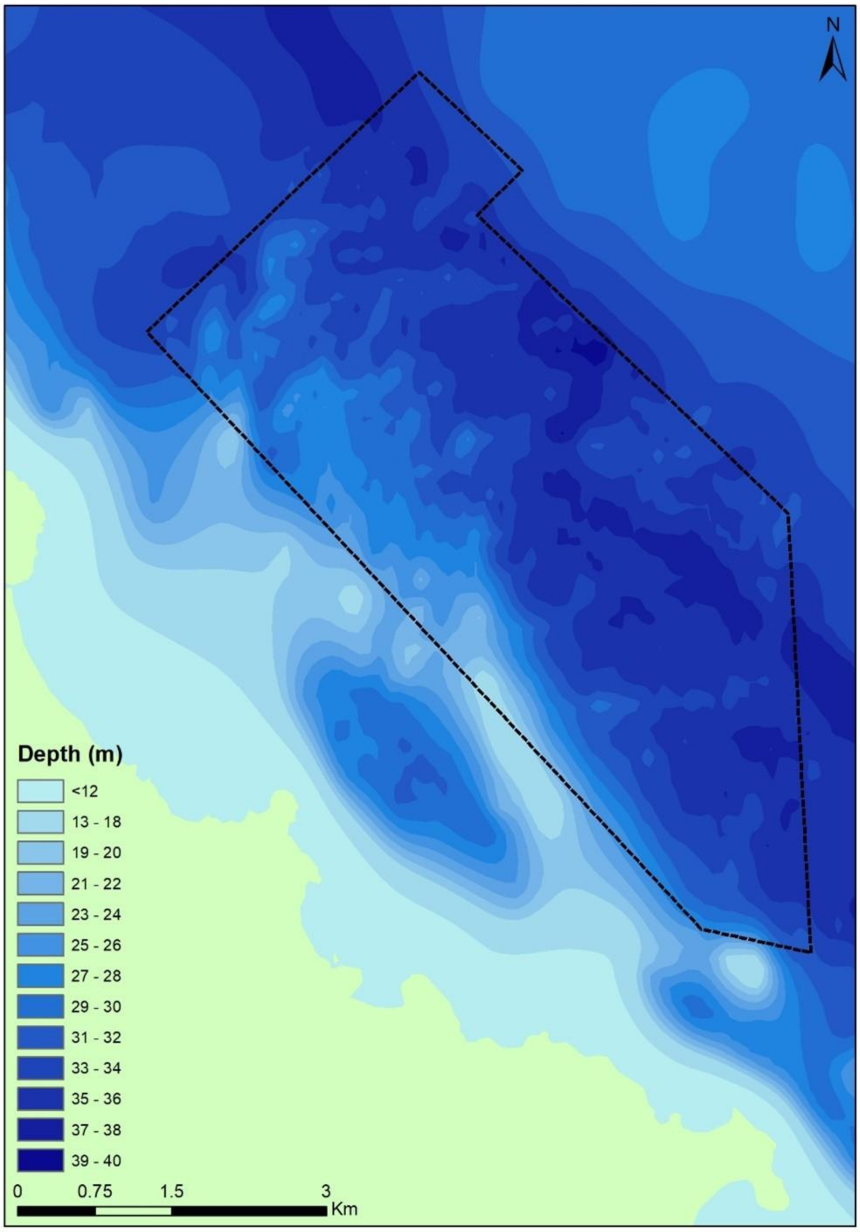

Figure 8. Bathymetric map using data collected during the preliminary scoping investigations and as a part of this assessment, as well as using sounding points from LINZ (where available). Data were processed in ArcMap v10.4.1. Depths are tidally corrected (using lowest astronomical tide). The Hananui proposal area is shown by a black dashed line.

3.3. Sediment physical and chemical properties

Sonar mapping provided high-level detail of seafloor topography and sediment characteristics across the survey area. A mosaic of all sonar data collected is presented in Figure 9. Generally, areas of high-backscatter (i.e. yellow areas in Figure 9) represent hard substrates, as well as areas of coarser-grained sediment and shell hash, while low-backscatter regions (darker areas) represent finer-grained sediments (e.g. mud and fine sand).

There was a high level of backscatter across the whole survey area, suggesting the presence of coarse-grained sediments (coarse sand, shell hash, gravel), rather than mud. Sand wave formations, including ripples, banks and large dunes (Figure 10a), were evident across 76% of the proposal area (68% of the wider survey area). Few other features were observed in the sonar imagery across this substrate type. Video imagery confirmed these areas as regions of ‘sand-dominated’ habitat. Areas of homogenous high-backscatter (Figure 10b) were observed across c. 1% of the proposal area (c. 13% of the wider survey area). These were identified as ‘sand dominated habitat’, but with a high proportion of shell hash, shell debris and / or gravel. Areas of heterogenous backscatter (usually darker mottled patches, Figure 10c) were observed primarily in the north-eastern region of the survey area, with smaller patches in the south and north-west (c. 22% of the proposal area and c. 18% of the total area surveyed). Video surveys identified these as areas of three-dimensional, biogenic habitat, including bushy bryozoan thickets and bryozoan-sponge reefs (see Section 3.4). Substrate type could not be determined from the side-scan sonar imagery within less than 1% of the area.

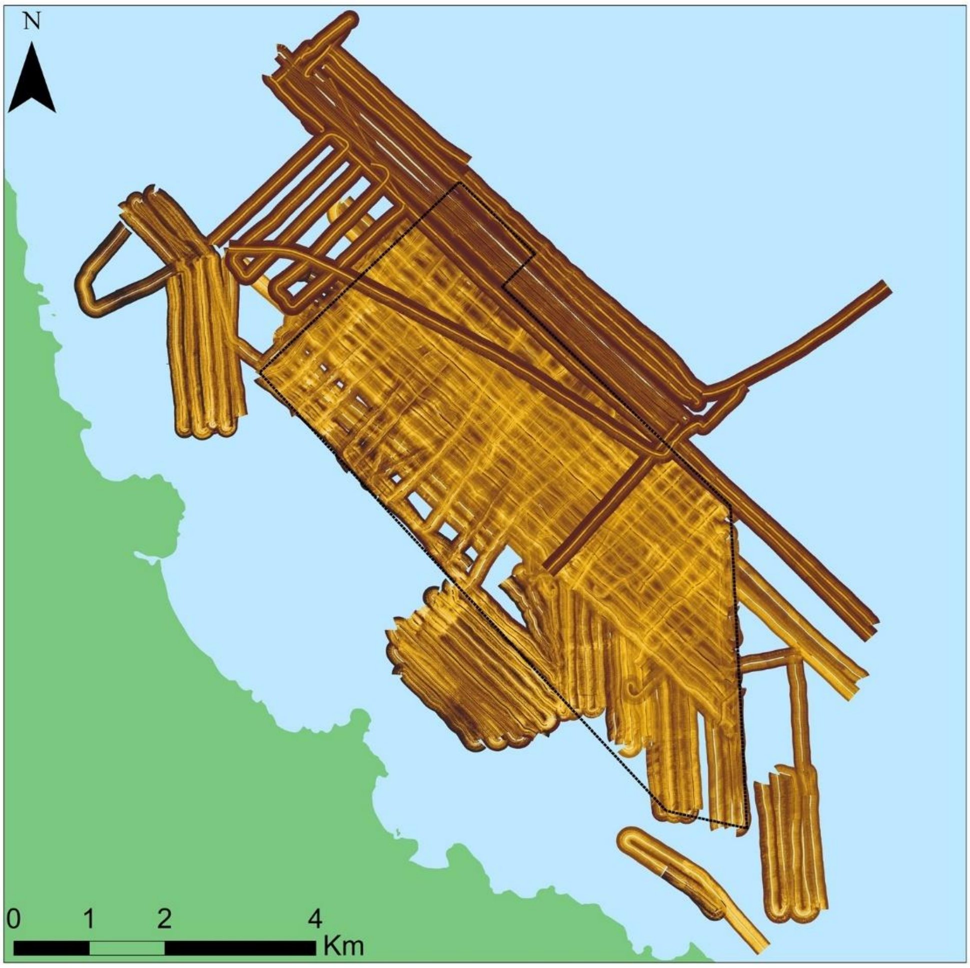

Figure 9. Mosaic of all side-scan sonar data collected across the survey area, to show the extent of coverage. The Hananui proposal area shown by the black line.

Particle grain-size analysis confirmed the results of the side-scan sonar survey. Sites within the proposal area were dominated by sandy sediments with varying amounts of gravel-sized particles (shell hash) and a low proportion of mud. Across the 31 sites sampled[7], the proportion of sand in the sediment ranged from 24.8 to 96.6% per sample, gravel-sized particles made up between < 0.1 to 72.2%, and mud made up between 2.7 to 9.4% (Figure 11). Organic-matter content was low across the proposal area (from 0.76 to 3.1% of sediment weight). Areas with a high proportion of sand tended to have a lower organic content than samples with a comparatively higher proportion of gravel-sized particles.

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[7] Sediment could not be sampled from regions of biogenic substrates or where shell debris content was high (see Figure 11 for attempted versus successful grabs).

Redox potential was high across all sites (average 382 Eh_{NHE}, mV) with little variability (range 321 to 423 Eh_{NHE}, mV), demonstrating well oxygenated sediments[8]. Full results of sediment grain-size fraction and sediment analyses are provided in Appendix 3.

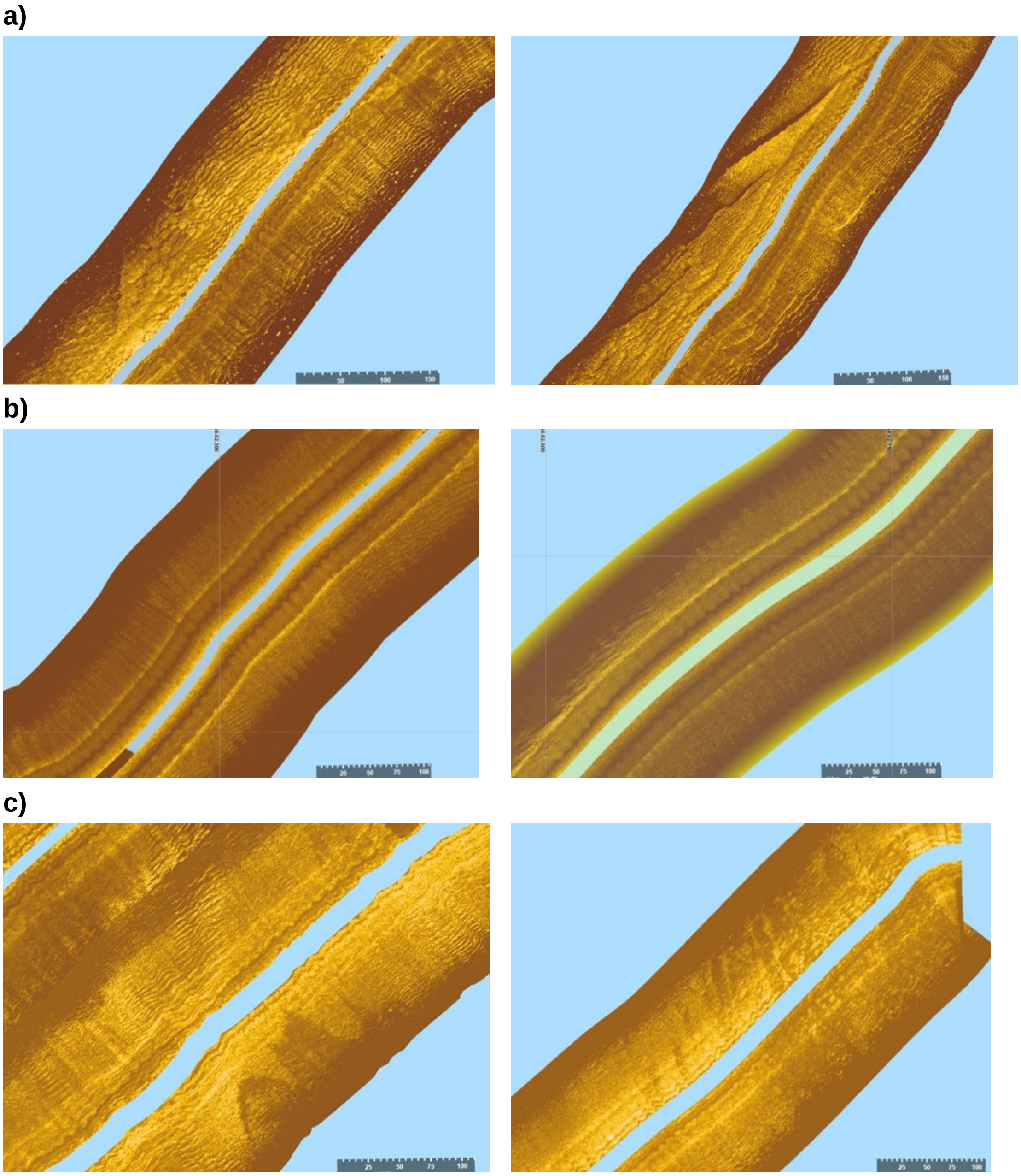

Figure 10. Types of backscatter observed in side-scan sonar imagery include: **a)** wave formations including ripples, banks and dunes characteristic of sand-dominated habitat; **b)** areas of homogenous high-backscatter characteristic of sand-dominated habitat with a high proportion of shell hash, shell debris and / or gravel; and **c)** areas of heterogenous backscatter (dark mottled patches) characteristic of three-dimensional, biogenic substrates.

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[8] High redox potential is associated with oxygen availability in the environment, because O_2 is an electron acceptor in oxidation-reduction reactions (transfer of electrons between molecules) used by microbes to decompose organic matter.

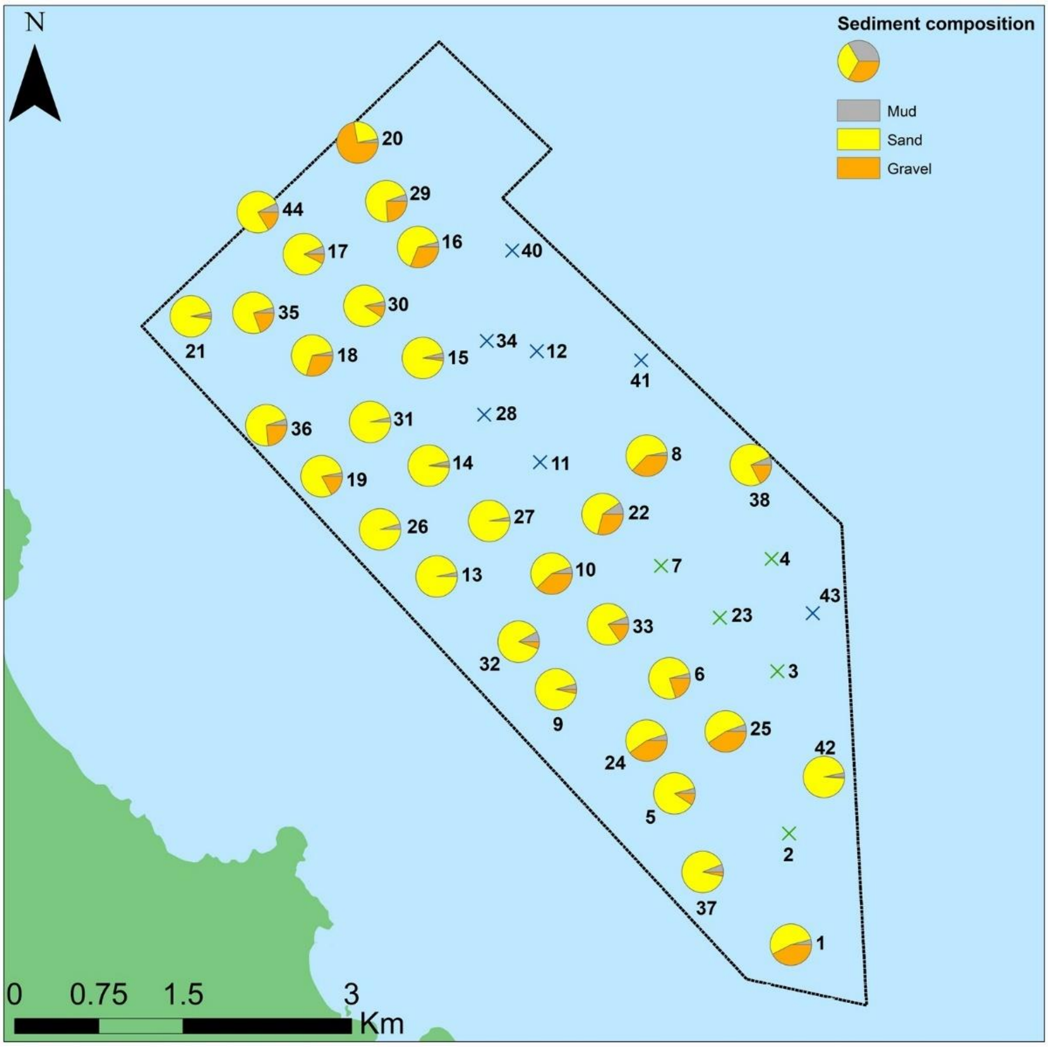

Figure 11. Sediment composition across the 31 grab sampling sites within the Hananui proposal area (black line). Sediment was unable to be sampled from regions of biogenic substrates or where shell debris content was high. Unsuccessful grabs indicated by ‘X’. Green X = biogenic habitat, blue X = shell debris.

3.4. Seabed communities

Video surveys were used to validate types of substrate and features identified in the side-scan sonar imaging survey. Video was also used to identify seabed characteristics (primarily epifaunal communities) not evident in the sonar imaging survey. Based on these methods, three main seabed habitat types were observed within the proposal area:

- *Sand with shell hash*

  Approximately 77% of the proposal area is estimated to be sand dominated, with varying amounts of shell hash, whole shell debris, gravel and isolated biogenic clumps. Sand ripples, waves and large sand banks were frequently observed across this habitat type. Sand habitats had relatively sparse epifaunal assemblages. Patches of biogenic structure were occasionally observed, mainly bushy bryozoans. Occasionally, blue cod (*Parapercis colias*) and leather jacket (*Parika scaber*) were seen and one triplefin was observed.

- *Bushy bryozoan thickets*

  Areas of abundant bushy bryozoans (likely to be *Orthoscuticella innominata*) were observed on sandy substrates with varying amounts of shell hash. The bryozoans were usually interspersed with calcareous tubeworms (likely *Galeolaria hystrix*), forming bushy bryozoan thickets. Bushy bryozoan thickets are estimated to cover c. 5% of the proposal area but vary in density from patchy (approximately 5% cover) to abundant (up to 80% cover). This habitat type has high epifaunal diversity and frequently provides habitat for taxa of ecological significance such as erect bryozoans and sponges, brachiopods and large bivalve species (see Section 3.4.1). Moderate to abundant fish included blue cod, leather jacket and tarakihi (*Nemadactylus macropterus*).

- *Bryozoan-sponge reefs*

  Bryozoan-sponge reefs are biodiverse habitats created by assemblages of erect and encrusting bryozoans, sponges and tubeworms. This habitat type is commonly referred to as ‘mullock’. Bryozoan-sponge reefs are estimated to cover c. 17% of the proposal area. Cover of the habitat-forming species ranged from ‘patchy’ (clumps of bryozoans and sponges with large areas of exposed sand and / or coarse sediments, i.e. gravel, shell and cobble) to areas where biogenic reef dominates the seabed. The most abundant reef-forming bryozoans seen were the massive encrusting *Celleporaria agglutinans* and erect branching *Cinctipora elegans*. Sponges commonly observed within bryozoan-sponge reefs included *Dactylia varia*, *Iophon minor*, and *Crella incrustans*. Bryozoan-sponge reefs have high epifaunal diversity and provide habitat for a number of taxa of ecological significance (see Section 3.4.1). Moderate to abundant fish included blue cod, leather jacket and tarakihi.

The conspicuous biota common among all habitat types (although varying in abundance) were the brittle star *Ophiopsammus maculata* and blue cod. Areas of bushy-bryozoan thickets and bryozoan-sponge reefs had significantly higher biodiversity than sand-dominated areas.

Some taxa were observed in all habitat types, including brachiopods (likely either *Neothyris lenticularis* or *Magasella sanguinea*) and large bivalve species such as dredge oysters (*Ostrea chilensis*), scallops (*Pecten novaezelandiae*), dog cockles (likely *Tucetona laticostata*) and bearded horse mussels (*Modiolus areolatus*). Abundances of these taxa were generally greater within bushy bryozoan thickets or bryozoan-sponge reefs than in sandy areas.

Drift algae were the only conspicuous plant life observed within the proposal area.

Habitat types and extent were assigned across the entire survey area based on substrate characteristics from sonar imagery and drop-camera footage (Figure 12, Figure 13). Habitat type was unable to be assigned (referred to as unknown) for less than 1% of the survey area. This habitat map is indicative only, given the size of the area and the low relative coverage of video validation. A full summary of conspicuous biota observed within each habitat type is provided in Table 1.

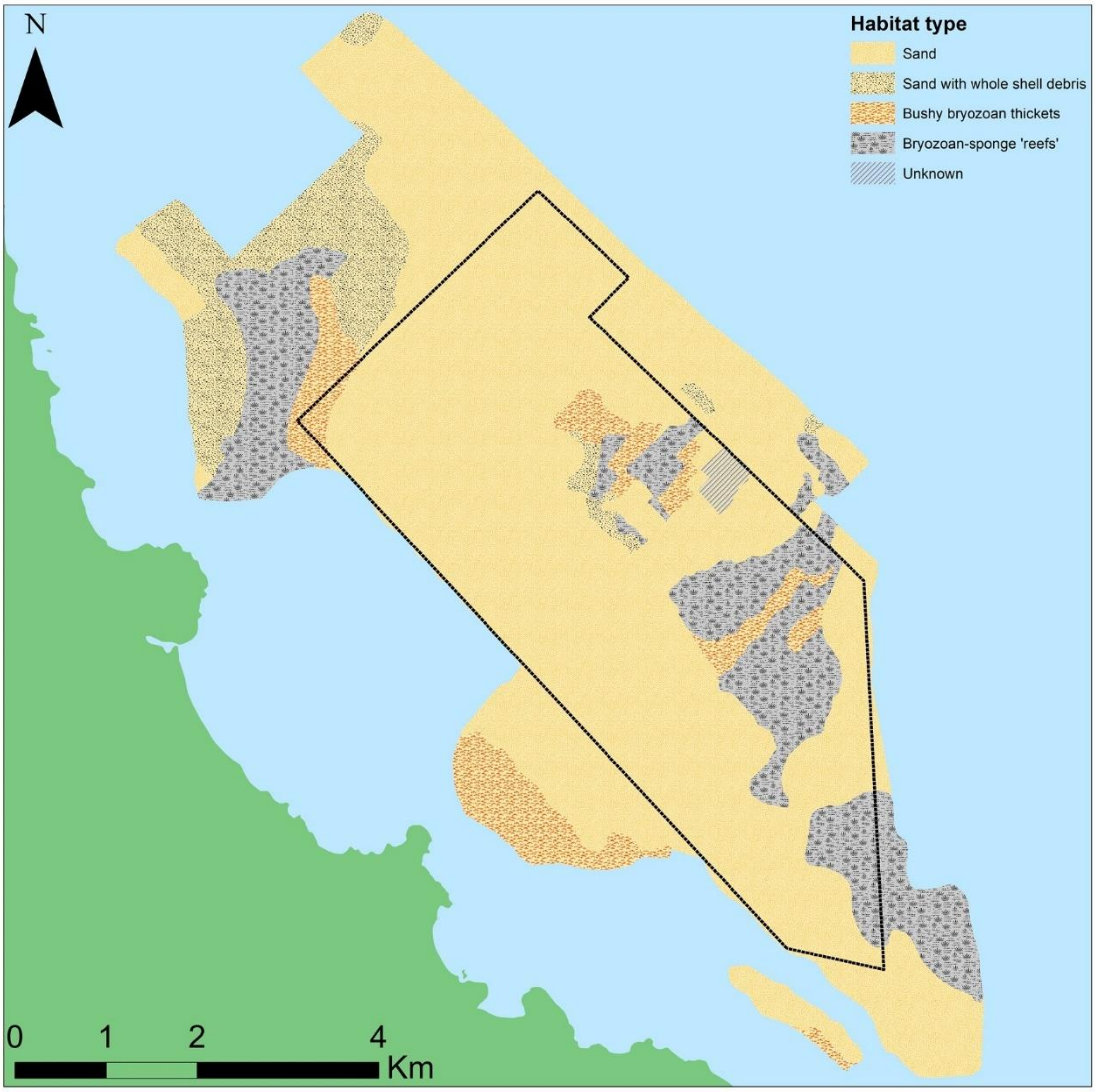

Figure 12. Coarse map of habitats showing the predicted extent of broad habitat in areas surveyed during this assessment and preliminary scoping investigations. Black outline = the Hananui proposal area. 'Unknown' refers to areas where habitat type could not be determined from the surveys.

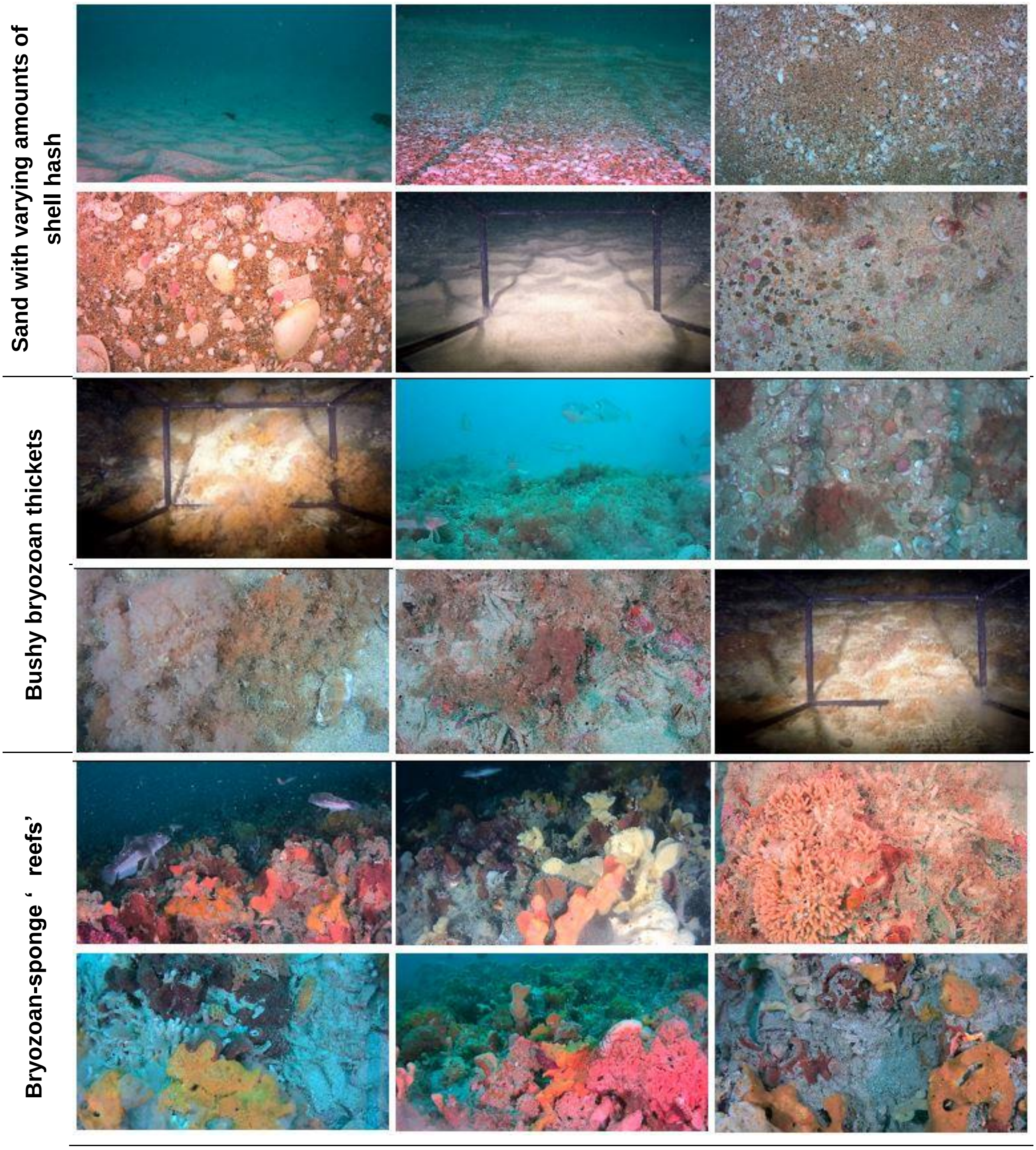

Figure 13. Example images of seabed habitats observed within the survey area.

Table 1. Conspicuous biota observed within each habitat type across the survey area.

Habitat type	Conspicuous benthic biota	Fish species
Sand with shell hash Sand (sand wave forms, with varying amounts of shell and gravel. In places, > 30% cover of large empty bivalve shells)	Brittle stars (mostly *Ophiopsammus maculata*). Some red and brown drift algae. Occasional tufts of bushy bryozoans and feather hydroids. Isolated encrusting bryozoans, sponges, ascidians (e.g. sea tulip, *Pyura pachydermatina*), sea cucumbers (*Australostichopus mollis*), 11-armed sea stars (*Coscinasterias muricata*) and cushion stars (*Patiriella regularis*). Occasional gastropods including saw shells (*Astraea heliotropium*) and turret shells (*Maoricolpus roseus*), brachiopods (likely *Neothyris lenticularis* or *Magasella sanguinea*), and large bivalve species including the dredge oyster (*Ostrea chilensis*), scallops (*Pecten novaezelandiae*), dog cockles (likely *Tucetona laticostata*), bearded horse mussel (*Modiolus areolatus*), tuatua (*Paphies subtriangulata*) and *Oxyperas elongatum.*	Blue cod (*Parapercis colias*), leather jacket (*Parika scaber*), triplefin
Bushy bryozoan thickets Clown-hair bryozoans with tubeworms (in places, > 30% cover of large empty bivalve shells)	Areas of abundant bushy bryozoans (*Orthoscuticella innominata*). Calcareous tube-worms (likely *Galeolaria hystrix*), often in mounds. In places a moderate abundance of small erect bryozoans (mainly *Cinctipora elegans*) and sponges. A moderate number of feather hydroids. Sparse foliose red algae. Some red and brown drift algae. Occasional individual or small patches of large bivalves including dredge oysters (sparse to patchy), scallops (sparse), bearded horse mussels (sparse) and dog cockles (sparse to abundant). Occasional patches of brachiopods. Occasional kina (*Evechinus chloroticus*), sea tulips, sea cucumbers. Gastropods, including saw shells. Occasional brittle stars, cushion stars and 11-armed sea stars.	Blue cod (*P. colias*), leather jacket (*P. scaber*), tarakihi (*Nemadactylus macropterus*)
Bryozoan-sponge 'reefs' AKA 'mullock' (in places, > 30% cover of large empty bivalve shells)	Biogenic clumps formed by the massive encrusting bryozoan *Celleporaria agglutinans* and erect bryozoan *C. elegans*. A number of other erect and encrusting species of bryozoan including fragile lacy forms such as *Hornera foliacea* and possibly *Hornera robusta.* Abundant encrusting and erect sponges (including *Dactylia varia, Iophon minor, Crella incrustans*). Colonial ascidians (including *Botrylloides* sp., *Botryllus* sp. and *Eudistoma circumvallatum*). Calcareous tubeworms (as above, likely *Galeolaria hystrix*). Moderate abundance of bushy bryozoan and feather hydroids. Sparse foliose and encrusting red algae. Occasional individual or small patches of large bivalves including dredge oysters (sparse to patchy), scallops (sparse), bearded horse mussels (sparse) and dog cockles (sparse to abundant). Occasional patches of brachiopods. Patches of sea anemones (*Anthothoe albocincta*) in some areas. Occasional kina, sea tulips, sea cucumbers, brittle stars, cushion stars, 11-armed sea stars and gastropods including saw shells.	Blue cod (*P. colias*), leather jacket (*P. scaber*), tarakihi (*N. macropterus*)

3.4.1. Sensitive taxa

Several taxa or groups of taxa were identified within the surveyed area that are of particular ecological significance and are known to be sensitive to anthropogenic impacts. These taxa include bryozoans, sponges, calcareous tubeworms, brachiopods, and several large bivalve taxa (scallops, dredge oysters, horse mussels and dog cockles). A description of each taxon or group, where they were found, and associated densities, is provided below. Reference images are provided in Figure 14.

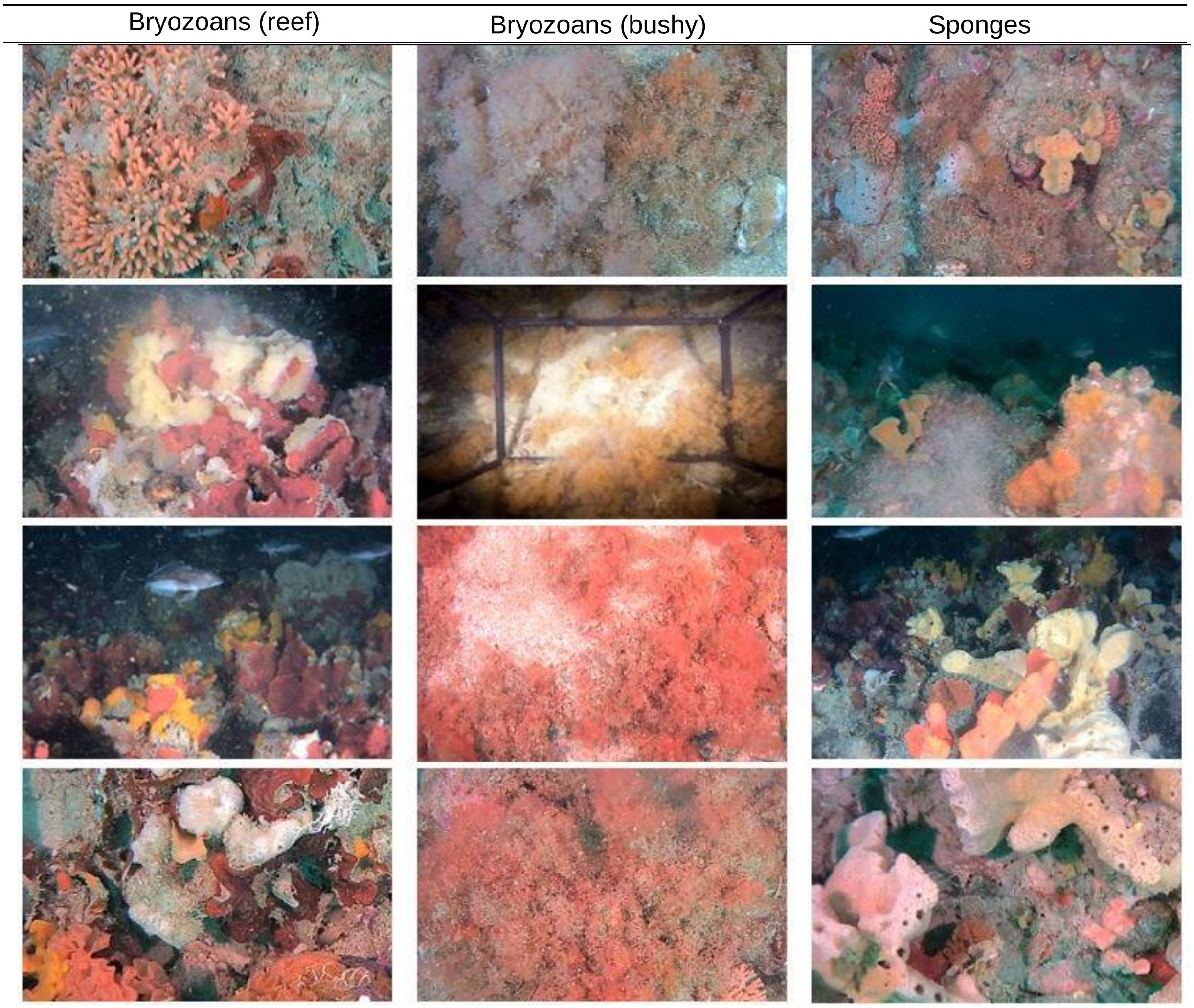

Figure 14. Example images of sensitive taxa identified within the surveyed area that are of ecological significance.

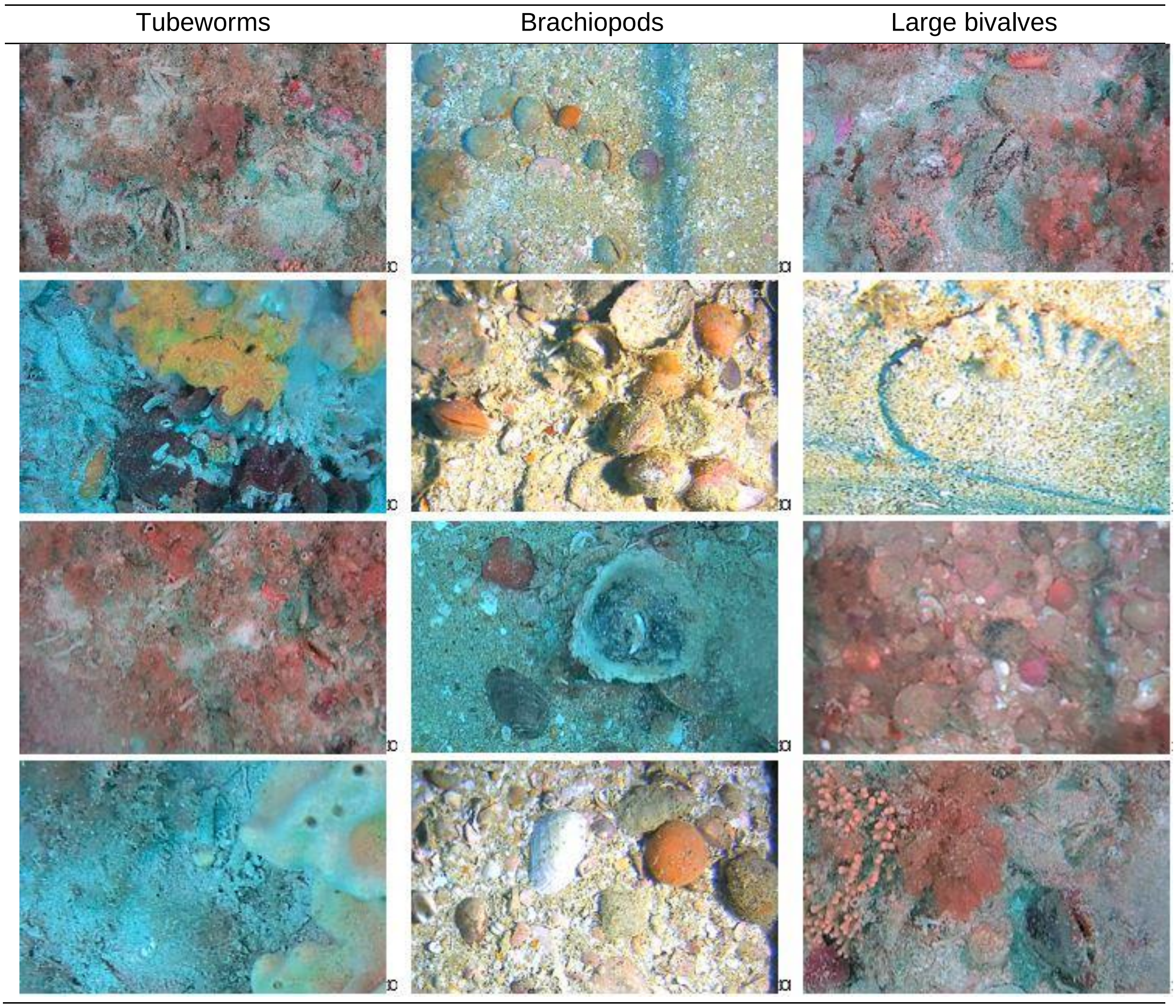

Figure 14, continued.

Bryozoans

Bryozoans provide habitat for a multitude of organisms, supporting local biodiversity (Wood 2005; MacDiarmid et al. 2013). Bryozoans of various forms were abundant in areas of biogenic habitat (Figure 15). Of ecological significance was the presence of reef-building bryozoans such as the massive encrusting *Celleporaria agglutinans* and erect branching *Cinctipora elegans. Celleporaria agglutinans*, thought to be one of the most important bryozoan species in New Zealand waters (Bradstock & Gordon 1983), was particularly abundant. *Celleporaria agglutinans* has a stony calcium carbonate skeleton that forms extensive mounds and, together with various sponges, they create the complex, three-dimensional bryozoan-sponge reefs. Bushy ‘clown-hair’ bryozoans (*Orthoscuticella innominata*) were also abundant (Figure 16), forming thickets in areas and creating habitat for a myriad of organisms, including small *C. elegans*.

