Habitat suitability modelling of bryozoan and *Galeolaria* mounds in Queen Charlotte Sound, Tory Channel and adjacent Cook Strait

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Contents

Tables

Figures

Executive summary

NIWA was requested by the Marlborough District Council (MDC) to undertake habitat suitability (HS) modelling to predict the spatial extents of two significant and notable habitat-forming benthic species (*Galeolaria hystrix* mounds and Bryozoan mounds) across the HS51 survey area - an area the includes Queen Charlotte Sound (QCS), Tory Channel (TC), and the adjacent section of Cook Strait - as a critical step to assist MDC with Ecologically Significant Marine Site (ESMS) planning in this region. As part of this project, MDC requested NIWA to post-process the tow-video footage from NIWA's four ground-truthing tow-video surveys (MDC18, CB17, BT17 and HS51) to quantify % cover estimates for *Galeolaria hystrix* mounds and Bryozoan mounds. This included differentiating between structurally intact versus damaged (i.e., dead base and rubble (DBR)) *Galeolaria hystrix* mounds.

Habitat suitability (HS) modelling using Boosted Regression Trees (BRT) and Random Forests (RF), and a two-step hurdle model was used to model the spatial distributions of the two habitat-forming species (i.e., bryozoa and *Galeolaria* mound fields), based on newly post-processed presence and absence and % cover abundance data and full-cover continuous physical and environmental data layers (incl. HS51 multibeam data layers, hydrodynamic modeled near-seabed current speeds, and spatially-derived data layers).

Although environmental variables (bathymetry and terrain metrics derived from bathymetry) were produced for the study area at a grid resolution of 2 x 2 m (approx. 650 M cells) computer processing constraints restricted model outputs to a coarser resolution of 8 x 8 m (approx. 25 M cells).

HS models reliably predicted the distribution of *Galeolaria* mounds, for both intact and damaged mound types, over broad-spatial scales (i.e., distribution across the entrance to QCS within the broader HS51 survey area), and at finer-spatial scales across known sites.

Predicted ensemble models of intact *Galeolaria* mounds closely matched the observed *Galeolaria* mound distributions. However, the combined model that included both intact and damaged mounds provided combined information that more accurately described the habitat suitability of *Galeolaria* mound habitats.

The predicted versus observed distributions of intact and combined mounds at zoomed-in example sites (i.e., Perano Shoals, Pihaka and Kumutoto Points and around Amerikiwhati Island) identified that the *Galeolaria* models were extremely good at predicting the % cover and extent of *Galeolaria* mounds and as such will provide MDC with an extremely valuable tool in helping to manage and conserve this unique habitat-forming species.

The threshold cut off of 0.02 for both intact-only and intact and damage *Galeolaria* mounds provided the best-fit across the scale of the survey, and for intact-mounds, but contracted the outer boundary of some edge-damaged sites. We therefore recommend that both the predicted and observed distributions of mounds be used to determine the outer boundaries of damaged sites.

HS models reliably predicted the distribution of bryozoan mounds (or bryo-reefs zones) over broad-spatial scales (i.e., distribution across the entrance to QCS within the broader HS51 survey area), but were less reliable at delineating finer-scale boundaries of these spatially-patchy bryozoan mounds.

Observed distributions of bryozoan mounds were visually-correlated with increased rugosity and higher reflectivity sediments compared to the surrounding matrix of low reflectivity sandy muds (depicted in the original 2 x 2 m resolution grids). Fine-scale associations with rugosity and seafloor classification, however, were likely muted by averaging environmental values at the 8 x 8 m grid cell-size – as logistically required to run the HS models.

The fine-scale 2-m rugosity and seafloor classification (along with the raw backscatter imagery were successfully used), however, in ArcGIS to delineate boundaries around patchy bryo-reef zones, and appear to provide good delineation of patchy bryo-reef zones at the scale of ≥ 2 m. We would therefore recommend that the combination of large scale modelling and the ArcGIS bryo-reef zone polygons be used to inform management decisions on bryozoan mounds across the entrance to QCS.

The development of these models now paves the way to predictively map the distributions of other benthic taxa across the HS51 survey area, as well being applied to other Marlborough Sounds areas. Finer-scale 2-m resolution models could also be run for smaller targeted areas - to capture fine-scale variability, such as across the bryo-reef zones at the entrance to QCS.

These findings provide MDC with an extremely valuable new tool to aid in the management and conservation of significant marine species and habitats within the Marlborough Sounds.

1 Introduction

Following the completion of the 'Life on the Seafloor' report (Anderson et al. 2020b), MDC requested NIWA undertake habitat suitability (HS) modelling to predict the spatial extents of two significant and notable habitat-forming species (*Galeolaria hystrix* mounds and Bryozoan mounds) across the HS51 survey area - an area the includes Queen Charlotte Sound, Tory Channel, and the adjacent section of Cook Strait - as a critical step to assist MDC with ESMS planning in this region.

Identifying and protecting critical habitats for significant and vulnerable species and community diversity is one of the targeted uses of habitat suitability (HS) models for management and conservation purposes (e.g. Rowden et al. 2017; Anderson et al. 2020a). HS modelling (sometimes called species distribution modelling), explores the relationships between point-sampled species observational records (commonly presence and usually absence or background records), and spatially continuous environmental variables (e.g. MBES data layers: e.g. bathymetry, backscatter, slope, rugosity, seafloor classifications etc., hydrodynamic near bed current strength, and map-derived spatial layers). These relationships are then used to predict the likelihood of occurrence of (or habitat suitability for) each taxon (or group of species) across unsampled environmental space (Reiss et al. 2015, Vierod et al. 2014). HS models employing Boosted Regression Tree (BRT), Random Forest (RF), and ensemble models (i.e., best combination of these approaches) are commonly employed methods used to account for complex non-linear correlations between species and environmental predictors, can model spatial autocorrelation in the observed data, assess model performance, and are proven to work well with New Zealand data (e.g., Georgian et al. 2019; Rowden et al. 2017; Anderson et al. 2020a).

