Earth Sciences New Zealand

Ecological risk assessment of debris from space vehicle launches on the marine environment

An update of the 2016 and 2017 reports

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Prepared by:
David Thompson, Matt Pinkerton, Owen Anderson, Linda Faulkner, Dan MacGibbon, Diana Macpherson, Tilmann Steinmetz, Tessa Thomson, Tom Brough, Ashley Rowden

For any information regarding this report please contact:

David Thompson
Seabird Ecologist
Pelagic Ecosystems
+64 4 386 0582

New Zealand Institute for Earth Science Limited
Private Bag 14901
Kilbirnie
Wellington 6241

Phone +64 4 386 0300

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Executive summary

This report presents the results of an environmental risk assessment (ERA) of debris from space vehicle launches falling back into Aotearoa New Zealand's marine environment. The ERA updates two earlier and similar pieces of work from 2016 and 2017. The approach adopted for this assessment was based on an expert-driven Level 1 consequence-likelihood-risk analysis.

The assessment considered risk to four classes of biota: (1) air-breathing fauna, primarily marine mammals and seabirds; (2) pelagic community, including plankton, invertebrates and pelagic fish; (3) demersal (bottom-associated) community including demersal fish; and (4) benthic invertebrate community. Three potential types of effect from launch vehicle debris were included: (1) direct strike causing mortality; (2) noise disturbance; and (3) smothering of organisms. The marine environment was divided spatially into five areas based on the Marine Environment Classification, with a sixth 'seamount' class. A powerful and flexible risk assessment methodology is presented based on 'standardised impact units' (SIUs) that allows the risk and confidence scores from the ERA to be used for a range of possible future vehicle launches from 1 to 10,000.

At 1,000 launches, risk scores fell into the 'moderate risk' category for noise disturbance and air-breathing fauna within the coastal and seamount environment classes and for direct strike causing mortality for benthic invertebrate community within the seamount environment class. At 10,000 launches, risk scores fell into the 'moderate risk' category for noise disturbance and air-breathing fauna within all environment classes, for direct strike causing mortality for air-breathing fauna and benthic invertebrate community within the seamount environment class and for smothering of organisms for benthic invertebrate community within the coastal and seamount environment classes.

The approach was applied to the debris location data supplied by Rocket Lab to provide a specific risk assessment of the cumulative risk from 1 to 10,000 launches, with each generating approximately 1,000 kg of debris in the form of the stage one assembly and two fairings. It was assumed that debris remained intact, all debris sank to the seafloor and there was zero toxicity. For Rocket Lab launches, all potential effects and for all receiving components, risk scores fell into the 'low risk' category for 1, 10, 100 and 1,000 launches. Beyond 1,000 Rocket Lab launches, risk scores fell into the 'moderate risk' category (risk scores 8-12) for noise disturbance of air-breathing fauna within the 'plateaus subtropical front central' spatial area. Between 2,000 and 10,000 Rocket Lab launches, risk scores were also 'moderate', triggered by noise impact on air-breathing fauna in the plateaus subtropical front central and seamount spatial areas, and by direct impact on benthic invertebrate community in the seamount spatial area. The risk assessment is appropriate for launches at the current Rocket Lab rate of about once a month. The same framework could be expanded if launches become substantially more frequent than monthly in the future.

Although there was agreement on risks between experts, empirical information to inform ecological risks from space vehicle debris is generally lacking. A 'riskscape' Level 2 risk assessment framework in which potential impacts from space vehicle debris could be quantified at more resolved spatial scales across the entire Aotearoa Exclusive Economic Zone and Extended Continental Shelf is discussed, but this would face the same lack of information on ecological impacts.

1 Background

The space vehicle launch industry is now well established in Aotearoa New Zealand, with Rocket Lab[1] completing over 60 launches (and with a schedule for further launches), the University of Canterbury three launches (with the third of these in January 2022 and with no plans for further launches in the next three to five years) and with other operators potentially becoming active in the next few years.

The Exclusive Economic Zone and Continental Shelf (Environmental Effects—Permitted Activities) Regulations 2013[2] (the Regulations) define what materials space launch vehicles can be made from, and where vehicle debris can and cannot be deposited. Operators have a relatively large area to the north, east and south of Aotearoa New Zealand into which debris can fall, but debris must avoid the closed seamount areas (Figure 1-1).

The Regulations also note that 'there are no more than 100 space vehicle launches from New Zealand in total (regardless of who undertook the activity)'. With this in mind, and given the recommendation of Lamarche et al. (2017) that a review of risk from space vehicle debris should occur after 50 launches, a situation now reached, the Ministry for the Environment (MfE) contracted NIWA (now New Zealand Institute for Earth Science (Earth Sciences New Zealand, hereafter Earth Sciences NZ)) to carry out a revised and updated Level 1 environmental risk assessment (ERA), incorporating new information (since the 2017 assessment: Lamarche et al. (2017)) where possible.

[1] https://rocketlabcorp.com/
[2] https://www.legislation.govt.nz/regulation/public/2013/0283/latest/DLM5270601.html

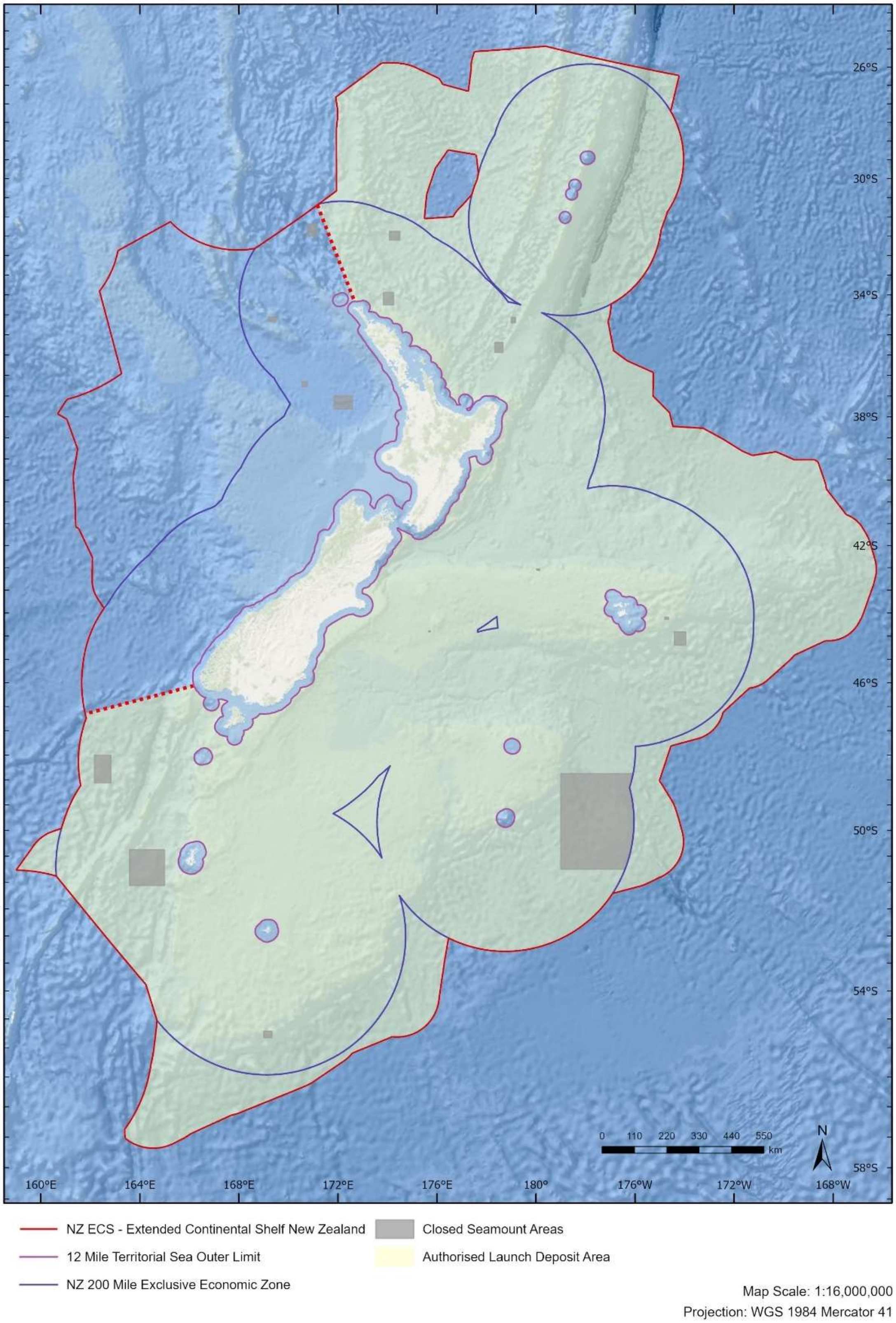

Figure 1-1: Map showing Aotearoa New Zealand, the limits of its Territorial Sea, Exclusive Economic Zone and Extended Continental Shelf. Also shown are the authorised launch deposit area, into which launch vehicle debris is permitted to fall, and the closed seamount areas, into which debris is not permitted.

1.1 Previous reports

The ERA presented in this report is an update on two earlier pieces of work (MacDiarmid et al. 2016, Lamarche et al. 2017). These two studies adopted slightly different approaches as outlined below, but both comprised a Level 1 'consequence-likelihood-risk' assessment.

1.1.1 The 2016 report

MacDiarmid et al. (2016) considered three receiving areas for vehicle debris: a number of relatively narrow ellipses receiving test launch debris to the south of Chatham Rise, and two wedge-shaped areas into which commercial launch debris would fall, one to the south of Chatham Rise and one to the east of Te Ika-a-Māui North Island (Figure 1-2). The assessment considered the effects of approximately 1,000 kg of debris derived from the Electron launch vehicle.

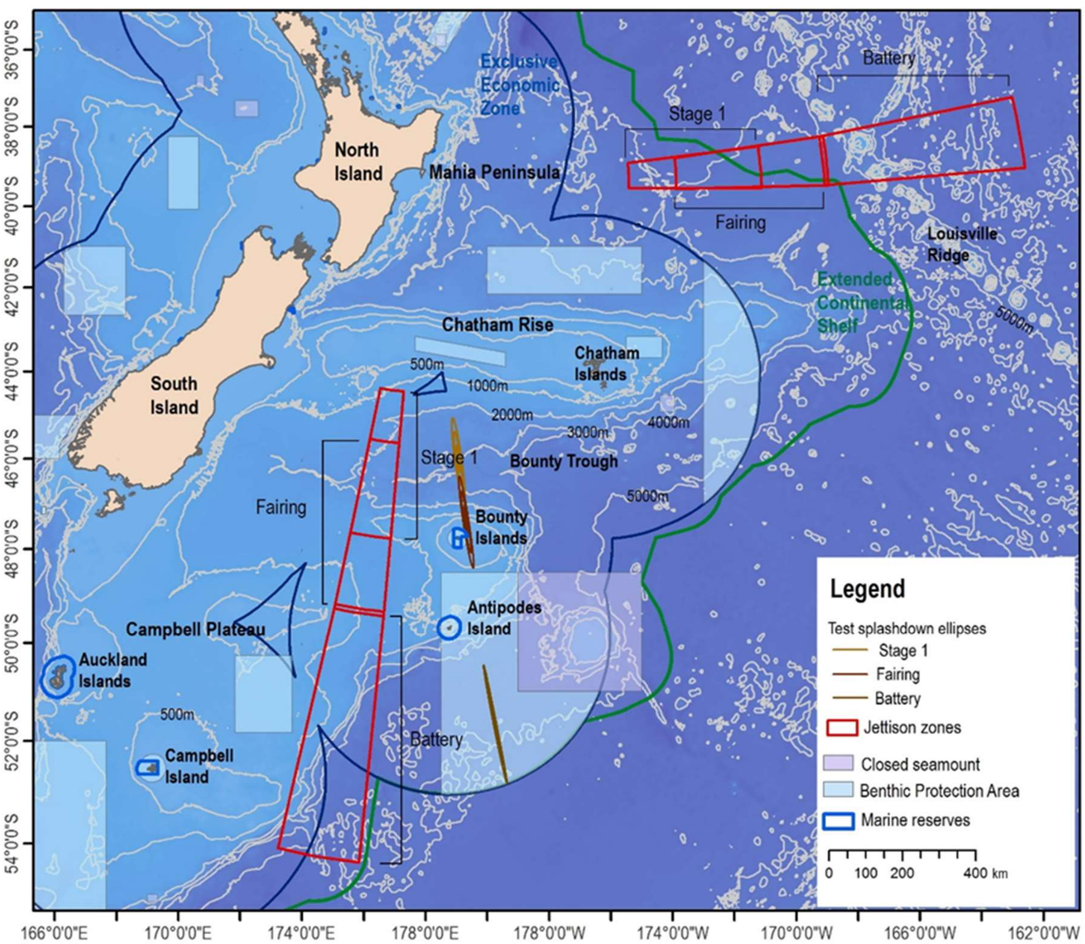

Figure 1-2: Figure taken from MacDiarmid et al. (2016) showing the debris areas.

Eight potential effects from launch debris were identified: direct strike causing mortality, underwater noise/disturbance, toxic contaminants, ingestion of debris, smothering of benthic organisms, provision of attachment substrate, displacement of commercial fishing effort and effects of floating debris. These potential effects included potentially positive effects (e.g., provision of attachment substrate). Five receiving ecosystem components were identified: benthic invertebrates, demersal fish and mobile invertebrates, air breathing fauna, sensitive benthic environments and the pelagic community.

Risk was considered for an increasing number of vehicle launches: 1, 10, 100, 1,000 and 10,000 at a theoretical rate of one launch per week.

Overall, MacDiarmid et al. (2016) found that risk was generally 'low' for all effects and for all receiving components up to 100 launches, and rarely 'moderate' or even 'high' at 1,000 and 10,000 launches.

1.1.2 The 2017 report

Lamarche et al. (2017) considered a single, relatively large receiving area, extending to the north, east and south, but not west, of Aotearoa New Zealand as far as the limit of the Exclusive Economic Zone (EEZ) and Extended Continental Shelf (ECS), but excluding the Territorial Sea (Figure 1-3), corresponding to the authorised launch deposit area. This area was divided in six benthic environment classes. Five classes were based on the Benthic Optimised Marine Environmental Classification (BOMEC: Leathwick et al. 2012), with a sixth benthic environment class corresponding to the seamounts that occur throughout the EEZ and ECS, and which frequently harbour sensitive environments.

Seven potential effects were considered, matching those identified by MacDiarmid et al. (2016) but excluding displacement of commercial fishing effort, and the same five receiving ecosystem components as identified by MacDiarmid et al. (2016) were used.

Unlike MacDiarmid et al. (2016), Lamarche et al. (2017) considered the impacts and risks from a single launch of a larger space vehicle resulting in debris of approximately 40,000 kg, finding that risk scores were uniformly in the low category across all effects and receiving components. However, Lamarche et al. (2017) suggested that at 100 launches risk could become moderate and at 1,000 launches could become high, although risk was not formally assessed at these higher launch numbers. Increased risk was suggested to be more likely if vehicle debris fell in a relatively restricted area. On this basis, Lamarche et al. (2017) recommended a review of risk from space vehicle debris after 50 launches, allowing for possible operational modifications before the 100-launch milestone and any possible increase in risk.

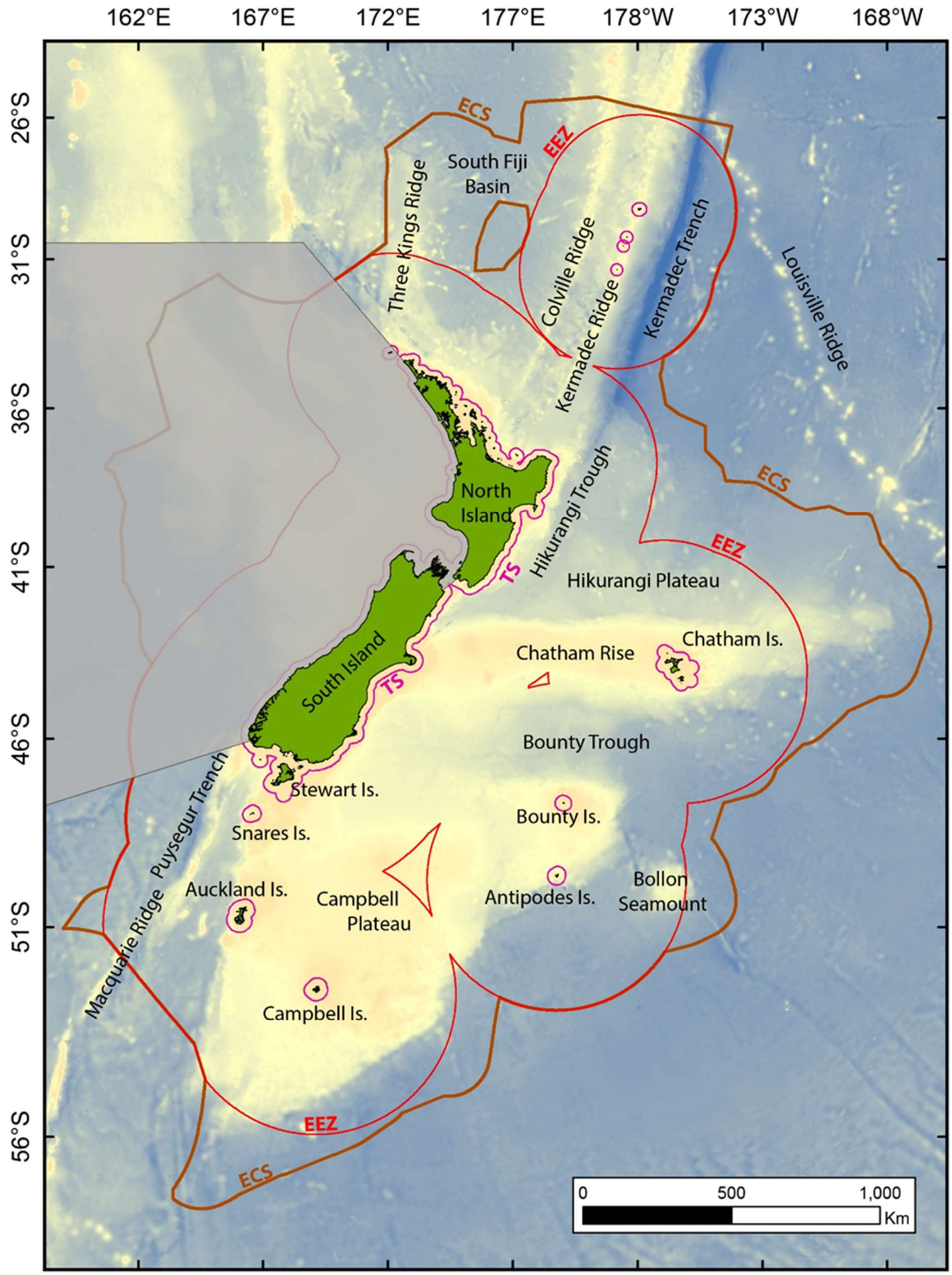

Figure 1-3: Figure taken from Lamarche et al. (2017) showing the relatively large, single (unshaded) debris area extending out to the EEZ and ECS. The shaded area to the west of Aotearoa New Zealand was excluded from the risk assessment, as was the Territorial Sea.