Ecological significance

Bryozoan beds, or thickets, are considered ‘significant’ if large frame-building bryozoans (> 50 mm in 3D) are greater than 4% mean cover over large areas (tens to hundreds of km^2) or dominate the seabed in small areas (> 50% on a scale of m^2) (MacDiarmid et al. 2013). Average reef-forming bryozoan cover was approximately 30% across the video footage and in places reef-forming bryozoan cover was estimated to be greater than 50% (i.e. where abundant cover was observed, Figure 15). Based on these descriptions, the bryozoan communities within the survey area are significant.

Coverage of the bushy clown-hair bryozoan was estimated to be up to 80% where it formed thickets (c. 22% coverage on average where it occurred). While bushy clown-hair bryozoans are not listed as ‘significant’, we consider that this is a valuable habitat that warrants protection from potentially adverse human activity.

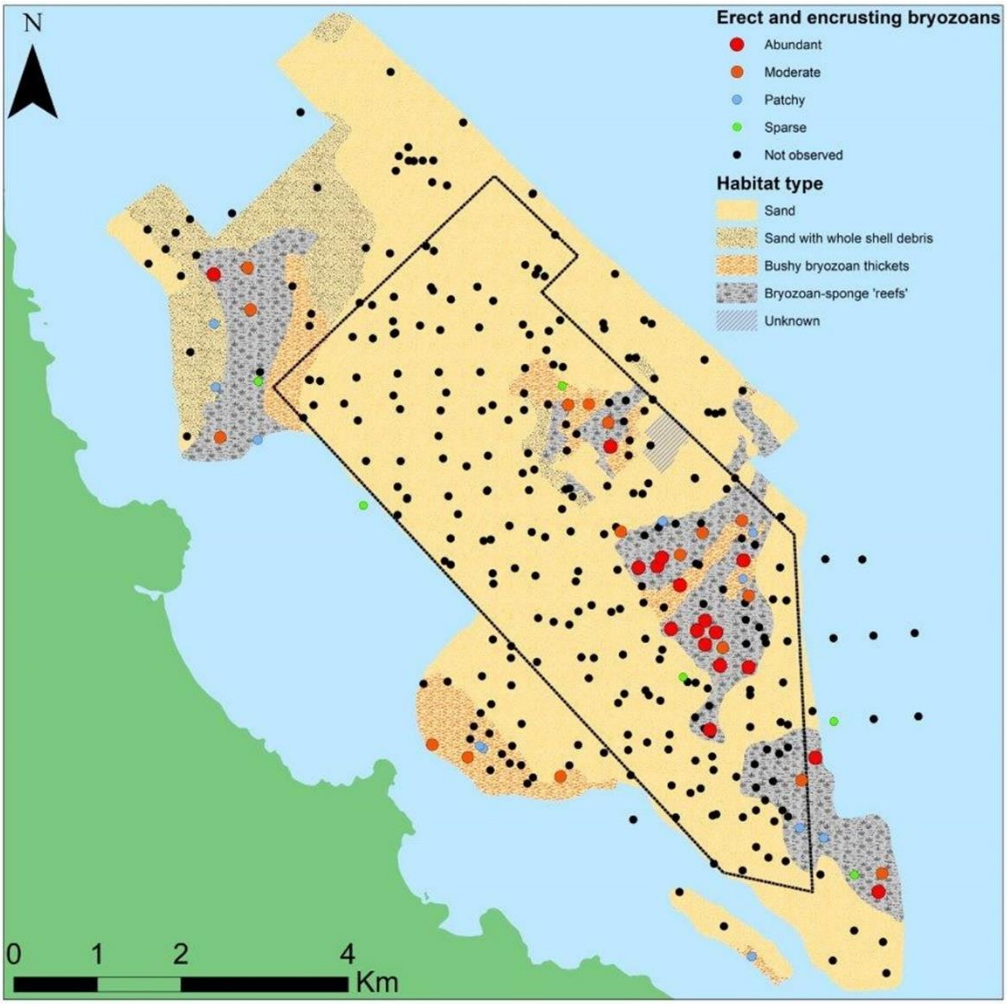

Figure 15. Abundance of erect and encrusting bryozoans observed at drop-camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 2–3 individuals in close proximity, moderate = 10 to 40% coverage, abundant = > 50% coverage.

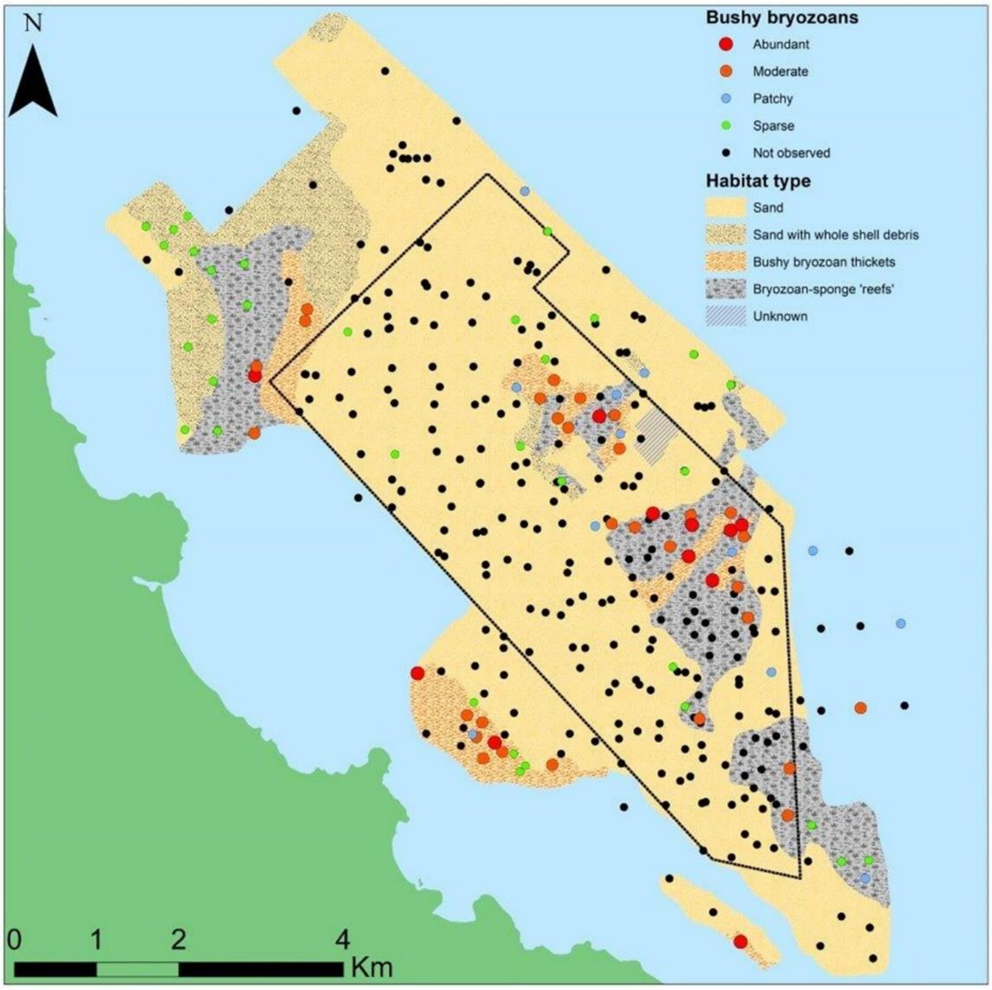

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Figure 16. Abundance of bushy bryozoans observed at drop camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 2–3 individuals in close proximity, moderate = 10 to 40% coverage, abundant = > 50% coverage.

Sponges

Sponges fulfil many important functional roles in benthic ecosystems including providing habitat, stabilising substrate, and facilitating nutrient-cycling processes (Bell 2008). Aggregations of erect and encrusting sponges were commonly associated with reef-forming bryozoans. The most abundant (and conspicuous) sponges observed were tentatively identified as *Dactylia varia*, *Iophon minor* and *Crella incrustans*.

Ecological significance

A sponge garden may be defined as 25% or greater cover of one or more species in either uniform or clumped distribution over an area of 100 m^2 or more (MacDiarmid et al. 2013). Based on this description, sponge communities within the survey area are significant (c. 28% coverage on average where they occurred, Figure 17).

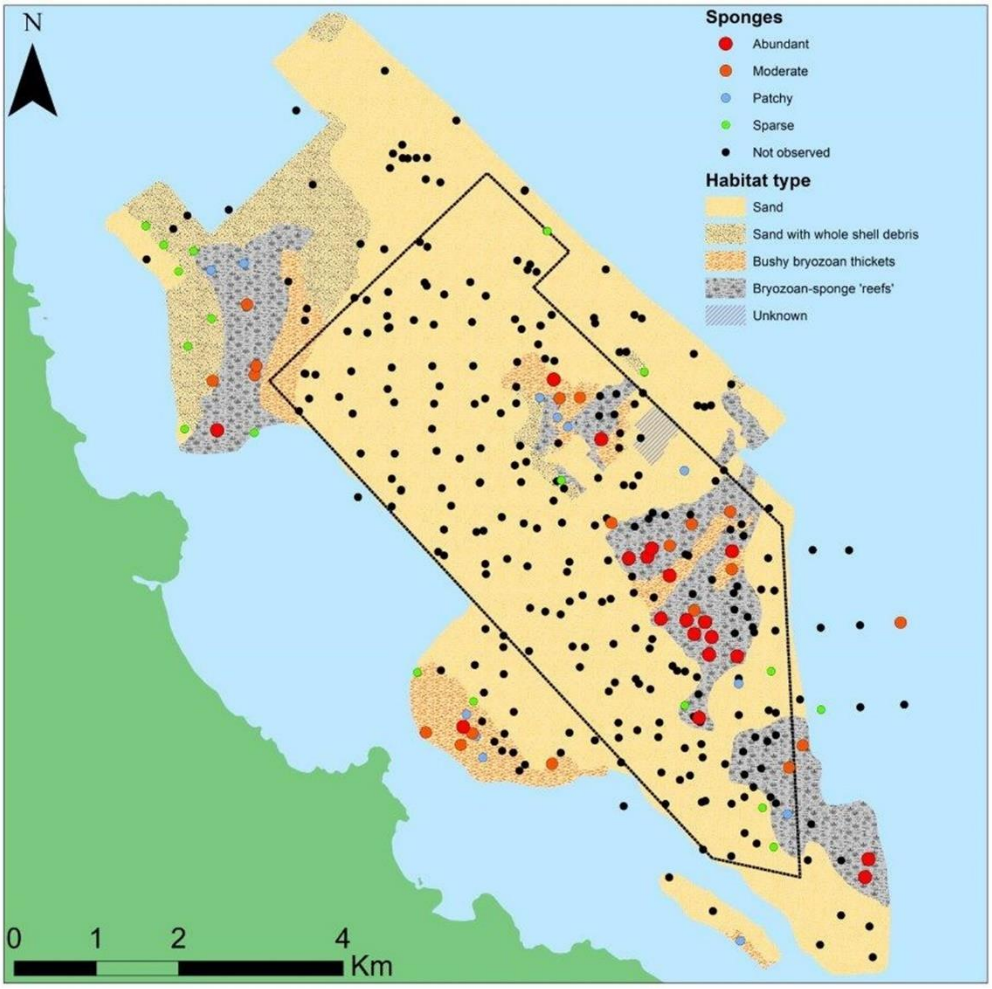

Figure 17. Abundance of sponges observed at drop camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 2–3 individuals in close proximity, moderate = 10 to 40% coverage, abundant = > 40% coverage.

Tubeworms

Worm species in the family Serpulidae secrete tubes of calcium carbonate and grow as either individuals or in colonies (Anderson et al. 2019). Tubeworms provide three-dimensional habitat for a variety of organisms, resulting in biodiversity hotspots (MacDiarmid et al. 2013). Clumps of worm tubes were observed in areas of biogenic habitat (bushy bryozoan thickets and bryozoan-sponge reefs); these are likely the serpulid *Galeolaria hystrix*, although only the tubes (not the inhabitants) were seen.

Ecological significance

A tubeworm mound is defined as a raised reef-like structure 1 to 100 m in diameter, while a thicket is present where one or more mounds occur or intertwined tubes account for over 10% of the seabed (MacDiarmid et al. 2013; Anderson et al. 2019). Where present, tubeworm abundance ranged from patchy (a few tubes present in video footage) to abundant (present in > 60% of area covered in video footage, Figure 18). While rarely mound forming, we consider tubeworm abundance to be of ecological significance where observed in moderate to abundant cover.

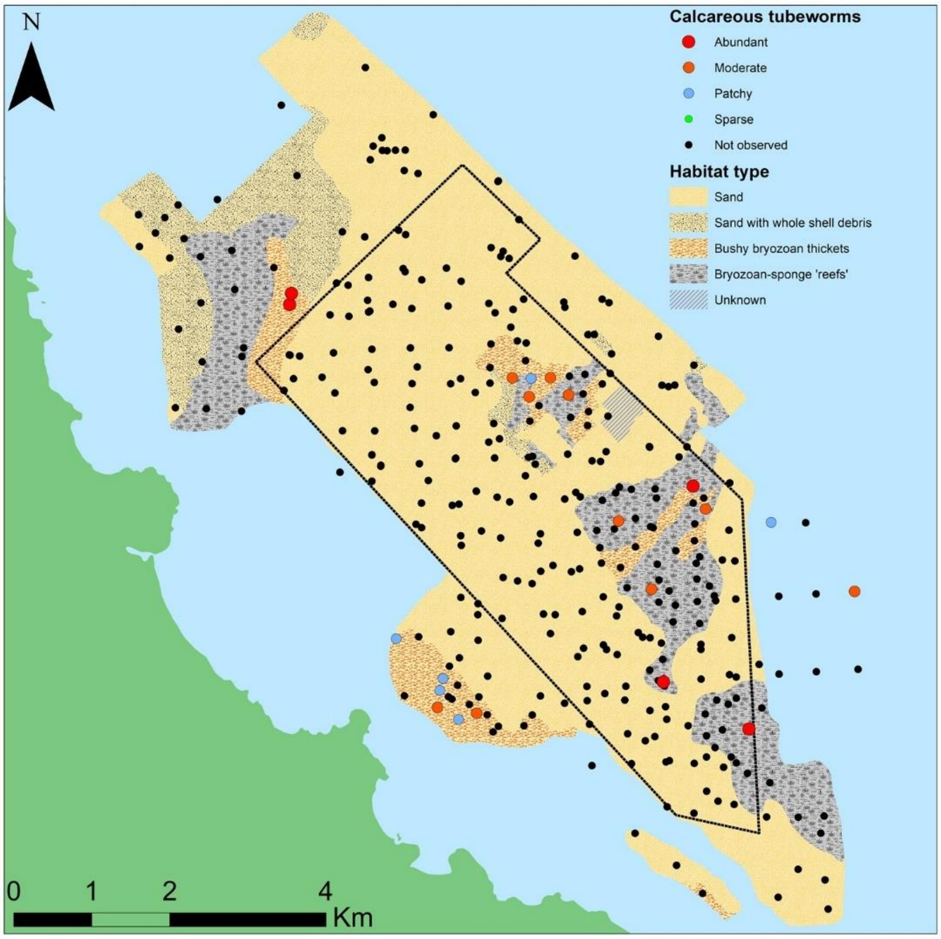

Figure 18. Abundance of calcareous tubeworms observed at drop camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 2–3 individuals in close proximity, moderate = observed in 10 to 20% of video footage, abundant = dense aggregations (observed in > 20% of video footage).

Brachiopods

Brachiopods, or lamp shells, superficially resemble bivalve molluscs but are part of an ancient phylum that has been largely unchanged for 500 million years—therefore of scientific, in addition to conservation, importance (MacDiarmid et al. 2013). Dense, stable beds of brachiopods are important contributors to benthic ecosystems and support a variety of organisms (Morrison et al. 2014). Brachiopods were most commonly associated with areas of biogenic habitat (bryozoan thickets and bryozoan-sponge reefs, Figure 19). The most common brachiopods in the videos were orange to pink. Two species fitting this description (*Neothyris lenticularis* and *Magasella sanguinea*) are known to be common in the Stewart Island region.

Ecological significance

A brachiopod bed is defined as significant if one or more specimens occur per m^2 of sampling (MacDiarmid et al. 2013). Brachiopod densities ranged from sparse (isolated individuals) to abundant (dense aggregations, at two sites only), although rarely were more than 5 observed at one site. While not dense enough to be defined as ‘significant’ by MacDiarmid et al. (2013), where abundance is moderate to abundant, we consider brachiopods warrant protection from potentially adverse activity.

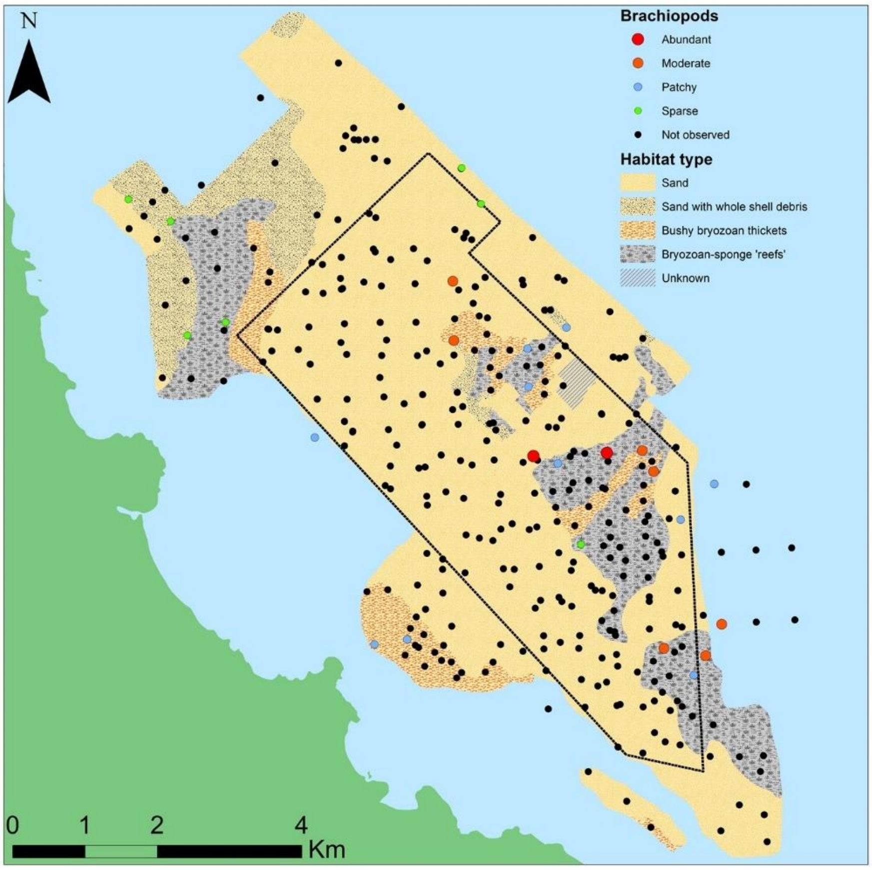

Figure 19. Abundance of brachiopods observed at drop camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 2–3 individuals in close proximity, moderate = several individuals in close proximity, abundant = dense aggregations.

Large bivalves

Large bivalve species are an important part of coastal and shelf ecosystems in New Zealand (Anderson et al. 2019). Bivalves fulfil a variety of functional roles integral to ecosystem functioning (MacDiarmid et al. 2013; Anderson et al. 2019). Bivalves are considered ecosystem engineers, both as living animals and shells of dead bivalves create habitat (including settlement substrates for oyster larvae, Cranfield et al. 2004) and increase complexity in what might otherwise be unsuitable habitat for a variety of organisms (MacDiarmid et al. 2013; Fletcher 2015; Anderson et al. 2019). Bivalves influence water quality through the process of filter feeding (Rothschild et al. 1994), act as a food source for predators (Cranfield et al. 2004), process nutrients (Hewitt et al. 2006), and fix carbon and provide nutrients through suspension-feeding and the production of pseudofaeces (Hewitt & Pilditch 2004). Many large bivalve species are also commercially important and are culturally important kaimoana.

Several types of large bivalve species were identified within the survey area. These include dredge oysters[9] (*Ostrea chilensis*), scallops (*Pecten novaezelandiae*), dog cockles (likely *Tucetona laticostata*) and bearded horse mussels (*Modiolus areolatus*). These bivalve species were observed in all habitat types; however, abundances were generally greater within bushy bryozoan thickets or bryozoan-sponge reefs. Further to this, recent dredge surveys undertaken throughout the proposal area by Michael (2019) confirm, at least for oysters, that distributions are patchy and abundances low within sand-dominated areas (oysters were either absent or found in low densities).

Ecological significance

The definition of a ‘significant’ large bivalve bed or community is 30% or higher coverage of both living and dead specimens covering 100 m^2 or more (MacDiarmid et al. 2013). With the exception of dog cockle abundance in four sites, cover of live large bivalve specimens within the survey area was rarely greater than 30% (Figure 20, Figure 21, Figure 22, Figure 23). However, in some areas, the percentage cover of empty large bivalve shells (predominantly oyster shells) was greater than 30% (Figure 24) so in these areas, we consider habitat formed by oysters to be significant.

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[9] Although we note that it is difficult to distinguish live oysters from oyster shell in video footage.

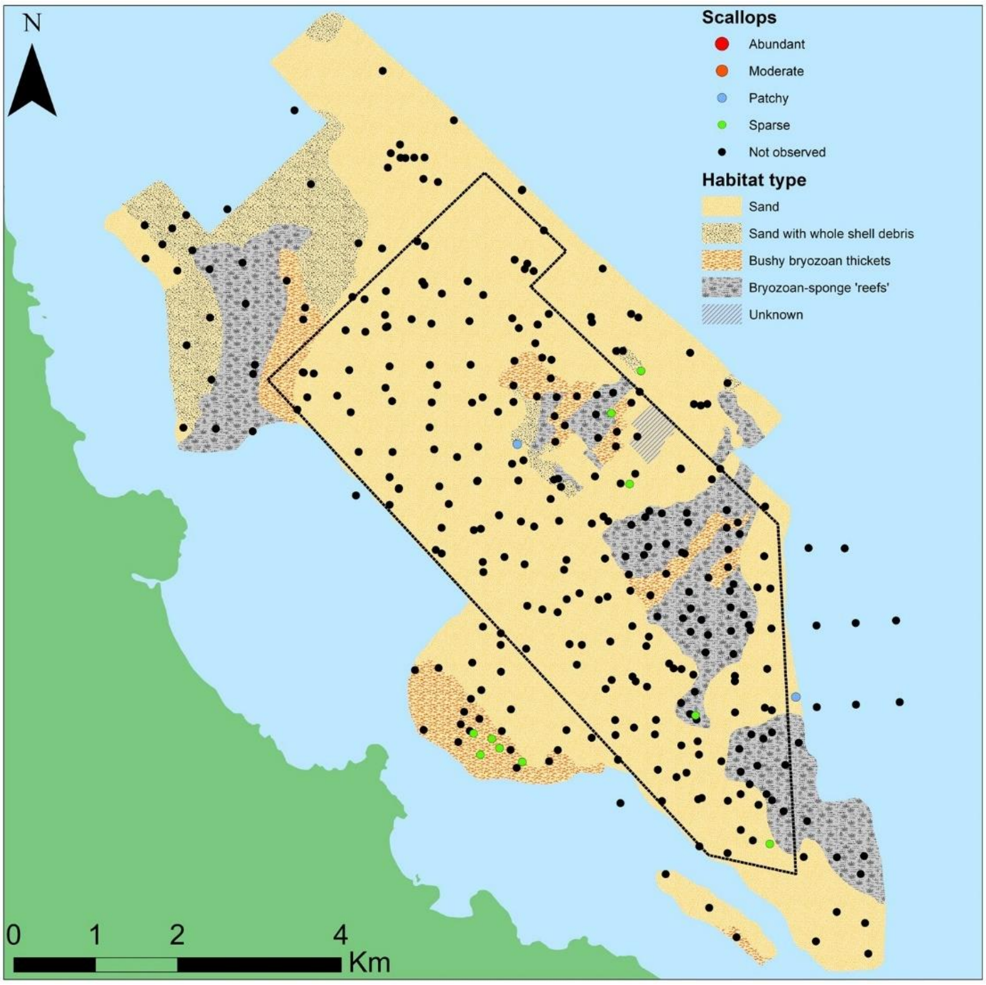

Figure 20. Abundance of scallops observed at drop camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 2–3 individuals in close proximity, moderate = several individuals in close proximity, abundant = dense aggregations.

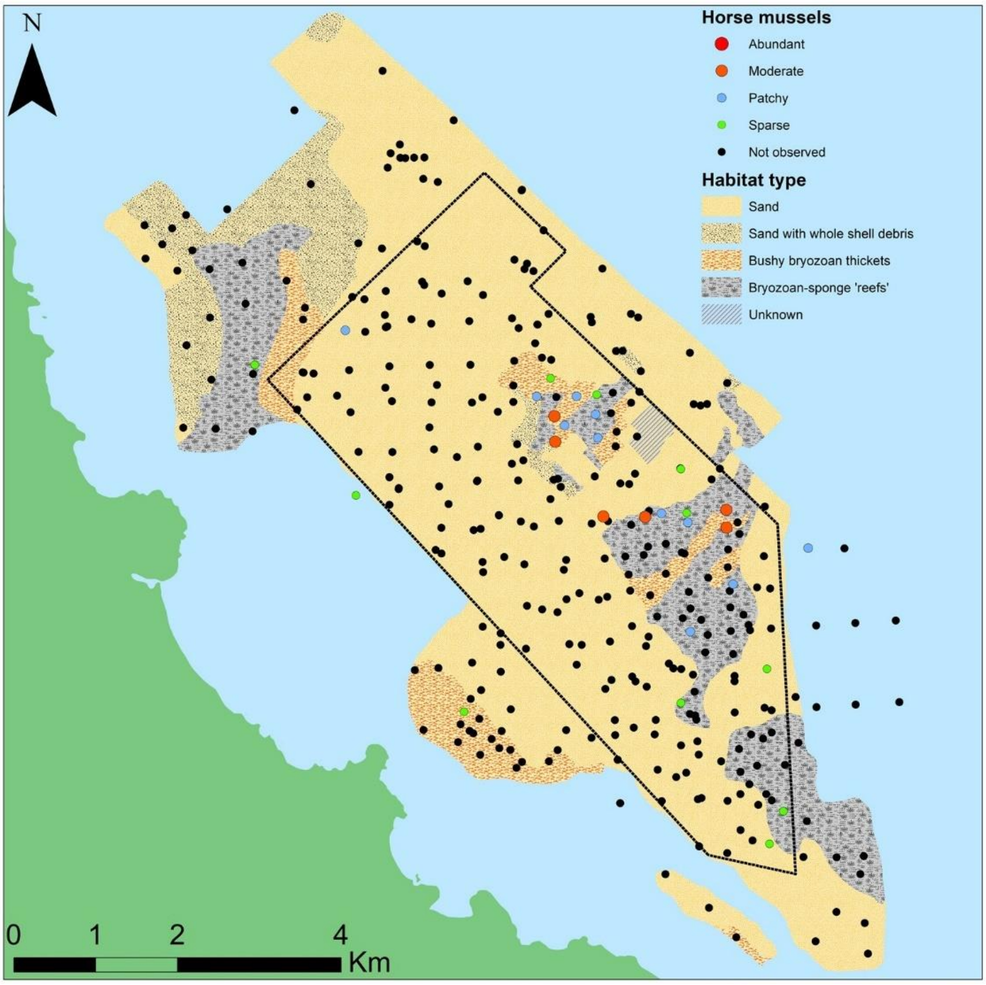

Figure 21. Abundance of bearded horse mussels (*Modiolus areolatus*) observed at drop camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 2–3 individuals in close proximity, moderate = several individuals in close proximity, abundant = dense aggregations.

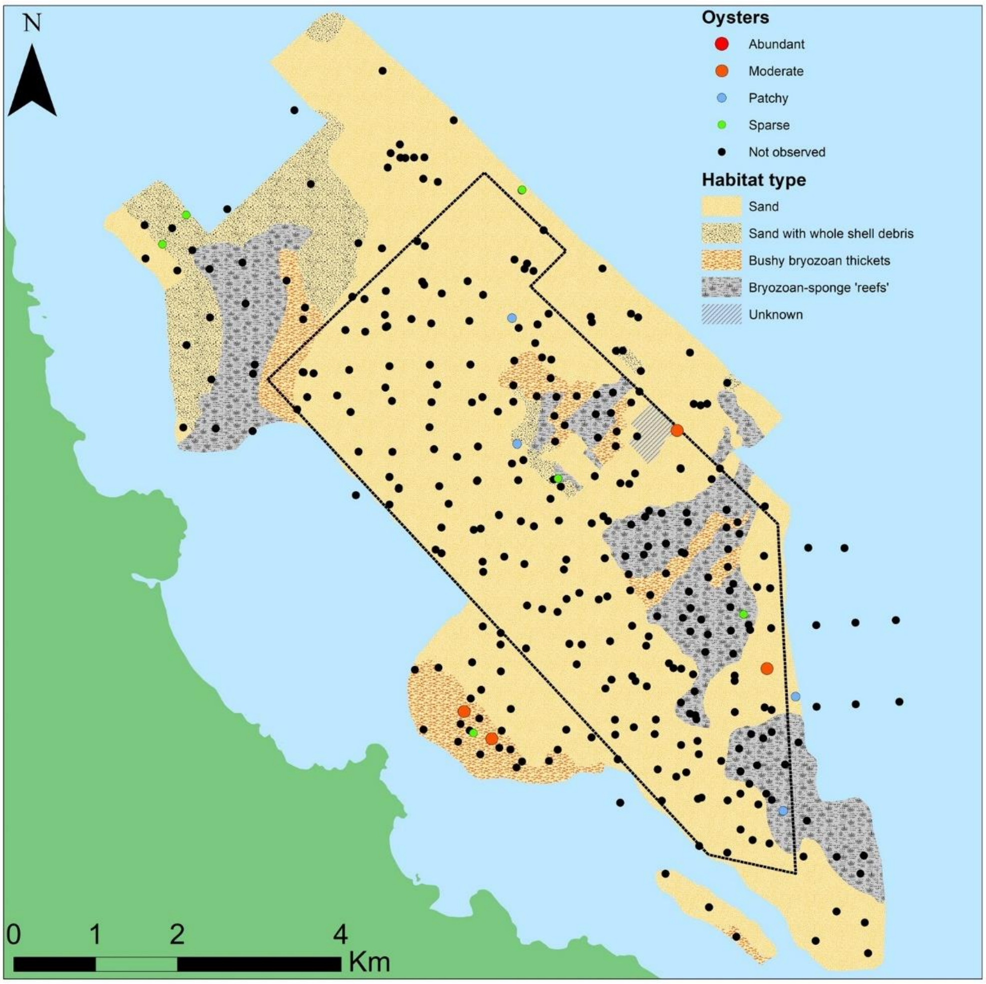

Figure 22. Abundance of dredge oysters observed at drop camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 2–3 individuals in close proximity, moderate = several individuals in close proximity, abundant = dense aggregations. Note that it is difficult to distinguish live oysters from oyster shell in video footage.

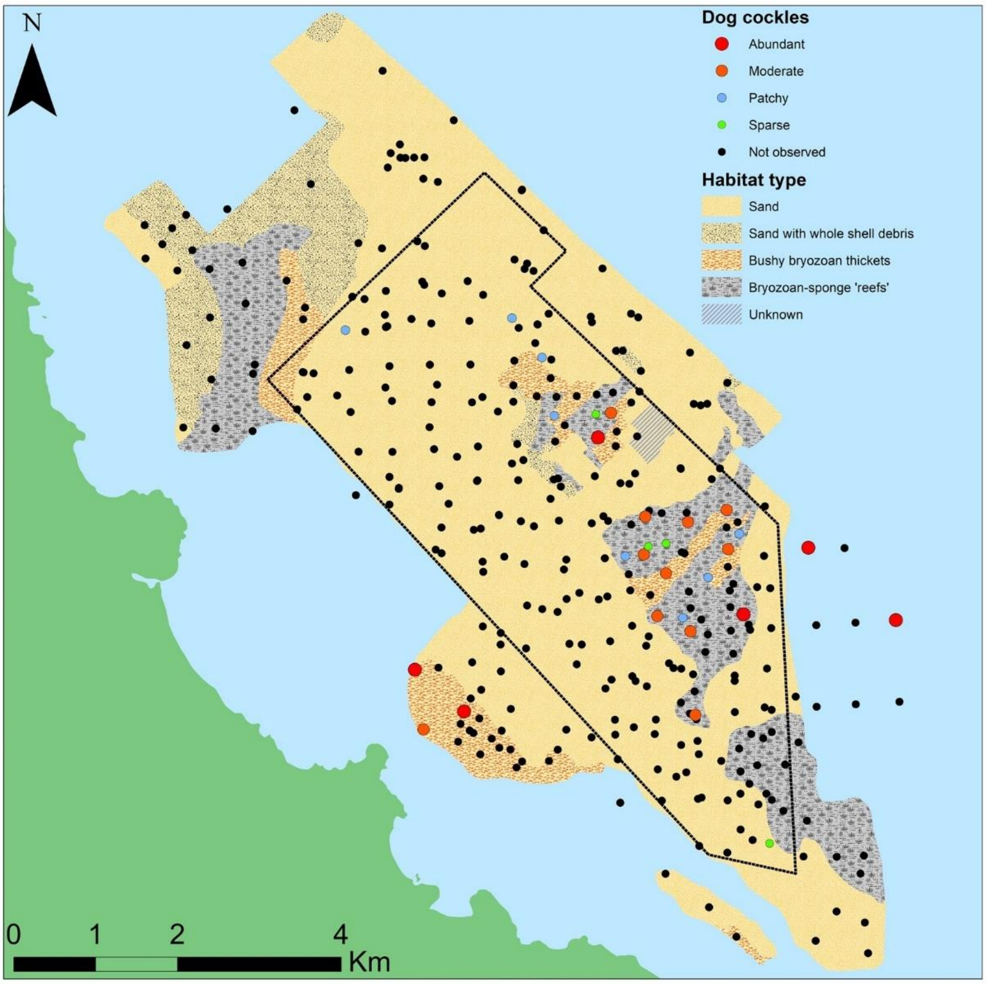

Figure 23. Abundance of dog cockles observed at drop camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 2–3 individuals in close proximity, moderate = several individuals in close proximity, abundant = dense aggregations.

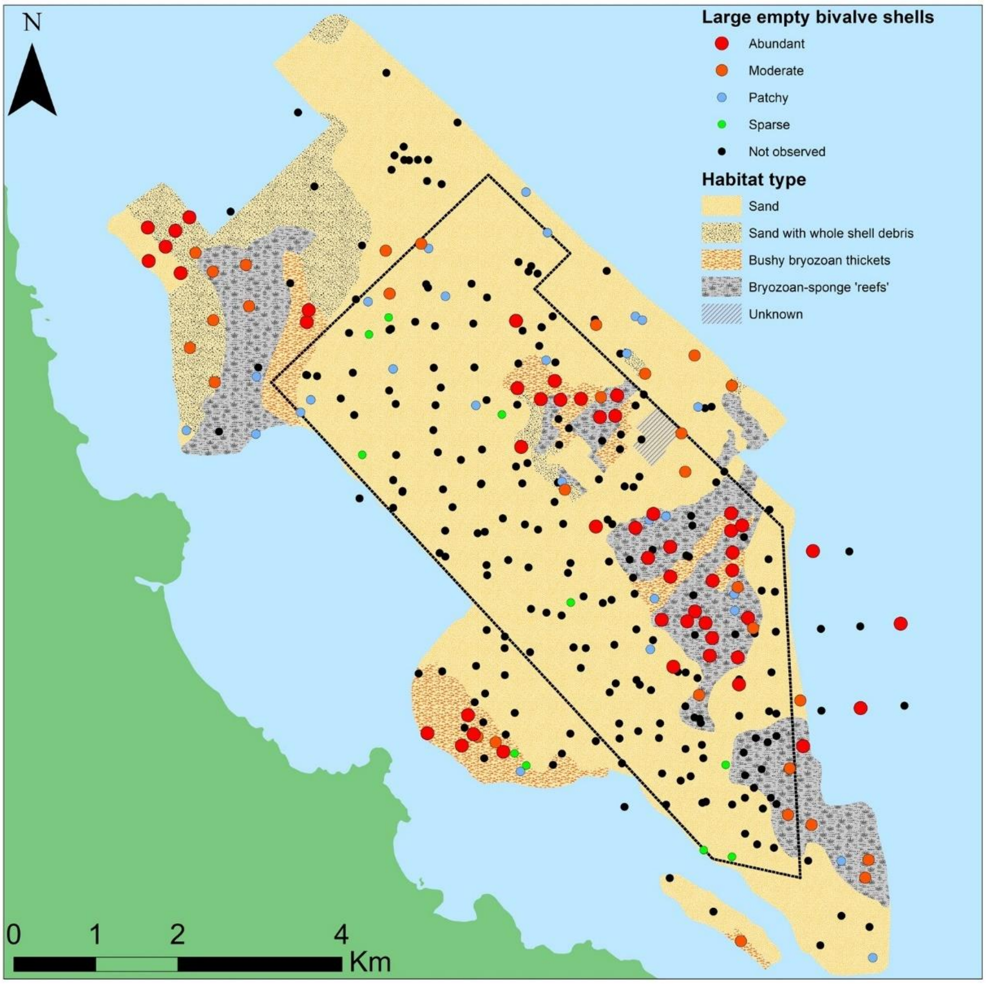

Figure 24. Abundance of large empty bivalve shells observed at drop camera sites across the survey area. Density estimates: absent = not observed, sparse = isolated individuals, patchy = 5% coverage, moderate = 10 to 30% coverage, abundant = > 30% coverage.

3.4.2. Sediment macrofauna

Macrofaunal community composition in the proposal area is reasonably comparable with communities found in coarse sandy sediments in the wider region (e.g. the entrance to Big Glory Bay, James et al. 2018), with no taxa of high ecological importance identified. A total of 1,060 individuals, representing 90 different taxa, was observed within the 31 sediment samples collected across the proposal area. Total abundance across the sites was low, ranging from 1 to 88 individuals per core (Figure 25), with an average of 34 individuals per core.

Low macrofauna abundance is typical of coarse sandy sediments with low organic matter (McLachlan et al. 1984) and is comparable to macrofauna abundance reported for other sandy sediments in the region. For example, the entrance to Big Glory Bay, Stewart Island is characterised as a sandy site with low average macrofauna abundance (12 to 60 individuals per core from 2012 to 2017, James et al. 2018).

The most abundant organisms were nematode worms (177 individuals). This is similar to other high-flow sandy sediments where nematodes are usually the dominant taxonomic group (Urban-Malinga et al. 2006). Oligochaete worms were the second most abundant organisms (153 individuals); these were present in every sample except one (sample 14).

Species richness (number of different taxa) ranged from 1 to 26 taxa per core (Figure 26), with an average of 11 taxa per core. This is similar to species richness values reported for other sandy substrates in the region; e.g. the entrance to Big Glory Bay averaged 9 to 18 taxa per core from 2012 to 2017 (James et al. 2018).

Sediments had a high diversity of polychaete worms (33 taxa identified). Polychaetes from the families Exogoninae, Cirratulidae, Syllidae, Spionidae and Terebellidae were particularly abundant. Twelve bivalve taxa were identified, although the total abundance of bivalve species was relatively low (1 to 5 individuals per taxon across all sites). Community structure was also similar to that at the Big Glory Bay entrance, where a range of polychaetes and bivalves was common (James et al. 2018), suggesting the communities observed across the proposal area are not uncommon in the wider Stewart Island / Rakiura region.

Taxa were grouped to phylum level and ranked by relative abundance across the sites and their distributions mapped (Figure 27). A full taxa list and calculated indices are provided in Appendix 4 and Appendix 5, respectively. The multivariate analysis of macrofaunal assemblage compositional data shows two main distinct groups, ‘e’ and ‘b’ (excluding three anomalous samples; 8, 15, and 38), at a level of 33% similarity (Figure 28). The macrofaunal communities appear to be influenced primarily by particle grain size, based on the vector overlay for the sediment properties (Figure 28a) and distribution of samples (Figure 28b). Group ‘b’ samples were from sand dominated areas, while group 'e' samples had a higher gravel and mud content. Group 'e' sites generally had higher taxa richness and total abundances than group 'b' (Figure 28). In terms of community composition, the strongest distinguishing factors between these two groups was the abundance of polychaetes (from families; Cirratulidae, Exogoninae, Syllidae, Terebellidae, and Spionidae), ribbon worms (Nemertea), nematodes and oligochaetes, as well as the presence of Munnidae isopods and cnidarians in group 'e' samples.