As part of this project, MDC also requested NIWA post-process the tow-video footage from NIWA's four ground-truthing tow-video surveys (MDC18, CB17, BT17 and HS51) to quantify % cover estimates for *Galeolaria hystrix* mounds, incl. differentiating between structurally intact *Galeolaria* mounds and damaged mounds (i.e., dead base and rubble (DBR)) and *Bryozoan* mounds. The provision of these revised observed data (% cover in addition to presence and absence) also enabled the prediction of numerical % cover using a multi-step BRT model (or Hurdle model) to predict the distribution and relative abundance of these two habitat-forming species/groups (more detailed information) rather than simply the probability of occurrence (presence/absence). This ensemble approach provides the best combined approach to model the predicted spatial extent of these habitat-forming taxon and structure types. The resulting predicted distribution maps for bryozoa and *Galeolaria* mound fields will provide critical to help inform MDC management (through the MEP process) on delineating and protecting these significant and highly vulnerable habitats.

The aim of this project was to predict species distributions for i) *Galeolaria* mounds, ii) *Galeolaria* mounds + DBR, and iii) bryozoan mounds across the entire mapped HS51 region, using the newly post-processed % cover data from NIWA's tow-video surveys (MDC18, CB17, BT17 and HS51) together with the existing spatially-continuous environmental variables (e.g. HS51 bathymetry and derived variables (Neil et al. 2018a,b); near-bottom current strength (Hadfield et al. 2014; Hadfield 2015), and map-derived spatial layers).

We were also asked to provide summary recommendations regarding future research, to: further improve model estimation of predicted distributions, fill gaps in ground-truthing data or improvements in environmental data layers (i.e., MBES or current data layers) identified during the modelling phase, as a means of providing guidance to MDC in their goal of designating representative and vulnerable areas for these two habitat-forming species.

2 Methods

2.1 Habitat suitability models

Two commonly used machine-learning model approaches were used to model the spatial distributions of the two habitat-forming species (i.e., bryozoa and *Galeolaria* mound fields), based on presence and absence data and % cover abundance data and full-cover continuous physical and environmental data layers: specifically NIWA's MBES data layers (bathymetry, backscatter, slope, rugosity, seafloor classifications etc., from Neil et al. 2018a,b) with modelled hydrodynamic current layers (near-bottom current strength from Hadfield et al. 2014; Hadfield 2015) and spatial-derived spatial layers (distance to headland, distance to reef) for the HS51 study area. Habitat suitability modelling using Boosted Regression Trees (BRT) (Elith et al. 2008) and Random Forests (RF) (Brieman 2001), were applied to the presence and absence data for each taxon/group. Abundance (numerical % cover) data for each taxon was then analysed using a two-part hurdle model that combined the predictions from a binomial presence-absence ensemble model, with those from an ensemble model predicting percent cover.

2.1.1 Observational tow-video data

Observed presence, absence and percent cover for *Galeolaria* mounds (three category) and bryozoan mounds (one category) were post-processed in July 2020 (referred to here as 'MDC20' data[1]). Percent cover estimates (0-100% cover, ±5% cover) were quantified from the 'Life on the Seafloor' video-footage (i.e., NIWA's four video surveys: MDC18, CB17, BT17 and HS51 – as described in Anderson et al. 2020b). Three categories were recorded for *Galeolaria* mounds. This included two *Galeolaria* mound classes: 1) Intact 3-dimensional *Galeolaria* mounds and 2) 'Dead Base and/or Rubble' (DBR) indicative of damaged/broken *Galeolaria* mounds; and 3) Non-mound forming solitary *Galeolaria hystrix*, seen growing individually of the seafloor. A single category was recorded for bryozoan mounds. A bryozoan mound was defined as any 3-dimensional bryozoan mound (or bryo-reefs) comprising living or relict structure (Anderson et al. 2020b; Anderson et al. 2019). These categories are defined in detail in Anderson et al. (2020b). Percent cover estimates (0-100% cover, ±5% cover) were recorded for all three *Galeolaria* categories and the one bryozoan mound category, but models were only run on the two 'mound-associated' *Galeolaria* categories (i.e., intact and damaged categories) and the bryozoan mound category.

2.1.2 Physical/environmental predictors

Predictor variables available to the model were based on a combination of bathymetry-derived rasters produced from the HS51 bathymetry survey of QCS and Tory Channel in 2017 (Neil et al. 2018a,b); a numerical classification of seafloor type based on backscatter data from the HS51 survey data (Neil et al. 2018a,b); modelled near-bottom current strength (Hadfield 2015 and Hadfield et al. 2014); percent of each substratum type (sand, gravel, silt etc.,) based on interpolated values from HS51's sediment grab sampling (Neil et al. 2018a,b); and spatially-derived grids of the calculated distance to the nearest cell comprising rocky reef; and distance to the nearest cell at a headland. To reduce model complexity and find a balance between providing models with as much explanatory

[1] to avoid confusion with the earlier semi-quantitative rank abundance estimates from the original surveys (as described in Anderson et al. 2020b).

power as possible and minimising the fitting of models to noise rather than signal, a subset of the environmental variables (Table 2-1) was selected based on knowledge of species ecology and the removal of highly correlated variables.

As taxon/group observations were collected at fine-scale intervals (<30 sec) along tow-video transects within sites across the survey area, closely neighbouring data points (within-sites) are likely to be more similar (i.e., autocorrelated) than data points further apart (e.g. between sub-regions), and thus may provide less independent information. To ensure HS models were not overfitting the data due to spatial autocorrelation, a further predictor was created to help account for spatial autocorrelation (the tendency for areas or sites that are close together to have similar values) in the taxon/group data. This Residual Autocorrelation (RAC) variable, represents the spatial correlation amongst the residuals from an initial detrended model based on the other variables (Crase et al. 2012); this approach has been found to be useful in other New Zealand Species Distribution Modelling (SDM) modelling efforts (e.g. Rowden et al. 2017, Georgian et al. 2019).