2 Methods

2.1 Approach

Several approaches and methods have been developed and applied to conduct ERAs in the Aotearoa New Zealand context (Rowden et al. 2008, Baird and Gilbert 2010). In cases for which the assessed activity is rare or unpredictable, such as the direct hit of rocket debris causing adverse effect to marine organisms, then a consequence-likelihood approach is the most suitable. Such an approach summarises risk as the product of the ecological consequence of an event and the expected likelihood of that event occurring. This approach contrasts with the approach taken to assess activities that are deliberate and programmed to take place regularly and repeatedly such as fishing in an area. In these cases, an exposure-effects approach (Smith et al. 2007, Sharp et al. 2009) is the most suitable.

Risk assessment typically consists of three levels, increasing in detail from a qualitative assessment (Level 1) to fully quantitative (Level 3). Level 1 assessments are generally used in data-poor situations where the scale of activity or its impacts on particular species, habitats or the ecosystem are uncertain or only partially described (Hobday et al. 2011).

The approach adopted for this assessment was based on a Level 1 consequence-likelihood-risk analysis (Hobday et al. 2011), in line with accepted New Zealand and Australian risk assessment standards (AS/NZ4360 standard 2004). Such an approach has been used previously by NIWA to undertake ERAs for the MfE (MacDiarmid et al. 2011, 2014, 2015), including for space launch vehicle debris (MacDiarmid et al. 2016, Lamarche et al. 2017). This ERA incorporates an approach that combines elements from MacDiarmid et al. (2016) and from Lamarche et al. (2017). Additionally, a risk assessment methodology is presented that allows the risk and confidence scores from the ERA to be used for a range of possible future vehicle launches. The approach was applied to the debris location data supplied by Rocket Lab as a specific example of how the generic method can provide a specific risk assessment.

A panel of subject matter experts was convened, comprising staff based at Wellington and Dunedin. The panellists were:

Dr Owen Anderson – Deep-sea fisheries and benthic ecology

Dr Tom Brough – Marine mammal ecology

Diana Macpherson – Benthic invertebrate ecology

Dr Dan MacGibbon – Fisheries

Dr Matt Pinkerton – Primary productivity and food webs

Dr David Thompson – Seabird ecology

2.2 Assumptions around launch vehicle debris

The type and form of debris from space launch vehicles returning back to the sea surface, and then sinking to the seafloor, clearly has implications for the range of potential effects that might impact marine biota. Lamarche et al. (2017) identified and considered seven potential effects (section 1.1.2). Based on information provided by Rocket Lab it was clear that several operational parameters had evolved since the 2016 and 2017 assessments, which affected the number of potential effects identified for this updated ERA. This assessment used information based on Rocket Lab's launches as Rocket Lab has carried out the majority of launches in Aotearoa New Zealand to date, and Rocket Lab is likely to continue to launch the majority of vehicles into the near future.

For this assessment we considered approximately 1,000 kg of debris (as was the case for the first assessment (MacDiarmid et al. 2016)). However, Rocket Lab advised that debris falling to the ocean remains intact (indeed, Rocket Lab have been successful in retrieving the stage one section of the vehicle on a number of occasions) and that the batteries jettisoned as stage two reaches orbit were very likely to burn up as they fell back towards the ocean, at an altitude of 75-40 km. We have assumed that batteries associated with stage one remain intact as part of the entire stage one assembly. Additionally, Rocket Lab advised that the stage one section of the vehicle would not contain any residual fuel and that debris would ultimately all sink to the seafloor. In this first part of the risk assessment, we first considered the number of Rocket Lab-type launches as the key metric, with each launch resulting in a small number of pieces of debris that enter the ocean intact. Highly fragmented vehicle debris would generate many more potentially impactful objects falling to the ocean, which in turn would affect risk. To generalise risk to other types of debris and other launch vehicles we introduce the idea of a 'standardised impact unit' (SIU) in section 5.

On this basis, we reduced the number of potential effects to three: direct strike causing mortality, noise disturbance and smothering of seafloor biota. A fourth potential effect, the provision of hard substrate for attachment of benthic organisms will occur but is very likely to be a positive but relatively modest effect, Lamarche et al. (2017) noting that this consequence of this effect at a community or population level would be negligible. We have not formally included this effect in the ERA process (i.e., we have not scored this potential effect) but have provided some commentary around the overall impact of debris as attachment surfaces (section 4.2). Further, the effect of displacement of fishing effort was considered in 2016 (MacDiarmid et al. 2016), but not in 2017 (Lamarche et al. 2017) nor in this ERA. The panel considered the impact of displacement (from the notified area during space vehicle launches) would likely be small, and that such displacement is more accurately considered an economic effect rather than an ecological or environmental impact.

We were provided with a data set, by Rocket Lab, comprising latitude and longitude coordinates of debris (rocket stage one and fairings) locations from the majority of space vehicle launches to date (August 2025, 62 launches in total) in Aotearoa New Zealand (Figure 2-1).

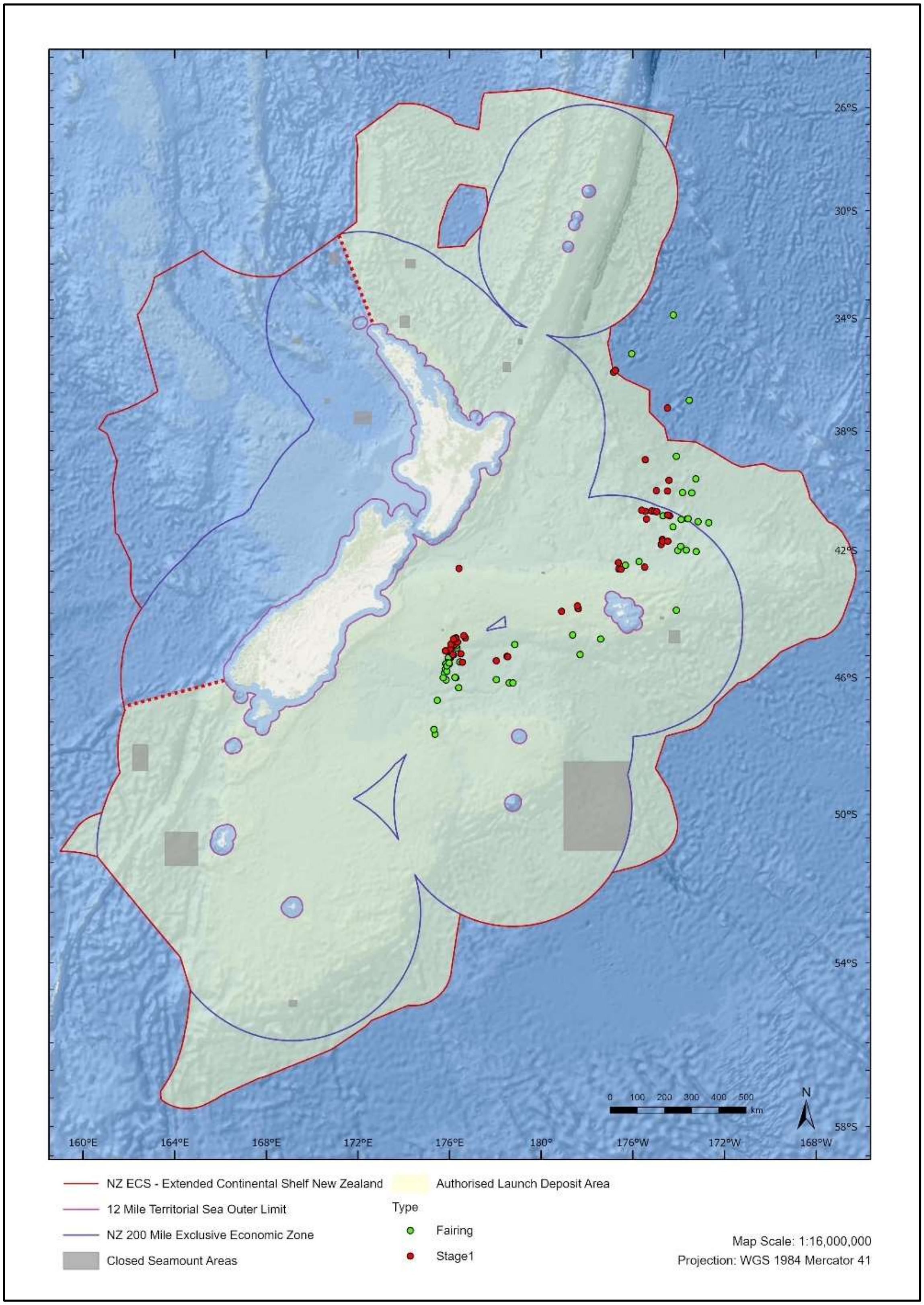

Figure 2-1: Map showing Aotearoa New Zealand with locations of space vehicle debris. Location data supplied by Rocket Lab.

2.3 Potential effects impacting the marine environment

As noted in section 2.2, potential effects of rocket debris on commercial fishing have not been considered here and were not considered by Lamarche et al. (2017) as they do not lead clearly to a potential environmental or ecological impact. However, we have explored the potential for debris on the seafloor to interact with mobile bottom fishing methods such as bottom trawling (section 4.2).

2.3.1 Direct strike causing mortality

Direct strikes from space vehicle debris could impact seabirds in the air or on the sea-surface, marine mammals when at or near (perhaps <10 m) the sea surface, pelagic invertebrates and fish near the sea surface, and sedentary or attached invertebrates on the seafloor.

2.3.2 Noise disturbance

The impact of debris on the sea surface is likely to cause noise above and below water, and perhaps a small acoustic shock wave underwater. This noise is likely to disturb nearby seabirds, marine mammals and fish. Effects of underwater noise include temporary and permanent impacts. Only the potential for immediate hearing injury was considered taking into account possibilities of behavioural responses, temporary threshold shift in hearing sensitivity, potential physiological injuries or permanent threshold shift in hearing sensitivity. Accumulated hearing injury or repeated disturbance to normal feeding or reproductive behaviours was considered as a function of repetitive launches.

2.3.3 Smothering of seafloor biota

This potential effect could prevent normal feeding behaviours and affect respiration. Smothering could occur if debris completely covered organisms or if a sediment plume is created when debris impact soft seafloor. This potential effect will only impact benthic invertebrate communities.

2.4 Ecosystems and habitats potentially at risk

The entire Aotearoa New Zealand EEZ and ECS cover approximately 4.1 M km^2 and 1.6 M km^2, respectively, totalling 5.9 M km^2, and the authorised launch deposit area covers approximately 4.2 M km^2. Clearly, assessing the authorised launch deposit area as one single entity is not practical nor scientifically robust to properly account for the various components of the marine ecosystems the area encapsulates.

Lamarche et al. (2017) used the BOMEC to divide the authorised launch deposit area into a workable number of environmental classes and then assessed all receiving ecosystem components in each of these areas. The justification for using the BOMEC was, in part, its focus on the benthic environment, which MacDiarmid et al. (2016) had shown was the most at-risk receiving component. However, the BOMEC remains an incomplete piece of work and has been superseded by the Seafloor Community Classification (SCC: Stephenson et al. 2022). Whilst we could have ‘collapsed’ the 75-group SCC to four or five groups, we decided against this option as the SCC’s value is to be found in its data richness, which we used as part of the assessment process.

Therefore, we used the Marine Environmental Classification (MEC), which is a surface to seafloor classification, and which doesn't favour one environment over another within the marine system (Snelder et al. 2006).

In keeping with Lamarche et al. (2017) we consider risk associated with all four receiving ecosystem components (biota) within a separate 'seamounts' environmental class.

2.4.1 MEC

Similarly to the BOMEC, the MEC uses a multivariate classification incorporating explicit environmental layers, selected for their role in defining spatial variation in biological patterns: depth, mean annual solar radiation, winter sea surface temperature, annual amplitude of sea surface temperature, spatial gradient of sea surface temperature, summer sea surface temperature anomaly, mean wave-induced orbital velocity at the seabed, tidal current velocity, and seabed slope. Variables were selected by assessing their degree of correlation with distributions of various biota, using separate data sets for demersal fish, benthic invertebrates, and chlorophyll-*a* (Snelder et al. 2006).

To maintain a similar scale of assessment to the classes defined by the BOMEC and used by Lamarche et al. (2017), we used a five-class MEC with the following environmental classes: subtropical, generally to the north of Aotearoa New Zealand, but extending southwards offshore from Te Ika-a-Māui North Island; coastal, covering the Territorial Sea (excluded from this assessment) but extending slightly further offshore from the main islands and additionally the sub-Antarctic islands; plateaus and subtropical front (central), covering offshore waters to the east of both main islands; plateaus and subtropical front (southern), primarily covering the relatively shallow waters of Campbell plateau; sub-Antarctic, covering deeper water to the south and east of Te Waipounamu South Island (Figure 2-2).

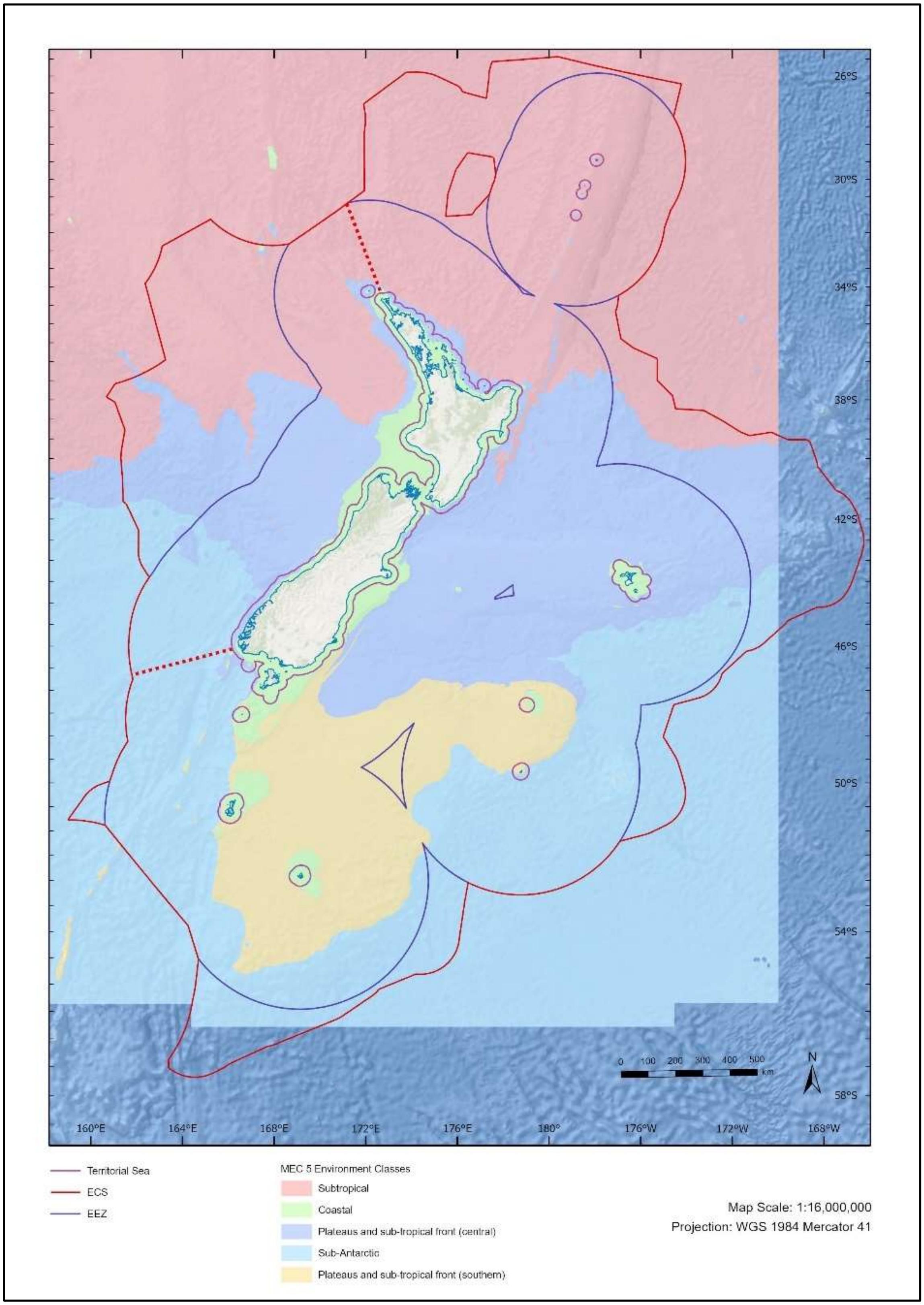

Figure 2-2: Map of Aotearoa New Zealand showing the five MEC environmental classes.

2.4.2 Seamounts

Seamounts occur throughout the Aotearoa New Zealand's EEZ and ECS, varying in size from 'hills' and 'knolls' of a few hundred metres elevation, to much larger seamounts such as Bollons Seamount that are thousands of metres high and kilometres in diameter (Figure 2-3). Many have been reasonably well sampled as part of NIWA's deep-sea research over the last 30 years (NIWA data include about 750 features in the EEZ-ECS). Together with ridges (which are an ecologically similar form of topography), these can be subject to high current flows and oceanographic complexity enhancing biodiversity but with highly variable faunal composition. For example, habitat-forming stony corals are frequently recorded from seamount features, especially in the mid-depth and deeper waters where in particular *Solenosmilia variabilis* and *Madrepora oculata* can occur in high densities (Clark and Rowden 2009, Tracey et al. 2011).