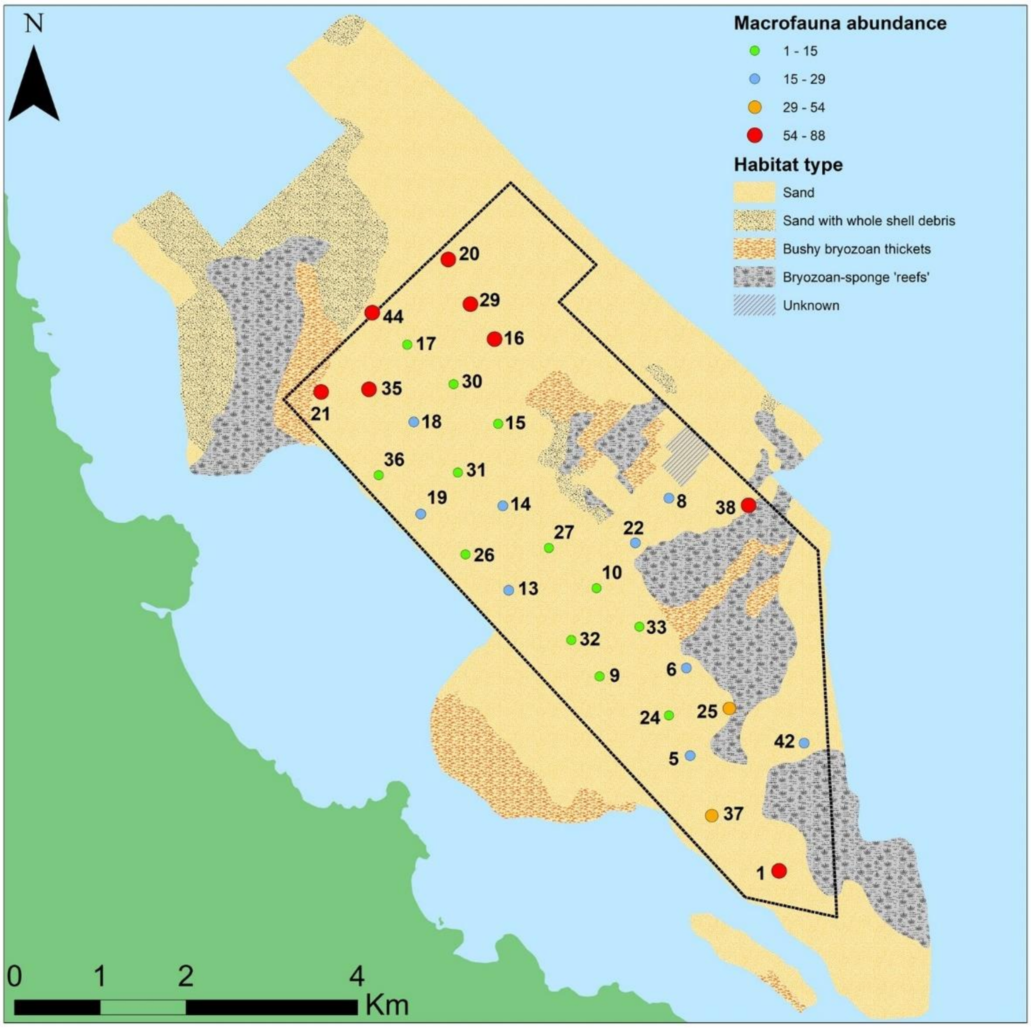

Figure 25. Macrofauna abundance per sediment core (10 cm deep and 113 cm^2 surface area) sampled across the survey area.

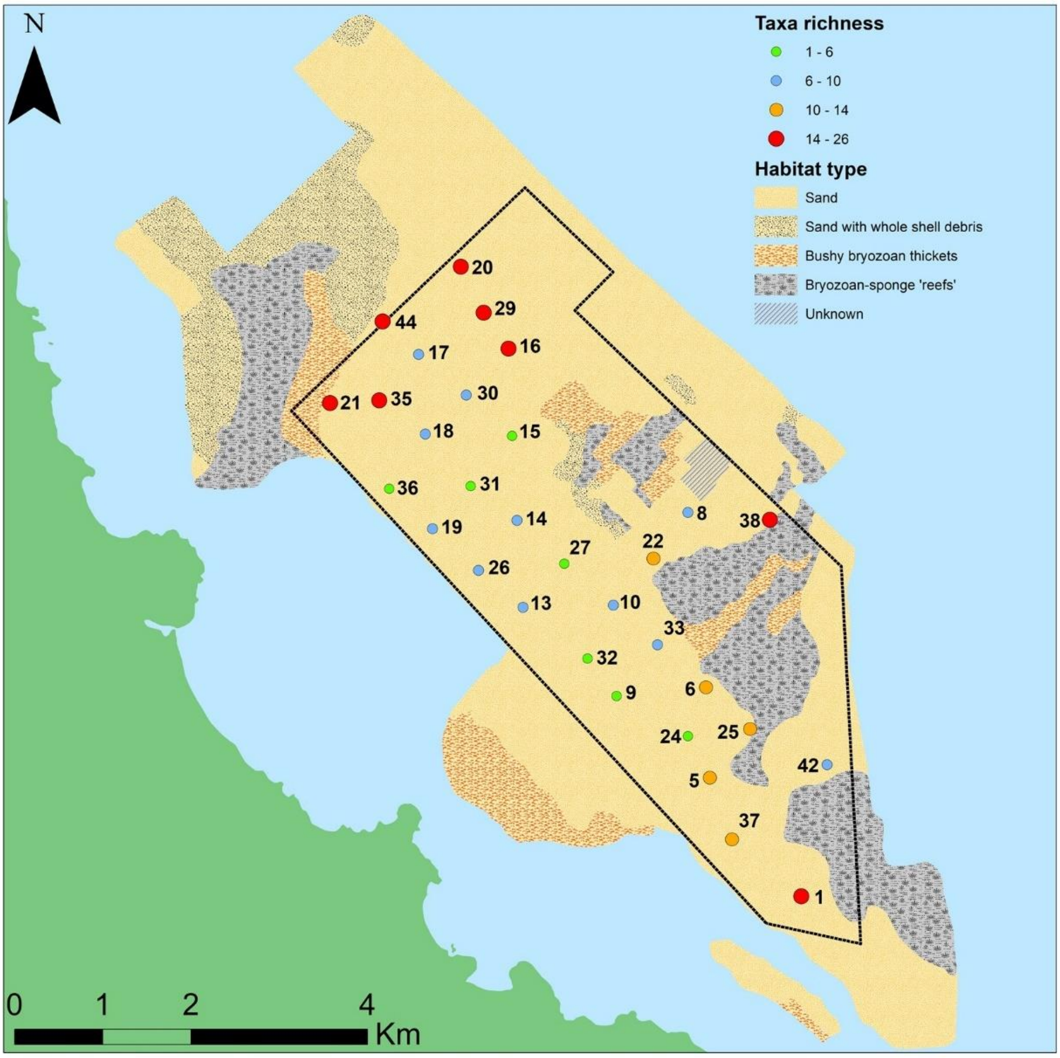

Figure 26. Macrofauna taxa richness (number of taxa) per sediment core (10 cm deep and 113 cm^2 surface area) sampled across the survey area.

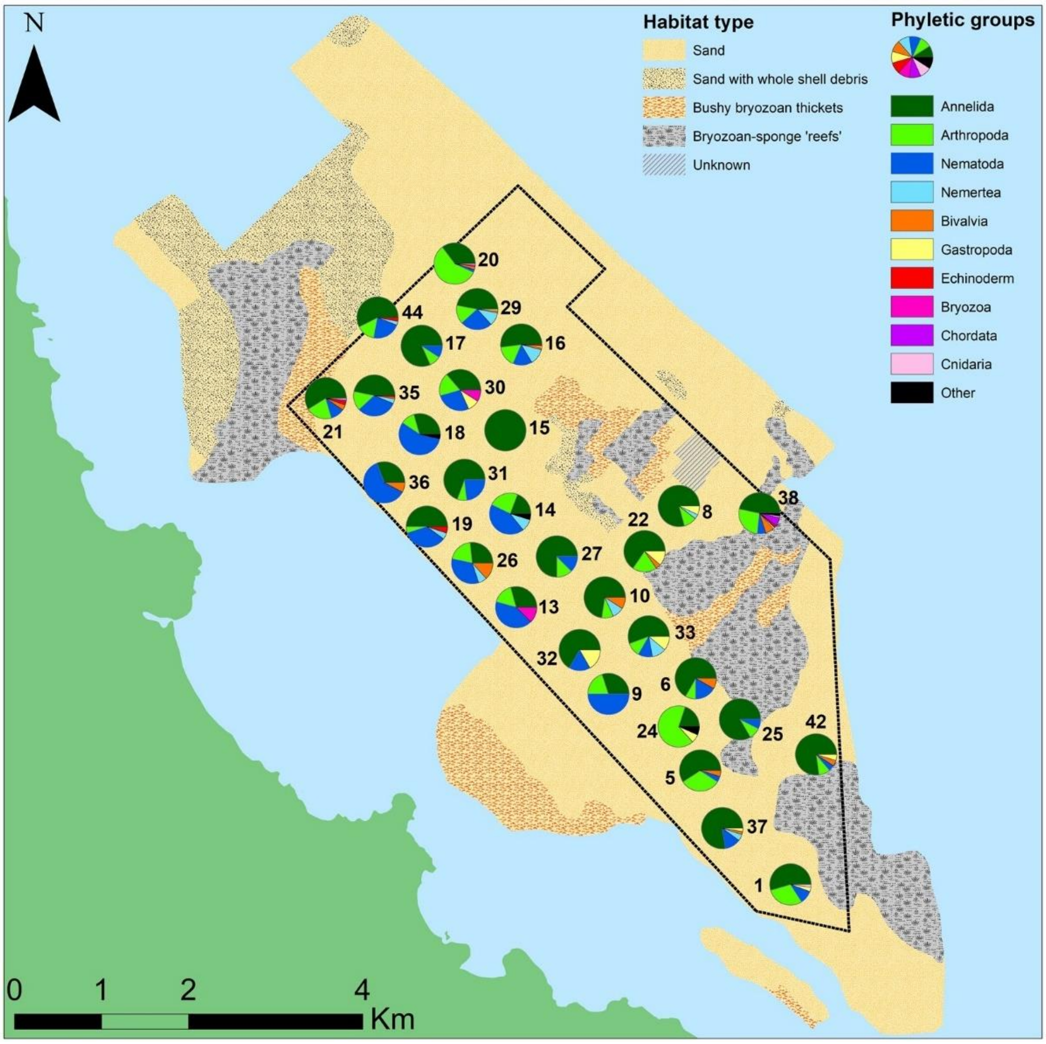

Figure 27. Macrofauna abundance (grouped by phylum) per sediment core (10 cm deep and 113 cm^2 surface area) sampled across the survey area. Only the most abundant phylum groups by number are presented for clarity. ‘Other’ includes: Porifera, Phoronida and Sipuncula.

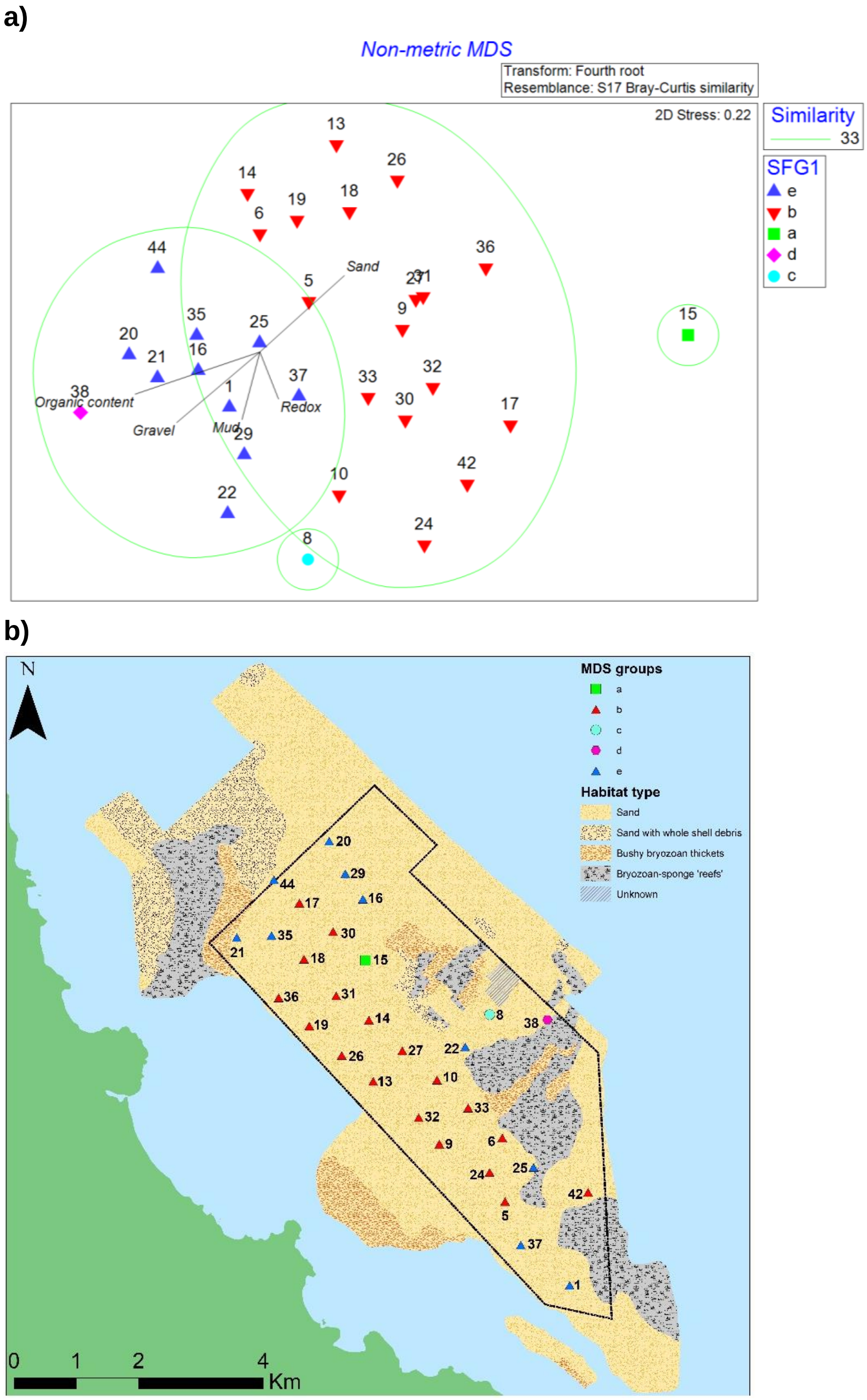

Figure 28. Similarity (%) among macrofauna communities from core sample contents across the proposal area shown by: a) Non-metric multi-dimensional scaling plot of similarities between macrofaunal assemblages (clustered at 33% similarity), overlaid with vectors of sediment properties (particle grain size, organic content, and redox). Abundance data were fourth-root transformed. Resemblance based on Bray-Curtis similarities. b) location of grab samples showing location of MDS groupings relative to habitat across the survey area.

4. MULTIBEAM SURVEY – SEABED MAPPING

Following the site characterisation surveys described above (and subsequent to the previous iterations of this report, e.g. Bennett et al. 2019 and Bennett et al. 2020) Discovery Marine Limited (DML) undertook a seabed mapping exercise across the proposal area as a part of a wider Land Information New Zealand (LINZ) survey. These surveys (17 January to 28 February 2022) used a multibeam echo sounder (MBES) to record bathymetry, acoustic backscatter and water column data, of which bathymetric and backscatter data covering approximately 12,500 ha were delivered to Cawthron. To validate the multibeam data, Cawthron undertook surveys in July and September 2022 to collect video footage using drop cameras and remote operated vehicles (ROV). These seafloor data collected by DML and video observations were used to produce a predictive model of the seafloor habitats across the proposal area (further details on this process are provided in Appendix 6). The habitat map created from the multibeam survey (presented in Figure 29) covers a larger area and has a much higher resolution than the habitat map presented in Section 3 and will be used in further analysis in this report. The main habitat types described previously (in Section 3.4) remain largely unchanged. The exception to this is a further breakdown in the 'sand with shell hash' category into three categories. Therefore, based on multibeam survey, five main seabed habitat types were observed within the proposal area:

- *Sand*

  Approximately 77% of the proposal area (and 45% of the area surveyed) is estimated to be sand-dominated habitat with sand ripples, waves and large sand banks frequently observed across this habitat type. Some shell hash was present, mainly in the troughs of sand ripples or waves. Sand habitats had relatively sparse epifaunal assemblages. Patches of biogenic structure were occasionally observed.
- *Sandy shell hash*

  Approximately 11% of the proposal area (and 25% of the area surveyed) is estimated to be sand-dominated habitat with varying amounts of shell hash. Generally when sandy shell hash was the dominate habitat there was relatively flat terrain (i.e. not strong rippling / wave sand forms). More epifauna were found than for sand habitat, and generally this was made up of brittle stars.
- *Coarse gravel shell and sand*

  Approximately 2.7% of the proposal area (and 16.6% of the area surveyed) is estimated to be sand habitat with varying amounts of shell hash, whole shell debris, gravel and some cobbles. Generally more brittle stars were found than in sand habitat. Patches of biogenic structure were occasionally observed, mainly bushy bryozoans.
- *Bushy bryozoan thickets*

  Bushy bryozoan thickets (as described in Section 3.4) are estimated to cover 0.3% of the proposal area (and 4% of the area surveyed).

- *Bryozoan-sponge reefs*

  Bryozoan-sponge reefs (as described in Section 3.4) are estimated to cover 9.1% of the proposal area (and 9.6% of the area surveyed).

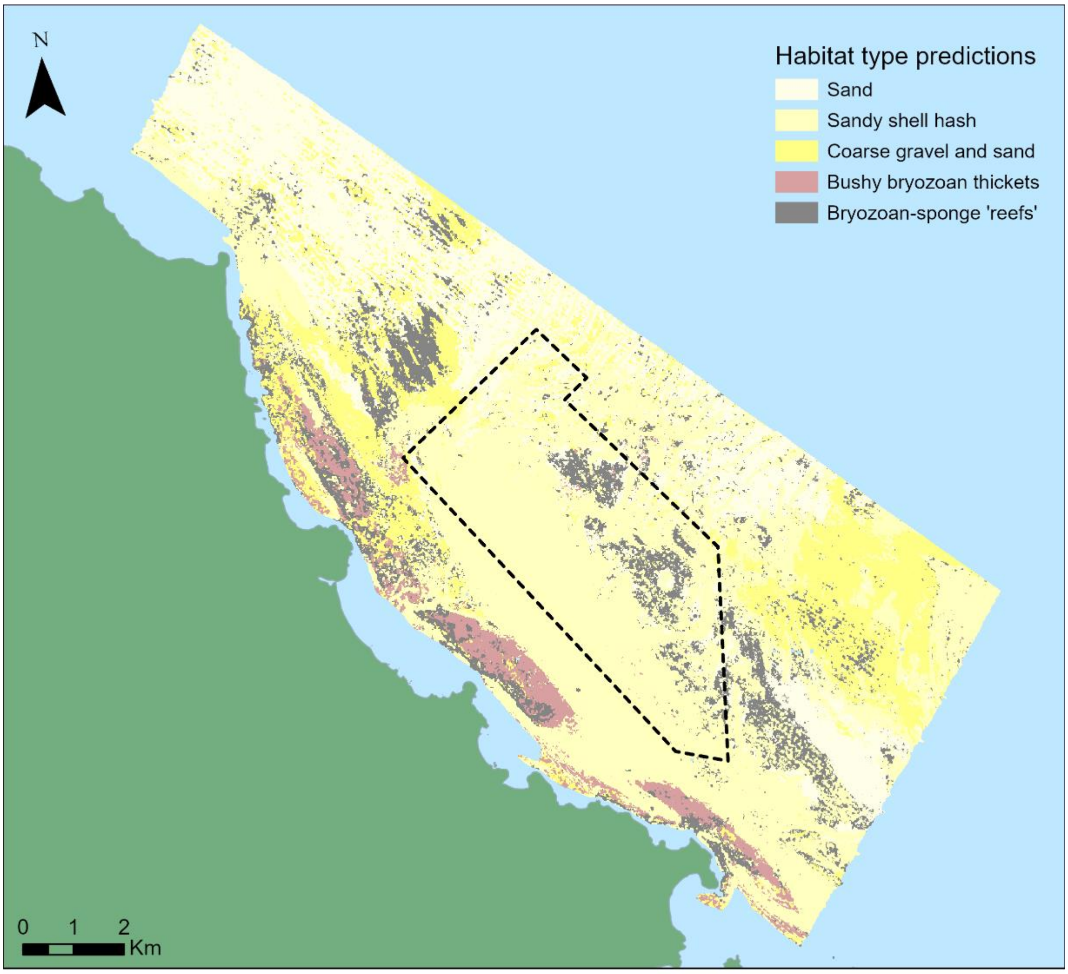

Figure 29. Updated habitat map showing the predicted extent of habitat based off the multibeam survey and subsequent video validation surveys. Black outline = the Hananui proposal area.

Table 2. Summary table of predicted extent of each habitat type identified across the multibeam area surveyed. Total area is the area predicted for each habitat type across the total survey area. Proposal area is the area of each habitat type predicted within the proposal area. Total area % composition is the percentage of each habitat type across the total area surveyed. Proposal area % contribution is the percentage of each habitat type that makes up the proposal area. Total habitat type is the percentage of the total of each habitat type found within the proposal area.

Habitat type	Total area (12,469 ha)	Proposal area (2,496 ha)	Total area % composition	Proposal area % composition	% of total habitat type
Sand	5594	1916	44.9	76.8	34.3
Sandy shell hash	3113	278	25.0	11.1	8.9
Coarse gravel	2069	67	16.6	2.7	3.2
Bushy bryozoan thickets	499	7	4.0	0.3	1.5
Bryozoan-sponge reef	1194	228	9.6	9.1	19.1

4.1. Rock outcrops

A small rock outcrop was identified towards the southern end of the proposal area during a video survey in October 2021 (prior to the multibeam survey, Figure 30, under the bottom pens of the proposed South-B farm, see Section 5 below). This was a low relief rock with some sponges, kina, sea cucumber and brittle stars. Parts of the outcrop were overlain with sand and there were small clumps and isolated individual bushy bryozoans, red and brown algae and encrusting coralline algae. (Figure 31). Several other more biodiverse outcrops were then identified outside of the southern boundary of the proposal area during the multibeam survey (Figure 30) and these were surveyed by ROV in September 2022. The surveyed outcrops were 1–2 m wide and heavily encrusted with epifauna, including sponges, bryozoans and ascidians (Figure 32).

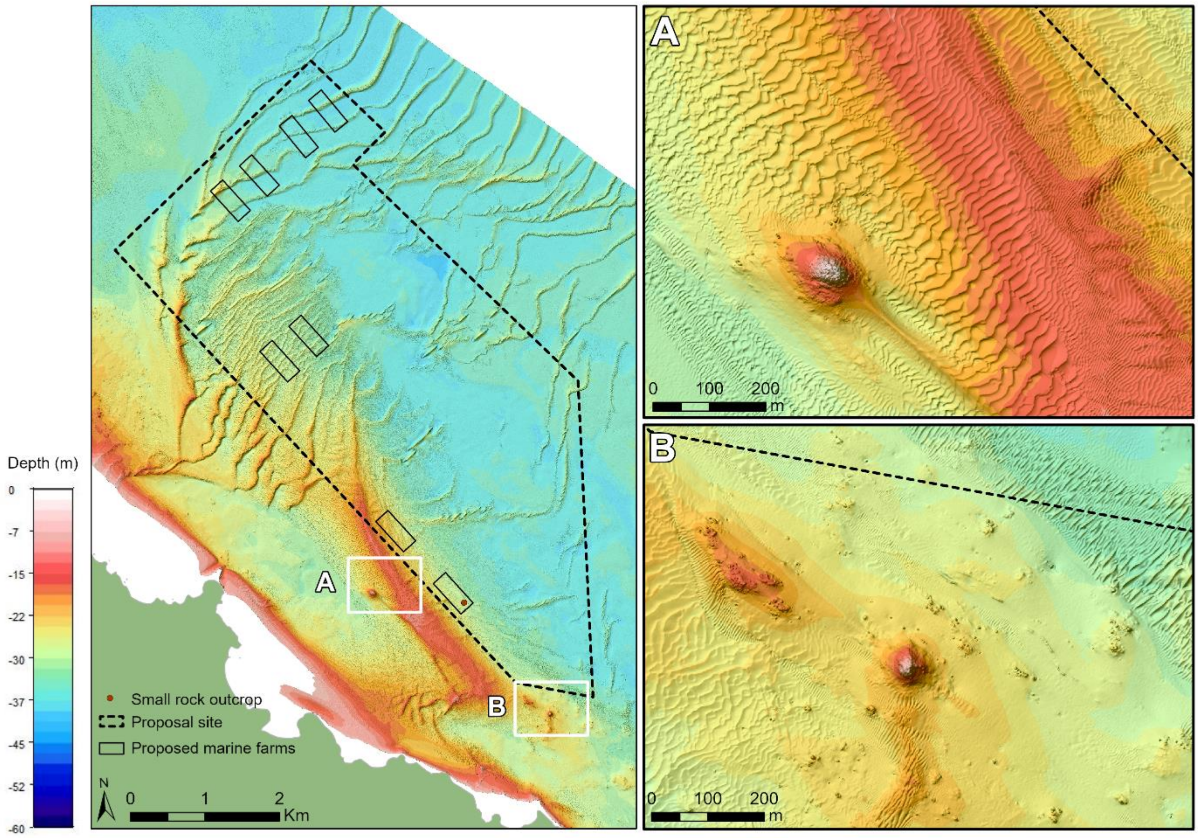

Figure 30. Multibeam sonar images of the seabed around the proposed site showing locations of known rocky outcrops near to the proposal area. The location of the small rock outcrop within the proposal area is shown as a red circle in the left map (under the southernmost proposed farm block). **A** shows Newton Rock and **B** shows the bigger outcrops surveyed by video in September 2022.

Figure 31. Example image of the rock outcrop to the southern end of the proposal area (below the proposed South-B farm).

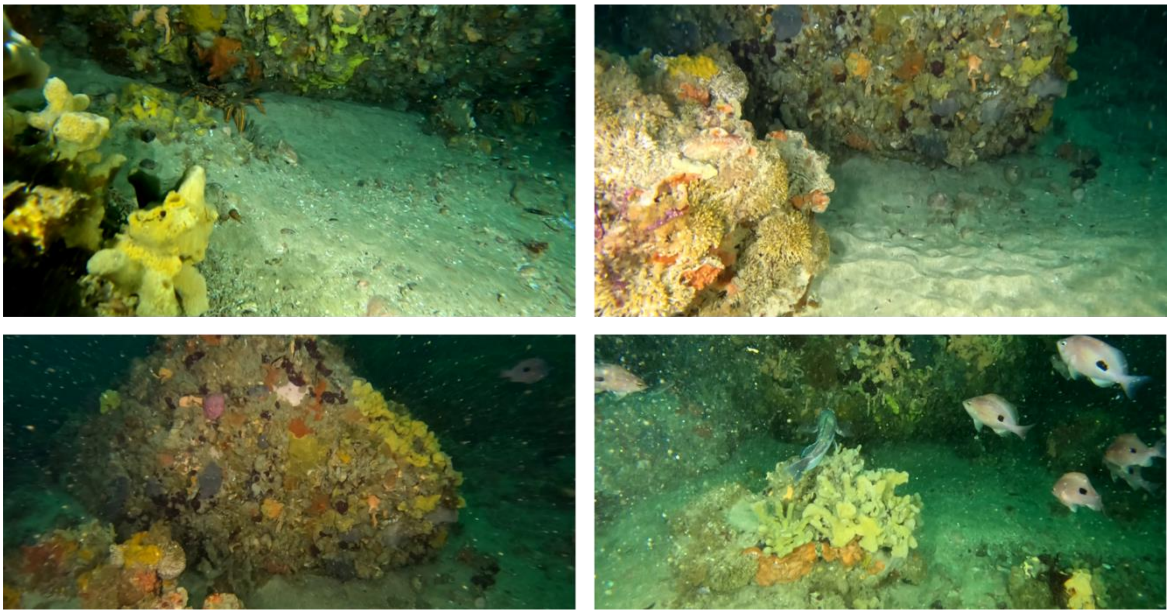

Figure 32. Example images from ROV videos taken in September 2022 of rocky outcrops along the southeast boundary of the proposed site.

5. SITE SELECTION

5.1. Index of suitable location

As part of preliminary scoping investigations, mean current (V) and depths (D) were taken from the 3-D hydrodynamic model (see Campos et al. 2020) and used to calculate an Index of Suitable Location ($ISL = DV^2$; Yokoyama et al. 2004) for the region (Bennett et al. 2018), to indicate the suitability of the area for finfish farming (Figure 33). Although application of this index for salmon farming is untested[10], it is appropriate for considering site suitability. It provides a single metric of water depth and flow, giving an indication of the assimilative capacity[11] and the upper limit of fish production at a given location (Yokoyama et al. 2004). The higher the ISL, the better the site for fish farming. The ISL of the proposal area ranges from 2 to 3 inshore to 6 to 7 further offshore (Figure 29), indicating that there is potential for finfish farming across the entire proposal area. To put these values into perspective, calculated ISLs for existing Marlborough Sounds farm sites in Ngamahau Bay and Te Pangu Bay (in Tory Channel) are 1.3 and 1.1 respectively, and those for Otanerau Bay and Ruakaka Bay farms (Queen Charlotte Sound) are 0.05 and 0.04, respectively.

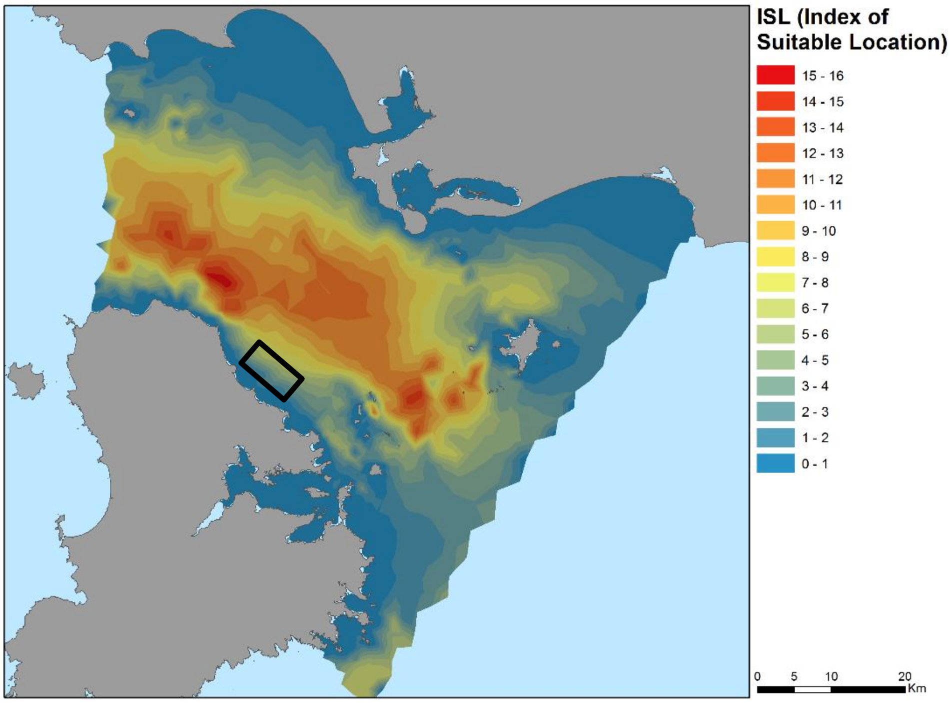

Figure 33. Index of suitable location (ISL) for northern Stewart Island / Rakiura. The ISL is calculated using fine-scale modelled current data (from Bennett et al. 2018). The approximate location of the Hananui proposal area is outlined in black.

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[10] The ISL was developed using data from a farming area in Japan that produces 15,000-20,000 metric tons of red sea bream (*Pagrus major*) and Japanese amberjack (*Seriola quinqueradiata*) per annum.

[11] i.e. the ability of an area to 'accommodate' wastes and maintain a 'healthy' environment.

5.2. Summary of measured site oceanographic features

Oceanographic features of a site, including depth, currents and wave climate, influence the deposition and resuspension rates of salmon farm waste. The proposal area is a high-flow environment where wastes should be readily dispersed. Water depths range from 20 to 40 m across the site. Mean depth-averaged current speeds range from 38 to 44 $cm \cdot s^{-1}$. Mean current speeds are strongest near the surface (47 to 59 $cm \cdot s^{-1}$) and weakest near the seabed (39 to 41 $cm \cdot s^{-1}$). The predominant current flows along a northwest / southeast axis. The mean and maximum significant wave heights predicted for the area (from a 37-year regional wave-hindcast model) are approximately 1 and 3 m, respectively. See Campos et al. (2020) for a detailed account of the oceanographic features of the proposal area.

5.3. Farm placement

Farm locations within the proposal area were selected to avoid known areas of significant biogenic habitat and ecologically important taxa (as discussed in Section 3.4). Proposed farms are a minimum of 200 m from bushy bryozoan thickets and bryozoan-sponge reefs (Figure 34).

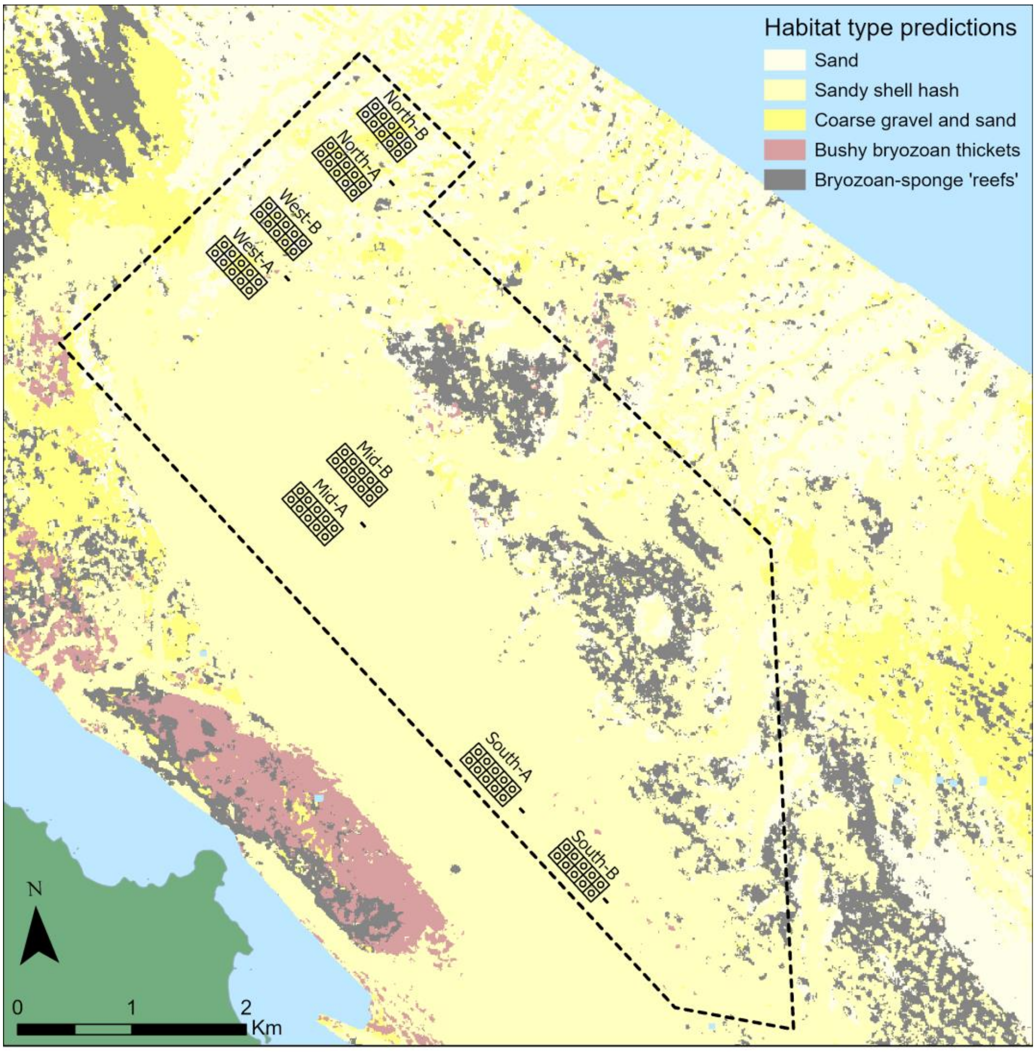

Figure 34. Proposed farm placement across the Ngāi Tahu Seafood Hananui proposal area (black outline) over predicted habitat types.

5.4. Staging approach

The proposed operation consists of four farms, each with two blocks (termed A and B). Each block consists of ten 168-m circumference pens (Figure 34). Depths range from 25 to 36 m across the proposed farms. Ngāi Tahu Seafood propose developing the c. 2,500 ha area in four stages (staging summary provided in Table 3). At Stage 1, one of the two blocks in each farm will be developed at 75% of the total 1-block feed production (c. 10,000 tonnes feed per year total across the four farms). At Stage 2, production in those blocks will increase to 100% of total feed production for the block (c. 15,000 tonnes feed per year). At Stage 3, the second block in each farm will be developed to 50% total feed production (c. 20,000 tonnes feed per year). At Stage 4, both blocks in all farms will operate at 100% total production (25,000 tonnes feed per year).

Table 3. Summary of Ngāi Tahu Seafood’s proposed staging approach for each farm. Note that either the A or B block within each farm may be developed first. Feed = tonnes per year.

Stage	Farm block	% total feed	Feed total across all farms
Stage 1	A	75%	10,000
	B	0%	
Stage 2	A	100%	15,000
	B	0%	
Stage 3	A	100%	20,000
	B	50%	
Stage 4	A	100%	25,000
	B	100%	

6. ASSESSMENT OF ENVIRONMENTAL EFFECTS

Seabed impacts beneath salmon farms are inevitable, even during initial development, due to the presence of structures and from discharges associated with farm operation. The following section provides an assessment of the likely effects that may result from these processes.

6.1. Seabed effects associated with the initial site development

Ngāi Tahu Seafood propose to install pens using an anchoring system similar to that currently used on salmon farms overseas (e.g. Petuna Aquaculture Pty Ltd, Storm Bay, Tasmania). Each pen will be individually moored using a combination of dual-shank anchors, chain and 5-tonne mooring blocks. Disturbance from mooring installation may cause physical damage to the seabed and short-term resuspension of sediments. Both factors could affect biota in the area directly surrounding the installation area. Consequences for sensitive species include habitat destruction, smothering, sedimentation-induced reductions in feeding efficiency, and possible mortality (Clark et al. 2011; Anderson et al. 2019). A summary of potential environmental effects associated with installation of mooring systems, and options to avoid, remedy or mitigate where applicable, is provided in Table 4.

6.1.1. Destruction / displacement of species and / or habitat

Substrates beneath the proposed farms are dominated by sand with varying amounts of shell hash (Figure 34). While the proposed farms do not overlap with areas of significant biogenic habitat, sensitive species including sponges, bryozoans, brachiopods and large bivalve species (e.g. oysters, scallops, dog cockles and horse mussels) occur occasionally in sand-dominated areas. The installation of anchors above or adjacent to these taxa is likely to result in effects ranging from reductions in densities through to complete exclusion. Any organisms present in the area of anchor installation will likely be displaced. However, the significance of this damage is reduced due to the low diversity of epibiota within the areas proposed for farm development.

6.1.2. Resuspension of sediments

While anchor installation is likely to resuspend sediment, which risks smothering epibiota, the disturbance is only likely to occur during installation and shortly thereafter (hours to days) so is unlikely to have a long-term impact on benthic communities within the area. Furthermore, effects from resuspension will be minimised by the high currents that will rapidly disperse the sediment.

It is Ngāi Tahu Seafood’s intention that installation of farms will be staged and therefore effects can be monitored during each stage of development. We also note the presence of anchorages near to the proposal area. These are used by large vessels whose anchoring may cause more disturbance (i.e. every time an anchor is deployed) than mooring (where disturbance occurs only at installation of multiple permanent structures). Consequently, the area is already subject to a certain amount of anthropogenic disturbance.

Table 4. Summary of potential environmental effects associated with the installation of mooring systems.

Potential effect	**Environmental implications**	**Options to avoid, remedy or mitigate (where applicable)**
Destruction/ displacement of species and / or habitat	The installation of each anchor is likely to result in the displacement of organisms in and on the sediment in a small area.	Areas to be used for anchorage are characterised by sand-dominated habitats, thus sensitive habitats (e.g. bryozoan-sponge reefs) would not be affected. Staged development will provide for monitoring of effects and for adjustment in installation processes if required.
Short-term resuspension of sediments	There will be small-scale resuspension and resettlement of fine particulates onto similar sediments, which will likely occur over a relatively short time frame (hours to days). Any far-field dispersal of sediments will be diluted due to the dispersive nature of the site.	Use of experienced and qualified personnel to install anchors and structures to minimise the amount of seabed disturbance. Staged development process will provide for monitoring of effects.