Table 2-1: Description of the environmental variables used in the HS models. Seafloor rugosity (or VRM) = Vector Ruggedness Measure (described in Neil et al. 2018a,b). Variables: [1] = HS51 MBES bathymetry (described in Neil et al. 2018a); [2]= MBES derivatives (as described in in Neil et al. 2018a,b); [3]=interpolated raster from HS51 sediment grab samples (Neil et al. 2018a); [4]=Seafloor classifications were from supervised classification of HS51 MBES backscatter intensity in combination with HS51 sediment grab samples and depicts the sediment type and hardness across the study area; [5]=Hydrodynamic model outputs for near-bottom current speed (i.e., ≤5 m above the seafloor).

Environmental variables	Units	Native resolution	Source	*Galeolaria*	Bryozoans
[1]Depth	m	2x2 m	NIWA	Used	Used
[2]Slope	Degrees	2x2 m	NIWA	Used	Not used
[2]Slope standard deviation	–	2x2 m	NIWA	Used	Not used
[2]Seafloor rugosity (VRM)	–	2x2 m	NIWA	Used	Used
[3]Percent sand	%	2x2 m	NIWA	Used	Not used
[4]Seafloor classification	-70 to 10	2x2 m	NIWA	Used	Used
[5]Near-bottom current speed	m/s	0.5x0.5 m	NIWA	Used	Used
[6]Distance to rock	m	2x2 m	NIWA	Used	Not used
[6]Distance to headland	m	2x2 m	NIWA	Used	Not used

2.1.3 Model structure, performance and outputs

Models predicting the percentage cover of bryozoan and *Galeolaria* mounds were produced by ensembling (ENS) the separate predictions from two decision tree-based modelling methods (BRT and RF). For each taxon a two-part hurdle (HUR) model was produced, combining the predictions from a binomial presence-absence ensemble model with those from an ensemble model predicting percent cover. In the binomial models, the response variable had values of either 0 (absence of the taxon) or 1 (presence of the taxon). In the hurdle model the response variable for the percent cover models was a logit transformation of the estimated percent cover values log(y/(1-y)) from observations of each taxon; this transformation produces a near normal distribution of the response variable while suppressing nonsensical predicted values (less than 0 or over 100%) when back-transformed (Warton & Hui 2011).

An ensemble model of the RF and BRT models for each taxon and model type (presence-absence and percent cover) was then created by taking a weighted average of the predictions from each model in such a way as to give greater weight to the better performing model overall, as well as to the model with the least uncertainty at the cell level. These weights therefore comprised two components: 1) the performance value for the model (AUC or R squared) applied to all cells equally, and 2) the prediction uncertainty (CV), applied to individual cells. These two components were given equal "weight" in the overall weighting. The final step in producing a single model to predict percent cover for each taxon was to combine the ensemble presence-absence model with the ensemble Hurdle percent cover model, and was done by simple multiplication.

Models were produced for 1) Intact *Galeolaria* mounds; 2) an additional model was produced for *Galeolaria* that combined the percent cover of intact-mounds with percent cover of damaged-mounds (i.e., DBR = dead based and rubble) so as to better predict the habitat suitability for this species, as an alternative to predicting its current (vs previous) distribution; 3) bryozoan mounds.

Model resolution

Although bathymetry and terrain metrics derived from bathymetry were produced for the study area at a grid resolution of 2 x 2 m (approx. 650 M cells) computer processing constraints restricted model outputs to a coarser resolution of 8 x 8 m (approx. 25 M cells). The New Zealand Transverse Mercator 2000 projection (EPGS:2193) was used as the Coordinate Reference System for all outputs.

Model performance and precision

Performance of the presence-absence models was measured by AUC, a threshold independent assessment of the ability of the model to rank occurrences above absences. For the percent cover models the model R^2 value was calculated. We applied a bootstrap technique to estimate uncertainty in the predictions. For each model type (BRT/RF, presence-absence/percent cover, *Galeolaria*/Bryozoans) 100 random samples of equal size to the original data set were selected from the taxon data, with replacement, and separate model runs performed with each sample. For the presence-absence models this was done in such a way as to retain the same proportion of presence and absence points as in the original data set. In this way 100 separate estimates of percent cover are produced for each cell of the model from which the mean value, the standard deviation (SD), and coefficient of variation (CV) can be calculated.

2.1.4 Distribution maps and GIS polygons

All maps were created in ESRI ArcGIS version 6.6. Shapefiles were created for all four taxon categories: structurally intact *Galeolaria* mounds, damaged *Galeolaria* mounds (DBR), solitary *Galeolaria* (individually attached to the seafloor), and bryozoan mounds. HS models run on each three taxon/group, produced two continuous-rasters (tiff) files for plotting in ArcGIS: 1) 'The predicted % cover distribution for that taxon/group within Queen Charlotte Sound and Tory Channel and adjacent Cook Strait', and 2) The precision (or uncertainty) of the predicted distribution for that taxon/group (i.e., how well the model predicted those distributions). As very few observations of *Galeolaria* mound (in terms of fields of mounds) were recorded within Tory Channel, and because damaged sites within the strong current environment of TC may reflect sinks of *Galeolaria* debris rather than potential source sites, the final predictive models for TC were removed from the rasters of both *Galeolaria* categories. The final raster layer for each taxon/group was then plotted in ArcGIS with a colour swath/classification depicting high to low % cover and uncertainty (red-blue colours, respectively), with associated layer files created for each raster.

In Anderson et al. (2020b), a preliminary ArcGIS polygon was created to the delineated bryozoan-mound areas at the eastern and western entrances to Queen Charlotte Sound (QCS) (hash polygon zone as presented in Figure 21, page 59 of Anderson et al. 2020b). This delineated bryozoan mound zone was revised during this project in ArcGIS as a polygon shapefile, and now includes four categorised patch types: i) the deep relict bryo-reef within the western channel (verified by video observations); ii) actively growing bryo-reefs along the eastern and western entrances of QCS (verified by video observations); iii) similar seafloor features likely to support bryo-reefs (unverified/no observational data), and a historic bryo-reef (of low density from limited observations).