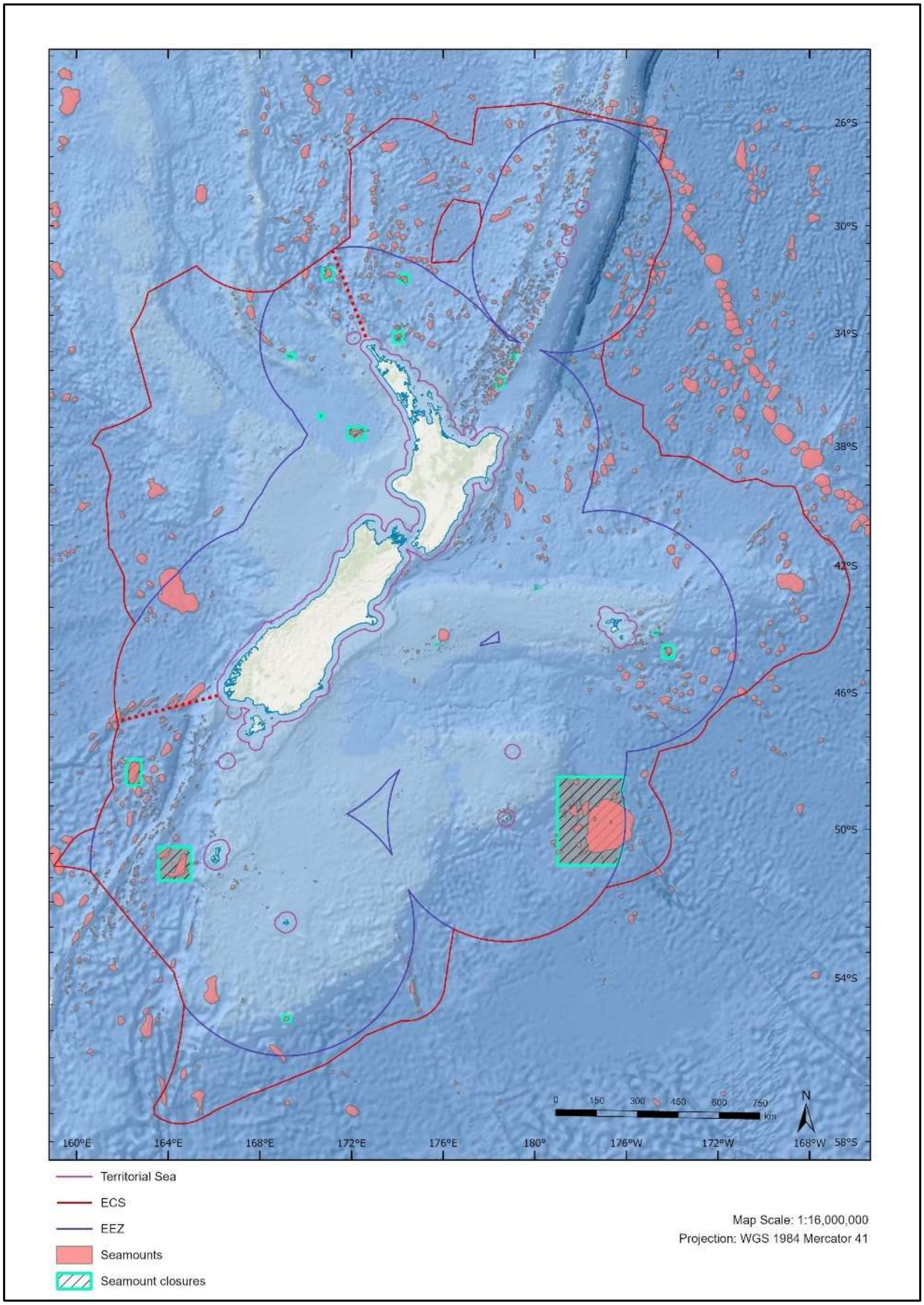

Figure 2-3: Map of Aotearoa New Zealand showing the distribution of seamounts and seamount closure areas.

2.5 Receiving ecosystem components

The potential effects (section 2.3) and their consequences arising from space vehicle launch debris were evaluated by the panel of experts for the following four receiving ecosystem components within each environment class (section 2.4):

1. Air-breathing fauna, primarily marine mammals and seabirds
2. The pelagic community, including plankton, larger invertebrates and fish
3. The demersal (bottom-associated) community, including fish and mobile invertebrates
4. The benthic invertebrate community

Lamarche et al. (2017) included a fifth ecosystem component - sensitive benthic environments – which is now captured in our 'benthic invertebrate community' ecosystem component. The 13 sensitive environments are defined and described in Schedule 6 of the Exclusive Economic Zone and Continental Shelf (Environmental Effects—Permitted Activities) Regulations 2013[3]. We recognise that not all benthic invertebrates constitute sensitive environments as defined by the Regulations noted above. However, when considering the benthic invertebrate community ecosystem component, we paid particular attention to the presence of sensitive environments where this information was available.

Earth Sciences NZ houses the National Invertebrate Collection containing approximately 350,000 samples collected over the last 50 years from the Aotearoa New Zealand region and wider southwest Pacific Ocean. Approximately half of the samples have been registered in the *Specify* database and these data underpin many of the distribution modelling studies applied to numerous taxonomic groups and used in this ERA. There have been relatively recent compilations of these invertebrate data that we have additionally drawn on, notably the SCC (Stephenson et al. 2022) and the Key Ecological Areas project undertaken by NIWA for the Department of Conservation (DOC: Stephenson et al. 2018, Lundquist et al. 2020).

NIWA databases, other data sources, and the published literature were used to assemble information on these ecosystem components for the ERA.

Specifically, when considering the benthic community, sensitive environments and those coral and hydrocoral taxa that are protected under the Wildlife Act 1953[4] were considered using a combination of *Specify* records and modelled distributions to inform the ERA process. Below are example plots of locations and distributions of selected taxa and groups of taxa.

In addition to plots of hotspots of abundance of protected of protected corals (Figure 2-4) and locations of seeps (Figure 2-5), Figure 2-6 shows the modelled species richness for biogenic habitat forming benthic invertebrates. Biogenic habitats are created by plants and animals that provide three-dimensional structures that in turn offer temporary or permanent living space and resources for other species. Larger invertebrates from genera within the key biogenic habitat forming groups of bryozoan thickets, sponge gardens, stony coral and other habitat-forming corals, and sea pens (all sensitive environments) were included in the modelling.

[3] https://www.legislation.govt.nz/regulation/public/2013/0283/latest/whole.html#DLM5270660
[4] https://www.legislation.govt.nz/act/public/1953/0031/latest/DLM276814.html

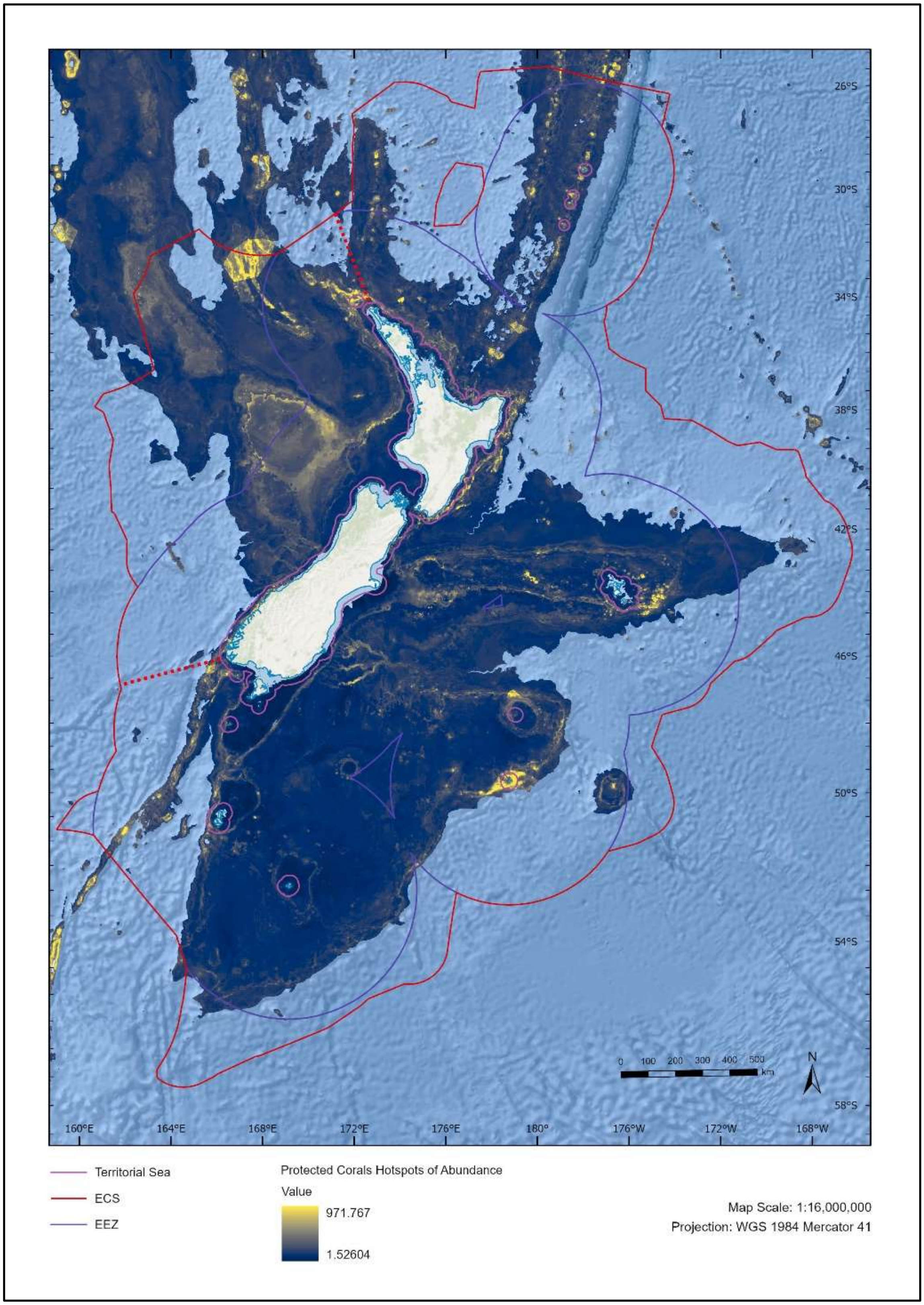

Figure 2-4: Plot of hotspots (shaded yellow) of abundance of protected corals and hydrocorals. Modelled extent limited to water depths of up to 3,000 m.

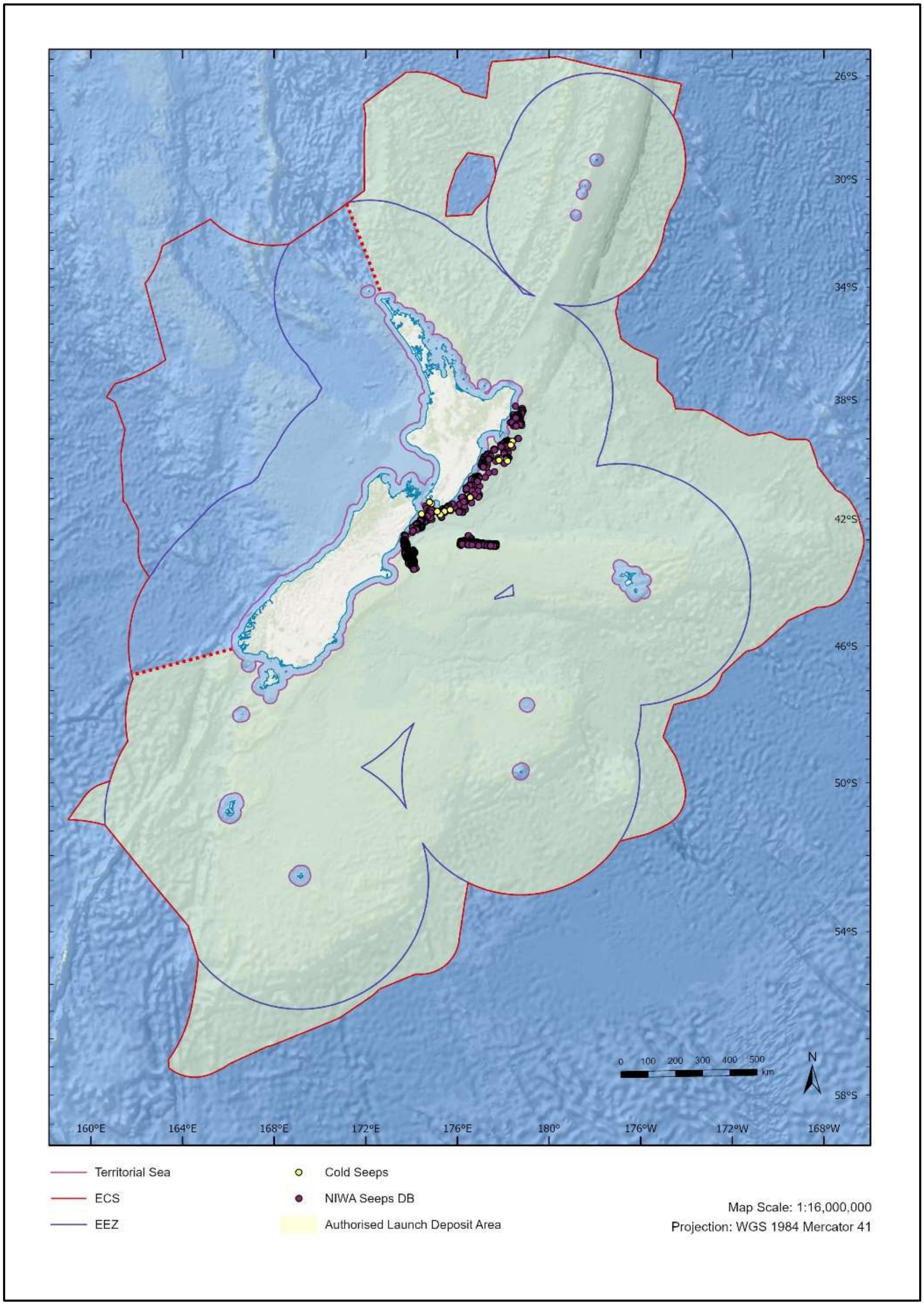

Figure 2-5: Plot of locations of known seeps.

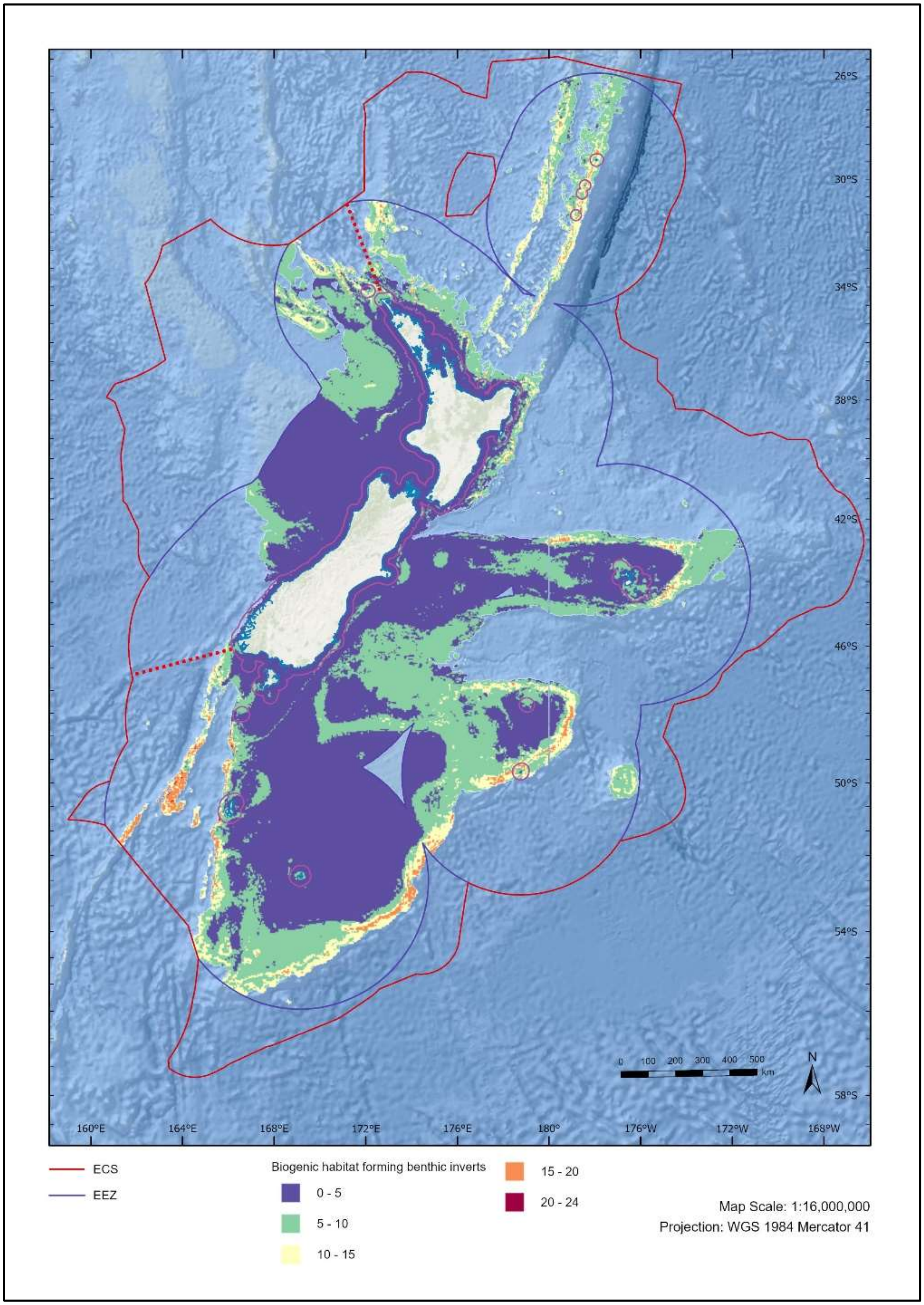

Figure 2-6: Plot of species richness for biogenic habitat forming invertebrates. Modelled extent limited to water depths of up to 2,000 m.

Demersal fish are perhaps one of the best-known taxonomic groups in Aotearoa New Zealand, due in large part to their importance for commercial fisheries. Earth Sciences NZ has allocated significant effort to research surveys, the results of which are generally contained in the TRAWL database, which includes approximately 400,000 records. Point records are available for most trawlable depths (<1,600 m). Figure 2-7 shows species richness for demersal fish taxa.

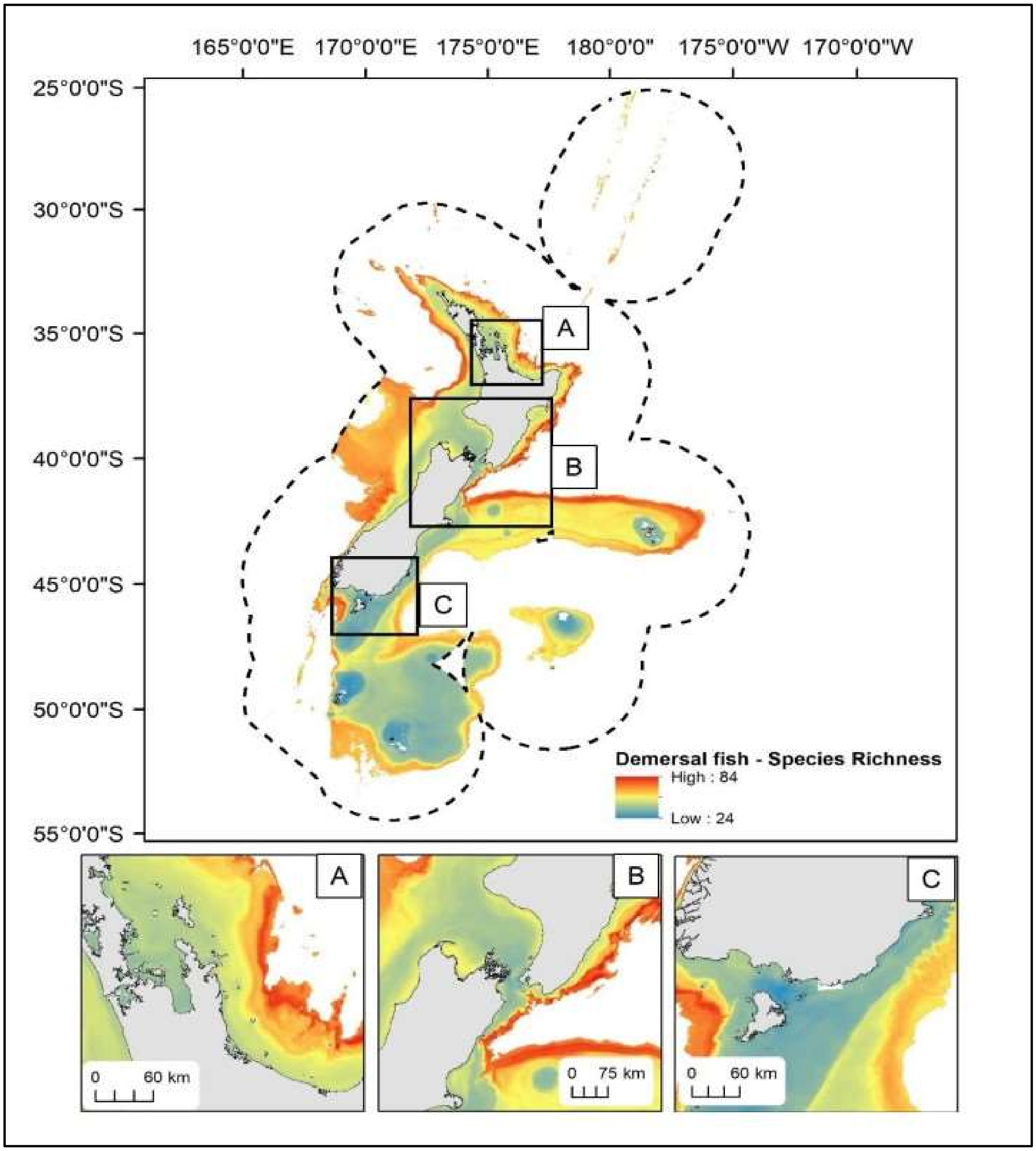

Figure 2-7: Demersal fish richness estimates (derived by stacking 239 bootstrapped species distribution models). Richness estimates are clipped to areas of adequate model environmental coverage (<2,000 m depth).