6.2. Seabed effects associated with the presence of farm structures

Once established, the presence of farm structures can reduce light penetration to the seabed and provide habitat for other organisms (i.e. fouling taxa, including pest species; Morrisey 2019). The presence of farm structures may also provide protection from destructive activities, e.g. dredging. A summary of potential environmental effects associated with the presence of farm structures is provided in Table 5, as are options to avoid, remedy or mitigate effects where applicable.

6.2.1. Shading

Shading by farm structures can block sunlight from reaching the seabed, potentially impacting photosynthetic organisms and their consumers (Keeley 2013). However, within the proposal area there are very few photosynthetic taxa, with only drift algae observed in areas likely to be impacted by farm shading effects (i.e. directly beneath the pens). The risk of shading causing effects to the seabed environment is therefore considered low.

6.2.2. Provision of habitat

The presence of farm structures provides habitat for other organisms (i.e. fouling taxa). Drop-off of fouling biomass can alter the physical and biological composition of the seabed and may exacerbate enrichment effects, e.g. through decomposition. Seabed-dwelling animals such as brittle stars or sea cucumbers may also scavenge fouling biota fallen from farm structures, and scavenger aggregations could alter epifaunal community composition. Seabed effects associated with fouling taxa are likely to be minimal and can be managed through regular monitoring and maintenance of farm structures (e.g. periodic removal of fouling, see the biosecurity management plan; Johnston & Forrest 2019).

Exotic and native pest species could colonise new structures and act as propagule 'banks' that supply nearby habitats with recruits. Risks associated with marine pests colonising farm structures are addressed separately in the Biosecurity Report (Morrisey 2019).

6.2.3. Protection

The presence of farm structures may be beneficial for some organisms and habitats (e.g. those tolerant to the effects of organic deposition), due to the protection they provide from destructive activities including dredging (Fletcher 2015). While observed only occasionally within the area directly beneath and adjacent to the proposed farms, sensitive taxa such as bryozoans, sponges, brachiopods and large bivalve species are all vulnerable to the effects of dredging (Anderson et al. 2019). This is a particularly relevant consideration in Foveaux Strait, due to the frequency of dredge fishing operations in this region.

Table 5. Summary of potential environmental effects associated with the presence of farm structures.

Potential effect	Environmental implications	Options to avoid, remedy or mitigate (where applicable)
Shading of seabed	Shading can block sunlight from reaching the seabed, potentially causing a reduction in food availability for some organisms. This is likely to have little impact at the proposal area due to the presence of very few, if any, photosynthetic organisms observed living there.	Not applicable.
Biofouling drop off	Colonisation of farm structures by biofouling taxa is likely. Some drop-off of biofouling taxa (e.g. from natural sloughing and net cleaning) to the seabed is expected from the pen structures. This may result in the colonisation of the seabed by these taxa as well as changes to the physical composition of the seabed. Deposition of biofouling communities to the seabed may also contribute to seabed enrichment.	Periodic inspection (and maintenance, if required) of structures to manage the amount of fouling organisms attached. An emphasis should be placed on this action in the initial stages of operation, to gain a rapid understanding of the nature and extent of fouling at the site. Refer to the biosecurity management plan (Johnston & Forrest 2019).
Colonisation by pest species	Structures may be colonised by pest species and may act as a propagule 'bank' for pest species.	As above (and refer to biosecurity assessment, Morrisey 2019 and management plan, Johnston & Forrest 2019).
Protection from destructive activities	Farm structures will provide protection from destructive activities including dredging.	Not applicable.

6.3. Seabed effects resulting from organic deposition during farm operation

Seabed effects arise primarily from the deposition of faeces of farmed fish and from uneaten feed. Over-enrichment can occur due to the high organic content of the deposited particles (Forrest et al. 2007) and microbial decay of this waste material can dramatically alter the chemistry and ecology of the seabed where deposition rates are high. Other effects that are likely to occur where deposition is high include: smothering of benthic organisms by farm-related biodeposits; an increased abundance of epibiota in response to increases in food availability; and an increase in turbidity levels that could reduce the amount of light reaching the seafloor and has the potential to reduce primary productivity (although we note this is unlikely to be an issue at this site as very few primary producers were observed within the proposal area). A reduction in near-bottom water column oxygen levels is also possible if the seabed becomes excessively enriched. A summary of potential environmental effects arising from organic deposition during farm operation is provided in Table 6, as are options to avoid, remedy or mitigate where applicable.

Table 6. Summary of potential environmental effects arising from organic deposition during farm operation.

Potential effect	**Environmental implications**	**Options to avoid, remedy or mitigate (where applicable)**
Aggregation of mobile epibiota	Biodeposition of feed / faeces (including from fouling organisms) may encourage aggregation of scavenging and / or predatory organisms (e.g. sea cucumbers, sea stars, crabs, isopods). This could cause changes in community structure; e.g. through increased predation pressure.	Avoid footprint overlap with areas of biogenic habitat. Monitor epifaunal composition and institute effects-based management (i.e. pair monitoring to detect any changes to nearby communities with appropriate operational responses).
Alterations to sediment properties	Microbial decay of waste material can alter seabed sediment chemistry; e.g. depleted oxygen levels, elevated free sulphides, reduced redox levels. Visible bacterial cover may occur.	Effects-based management (e.g. fallowing and rotational use of farm sites) to ensure an undesirable level effect is avoided. Feed optimisation, limit feed waste.
Alteration to macrofaunal communities	Increased particulate organic matter such as uneaten feed and faeces provides an additional food source and changes sediment conditions for macrofaunal communities. Depending on the level of deposition, this can manifest as low macrofaunal species richness and extremely high abundances of a few opportunistic taxa responding to increased food supply. In this state, total biomass and the assimilative capacity of the community is enhanced. If enrichment is high enough, azoic conditions (no life present) can manifest because of alteration to sediment properties and smothering. The primary effect will decrease with increasing distance from the farm to the edge of depositional footprint. However, due to the dispersive nature of the site and non-cohesive nature of sandy sediments, resuspension and dispersal of organic matter may result in localised far-field enrichment effects. Low-flow environments and deeper pockets are particularly sensitive to enrichment.	Effects-based management (e.g. fallowing and rotational use of farm sites) to ensure an undesirable level of effect is avoided. Feed optimisation, limit feed waste. Particle dispersal modelling to identify potential hotspots of enrichment.
Alteration to epifaunal communities, particularly sensitive taxa	Increased particulate organic matter such as uneaten feed and faeces provides an additional food source and changes sediment conditions. Increased particulate organic matter also increases sedimentation and turbidity. Depending on the level of deposition, effects may range from positive effects of an enhanced food supply, through to displacement or mortality caused by smothering. Population-level effects may also occur through reduced reproductive success or larval settlement and recruitment. Increased turbidity could reduce the amount of light reaching the seafloor, with implications for primary productivity (although very few primary producers observed within proposal area).	Avoid siting farm in locations where important biogenic habitat and sensitive communities will be impacted by deposition. Use effects-based management (e.g. fallowing and rotational use of farm sites) to ensure adverse effects are avoided (i.e. nearby sensitive communities remain healthy). Feed optimisation, limit feed waste. Particle dispersal modelling to identify potential hotspots of enrichment.
Oxygen depletion of overlying waters	Possible near-bottom oxygen depletion immediately beneath the pens. Based on the dispersive nature of the site, significant depletion is unlikely but possible at high enough farming intensity (see Campos et al. [2020] for further discussion on expected effects of the proposed farm on dissolved oxygen concentrations).	Manageable through effects-based management (e.g. fallowing and rotational use of farm sites) and best farming practices (feed optimisation, limit feed waste).

The magnitude and spatial extent of seabed effects from finfish farms are a function of many inter-related factors including attributes of the farm operation and physical characteristics of the farm environment (Keeley & Taylor 2011). The quantity of organic material loading on the seabed is directly related to stocking density, the settling velocity of fish faeces, the type of feed and feeding system, the type of pen structure used and the amount of flow reduction caused by the pen system (Keeley & Taylor 2011). The flushing potential and environmental assimilation of farm wastes at a given site are dictated largely by water depth and current speed (Keeley & Taylor 2011). To a lesser extent, other factors such as seabed topography and seasonal factors such as water temperature may also influence regional hydrodynamics (Keeley & Taylor 2011). Increased flushing not only reduces local biodeposition and sedimentation, but also increases oxygenation of sediments (Findlay & Watling 1997).

Seabed effects tend to be most evident directly beneath the pens and exhibit a strong gradient of decreasing impact with distance. However, sites in deep water (c. 30 m or greater) with strong current speeds (depth averaged current speed > 15 cm per second), such as the proposal area, will have a more dispersed depositional footprint with less concentrated enrichment than shallower sites with lower flushing ability, due to increased levels of resuspension and dispersion (Keeley et al. 2019). Seabed sediment texture also plays a major role in waste resuspension and dispersal (Law 2019). Coarse sandy sediments, as seen across the proposal area, are less cohesive (i.e. they are less sticky and more mobile) than finer sediments (Law et al. 2016). While sandy substrates will retain some farm waste, resuspension potential is greater than at a site with more cohesive sediments.

Resuspension of material from the seabed below and around the farm will result in its dispersion over a larger area, reducing effects near the farm. While our understanding of far-field effects is limited (Law et al. 2016), it is expected that far-field deposition will occur at a reduced rate and that waste will be assimilated without causing measurable ecological changes (Keeley & Taylor 2011; Bannister et al. 2019). Nevertheless, a significant portion of particulate organic matter may deposit in areas prone to deposition (i.e. nearby low-flow areas, seafloor depressions and areas with greater rugosity such as reefs or bivalve beds). If depositional inputs are sufficiently elevated, this could result in localised enrichment, an increase in the availability of organic particulates and dissolved nutrients, and an increase in turbidity (Woodcock et al. 2017; Weitzman et al. 2019) in areas outside of the immediate depositional footprint.

Given the strong current speeds and non-cohesive nature of the sediments across the proposal area, significant resuspension / dispersion of deposited particles is likely, as is the dispersal and redeposition of particles outside of the main footprint, into the far-field.

6.3.1. Sediment properties

Microbial decay of salmon farm waste material alters sediment chemistry, resulting in depleted oxygen levels, elevated sulphide levels and reduced redox potential. It can also result in anoxic conditions in the overlying water and increased concentrations of dissolved nutrients in sediment porewater and overlying water. These changes are typically followed by changes to the plant and animal communities on and in the seabed.

However, in high-flow environments such as the proposal area, the excessive accumulation of organic waste on the seabed is unlikely. Furthermore, coarse sandy sediments found across the proposal area are more readily oxygenated and these conditions may facilitate decomposition of farm wastes (Martinez-Garcia et al. 2015). Consequently, effects attributable to the excessive accumulation of organic waste are less likely to be as discernible at this site, than at a lower-flow, muddier site.

6.3.2. Sediment macrofauna

In general, it is expected that sediment macrofaunal communities will follow the succession pattern of response to organic enrichment described by Pearson and Rosenberg (1978). Initially, abundance is expected to rise as organic matter is deposited. This may be a gradual change, but when the organic matter load increases to high levels, abundance rises more sharply, and the number of species declines. With continued input of organic matter, this effect reaches a maximum (the ‘peak of opportunists’) and abundance then falls sharply as the oxygen concentration declines.

Sediment macrofaunal communities across the proposal area are typical of coarse sandy sediments with low organic content, with low overall abundance and moderate diversity (see Section 3.4). While sediments with low organic content are likely to be able to accommodate some addition of organic waste and nutrients (Papageorgiou et al. 2010), even a small increase in organic content is likely to affect macrofaunal community composition (Hyland et al. 2005). The sediment macrofaunal species present in the proposal area may have a limited capacity to assimilate organic matter because they are adapted to low food conditions (Macleod et al. 2007). However, deposit feeders (e.g. oligochaete worms, various polychaete worms and scavenging amphipods) are present in the existing community and could increase in abundance, thereby increasing the waste-processing capacity of the community.

6.3.3. Epibiota

Research to date has focused primarily on the ecological effect of salmon farms on sediment macrofaunal communities, while the direct depositional effects on large epibiota (i.e. > 0.5 mm) are poorly documented (Keeley & Taylor 2011). Accordingly, there is limited information on the direct farm-related impacts on these important taxa. Generally, if organisms consume farm waste, there may be positive effects such as increased growth due to an enhanced food supply (George & Parrish 2015; Bergvik et al. 2019), which may lead to increased population densities. Sub-lethal adverse effects are also possible; for example, a reduction in food quality due to epibiota consuming salmon feed may lower growth or reproduction potential (see for example White et al. 2016), resulting in reduced densities. Smothering may also directly displace some organisms. Ultimately, effects are likely to be species-specific and known responses to organic deposition of epibiota found in the proposal area are discussed below.

Mobile scavengers and deposit feeders may also aggregate in areas where farm wastes and drop-off of fouling organisms provide a food supply (see also Section 4.3.2).

Bryozoans and sponges

Bryozoans and sponges are thought to be sensitive to organic deposition (e.g. Clark et al. 2011; Morrisey et al. 2015) and the effects of sedimentation (Dunlop et al. 2021). Bryozoans in particular, are slow growing animals and recovery from wide-scale impact can take decades (Batson & Probert 2000). While this suggests they would potentially be very sensitive to the effects of salmon farming, tolerance to organic deposition from salmon farming has been demonstrated for some species. For example, bryozoans settled and grew on artificial structures under and near salmon farms in Iceland and the Gulf of Aqaba, Red Sea (Israel et al. 2016, Angel et al. 2022). Further to this, the biomass of epiphytic bryozoan species growing on seaweed stipes increased with levels of salmon farm waste discharge (Haugland et al. 2021).

Tubeworms

Tubeworms are suspension feeders that that are susceptible to increased suspended sediments that can block feeding appendages and affect respiration (Kupriyanova et al. 2001) and to sedimentation that can smoother and kill colonies. While tubeworms are likely to be sensitive to high levels of farm related deposition, the presence of tubeworm (*Galeolaria*) reefs near salmon farms in Big Glory Bay suggest that these organisms are tolerant to low levels of deposition and salmon farm-related enrichment effects (Anderson et al. 2019).

Brachiopods and large bivalve species

While there is very little information available on brachiopod sensitivity to organic enrichment, increased suspended sediments, sedimentation and increased nutrification can be critical stressors to filter-feeding bivalves (Hewitt & Pilditch 2004; Lohrer et al. 2006)[12]. Brachiopods and bivalves are both ciliary filter feeders that draw in suspended particles and expel wastes typically using filament movements.

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[12] We note that these studies were of suspended terrigenous sediments rather than organic material. The former might incur higher energetic costs of processing and rejecting and less benefit while the latter may provide (some) food.

Therefore, it is expected that the effects of farm-related organic deposition will be the same for both groups of taxa. At high levels of deposition, populations of brachiopods and large bivalve species may be reduced or completely excluded.

Effects of fallowing on seabed enrichment

Fallowing farms between production cycles is a common management approach used overseas and is likely to reduce seabed impacts by allowing time for the recovery of sediments before farming commences again (Black et al. 2008). The rate of recovery is dependent on the extent of the impact (e.g. the amount of organic matter released and the timescale of the release), site-specific characteristics (e.g. sediment type, dispersal capability) and fallowing duration (Macleod et al. 2006; Zhulay et al. 2015). In Norway, a standard fallow period of 6–8 weeks is used at the end of an 18-month production cycle (Black et al. 2008). During this time a degree of recovery has been measured (e.g. Zhulay et al. 2015) although complete seabed recovery (i.e. the return of seabed conditions to a pre-farming state) is expected to take several years (Keeley et al. 2014, 2019).

6.3.4. Predicted spatial extent and magnitude of seabed deposition

This section contains descriptions of two modelling approaches:

- *Modelling without resuspension:* calculation of one-way flux of organic material that falls to the seabed from the farm. This can also be termed primary deposition and is presented as a rate (e.g. kg solids m^2 y^{-1}). Resuspension, redeposition and decay processes are not included in this calculation.
- *Resuspension modelling*: calculation of the amount of farm derived material on the seabed at any point in time. This is termed residual solids and is presented as a mass per unit area (e.g. g solids m^2). This calculation includes the effects of resuspension and redeposition as well as decay of organic material.

$$Flux\ + resuspended\ material\ entering - resuspended\ material\ leaving \\ - decay = residual\ solids.$$

Each approach has strengths and weaknesses. We introduce some key points here to help the reader with interpretation of the more detailed information in the main body of this section.

Deposition of organic material (principally waste food and fish faeces) on the seabed can be the ecological effect of most concern from finfish farming. In sites with low water flow, farm wastes fall to the seabed and largely remain near the farm. However, the currents in higher-flow environments can spread wastes further afield. Modelling of salmon farm seabed enrichment has traditionally relied on primary deposition; i.e. it has assumed that that the effects arising from particle resuspension are negligible. However, with the move to farming in higher-flow environments, it becomes more important to consider the influence that resuspension of particles has on organic enrichment patterns.

Requirements of the models are such that the units used to describe deposition of organic material are not the same for primary deposition and for deposition with resuspension. Primary deposition is described as one-way flux, i.e. the rate of fall of material to the seabed expressed, for example, in kilograms deposited on a one m^2 area over a year. This approach is widely used (in current best practice and other available literature) to draw relationships between levels of deposition and enrichment levels (which in turn lead to ecological change, e.g. MPI 2019). For example, Petuna™ used primary deposition to predict effects of farming salmon on mud and sand environments in the dynamic Storm Bay in Tasmania (see the environmental impact assessment, Rockcliff & Rockcliff 2017). A similar approach was used to measure the extent of salmon farm deposition and subsequent enrichment at dispersive sites with mixed substrates (including coarse shelly sand) in Norway (Keeley et al. 2019). The one-way flux (primary deposition) is an important consideration, as it allows for comparison with other salmon-farming operations in New Zealand. Enrichment stages have been developed for the Marlborough Sounds on the basis of one-way flux, and interpretation of the Hananui proposal on this basis is of value. However, limitations exist in applying these stages to the proposal area because:

- these relationships were developed based on multiple year class farming where feed inputs are relatively constant. In contrast, the Hananui proposal site farms will hold a single year class at any given time, so periods of high feed discharge will be followed by periods of low to no feed input.
- the relationship between predicted depositional flux and enrichment effects will vary depending on site characteristics, e.g. the sandy seabed of the proposal area differs to that for which these relationships were derived (i.e. sandy-mud and muddy-sand habitats in the Marlborough Sounds).

Therefore, until data from the proposal area become available, these are used as an estimate of potential effects only.

To operate a model that can incorporate resuspension, organic matter is expressed as residual solids (e.g. grams per m^2). This model also incorporates decay of organic matter. Resuspension modelling allows for an assessment of the way wastes may be distributed after they initially fall to the seabed and it allows for identification of sites where waste accumulation may be expected away from the immediate farming area. This is an important consideration in ensuring any areas of accumulated redeposition (accumulation-spots) are monitored. However, a limitation of this approach is that it is not yet possible to relate the calculation of residual solids to an expected organic loading and a potential ecological change. The best available information for relating residual solids to ‘effects’ is a residual solids modelling exercise performed in Tory Channel, Marlborough Sounds (Elvines et al. 2021). According to this work, the residual solids level at which moderate enrichment to soft sediments is likely is approximately 12.5 g·m^{-2} (the midpoint between 7 and 18 g·m^{-2}, see Elvines et al. 2021). Further to this, a residual solids level of 9 g·m^{-2} is below a value that would result in discernible effects to rocky-reef communities (based on monitoring of rocky reefs around salmon farms in the Marlborough Sounds, Elvines et al. 2021). While these thresholds will be considered to infer potential effects from residual solids at the Hananui farm site, it is important to emphasise the potential for site-specificity (as discussed above).

Further to this, while the one-way flux is a rate, and therefore not comparable to the residual solids, there is a way of providing a comparison between the non-resuspension and resuspension scenarios: residual solids can be calculated with resuspension turned off—this is, in effect, the same as adding decay to the primary deposition model. This exercise allows us to view the primary deposition in the residual solid units (g·m^{-2}) rather than as a one-way flux (kg m^{-2}·yr^{-1}). We present this scenario below to visualise the one-way flux in the same units as the resuspension scenarios.

Comparison of the deposition of residual solids with and without resuspension shows that resuspension is likely to significantly reduce the level of enrichment beneath the pens, and substantially increase the overall footprint of the farms. The non-cohesive nature of the coarse sediments at the proposal area is also likely to facilitate spread of fish farm wastes away from the immediate farming area. As a result, we recognise that the one-way flux is likely to represent a worst-case scenario of seabed enrichment.

Particle tracking models have become an accepted and useful tool to predict the extent of seabed deposition (Henderson et al. 2001). For this assessment, the ocean tracker model ‘VenOM’ was used to predict deposition from the proposed farms to the seabed[13]. Model parameters are provided in Appendix 7 and full model details can be found in Smeaton and Vennell (2020).

Depositional modelling (one-way flux without resuspension)

For the purposes of this assessment, ‘primary’ deposition refers to organic material (solids) that falls from the farm and settles for the first time on the seabed, as opposed to resuspension and redeposition, which is considered only in the second model. The ‘main’ footprint (from the no resuspension model) refers to those areas that have a flux of organic material (solids) greater than 1 kg·m^{-2}·yr^{-1}, while the ‘total’ footprint includes all solid flux to the seabed (including less than 1 kg·m^{-2}·yr^{-1}).

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[13] Previous assessments have used DEPOMOD (Cromey et al. 2002), a widely used and published model designed specifically for managing fish farm wastes. However, DEPOMOD is limited in the size of the area it can simulate and multiple runs would be required to model the proposed farm layout. This reduces the potential to model footprint overlap between the farm blocks and capture the full extent of deposition in high flow sites.

Depositional modelling (residual solids with potential for resuspension modelling capability)

Resuspension occurs when current speeds near the seabed exceed a critical threshold. Values for this threshold vary between studies: the model developed by Cromey et al. (2002) used a single near-seabed velocity threshold of 0.095 m s^{-1} for both faeces and food. Law (2019) proposed separate bed shear velocity thresholds of 0.009 $m{\cdot}s^{-1}$ and 0.015 $m{\cdot}s^{-1}$ for faeces and food pellets, respectively. Choosing an optimal velocity threshold beyond which particles resuspend is a contentious problem (Keeley et al. 2013). We modelled scenarios whereby: 1) all particles are resuspended (noting that near seabed current speeds in this area are usually higher than reported threshold values), 2) particles are sometimes resuspended (using critical bed shear velocity thresholds from Law 2019) and 3) particles are never resuspended. A comparison of this last scenario (where particles are never resuspended) with the first two scenarios provides some context for the potential influence of resuspension processes on the amount of deposition reaching the seabed (noting that results cannot be directly related to the one-way flux / no-resuspension model outputs presented previously).

Particle decay (assumed to be exponential with a half-life of 8 days, approximated from Keeley et al. 2019) was applied to the resuspension model to prevent particles resuspending indefinitely. Particles were assumed to begin decaying immediately upon release. The resuspension model outputs therefore reflect the predicted residual accumulation of solids ($g{\cdot}m^{-2}$) on the seabed accounting for resuspension and decay processes. This differs from one-way solids flux (expressed as $kg{\cdot}m^{-2}{\cdot}yr^{-1}$) which describes only the rate at which solids fall to the seabed in the absence of resuspension and decay. Solids flux is a less appropriate metric when considering resuspension effects. This is because, although particles may land for the first time in one place (e.g. under the pens), they can be lifted up again from the seabed by currents and be redeposited elsewhere. It is therefore important to note that the one-way flux and residual solids outputs are not directly comparable as explained in Section 5.3.4. It is also important to note that it is not yet possible to relate the residual level of solids with resuspension to an expected seabed state (as measures of enrichment to date are based on a one-way flux; e.g. MPI 2019).

Ultimately, the resuspension outputs provide an idea of the spatial extent of dispersal and identify places in the environment where the accumulation of solids is likely. Further to this, comparison between the different resuspension scenarios (always resuspend, sometimes resuspend, never resuspend) allows for some understanding of the potential effects of resuspension and decay processes on the magnitude of seabed deposition.

Modelled scenarios

Ngāi Tahu Seafood propose to farm under a single year class (SYC) regime whereby feed discharges will vary substantially throughout a production cycle. Under this regime, feed will increase prior to harvest then decrease to zero as fish are harvested. Ngāi Tahu Seafood plan to fallow each farm site for at least 3 months (with the potential for sites to be fallowed for up to 6 months) at the end of each production cycle. In the operation proposed by Ngāi Tahu Seafood, production at each of the four farms will reach a peak (and therefore peak feed discharge) at different times, and similarly, low feed inputs and fallow periods will occur at different times at each farm. In the previous version of this report (Bennett et al. 2019), feed discharge was averaged across the year. However, to more accurately reflect the farming style proposed for this operation, in this version we have modelled both average feed discharge (for comparison to the previous version of this report) as well as scenarios whereby each farm is represented at peak production (referred to as rolling peaks)[14]. The level of deposition expected during these periods of peak feed discharge are expected to be higher than previously reported, however we note that the pressure is short-lived and during other times of the production cycle each farm will receive little to no feed input, potentially allowing for a degree of seabed recovery.

Stage 1

Under the initial production scenario, either the A or B block will be developed in each farm at 75% of the total maximum feed input. The results for all A blocks at 75% are presented below and the results for all B blocks are presented in Appendix 8.The modelled scenarios for Stage 1 include:

- monthly feed discharges averaged from the annual total feed discharge (10,000 tonnes of feed per year), and
- four rolling peaks, capturing each farm at its peak projected monthly feed discharge (see Table 7).

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[14] Ngāi Tahu Seafood propose an 8.5 kg m^3 block-wide average fish biomass limit and a limit for any given pen of 10 kg·m^{-3} fish biomass. Our modelling captures the highest feed discharges possible under these conditions.

Table 7. Modelled Stage 1 monthly feed inputs (tonnes) per farm block Rolling peaks 1-4 refer to feed loadings at each farm over various stages of the production cycle and capture each farm at its peak projected monthly feed discharge. Feed data provided by Ngāi Tahu Seafood.

Farm	**Average monthly (A blocks only)**	**Peak monthly feed input (*rolling peak 1*)**	**Peak monthly feed input (*rolling peak 2)***	**Peak monthly feed input (*rolling peak 3)***	**Peak monthly feed input (*rolling peak 4)***
North-A	208	600	0	60	300
North-B	0	0	0	0	0
West-A	208	0	60	300	600
West-B	0	0	0	0	0
Mid-A	208	60	300	600	0
Mid-B	0	0	0	0	0
South-A	208	300	600	0	60
South-B	0	0	0	0	0

Stage 4

The modelled scenarios for Stage 4 include:

- monthly feed discharges averaged from the annual total feed discharge (25,000 tonnes of feed per year), and
- four rolling peaks, capturing each farm at its peak projected monthly feed discharge (see Table 8).

Table 8. Modelled Stage 4 monthly feed inputs (tonnes) per farm block. Rolling peaks 1-4 refer to feed loadings at each farm over various stages of the production cycle and capture each farm at its peak projected monthly feed discharge. Feed data provided by Ngāi Tahu Seafood.

Farm	**Average monthly**	**Peak monthly feed input (*rolling peak 1*)**	**Peak monthly feed input (*rolling peak 2)***	**Peak monthly feed input (*rolling peak 3)***	**Peak monthly feed input (*rolling peak 4)***
North-A	260	800	0	80	400
North-B	260	800	0	80	400
West-A	260	0	80	400	800
West-B	260	0	80	400	800
Mid-A	260	80	400	800	0
Mid-B	260	80	400	800	0
South-A	260	400	800	0	80
South-B	260	400	800	0	80

Predicted depositional footprint at the proposal area (without resuspension)

The modelling results for Stage 1 and Stage 4 without resuspension are presented below (images for the monthly average and the rolling peak scenario with the highest maximum depositional flux). Images for all rolling peak scenarios are provided in Appendix 9. Depositional footprints without resuspension (the ‘primary footprint’) are depicted as solids flux to the seabed. The ‘main footprint’ is defined as where the particles may fall on initial settlement and where effects are most pronounced (enrichment that is likely to be discernible using indicators used for routine monitoring; i.e. solids > 1 kg $m^{-2} \cdot yr^{-1}$ [Keeley et al. 2013; MPI 2019]). At a high-flow site with low background enrichment, such as the proposal area, farm-related enrichment may become discernible at a lower level, thus the ‘total footprint’ area will also be considered (including solids flux < 1 kg $m^{-2} \cdot yr^{-1}$). Levels of solids flux to the seabed will also be discussed with respect to corresponding levels of enrichment (approximated from Keeley et al. (2013) and MPI (2019), Table 9[15]). Higher resolution images for each farm at peak production (Stage 4 rolling peaks) provided in Appendix 10. Additional information including maximum depositional flux and areas of the predicted main and total footprints for each farm are provided in Appendix 11. Depositional modelling outputs for the Stage 4 monthly average and rolling peak scenario with the highest maximum depositional flux presented as the carbon fraction of solids flux (kg carbon$\cdot m^{-2}$) are provided in Appendix 12.

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[15] Note that these are only estimates of potential levels of enrichment because the relationship between depositional flux and enrichment effects will vary depending on site characteristics.

Table 9. Total areas (ha) predicted to receive varying levels of solids flux ($kg \cdot m^{-2} \cdot yr^{-1}$), the area of the predicted main depositional footprint (solids flux > 1 kg $m^{-2} \cdot yr^{-1}$), the area of total depositional footprint (including solids flux < 1 $kg \cdot m^{-2} \cdot yr^{-1}$) and maximum solids flux level ($kg \cdot m^{-2} \cdot yr^{-1}$) at Stage 1 (A blocks only) and Stage 4 of development for the monthly average and the four modelled rolling peak (RP) scenarios. Corresponding category of enrichment (low, moderate, high, very high) approximated from Keeley et al. (2013) and MPI (2019) for high-flow (dispersive) sites in brackets[16].

		Level of flux (enrichment categories)				Footprint area (hectares)		
		< 1 (low)	1 to 5 (moderate)	> 5 to 13 (high)	> 13 (very high)	Main footprint	Total footprint	Maximum Flux
Stage 1	Average	164	61	0	0	61	224	4.9
	RP1	124	40	10	0	50	174	7.6
	RP2	118	27	11	1	39	156	13.5
	RP3	153	33	10	0	43	196	10.7
	RP4	134	45	7	0	52	187	12.1
Stage 4	Average	387	144	2	0	146	534	5.9
	RP1	242	86	33	0	119	361	10.2
	RP2	242	57	28	4	89	330	18
	RP3	307	75	27	2	104	412	15.2
	RP4	264	102	24	1	127	391	16.1

Stage 1 (initial) production scenario

Average monthly feed discharge

The predicted main footprint (solids flux > 1 $kg \cdot m^{-2} \cdot yr^{-1}$) across all farms under the initial production scenario is 61 ha and the total footprint (including solids flux < 1 $kg \cdot m^{-2} \cdot yr^{-1}$) is 224 ha (Table 9). The maximum depositional flux predicted during the first stage of development is 4.9 kg $solids \cdot m^{-2} \cdot yr^{-1}$ (corresponding to moderate levels of enrichment, i.e. ranging from 1 to 5 kg $solids \cdot m^{-2} \cdot yr^{-1}$), directly under the pens of South farm A (Figure 35). Moderate enrichment is predicted up to 390 m from the pen edges (North farm A, Figure 35). Depositional flux less than 1 $kg \cdot m^{-2} \cdot yr^{-1}$ (corresponding to low levels of enrichment, Table 9) is predicted up to 676 m from the pen edges (North farm A, Figure 35).

Rolling peaks

The rolling peak scenario 2 has the highest maximum depositional flux (13.5 kg $solids \cdot m^{-2} \cdot yr^{-1}$, corresponding to very high enrichment), with very high enrichment predicted directly under the South farm block A pens during peak production (Figure 35). The predicted main footprint (solids > 1 $kg \cdot m^{-2} \cdot yr^{-1}$) across all farms under the Stage 1 rolling peak scenarios ranges from 39 to 52 ha and the total

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[16] These relationships were developed based on multiple year class farming where feed inputs are relatively constant. In contrast, the Hananui proposal site farms will hold a single year class at any given time, so periods of high feed discharge will be followed by periods of low to no feed input. Additionally, the sandy seabed of the proposal area differs to that for which these relationships were derived (i.e. sandy-mud and muddy-sand habitats in the Marlborough Sounds). Therefore, levels of enrichment predicted for the proposal area are estimates only. Footprints are for one-way flux scenarios modelled (without resuspension).

footprint (including solids < 1 kg·m^{-2}·yr^{-1}) ranges from 156 to 196 ha (Table 9). During periods of peak production at Stage 1, deposition greater than 5 kg solids·m^{-2}·yr^{-1} (corresponding to high enrichment, Table 9) is predicted to cover up to 11 ha (South farm A, rolling peak 2, Table 9), extending up to 180 m from the pen edges (Mid farm A, rolling peak 3; Appendix 9). Depositional flux of 1 to 5 kg solids m^{-2}·yr^{-1} (corresponding to moderate levels of enrichment, Table 9) is predicted up to 640 m from the pen edges (North farm A, rolling peak 1; Appendix 9). Depositional flux less than 1 kg m^{-2}·yr^{-1} (corresponding to low levels of enrichment, Table 9) is predicted up to 750 m from the pen edges (North farm A, rolling peak 4; Appendix 9).

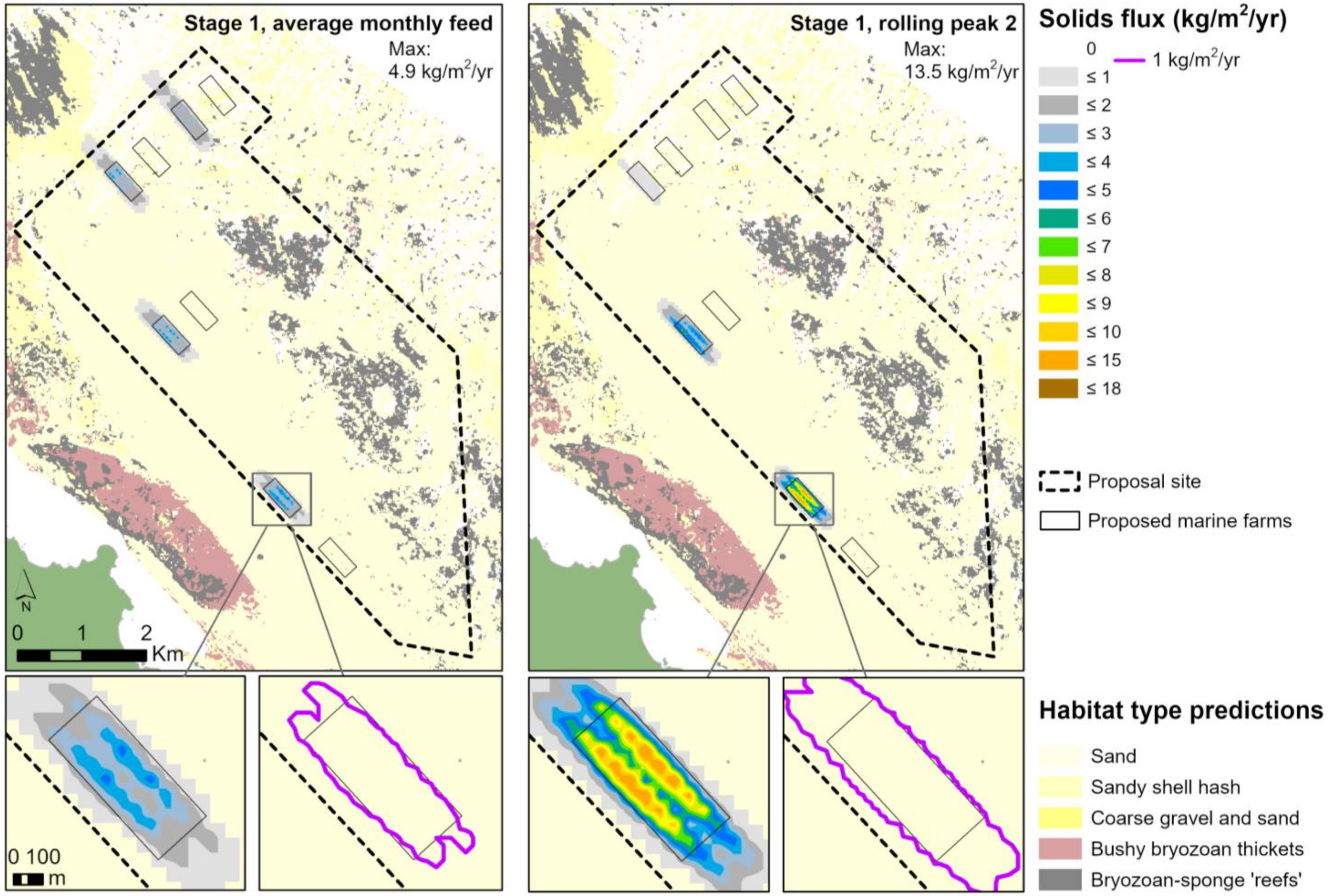

Figure 35. Depositional footprint (annual solids flux in kg per m^2) without resuspension at the intial stage of production (Stage 1, c. 10,000 tonnes feed per year) for two modelled scenarios: average monthly feed discharge **(left)** and rolling peak scenario 2 (capturing the south farm at its peak projected monthly feed discharge **(right)**. Inset maps show the farm with the highest level of solids flux and habitat type under that farm (with the 1 kg/m^2/yr flux footprint). Total areas (ha) predicted to receive varying levels of solids flux and areas of the predicted main and total footprint are provided in Table 9. Note that either the A or B block within each farm may be developed first. The Stage 1 depositional footprint for all B blocks is provided in Appendix 8.

Stage 4 (full) production scenario

Average monthly feed discharge

Using the no-resuspension model, the predicted main footprint at full production is 146 ha and the total footprint is 534 ha (Table 9). The maximum depositional flux predicted during full production is 5.9 kg solids$\cdot$m$^{-2}\cdot$yr^{-1} (South farm A, Figure 36), which is much less than the upper value in the 'high' enrichment category (13 kg solids$\cdot$m$^{-2}\cdot$yr^{-1}). Depositional flux greater than 5 kg solids$\cdot$m$^{-2}\cdot$yr^{-1} (corresponding to high levels of enrichment, Table 9) is predicted across 2 ha directly beneath the pens (South farm A). Depositional flux of 1 to 5 kg solids$\cdot$m$^{-2}\cdot$yr^{-1} (corresponding to moderate levels of enrichment, Table 9) is predicted up to 480 m from the pen edges (North farm B, Figure 36). Depositional flux less than 1 kg$\cdot$m$^{-2}\cdot$yr^{-1} (corresponding to low levels of enrichment, Table 9) is predicted up to 680 m from the pen edges (North farm B, Figure 36).

Rolling peaks

The rolling peak scenario 2 has the highest maximum depositional flux (18 kg solids$\cdot$m$^{-2}\cdot$yr^{-1}, corresponding to very high enrichment), with very high deposition predicted under the South farm block A pens during peak production (Figure 36). The predicted main footprint (solids > 1 kg$\cdot$m$^{-2}\cdot$yr^{-1}) across the rolling peak scenarios for all farms ranges from 89 to 127 ha and the total footprint (including solids < 1 kg$\cdot$m^{-2} yr^{-1}) ranges from 330 to 412 ha (Table 9). During peak production, deposition greater than 5 kg solids$\cdot$m$^{-2}\cdot$yr^{-1} (corresponding to high enrichment) is predicted across 24 to 33 ha and up to 350 m from the pen edges (North A, rolling peak 1; Appendix 9). Depositional flux of 1 to 5 kg solids$\cdot$m$^{-2}\cdot$yr^{-1} (corresponding to moderate levels of enrichment, Table 9) is predicted up to 687 m from the pen edges (North farm B, Appendix 9). Depositional flux less than 1 kg$\cdot$m$^{-2}\cdot$yr^{-1} (corresponding to low levels of enrichment, Table 9) is predicted up to 865 m from the pen edges (North farm B, Appendix 9).