3 Results

3.1 Habitat suitability modelling

3.1.1 Overall model Performance

Habitat suitability models predicted taxon distributions well, with binomial BRT models explaining 0.95% of the deviation explained in the binomial (presence/absence) data, and between 0.5 and 0.76 of % cover data (Table 3-1). The Residual Autocorrelation (RAC) variable was strongly influential in both the *Galeolaria* percent cover models (Table 3-2 to Table 3-5) and the bryozoan presence-absence models (Table 3-6 and Figure 3-7) as would be expected in mound-forming taxon, but RAC had a relatively minor influence in the detrended HS models. This indicates that, for the RAC-influenced models, there is some spatial correlation in the biological data that is not fully explained by the available variables, and this new RAC variable is a useful model component to account for this variation, in these cases. The two variables with the strongest influence overall in the models, and always in the top three, were 'near-bottom current speed' and 'depth', with both taxa having clear associations with a specific range of 'near-bottom current speeds' and depths. Seafloor rugosity (Vector Ruggedness Measure), distance to headland, and distance to rock were also important drivers of *Galeolaria* mound distributions, but were not influential in the bryozoan models. Seafloor classification (numeric variable defining sediment hardness based on seafloor backscatter and sediment composition – Neil et al. 2018a,b) had the lowest influence in all models apart from the bryozoan presence-absence model (second lowest).

Table 3-1: Comparison of model performance for *Galeolaria* and Bryozoan mounds. RF=Random forest models, BRT=Boosted Regression Trees.

Taxon: *Galeolaria* mounds	Deviation explained	
	RF	BRT
Galeolaria - Intact mounds (only)		
Binomial	0.81	0.95
Percent cover	0.70	0.55
Galeolaria - Intact and damaged mounds (combined)		
Binomial	0.77	0.95
Percent cover	0.76	0.60
Bryozoan mounds (bryo-reefs)		
Binomial	0.86	0.95
Percent cover	0.60	0.50

3.1.2 Predicted distributions for *Galeolaria* mounds

Model performance and predictive success for both intact-*Galeolaria* mounds and intact and damage mounds was high (Table 3-1), with models successfully predicting *Galeolaria* mounds at both broad-spatial scales across QCS (Figure 3-1, Figure 3-2 to Figure 3-4) and at fine scales across known sites (e.g. Figure 3-5 to Figure 3-10). The environmental variables RAC, near-bottom current speeds, depth, distance to rocks, distance to headlands and slope were consistently important in explaining and predicting both intact and damaged *Galeolaria* mounds, for all three model types (RF, BRT and ensemble models) (Table 3-2 to Table 3-5). Models were run on both the' intact-only' mounds and on the 'intact and damaged' mounds (combined). While the intact-only model closely matched the observed *Galeolaria* mound distributions, the combined model provided additional information that more accurately described the habitat suitable of *Galeolaria* mound habitats. The predicted distributions of the mound areas was also more extensive at fine-scales (within sites) when damaged mound areas were included.

At Perano Shoals, both models ('intact-only' and 'combined') matched the observed *Galeolaria* mound observations (Figure 3-5 a vs b), however, the combined model increased the predicted % cover within the centre of this feature – more closely matching our observed tow-video data, and other available ground-truthing data (i.e., Rob Davidson's drop camera observations – shown in Figure 23d of Anderson et al. 2020b). Maps depicting the precision of these models (as shown in Figure 3-6a,b) identified little to low uncertainty (blue colour swaths) in the predicted distributions of both models across the mound fields of Perano Shoals, with uncertainty only increasing slightly at the base of the bank well beyond the predicted occurrence of *Galeolaria*. MDC's revised 2015 boundaries for the Significant Site 4.16 around Perano Shoals (Davidson et al. 2015, black-dotted polygons in Figure 3-5a,b) can now be seen to encompasses the majority of the predicted (and observed) *Galeolaria* mound fields. However, a slightly larger area would be recommended to protect the outer edges of these mound fields. These predicted % cover maps can now also be used by managers to determine the area covered by these mound fields and to inform the position of any additional marine site boundaries or changes to planned boundaries.

Newly discovered *Galeolaria* mound fields off Pihaka Point, Kumutoto Point and Amerikiwhati Island were also well predicted by both the intact-only and combined HS models (Figure 3-7-Figure 3-8; Figure 3-9; Figure 3-10, respectively), although some small patches of observed damage along the edge of these mound fields were not captured in the threshold cut-off (>0.020, Figure 3-7b; Figure 3-9b; and Figure 3-10b, respectively). Like Perano Shoals, the maps depicting the precision of the models across Pihaka Point, Kumutoto Point and Amerikiwhati Island (as shown in Figure 3-8; Figure 3-9c-d; and Figure 3-10c-d) identified little to low uncertainty (blue colour swaths) in the predicted distributions of both models across these mound fields, with uncertainty only increasing at the base of the slope well beyond the predicted occurrence of *Galeolaria*.

The threshold cut off of 0.02 (i.e., the lowest colour gradient in the mapped distributions), was an optimal cut-off across the entire survey and for intact-mounds. However, while this threshold value captured the edge at some sites very well (e.g. Perano Shoals), it missed the very outer damaged-edge at other sites (e.g. Pihaka Point, Kumutoto Point and Amerikiwhati Island). A lower cut-off could extend the predicted edge to capture these missed observed records (positive), but this would also mean other sites whose edges were already well delineated would become larger than observed (negative). Consequently, we have retained the 0.02 threshold, but recommend both the assessment of both the predicted and observed distributions be used to delineate the outer boundaries of damaged sites.

Table 3-2: Intact *Galeolaria*-mounds % cover models. Mean percent influence from 100 bootstrap model runs, ordered from most to least influential environmental variables overall.

Environmental variable	RF	BRT	Ensemble
RAC	15.91	18.22	17.07
Near-bottom current speed	15.09	18.54	16.82
Depth	10.64	11.22	10.93
Distance to headland	11.40	10.00	10.70
Seafloor rugosity (VRM)	9.52	8.10	8.81
Slope	8.50	8.83	8.67
Slope standard deviation	8.93	7.61	8.27
Distance to rock	7.80	7.26	7.53
Percent sand	6.28	6.19	6.23
Seafloor classification	5.92	4.02	4.97

Table 3-3: Intact *Galeolaria* mounds – presence/absence models. Mean percent influence from 100 bootstrap model runs, ordered from most to least influential environmental variables in the ensemble model.