There is no single, comprehensive database of distributional information covering all Aotearoa New Zealand seabird taxa. Therefore, distribution data were gathered from a number of sources, including published tracking studies and unpublished in-house seabird location information, publicly available sightings data held by the eBird database[5], data held by the Seabird Tracking Database[6] (the primary repository of seabird tracking data) and information on the breeding sites of seabirds, mainly from the New Zealand Birds Online website[7]. We assumed seabirds will be more commonly encountered in waters relatively close to their breeding sites, although it should be noted that most seabird taxa range widely, particularly over seasonal timescales, and can occupy waters relatively distant from breeding sites at certain times of the year (e.g., Figure 2-8).

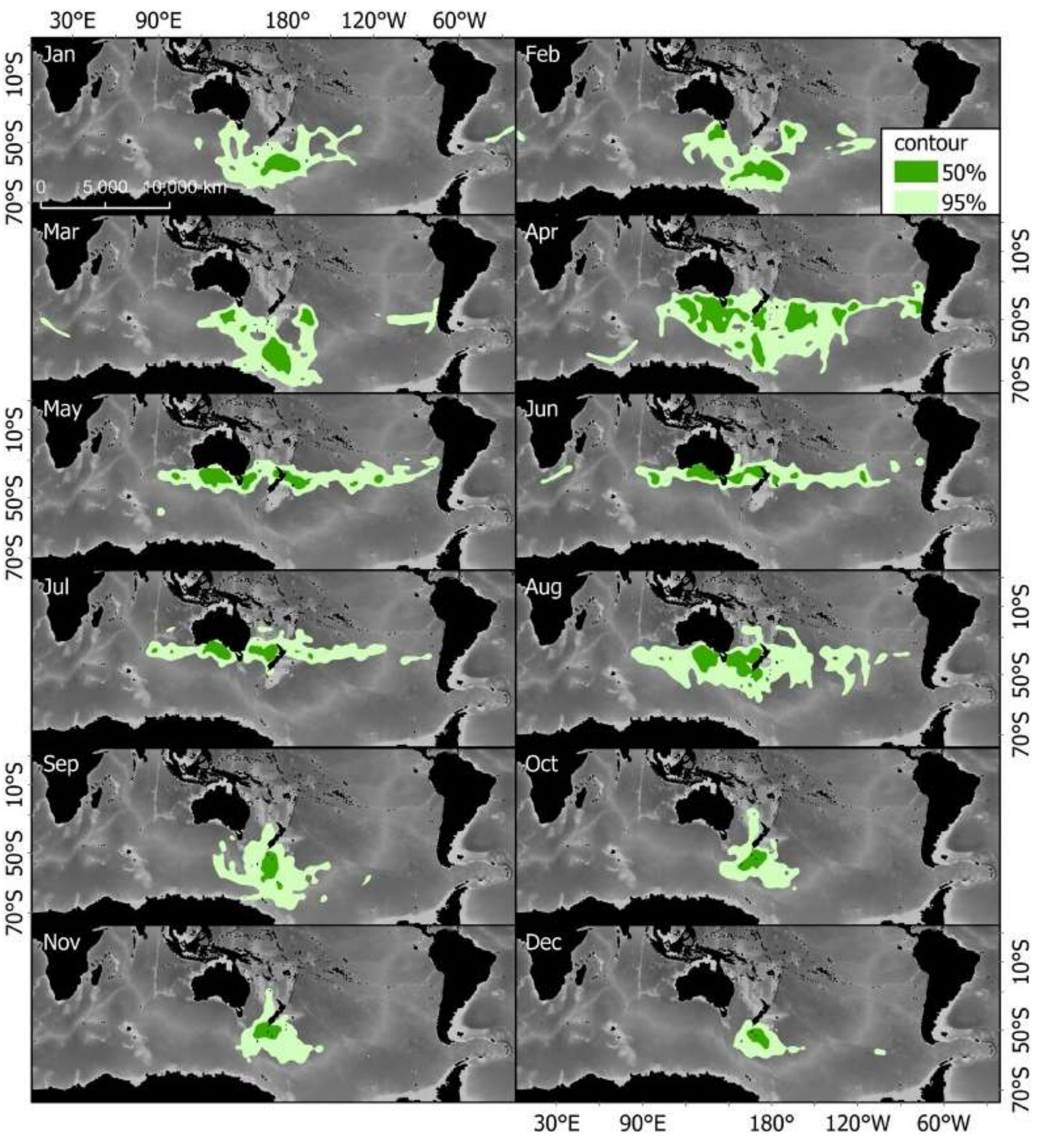

Figure 2-8: Plots of monthly kernel density for adult Campbell albatrosses, derived from geolocation tracking data from breeding birds at Campbell Island. Dark green - 50% kernel, light green - 95% kernel. Data acquired from 2009 and 2010, both years combined. From Thompson et al. (2021).

[5] https://ebird.org/home
[6] https://www.seabirdtracking.org/
[7] https://www.nzbirdsonline.org.nz/

Data for marine mammals were obtained from incidental sightings collated and administered by the DOC, which were additionally used for spatial distribution modelling (relative environmental suitability (RES) models for species with few sightings and boosted regression tree (BRT) models for species with adequate sightings) across a broad suite of taxa (Stephenson et al. 2020a, 2020b). Example model outputs are presented in Figure 2-9 and Figure 2-10.

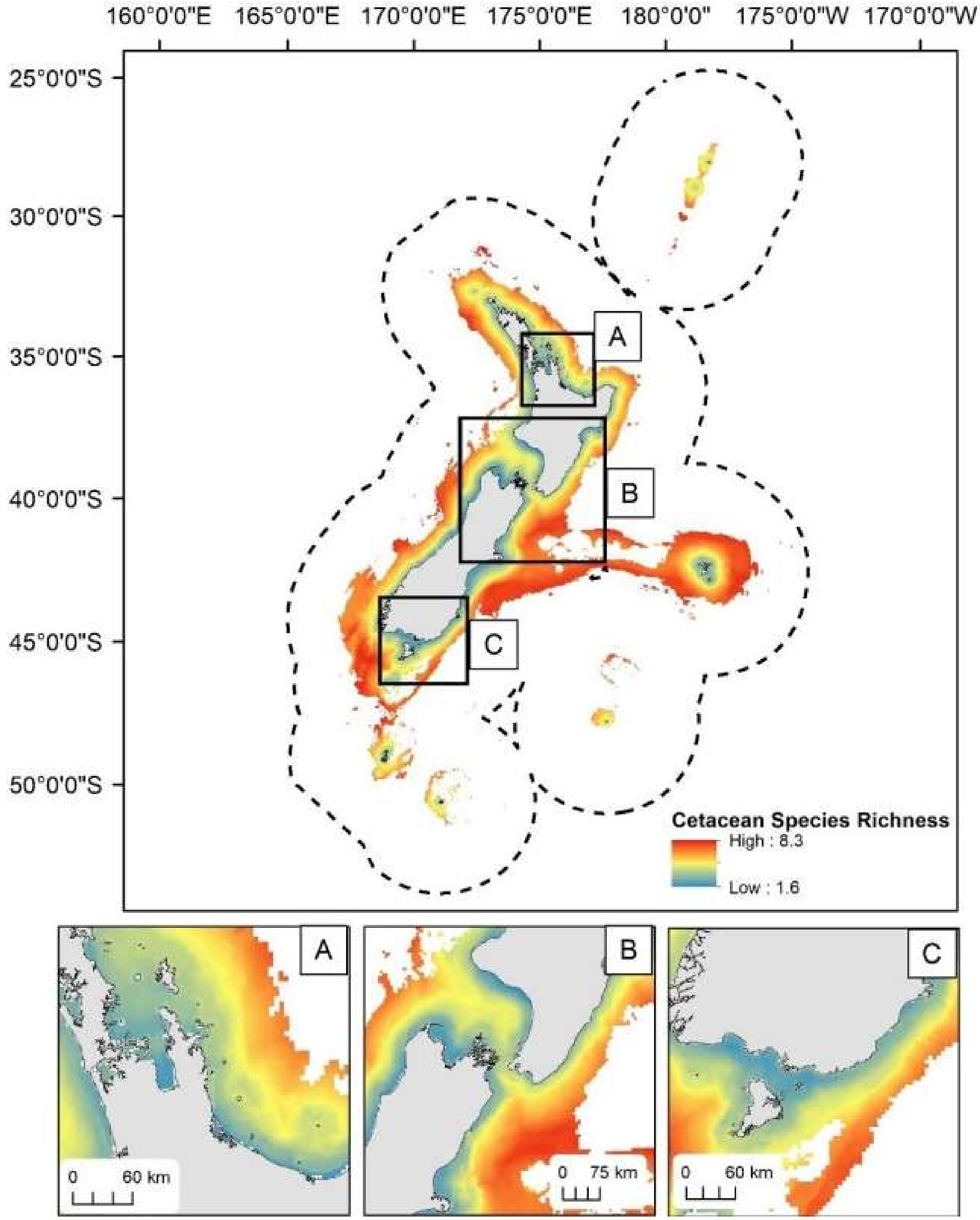

Figure 2-9: Species richness of New Zealand cetacean species based on weighted stacking of 30 models of species occurrences. Richness estimates are clipped to areas of adequate model environmental coverage. From Lundquist et al. (2020).

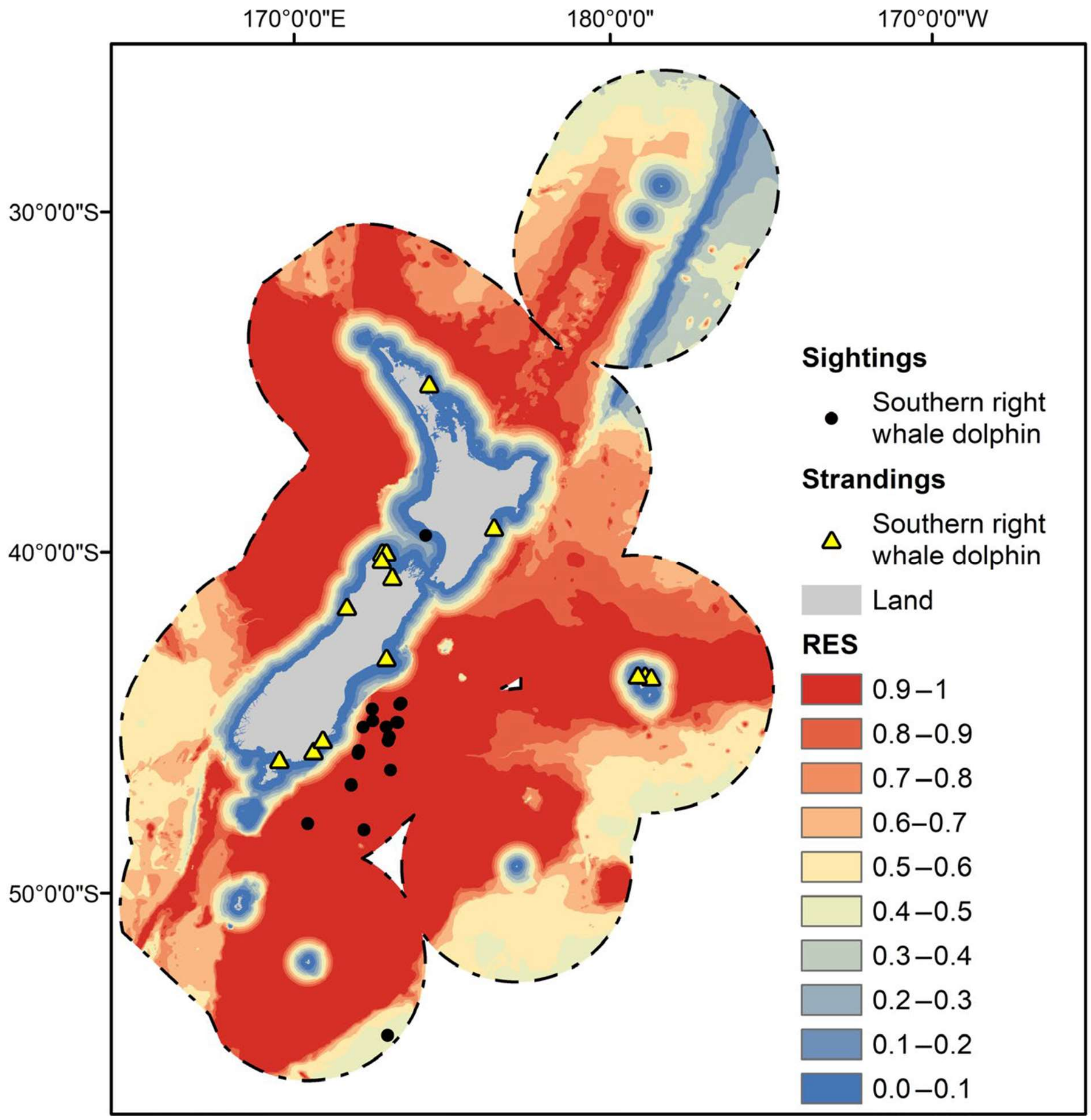

Figure 2-10: Predicted RES scores for southern right whale dolphin *Lissodelpis peronii*, ranging from less suitable (blue) to very suitable (red). Predicted RES scores are shown with sightings at sea and location of recorded strandings (from the DOC marine mammal strandings database). Sightings at sea and location of recorded strandings were not used as inputs in the model but were used as a visual validation only. From Stephenson et al. 2020b.

2.6 Risk assessment methodology

Having identified the suite of potential effects (section 2.3) and ecosystem components (section 2.4) that could be impacted, the assessment process, carried out by a panel of experts, comprised three steps.

Firstly, the consequence or magnitude of each potential effect on each ecosystem component is defined. Consequence is scored on a six-point scale from 0 (zero) to 5 using a standardised set of consequence descriptions, ranging from negligible (0) to catastrophic (5). Consequence descriptions are presented in Table 2-1 and have been adapted from those used by Fletcher

(2005) and later by MacDiarmid et al. (2011, 2015, 2016) and Lamarche et al. (2017). The panel considered consequence with regard to three aspects of the environment: the proportion of habitat affected by a potential effect, the functional impact on populations, communities of organisms or the habitat, and the time for these functions to recover if the effect stopped. These are all key indicators of ecological response at a range of scales. The proportion of a habitat affected by an activity is critical to assessing the spatial extent of any impact. The ecological functional impact is likewise a broad indicator of the ecological significance of a disturbance. Lastly recovery period provides an indication of the affected species and habitat ability to recover from the threat taking into account knowledge of the biology and ecology.

Secondly, the likelihood of a particular effect occurring was assessed and scored on a six-point scale, again using a set of standardised descriptions, ranging from 1 (remote) to 6 (likely). Likelihood descriptions are presented in Table 2-2.

Following the scoring of consequences and likelihoods the panellists assessed the level of confidence in the information available to make each assessment based on the categories provided in Table 2-3. To reach a decision, the panel engaged in open discussion until a consensus was reached for a draft score of each potential effect to each ecosystem component. The draft table of scores was then assessed independently by each panellist and suggested changes offered to the whole panel. Final score values were again reached by consensus.

Thirdly, using the scores of consequence (Table 2-1) and likelihood (Table 2-2), ecological risk scores were calculated as the product (multiplication) of consequence and likelihood. Risk scores can therefore range from a minimum of 0 (zero) to a maximum of 30 (Table 2-4). This approach identified the level of risk for each ecosystem component from each potential effect arising from the fall of rocket debris into each of the environment classes.

Following the classification adopted by MacDiarmid et al. (2011, 2016) and Lamarche et al. (2017), activities with risk scores of 6 or less are categorised as low. These scores arise from the lowest two levels of consequence (0 - negligible and 1 - minor) (see Table 2-4) at all levels of likelihood (including 6 - likely), from moderate levels of consequence (2) at unlikely (3) or lower levels of likelihood, from severe levels of consequence (3) at rare (2) or remote (1) levels of likelihood, or from major and catastrophic levels of consequence at remote levels of likelihood. At the upper end of the score scale, activities with risk scores of 24 or more are categorised as extreme (Table 2-4). These levels of risk arise only from those activities judged to have major (4) consequences at the highest level of likelihood (6) and catastrophic consequences (5) at the two highest levels of likelihood (5 and 6). Between these extremes, activities with risk scores from 8 to 12 are categorised as moderate, and those with risk scores from 15 to 20 are categorised as high (Table 2-4).

Table 2-1: Consequence levels for each potential effect. Summary descriptions of the six sets of consequence levels for the percent overlap of population distribution with debris area, the impact on the population, community or habitat, and the likely recovery period. Adapted from MacDiarmid et al. (2016).

Consequence level	Percent overlap of population distribution with debris area	Population/ community/ habitat impact	Recovery Period
0 - Negligible	Affects <1% of distribution	Interactions may be occurring but unlikely to be ecologically significant (<1% changes in abundance, biomass, or composition) or be detectable at the scale of the population, habitat or community	No recovery time required
1 - Minor	Measurable but localised; affects 1-5% of distribution	Possibly detectable with 1-5% change in population size or community composition and no detectable impact on dynamics of specific populations	Rapid recovery would begin if activity stopped – less than 8 weeks
2 - Moderate	Impacts more common; >5-20% of distribution affected	Measurable with >5-20% changes to the population, habitat, community, or biodiversity components without there being a major change in function. There may some change in species ranges	Recovery in >2 months to 1-2 years if activity stopped
3 - Major	Impacts very widespread; >20-50% of distribution is affected	Populations, habitats, communities, and biodiversity measures substantially altered (>20-50%), with some function or components missing/ declining/ increasing well outside historical ranges. Some additional species appear in the affected environment while others have shrinking ranges	Recovery occurs in 2-10 years if activity stopped
4 - Severe	Impact extensive; >50-80% of distribution affected	Likely to cause local extinctions of vulnerable species if impact continues, with a >50-80% change to habitat and community structure and function. Significant change in range of some species. Different population dynamics now occur with biodiversity measures greatly affected	Recovery period 1-2 decades if activity stopped
5 - Catastrophic	Almost entire distribution is affected; >80%	Local extinctions or surges of a variety of species are imminent/immediate. Total change in habitat, community or ecosystem processes. The abundance, biomass or diversity of most groups is drastically changed (by >80%)	Long term recovery to former levels will be greater than 1-2 decades, perhaps centuries, even if activity stopped

Table 2-2: Threat likelihood categories.