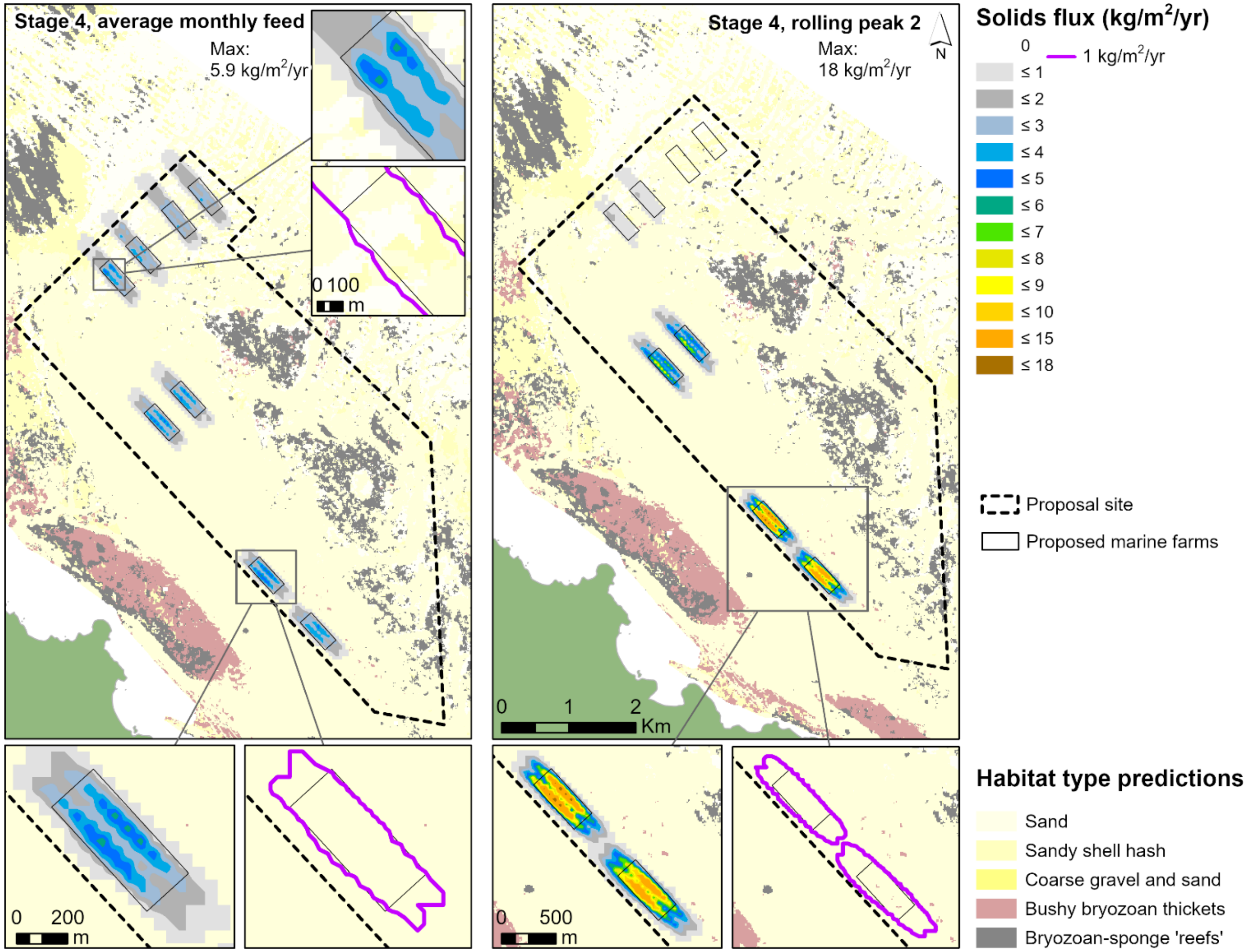

Figure 36. Depositional footprint (annual solids flux in kg per m^2) without resuspension at full production (Stage 4, c. 25, 000 tonnes feed per year) for two modelled scenarios average monthly feed discharge **(left)** and rolling peak scenario two (capturing the south farm at its peak projected monthly feed discharge **(right)**. Inset maps show the farm with the highest level of solids flux and habitat type under that farm (with the 1 kg·m^{-2}·yr^{-1} flux footprint). Total areas (ha) predicted to receive varying levels of solids flux and areas of the predicted main and total footprint are provided in Table 9.

Potential influence of resuspension on seabed deposition

Below we present outputs from the resuspension modelling (grams of residual solids per m^2) for the Stage 1 and Stage 4 monthly average (Figure 37 and Figure 39) and rolling peak scenarios (Figure 38 and Figure 40). Images are provided for the average and rolling peak scenario with the highest maximum depositional flux only (rolling peak 2, as presented above). Images for all rolling peak scenarios (sometimes resuspend only) are provided in Appendix 13. For each of these scenarios, three outputs are presented whereby particles always resuspend, sometimes resuspend and never resuspend. As discussed, the one-way flux model outputs without resuspension (above) have different units and are therefore not directly comparable to those using the resuspension model. Nevertheless, the resuspension model outputs provide a useful depiction of where farm waste is likely to go in this high-flow area (compared to the conservative one-way flux scenarios above). Resuspension modelling outputs presented as the carbon fraction of residual solids (grams of carbon·m^{-2}) are provided in Appendix 14.

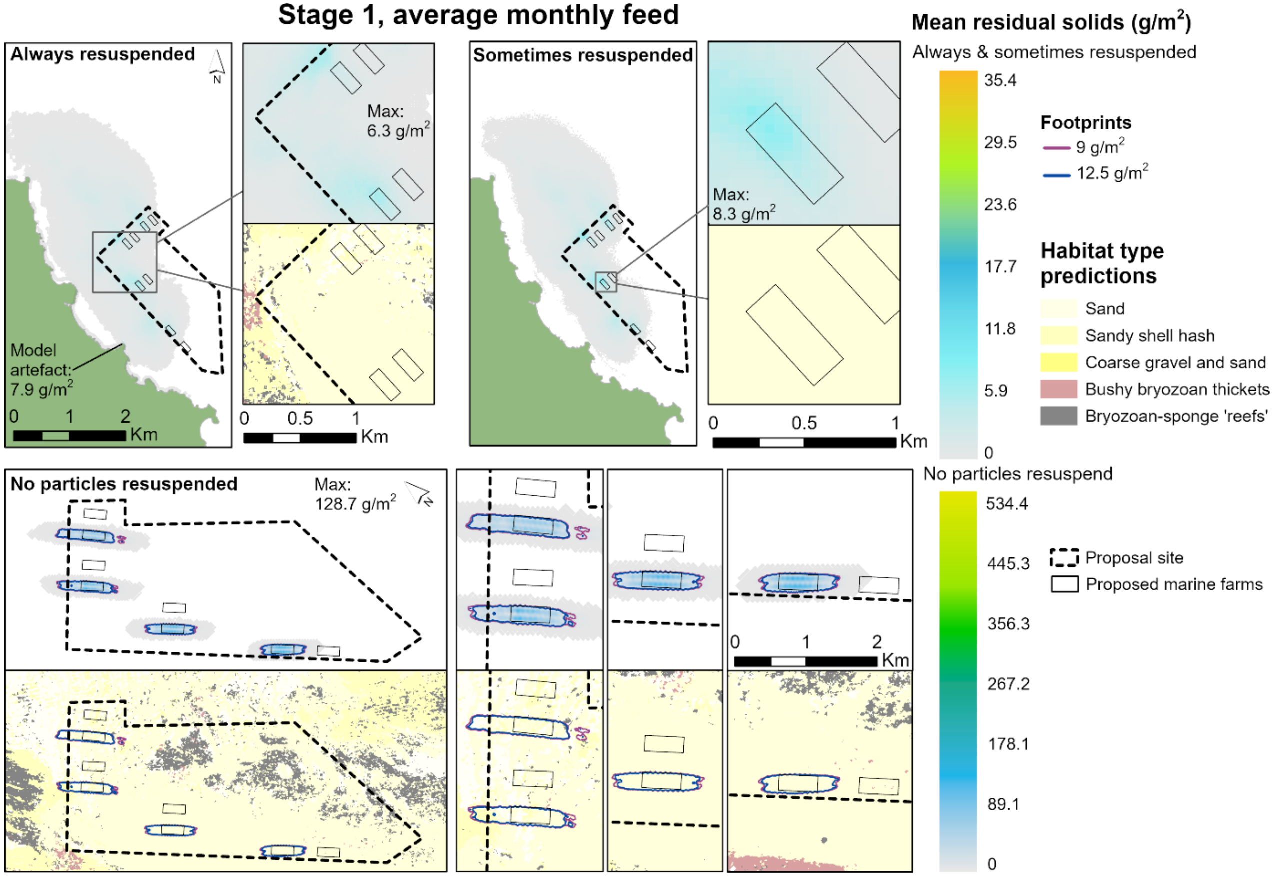

Figure 37. Predicted extent of solids deposition (g·m^{-2}) at the initial stage of production (Stage 1, c. 10,000 tonnes feed per year) for the average monthly feed discharge. Either the A or B block within each farm may be developed first. The outputs presented are for when particles always resuspend (top left) and sometimes resuspend (top right) compared to no particles resuspend (bottom panel, note the colour scale for this scenario differs to those above, to reflect the substantially higher amounts of residual solids predicted). Outputs highlight where farm waste is likely to go as well as the potential effect of resuspension on the magnitude of deposition reaching the seabed at this level of production. The inset maps for the always and sometimes resuspend scenarios show the farm with the highest level of residual solids and habitat type beneath that farm with the predicted 9 and 12.5 g·m^{-2} residual solids footprints. For the no resuspend output the habitat type beneath each farm is shown. The solids accumulation-spot on the coast (always resuspend scenario) is almost certainly an artefact of the model. These results are presented as accumulation of solids (g·m^{-2}) on the seabed which differs to one-way solids flux presented in previous figures (kg·m^{-2}·yr^{-1}).

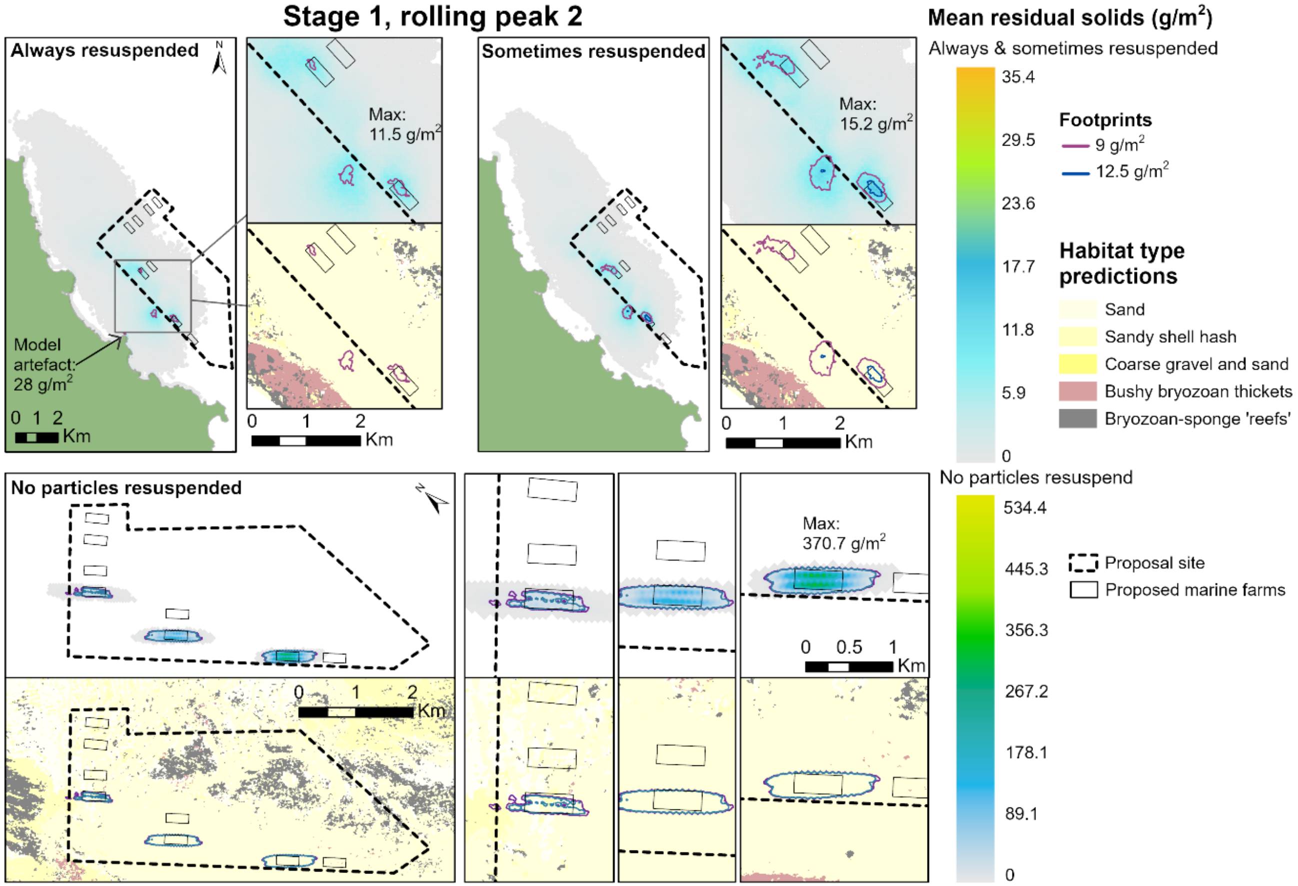

Figure 38. Predicted extent of solids deposition (g·m^{-2}) at the initial stage of production (Stage 1, c. 10,000 tonnes feed per year) for the rolling peak scenario 2 (capturing the south farm at its peak projected monthly feed discharge). Either the A or B block within each farm may be developed first. The outputs presented are for when particles always resuspend (top left) and sometimes resuspend (top right) compared to no particles resuspend (bottom panel, note the colour scale for this scenario differs to those above, to reflect the substantially higher amounts of residual solids predicted). Outputs highlight where farm waste is likely to go as well as the potential effect of resuspension on the magnitude of deposition reaching the seabed at this level of production. The inset maps for the always and sometimes resuspend scenarios show the farm with the highest level of residual solids and habitat type beneath that farm with the predicted 9 and 12.5 g/m^2 residual solids footprints. For the no resuspend output the habitat type beneath each farm is shown. The solids accumulation-spot on the coast (always resuspend scenario) is almost certainly an artefact of the model. These results are presented as accumulation of solids (g·m^{-2}) on the seabed which differs to one-way solids flux presented for the no-resuspension modelling (kg·m^{-2} yr^{-1}).

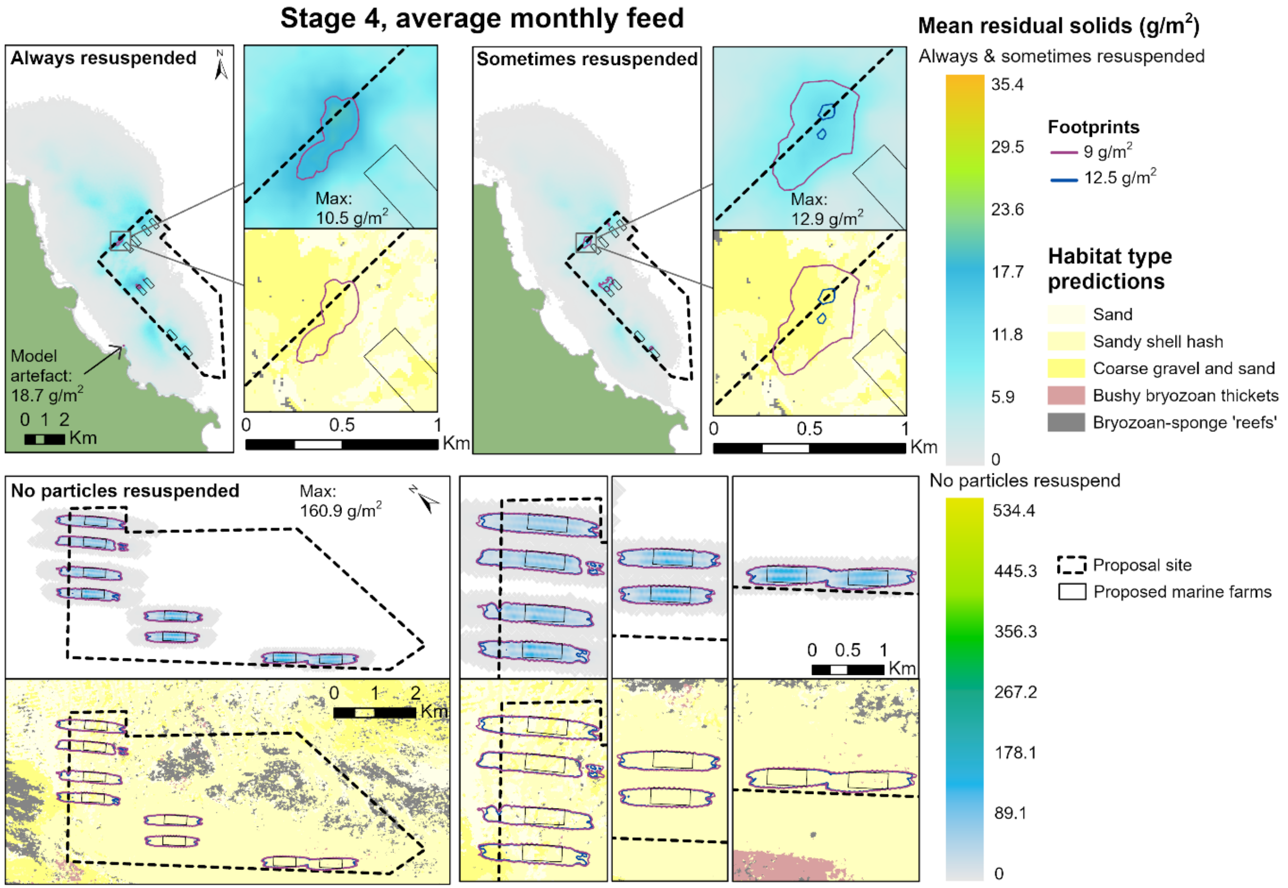

Figure 39. Predicted extent of solids deposition (g·m⁻²) at full production (Stage 4, c. 25,000 tonnes feed per year) for the average monthly feed discharge. The outputs presented are for when particles always resuspend (top left) and sometimes resuspend (top right) compared to no particles resuspend (bottom panel, note the colour scale for this scenario differs to those above, to reflect the substantially higher amounts of residual solids predicted). Outputs highlight where farm waste is likely to go as well as the potential effect resuspension could have on the magnitude of deposition reaching the seabed at full production. The inset maps for the always and sometimes resuspend scenarios show the farm with the highest level of residual solids and habitat type beneath that farm with the predicted 9 and 12.5 g·m⁻² residual solids footprints. For the no resuspend output the habitat type beneath each farm is shown. The solids accumulation-spots in inshore coastal areas (always resuspend scenario) are almost certainly an artefact of the model. These results are presented as accumulation of solids (g·m⁻²) on the seabed which differs to one-way solids flux presented for the no-resuspension modelling (kg·m⁻²·yr⁻¹).

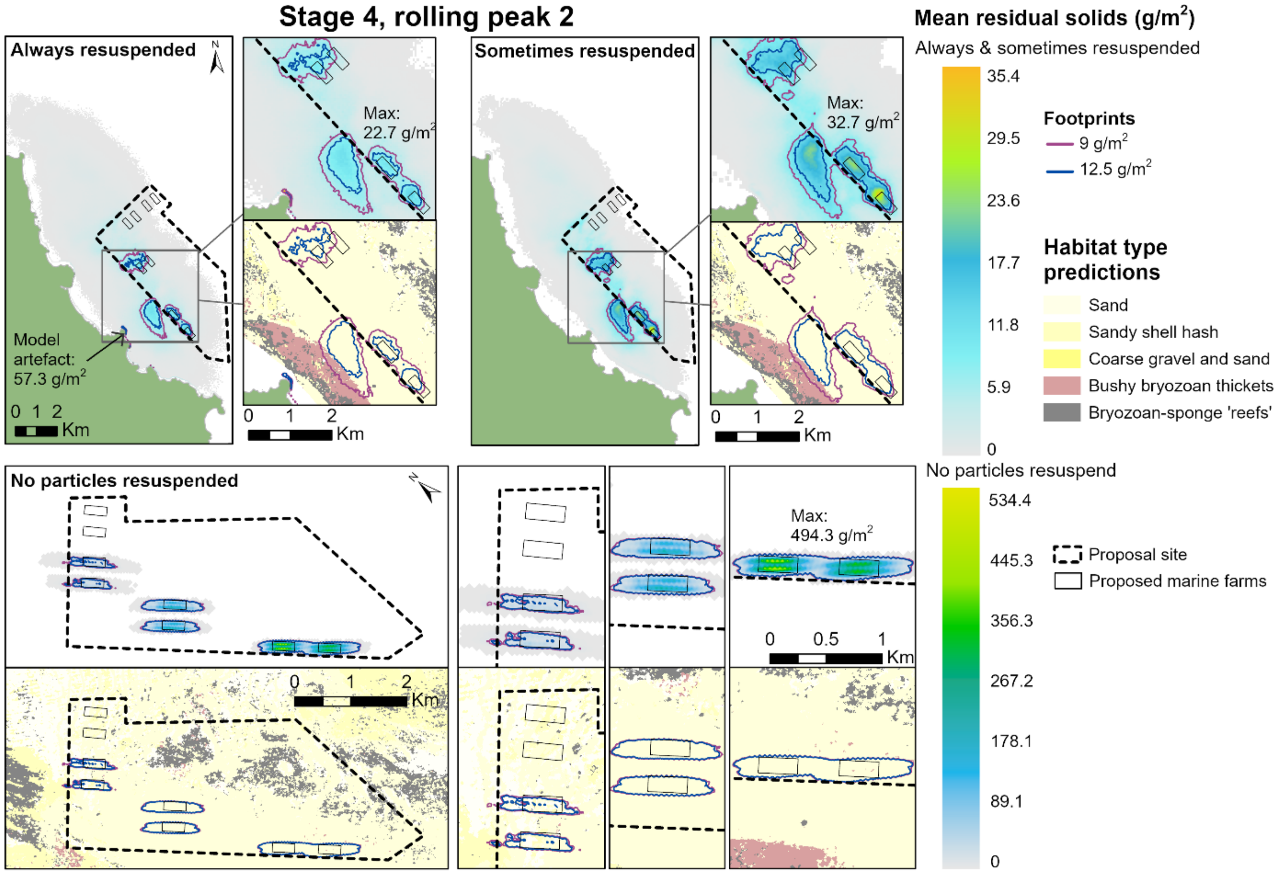

Figure 40. Predicted extent of solids deposition (g·m^{-2}) at full production (Stage 4, c. 25,000 tonnes feed per year) for the rolling peak scenario 2 (capturing the south farm at its peak projected monthly feed discharge). The outputs presented are for when particles always resuspend (top left) and sometimes resuspend (top right) compared to no particles resuspend (bottom panel, note the colour scale for this scenario differs to those presented above, to reflect the substantially higher amounts of residual solids predicted). Outputs highlight where farm waste is likely to go as well as the potential effect resuspension could have on the magnitude of deposition reaching the seabed at full production. The inset maps for the always and sometimes resuspend scenarios show the farm with the highest level of residual solids and habitat type beneath that farm with the predicted 9 and 12.5 g·m^{-2}residual solids footprints. For the no resuspend output the habitat type beneath each farm is shown. The solids accumulation-spots in inshore coastal areas (always resuspend scenario) are almost certainly an artefact of the model. These results are presented as accumulation of solids (g·m^{-2}) on the seabed which differs to one-way solids flux presented for the no-resuspension modelling (kg·m^{-2}·yr^{-1}).

The always resuspend and sometimes resuspend scenarios were similar, confirming that near-seabed current speeds in this area are higher than reported critical velocities for resuspension. The results discussed below are for the sometimes and never resuspend scenarios.

The resuspension scenarios show that at full production farm derived organic material could disperse over 10 km north-west and up to 4 km to the south-east of the proposal area boundary.

Large areas of the total footprint with resuspension for all modelled scenarios include areas with residual solids of < 5 $g{\cdot}m^{-2}$. At very low levels of deposition we would not expect significant ecological effects to manifest although, in the absence of data from the site, it is not yet possible to predict community change at low levels of deposition or to define thresholds. However, some areas of accumulated redeposition (accumulation-spots) were predicted in areas of sand / shell hash, where residual solids mass was similar to that predicted for many areas immediately adjacent to the farms, including:

- to the northern boundary of the proposal area when the north farm is at peak production (i.e. under the rolling peak scenario 1, Appendix 13).
- to the west of the proposal area when the south farm is at peak production (i.e. under the rolling peak scenario 2, Appendix 13)
- to the north-west of the mid farm when this farm is a at peak production (i.e. under the rolling peak scenario 3, Appendix 13) and
- to the north-west of the proposal area when the west farm is at peak production (i.e. under the rolling peak scenario 4, Appendix 13).

Under the initial production scenario, the maximum concentration of residual solids predicted in these accumulation-spots under the modelled rolling peak scenarios ranges from 15.2 (Stage 1 rolling peak 2) to 22.6 $g{\cdot}m^{-2}$ (Stage 1 rolling peak 3). At full production, residual solid concentrations in these accumulation-spots is 27.8 (Stage 4 rolling peak 1) to 35.4 $g{\cdot}m^{-2}$ (Stage 4 rolling peak 3).

It is important to note that while these accumulation-spots are expected during periods of peak feed discharge, at other stages of the production cycle deposition in the same area is low (i.e. < 5 $g{\cdot}m^{-2}$) or zero.

Patches of apparent moderate to high (relative to other areas of redeposition) solids accumulation in inshore coastal areas under the always resuspend scenarios (e.g. Gull Rock, Garden Point, Saddle Point as well as West Point north to Big Bungaree) are almost certainly an artefact of the model. Particles that reach the edge of the model in steep coastal areas cannot re-enter the model (i.e. cannot resuspend) and therefore apparently accumulate on steep headlands. In reality, resuspension and coastal decay processes (wave energy, sunlight) in these areas would be expected to prevent accumulation.

Across all scenarios the level of residual solids accumulation with resuspension is at least an order of magnitude less than solids accumulation predicted with no resuspension. For example, at full production under the rolling peak scenario 2, maximum residual solids with no resuspension are 534 $g \cdot m^{-2}$, while the maximum with resuspension is 33 $g \cdot m^{-2}$ (Figure 40). As discussed above, these results use a different metric to the one-way flux (no resuspension) model outputs. However, comparison of the residual solids accumulation with and without resuspension suggests that after primary deposition, resuspension is likely to greatly reduce the accumulation of solids on the seabed.

Seabed deposition from water column enrichment

In addition to deposition of farm-produced wastes, existing water column production and farm-associated water column enrichment also lead to deposition of organic material to the seabed. Increases in nitrogen in the water column are expected to lead to increases in phytoplankton productivity. In some cases, these phytoplankton will die and fall to the seabed or, if consumed by browsers and grazers, a fraction may also fall to the seabed as waste (faeces, etc.). Both processes have the potential to provide an additional indirect organic load to the seabed that has not been considered in our modelling.

Nitrogen makes up a small proportion of the waste from the farm (about 50 kg of N released per tonne of feed) but, if nitrogen is limiting, it may increase the amount of carbon ‘fixed’ (incorporated into the bodies of organisms such as phytoplankton). For every 1 kg of nitrogen, up to 5.7 kg of carbon can be captured by primary producers (i.e. phytoplankton). In the case of nitrogen released into the water column from fish farming, the potential amount of carbon fixed could therefore be up to 284 kg per ton of feed (50 $kg \cdot t^{-1}$ feed x 5.7), or 28% of the feed by weight. When we compare this to the direct carbon deposition through faeces and waste food (about 53 $kg\ C \cdot t^{-1}$ feed) the indirect deposition could be up to about five times higher. However, when we consider that the fixing of carbon occurs over several days and is subject to the strong currents in the area, it is likely that the intensity of indirect deposition of carbon from water column enrichment (i.e. indirect flux) is much smaller than the direct carbon fluxes from faeces near the net pens.

One way to estimate this indirect flux is to assume that this indirect depositional flux is proportional to the amount of N in the water column. This information is available in the water column report (Campos et al. 2020)[17] that estimated changes in nitrogen concentrations resulting from fish farming. The model employed by Campos et al.

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[17] We note that the modelling in Campos et al. (2020) is based on an old staging approach with much higher feed levels compared to those currently proposed by Ngāi Tahu Seafood.

(2020) predicts that at the Stage 1 development, the amount of total nitrogen (TN) in the water column could increase by about 10% over background levels, over an area of about 10,000 ha. At Stage 6 the increase in TN over this area is predicted to be 20 to 38%. Seabed deposition resulting from water column enrichment could be less than the increase in TN due to metabolic losses of carbon (i.e. respiration to CO_2). As a result, water column enrichment would be predicted to increase seabed deposition by less than 10% above background levels at Stage 1, and by less than 38% at Stage 6. Higher concentrations of TN are predicted near the farm (Campos et al. 2020); however, as the biological processes that would lead to increased seabed deposition take some time (days) to occur, we do not anticipate that water column enrichment would lead to substantially greater near-farm deposition.

Seabed monitoring would capture changes in the seabed due to water column enrichment, therefore any measurable effects would be detected in a monitoring programme as the proposal developed from Stage 1 to higher levels of salmon production.

6.3.5. Predicted effects of the proposal on the seabed

At full production (under the 'worst-case' modelling scenario; i.e. one-way flux without resuspension) it is predicted that up to 4 ha (ranging from 0 ha under rolling peak 1 to 4 ha under rolling peak 2) of the seabed (up to c. 0.2% of the proposal area) will receive a very high level of deposition during periods of high intensity farming prior to harvest (i.e. the modelled rolling peak scenarios: Table 9). However, under the SYC farming regime proposed by Ngāi Tahu Seafood these periods of very high deposition will be followed by periods of low to no deposition, during which a degree of seabed recovery would be expected. It is predicted that 24 to 33 ha of the seabed (up to 1.3% of the proposal area) will receive a high level of deposition of organic waste from the farms (Table 9) and a further 57 to 102 ha will receive a moderate level of deposition (Table 9). Outside of the main footprint of each farm, up to 9.5% of the proposal area (c. 242 to 307 ha, Table 9) is predicted to receive low level (0–1 kg solids$\cdot$m$^{-2}\cdot$yr^{-1}) deposition of farm-related organic waste.

Sediment properties

Seabed conditions in the middle of the footprints are expected to have altered sediment chemistry (elevated total free sulphides and reduced redox potential) due to increased microbial activity from waste decay (Hamoutene 2014). Sediment organic content will be elevated. In addition, patches of bacteria may be visible. Out-gassing (of methane and hydrogen sulphide) may be possible under conditions of very high enrichment, although as very high enrichment is only predicted during periods of peak production at the Hananui proposal site, it is unclear whether outgassing will occur.

Sediment macrofauna

When considering enrichment classifications developed from observations made from dispersive sites in the Marlborough Sounds (MPI 2019), it is predicted that at full production of the Hananui proposal site, up to 4 ha of the seabed may become 'very highly[18]' enriched during periods of high feed discharge (under the rolling peak scenario 2, Table 9). Very high enrichment can result in major reductions in community diversity and extreme abundances of opportunistic species. However, during other stages of the production cycle, when feed discharge is low or reduced to zero at these sites, sediment macrofaunal communities would be expected to show reduced effects, and possible recovery, from enrichment.

The seabed is predicted to become 'highly' enriched across up to 33 ha (rolling peak 1; Table 9), with high enrichment extending up to 350 m from the pens (North farm A; Appendix 9). High enrichment can result in major changes to sediment macrofaunal community composition. Sediment macrofaunal abundance may be very high and opportunistic taxa are likely to dominate (although other taxa may still persist, MPI 2019). It is anticipated that approximately 102 ha of the seabed in the proposal area (rolling peak 4; Table 9) will be moderately enriched (with this effect extending up to 687 m from the pens, North farm B; Appendix 9). Sediment macrofaunal abundance in moderately enriched seabed is generally elevated and macrofaunal species richness and diversity may be lower than reference conditions (MPI 2019). Opportunistic and tolerant species (e.g. capitellids, dorvilleids) are likely to begin to dominate moderately enriched communities. Enrichment levels are expected to have reduced progressively to near-background conditions within 865 m of the pen edges (North farm B, Appendix 9).

Ngāi Tahu Seafood propose a staged approach to development whereby Stage 4 (full production) will not be reached until farming is demonstrated to be sustainable for at least 12 years of lower-level production. During the initial stage of development (under the 'worst-case' / one-way flux without resuspension modelling scenario) very high enrichment is predicted only directly under the South farm block A pens during peak production. Up to 11 ha (up to c. 0.4% of the proposal area) is predicted to receive a high-level deposition of farm wastes during periods of higher feed discharge (Table 9). Up to 45 ha of seabed (c. 1.8% of the proposal area) is predicted to receive moderate levels of deposition (rolling peak 4; Table 9), with up to 143 ha predicted to receive a low degree of deposition (rolling peak 3; Table 9). This staged approach will enable monitoring and understanding of the response of the proposal area to such levels of deposition before development is increased.

The potential influence of resuspension on seabed deposition

Due to the non-cohesive nature of the coarse sediments and significant resuspension likely at the proposal area, the accumulation of organic material within the sediments

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[18] These are only estimates of potential levels of enrichment because the relationship between depositional flux and enrichment effects will vary depending on site characteristics. These relationships were also developed based on multiple year class farming whereby feed inputs are relatively constant. Whereas, the Hananui proposal site farms will be farmed as SYC whereby periods of high feed discharge are followed by periods of low to no feed input.

under and near the pens is expected to be significantly less than that predicted using the depositional model without resuspension (e.g. modelling with resuspension demonstrates the level of solids accumulating on the seabed to be at least 10 times less). However, it is important to note that even at dispersive sites where organic deposition is reduced, changes to sediment macrofaunal communities are possible (Keeley et al. 2012). These changes may include increases in abundance and diversity. Changes are particularly likely to occur at the proposal area because background organic content is low, so even a small increased organic load is likely to cause some changes to local sediment macrofaunal communities (Hyland et al. 2005).

The seabed outside the predicted primary depositional footprints (where particles first fall from the farm to the seabed) will likely be subjected to waste particles dispersed by resuspension (up to at least 10 km from the proposal area boundary). As a result, far-field effects on sediment macrofaunal communities are possible (as described above but likely milder). While levels of residual solids predicted using the resuspension-capable model are generally low, a few potential accumulation-spots were identified across a small area of the resuspension footprint during peak production at each farm. The accumulation-spots are predicted for areas dominated by sand and shell debris where up to 35 g solids·m^{-2} could accumulate at a given time[19].

If we assume that salmon-farm waste has the same density as water, 35 g·m^{-2} would equate to a layer up to 0.035 mm thick over the seabed. This would be the thickest deposition outside of the immediate area of the pens, and would only occur in the middle of the most intensive redeposition (away from the areas immediately adjacent to the pens), at the point of the feeding cycle when maximum feed inputs are occurring. In reality, small-scale hydrodynamics would lead to uneven distribution. Waste is likely to accumulate in hollows and crevices where they occur on the seabed or on and in the lee of any structures (e.g. sessile benthic organisms) on the seabed. If the waste was concentrated on only 10% of the area of the seabed, for example, the estimated layer would be 0.35 mm thick.

In terms of the organic content of the sediment, if we assume that the non-organic components of the farm-derived wastes are negligible (i.e., farm wastes have an organic content of 100%) 35 g·m^{-2} of waste in a 3-cm deep sediment core (as used in the site characterisation, see Methods in Section 3, and results in Appendix 5) equates to 1% organic content of sediment. The minimum and maximum percent organic content (AFDW) measured during the site characterisation were 0.76 and 3.10%, respectively (mean 1.80%, Appendix 5). Accordingly, organic matter in sediment cores in these accumulation-spots could temporarily double in some places.

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[19] Solids accumulation-spots in inshore coastal areas are not discussed here as these are likely an artefact of the model.

This assumes even distribution of the waste on the scale of metres, and that no waste penetrates more than 3 cm into the seabed.

Epibiota

The substratum within the boundaries of each of the proposed farms and associated depositional footprints (without resuspension) is sand with varying amounts of shell hash. Epibiota are patchy within this habitat type. Outside of the proposed farms and their respective depositional footprints are areas of high biogenic cover with sensitive species. The resuspension model demonstrates that low levels of farm-related organic waste may be dispersed up to at least 10 km from the proposal area boundary. Identified redeposition accumulation-spots are mainly restricted to sand-dominated habitats, with just minor deposition expected in areas with high bushy-bryozoan and bryozoan-sponge reef cover. Potential effects associated with farm-related deposition (near-field and far-field) are discussed below.

Effects on epibiota within the primary (without resuspension) depositional footprint

Farm placement is such that primary organic deposition and the associated effects are unlikely to overlap with areas of dense bryozoans, sponges, tubeworms and large bivalve and brachiopod species. However, where these taxa occur in low densities (including the small rock outcrop identified under south farm B) within the primary depositional footprint (where particles first fall from the farm to the seabed), suspension / filter feeding efficiencies may be reduced by increased sedimentation associated with farm-related deposition. It is likely that at high levels of deposition, populations may be reduced or completely excluded. Localised increases in epibiota abundance in response to increases in food availability may lead to aggregating scavengers and / or predators (e.g. sea cucumbers, crabs, cushion stars, snake stars). These aggregations may act as competitors (i.e. for suitable settlement space) or predators for these sensitive sessile species, particularly those in the juvenile phase. This may reduce recruitment of sensitive taxa into these areas.

Effects on epibiota outside the primary depositional footprint from resuspended organic material

Due to resuspension, it is expected that low levels of farm-related material may be dispersed into areas where bryozoans, sponges, tubeworms, large bivalves and brachiopods are abundant. These taxa are suspension feeders, and increased availability of organic particulates at low levels of deposition may lead to enhanced food supply for these organisms. Many of these taxa are likely to tolerate (or possibly benefit from) low levels of deposition. Tubeworm ‘reefs’ existing near salmon farms in Big Glory Bay are host to an array of epibiota (Smith et al. 2005). In the case of subtropical coral communities, it has been suggested that while high impacts of fish farming reduce diversity, intermediate levels of nutrient enrichment may increase diversity (Huang et al. 2011). Bryozoans may also increase their diversity in moderately organically enriched environments (Koçak 2008). However, for any of these taxa if the level of deposition is high enough, reductions in growth or survival, recruitment and abundance could occur.

Over large areas of the total farm footprint, the level of dispersed waste accumulating on the seabed outside of the farms is expected to be below ecologically detectable levels. Further to this, accumulation-spots are not predicted for areas where these communities are known to occur.

Thresholds developed for the Marlborough Sounds provides the best available information from which potential effects from residual solids to these communities can be explored. It is important to note that the relationship between residual solids levels and ‘effects’ are likely to vary depending on site characteristics (the sandy seabed of the proposal area differs to the sandy-mud and muddy-sand habitats in the Marlborough Sounds from which these thresholds were derived). Nevertheless, since this work is the only available context, these thresholds will be used to infer potential effects from residual solids at the Hananui farm site

At Stage 1 of the proposed development, larger areas of biogenic habitat where these communities are known to occur are outside of the predicted 9 $g \cdot m^{-2}$ residual solids footprint (the level of deposition at which no effect is expected, see Table 10 and Appendix 13). At full production (Stage 4) a small area of bushy bryozoan thickets (0.20 ha total across the four rolling peaks, Table 10) and bryozoan-sponge reef (5.97 ha total across the four rolling peaks, Table 10) is within the predicted 12.5 $g \cdot m^{-2}$ residual solids footprints (the level at which moderate enrichment to soft sediments is likely; Elvines et al. 2021). These values represent < 0.1% and 0.5%, respectively, of the total area of each habitat estimated to occur within the area mapped (Table 10 and Appendix 13).

Larger areas of biogenic habitat lie within the 9 $g \cdot m^{-2}$ residual solids footprint under Stage 4. Across the four rolling peaks, 18.80 ha of bushy bryozoan thickets are within the footprint (3.8% of the total area of this habitat estimated to exist within the mapped area, Table 10). The total area of bryozoan-sponge reef within the 9 $g \cdot m^{-2}$ residual solids footprint is 54.3 ha, representing 4.6% of the total area of this habitat within the mapped area (Table 10 and Appendix 13).

The rocky outcrops identified outside of the southern boundary of the proposal area are well outside both the 9 $g \cdot m^{-2}$ and the 12.5 $g \cdot m^{-2}$ residual solids footprints.

Based on the 9 $g \cdot m^{-2}$ residual solids footprint, at peak production deposition of organic material from the proposed farm could affect up to 4.6% of the area of bryozoan-sponge reef and 3.8% of the area of bushy bryozoan thickets estimated to occur within the 12,500 ha area mapped in and around the proposed site. However, at other stages of the production cycle deposition across these same areas is low (i.e. < 5 $g \cdot m^{-2}$) or zero. It is also important to note that the 9 $g \cdot m^{-2}$ residual solids threshold represents the level of deposition at which no community-level effects are expected (based on monitoring of rocky reefs around salmon farms in the Marlborough Sounds), therefore these are only proposed levels at which effects may manifest.