Environmental variable	RF	BRT	Ensemble
Near-bottom current speed	23.04	29.82	26.43
Depth	14.88	14.70	14.79
Distance to rock	12.38	15.69	14.03
Distance to headland	11.75	10.96	11.36
Slope	8.57	8.31	8.44
Vector Ruggedness Measure	8.26	6.02	7.14
Percent sand	6.64	4.42	5.53
Slope standard deviation	6.91	4.11	5.51
RAC	3.65	3.94	3.80
Seafloor classification	3.90	2.04	2.97

Table 3-4: Combined (intact and damaged) *Galeolaria*-mounds % cover models. Mean percent influence from 100 bootstrap model runs, ordered from most to least influential environmental variables overall.

Environmental variable	RF	BRT	Ensemble
RAC	18.38	23.94	21.16
Depth	12.43	14.64	13.54
Near-bottom current speed	11.29	13.73	12.51
Distance to rock	9.97	11.13	10.55
Percent sand	9.76	8.77	9.27
Distance to headland	9.55	8.51	9.03
Seafloor rugosity (VRM)	9.00	6.62	7.81
Slope	7.72	6.58	7.15
Slope standard deviation	7.37	3.74	5.56
Seafloor classification	4.51	2.35	3.43

Table 3-5: Combined (intact and damaged) *Galeolaria*-mounds - presence/absence models. Mean percent influence from 100 bootstrap model runs, ordered from most to least influential environmental variables in the ensemble model.

Environmental variable	RF	BRT	Ensemble
Near-bottom current speed	23.01	29.91	26.46
Depth	14.96	14.87	14.92
Distance to rock	12.74	16.04	14.39
Distance to headland	11.50	11.04	11.27
Slope	8.42	8.18	8.30
Vector Ruggedness Measure	8.12	5.78	6.95
Percent sand	6.87	4.60	5.74
Slope standard deviation	6.76	4.11	5.43
RAC	3.74	3.34	3.54
Seafloor classification	3.88	2.14	3.01

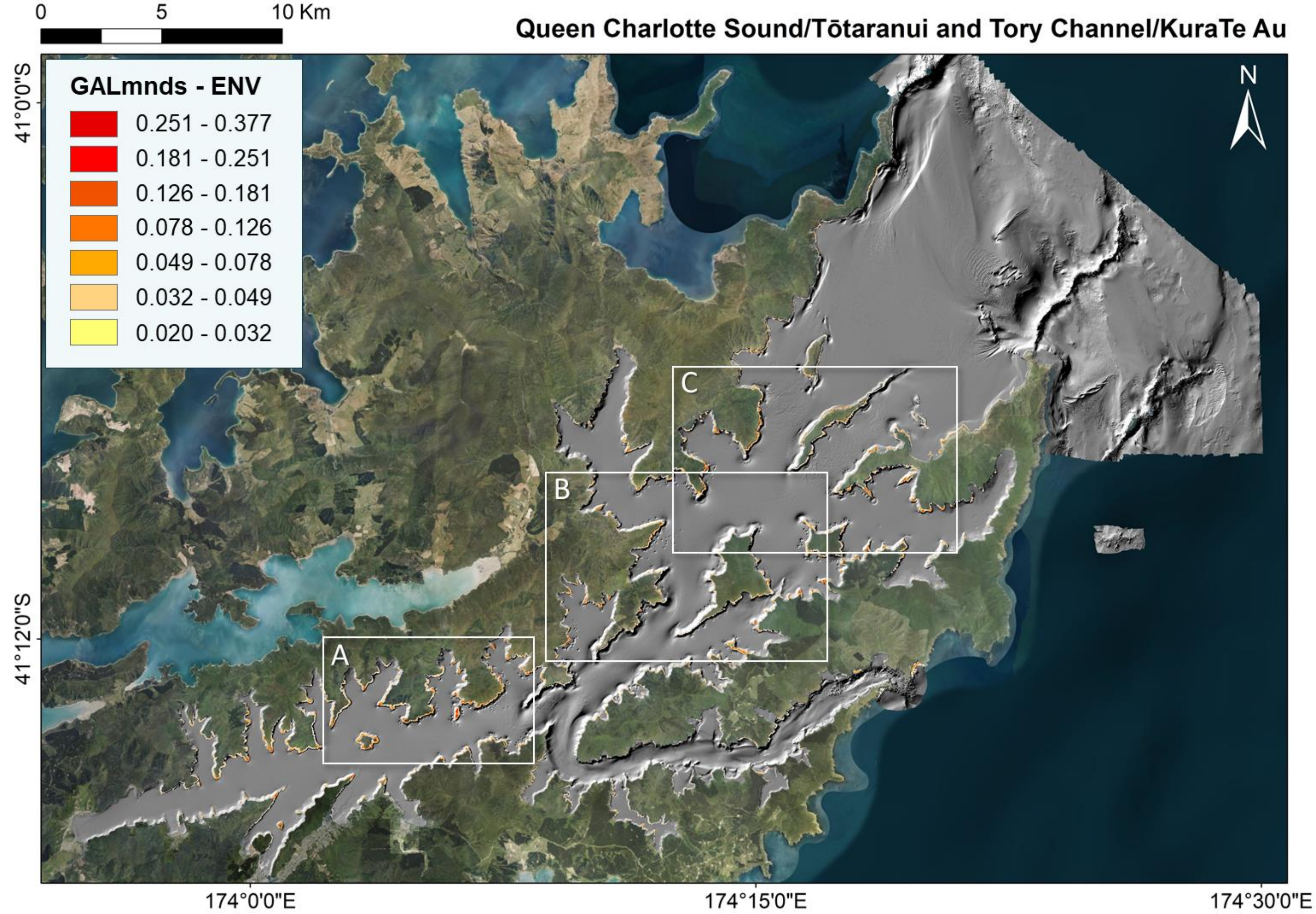

Figure 3-1: Predicted habitat suitability of *Galeolaria hystrix* mounds, across the HS51 survey area. GALmnds=*Galeolaria* mounds, where ENV=environmental predictions; Graduated ENV colours (from blue to red, as shown on the scale-bar) indicate the fraction of predicted % cover (0–1) with predicted distributions associated with ridges along the channel slopes (see Zoomed-in boxes A-C in Figure 3-2, Figure 3-3 and Figure 3-4 below). Overlaid on MBES grey-coloured hillshaded relief.