Level/score	Descriptor	Likelihood
1	Remote	Highly unlikely
2	Rare	May occur in exceptional circumstances
3	Unlikely	Uncommon, but has been known to occur elsewhere
4	Possible	Some evidence to suggest this is possible
5	Occasional	Will occasionally occur
6	Likely	It is expected to occur

Table 2-3: Confidence rating, score and description.

Confidence rating	Score	Rationale for confidence score
Low	1a	No data and no consensus among experts with low confidence
	1b	No data exist and tentative consensus among experts with low confidence
	1c	No data exist but consensus among experts with low confidence
High	2a	No data exist but consensus among experts with high confidence
	2b	Some data (unpublished, not peer-reviewed but considered sound) and consensus among experts with high confidence
	2c	Reliable peer-reviewed data or information (published journal articles or reports) and consensus among experts with high confidence

Table 2-4: Risk levels and categories.

Risk Level	Risk score range	Risk score derivation	
		Consequence level	Likelihood levels
Low	0-6	0 – negligible	1-6 (remote to likely)
		1 – minor	1-6 (remote to likely)
		2 – moderate	1-3 (remote, rare or unlikely)
		3 – severe	1-2 (remote or rare)
		4 – major	1 (remote)
		5 – catastrophic	1 (remote)
Moderate	8-12	2 – moderate	4-6 (possible, occasional, likely)
		3 – severe	3-4 (unlikely, possible)
		4 – major	2-3 (rare, unlikely)
		5 – catastrophic	2 (rare)
High	15-20	3 – severe	5-6 (occasional, likely)
		4 – major	4-5 (possible, occasional)
		5 – catastrophic	3-4 (unlikely, possible)
Extreme	24-30	4 – major	6 (likely)
		5 – catastrophic	5-6 (occasional or likely)

3 Potential effects impacting Māori interests

Māori have a deep relationship to space through whakapapa – the enduring connection to Ranginui, Papatūānuku and the many celestial bodies that have, and continue to guide te ao Māori. This relationship has been acknowledged through the Waitangi Tribunal, and government decisions, policy and regulation including the allocation of radio spectrum under the Radiocommunications Act, and through Te Kāhui o Matariki Public Holiday Bill 2022. The recognition and celebration of Matariki in Aotearoa (and across the Pacific) has increased the visibility and revitalisation of Māori celestial knowledge and practice (Harris et al. 2024).

In considering the potential for impacts to the interests of Māori from space vehicle debris in the marine environment, we acknowledge a significant dearth of specific and available research and information. We do know from *Te Puawānanga Report: A Landscape Report on the Aims, Aspirations, Opportunities, Issues and Concerns on Aerospace for Māori*, that there is a significant interest amongst Māori to explore space through an indigenous lens. Equally, there is considerable concern amongst Māori about aerospace junk, debris and waste pollution and safety issues in general around unknown, untracked, uncontrolled and unclaimed debris (Harris et al. 2024).

The report further notes that interview and survey participants described the importance of protecting and looking after Ranginui and Papatūānuku and other atua of relevance to the aerospace industry. This concern centres on the health and wellbeing of these atua and the impacts on current and future generations. The report goes on to comment on a lack of transparency and quality in environmental impact assessments and decision-making processes undertaken to date, noting the absence of adequate consideration to te ao Māori and the impacts to the interests of Māori. In addition, some communities have highlighted issues surrounding exclusion zones created by aerospace activities restricting fishing, mahinga kai (traditional food gathering) practices, access to land, and the ability to apply cultural practices such as rāhui (a spatial or practice restriction for sustainability or wellbeing purposes) (Harris et al. 2024).

Although conclusions can be drawn from the results of the ERA to impacts to taonga species and ecosystems, there has been no direct research addressing the potential impact from a te ao Māori perspective. We consider such research to be vital to understanding and addressing the impacts to Māori interests moving forward.

4 Risk assessment

Table 4-1 presents scores for consequence, likelihood, confidence and risk from the three potential effects considered and for four ecosystem components across a range of environmental classes. Scores are presented for an increasing number of space vehicle launches (actually, 'Standardised Impact Units', see section 5): 1, 10, 100, 1,000 and 10,000. This categorical approach to scoring risk is in keeping with the Level 1 qualitative risk assessment methodology, whereas risk scored continuously would be more in keeping with semi-quantitative or fully quantitative risk assessment methodologies. Nevertheless, risk has been estimated for different numbers of launches in section 5, a risk assessment that utilises the locations of space vehicle debris to date.

For all potential effects and for all receiving components, risk scores fell into the 'low risk' category (scores 0-6) for 1, 10 and 100 nominal launches. At 1,000 nominal launches, risk scores fell into the ‘moderate risk’ category (scores 8-12) for noise disturbance and air-breathing fauna within the coastal and seamount environment classes and for direct strike causing mortality for benthic invertebrate community within the seamount environment class. At 10,000 nominal launches, risk scores fell into the ‘moderate risk’ category for noise disturbance and air-breathing fauna within all environment classes, for direct strike causing mortality for air-breathing fauna and benthic invertebrate community within the seamount environment class and for smothering of benthic organisms for benthic invertebrate community within the coastal and seamount environment classes (Table 4-1).

4.1 Discussion of scores

The risk scores resulting from this ERA (Table 4-1) are broadly in line with those reported by MacDiarmid et al. (2016) and Lamarche et al. (2017), in that for the majority of effect-receiving component-environment class combinations risk fell within the ‘low’ risk category. However, Lamarche et al. (2017) suggested that at 100 launches risk could move into the ‘moderate’ category and at 1,000 launches could become ‘high’ (i.e., risk could become ‘moderate’ at an order of magnitude fewer launches than in the ERA presented here), a category not achieved here (see Table 4-1).

It should be noted that there were several key differences between the 2017 and present ERAs. Lamarche et al. (2017) only formally assessed the risk from a single launch and simply provided commentary on how risk might track upwards with an increasing number of launches. Importantly, Lamarche et al. (2017) considered a launch of a substantially larger vehicle, resulting in 40,000 kg of debris, comprising stage one, fairings and batteries, that would return to the ocean and would fragment during descent into numerous pieces. Hence, Lamarche et al. (2017) considered a scenario where there were very many more pieces of debris all capable of contributing to the range of effects assessed. Finally, Lamarche et al. (2017) noted that the higher risk levels they suggested may occur at 100 launches and above would be dependent, in part, on whether the debris fell into a relatively small area (effectively ‘concentrating’ effects), or whether the debris was dispersed over a wider spatial extent. It is now clear that debris falls over a relatively large area of ocean to the east of Aotearoa New Zealand (Figure 2-1). Given that this ERA considered non-fragmenting stage one and fairings and that this debris was relatively dispersed in splashdown locations, it would seem reasonable that ‘moderate’ risk was only achieved at 1,000 nominal launches (Table 4-1).

A larger vehicle generating 40,000 kg of debris (in line with the 2017 assessment (Lamarche et al. (2017)), but which remained largely intact (as in the current assessment) would result in risk scores similar to those presented here (Table 4-1) and would reach ‘moderate’ levels only after 1,000 launches. Intact debris falling as a relatively small number of pieces is less impactful than the same mass of debris fragmenting into a relatively large number of pieces (see also section 5).

4.1.1 Direct strike causing mortality

Risk from this potential effect was scored as ‘moderate’ for air-breathing fauna and benthic invertebrate community only within the seamount environment class and only at 1,000 launches and above (Table 4-1). The panel considered these elevated risk scores were justified primarily due to an increasing likelihood of strike at higher launch levels combined with ‘moderate’ consequence scores.

For air-breathing fauna as a whole, the overall Aotearoa New Zealand population is highly likely to be too large for direct strike from vehicle debris to have a consequential effect. However, seamounts are known to be favoured by both marine mammals and seabirds, presumably as foraging destinations. For example, Kaschner (2007) reported a highly significant relationship between seamount density and modelled marine mammal species richness, and there is a growing body of research highlighting the importance of seamounts for seabirds (e.g., Thompson 2007, Weber et al. 2025). The panel felt that for some taxa that were characterised by relatively small populations and for which seamounts act as points of aggregation, there could be 'moderate' consequences from mortality resulting from debris strike.

Seamount habitats can support diverse and abundant assemblages of benthic invertebrates, including corals and other sensitive environments (see Rogers et al. 2007, Samadi et al. 2007, Rogers 2018). These benthic communities are susceptible to damage from human activities, notably trawling (Goode et al. 2025), and would be similarly vulnerable to launch vehicle debris. The panel felt that if launch debris falling on seamounts there would be potential for that debris to move across the substrate given the sloping topography and relatively strong water currents typical of seamounts, causing further impact.

4.1.2 Noise disturbance

Noise disturbance was considered to pose 'moderate' risk to air-breathing fauna across all environment classes at 10,000 nominal launches and at 1,000 nominal launches for the coastal and seamount classes (Table 4-1). Whilst all marine mammals and seabirds can both produce and respond to noise, underwater noise can cause auditory masking, behavioural disturbance, hearing damage, and even death for marine animals. Although the noise characteristics of debris hitting the sea surface were unknown, the panel assumed that some of the noise would dissipate above the ocean and be detectable by seabirds, but would be of negligible consequence for this group, and some would propagate into the ocean. Underwater noise would be detected by members of the pelagic community but result in negligible consequence for this receiving component. Marine mammals would also be likely to detect underwater noise and at high launch numbers the panel felt that there was potential for this noise to disrupt feeding and breeding behaviours with 'moderate' levels of consequence for some populations.

4.1.3 Smothering of benthic organisms

There was 'moderate' risk to the benthic invertebrate community at the 10,000 nominal-launch level within the coastal and seamount environment classes (Table 4-1), largely as a result of a relatively large number of debris pieces falling within two smaller environment classes. The extent to which a sediment plume extends outwards from the point of contact between debris and the seafloor is unknown but will depend in part on the characteristics of the sediment impacted. Nevertheless, whilst the panel recognised that any such plume would extend the smothering effect beyond the area contacted by debris, the area impacted by a plume would be relatively modest.

Table 4-1: Consequence, likelihood, confidence and risk scores for the impact of space launch vehicle debris on the marine ecosystem. Scores are for three potential effects on four ecosystem components within five environmental classes and for seamounts. Scores are based on an increasing number of nominal launches from 1 to 10,000, where a 'nominal launch is equivalent to one Standardised Impact Unit (section 5). NA - not applicable. See Figure 2-2 and Figure 2-3 for the locations of environment classes and seamounts, respectively.

				Potential effect											
				Direct strike causing mortality				Noise disturbance				Smothering of benthic organisms			
				Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence
		Receiving component	Nominal launches												
Marine Environment Classification	Subtropical	Air-breathing fauna	1	0	1	0	2a	0	1	0	1c	NA			
			10	0	1	0	2a	0	2	0	1c	NA			
			100	0	2	0	1c	1	3	3	1c	NA			
			1000	1	2	2	1c	1	4	4	1c	NA			
			10000	1	3	3	1c	2	5	10	1c	NA			
		Pelagic community	1	0	6	0	2a	0	6	0	1c	NA			
			10	0	6	0	2a	0	6	0	1c	NA			
			100	0	6	0	2a	0	6	0	1c	NA			
			1000	0	6	0	2a	0	6	0	1c	NA			
			10000	0	6	0	2a	0	6	0	1c	NA			

				Potential effect											
				Direct strike causing mortality				Noise disturbance				Smothering of benthic organisms			
				Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence
Marine Environment Classification		Demersal community	1	0	3	0	2a	0	1	0	2a	NA			
			10	0	3	0	2a	0	1	0	2a	NA			
			100	0	3	0	2a	0	1	0	1c	NA			
			1000	0	3	0	1c	0	1	0	1c	NA			
			10000	0	3	0	1c	0	1	0	1c	NA			
		Benthic invertebrate community	1	0	1	0	2a	0	1	0	2a	0	1	0	2a
			10	0	1	0	2a	0	1	0	2a	0	1	0	2a
			100	0	1	0	2a	0	1	0	2a	0	1	0	1c
			1000	1	1	1	1c	0	1	0	2a	1	2	2	1c
			10000	1	2	2	1c	0	1	0	1c	1	2	2	1c
	Plateaus and subtropical front (central)	Air-breathing fauna	1	0	1	0	2a	0	1	0	1c	NA			
			10	0	1	0	2a	0	2	0	1c	NA			
			100	0	2	0	1c	1	3	3	1c	NA			
			100	1	2	2	1c	1	4	4	1c	NA			
			10000	1	3	3	1c	2	5	10	1c	NA			

			Potential effect											
			Direct strike causing mortality				Noise disturbance				Smothering of benthic organisms			
			Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence
Marine Environment Classification	Pelagic community	1	0	6	0	2a	0	6	0	1c	NA			
		10	0	6	0	2a	0	6	0	1c	NA			
		100	0	6	0	2a	0	6	0	1c	NA			
		1000	0	6	0	2a	0	6	0	1c	NA			
		10000	0	6	0	2a	0	6	0	1c	NA			
	Demersal community	1	0	3	0	2a	0	1	0	2a	NA			
		10	0	3	0	2a	0	1	0	2a	NA			
		100	0	3	0	2a	0	1	0	1c	NA			
		1000	0	3	0	1c	0	2	0	1c	NA			
		10000	0	3	0	1c	0	3	0	1c	NA			
	Benthic invertebrate community	1	0	1	0	2a	0	1	0	2a	0	1	0	2a
		10	0	1	0	2a	0	1	0	2a	0	1	0	2a
		100	0	1	0	2a	0	1	0	2a	0	1	0	1c
		1000	1	2	2	1c	0	1	0	2a	1	2	2	1c
		10000	1	2	2	1c	0	1	0	1c	1	3	3	1c

				Potential effect											
				Direct strike causing mortality				Noise disturbance				Smothering of benthic organisms			
				Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence
Marine Environment Classification		Air-breathing fauna	1	0	1	0	2a	0	1	0	1c	NA			
			10	0	1	0	2a	0	2	0	1c	NA			
			100	0	2	0	1c	1	3	3	1c	NA			
			1000	1	2	2	1c	1	4	4	1c	NA			
			10000	1	3	3	1c	2	5	10	1c	NA			
		Pelagic community	1	0	6	0	2a	0	6	0	1c	NA			
			10	0	6	0	2a	0	6	0	1c	NA			
			100	0	6	0	2a	0	6	0	1c	NA			
			1000	0	6	0	2a	0	6	0	1c	NA			
			10000	0	6	0	2a	0	6	0	1c	NA			
	Plateaus and subtropical front (southern)	Demersal community	1	0	3	0	2a	0	1	0	2a	NA			
			10	0	3	0	2a	0	1	0	2a	NA			
			100	0	3	0	2a	0	1	0	1c	NA			
			1000	0	3	0	1c	0	1	0	1c	NA			
			10000	0	3	0	1c	0	2	0	1c	NA			

				Potential effect											
				Direct strike causing mortality				Noise disturbance				Smothering of benthic organisms			
				Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence
Marine Environment Classification		Benthic invertebrate community	1	0	1	0	2a	0	1	0	2a	0	1	0	2a
			10	0	1	0	2a	0	1	0	2a	0	1	0	2a
			100	0	1	0	2a	0	1	0	2a	0	1	0	1c
			1000	1	1	0	1c	0	1	0	2a	1	2	2	1c
			10000	1	2	0	1c	0	1	0	1c	1	2	2	1c
	Sub-Antarctic	Air-breathing fauna	1	0	1	0	2a	0	1	0	1c	NA			
			10	0	1	0	2a	0	2	0	1c	NA			
			100	0	2	0	1c	1	3	3	1c	NA			
			1000	1	2	2	1c	1	4	4	1c	NA			
			10000	1	3	3	1c	2	5	10	1c	NA			
		Pelagic community	1	0	6	0	2a	0	6	0	1c	NA			
			10	0	6	0	2a	0	6	0	1c	NA			
			100	0	6	0	2a	0	6	0	1c	NA			
			1000	0	6	0	2a	0	6	0	1c	NA			
			10000	0	6	0	2a	0	6	0	1c	NA			

				Potential effect											
				Direct strike causing mortality				Noise disturbance				Smothering of benthic organisms			
				Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence
Marine Environment Classification		Demersal community	1	0	3	0	2a	0	1	0	2a	NA			
			10	0	3	0	2a	0	1	0	2a	NA			
			100	0	3	0	2a	0	1	0	1c	NA			
			1000	0	3	0	1c	0	1	0	1c	NA			
			10000	0	3	0	1c	0	1	0	1c	NA			
		Benthic invertebrate community	1	0	1	0	2a	0	1	0	2a	0	1	0	2a
			10	0	1	0	2a	0	1	0	2a	0	1	0	2a
			100	0	1	0	2a	0	1	0	2a	0	1	0	1c
			1000	1	1	1	1c	0	1	0	2a	1	2	2	1c
			10000	1	2	2	1c	0	1	0	1c	1	2	2	1c
	Coastal	Air-breathing fauna	1	0	1	0	2a	0	1	0	1c	NA			
			10	0	2	0	2a	1	2	2	1c	NA			
			100	1	2	2	1c	2	3	6	1c	NA			
			1000	1	3	3	1c	2	4	8	1c	NA			
			10000	1	4	4	1c	2	5	10	1c	NA			

			Potential effect											
			Direct strike causing mortality				Noise disturbance				Smothering of benthic organisms			
			Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence
Marine Environment Classification	Pelagic community	1	0	6	0	2a	0	6	0	1c	NA			
		10	0	6	0	2a	0	6	0	1c	NA			
		100	0	6	0	2a	0	6	0	1c	NA			
		1000	0	6	0	2a	0	6	0	1c	NA			
		10000	0	6	0	2a	1	6	6	1c	NA			
	Demersal community	1	0	3	0	2a	0	1	0	2a	NA			
		10	0	3	0	2a	0	1	0	2a	NA			
		100	0	3	0	2a	0	1	0	1c	NA			
		1000	0	3	0	1c	0	2	0	1c	NA			
		10000	0	3	0	1c	1	3	3	1c	NA			
	Benthic invertebrate community	1	0	1	0	2a	0	1	0	2a	0	1	0	2a
		10	0	1	0	2a	0	1	0	2a	0	1	0	2a
		100	0	1	0	2a	0	1	0	2a	0	2	0	1c
		1000	1	2	2	1c	0	1	0	2a	1	3	3	1c
		10000	2	3	6	1c	1	1	1	1c	2	4	8	1c

			Potential effect											
			Direct strike causing mortality				Noise disturbance				Smothering of benthic organisms			
			Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence
Seamount	Air-breathing fauna	1	0	1	0	2a	0	1	0	1c	NA			
		10	0	2	0	2a	1	2	2	1c	NA			
		100	1	2	2	1c	2	3	6	1c	NA			
		1000	1	3	3	1c	2	4	8	1c	NA			
		10000	2	4	8	1c	2	5	10	1c	NA			
	Pelagic community	1	0	6	0	2a	0	6	0	1c	NA			
		10	0	6	0	2a	0	6	0	1c	NA			
		100	0	6	0	2a	0	6	0	1c	NA			
		1000	0	6	0	2a	0	6	0	1c	NA			
		10000	0	6	0	2a	1	6	6	1c	NA			
	Demersal community	1	0	4	0	2a	0	1	0	2a	NA			
		10	0	4	0	2a	0	1	0	2a	NA			
		100	0	4	0	2a	0	1	0	1c	NA			
		1000	0	4	0	1c	0	2	0	1c	NA			
		10000	0	4	0	1c	1	3	3	1c	NA			

			Potential effect											
			Direct strike causing mortality				Noise disturbance				Smothering of benthic organisms			
			Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence	Consequence	Likelihood	Risk	Confidence
Seamount														
	Benthic invertebrate community	1	0	1	0	2a	0	1	0	2a	0	1	0	2a
		10	0	2	0	2a	0	1	0	2a	0	1	0	2a
		100	1	3	3	1c	0	1	0	2a	1	2	2	1c
		1000	2	4	8	1c	1	2	2	1c	1	3	3	1c
		10000	2	5	10	1c	1	2	2	1c	2	4	8	1c

4.2 Debris as attachment surfaces

Debris falling to the seafloor and which does not become buried in the seafloor sediments will provide settlement surfaces for benthic invertebrates. These would represent additional attachment sites and would be a positive effect for populations of invertebrates living on hard surfaces. However, the debris would also be negative for those organisms inhabiting soft sediments. Assessing whether this trade-off results in an overall net positive or negative outcome for benthic invertebrates is not straight forward, but MacDiarmid et al. (2016) reported that this effect was positive at 1,000 and 10,000 nominal launches. Even at the 10,000 nominal-launch level, the area of space vehicle debris reaching the seafloor will be approximately 0.5 km^2.