Near salmon farms in Norway the abundance of sponges and soft corals decline in density with increasing sedimentation from farms (Dunlop et al. 2021). However, these taxa were said to be ‘common’ again in areas greater than 200 m from the farm where the flux of total particulate matter was less than 5 to 10 $g \cdot m^{-2}$ per day (Dunlop et al. 2021). While we can’t relate such flux values to levels of residual solids, it is useful to note that the proposed farms at the Hananui proposal area are all at least 1km from large areas of biogenic habitat.

As the exact nature of effects on these taxa, and the level of deposition at which they occur, are difficult to predict in the absence of targeted research monitoring of these communities is crucial at all stages of development. Monitoring combined with the staged approach to development will enable the predicted levels of deposition to be incrementally tested, and their ecological effects (if any) monitored before development is increased.

Table 10. Areas of biogenic habitats within the residual solids footprints (12.5 g·m^{-2} and 9 g·m^{-2}) during each rolling peak of Stage 1 and Stage 4 of farm development. Areas within footprints are shown as absolute values and as percentages of the total area of the footprint and of the total area of the habitat estimated to occur in the mapped area around the proposed site (see Appendix 13). 'na' not applicable.

Footprint (g·m^{-2})	Rolling peak	Area of footprint (ha)	Area of habitat in footprint (ha)	Area of habitat in footprint as % of total footprint area	Area of habitat in footprint as % of total mapped
Bryozoan-sponge reef (total area mapped 1194 ha = 9.6% of total mapped area)					
Stage 1					
While the 9 g·m^{-2} footprint does not extend into any large areas of biogenic habitat cover, small patches occur occasionally throughout the sand dominated habitat. As a result, 0.01% of the total area of mapped bryozoan-sponge reef is predicted to receive deposition > 9 g·m^{-2} during Stage 1.					
Stage 4					
12.5	1 (North farm)	163.1	2.67	1.6	0.22
	2 (South farm)	204.9	0.0	0.0	0.0
	3 (Mid farm)	183.4	1.26	0.7	0.11
	4 (West farm)	124.5	2.04	1.6	0.17
	Total	**na**	**5.97**	**na**	**0.5**
9	1 (North farm)	307.5	6.31	2.1	0.53
	2 (South farm)	383.9	0.20	0.1	0.02
	3 (Mid farm)	294.7	1.72	0.6	0.14
	4 (West farm)	440.1	46.07	10.5	3.86
	Total	**na**	**54.3**	**na**	**4.55**
Bushy bryozoan thicket (total area mapped 499 ha = 4.0% of total mapped area)					
Stage 1					
No area of bushy-bryozoan thicket predicted to receive > 9 g·m^{-2} residual solids during Stage 1.					
Stage 4					
12.5	1 (North farm)	163.1	0.0	0.0	0.0
	2 (South farm)	204.9	0.20	0.1	0.04
	3 (Mid farm)	183.4	0.0	0.0	0.0
	4 (West farm)	124.5	0.0	0.0	0.0
	Total	**na**	**0.20**	**na**	**0.04**
9	1 (North farm)	307.5	0.05	0.02	0.01
	2 (South farm)	383.9	18.75	4.88	3.76
	3 (Mid farm)	294.7	0.0	0.0	0.0
	4 (West farm)	440.1	0.0	0.0	0.0
	Total	**na**	**18.80**	**na**	**3.77**

Protection provided by the proposal area

While the Hananui proposal area partially overlaps with the southwestern extent of the Foveaux Strait dredge oyster fishery area (Hill et al. 2010), it is predominantly outside of the main oyster beds and over the last decade a low distribution of catch has come from within the proposal (Michael 2019). Nevertheless, dredging still occurs within this area. Bryozoans, sponges, brachiopods and large bivalve species are all highly sensitive to the effects of dredging (Anderson et al. 2019), with benthic fishing activity already causing significant loss to bryozoan thickets in this region (see Michael 2007). Therefore, although far-field effects associated with organic deposition from farm operations are possible, farm infrastructure and low oyster densities may deter dredging within the Hananui proposal area.

6.4. Seabed effects resulting from farm additives

Secondary to organic enrichment effects, there are also potential impacts associated with additives in feed (i.e. zinc), antifoulants (which are often copper based), and therapeutants used to treat stock (e.g. antibiotics, parasiticides and anaesthetics). A summary of each of these potential additives, and the associated hazard and likelihood of adverse effects resulting from the proposed operation, is provided below. A summary of potential environmental effects arising from farm additives during farm operation and options to avoid, remedy or mitigate where applicable is provided in Table 11.

6.4.1. Metals (copper and zinc)

Copper contamination has, in the past, resulted from the use of antifouling paints on farm structures, including nets; however, antifouling paints are now less used in fish farming than in the past, and are not proposed for nets used at this site (pers. comm. Thomas Hildebrand, Ngāi Tahu Seafood, 2020). Zinc is an additive in fish feeds. Both copper and zinc are metals that occur naturally in the environment and are nutrients required at low concentrations by nearly all organisms. However, toxic effects can occur where these metals are concentrated in biologically available (‘bioavailable’) forms above threshold concentrations (Drever 1982). Metals can be released from finfish farming operations in quantities that have the potential to result in their accumulation within sediments beneath and adjacent to farms (Morrisey et al 2000; Sneddon & Tremblay 2011; Champeau 2013). Potential seabed effects arising from copper and zinc include:

- accumulation of metals in the sediments at concentrations which may result in toxic effects on seabed communities
- persistence of elevated sediment metals concentrations over timeframes exceeding those for organic-enrichment effects
- bioaccumulation of metals within marine organisms and uptake by higher trophic levels

- effects on reef communities in the vicinity of farms either from direct (water column) or indirect (e.g. food web) pathways.

Deposition and accumulation of metals is expected to follow the pattern predicted for deposition of organic waste (as it is mediated by settlement processes), whereby effects will be most evident directly beneath the pens and decrease with distance from the farms. However, due to the dispersive nature of the proposal area, excessive concentrations of metals are less likely to accumulate. Moreover, if anti-fouling paints are not used, metals contamination is expected to be substantially reduced. Nevertheless, it is important to consider that metals are persistent in sediments and can be resuspended and dispersed in the wider environment (Law 2019). Metals associate with finer particles, and these will disperse most widely. However, we note that at high-flow salmon farms in the Marlborough Sounds concentrations of metals fall to background levels within 200 m from the farm centre (Sneddon & Tremblay 2011).

6.4.2. Therapeutants (antibiotics and parasiticides)

Currently, there is minimal use of chemical therapeutants such as antibiotics, antibacterials and parasiticides in the New Zealand aquaculture industry, and thus little is known on their fate or effects in the marine environment here. Generally, it is thought that most therapeutants have limited environmental significance as they are usually water soluble and break down readily (Forrest et al. 2007). The main concern with these compounds is their potential to affect non-target organisms (phytoplankton and zooplankton, sediment bacteria) and the rise of resistant bacteria and / or parasites (Champeau 2013). As with metals, dispersal of (non-water soluble) therapeutants is predicted to follow the depositional pattern of organic matter discharges from farms. Therefore, if the accumulation of more persistent compounds such as zinc is managed effectively, effects from other, less persistent compounds including some therapeutants may be less problematic. Furthermore, operational practices such as fallowing and rotational use of farm sites, alongside good animal husbandry will reduce the need for therapeutants. However, should the use of therapeutants increase, effects will need to be assessed on a case by case basis and appropriate monitoring and management will be necessary.

Table 11. Summary of potential environmental effects arising from farm additives.

Potential impact	Environmental implications	Options to avoid, remedy or mitigate (where applicable)
Toxic effects on seabed biota	Deposition of metals and other contaminants from feed / substances used on farm. Persistent contaminants (e.g. zinc and copper) may accumulate in the sediments to levels that can cause toxic effects on biota. Accumulation will be mitigated by physical dispersal by strong currents at the site, and elevated concentrations should be restricted primarily to below the farms. Elevated concentrations may persist in sediments for many years following farm removal, although dispersal and dilution is expected to be high because metals associate with finer sediment particles. Effects of therapeutants include impact to non-target species and the rise of antibiotic resistant bacteria, although the effects within New Zealand marine environments are poorly known.	Monitoring of physiochemical and biological properties of sediment until contaminant levels are well understood. Avoid areas with conspicuous epifaunal communities and sensitive taxa. Use most recent antifouling technologies (seek to minimise the use of copper-based antifouling paint), net clean rather than treat with antifoulants. Fallowing and rotational use of farm sites, good husbandry to reduce the need for therapeutants.

6.5. Summary of effects

The predicted effects on the seabed from the proposed operation are summarised in Table 12. The likelihood of the effect occurring as a result of the proposed operation and subsequent significance to the seabed environment is assessed. Recommended mitigation measures are provided as a mechanism for reducing potential effects of the proposal on the seabed (see Section 7). The associated risk for each potential effect is then reassessed assuming recommended mitigation measures are adopted.

Overall, potential effects on the seabed environment have been partially avoided or mitigated from the outset by selecting for, and placing farm blocks over, soft sediment habitats (away from areas with high biogenic cover) and in an area with great flushing potential. The most significant effects identified by our assessment include:

- Effects on macrofaunal communities from deposition of organic material and potential contaminants. While the expected effects within the immediate vicinity of the farms are likely to be low due to high levels of resuspension and dispersion, deposition at lower levels is expected across a large area. Communities should be monitored in areas where the model suggests solids could accumulate.
- Effects on biogenic habitat including bushy bryozoan thickets and bryozoan-sponge reefs (and associated sensitive taxa) from deposition of organic material, and (to a lesser extent) other farm additives. The placement of the proposed farms is such that these effects should be reduced to minor. However, it is important that monitoring includes these habitats to determine whether far-field effects are occurring.

Ultimately, to ensure that effects from marine farming within the proposal area do not exceed acceptable levels, effects-based management should occur within a staged development approach. With such an approach, the potential effects of concern can be monitored, and farming practices adapted to minimise risk of unacceptable effects occurring as the scale of the development progresses (see Section 7).

Table 12. Summary of potential seabed issues resulting from the proposed activities, and overview of their significance.

Activity	***Effect***	***Proximity to 'primary' footprint***	***Environmental implications***	***Likelihood ****	***Significance *****	***Mitigation***	***Residual significance***
Mooring installation	Resuspension of sediments + physical disturbance	Within	Short-term smothering could affect feeding efficiency of some taxa. Destruction of habitats / biota. *Localised and will occur only during installation.*	High	Minor	Avoid areas of biogenic habitat. Use experienced personnel for installation.	**Less than minor**
		Outside	Unlikely to be affected.	n/a	Nil	n/a	**Nil**
Presence of structures	Biofouling drop-off	Within	Changes to physical and biological composition if biofouling colonises seabed. Deposition of fouling biota may contribute to seabed enrichment. *Dispersal range may increase at dispersive sites but only tens of metres from the cages. Recovery will be on the order of months to years following removal of structures (unless fouling organisms colonise the seabed and persist).* Fouling biota may include pest species (risks considered in the biosecurity assessment, Morrisey 2019)	High	More than minor	Avoid areas of biogenic habitat. Monitoring and management of fouling levels (see the Biosecurity Management Plan, Johnston and Forrest 2019).	**Minor**
		Outside	Unlikely to be affected. Note: structures may act as a propagule 'bank' for pest species (risks considered in the biosecurity assessment, Morrisey 2019).	n/a	Nil	n/a	**Nil**
	Shading of seabed	Within	Localised reduction in the amount of light reaching the seafloor could reduce the productivity of primary producers. Very few multicellular primary producers observed within proposal area. *Localised and reversable upon removal of structures.*	Moderate	Negligible	n/a	**Negligible**
		Outside	Unlikely to be affected.	n/a	Nil	n/a	**Nil**
Deposition	Attraction of scavengers and predators	Within	Increased abundance of scavengers and predators from attraction to biodeposits, results in increased competition for and / or predation on epibiota. *Effect reversible if feed inputs cease; recovery on the scale of months to years for community composition to return to existing state, depending on level of effect.*	Moderate	More than minor	Limit deposition on areas of biogenic habitat. Effects-based management.	**Minor**
		Outside	Localised increase in epibiota abundance. *Limited ecological significance. Effect reversible within months to years if feed inputs cease.*	Moderate	Minor	Monitoring of nearby habitats can trigger management action.	**Less than minor**
	Sediment macrofaunal communities	Within	Changes to sediment macrofaunal communities from increased organic material and altered sediment chemistry. Very high enrichment modelled beneath pens during periods of peak production. High enrichment modelled up to 350 m from pens and moderate enrichment out to ~770 m. Resuspension expected to significantly reduce levels of deposition. *Effect reversible if feed inputs cease; recovery on the order of months to years, depending on level of effect*.	High	Significant	Effects-based management. Limit feed waste. Fallow periods to allow seabed recovery. Particle dispersal modelling to identify enrichment hotspots. Monitoring to ensure intensity of deposition is as predicted, and is within the acceptable level of impact	**More than minor**
		Outside	Possible low-level enrichment effects on macrofaunal communities, particularly in accumulation-spots. *Effects reversible within months to years once feed inputs cease.*	Low	Minor	Monitoring of nearby habitats can trigger management action.	**Less than minor**
	Epibiota	Within	Alteration to epifaunal communities and sensitive taxa. *Effect will occur throughout deposition zone, but intensity will be higher in the middle. Effect reversible if feed inputs cease; recovery on the scale of months to years depending on the level of effect.*	High	Significant	Avoid areas of biogenic habitat. Effects-based management.	**Minor**
		Outside	Increased food availability for sessile filter feeders. Low-level enrichment may result in localised changes in abundance, growth and recruitment, potential increased epiphyte growth resulting in competitive exclusion, and an increased abundance of grazing species. *Possible enrichment effects, particularly in accumulation-spots and areas receiving* $> 9\ \text{g}\cdot\text{m}^{-2}$ *residual solids, reversible within months to years once feed inputs cease.*	Moderate	More than minor	Limit deposition on areas of biogenic habitat. Monitoring of nearby habitats can trigger management action.	**Minor**
	Oxygen depletion	Within	Possible near-bottom oxygen depletion immediately beneath the pens if site becomes excessively enriched. *Has ramifications for biota in overlying waters. Limited spatial extent and duration. Effects reversible within months to years once feed inputs cease.*	Moderate	More than minor	Avoid areas of biogenic habitat. Effects-based management.	**Minor**
		Outside	Minimal beyond the most impacted area of the footprint.	Low	Nil	*n/a*	**Nil**
	Farm additives	Within	Persistent antifouling and chemical constituents of feed may accumulate in the sediments. Effects of therapeutants and low-level sublethal effects on sensitive species unknown. *Primarily restricted to areas of accumulation, and/or high deposition. Persistent for duration of farm effects. Recovery on scale of years.*	High	Significant	Avoid areas of biogenic habitat. Monitoring of sediment properties and / or epibiota can trigger management action. Minimise accumulation of contaminants through farm practices (e.g. net clean rather than treat with antifoulants reduce the need for stock treatments).	**Minor**
		Outside	Minimal accumulation beyond the footprint	Low	Nil	*n/a*	**Nil**

* Likelihood of effect – n/a (not applicable), low (unlikely), moderate (possible), high (probable).

**Significance of effect - nil (no effects at all), negligible (effect too small to be discernible or of concern), less than minor (discernible effect but very limited in area or duration, or only a very slight change in existing conditions), minor (noticeable but will not cause any significant adverse effects), more than minor (noticeable that may cause adverse impact), significant (noticeable and will have serious adverse impact).

7. MITIGATION AND MANAGEMENT OF SEABED EFFECTS

The proposed Hananui farming operation may be the first of its kind and scale in New Zealand. While seabed effects arising from salmon farming are well studied in more sheltered, soft-sediment environments, the proposal area therefore presents some challenges for monitoring design. Effects at coarse-grained dispersive sites such as the proposal area will differ from those at less dispersive sites. To date, research has focused primarily on the ‘near-field effects’ of deposition of organic waste immediately under or adjacent to salmon net pens, while the far-field has received far less attention. Monitoring of effects at dispersive sites will need to consider wider ecological effects because wastes will be transported away from the immediate area of the farms. This is particularly relevant considering the areas of significant biogenic habitat within the proposal area, which warrant special consideration. Ngāi Tahu Seafood intend to take a staged approach to development. This is an important mechanism to ensure that development takes place within acceptable environmental limits. Staging will allow for assessment of effects of initial levels of farming activity, and adaptation of activity and development plans if required.

We recommend that an effects-based management strategy is adopted as a mechanism for reducing and mitigating potential effects of the proposal to ensure the farm is managed within a level of allowable effect. Given the scale of the proposed operation, and uncertainty around potential far-field effects, an adaptive approach will also need to be taken with respect to monitoring design and assessment of environmental impacts.

Best management practise (BMP) guidelines have been developed for assessment of salmon farming effects on soft sediment environments in the Marlborough Sounds (MPI 2019). These define allowable spatial extents and thresholds for salmon farm effects. Within the Marlborough Sounds context, seabed effects are managed by both a limit on the intensity of the deposition (Enrichment Stage score [ES] 5.0; see MPI 2019, roughly equivalent to a flux of 13 kg solids$\cdot$m$^{-2}\cdot$yr^{-1} at high-flow sites[20]), and a limit on the spatial extent of the area that experiences > ES 3.0, or a flux of c. 1 kg solids$\cdot$m$^{-2}\cdot$yr^{-1}. While the combination of the thresholds and the zoning approach defined in MPI (2019) may not be appropriate for the proposal area, due to the high current flows and coarse sediments at this site, these guidelines provide a framework that could be adapted.

Rocky reef environments are also monitored at some salmon farming sites (e.g. Dunmore 2022), and a monitoring programme for biogenic habitats in the proposal area will similarly be needed to ensure that habitats adjacent to farmed areas are considered in effects assessment.

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[20] sites with mean mid-water current speeds ≥ 10 cm$\cdot$s^{-1}.

As salmon farming in New Zealand moves towards operating in much more dispersive sites, it is expected that guidelines will be updated as a result of changing knowledge and understanding. Specifically, these guidelines need to be updated to consider farming effects in dispersive environments. Monitoring at the proposal area must be adaptable and should be updated to accommodate changes in activity, relevant new technology and up to date scientific information (including Best Management Practice guidance as it is developed), particularly as our understanding of farming effects in high-flow sites increases. We note that resource consents are static documents that capture only the knowledge at the time a decision is made on an application. As such, resource consent conditions that contain details specific to the design of scientific monitoring can fast become outdated. If instead, only the primary objectives of consent monitoring are provided in the consent, appropriately qualified scientists can design a monitoring programme around these objectives, without the risk of monitoring becoming outdated.

Monitoring recommendations for the proposal area are under development but will reflect the need for an improved body of information at the site to provide a context for assessment of fish farming effects. These recommendations will consider the need for far-field monitoring (e.g. in depositional accumulation-spots) and issues relevant to the assessment of high-value habitats in the proposal area (i.e. biogenic habitats). Monitoring would be designed to assess effects on seabed species, and data analysis would consider both community level measures and the presence and abundance of individual species. A community-level assessment would include changes in abundance (or cover) and diversity of species. Species identity is also an important consideration. For example, if a species is seen to reduce in abundance in the presence of seabed or water column enrichment, before large-scale community change becomes apparent, this species may be a suitable indicator for early indication of low-level effects.

In the absence of appropriate guidelines for the proposal area, site-specific limits of acceptable effect will need to be developed. We envisage that primary objectives for seabed monitoring (principles of environmental protection) will be developed or refined as a part of the consenting process in consultation with stakeholders including iwi, community and science providers. The finer detail of monitoring design and development of specific environmental standards should be captured in regularly revised Environmental Monitoring Plans (EMPs), which are a means of defining rigorous but flexible environmental monitoring requirements and methods.

In addition to siting farms away from higher-value habitats and effects-based management options, adaptive management actions to limit the effect of seabed deposition during active farming operations could include (but are not limited to):

- site fallowing / rotation to reduce intensity of impact and allow time for recovery between production cycles in a given area

  - Under the SYC farming regime proposed by Ngāi Tahu Seafood each farm site will be fallowed for at least 3 months at the end of each production cycle
- A reduction in farming intensity (reduced feed / stocking density in some areas to reduce the spatial extent or intensity of footprint).

8. KEY FINDINGS

The main findings of our seabed assessment are as follows:

- Water depths in the proposal area are 20 to 40 m and water currents are strong (depth-averaged mean current speeds of approximately 40 $cm \cdot s^{-1}$).
- The substrate across the proposal area is dominated by sandy sediments with varying amounts of gravel-sized particles (shell hash) and a small proportion of mud. The sediment is well oxygenated with low organic content. The sediment macrofaunal community abundance is low with moderate diversity.
- The five dominant habitat types are sand, sandy shell hash, coarse gravel shell and sand, bushy bryozoan 'thickets' and bryozoan-sponge reefs. The main habitat type across the proposal area is sand (c. 77% of the proposal area). Sand habitats generally have sparse epifaunal assemblages. In areas with more shell hash (sandy shell hash, covering c. 11% of the proposal area) more epifauna were observed, mainly brittle stars. Coarse gravel shell and sand (i.e. habitat with shell hash, whole shell debris, gravel and some cobbles) covered 2.7% of the proposal area. Brittle stars were the most common epifauna and some isolated biogenic clumps, mainly bushy bryozoans were observed. Bushy bryozoan thickets are areas of clown-hair-like bryozoans interspersed with calcareous tubeworms. These cover around 0.3% of the proposal area. This habitat type has high epifaunal diversity and holds taxa of ecological importance such as erect bryozoans and sponges, brachiopods and large bivalve species. Bryozoan-sponge reefs are biodiverse habitats created by erect and encrusting bryozoans, sponges and tubeworms. These reefs cover approximately 9% of the proposal area
- At the Stage 1 production level (10,000 tonnes of feed discharged per year) depositional modelling without resuspension indicated that the maximum depositional flux would be up to 13.5 kg $solids \cdot m^{-2} \cdot yr^{-1}$. This level of enrichment is expected directly under the South farm block A pens during peak production. High enrichment is predicted across 7 to 11 ha (up to c. 0.4% of the proposal area), with total footprint areas ranging from 156 to 198 ha at peak production.
- At full production (25,000 tonnes of feed discharged per year) depositional modelling without resuspension indicated that the maximum depositional flux would be up to 18 kg $solids \cdot m^{-2} \cdot yr^{-1}$ under the South farm pens during peak production, with total footprint areas across all farms and rolling peaks ranging from 330 to 391 ha. Very-high enrichment was predicted across 4 ha (range from 0 ha under rolling peak 1 to 4 ha under rolling peak 2) of the seabed (up to c. 0.2% of the proposal area) during periods of peak production. During stages of the production cycle when feed discharge is low or reduced to zero at each site, enrichment levels are expected to be much lower. High enrichment was predicted across 24 to 33 ha of the seabed (up to 1.3% of the proposal area). Enrichment levels reduce progressively to near-background conditions within 865 m of the pen edges.

- The proposed farm blocks have been placed so that primary organic deposition (where particles first fall from the farm to the seabed) and the associated effects are unlikely to overlap with areas of high biogenic cover. The substratum within the boundaries of each farm block and associated depositional footprint is mainly sand with varying amounts of shell hash. Epibiota are patchy within this habitat type. Brittle stars are the most common taxa, while bryozoans, sponges, tubeworms, ascidians, hydroids, brachiopods and large bivalve species including scallops, oysters, bearded horse mussels and dog cockles are scarce.
- Due to the non-cohesive nature of the coarse sediments and significant resuspension likely at the proposal area, sediment resuspension processes and water column transport will disperse fine waste to the far-field. Therefore, far-field effects on sediment macrofaunal and epifaunal communities are possible, although enrichment levels are likely to be much lower.
- Modelling with resuspension suggests farm-derived organic material could accumulate up to at least 10 km from the proposal area boundary. However, apart from a few potential redepositional accumulation-spots, the predicted amount of residual organic material (solids remaining after resuspension and decay processes are accounted for) is low.
- Potential depositional accumulation-spots were identified outside of the primary farm footprints (where particles first fall from the farm to the seabed) in areas dominated by sand and shell debris. These areas of accumulation are expected during periods of peak feed discharge. However, at other stages in the production cycle deposition is very low (i.e. $< 5\ g{\cdot}m^{-2}$) or reduced to zero.
- In considering residual solids thresholds developed for the Marlborough Sounds (which suggest effects to biogenic habitats and their associated communities are unlikely at or below $9\ g{\cdot}m^{-2}$ of residual solids), deposition of organic material from the proposed farm could affect up to 4.6% of the total surveyed area of bryozoan-sponge reef and 3.8% of the total surveyed area of bushy bryozoan thickets in and around the proposed site at full production. Larger areas of biogenic habitat are not expected to receive $9\ g{\cdot}m^{-2}$ residual solids or more during Stage 1.
- A comparison of residual solids accumulated with resuspension and no-resuspension suggests solids accumulation with resuspension is at least 10 times less than solids accumulation predicted with no resuspension. However, it is important to note that even at dispersive sites where organic deposition is reduced, changes to biological communities are possible.
- Effects-based management combined with a staged development approach will allow potential effects of concern to be monitored. Farming practices can be adapted to minimise risk of unacceptable effects occurring as the scale of the development progresses. These actions will ensure the farm is managed within a level of allowable effect to the community.

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11. APPENDICES

Appendix 1. Laboratory analytical methods for sediment samples processed by Hill Laboratories.

Analyte	Method	Default detection limit
Particle grain-size	Wet sieving using dispersant with gravimetric calculation applied. Seven size classes applied based on the Udden-Wentworth scale: ≥ 2 mm = Gravel ≥ 1 mm to < 2 mm = Very Coarse Sand ≥ 500 µm to < 1 mm = Coarse Sand ≥ 250 µm to < 500 µm = Medium Sand ≥ 125 µm to < 250 µm = Fine Sand ≥ 63 µm to < 125 µm = Very Fine Sand < 63 µm = Mud (Silt & Clay)	0.1 g/100 g dry wt
Organic matter (as ash-free dry weight; AFDW)	Ignition in muffle furnace 550°C, 6hr, gravimetric. APHA 2540 G 22nd ed. 2012.Calculation: 100 - Ash (dry weight).	0.04 g/100 g dry wt

Appendix 2. Definitions of community measures.

Indicator	Calculation and description	Reference
N	Sum (n) Total macrofauna abundance = number of individuals per 13 cm diameter core	-
S	Count (taxa) Taxa richness = number of taxa per 13 cm diameter core	-
d	(S-1) / log N Margalef's diversity index. Ranges from 0 (very low diversity) to ~12 (very high diversity)	Margalef (1958)
J'	*H'* / log S Pielou's evenness index. A measure of equitability, or how evenly the individuals are distributed among the different species. Values can range from 0.00 to 1.00, a high value indicates an even distribution and a low value indicates an uneven distribution or dominance by a few taxa.	Pielou (1966)
H'	$-\sum_i p_i \log(p_i)$ where p is the proportion of the total count arising from the *i*th species Shannon-Wiener diversity index (SWDI). A diversity index that describes, in a single number, the different types and amounts of animals present in a collection. Varies with both the number of species and the relative distribution of individual organisms among the species. The index ranges from 0 for communities containing a single species to high values for communities containing many species with each represented by a small number of individuals.	-
AMBI	= [(0 × %GI + 1.5 × %GII + 3 × %GIII + 4.5 × % GIV + 6 × %GV)] / 100 where GI, GII, GIII, GIV and GV are ecological groups (see Section 2.3). Azites Marine Biotic Index: relies on the distribution of individual abundances of soft-bottom communities according to five Ecological Groups (GI-GV). GI being species sensitive to organic pollution and present under unpolluted conditions, whereas, at the other end of the spectrum, GV species are first order opportunists adapted to pronounced unbalanced situations (*e.g. Capitella capitata*). Index values are between 1 (normal) and 6 (extremely disturbed)	Borja et al. (2000)
M-AMBI	Uses AMBI, S and H', combined with factor analysis and discriminant analysis (see source reference). Multivariate-AMBI. Integrates the AMBI with measures of species richness and SWDI using discriminant analysis (DA) and factorial analysis (FA) techniques. Uses reference conditions for each parameter (based on 'pristine conditions') that allows the index to be tailored to accommodate environments with different base ecological characteristics. Scores are from 1 (high ecological quality) to 0 (low ecological quality).	Muxika et al. (2007)
BQI	$= (\sum_{i=1}^{n}(\frac{A_i}{totA} \times \mathrm{ES50}_{0.05i})) \times {}^{10}\log(S+1)$ Where ES50 = expected number of species as per Hurlbert (1971) And, $\mathrm{ES50}_{0.05}$ the species tolerance value, given here as the 5th percentile of the ES50 scores for the given taxa as per Rosenberg et al. (2004). Benthic quality index uses species specific tolerance scores ($\mathrm{ES50}_{0.05}$), abundance and diversity factors. Results can range from 0 (being highly impacted) and 20 (reference conditions).	Rosenberg et al. (2004)

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Appendix 3. Particle grain-size distribution (% dry weight) and organic content (% ash-free dry weight; AFDW) of sediments from 31 sites across the Hananui proposal area.

Site	Silt & Clay % (< 63 µm)	Very Fine Sand % (63 to < 125 µm)	Fine Sand % (125 to < 250 µm)	Medium Sand % (250 to < 500 µm)	Coarse Sand % (500 µm to < 1 mm)	Very Coarse Sand % (1 to < 2 mm)	Gravel % (≥ 2 mm)	AFDW %
1	4	1.1	17	19.2	5.5	10.7	42.4	2.5
5	4	0.4	27.2	36.7	16.5	6	9.3	1.36
6	3.9	0.2	7.4	39.7	18.1	10.5	20.2	1.49
8	2.7	0.2	0.7	13.2	19.3	26.7	37.2	1.99
9	4.5	0.3	23.7	54	10.1	4.2	3.2	1.54
10	5.5	0.3	4	29.3	16.2	6.9	37.8	2.5
13	3.2	0.6	42	46.7	6.1	1	0.2	1.33
14	3.7	0.2	9.3	69.2	13.2	2.8	1.5	1.41
15	4	< 0.1	0.4	36.5	51	5.9	2.2	0.96
16	4	0.9	12	23.5	17	11.6	31	2.4
17	6.4	0.2	5.1	48.9	24.6	7.4	7.4	1.84
18	3.1	0.6	14.1	23.2	14.8	14.6	29.7	2.4
19	2.8	1	39.3	32.3	4.3	3.2	17.1	1.77
20	2.9	0.7	2.6	4.1	5.8	11.6	72.2	3.1
21	3.5	0.4	18.1	60.1	12.4	3.3	2.2	1.52
22	9.4	0.3	1.7	24.1	16.6	19	28.8	1.74
24	5	0.1	3.3	30.5	14.9	6.2	40	2
25	5.6	0.4	2.5	18.6	14.6	17.7	40.6	2.3
26	4.3	0.1	19.4	49.5	21.4	4.7	0.4	1.67
27	2.8	< 0.1	6.2	73.2	13.4	3.5	0.9	1.39
29	5.5	0.4	5	23.7	25.1	16.3	24.1	2.5
30	3.5	0.1	2.2	41.5	32.5	10.8	9.3	1.17
31	3.5	< 0.1	0.1	41.5	54.3	0.7	< 0.1	0.76
32	8.1	< 0.1	10.3	59.6	12.3	4.1	5.5	1.65
33	6.1	0.2	3.8	36.9	30.8	6.9	15.3	1.57
35	4.3	0.7	18.7	34.8	14.1	8	19.5	2.4
36	5	0.2	2.7	37.4	18.1	13.1	23.5	1.42
37	6.1	0.9	45.1	39.8	2.9	1.8	3.3	1.23
38	6.4	2.6	21.8	13	22.8	16	17.4	2.6
42	3.3	< 0.1	< 0.1	37.7	49.7	8.2	1	0.99
44	7.2	0.7	29	30.8	9.8	6.4	16.3	2.2

Appendix 4. Abundances of macrofauna in benthic grab samples from 31 sites (1 to 22) across the Hananui proposal area..

Phylum	**Family**	**Taxon**	**1**	**5**	**6**	**8**	**9**	**10**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Porifera	Unclassified	Porifera												1				
Porifera	Scyettidae	*Sycon* sp.																1
Cnidaria	Unclassified	Hydrozoa														1	1	
Cnidaria	Unclassified	Ceriantharia	2															
Nemertea	Unclassified	Nemertea				1		1		2		9			1			
Nematoda	Unclassified	Nematoda	9	1	4		5		10	9		11	1	15	7	2	8	
Sipuncula	Unclassified	Sipuncula																
Gastropoda	Unclassified	Gastropoda	3			2						1						1
Bivalvia	Unclassified	Bivalvia																2
Bivalvia	Lasaeidae	Lasaeidae														1		
Bivalvia	Ungulinidae	*Diplodonta zelandica*																
Bivalvia	Tellinidae	*Elliptotellina urinatoria*																
Bivalvia	Psammobiidae	*Gari convexa*						1										
Bivalvia	Psammobiidae	*Gari lineolata*														1		
Bivalvia	Psammobiidae	*Gari* sp.																
Bivalvia	Psammobiidae	*Gari stangeri*																1
Bivalvia	Glycymerididae	*Glycymeris modesta*			2							1						
Bivalvia	Nuculidae	*Nucula nitidula*															2	
Bivalvia	Veneridae	*Ruditapes largillierti*		1														
Bivalvia	Mactridae	*Scalpomactra scalpellum*															1	
Bivalvia	Glycymerididae	*Tucetona laticostata*																
Annelida	Unclassified	Oligochaeta	24	7	3	12	1	1	1		1	17	2	5	4	3	13	5
Annelida	Orbiniidae	*Orbinia papillosa*	1															
Annelida	Orbiniidae	*Scoloplos* sp.			1			1		1					2	1		

Phylum	**Family**	**Taxon**	**1**	**5**	**6**	**8**	**9**	**10**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Annelida	Paraonidae	Paraonidae	1	1	5			2				3			1	2		
Annelida	Paraonidae	*Aricidea* sp.																
Annelida	Spionidae	*Prionospio* sp.	1			4		2				1				5		
Annelida	Spionidae	*Prionospio tridentata*																
Annelida	Spionidae	*Spio* sp.																3
Annelida	Chaetopteridae	*Phyllochaetopterus* sp.										1						
Annelida	Capitellidae	*Barantolla lepte*										1						
Annelida	Capitellidae	*Heteromastus filiformis*																
Annelida	Capitellidae	*Heteromastus* sp.																
Annelida	Maldanidae	Maldanidae	1										2					
Annelida	Opheliidae	*Armandia maculata*		1														
Annelida	Phyllodocidae	Phyllodocidae											1					
Annelida	Piligaridae	Pilargidae														1		
Annelida	Polynoidae	Polynoidae	1															
Annelida	Sigalionidae	Sigalionidae	1		1	1				1					1		2	
Annelida	Sigalionidae	*Sigalion* sp.																
Annelida	Pisionidae	Pisionidae											1					
Annelida	Hesionidae	Hesionidae				1						1		2		1	1	
Annelida	Syllidae	Exogoninae	6	2	3			1		2		3		1	1	7	6	4
Annelida	Syllidae	Syllidae	2			4	2	1				9	1			1	4	1
Annelida	Syllidae	*Exogone* sp.							1									
Annelida	Glyceridae	Glyceridae		1					1			1					1	
Annelida	Goniadidae	Goniadidae				1												
Annelida	Eunicidae	*Lysidice* sp.																
Annelida	Lumbrineridae	Lumbrineridae														1	1	
Annelida	Dorvilleidae	Dorvilleidae			1											1	4	

Phylum	**Family**	**Taxon**	**1**	**5**	**6**	**8**	**9**	**10**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Annelida	Cirratulidae	Cirratulidae	3						3			2				3	7	3
Annelida	Flabelligeridae	Flabelligeridae	2															
Annelida	Terebellidae	Terebellidae	5	1	2								2			4	4	1
Annelida	Sabellidae	*Euchone* sp.							1									
Annelida	Sabellidae	Sabellidae													1	1		
Arthropoda	Tanaidae	Tanaidacea											1					
Arthropoda	Unclassified	Mysidacea																
Arthropoda	Unclassified	Cumacea								1		1						
Arthropoda	Munnidae	Munnidae	2									1				3		1
Arthropoda	Anthuridae	Anthuridae				2												
Arthropoda	Unclassified	Asellota										1						
Arthropoda	Unclassified	Isopoda																
Arthropoda	Aoridae	Aoridae																
Arthropoda	Caprellidae	Caprellidae		1								3		1		1		
Arthropoda	Dexaminidae	Dexaminidae														21		
Arthropoda	Haustoriidae	Haustoriidae																
Arthropoda	Lysianassidae	Lysianassidae	1									2				1		
Arthropoda	Phoxocephalidae	Phoxocephalidae	1	2	1	1	1		4	3		1		2	1	4		
Arthropoda	Stenothoidae	Stenothoidae														2		
Arthropoda	Unclassified	Amphipoda	22	4			1	1		1		2				18	11	2
Arthropoda	Hymenosomatidae	*Halicarcinus* sp.															1	
Arthropoda	Portunidae	*Nectocarcinus benetti*																1
Arthropoda	Unclassified	Brachyura															1	
Arthropoda	Cylindroleberididae	*Leuroleberis zealandica*			1													
Arthropoda	Cylindroleberididae	*Parasterope quadrata*																
Arthropoda	Paracyprididae	*Phylctenophora zealandica*																

Phylum	Family	Taxon	1	5	6	8	9	10	13	14	15	16	17	18	19	20	21	22
Arthropoda	Unclassified	Ostracoda														1		
Arthropoda	Unclassified	Copepoda																
Arthropoda	Unclassified	Pycnogonida										1					2	
Arthropoda	Pycnogonidae	Pycnogonidae																
Arthropoda	Unclassified	Acarina																1
Phoronida	Unclassified	Phoronida			2													
Bryozoa	Unclassified	Bryozoa							3							1	1	
Echinodermata	Echinoidae	*Echinocardium* spat													1			
Echinodermata	Unclassified	Asteroidea																
Echinodermata	Unclassified	Ophiuroidea															2	
Echinodermata	Chiridotidae	*Taeniogyrus dendyi*																
Echinodermata	Chiridotidae	*Trochodota dendyi*										1						
Chordata	Unclassified	Ascidiacea																
Chordata	Mullidae	Mullidae																

Appendix 4 continued. Abundances of macrofauna in benthic grab samples from 31 sites (24 to 44) across the Hananui proposal area.