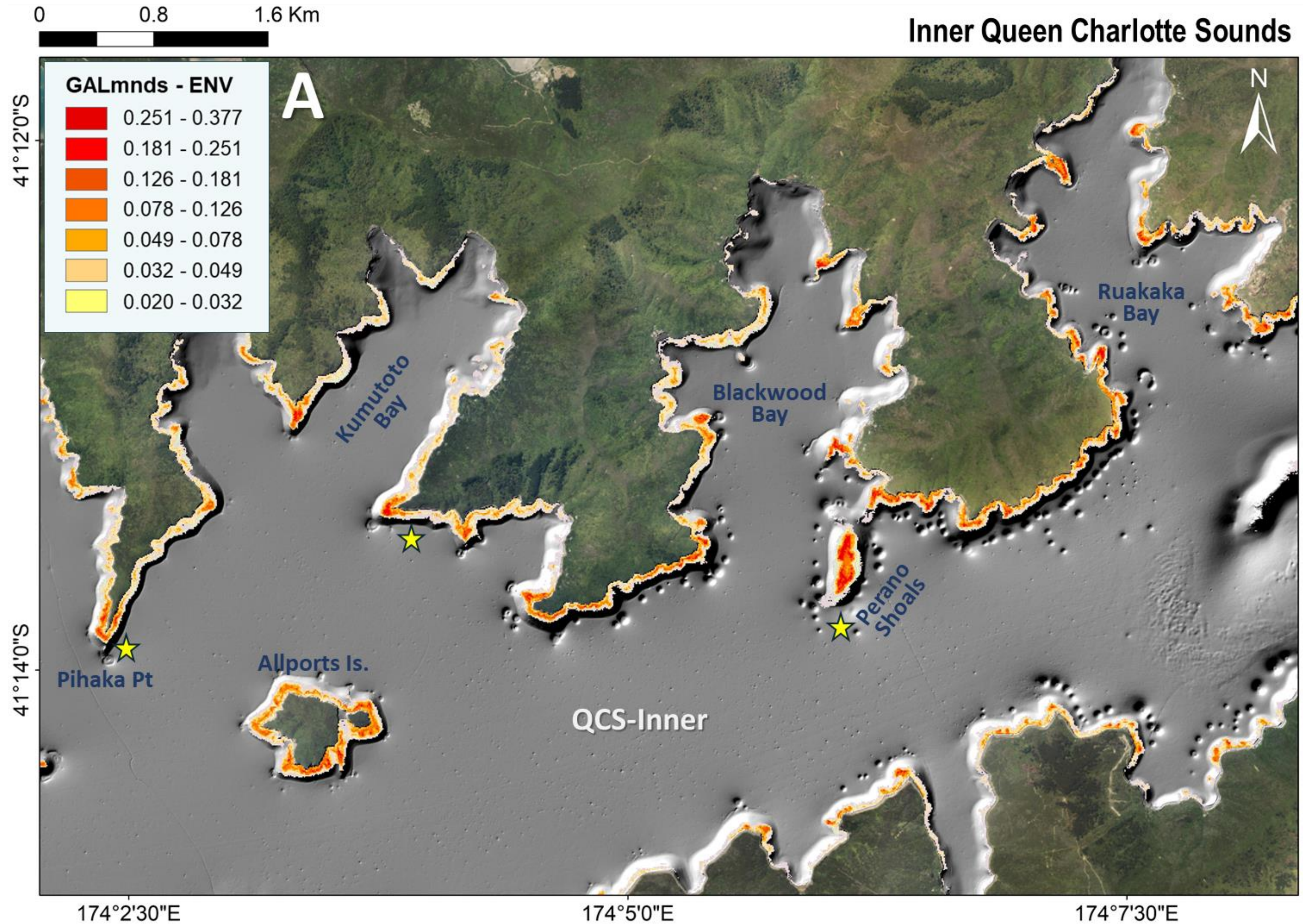

Figure 3-2: Predicted habitat suitability of *Galeolaria hystrix* mounds, within inner QCS (box-A). The location of box-A is shown in Figure 3-1. GALmnds=*Galeolaria* mounds, where ENV=environmental predictions; Graduated ENV colours (from blue to red, as shown on the scale-bar) indicate the fraction of predicted % cover (0–1). Overlaid on MBES grey-coloured hillshaded relief. Zoomed-in examples (areas depicted by yellow stars) are presented in Figure 3-5 to Figure 3-9.