4.3 Launch vehicle debris and bottom contact trawling

Debris from rocket launches have the potential to accumulate on the seafloor and interact with mobile bottom fishing methods such as bottom trawling. An analysis was undertaken to determine the overlap between debris locations (Figure 2-1) and the spatial extent or 'footprint' of recent bottom trawling in Aotearoa New Zealand's EEZ.

Fisheries New Zealand (FNZ) have contracted Earth Sciences NZ to carry out analyses of the extent and intensity of bottom contacting trawling in Aotearoa New Zealand's EEZ for a number of years (see MacGibbon et al. (2024) for the most recently published report). These analyses map the area covered by bottom contacting trawling (defined as bottom trawling or midwater trawling within one metre of the seabed) as reported by commercial fishers and overlay it on the 'fishable area' – defined as areas open to bottom trawling in the EEZ in depths as deep as 1600 m. There is almost no bottom trawling beyond the 1600 m depth contour. The fishable area is approximately 1.38 M km^2 and is divided into cells of 25 km^2 (5 × 5 km). These cells contain summary information such as depth, the discrete and cumulative areas swept by trawling (footprint and aggregate areas), and the number of tows that occurred in those cells.

The analyses here used the footprint data from the most recent footprint project (MacGibbon et al. in press) with permission from FNZ. The data cover the period from the 2018-19 to 2022-23 fishing years. Note that the fishing year runs from 1 October to 30 September, but fishing years here will be referred to as the most recent year: e.g., the 2018-19 fishing year will be referred to as 2019. There are two reasons why the 2019–2023 period has been chosen. Firstly, this period better reflects the more recent extent of the trawl footprint, which has been decreasing for a number of years and is substantially smaller than it was 30 years ago. Secondly, from 2019, the introduction of Geospatial Position Reporting devices on fishing vessels allowed for more accurate mapping of the true path taken of the individual trawls that collectively make up the overall footprint extent.

The locations of stage one and fairing debris were mapped to the overall fishable area and also the footprint within the fishable area (not all of the fishable area is trawled even though it is open to trawling). Summaries were then made of the fishing activity that has occurred in the contacted cells. The locations of stage one and fairing debris in relation to the EEZ, fishable area, footprint, and aggregate area (cumulative sum of the footprint as areas trawled are repeatedly covered) are mapped in Figure 4-1.

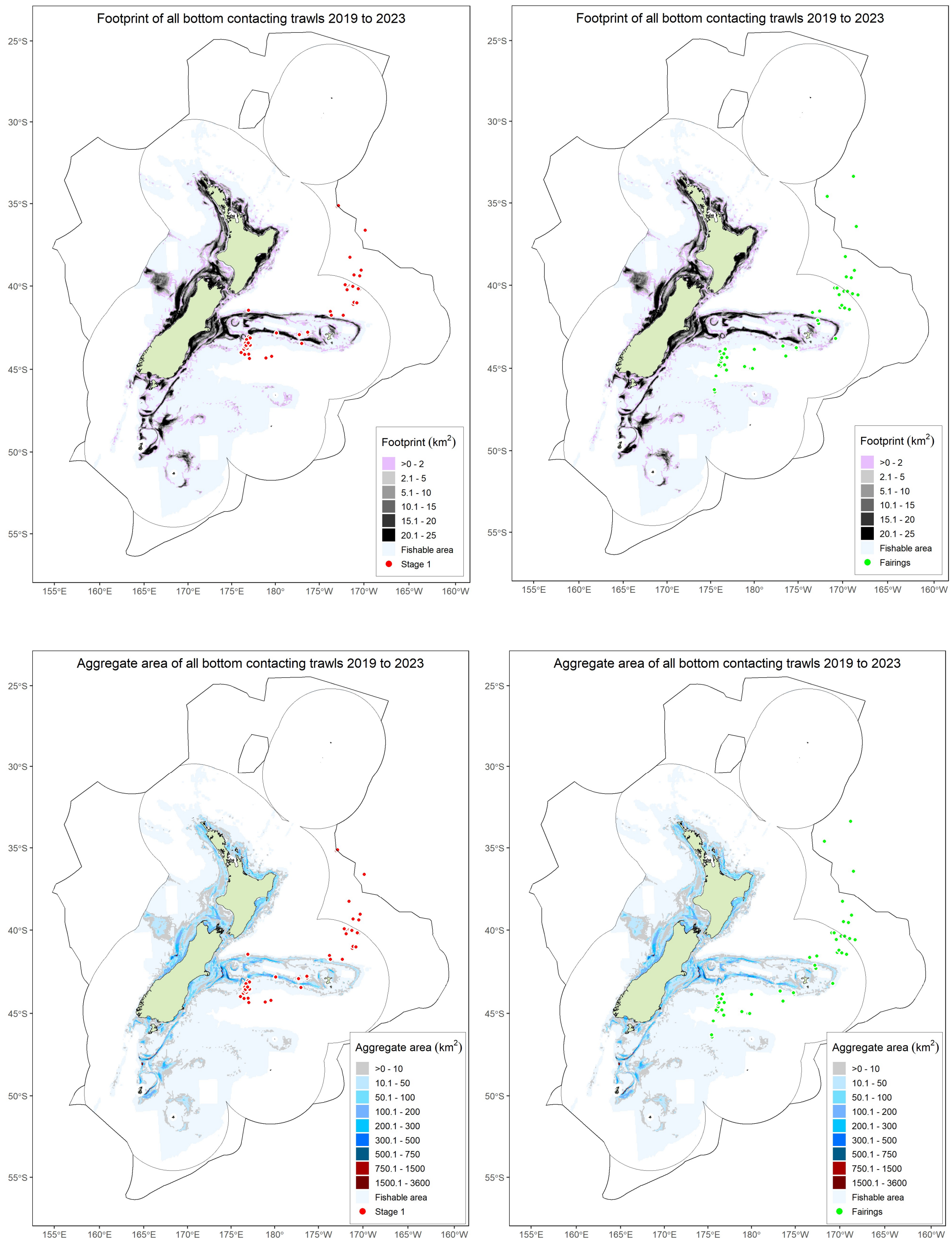

Figure 4-1: Locations of stage one and fairing debris in relation to the trawl footprint (upper plots) and aggregate area (lower plots).

4.3.1 Rocket Lab stage one debris in the fishable area

Stage one debris fell within the fishable area from 33 Rocket Lab launches, contacting 30 unique cells. One cell was contacted by stage one debris from three Rocket Lab launches and another cell was contacted by two, hence the number of unique cells contacted is lower than the number of launches that contacted cells. The depth classes of these were mostly deep with 19 of the 33 being in 1,000+ m water depth but the shallowest depth class was 200–250 m.

4.3.2 Rocket Lab stage one debris in the trawl footprint

Stage one debris fell within the trawl footprint from four Rocket Lab launches, contacting four unique cells. The depth classes of these cells ranged from 250–400 m up to 1,000–1,200 m. The four locations were all along the southern edge of the Chatham Rise, although relatively dispersed. Fishing intensity was relatively high in one cell but not in the other three. The minimum trawl footprint in the cells contacted by stage one debris was 0.6 km^2 or 2.4% of the area of a cell. The maximum footprint was 24.9 km^2, or 99.6% of the cell area. The mean and median footprint values were 1.3 and 7 km^2, respectively. The aggregate area was also very skewed with a minimum of 1.1 km^2, but the maximum aggregate area was 593.3 km^2. This is almost 24 times the area of the cell, indicating that fishing intensity is high in this area. The median aggregate area was 1.4 km^2 and the mean was 149.2 km^2. Predictably, the number of trawl tows in each cell is also very skewed, with the minimum number of tows being three, the maximum number being 376, and median and mean values of five and 97, respectively.

4.3.3 Rocket Lab fairing debris in the fishable area

Rocket Lab fairings fell within the fishable area from 23 launches, contacting 21 unique cells. Two cells were contacted twice each, hence the number of unique cells is lower than the number of launches where fairings contacted the fishable area. The depth classes of the cells contacted ranged from 600–800 m to 1,400–1,600 m, although most (19 launches) were in 1,000+ m.

4.3.4 Rocket Lab fairing debris in the trawl footprint

Rocket Lab fairings landed in the trawl footprint from just two launches. The trawl footprint of one of the cells was 0.3 km^2 whilst the other was 3.4 km^2. The aggregate area was almost identical, indicating that fishing in these two cells was of relatively low intensity. One cell had two trawl tows conducted in it, the other had five.

4.3.5 Summary

Just six unique cells in the trawl footprint from 2019–2023 were contacted by stage one or fairing debris from historical Rocket Lab launches. The metrics used to quantify fishing intensity (footprint area, aggregate area and number of tows in contacted cells) was high in only one of these cells. Forty-nine unique cells were contacted by debris in the total fishable area (this includes the six cells in the trawl footprint). The majority of contacted cells were in waters deeper than 1,000 m where there is less fishing activity. While only a handful of launches saw debris of either kind fall in the trawl footprint over half of all launches had debris fall somewhere inside the fishable area. Increasing numbers of launches could potentially see more debris fall in the trawl footprint or the wider fishable area.

Either scenario could result in interactions between bottom contacting trawling and debris post launch and have negative impacts through displacement of rocket debris on the seafloor, damage to trawl gear, damage to the fish catch, and hazards to ships' crews dealing with debris tangled in trawl gear.

In terms of impact on commercial fishing operations, it is likely that Rocket Lab launches that allow for debris to land outside of the fishable area would be preferable. The fishable area off Te Ika-a-Māui North Island's east coast is relatively small and close to land, due to a rapid increase in depth with distance offshore, and extends to part way down the east coast of Te Waipounamu South Island until the north Chatham Rise is encountered. The Bounty Trough, between the south Chatham Rise and the Bounty Plateau, and Pukaki Rise regions is also a substantial area outside of the fishable area but within the authorized launch deposit area. Debris from a number of Rocket Lab launches has fallen in these areas, which the fishing industry is likely to find preferable to the Chatham Rise region where extensive commercial fisheries operate.

A variety of other fishing methods also occur in the authorized launch deposit area. Static methods such as potting and longlining are less likely to be impacted by rocket debris on the seabed. Other, more mobile methods such as dredging and Danish seining tend to occur mostly in inshore areas and may be less likely to be impacted by rocket debris, although the areal extent has not been investigated in this study and so this can't be concluded unequivocally.

4.4 Cumulative and synergistic effects

Cumulative and synergistic effects could be those additive effects derived from multiple events, in this case an increasing number of launches over time, from other impact sources (e.g., from commercial fishing or from climate change) or a combination of these sources.

This ERA incorporated scenarios with an increasing number of space vehicle launches and found that risk increased from 'low' to 'moderate' at 1,000 and 10,000 launches. These increased levels of risk, which were confined to air-breathing fauna and benthic invertebrate community receiving components, resulted from both an increase in consequence and an increase in likelihood. Clearly, with increasing numbers of launches, cumulative and synergistic effects have the potential to become more substantial.

Assessing cumulative impacts from multiple stressors was beyond the scope of this work but would be a relatively substantial undertaking. Bottom trawling is the most widespread and severe disturbance affecting deep-sea environments (Ramirez-Llodra et al., 2011), causing damage or removal of non-target species, reduced habitat complexity, and altered benthic community structure (Clark et al. 2016). Benthic communities associated with seamounts are especially vulnerable to trawling impacts because they are often dominated by large, fragile, long-lived, sessile epifauna, such as corals (Clark et al. 2010). The trawl footprint (i.e., the total area of the seabed that has or may have been contacted by trawl gear at least once) in Aotearoa New Zealand is approximately 450,000 km^2. Additionally, commercial fishing activity often results in the bycatch of marine megafauna (Edwards et al. 2023), which has the potential to negatively impact population trajectories of these taxa. It would seem reasonable to conclude that it is very likely that debris from space launch vehicles will constitute a much less important component than commercial fishing operations in an assessment of cumulative impacts.

Similarly, the effects of human-induced climate change on ocean systems are likely to be both greater in magnitude and more widespread than those from space vehicle launch debris. Over the next years to decades, ocean temperatures are projected to rise and ocean pH to fall (acidity of the oceans to increase). Climate change may lead to increased variability in harvested populations from fisheries and aquaculture operations, changes to spatial and/or seasonal patterns of production, increased potential for unforeseen rapid change in species and communities, and greater risk of invasive species becoming established in Aotearoa New Zealand waters (Pinkerton 2017).

5 Risk assessment incorporating existing space launch vehicle debris location information

5.1 Introduction

This section describes how the risk assessment table from section 4 (Table 4-1) can be used to a provide generic risk assessment methodology for the environmental effects of space vehicle debris in the Aotearoa New Zealand region.

The aim is to develop a method allowing the risk and confidence scores from the ERA to be used for a range of possible vehicle launches. These launches could lead to different types of debris being introduced into the marine environment, with different spatial distributions. The approach will be applied to the debris location data supplied by Rocket Lab to show how a specific risk assessment for a particular space launch operation can be provided.

The generic risk assessment methodology has three parts:

1. Specify the types of debris and how these translate into 'standardised impact units' (SIUs), allowing the debris to have different physical characteristics, and allowing for different types of effect/impact (here three: 'direct strike', 'noise' and 'smothering').
2. Determine the spatial patterns of where the debris will fall, noting that there will very likely be covariation between where different types of debris fall from a single launch.
3. Apply the expert-derived ERA scores to the particular types and spatial patterns of debris and then combine and summarise the results.

5.2 Method

5.2.1 Standardised Impact Unit (SIU)

For each type of impact, we introduce a 'Standardised Impact Unit' (SIU) to allow different types of debris to be used with risk in Table 4-1. In the development of the risk assessment table, each piece of Rocket Lab debris from a 'nominal launch' was considered to lead to one SIU for each type of impact. In order to generalise to other types of launch and debris in the future, we propose defining SIU as:

1. Direct strike: number of separate pieces of >1 kg of falling mass (any type)
2. Noise: number of separate pieces of >1 kg of falling mass (any type)
3. Smothering: number of ~10 m^2 surface area pieces reaching the seabed

These SIUs may be reconsidered in the future.

5.2.2 Approach

The proposed methodology is outlined in Figure 5-1 and explained in in Table 5-1.

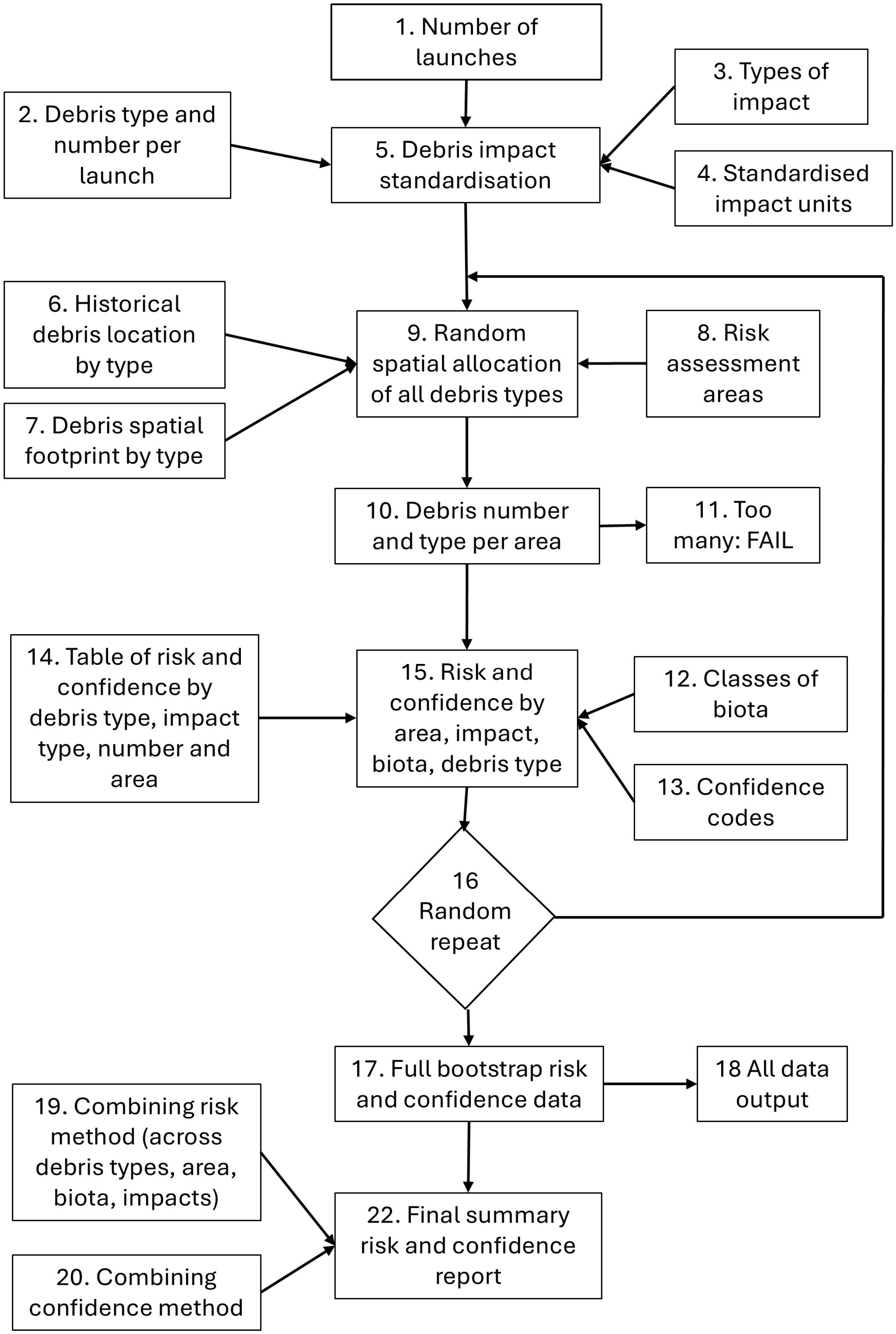

Figure 5-1: **Flow diagram outlining steps in proposed risk assessment methodology.**

Table 5-1: Descriptions for each risk assessment component. Numbers in the first column (#) refer to boxes in Figure 5-1.