Phylum	**Family**	**Taxon**	**24**	**25**	**26**	**27**	**29**	**30**	**31**	**32**	**33**	**35**	**36**	**37**	**38**	**42**	**44**
Porifera	Unclassified	Porifera															
Porifera	Scyettidae	*Sycon* sp.															
Cnidaria	Unclassified	Hydrozoa													1		
Cnidaria	Unclassified	Ceriantharia															
Nemertea	Unclassified	Nemertea			1		7				1	3		2			2
Nematoda	Unclassified	Nematoda		4	5	1	17	3	3	1	1	25	8	5	6	1	15
Sipuncula	Unclassified	Sipuncula					1										
Gastropoda	Unclassified	Gastropoda	1				1	1		1	1			1	1	1	
Bivalvia	Unclassified	Bivalvia															
Bivalvia	Lasaeidae	Lasaeidae													1		
Bivalvia	Ungulinidae	*Diplodonta zelandica*											1				
Bivalvia	Tellinidae	*Elliptotellina urinatoria*			2											1	
Bivalvia	Psammobiidae	*Gari convexa*															
Bivalvia	Psammobiidae	*Gari lineolata*												1	3		
Bivalvia	Psammobiidae	Gari sp.					1										
Bivalvia	Psammobiidae	*Gari stangeri*															
Bivalvia	Glycymerididae	*Glycymeris modesta*										1					
Bivalvia	Nuculidae	*Nucula nitidula*															
Bivalvia	Veneridae	*Ruditapes largillierti*															
Bivalvia	Mactridae	*Scalpomactra scalpellum*															
Bivalvia	Glycymerididae	*Tucetona laticostata*													2		
Annelida	Unclassified	Oligochaeta	2	5	2	2	13	2	1	1	2	7	3	1	6	1	6
Annelida	Orbiniidae	*Orbinia papillosa*															
Annelida	Orbiniidae	*Scoloplos* sp.			1												

Phylum	**Family**	**Taxon**	**24**	**25**	**26**	**27**	**29**	**30**	**31**	**32**	**33**	**35**	**36**	**37**	**38**	**42**	**44**
Annelida	Paraonidae	Paraonidae										9					2
Annelida	Paraonidae	*Aricidea* sp.														12	
Annelida	Spionidae	*Prionospio* sp.					1										
Annelida	Spionidae	*Prionospio tridentata*		1													
Annelida	Spionidae	*Spio* sp.		17			8					1			3		7
Annelida	Chaetopteridae	*Phyllochaetopterus* sp.			1		1					1					
Annelida	Capitellidae	*Barantolla lepte*															
Annelida	Capitellidae	*Heteromastus filiformis*															3
Annelida	Capitellidae	*Heteromastus* sp.													1		
Annelida	Maldanidae	Maldanidae															
Annelida	Opheliidae	*Armandia maculata*												1			
Annelida	Phyllodocidae	Phyllodocidae															1
Annelida	Piligaridae	Pilargidae															
Annelida	Polynoidae	Polynoidae															
Annelida	Sigalionidae	Sigalionidae		1								1					
Annelida	Sigalionidae	*Sigalion* sp.													1		
Annelida	Pisionidae	Pisionidae															
Annelida	Hesionidae	Hesionidae		1								1					1
Annelida	Syllidae	Exogoninae		5		3	5		8	1	1	4		1			12
Annelida	Syllidae	Syllidae	1	6			3	1		1	1	2		8	15	1	
Annelida	Syllidae	*Exogone* sp.													6		
Annelida	Glyceridae	Glyceridae		1		1				1				1			1
Annelida	Goniadidae	Goniadidae															
Annelida	Eunicidae	*Lysidice* sp.												1			
Annelida	Lumbrineridae	Lumbrineridae													1		
Annelida	Dorvilleidae	Dorvilleidae												1			

Phylum	**Family**	**Taxon**	**24**	**25**	**26**	**27**	**29**	**30**	**31**	**32**	**33**	**35**	**36**	**37**	**38**	**42**	**44**
Annelida	Cirratulidae	Cirratulidae		5								6		15	2		5
Annelida	Flabelligeridae	Flabelligeridae															
Annelida	Terebellidae	Terebellidae		3			1	1			1	4	1	2	7	3	1
Annelida	Sabellidae	*Euchone* sp.															
Annelida	Sabellidae	Sabellidae										1					
Arthropoda	Tanaidae	Tanaidacea					1										
Arthropoda	Unclassified	Mysidacea															1
Arthropoda	Unclassified	Cumacea		2			2								2		
Arthropoda	Munnidae	Munnidae					1					2					
Arthropoda	Anthuridae	Anthuridae	1														2
Arthropoda	Unclassified	Asellota															
Arthropoda	Unclassified	Isopoda													1		
Arthropoda	Aoridae	Aoridae										1			2	1	3
Arthropoda	Caprellidae	Caprellidae															
Arthropoda	Dexaminidae	Dexaminidae															
Arthropoda	Haustoriidae	Haustoriidae						1									
Arthropoda	Lysianassidae	Lysianassidae										2				1	
Arthropoda	Phoxocephalidae	Phoxocephalidae		1	3							4			5		1
Arthropoda	Stenothoidae	Stenothoidae															
Arthropoda	Unclassified	Amphipoda	9	2		1	3	1	1		1	2			8		
Arthropoda	Hymenosomatidae	*Halicarcinus* sp.															
Arthropoda	Portunidae	*Nectocarcinus benetti*															
Arthropoda	Unclassified	Brachyura															
Arthropoda	Cylindroleberididae	*Leuroleberis zealandica*										1					
Arthropoda	Cylindroleberididae	*Parasterope quadrata*															1
Arthropoda	Paracyprididae	*Phylctenophora zealandica*					1										

Phylum	**Family**	**Taxon**	**24**	**25**	**26**	**27**	**29**	**30**	**31**	**32**	**33**	**35**	**36**	**37**	**38**	**42**	**44**
Arthropoda	Unclassified	Ostracoda															
Arthropoda	Unclassified	Copepoda					2										
Arthropoda	Unclassified	Pycnogonida															
Arthropoda	Pycnogonidae	Pycnogonidae													6		2
Arthropoda	Unclassified	Acarina															
Phoronida	Unclassified	Phoronida															
Bryozoa	Unclassified	Bryozoa						1							1		
Echinodermata	Echinoidae	*Echinocardium* spat															
Echinodermata	Unclassified	Asteroidea													1		
Echinodermata	Unclassified	Ophiuroidea										1					1
Echinodermata	Chiridotidae	*Taeniogyrus dendyi*															1
Echinodermata	Chiridotidae	*Trochodota dendyi*															
Chordata	Unclassified	Ascidiacea													1		
Chordata	Mullidae	Mullidae													5		

Appendix 5. Sediment physical and chemical properties and community level macrofauna variables for grab samples in benthic grab samples from 31 sites across the Hananui proposal area, Northern Stewart Island / Rakiura. Indices include: Shannon-Weiner diversity index (SWDI), Pielou's evenness index (Evenness), Margalef richness index (Richness), AMBI biotic coefficient (AMBI), M-AMBI ecological quality ratio (M-AMBI) and benthic quality index (BQI).

Site	Depth	Organic matter	Redox	Bacterial mat	Odour	Abundance	No. taxa	Evenness	Richness	SWDI (*H′*)	AMBI	M-AMBI
unit	m	% AFDW	Eh_{NHE}, mV	-	-	No./core	No./core	Stat.	Stat.	Index	Index	Index
NTS-1	35	2.5	399	no	no	88	19	0.77	4.02	2.26	3.32	0.59
NTS-5	36	1.36	347	no	no	22	11	0.87	3.24	2.09	2.89	0.52
NTS-6	38	1.49	351	no	no	26	12	0.93	3.38	2.32	2.55	0.59
NTS-8	35	1.99	351	no	no	29	10	0.81	2.67	1.86	3.38	0.44
NTS-9	32	1.54	352	no	no	10	5	0.84	1.74	1.36	3.00	0.39
NTS-10	35	2.5	362	no	no	11	9	0.98	3.34	2.15	2.45	0.56
NTS-13	29	1.33	334	no	no	24	8	0.82	2.20	1.71	2.44	0.50
NTS-14	32	1.41	351	no	no	20	8	0.82	2.34	1.70	1.63	0.52
NTS-15	34	0.96	356	no	no	1	1	-	-	0.00	6.00	0.01
NTS-16	38	2.4	355	no	no	74	23	0.82	5.11	2.57	2.77	0.73
NTS-17	34	1.84	351	no	no	11	8	0.97	2.92	2.02	2.69	0.52
NTS-18	31	2.4	342	no	no	27	7	0.71	1.82	1.39	2.98	0.40
NTS-19		1.77	352	no	no	20	10	0.85	3.00	1.97	2.50	0.52
NTS-20	38	3.1	358	no	no	88	26	0.81	5.58	2.63	1.93	0.85
NTS-21	35	1.52	321	no	no	73	20	0.87	4.43	2.61	2.85	0.69
NTS-22	37	1.74	396	no	no	27	14	0.93	3.94	2.45	3.88	0.55
NTS-24	31	2	412	no	no	14	5	0.70	1.52	1.13	3.50	0.31
NTS-25	35	2.3	409	no	no	54	14	0.85	3.26	2.24	2.98	0.59
NTS-26	24	1.67	423	no	no	15	7	0.91	2.22	1.77	1.86	0.52
NTS-27	30	1.39	409	no	no	8	5	0.93	1.92	1.49	3.81	0.34
NTS-29	37	2.5	406	no	no	69	18	0.82	4.02	2.36	2.69	0.65
NTS-30	34	1.17	416	no	no	11	8	0.95	2.92	1.97	3.63	0.46
NTS-31	30	0.76	414	no	no	13	4	0.74	1.17	1.03	4.13	0.30
NTS-32	22	1.65	417	no	no	6	6	1.00	2.79	1.79	3.50	0.42
NTS-33	32	1.57	382	no	no	9	8	0.98	3.19	2.04	4.25	0.42
NTS-35	32	2.4	409	no	no	79	21	0.81	4.58	2.47	2.47	0.72
NTS-36	32	1.42	411	no	no	13	4	0.74	1.17	1.03	3.56	0.30
NTS-37	32	1.23	413	no	no	40	13	0.77	3.25	1.99	3.27	0.52
NTS-38	35	2.6	407	no	no	88	25	0.89	5.36	2.86	2.01	0.87
NTS-42	37	0.99	418	no	no	22	9	0.72	2.59	1.59	1.80	0.53
NTS-44	35	2.2	409	no	no	68	20	0.84	4.50	2.53	2.75	0.71

Appendix 6. Predictive habitat map - multibeam data ground truthing and analysis.

A6.1 Introduction

High resolution MBES (multibeam echosounders) have been instrumental in a number of studies which have demonstrated the relationships between backscatter intensity and sediment type as well as bathymetry and bathymetric derivatives with seafloor features and corresponding biogenic habitats (reviewed in Brown et al. 2011). These relationships have been combined with machine learning and other statistical approaches to use these environmental variables to predict the extent of, or suitability of an area for biogenic habitats (Trzcinska et al. 2020; Xu et al. 2021).

A6.2 Methodology

A6.2.1 Multibeam data processing / model inputs

Predictor variables used in the model included the bathymetry and backscatter data as well as geomorphic statistics extracted from the bathymetry datasets, and the maximum current velocities in the area. Bathymetric predictors included the slope, curvature, (calculated from the bathymetry surface using the Benthic Terrain Modeler toolbox for ArcGIS, Walbridge et al. 2018) and Terrain Ruggedness Index rugosity (height difference between a central and the adjacent cells in the raster, calculated using the spatialEco package in the R environment). Additionally, Textural statistics from the bathymetry, bathymetry derivatives, and backscatter were derived from grey-level co-occurrence matrices (these included 'mean', 'variance', 'homogeneity', 'contrast', 'dissimilarity', 'entropy', 'second moment', and 'correlation'), using the package glcm (Zvoleff 2020) within the R environment. The texture analysis allowed the variability of the sea floor to be quantified and included as predictor variables.
To include current velocities as a predictor into the model, a raster of maximum current velocities was calculated from a dataset of ocean currents derived from two spring neap cycles (29.2 days) from the 1st of December 2018. Because the data points from the current dataset were not evenly distributed across the area of interest, we interpolated the maximum values using an inverse distance weighted method (Pebesma 2004; Benedikt et al. 2016).

All predictor variables were initially calculated as 1-m^2 resolution rasters and resampled to a resolution of 10 m^2 using a bilinear interpolation, where the new value of a cell is based on a weighted distance average of the four nearest input cell centres. This was to account for inaccuracies in ROV due to how the Ultra Short Base Line (USBL, a method of underwater positioning) calculates the position of the ROV. The USBL calculates the position of the ROV by measuring signals between the unit attached to the ROV and the transceiver and calculates the range (time between singles) and angle between them. Typically, accuracy is 2% of the slant range (distance across planes, approx. 100 m in our case or a 2 m error), however, other factors such as uncalibrated boat movements and the signal frequency can increase the error, leading us to use a 10 m estimate of error and consequently resample the predictor variables to 10 m^2 rasters. These were used as predictor variables to train the model, using drop camera and ROV imagery of habitats as response variables.

A6.2.2 Ground truthing

Ground truthing data came from three different surveys:

- Drop camera surveys designed to ground truth side-scan sonar collected across six surveys from 2018 to 2021
- ROV survey designed to observe the seabed under potential farm locations (October 2021)
- ROV survey designed to ground truth the DML multibeam imagery (July 2022)
- ROV survey to validate initial model results (September 2022).

All of the imagery was collected with an associated geolocation. For the drop camera surveys this was the GPS on the boat, whereas for the ROV surveys, a USBL system was used, enabling the ROV and imagery to be tracked separately from the boat. The USBL sends a location ping back to the receiver every three seconds. The positions of each of these pings were used as the input points for the model.

The imagery from these surveys were classified into five classes:

- Bryozoan-sponge ‘reefs’
- Bushy bryozoan thickets
- Sand
- Sandy shell hash (SSH)
- Coarse gravel with sand and shell (CGSS).

The bryozoan-sponge ‘reef’ and bushy bryozoan thickets are described in the AEE, whereas the substrate (sand, SSH and CGSS) related categories were all described under the ‘sand’ habitat type in the AEE. From these surveys 8442 points labelled with the habitats observed, timestamps and locations were collected (Figure A6.1).

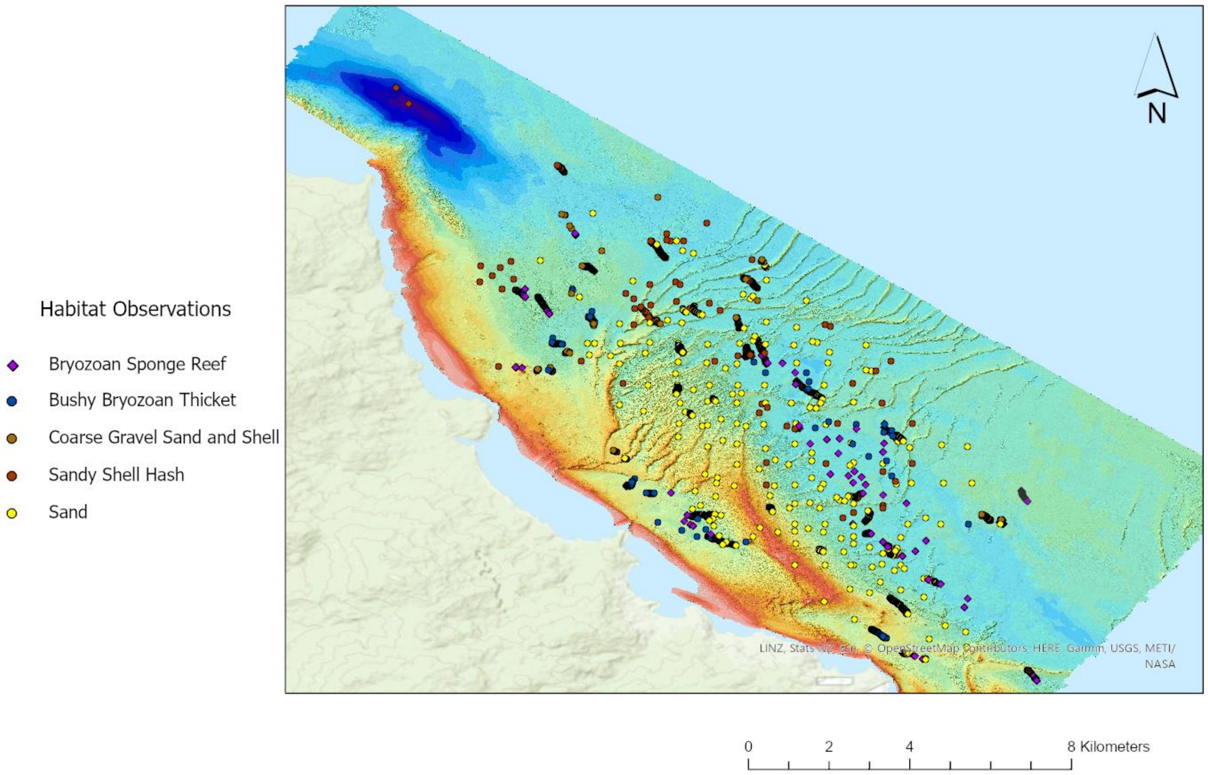


Figure A6.1. All drop camera and ROV imagery collected and used in the ground truthing of the predictive model.

A6.2.3 Model validation / performance

The raster layers for each predictor variable were sampled using the locations of the ground truthing points to obtain the inputs for the benthic habitat predictive model. The modelling approach used an Extreme Gradient Boosting model. This model is an implementation of gradient boosted decision trees, a class of machine learning algorithms which can be used for classification or regression predictive modelling problems. This technique works by sequentially creating an ensemble of weak predictive models, with each new model attempting to correct for the deficiencies in the previous model (Friedman 2001). For this, we used the packages xgboost (Chen et al. 2022) and caret (Kuhn 2022). To cross-validate the model outputs we divided the ground truthing data into two equal datasets and used 50% of the data for training the models, and 50% of the data to test the resulting best model. From this cross-validation we analysed two model evaluation metrics, accuracy and Cohen’s Kappa. Accuracy is the percentage of correct classifications out of all instances, and Cohen’s Kappa is the accuracy normalised at the baseline of random chance on the dataset (agreement between categories). Cohen’s Kappa is useful as accuracy can be unclear when the classification problem has more than two classes; we also analysed the confusion matrices which visualise the model performance. Lastly, we obtained metrics concerning the variable importance for the models. Variable importance is determined by calculating the relative influence of each variable dependent on if the variable was used during the tree building process, and how much the squared error (over all trees) improved or decreased as a result. The best performing model was then used to predict the habitat classes for the whole area, using the 10 m raster information (bathymetry, bathymetry derivatives, backscatter and their texture variables).

Because the 50% of data used for training purposes was randomly selected, the resulting best model and predictions could potentially be influenced by the choice of training set. Therefore, we ran the above process 100 times to analyse the average model evaluation metrics, the average confusion matrix, and determine the uncertainty in the results for each class of habitat. We also calculated the average variable importance, and their standard deviation. In the resulting percentage-based predicted benthic habitat raster, each pixel represents the most common class that was predicted out of 100 iterations of the process. Additionally, a probability raster was created for each class representing the number of times that each pixel was predicted to be that class from the 100 iterations.

A6.3 Results

A6.3.1 Mapping / discrimination of ground truth samples

From the inputs, the model classified 12,469 ha of the benthic environment into the habitat categories (Figure A6.2). Of this area, 1,194 ha (9.5%) was classified as bryozoan-sponge ‘reefs’, 499 ha (4.0%) was classified as bushy bryozoan thickets, 2069 ha (16.6%) was classified as coarse gravel and sand, 5594 ha (44.9%) was classified as sand, and 3113 ha (24.9%) was classified as sandy shell hash.

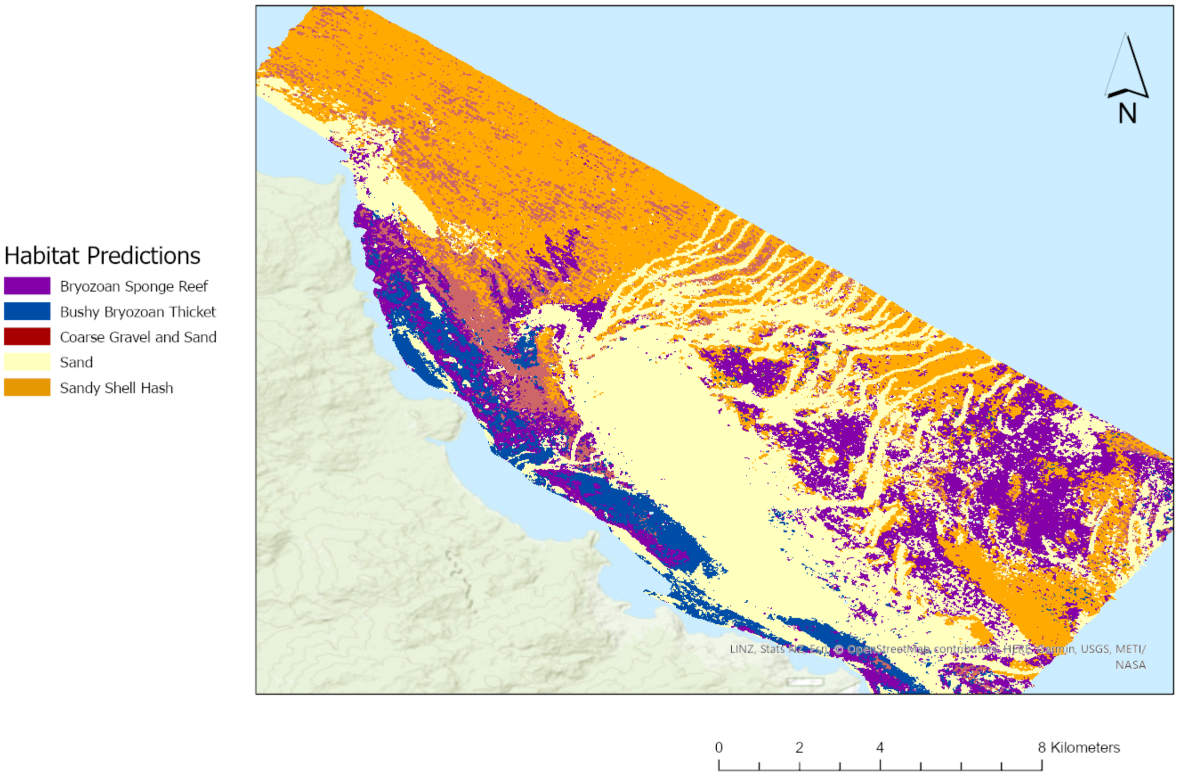


Figure A6.2. Map of the predicated habitats using 50% of the ground-truthed data as the training set.

A6.3.2 Accuracy and model performance

When using 80% of the data as a training data set, the model accurately predicted 84.2 ± 0.4% of the test data points, with a Cohen’s Kappa of 0.78 ± 0.06 indicating substantial agreement between the classes (Landis & Koch 1977). Sand had the highest accuracy percentage (94.1%), followed by coarse gravel sand and shell (84%),bryozoan sponge reef (82%), sandy shell hash (79%), and bushy bryozoan thickets (73%) (Table A6.1).

Table A6.1. Confusion matrix for the predictions from the model using 80% of the data as the training data set. The top ‘Actual’ row indicates what the ground-truthed assessment of that spot was and the 'Prediction' column indicates what percentage of the time the model predicted that cell to be. BS Reef = bryozoan-sponge ‘reef’, Bushy Bry = Bushy bryozoan thickets, CGSS – Coarse gravel, shells and sand, Sand = Sand, SSH = Sandy shell hash. Percentages reflect the frequency each ground truth spot (actual) were predicted to be that type by the model. Green cells indicate the accuracy for each habitat type.

		Actual				
		BS Reef	Bushy Bry	CGSS	Sand	SSH
Prediction	BS Reef	82%	9%	7%	2%	4%
	Bushy Bry	1%	73%	0%	1%	0%
	CGSS	5%	2%	84%	2%	4%
	Sand	10%	15%	6%	94%	13%
	SSH	2%	1%	2%	2%	79%

A6.3.3 Variable importance

The maximum current velocity was observed to be the most important variable in predicting the habitats (Figure A6.3). In next order of importance were the bathymetry and backscatter textural statistics. These variables represent a range of geomorphological features and the overlying hydrographic environment, which either drive the patterns of species distribution or represent benthic biological features (i.e. structures) that can be detected in the environmental data layers (Brown et al. 2011; Trzcinska 2020).

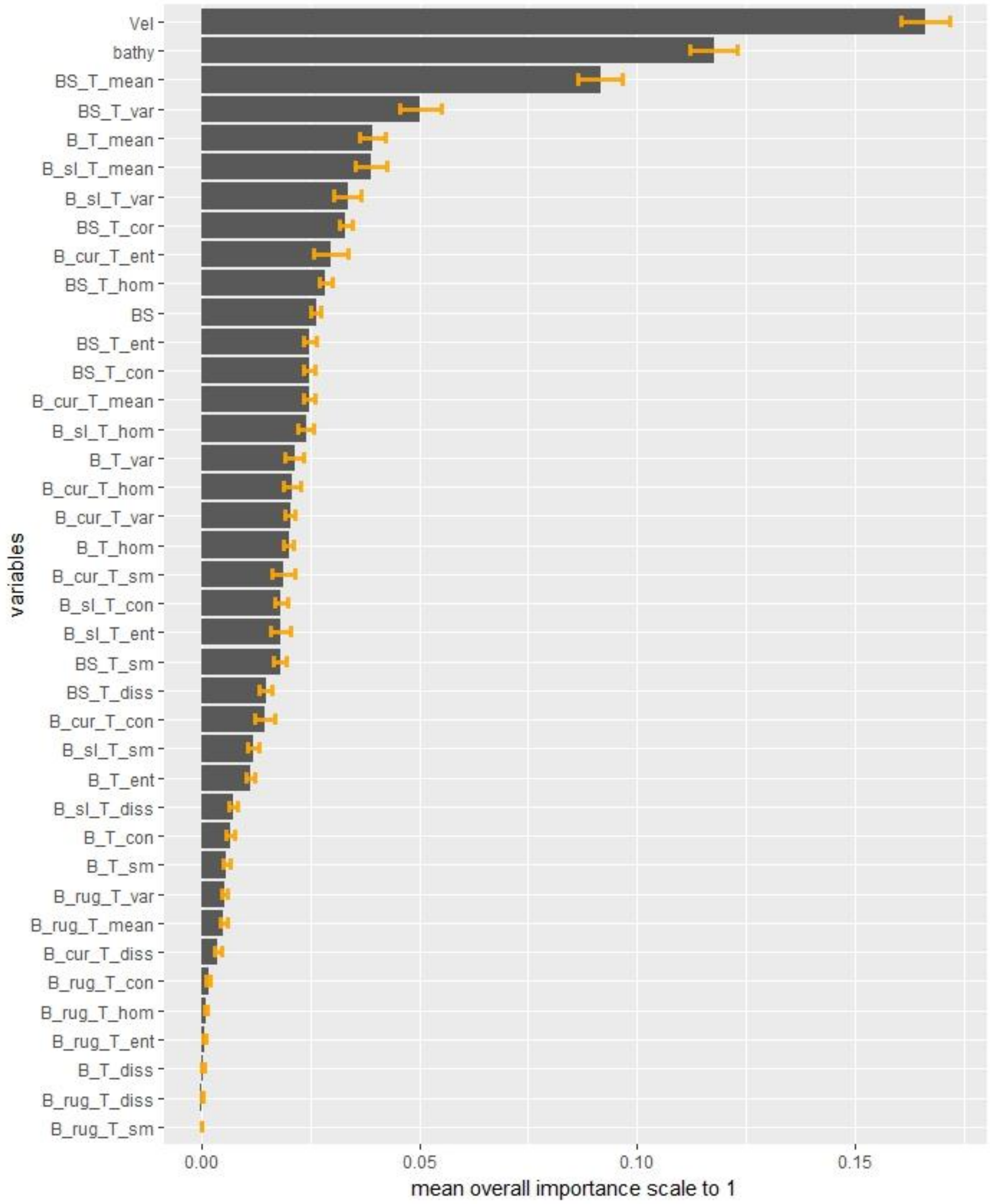


Figure A6.3. The mean importance of each input parameter into the final prediction model. Error bars indicate the variance over the 100 model runs of the uncertainty assessment. Vel = max current velocity, BS = Backscatter, B = Bathymetry, T= texture analysis, var = variance, cor = correlation, hom = homogeneity, ent = entropy, sm = second movement, diss = dissimilarity, sl = slope, cur = curvature, rug = TRI rugosity.

A6.3.4 Uncertainty assessment

The uncertainty assessment (Figure A6.4) observed that within the primary areas of biogenic habitat the predictions were consistent between the 90 model iterations. The habitats were more likely to vary between different groups on the edges of these primary areas, indicating a predictive buffer or area of uncertainty, which was typically only a few pixels (10s of m) wide. The frequency of percent classifications (Figure A6.5) shows that for both the bushy bryozoan and bryozoan sponge reefs there were very few classifications between 30 and 80%. This indicates that the model was consistent in predicting the habitats regardless of the training data set selected and is in agreement with the Cohen's kappa metric.

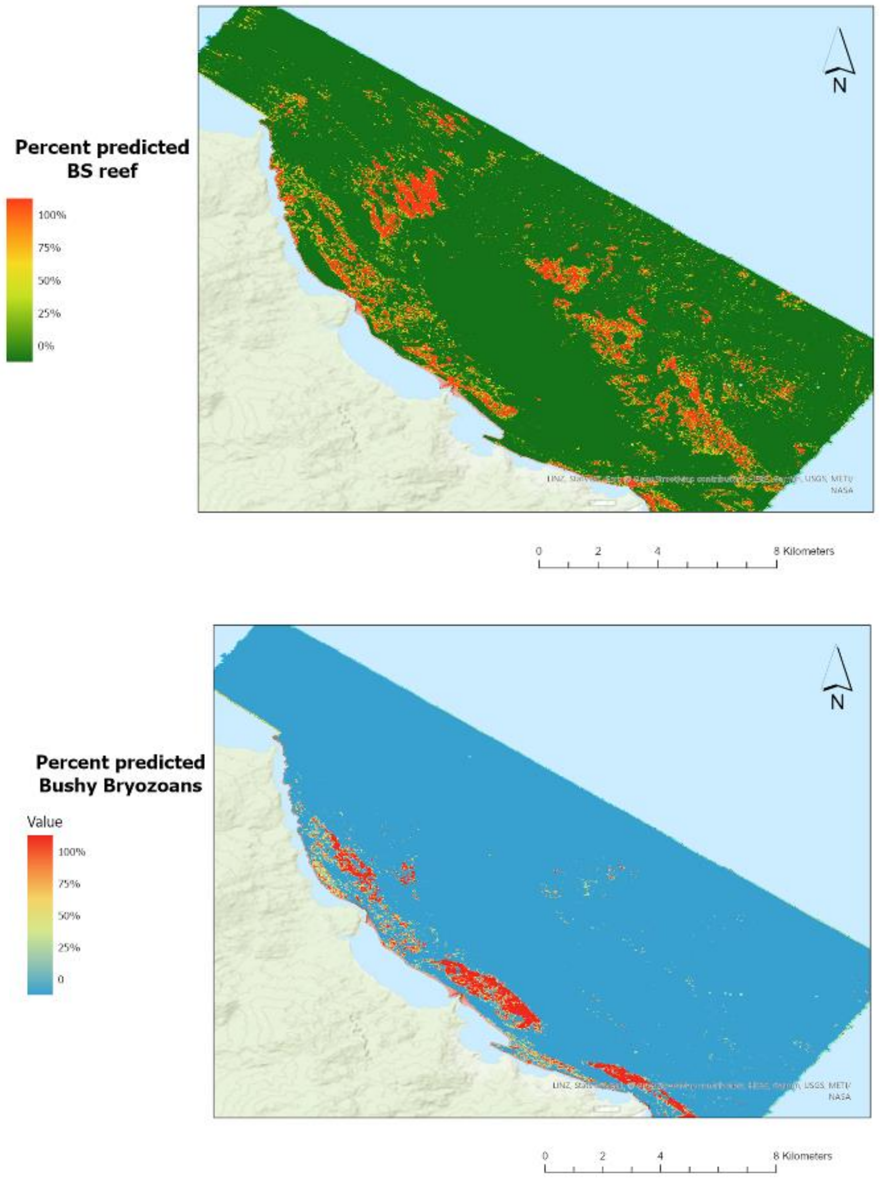
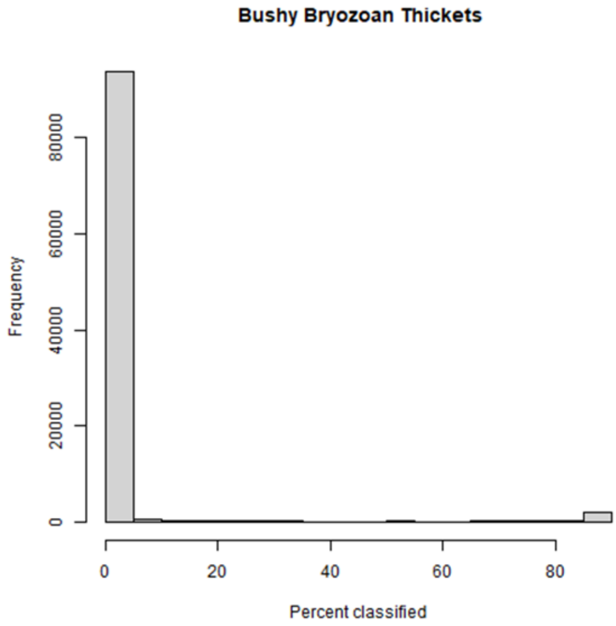


Figure A6.4. Maps of the percentage of model iterations which categorised each 10 x 10 m pixel into the bryozoan-sponge 'reef' (top) or bushy bryozoan thicket (bottom) habitats across the 90 model runs.



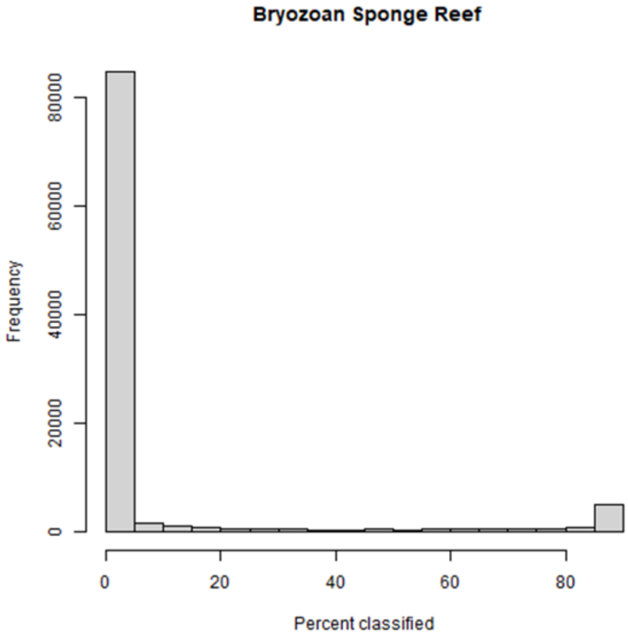


Figure A6.5. Histograms of the frequency each 10 x 10m pixel was classified into either the bushy bryozoan (top) or bryozoan-sponge 'reef' (bottom) categories.

Appendix 7. Depositional modelling methods.

Depositional modelling was undertaken using a new in-house-developed particle tracking tool called VenOM (Vennell's OceanTracker model). This new tool has significant advantages over the traditional model DEPOMOD (Cromey et al. 2002; Smeaton & Vennell 2020), including:

- removal of limitations on the number of cages, particles and extent of the modelled area,
- ability to use spatially varying currents (3-D hydrodynamic model or multiple ADCPs), and
- freedom to include/exclude cages from modelled stages and change feed levels without re-running the (time consuming) particle tracking aspect of the model.

A recent report compares one-way flux results from DEPOMOD and VenOM at two sites and shows they give similar results for non-resuspending particles (Smeaton & Vennell 2020).

Here we outline the depositional model results used for this project, which include resuspension of material. The 3D MetOcean-developed hydrodynamic model (see Campos et al. (2020) for further details) of the area was used to describe the currents in Foveaux Strait. This model has not been formally validated but shows good agreement with measurements taken in Campos et al. (2020). Particle movements in VenOM are dispersed by currents and a random walk based on constant vertical and horizontal dispersion coefficients with values of $D_v = 0.001$ m^2 s^{-1} and $D_H = 0.1$ m^2 s^{-1}, respectively.

Model particles were released from eight depths between the bottom of the cage and the sea surface. At each release depth, particles were released at random locations within the circular cage perimeter of radius R:

$$\mathbf{x}_0 = \mathbf{x}_C + (\mathrm{rand}\, R\cos[\mathrm{rand}\, 2\pi], \mathrm{rand}\, R\ \sin[\mathrm{rand}\, 2\pi], z_0), \quad \text{rand} \in [0,1].$$

Here, $\mathbf{x}_0$ is the particle release point and $\mathbf{x}_C$ is the cage centre. Two particles were released from each depth in each cage every hour, one representing wasted feed pellets, and one particle representing faeces. Thus, a total of sixteen particles were released per cage per hour. Sinking velocities of 0.032 m s^{-1} and 0.095 m s^{-1} were used for faeces and feed pellets, respectively (Cromey et al. 2002). Once released, particles drifted according to the velocity field and their paths were modelled using a fourth order Runge-Kutta solver with a time step of Δt = 30 seconds. At each time step, a random walk adjustment was applied to account for turbulent effects such that the final particle position ($\mathbf{x}_f$) differed from the initially calculated position ($\mathbf{x}_i$) by:

$$\mathbf{x}_f = \mathbf{x}_i + \left(\mathrm{randn}\sqrt{6\,\Delta t\, D_H}, \mathrm{randn}\sqrt{6\,\Delta t\, D_H}, \mathrm{randn}\sqrt{6\,\Delta t\, D_v}\right)$$

where randn is a random number drawn from a normal Gaussian distribution. Once the random walk adjustment was made, particle depths were checked against local bathymetry data, if the particle depth was equal to or deeper than the total depth at the particle's *x-y* location, the particle was removed from the simulation.

Upon completion of the particle tracking simulation, particles were assigned a mass value according to the feed loadings for the scenario being modelled (i.e. Table 7 and Table 8), and whether particles were representative of food or faeces (see values given in Table A6.1). Particles were then binned into a 25 m by 25 m grid (the near-cage hydrodynamic model resolution) in the case of no-resuspension and a 50 by 50 m grid for cases with resuspension. The reason a larger bin size was used for the resuspension results is that the extent of dispersion was much greater for this scenario. Mean flux and mean residual solids values were averaged over the last spring-neap cycle of the simulation.

Table A6.1. Input values used for depositional modelling. All values taken from Cromey et al. (2002).

Parameter	**Value (%)**
Food wasted as % of food fed, f_w	3
Water content of feed, f_{H2O}	9
Digestibility, f_d	85
Carbon % of food pellets (dry weight)	49
Carbon % of faeces (dry weight)	30
Fraction of feed wasted to floor (dry weight) $(1 - f_{H2O})f_w$	2.7
Fraction of feed converted to faeces (dry weight) $(1 - f_{H2O})(1 - f_w)(1 - f_d)$	13.2

Resuspension

Resuspension of particles from the seabed occurs when the shear velocity near the seabed exceeds a critical threshold. The factors governing particle resuspension are complex, and not only depend on particle size/density, but also substrate type (e.g. cohesiveness, rugosity) (Law 2016). Choosing an 'optimal' velocity threshold beyond which particles resuspend is a contentious problem (Keeley et al. 2013), and values for such a threshold vary between studies. Cromey et al. (2002) use a hard-coded near-seabed velocity of 0.095 m/s in DEPOMOD, while Law (2019) propose individual critical shear-velocities of 0.009 m/s and 0.015 m/s for faeces and food pellets, respectively (and additional thresholds to account for fine-grained and flocculant particles).

We used the simple approach of modelling faeces and food pellet resuspension in VenOM, using the threshold values given in Law (2019). Therefore, using currents from a spatially varying 3-D hydrodynamic model, particle resuspension occurred when bed shear-velocities exceeded 0.009 m·s^{-1} (for faeces pellets), or 0.015 m·s^{-1} (for feed pellets). Once exceeded, particles on the seafloor were resuspended using a random jump calculated by:

$$\Delta z = \left(\text{randn}\sqrt{6\,\Delta t\, D_v}\right)\Delta t,$$

where the bracketed term is the same expression as the random walk correction in the vertical direction and Δt is the model time step.

Particles can resuspend indefinitely in VenOM, however their mass decays over time due to microbial and macrobial consumption and oxidation. To model this mass loss a decay function was applied to all particles in the resuspension model. Particles mass decays upon release according to an exponential decay law:

$$m(t) = m_0 e^{-Kt}.$$

Here $m(t)$ is the mass of the particle at time t, m_0 is the original particle mass at the time of release and K is the decay constant. Particle decay was estimated from macrofauna respiration rates given in Figure 8 of Keeley et al. (2019). These measured values are from an Atlantic salmon farm off the central west coast of Norway (production 9 kt·yr^{-1}). Measurements were taken near the beginning and end of the production cycle at distances between 0 and 600 m from the farm cages. Particle decay can vary with environment but in the absence of site-specific data, Keeley et al. (2019) is the best indication of decay rate that we have. Note that changing the decay rate will not affect the location of hotspots, but will affect their intensity.

Mean mass flux was approximated from Figure 8 of Keeley et al. (2019) as 12 gC·m^{-2}·d^{-1}. Mean macro-fauna respiration was approximated as 1 gC·m^{-2}·d^{-1}. Assuming exponential decay:

$$m = m_0 e^{-Kt},$$

where after one day, over 1 m^2: m_0 = 12 gC, m = 11 gC, t = 1 d

$K = -\ln\frac{11}{12}$ or K = 0.087 d^{-1}

We believe this decay constant is conservative because:

- The mass flux value used in our calculation above is based on measurements Keeley et al. took from underneath the cages.
- Measured flux values were lower at stations > 50 m away.

- Using a higher mass flux value results in a lower K value and slower decay. The mean rate of macrofauna respiration (below) inferred from Figure 8 of Keeley et al. (2019) is about half of what was measured at stations 50 to 100 m from the cages. Using a lower respiration rate results in a lower K value and slower decay. Farm waste in Keeley et al. (2019) was also consumed by microbial oxidation which we did not include in our decay rate calculation.

Additional caveats

The following assumptions have been made in this modelling process

- Feed composition and particle sinking velocities have been taken from Cromey et al. (2002). These values are for Atlantic salmon. Past work (Keeley et al. 2013) completed at existing salmon farms in the Marlborough Sounds, that used these Atlantic salmon values, found reasonable agreement between observed and modelled flux footprints although did not consider resuspension.
- Critical bed shear velocities will depend on substrate type. We have assumed a uniform value across the entire domain. VenOM is currently unable to apply spatially-varying critical bed shear thresholds.
- Derivation for the decay constant is based on a Norwegian salmon farm containing Atlantic salmon. Decay will likely be sensitive to site location although we believe the decay constant used is conservative for this farm due to reasons presented in the preceding section.
- Common across many particle tracking tools is the anomaly that particles can get artificially trapped in parts of the model domain (e.g. near coastlines). We have discussed this in the report and identified areas that we believe are artefacts of the model rather than real hotspots.