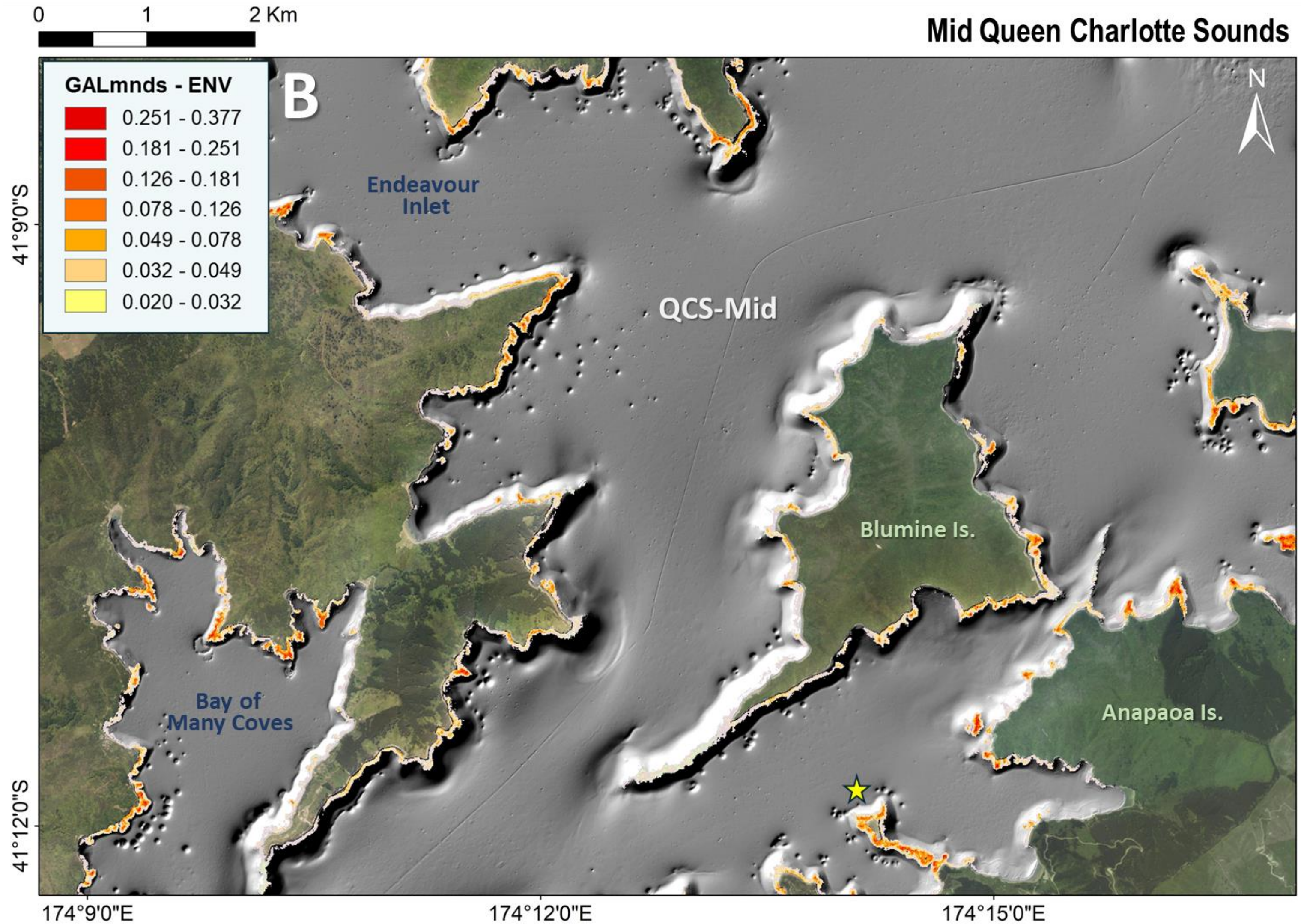

Figure 3-3: Predicted habitat suitability of *Galeolaria hystrix* mounds, within mid QCS (box-B). The location of box-B is shown in Figure 3-1. GALmnds=*Galeolaria* mounds, where ENV=environmental predictions; Graduated ENV colours (from blue to red, as shown on the scale-bar) indicate the fraction of predicted % cover (0–1). Overlaid on MBES grey-coloured hillshaded relief. Yellow star= Zoomed-in example presented in Figure 3-10.