#	Component	Description
1	Number launches	Specify how many launches are being considered
2	Debris type and number	Specify the type of debris that will be ejected, considering only material within the spatial domain of the risk assessment. There will be multiple types of debris (e.g., 'stage one', 'fairings', 'battery', etc.). Any number of debris types can be included. For each type, specify how many pieces of that type will be emitted (released) per launch (before any fragmentation).
3	Types of impact in the risk assessment	We have used three types of impact: (1) Direct strike; (2) Noise; (3) Smothering. This can be increased or changed in the future.
4	Standardised impact units	For each impact, we specify a 'standardised impact unit' (SIU). In the development of the risk assessment table, one piece of Rocket Lab debris was considered to lead to about one SIU for each separate type of debris. Initially, for consistency between different types of debris from Rocket Lab launches and in order to generalise to other types of launch and debris in the future, we define SIU as: (1) Direct strike: Number of separate pieces of >1 kg of falling mass (any type) (2) Noise: Number of separate pieces of >1 kg of falling mass (any type) (3) Smothering: Number of ~10 m^2 surface area pieces reaching the seabed These SIUs may be reconsidered in the future.
5	Debris impact standardisation	This process relates the debris type and number to the SIUs for each type of impact. This allows any type of debris to be mapped onto any type of impact in a flexible way, for example, allowing different types of debris to have different effects, and for the type of debris entering the marine environment to be different to the number of pieces of debris emitted from the rocket, as some debris may break up on descent.
6	Historical debris location by type	A list of all the locations (latitude-longitude) where the different types of debris (see #2) have fallen to date. Each location is tagged to a launch identification so that different types of debris emitted by the same launch can be kept together. To be useful, this assumes: - there have been a reasonable number of historical launches to date (more than about 50) - the spatial patterns of debris will continue to follow the same spatial pattern If there are zero or too few launches to date, or the location of the launches will change in the future, the method in #7 should be used.

#	Component	Description
7	Debris spatial footprint by type	This is an alternative (to #6) way of specifying where the different types of debris will fall. Here, a number of spatial maps are produced of the probability where each type of debris will fall. These may be simply polygons of 'possible' versus 'not possible' locations, but more detailed information will be preferred. For example, a set of probability areas for each type of debris showing: '50% falling in zone 1; 30% falling in zone 2; 20% falling in zone 3'. Ideally, the maps for different type of debris would be linked so that the location of type A debris will be linked to the location of type B debris from the same launch. At present, this method is not implemented as information from Rocket Lab is provided as #6.
8	Risk assessment areas	The risk assessment for some types of impact is divided into different spatial areas, such as MEC classes or seamounts.
9	Random allocation of debris to risk assessment areas	To determine the risk assessment for a given number of launches, it is necessary to allocate the different types of debris to the risk assessment spatial areas. For example, we need to know how many of type A debris will fall into the seamount areas. Because this is a statistical question, a random numerical sampling ('Monte Carlo') approach is used to provide a statistical sample of risk. We initially propose to use N=10,000 randomly chosen spatial distributions of debris. For method #6, these will be obtained by classifying each historical debris location into risk assessment spatial class, and then drawing N random (bootstrap) samples from this with replacement. For method #7, distributions of the debris will be obtained by random spatial sampling with a probability of acceptance conditioned by the spatial maps, respecting covariance between different types of debris. This second method is not implemented under the present project.
10	Debris number and type by area	The key output here is a particular sample of the number of different types of SIUs units per risk assessment spatial area.
11	Too many: FAIL	It is possible that, for very high numbers of launches (10,000) the risk assessment method proposed will fail at this stage because there are more than 10,000 SIUs falling in any particular area. This is unlikely and will only occur: (1) for very high number of launches; (2) when the debris is highly spatially concentrated or the spatial risk assessment areas are large; (3) the mapping to SIUs increases the number of debris pieces substantially. This is unlikely and could be addressed by allowing the '10,000 launch' risk assessment to cover up to 30,000 SIUs until an updated risk assessment table is produced.
12	Classes of biota	In the risk assessment table, impacts are considered by classes of biota. Initially, we use four biota classes, but this can be changed in the future as required: (1) Benthic invertebrate community; (2) Demersal community; (3) Air-breathing fauna; (4) Pelagic community.
13	Confidence codes	The risk assessment includes confidence codes which the methodology will promulgate and summarise in the output. Where it is desirable to combine confidence codes, using a quantitative mapping is proposed: 1a=1...2c=6.

#	Component	Description
14	Risk assessment main table	The risk assessment is based around a table which provides the likelihood, consequence, risk and confidence for different numbers of SIUs (#4) falling into different spatial areas (#8), broken down by type of impact (#3) and different biota (#12). In this table, the scores (risk, confidence) for SIU=M(i) should be read as appropriate for SIU=M(i-1) to SIU=3*M(i). See Table 5-3 for details.
15	Risk and confidence by area, impact, biota, debris type	Interpolation from the risk assessment table provides an estimate of risk and confidence for the given area, impact, biota and type of debris. This information is stored.
16	Random repeat	A different spatial distribution of debris (all debris types) is produced (bootstrap sampling or spatial resampling) and the risk assessment repeated.
17	Full bootstrap risk and confidence data	After N iterations, a full set of information for risk and confidence for all areas, impacts, biota and types of debris will be obtained.
18	All data output	This full set of data will be stored and could be output and shared as required. Saving the full data allows different compositing / summary methods to be investigated without repeating the random sampling.
19	Combining risk method	The overall risk score is produced from the scores for different types of debris, areas, impacts and biota. At present, we propose to use the 95th percentile of the risk score. The maximum (highest) risk score will be somewhat dependent on the number of random repeats, so a high percentile is preferred. This could be considered approximately the 'worst risk case with 95% confidence'. Risks are combined in order across impacts, then across areas and then across biota, at each time taking the highest risk score.
20	Combining confidence method	The overall confidence assessment is produced by combining the confidence ratings for different types of debris, impacts, areas, and biota. At each stage, the confidence value is that associated with values leading to the risk score (as in #19). Where there is a tie of risk scores from different parts of the assessment and the confidence values are different, the lower confidence value is taken.
21	Final summary and reporting	The final summary report giving the risk assessment, confidence and any other required information for users. The content, format and style of this report can be changed as required from the full data table (#18).

5.2.3 Input location data

Data on the location of rocket debris was supplied by Rocket Lab and used for step #6. In total we had information on the location of two types of debris ('Fairing' and 'Stage one'), from 61 launches. We assigned these locations to one of: 'Subtropical', 'Plateaus_STF_central', 'Plateaus_STF_south', 'Sub-Antarctic', 'Coastal', 'Seamount', 'Outside_ECS' areas (section 2.4).

A total of three 'Fairing' locations and two 'Stage one' locations were 'Outside_ECS'. These were included in the analysis and assigned a risk score of zero as the risk assessment does not assign risk to material outside the ECS area. We note also that three 'Fairing' locations and no 'Stage one' locations were in 'Seamount'.

5.2.4 Rocket Lab Standardised Impact Units

In order to obtain the number of SIU (see section 5.2.1 and Table 5-1, #5) we used Table 5-2. This follows the principles given in Table 5-1, #4, noting that there are two 'Fairing' units of debris per launch. The debris type 'Batteries' is included here for completeness, but this debris type was not included in the analysis as all batteries were assumed to burn up on descent, and therefore have a SIU of zero (Table 5-2).

Table 5-2: Standardised impact unit (SIU) from impact and debris type.

Impact	Debris type		
	Stage one	Fairing	Battery
Direct strike	1	2	0
Noise	1	1	0
Smothering	1	1	0

The expert assessment of risk and confidence aligns to the SIUs in that, for example, SIU=100 means 'use the risk and confidence for 100 launches'. As given in Table 5-1, #14, we need to determine which number of launches from Table 4-1 to use for a SIU that is not equal to 1, 10, 100, 1,000 or 10,000. For example, if we have 412 SIUs falling into a given area, which scores do we take from Table 4-1 as this is between the 100 and 1,000 launch information. Here. we have used the division equally spaced in log-units between the number of launches. The geometric mean of N and 10N is ~3.16N, so we split the tables as shown in Table 5-3. It would be possible to use a more continuous method of risk analysis where we interpolate between the risk scores in Table 4-1 and then combine these by categories of risk later. However, for the first instance, we think it is clearer to maintain the risk and confidences scores as categorical rather than continuous and assign from an actual value in one of the tables. This has the advantage of allowing people to simply follow through the risk assessment from the general to the particular case.

Table 5-3: Risk table used for different Standardised Impact Units (SIUs).

SIU range	Nominal launches
0	Zero risk
1 – 3	1
4 – 30	10
31 – 300	100
301 – 3,000	1,000
3,001 – 30,000	10,000
> 30,000	Fail – no risk assessment possible

5.3 Results

The results from applying the generic risk assessment (Figure 5-1 and Table 5-1) to the Rocket Lab launch data are show in the tables below. We consider between 1 and 10,000 Rocket Lab launches at the usual 1, 10, 100, 1,000 and 10,000 values and also adding in some intermediate numbers of launches between 1,000 and 10,000 to better understand how the risk and confidence levels change across this wide range. Additional numbers of launches can be easily added as required, noting that this method will provide a risk and confidence level for any number of Rocket Lab launches between about 1 and 10,000.

5.3.1 Debris by area

The number of items of debris falling into each of the risk assessment areas for a given number of launches, and separated by debris type are given in Table 5-4 (fairing) and Table 5-5 (stage one). Different percentiles are provided showing that there is little effect of changing from 95th to 99.5th percentile on the number of items of debris per area. Note that the 50th percentile (median) number is given simply as a check that these total across spatial areas to the expected total number of pieces released per launch. The recommended 95th percentile values used in the final risk assessment are in bold. No debris falls into either the 'Sub-Antarctic' or 'Coastal' areas, and no stage one debris falls in the 'Seamount' area in the data we have been provided with.

5.3.2 SIUs by area

The number of items of debris are then converted to SIUs for the three types of impact (direct strike, noise and smothering) in Table 5-6. These values are simply the result of applying Table 5-2 to the debris numbers in Table 5-4 and Table 5-5, and using the 95th confidence level.

5.3.3 Risk and confidence

Table 5-7 shows the risk scores and confidence scores by area and biota – this table contains the highest level of detail to trace values through the risk assessment process. Codes after the risk scores show which impact(s) are giving the risk shown: i=direct impact; n=noise; s=smothering. Confidence codes are given in brackets following the risk score. These separate values for risk and confidence are combined across areas and arranged by biota in Table 5-8

. Similarly, the separate scores for risk and confidence are combined across biota and arranged by area in Table 5-9. An overall assessment of risk and confidence is given in the last line of

Table 5-8 and of Table 5-9 by combining across the different classes of biota and different areas, respectively.

As an example, consider 1,000 launches. For air-breathing fauna, the risk/confidence in the 'Seamount' region is '6n(1C)', which means we have a risk score of 6, which arises from a 'noise' impact only, and we have 1C confidence in this risk score (Table 5-7). This is also the highest risk score across all fauna for 1,000 launches; the next highest risk at 1,000 launches is '4n(1C)' for air-breathing fauna in the 'Plateaus_STF_central' region – again this is a noise impact (Table 5-7). Note that this appears as a risk score of 6 for air-breathing fauna and 'All' at 1,000 launches in Table 5-8, and the risk score of 6 for 'Seamount' region and 'All' at 1,000 launches in Table 5-9

The highest impact excluding air-breathing fauna for 1,000 launches is '3i(1C)' for benthic invertebrate community in the 'Seamount' region. This is a 'direct strike' impact (Table 5-7). Note the corresponding risk score of 3 for 'benthic' in Table 5-8. In Table 5-9 for 1,000 launches, the risk score is 6 in the 'Seamount' region (the regional highest, from air-breathing fauna), and the highest across other spatial areas is 3 in the 'Subtropical' and 'P STF south' regions, both from air-breathing fauna.

Table 5-4: Number of 'fairing' debris items falling into each area.

			Number of launches									
Debris type	**Area**	**Percentile**	**1**	**10**	**100**	**500**	**1000**	**2000**	**3000**	**4000**	**7000**	**10000**
Fairing	Subtropical	50	0	0	3	16	33	65	98	131	229	328
Fairing	**Subtropical**	**95**	**0**	**1**	**6**	**23**	**42**	**79**	**115**	**150**	**254**	**358**
Fairing	Subtropical	99	1	2	8	26	46	85	122	158	265	371
Fairing	Subtropical	99.5	1	2	8	28	48	87	125	161	270	375
Fairing	Plateaus_STF_central	50	1	8	84	418	836	1672	2508	3344	5852	8360
Fairing	**Plateaus_STF_central**	**95**	**1**	**10**	**89**	**431**	**855**	**1699**	**2541**	**3382**	**5905**	**8422**
Fairing	Plateaus_STF_central	99	1	10	92	437	863	1710	2555	3398	5924	8447
Fairing	Plateaus_STF_central	99.5	1	10	92	438	865	1714	2559	3403	5933	8454
Fairing	Plateaus_STF_south	50	0	0	3	16	33	66	98	131	230	328
Fairing	**Plateaus_STF_south**	**95**	**0**	**1**	**7**	**23**	**42**	**79**	**115**	**150**	**255**	**358**
Fairing	Plateaus_STF_south	99	1	2	8	26	46	85	121	158	265	371
Fairing	Plateaus_STF_south	99.5	1	2	9	27	48	88	125	161	269	375
Fairing	Sub-Antarctic	50	0	0	0	0	0	0	0	0	0	0
Fairing	**Sub-Antarctic**	**95**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Fairing	Sub-Antarctic	99	0	0	0	0	0	0	0	0	0	0
Fairing	Sub-Antarctic	99.5	0	0	0	0	0	0	0	0	0	0
Fairing	Coastal	50	0	0	0	0	0	0	0	0	0	0
Fairing	**Coastal**	**95**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Fairing	Coastal	99	0	0	0	0	0	0	0	0	0	0
Fairing	Coastal	99.5	0	0	0	0	0	0	0	0	0	0
Fairing	Seamount	50	0	0	5	24	49	99	147	197	344	491
Fairing	**Seamount**	**95**	**1**	**2**	**9**	**33**	**61**	**114**	**167**	**220**	**375**	**527**
Fairing	Seamount	99	1	2	11	36	66	121	176	230	388	541
Fairing	Seamount	99.5	1	3	11	37	68	124	179	233	392	546

Table 5-5: Number of 'stage one' debris items falling into each area.

			Number of launches									
Debris type	**Area**	**Percentile**	**1**	**10**	**100**	**500**	**1000**	**2000**	**3000**	**4000**	**7000**	**10000**
Stage one	Subtropical	50	0	0	5	24	49	98	147	196	344	492
Stage one	**Subtropical**	**95**	**0**	**2**	**9**	**33**	**60**	**114**	**168**	**220**	**375**	**528**
Stage one	Subtropical	99	1	3	11	36	66	120	175	229	388	542
Stage one	Subtropical	99.5	1	3	11	38	67	123	178	231	393	547
Stage one	Plateaus_STF_central	50	1	9	92	459	918	1837	2754	3673	6426	9180
Stage one	**Plateaus_STF_central**	**95**	**1**	**10**	**96**	**469**	**932**	**1856**	**2778**	**3700**	**6463**	**9224**
Stage one	Plateaus_STF_central	99	1	10	98	473	937	1863	2787	3711	6478	9241
Stage one	Plateaus_STF_central	99.5	1	10	98	474	939	1866	2790	3715	6483	9248
Stage one	Plateaus_STF_south	50	0	0	0	0	0	0	0	0	0	0
Stage one	**Plateaus_STF_south**	**95**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Stage one	Plateaus_STF_south	99	0	0	0	0	0	0	0	0	0	0
Stage one	Plateaus_STF_south	99.5	0	0	0	0	0	0	0	0	0	0
Stage one	Sub-Antarctic	50	0	0	0	0	0	0	0	0	0	0
Stage one	**Sub-Antarctic**	**95**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Stage one	Sub-Antarctic	99	0	0	0	0	0	0	0	0	0	0
Stage one	Sub-Antarctic	99.5	0	0	0	0	0	0	0	0	0	0
Stage one	Coastal	50	0	0	0	0	0	0	0	0	0	0
Stage one	**Coastal**	**95**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Stage one	Coastal	99	0	0	0	0	0	0	0	0	0	0
Stage one	Coastal	99.5	0	0	0	0	0	0	0	0	0	0
Stage one	Seamount	50	0	0	0	0	0	0	0	0	0	0
Stage one	**Seamount**	**95**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Stage one	Seamount	99	0	0	0	0	0	0	0	0	0	0
Stage one	Seamount	99.5	0	0	0	0	0	0	0	0	0	0

Table 5-6: Number of SIUs by impact type using the 95th confidence level.

		Number of launches									
Impact	**Area**	**1**	**10**	**100**	**500**	**1000**	**2000**	**3000**	**4000**	**7000**	**10000**
Direct strike	Subtropical	1	4	20	76	140	266	388	509	873	1228
Direct strike	Plateaus_STF_central	3	30	274	1328	2637	5245	7851	10454	18258	26052
Direct strike	Plateaus_STF_south	0	2	14	46	84	158	230	300	510	716
Direct strike	Sub-Antarctic	0	0	0	0	0	0	0	0	0	0
Direct strike	Coastal	0	0	0	0	0	0	0	0	0	0
Direct strike	Seamount	2	4	18	66	122	228	334	440	750	1054
Noise	Subtropical	1	3	14	53	99	189	276	362	621	874
Noise	Plateaus_STF_central	2	20	184	897	1783	3548	5312	7074	12357	17634
Noise	Plateaus_STF_south	0	1	7	23	42	79	115	150	255	358
Noise	Sub-Antarctic	0	0	0	0	0	0	0	0	0	0
Noise	Coastal	0	0	0	0	0	0	0	0	0	0
Noise	Seamount	1	2	9	33	61	114	167	220	375	527
Smothering	Subtropical	1	3	14	53	99	189	276	362	621	874
Smothering	Plateaus_STF_central	2	20	184	897	1783	3548	5312	7074	12357	17634
Smothering	Plateaus_STF_south	0	1	7	23	42	79	115	150	255	358
Smothering	Sub-Antarctic	0	0	0	0	0	0	0	0	0	0
Smothering	Coastal	0	0	0	0	0	0	0	0	0	0
Smothering	Seamount	1	2	9	33	61	114	167	220	375	527

Table 5-7: Risk scores and confidence levels by area and biota, for 95% percentile. Codes after the risk scores indicate impact(s) giving the risk shown: i=impact; n=noise; s=smothering. P_STF=Plateaus_STF; ABF=Air-breathing fauna; Pelagic=Pelagic community; Demersal=Demersal community; Benthic=Benthic invertebrate community. Confidence codes are given in brackets following the risk score. '0' = no debris fell within that area in any bootstrap sample, no risk assessment was made. Risk scores of 0-6 are classified as 'low', risk scores of 8-12 as 'moderate' (see Table 2-4). Confidence scores of 1C = no data exist but consensus among experts with low confidence, scores of 2A = no data exist but consensus among experts with high confidence (see Table 2-3).