Appendix 8. Depositional modelling results (without resuspension) for all B blocks at Stage 1 (75% production) for the monthly average and the rolling peak scenario with the highest maximum depositional flux.

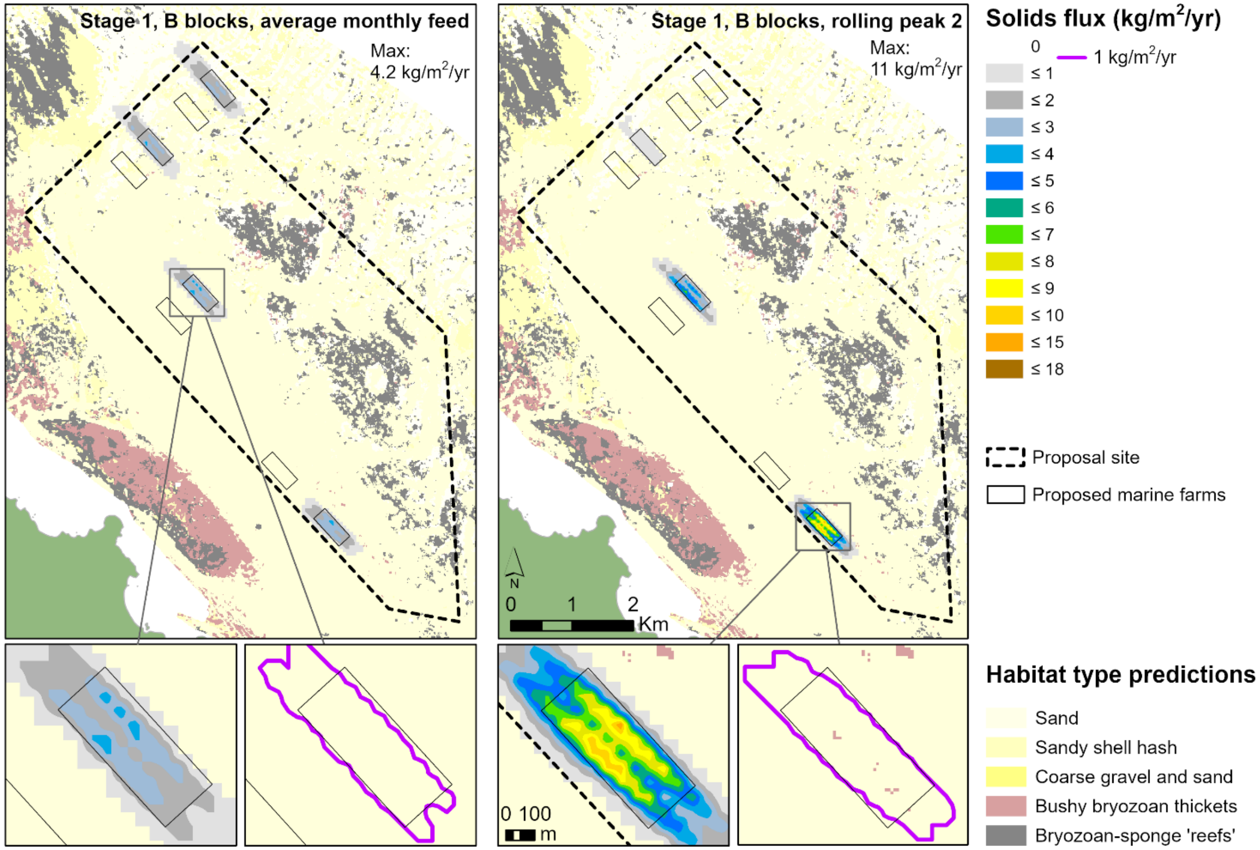


Figure A8.1. Depositional footprint (annual solids flux in kg per m²) without resuspension at the initial stage of production (Stage 1, c. 10,000 tonnes feed per year) for two modelled scenarios left) average monthly feed discharge and right) rolling peak scenario two (capturing the south farm at its peak projected monthly feed discharge). Inset maps show the farm with the highest level of solids flux and habitat type under that farm (with the 1 $kg \cdot m^{-2} \cdot yr^{-1}$ flux footprint). Note that either the A or B block within each farm may be developed first. The Stage 1 depositional footprint for all A blocks are presented in Section 6.3.4.

Appendix 9. Depositional modelling results (without resuspension) for four rolling peaks, capturing each farm at its peak projected monthly feed discharge for Stages 1 and 4 of development.

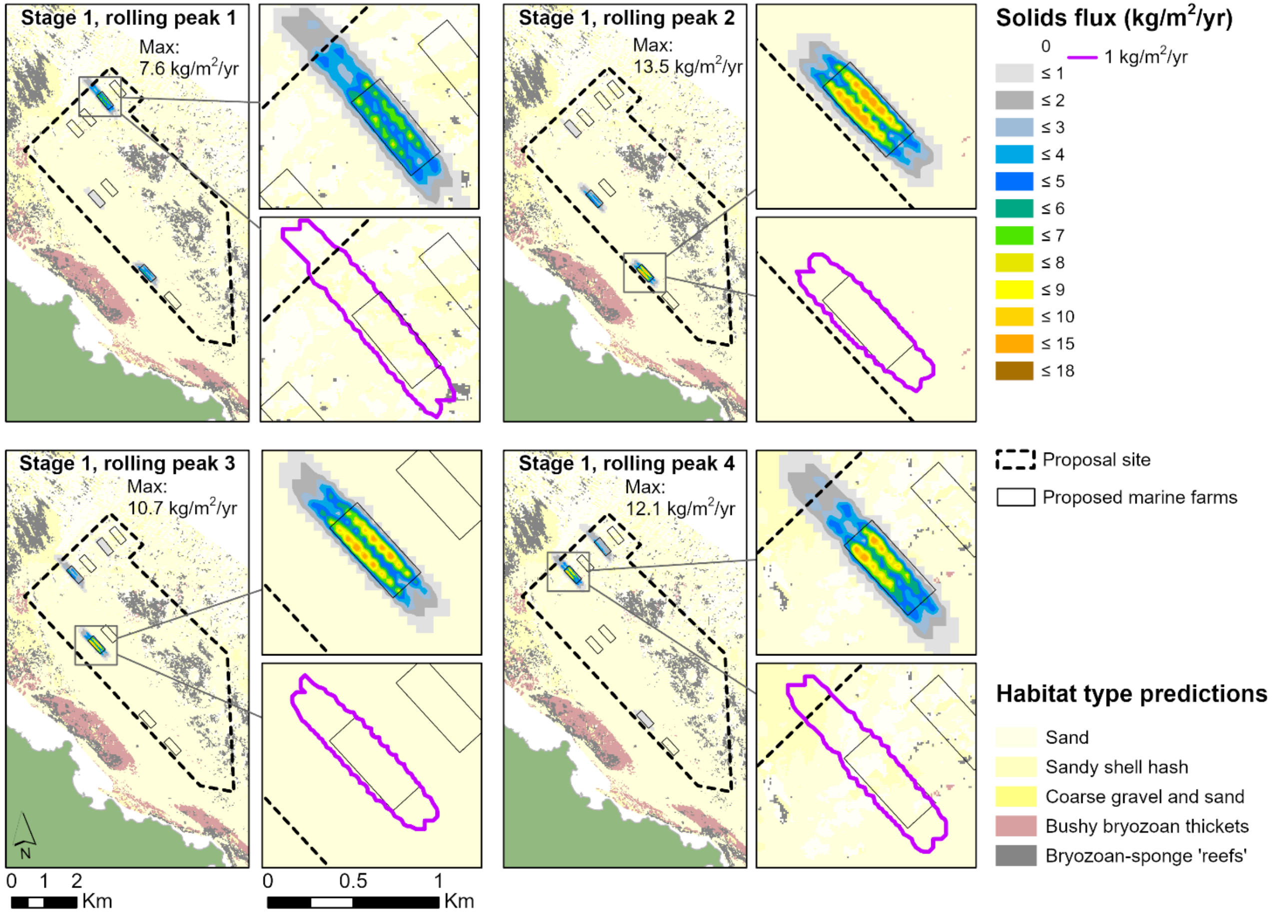


Figure A9.1 Depositional footprint (annual solids flux in kg per m²) without resuspension at the initial stage of production (Stage 1, c. 10,000 tonnes feed per year) for four rolling peaks capturing each farm at its peak projected monthly feed discharge**).** Inset maps show the farm with the highest level of solids flux and habitat type under that farm (with the 1 kg·m^{-2}·yr^{-1} flux footprint). Note that either the A or B block within each farm may be developed first.

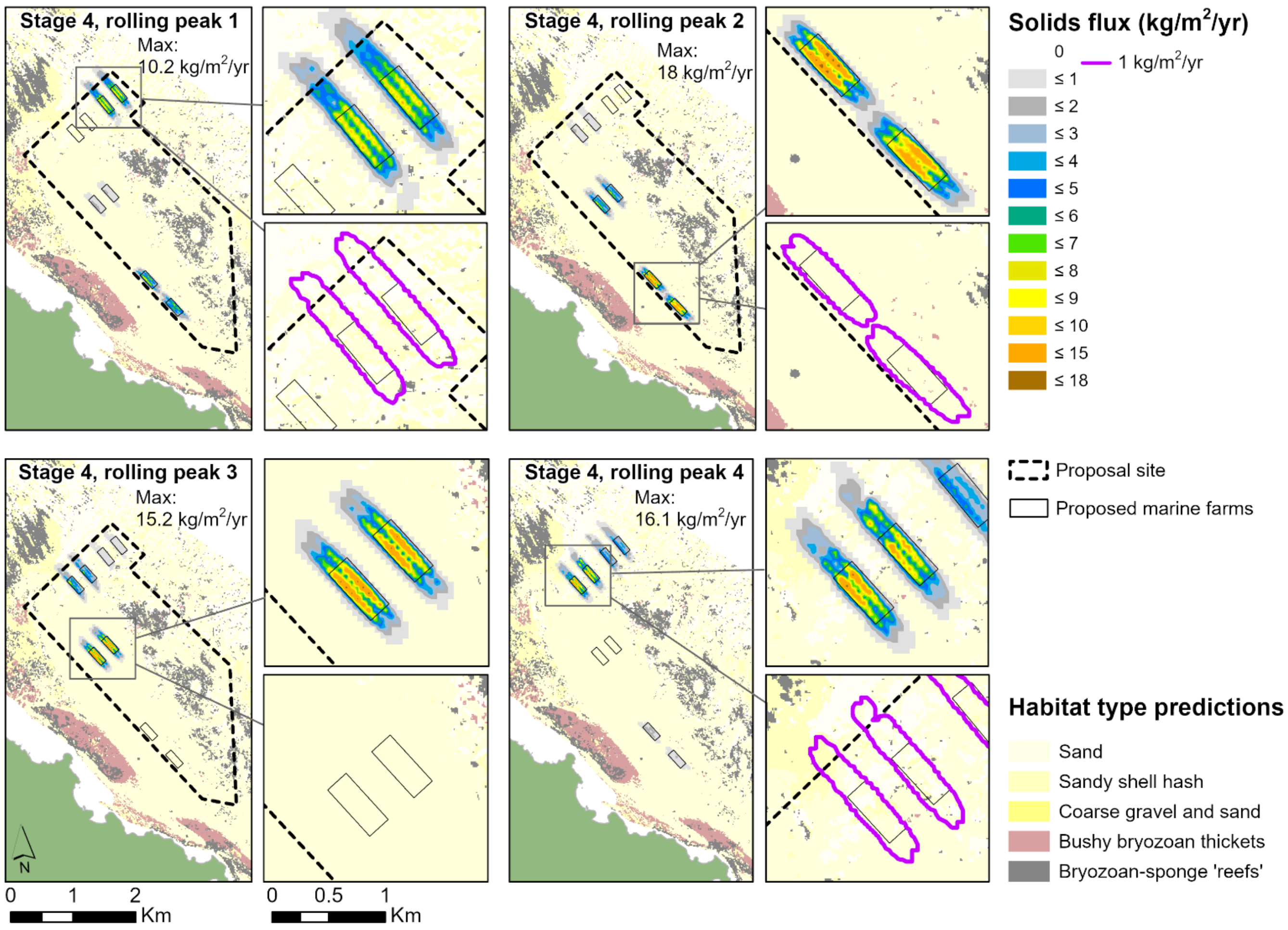


Figure A9.2 Depositional footprint (annual solids flux in kg per m^2) without resuspension at full production (Stage 4, c. 25, 000 tonnes feed per year) for four rolling peaks capturing each farm at its peak projected monthly feed discharge. Inset maps show the farm with the highest level of solids flux and habitat type under that farm (with the 1 kg·m^{-2}·yr^{-1} flux footprint).

Appendix 10. High resolution depositional modelling results (without resuspension) for each of the proposed farms at peak production (Stage 4 rolling peaks).

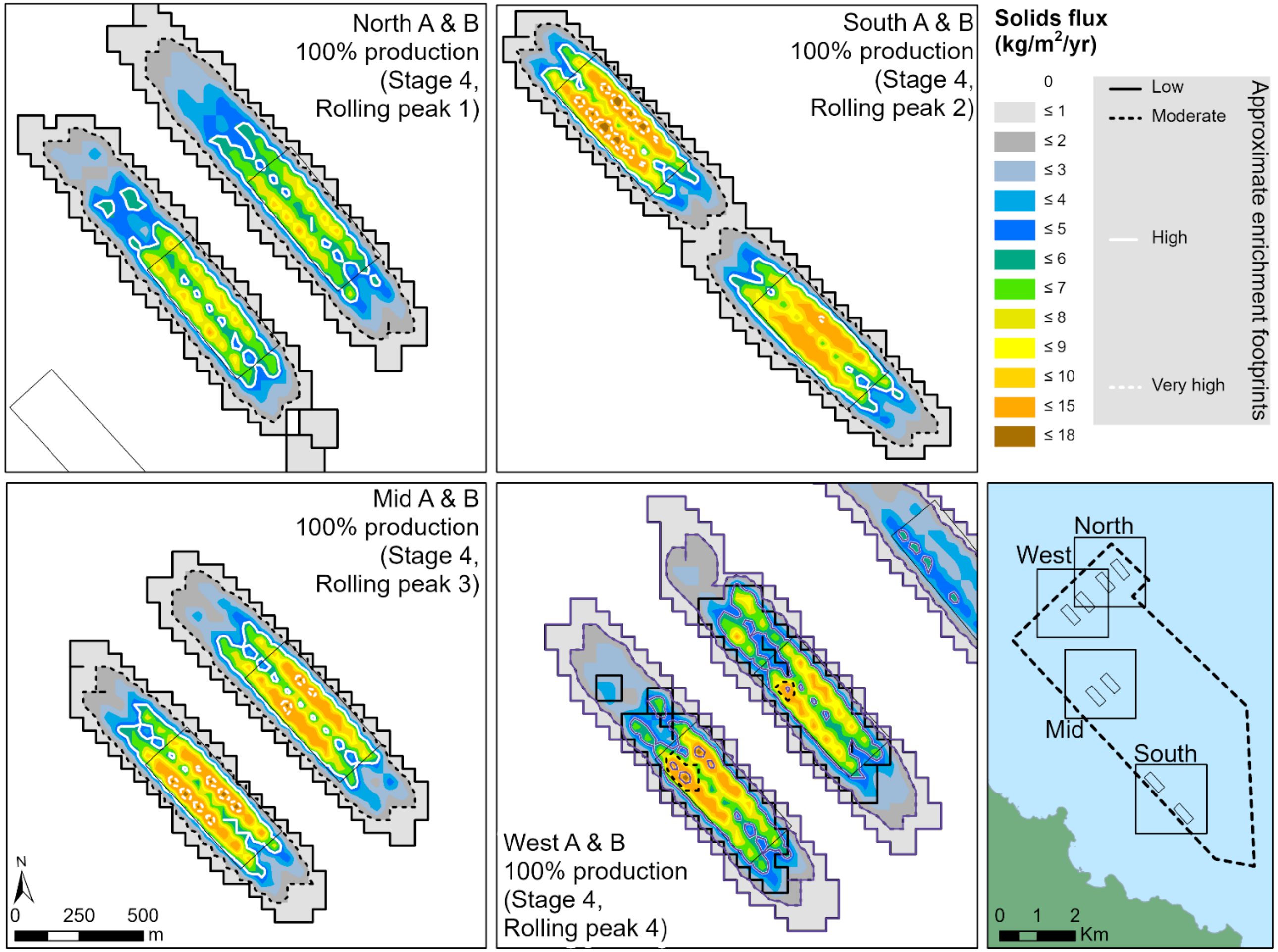


Figure A10.1 Depositional footprint (annual solids flux in kg per m^2) for each of the proposed farms at full production (Stage 4).

Appendix 11. Maximum solids flux level ($\mathrm{kg \cdot m^{-2} \cdot yr^{-1}}$), total per farm area (ha) of the predicted main depositional footprint (solids flux > 1 $\mathrm{kg \cdot m^{-2} \cdot yr^{-1}}$) and total depositional footprint (including solids flux < 1 $\mathrm{kg \cdot m^{-2} \cdot yr^{-1}}$), and the approximate extent of the predicted main and total footprint (distance in metres from the pen edges) at Stage 1 and Stage 4 of development for the monthly average and the four modelled rolling peak (RP) scenarios. Results are for depositional modelling results without resuspension.

Farm / block	Stage 1 average A	Stage 1 average B	Stage 1 RP1	Stage 1 RP2	Stage 1 RP3	Stage 1 RP4	Stage 4 average	Stage 4 RP1	Stage 4 RP2	Stage 4 RP3	Stage 4 RP4
Maximum solids flux ($\mathrm{kg \cdot m^{-2} \cdot yr^{-1}}$)											
North A	2.9		7.0		0.8	4.0	3.0	9.3		1.1	5.4
North B		2.9					2.8	8.7		1.0	5.0
West A	4.5			1.5	7.6	12.1	5.2		2.0	10.1	16.1
West B		3.5					3.1		1.2	6.0	9.6
Mid A	4.4		1.2	5.9	10.7		4.6	1.6	7.8	14.3	
Mid B		4.2					4.9	1.6	7.8	15.2	
South A	4.9		7.6	13.5		1.5	5.9	10.2	18		2.0
South B		3.7					4.7	7.8	14		1.6
Main footprint area in hectares (solids flux > 1 $\mathrm{kg \cdot m^{-2} \cdot yr^{-1}}$)											
North A	18		32		0	22	19	36		1	27
North B		16					21	37		1	26
West A	14			1	21	28	19		2.5	24	31
West B		16					20		1	25	33
Mid A	15		2	18	23		17	4	19	26	
Mid B		13					17	3	21	28	
South A	15		16	20		3	15	18	23		5
South B		16					18	21	26		5
Total footprint area in hectares (including solids flux < 1 $\mathrm{kg \cdot m^{-2} \cdot yr^{-1}}$)											
North A	75		86		79	79	87	87		80	80
North B		74					89	89		79	79
West A	60			63	63	69	70		63	63	71
West B		67					82		73	73	82
Mid A	49		49	49	54		54	49	49	54	
Mid B		56					63	56	56	63	
South A	41		39	44		39	42	35	42		36
South B		48					46	44	48		43
Extent of main footprint (distance of solids flux > 1 $\mathrm{kg \cdot m^{-2}\ yr^{-1}}$ from pen edges)											
North A	390		640			466	400	680			674
North B		290					480	687			570

Farm / block	Stage 1 average A	Stage 1 average B	Stage 1 RP1	Stage 1 RP2	Stage 1 RP3	Stage 1 RP4	Stage 4 average	Stage 4 RP1	Stage 4 RP2	Stage 4 RP3	Stage 4 RP4
West A	240				496	566	278			496	608
West B		320					347			566	609
Mid A	260			311	426		284		549	447	
Mid B		240					302		476	500	
South A	170		220	280			192	245	280		67
South B		230					268	335	340		
Extent of total footprint (distance of solids flux < 1 kg·m^{-2}·yr^{-1} from pen edges)											
North A	676		700		390	750	676	818		429	749
North B		680					680	865		427	819
West A	607			247	640	680	615		425	640	718
West B		640					640		390	639	824
Mid A	450		215	440	550		448	270	376	590	
Mid B		470					514	260	387	588	
South A	300		280	370		218	307	333	372		265
South B		340					344	405	407		271

Appendix 12. Depositional modelling results (without resuspension) presented as kg carbon·m^{-2} for the Stage 4 monthly average and rolling peak scenario with the highest maximum depositional flux.

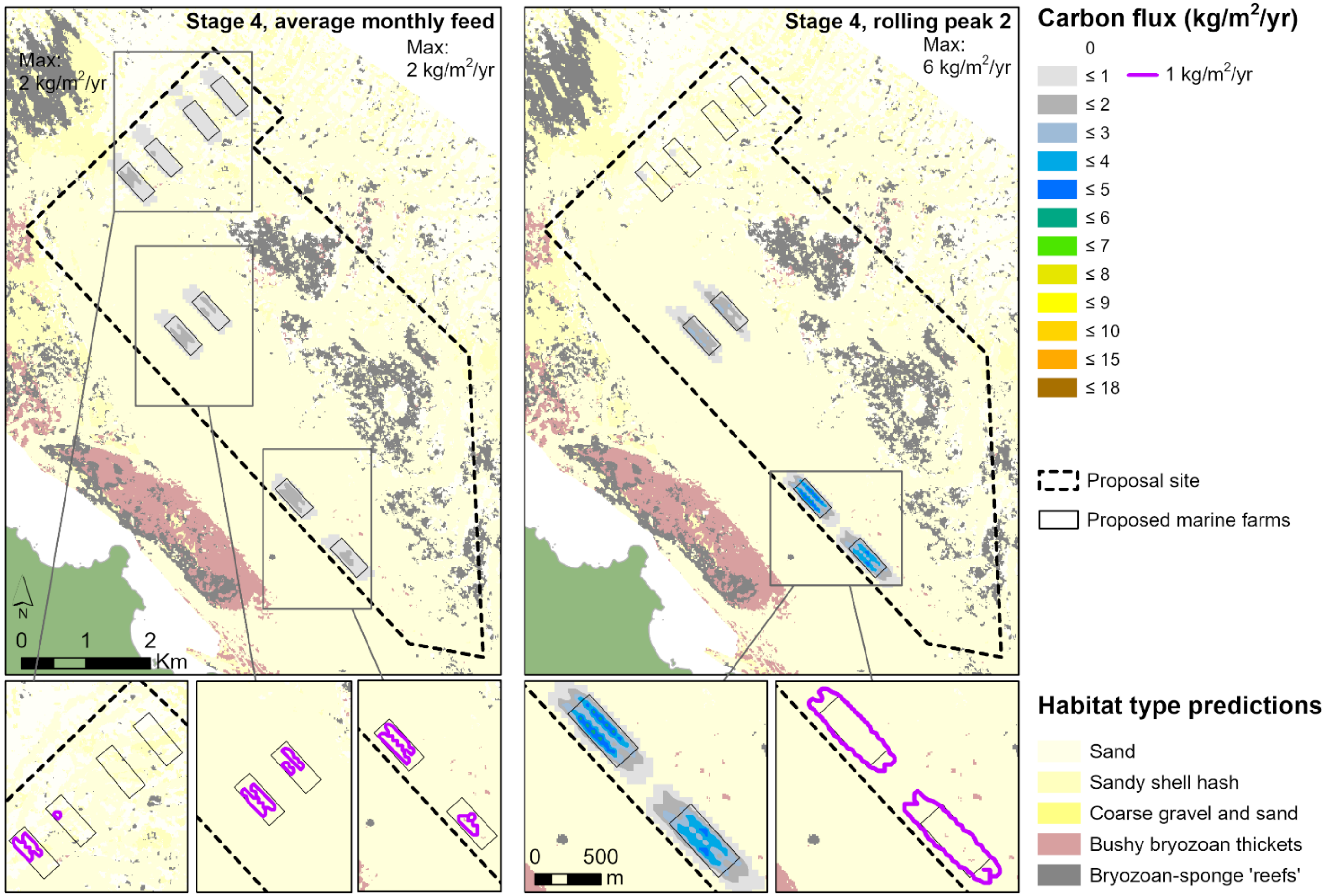


Figure A12.1 Depositional footprint (annual solids flux in kg carbon·m^{-2}) without resuspension for the Stage 4 **Left**) monthly average and **Right**) rolling peak scenario two (capturing the south farm at its peak projected monthly feed discharge). Inset maps show the farm with the highest level of solids flux and habitat type under that farm (with the 1 kg·m^{-2}·yr^{-1} flux footprint).

Appendix 13. Resuspension modelling results (sometimes resuspend) for four rolling peaks capturing each farm at its peak projected monthly feed discharge for Stages 1 and 4 of development.

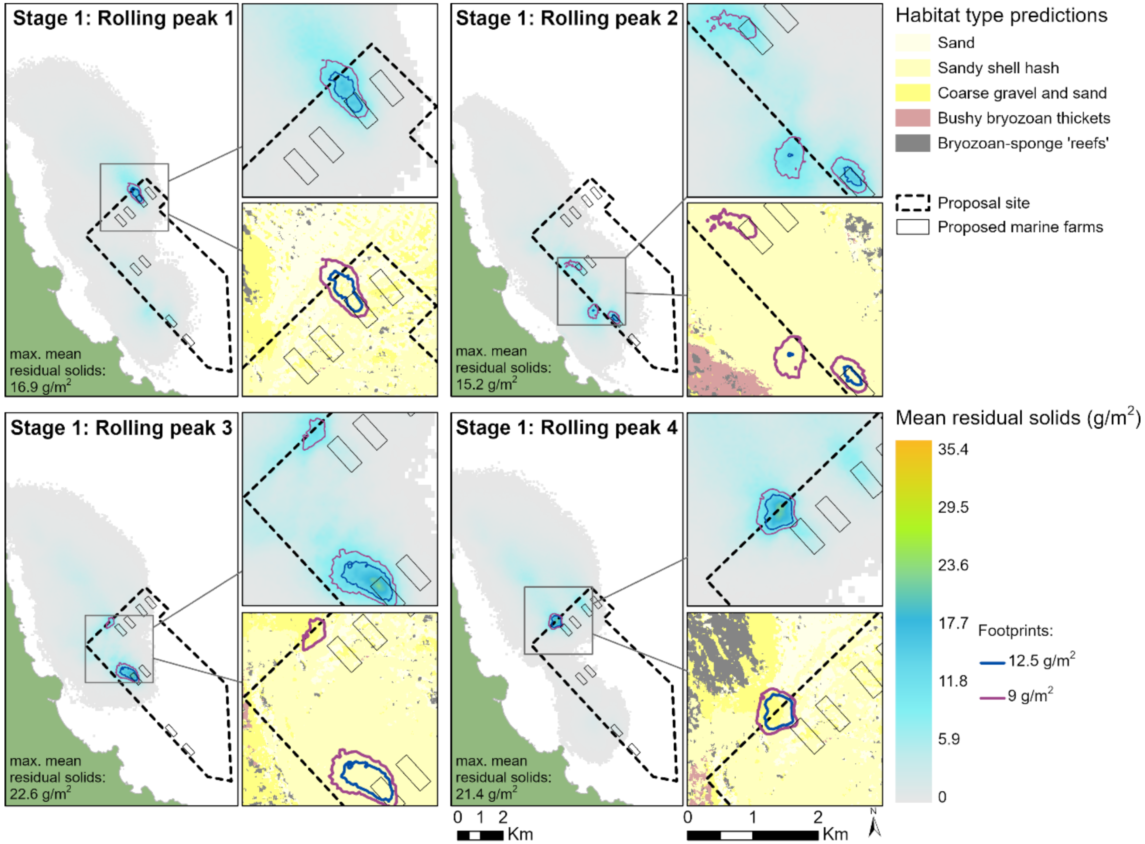


Figure A13.1 Predicted extent of solids deposition (g·m^{-2}) at the initial stage of production (Stage 1, c. 10,000 tonnes feed per year) for four rolling peaks capturing each farm at its peak projected monthly feed discharge. Note that either the A or B block within each farm may be developed first. The outputs presented are for when particles sometimes resuspend. These highlight where farm waste is likely to go in this high-flow area. For each rolling peak, the left map shows the predicted extent of the residual solids deposition (g·m^{-2}) and the right maps show the farm with the highest level of residual solids and habitat type beneath that farm with the predicted 9 and 12.5 g·m^{-2} residual solids footprints. These results are presented as accumulation of solids (g·m^{-2}) on the seabed which differs to one-way solids flux presented in previous figures (kg·m^{-2}·yr^{-1}).

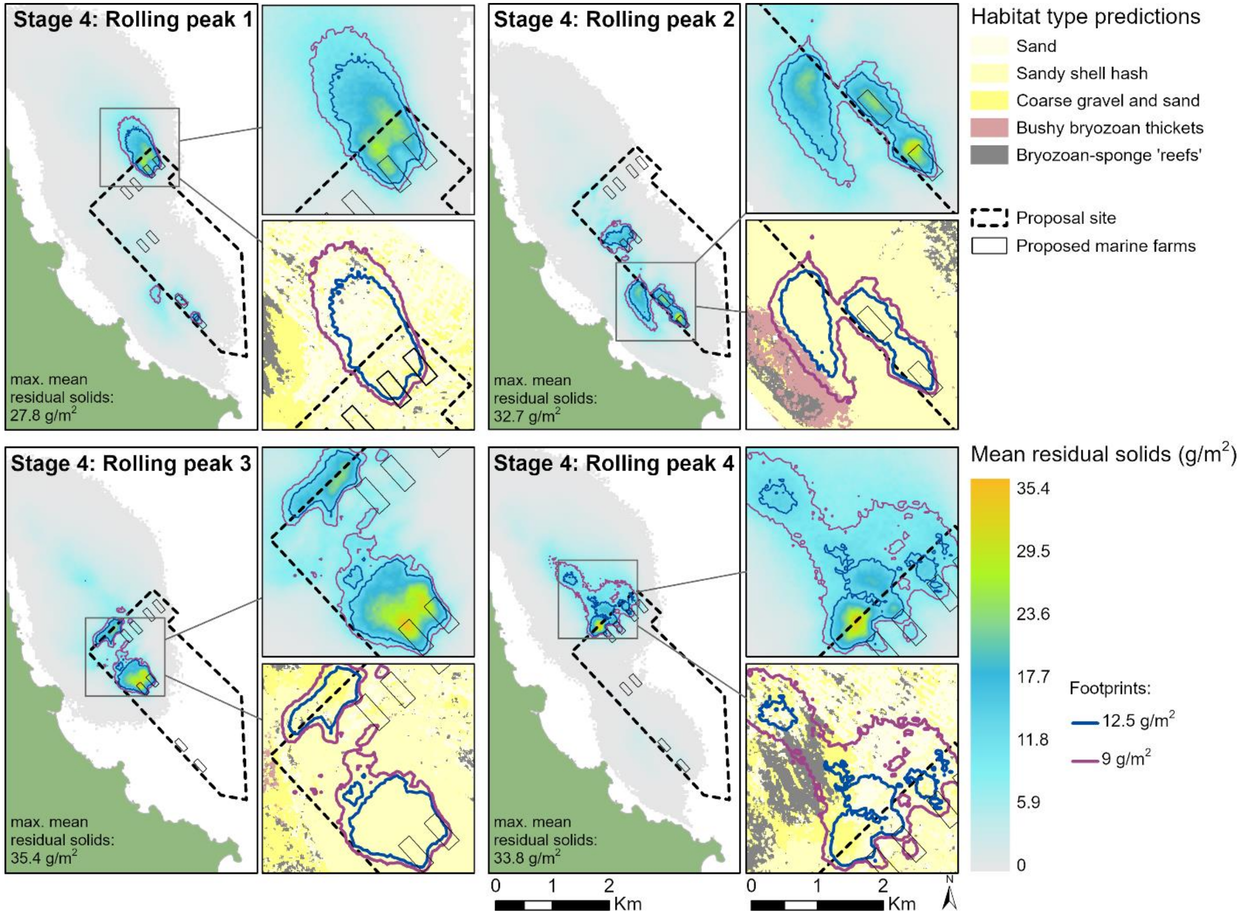


Figure A13.2 Predicted extent of solids deposition (g·m^{-2}) at full production (Stage 4, c. 25,000 tonnes feed per year) for four rolling peaks capturing each farm at its peak projected monthly feed discharge. The outputs presented are for when particles sometimes resuspend. These highlight where farm waste is likely to go in this high-flow area. For each rolling peak, the left map shows the predicted extent of the residual solids deposition (g·m^{-2}) and the right maps show the farm with the highest level of residual solids and habitat type beneath that farm with the predicted 9 and 12.5 g·m^{-2} residual solids footprints. These results are presented as accumulation of solids (g·m^{-2}) on the seabed which differs to one-way solids flux presented in previous figures (kg·m^{-2}·yr^{-1}).

Appendix 14. Resuspension modelling outputs presented as g·carbon·m^{-2} for the Stage 4 monthly average and the rolling peak scenario with the highest maximum depositional flux (under the no resuspension modelling).

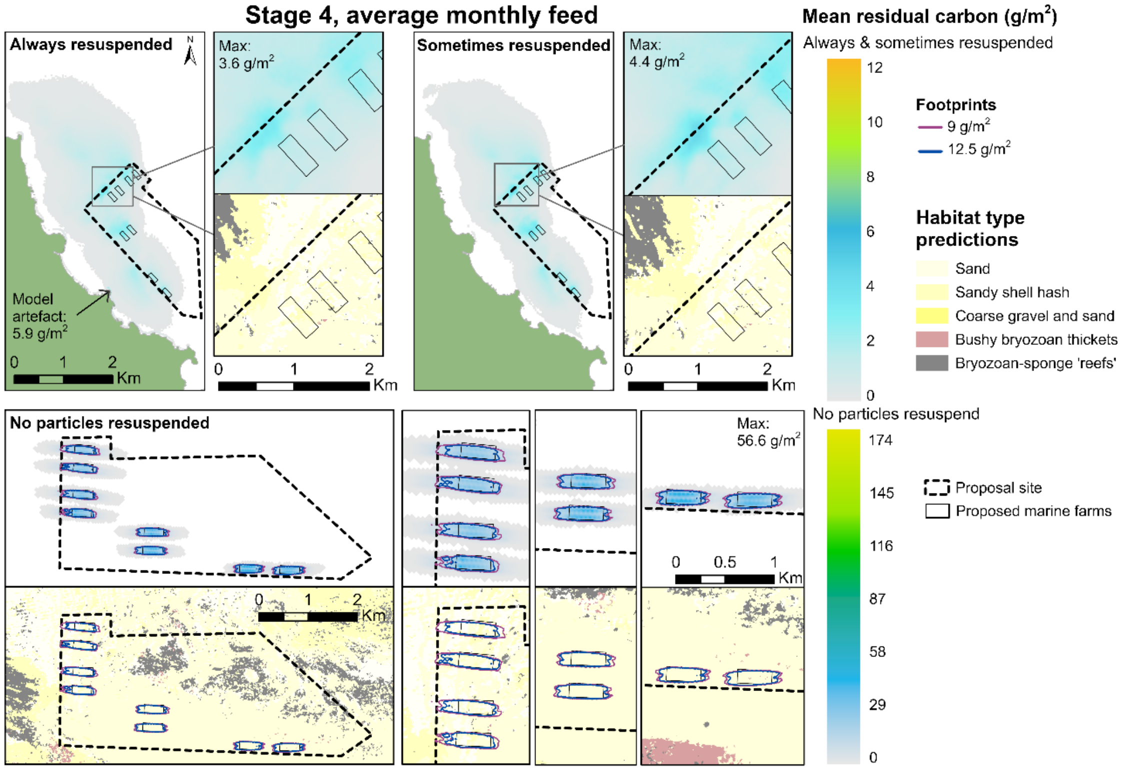


Figure A14.1 Predicted extent of carbon deposition (g·m^{-2}) at full production (Stage 4, c. 25,000 tonnes feed per year) for the average monthly feed discharge. The outputs presented are for when particles always resuspend (top left) and sometimes resuspend (top right) compared to no particles resuspend (bottom panel, note that the colour scale for this scenario differs to those presented above, to reflect the substantially higher amounts of residual solids predicted). These highlight where farm waste is likely to go in this high-flow area as well as the potential effect resuspension could have on the magnitude of deposition reaching the seabed (from the proposed farms) at this level of production. The inset maps for the always and sometimes resuspend scenarios show the farm with the highest level of mean residual carbon and habitat type beneath that farm with the predicted 9 and 12.5 g·m^{-2} residual carbon footprints. For the no resuspend output the habitat type beneath each farm is shown. The solids accumulation-spot on the coast in the always resuspend scenario is almost certainly an artefact of the model.

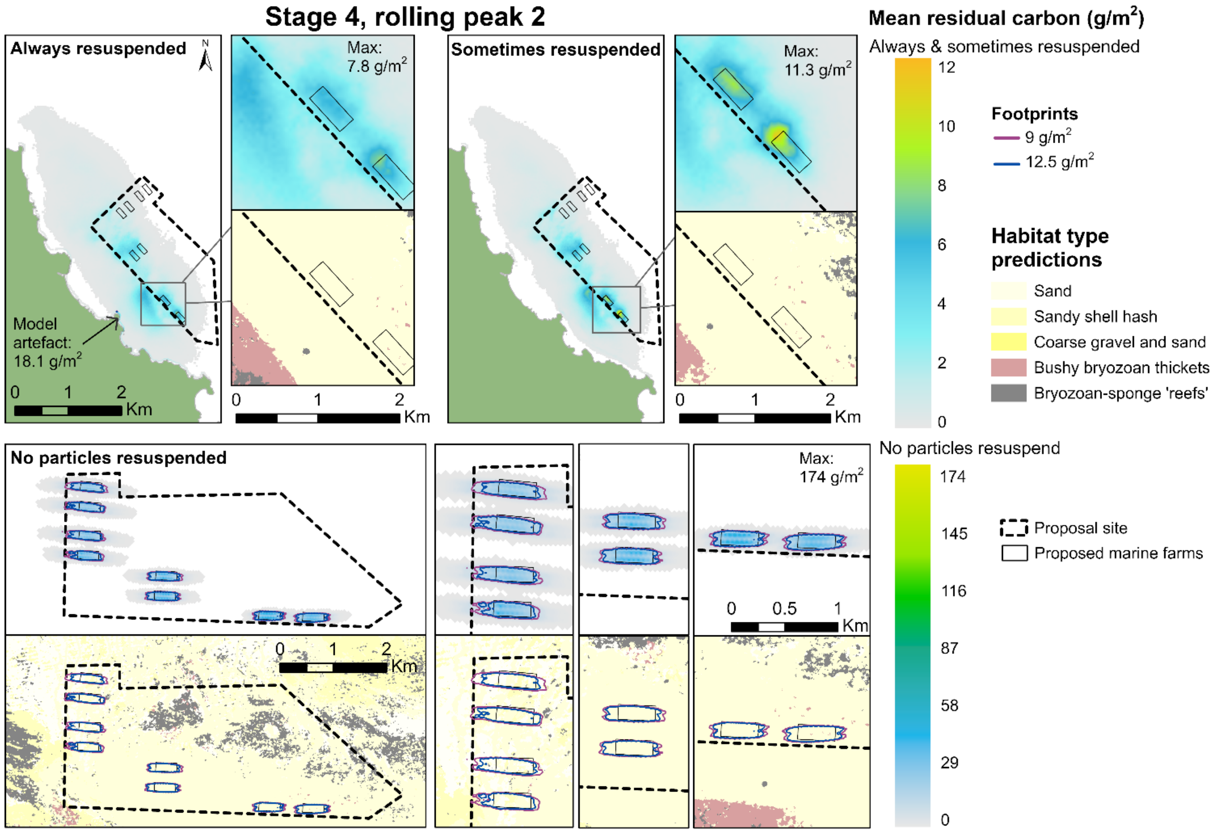


Figure A14.2. Predicted extent of carbon deposition (g·m^{-2}) at full production (Stage 4, c. 25,000 tonnes feed per year) for the rolling peak scenario two (capturing the south farm at its peak projected monthly feed discharge). The outputs presented are for when particles always resuspend (top left) and sometimes resuspend (top right) compared to no particles resuspend (bottom panel, note that the colour scale for this scenario differs to those presented above, to reflect the substantially higher amounts of residual solids predicted). These highlight where farm waste is likely to go in this high-flow area as well as the potential effect resuspension could have on the magnitude of deposition reaching the seabed (from the proposed farms) at this level of production. The inset maps for the always and sometimes resuspend scenarios show the farm with the highest level of mean residual carbon and habitat type beneath that farm with the predicted 9 and 12.5 g·m^{-2} residual carbon footprints. For the no resuspend output the habitat type beneath each farm is shown. The solids accumulation-spot on the coast in the always resuspend scenario is almost certainly an artefact of the model.