		Number of launches									
		1	10	100	500	1000	2000	3000	4000	7000	10000
ABF	Subtropical	0in(1C)	0in(1C)	0in(1C)	3n(1C)	3n(1C)	3n(1C)	3n(1C)	4n(1C)	4n(1C)	4n(1C)
ABF	P_STF_central	0in(1C)	0in(1C)	3n(1C)	4n(1C)	4n(1C)	10n(1C)	10n(1C)	10n(1C)	10n(1C)	10n(1C)
ABF	P_STF_south	0in(1C)	0in(1C)	0in(1C)	0in(1C)	3n(1C)	3n(1C)	3n(1C)	3n(1C)	3n(1C)	4n(1C)
ABF	Sub-Antarctic	0	0	0	0	0	0	0	0	0	0
ABF	Coastal	0	0	0	0	0	0	0	0	0	0
ABF	Seamount	0in(1C)	0in(1C)	2in(1C)	6n(1C)	6n(1C)	6n(1C)	6n(1C)	6n(1C)	8n(1C)	8n(1C)
Pelagic	Subtropical	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)
Pelagic	P_STF_central	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)
Pelagic	P_STF_south	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)
Pelagic	Sub-Antarctic	0	0	0	0	0	0	0	0	0	0
Pelagic	Coastal	0	0	0	0	0	0	0	0	0	0
Pelagic	Seamount	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)
Demersal	Subtropical	0in(2A)	0in(2A)	0in(2A)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)
Demersal	P_STF_central	0in(2A)	0in(2A)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)
Demersal	P_STF_south	0in(2A)	0in(2A)	0in(2A)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)
Demersal	Sub-Antarctic	0	0	0	0	0	0	0	0	0	0
Demersal	Coastal	0	0	0	0	0	0	0	0	0	0
Demersal	Seamount	0in(2A)	0in(2A)	0in(2A)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)	0in(1C)
Benthic	Subtropical	0ins(2A)	0ins(2A)	0ins(2A)	0ins(1C)	0ins(1C)	0ins(1C)	1i(1C)	2s(1C)	2s(1C)	2s(1C)
Benthic	P_STF_central	0ins(2A)	0ins(2A)	0ins(1C)	2is(1C)	2is(1C)	3s(1C)	3s(1C)	3s(1C)	3s(1C)	3s(1C)
Benthic	P_STF_south	0ins(2A)	0ins(2A)	0ins(2A)	0ins(1C)	0ins(1C)	0ins(1C)	0ins(1C)	0ins(1C)	0ins(1C)	2s(1C)
Benthic	Sub-Antarctic	0	0	0	0	0	0	0	0	0	0
Benthic	Coastal	0	0	0	0	0	0	0	0	0	0
Benthic	Seamount	0ins(2A)	0ins(2A)	0ins(1C)	3i(1C)	3i(1C)	3i(1C)	8i(1C)	8i(1C)	8i(1C)	8i(1C)

Table 5-8: Overall risk and confidence scores by biota and combined ('All') for 95th percentile. ABF= Air-breathing fauna; Pelagic= Pelagic community; Demersal= Demersal community; Benthic= Benthic invertebrate community. Risk scores of 0-6 are classified as 'low', risk scores of 8-12 as 'moderate' (see Table 2-4). Confidence scores of 1C = no data exist but consensus among experts with low confidence, scores of 2A = no data exist but consensus among experts with high confidence (see Table 2-3).

	Biota	Number of launches									
		1	10	100	500	1000	2000	3000	4000	7000	10,000
Risk	ABF	0	0	3	6	6	10	10	10	10	10
	Pelagic	0	0	0	0	0	0	0	0	0	0
	Demersal	0	0	0	0	0	0	0	0	0	0
	Benthic	0	0	0	3	3	3	8	8	8	8
	All	**0**	**0**	**3**	**6**	**6**	**10**	**10**	**10**	**10**	**10**
Confidence	ABF	1C	1C	1C	1C	1C	1C	1C	1C	1C	1C
	Pelagic	1C	1C	1C	1C	1C	1C	1C	1C	1C	1C
	Demersal	2A	2A	1C	1C	1C	1C	1C	1C	1C	1C
	Benthic	2A	2A	1C	1C	1C	1C	1C	1C	1C	1C
	All	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**

Table 5-9: Overall risk and confidence scores by area and combined ('All') for 95th percentile. 'P-STF'=Plateaus_STF. '0*'=not assessed (because no debris falls into the area). Risk scores of 0-6 are classified as 'low', risk scores of 8-12 as 'moderate' (see Table 2-4). Confidence scores of 1C = no data exist but consensus among experts with low confidence, scores of 2A = no data exist but consensus among experts with high confidence (see Table 2-3).

	Area	Number of launches									
		1	10	100	500	1000	2000	3000	4000	7000	10,000
Risk	Subtropical	0	0	0	3	3	3	3	4	4	4
	P-STF central	0	0	3	4	4	10	10	10	10	10
	P-STF south	0	0	0	0	3	3	3	3	3	4
	Sub-Antarctic	0*	0*	0*	0*	0*	0*	0*	0*	0*	0*
	Coastal	0*	0*	0*	0*	0*	0*	0*	0*	0*	0*
	Seamount	0	0	2	6	6	6	8	8	8	8
	All	**0**	**0**	**3**	**6**	**6**	**10**	**10**	**10**	**10**	**10**
Confidence	Subtropical	1C	1C	1C	1C	1C	1C	1C	1C	1C	1C
	P-STF central	1C	1C	1C	1C	1C	1C	1C	1C	1C	1C
	P-STF south	1C	1C	1C	1C	1C	1C	1C	1C	1C	1C
	Sub-Antarctic	0*	0*	0*	0*	0*	0*	0*	0*	0*	0*
	Coastal	0*	0*	0*	0*	0*	0*	0*	0*	0*	0*
	Seamount	1C	1C	1C	1C	1C	1C	1C	1C	1C	1C
	All	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**	**1C**

5.4 Discussion

The generic risk assessment method outlined here allows the risk and confidence scores from the expert-driven ERA to be used for a range of possible space vehicle launches. The approach has been applied to the data supplied by Rocket Lab to provide a specific example of how the generic method can provide a specific risk assessment. In this case, the risk is assessed across different types of impact (Table 5-7), different types of biota (Table 5-8) and different areas (Table 5-9). The reporting method allows the level of risk, for a given number of launches, of what type, where and impacting what biota, to be identified.

5.4.1 Rocket Lab insights

It can be seen from Table 5-7 that noise impacts on air-breathing fauna in the 'Seamount' region gives the highest risk score between ~150 and ~1,500 launches, but noise in the 'Plateaus_STF_central' region tends to give the highest risk score at lower and higher launch numbers, outside the range noted above. In this case, the spatial distribution of debris is a crucial factor and avoiding the seamounts would reduce risk scores around these mid-range Rocket Lab launch numbers.

The fact that impacts due to direct strike are not higher results from the low number of separate pieces of debris per launch (three only, one stage one and two fairings). If the same mass of debris per launch were fragmented into a large number of separate pieces, the risk due to direct strike impact would likely predominate and could lead to higher risk values. Avoiding fragmentation of debris is hence advisable to minimise environmental/ecological risk.

5.4.2 Built-in conservativeness

At all stages, we have taken a conservative (near 'worst-case') approach to assessing and combining risk across the different categories. This conservativeness arises from three main parts:

1. The method considers 10,000 possible spatial distributions of debris consistent with the information provided on possible/likely locations and then takes the 95th percentile of the impact from these. This is similar to saying 'we do not know exactly where the debris will fall in the future, but we are 95% confident that the debris will fall in a pattern that gives a risk no worse than we have reported'. We note that better information on where the debris will fall will reduce the difference between actual risk and that based on the 95th percentile of possible locations, so it is in the interests of the operators to be as specific and as accurate as possible about historical and future debris locations.

2. Impacts are assessed in turn across types of impact, locations of impact and biota affected, with the highest risk promulgated at each point. Considering these as separate categories and carrying forward the highest risk makes this more precautionary than considering all risks together.

3. Confidence is similarly combined as for risk, at each stage taking the lowest confidence.

5.4.3 Application to future operations

To apply this methodology to future operations, four considerations are important:

First, what are the types of debris and how will they lead to impact? For the current risk assessment specifically, the method needs information on: (a) how many separate pieces of debris are released per launch that are capable of causing mortality to air-breathing fauna? This is likely to be the number of separate pieces of debris greater than about 1 kg in mass. (b) How much noise will the debris cause on impact with the sea surface? It is likely the noise impact will increase with the number and mass of the debris, but details of this remain to be determined. (c) How much benthic smothering will be caused by the debris? This is likely to scale with total cross-sectional area of the debris, but there could also be a mass and/or number component to this estimation.

Second, how can the spatial distribution of debris be mapped? Two methods are immediately possible for mapping where debris will fall in the future (Table 5-1, #6 and #7). In the methodology provided, locations are subsampled from the locations of historical debris fall. This has the advantage of being very specific to the type of launch (including the covariance between the fairing and stage one debris) but relies on a large number of launches to date (>50 at least) and an assumption that the pattern of launches will not change in the future. An alternative method (not implemented here) is to provide spatial maps of debris locations, ideally with some graduation of probability. These maps should include information on whether the location of the different types of debris will be co-located to some degree. Further work could be carried out to further develop and implement this method within the existing risk assessment paradigm.

Third, are any impacts of debris not considered by the current risk assessment? We note that we have not considered several potential effects/impacts considered in previous ERAs (MacDiarmid et al. 2016, Lamarche et al. 2017). For future space vehicle launches other types of risk not considered in the present assessment should be evaluated if required. Importantly, the risk assessment methodology described here could accommodate such extensions to additional types of impact.

Fourth, the current risk assessment only considers the cumulative number of launches. This risk assessment would be appropriate to use provided that the rate of launches is approximately the same as current used for Rocket Lab i.e., about once a month. If the rate of launches increases substantially above this rate (where the average time between launches is less than about 2 weeks say), we recommend adding a second part to the risk assessment considering different rates of launches (e.g. monthly, 2-weekly, weekly, every-3-days, daily) be added. The two parts to the risk assessment, one part for the cumulative number of SIU (as presented here) and a second part for different rates of launches could be combined following the same process as used to combine risk and confidence across different impacts, biota and areas.

Finally, we note that the computer code to apply the risk assessment methodology is currently written in commercially-licensed software (IDL, NV5 Global, Inc., USA), and if the intention is to apply this approach more widely in the future, it would be sensible to translate it to something open-source and more widely used, such as R or Python.

6 Recommendations

The Level 1 ERA carried out here was an expert-driven qualitative process that scored risk from space vehicle debris across relatively large spatial scales. It is arguable that such a process doesn't exploit the full potential of the available data. Furthermore, estimating risk at specific locations is not possible using the Level 1 approach as used here, yet as space vehicle launches continue, and possibly increase over the near to medium term as new operators join the industry, being able to address questions of risk at relatively precise locations will become more important.

Developing a framework in which risk from space vehicle debris could be quantified at relatively small spatial scales across the entire EEZ and ECS (a 'riskscape') would enable risk to be determined at specific locations. Additionally, such a framework could be augmented and refined as new environmental data became available. This type of approach has been applied, for example, to explore the risk of impacts from trawling on benthic systems (Rijnsdorp et al. 2016, Rowden et al. 2024) and on sedimentary carbon stores (Black et al. 2022). Rijnsdorp et al. (2016) envisaged the components of such a framework as outlined in Figure 6-1, with trawling affecting seabed habitat, and the structure and function of the benthos.

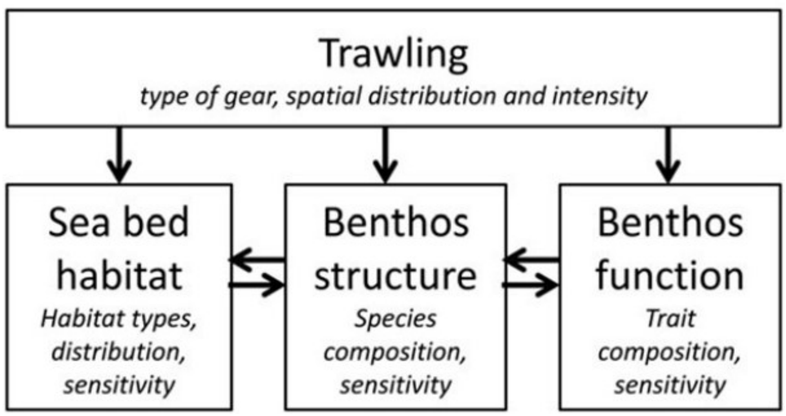

Figure 6-1: Components of a framework to assess the impact of trawling on the seabed and benthic ecosystem. From Rijnsdorp et al. (2016).

Space vehicle debris would replace trawling in Figure 6-1, and would be characterized by size, composition, distribution and intensity. The intensity component would encompass the rate at which launches occur, which was not explicitly included in the Level 1 ERA, but which could be modified as required in this framework. The rate at which debris impacts receiving components has implications for the extent to which populations or habitats are depleted. The recovery of impacted populations or habitats will also depend in part on the rate at which impacts from debris are received, with relatively frequent impacts making recovery less likely, particularly if the populations or habitats have not been previously disturbed (naturally or by other human activities).

Rijnsdorp et al. (2016) also noted that seabed habitats and benthic communities differ in their spatial distributions and in their sensitivity to trawling, and that benthic ecosystem function depends on the composition of the functional traits, which may also differ in their sensitivity to trawling (Figure 6-1).

Black et al. (2022) employed this type of impact risk assessment approach to produce maps of 'carbon vulnerability' to different types of trawling around the United Kingdom (UK) and were able to identify vulnerability hotspots (Figure 6-2) that were specific to each type of trawl fishing gear.

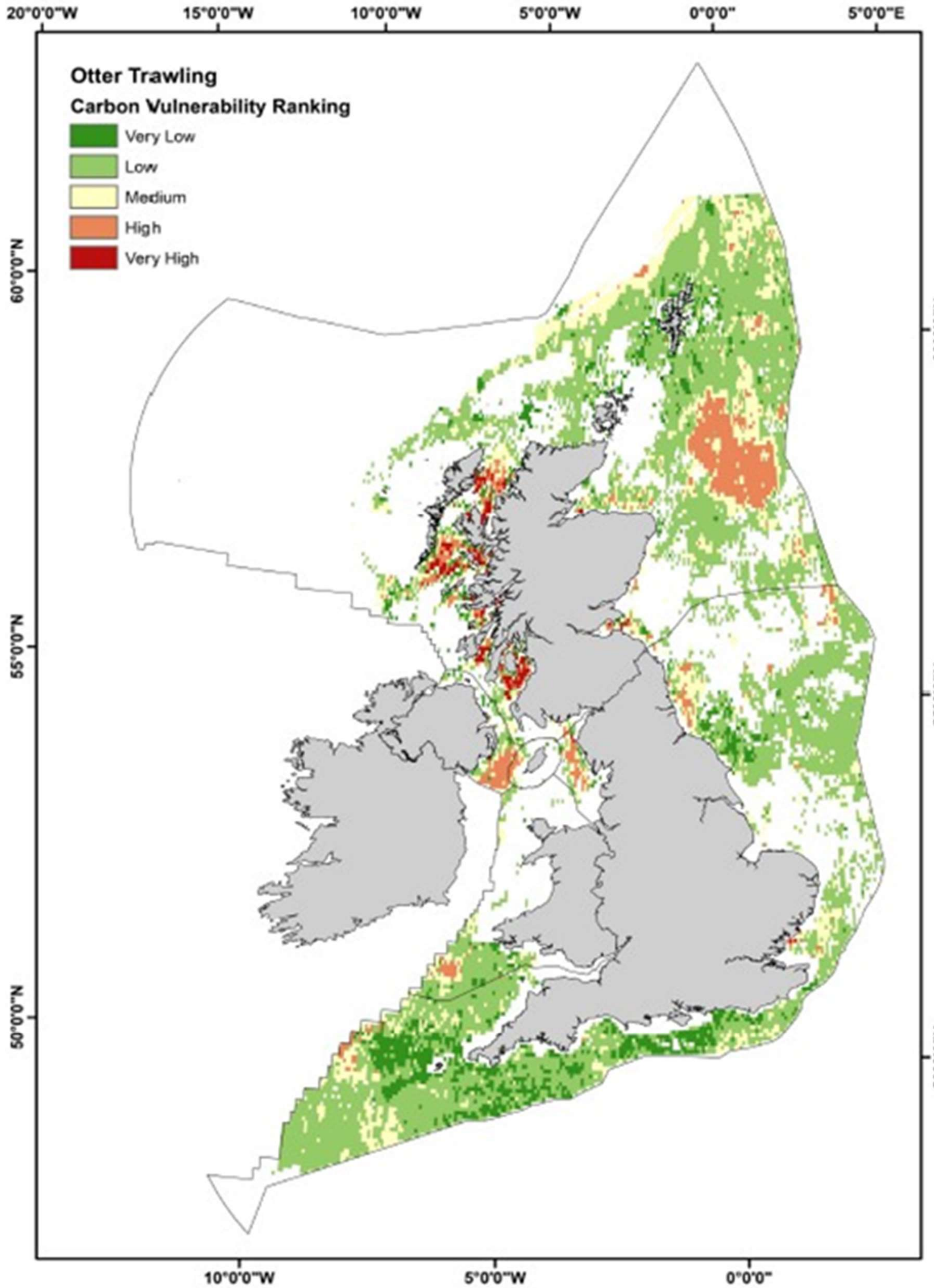

Figure 6-2: Map of the UK showing sedimentary carbon vulnerability to otter trawling. From Black et al. (2022).

The riskscape framework outlined here could be further expanded to include non-benthic components of the marine environment, specifically demersal and pelagic biota and air-breathing fauna. These components can be highly dynamic, with individuals and populations often undertaking relatively large-scale movements, both within Aotearoa New Zealand waters and at larger, ocean basin scales, meaning that risk for these biotic groups would vary temporally. For example, many seabirds migrate out of Aotearoa New Zealand waters at the end of the breeding season (e.g., Shaffer et al. 2006), during which time the risk from space vehicle debris would be zero.

A riskscape framework as outlined here would allow existing and future data on the distributions of biota to be combined so that risk from space vehicle debris could be estimated at any location across the EEZ and ECS, and further, would enable cumulative impacts, including impacts from other sources, to be considered.

We conclude by noting that the customary and commercial rights and interests of Māori in the marine estate is well recognised in government policy, regulation and through iwi Treaty of Waitangi settlements. Such rights and interests have seen Iwi, hapū and Māori businesses and operators become increasingly visible and significant players in the marine sector commercially and in fulfilling their kaitiakitanga role through research and decision-making around a range of activities.

The current absence of specific research of direct relevance to the potential impacts of rocket debris in the marine environment from a te ao Māori perspective, will be an increasingly problematic gap to ensuring appropriate decision-making, mitigation and management as aerospace activity increases. Providing dedicated funding and support to enabling such research to be undertaken, under the leadership of Māori communities and researchers, will help facilitate the development of a risk assessment framework and approach more aligned to adequately protecting the rights and interests of Māori.

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7 References

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