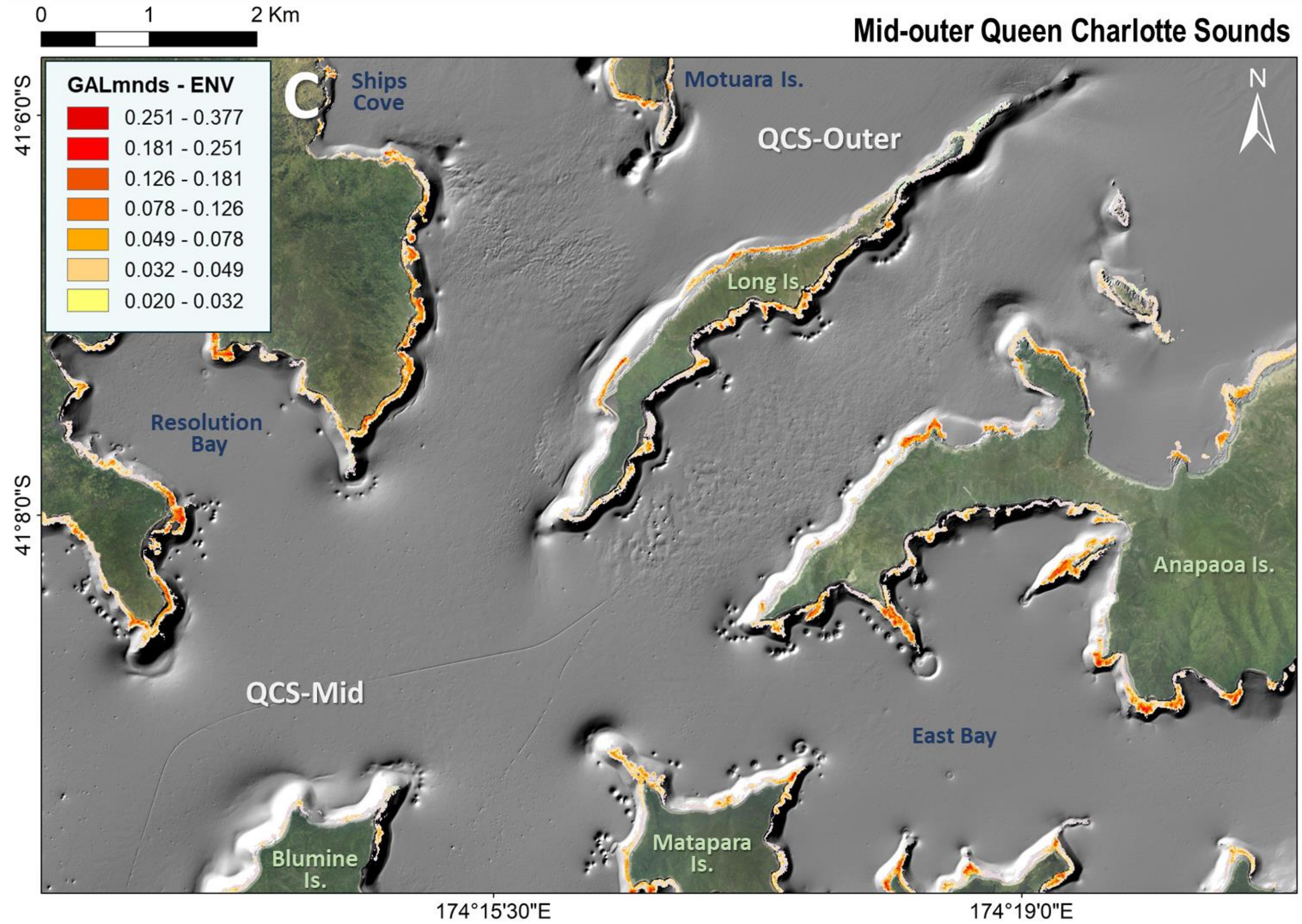

Figure 3-4: Predicted habitat suitability of *Galeolaria hystrix* mounds, within mid-outer QCS (box-C). The location of box-C is shown in Figure 3-1. GALmnds=*Galeolaria* mounds, where ENV=environmental predictions; Graduated ENV colours (from blue to red, as shown on the scale-bar) indicate the fraction of predicted % cover (0–1). Overlaid on MBES grey-coloured hillshaded relief.

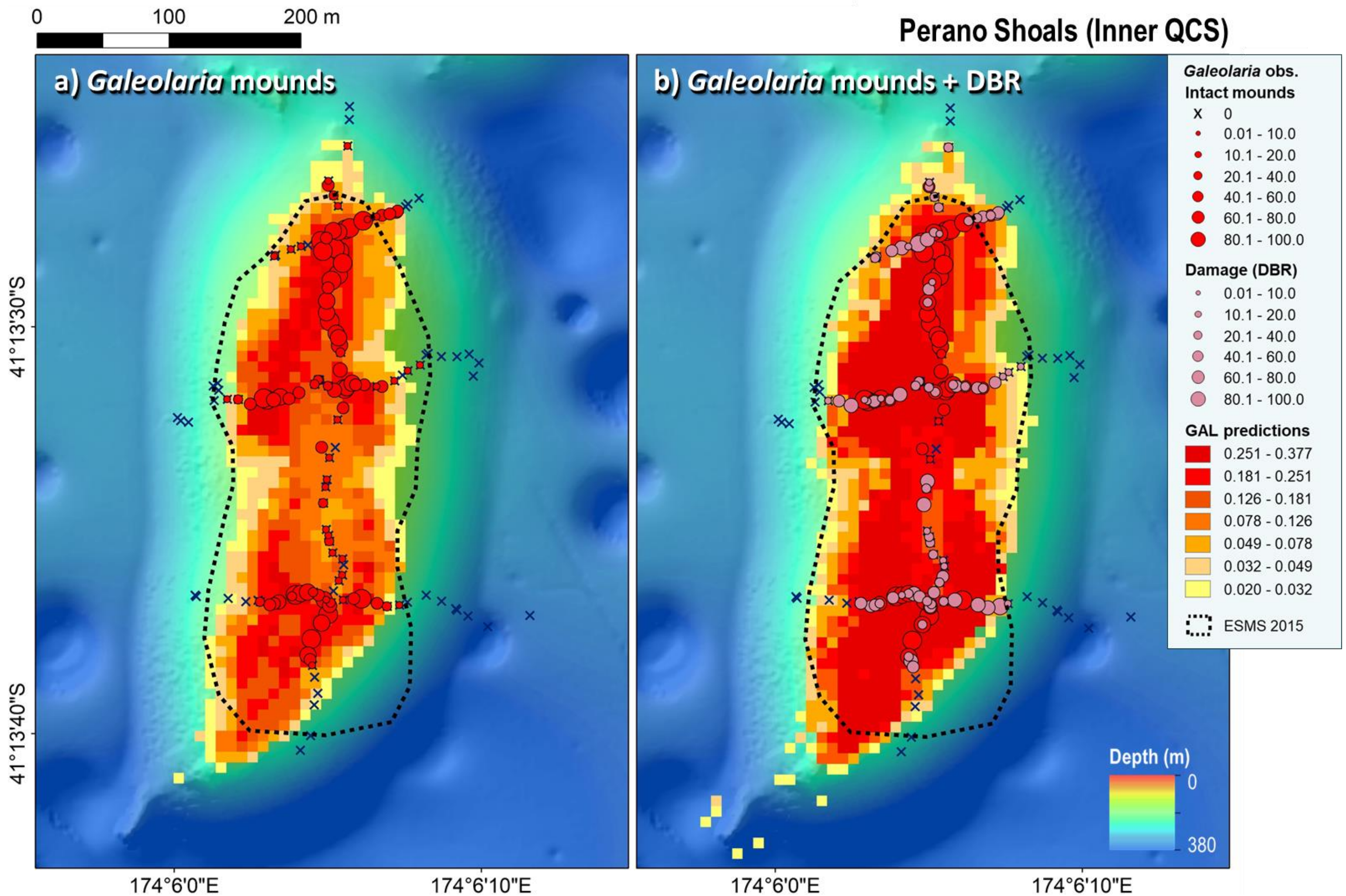

Figure 3-5: Predicted habitat suitability of *Galeolaria hystrix* mounds across Perano Shoals, Inner QCS. GAL=*Galeolaria*; Observed (obs.) and predicted *Galeolaria* mound distributions for: a) Intact *Galeolaria hystrix* mounds; b) Intact and damaged (DBR= dead base and rubble) mounds; Red and mauve bubbles = observed intact and damaged bryozoan % cover, respectively (as per legend); Graduated prediction colours (from blue to red, as shown in legend) indicate the fraction of predicted % cover (0–1); Overlaid on 2-m resolution MBES bathymetry. Black dotted polygon = MDC significant Site 4.16.

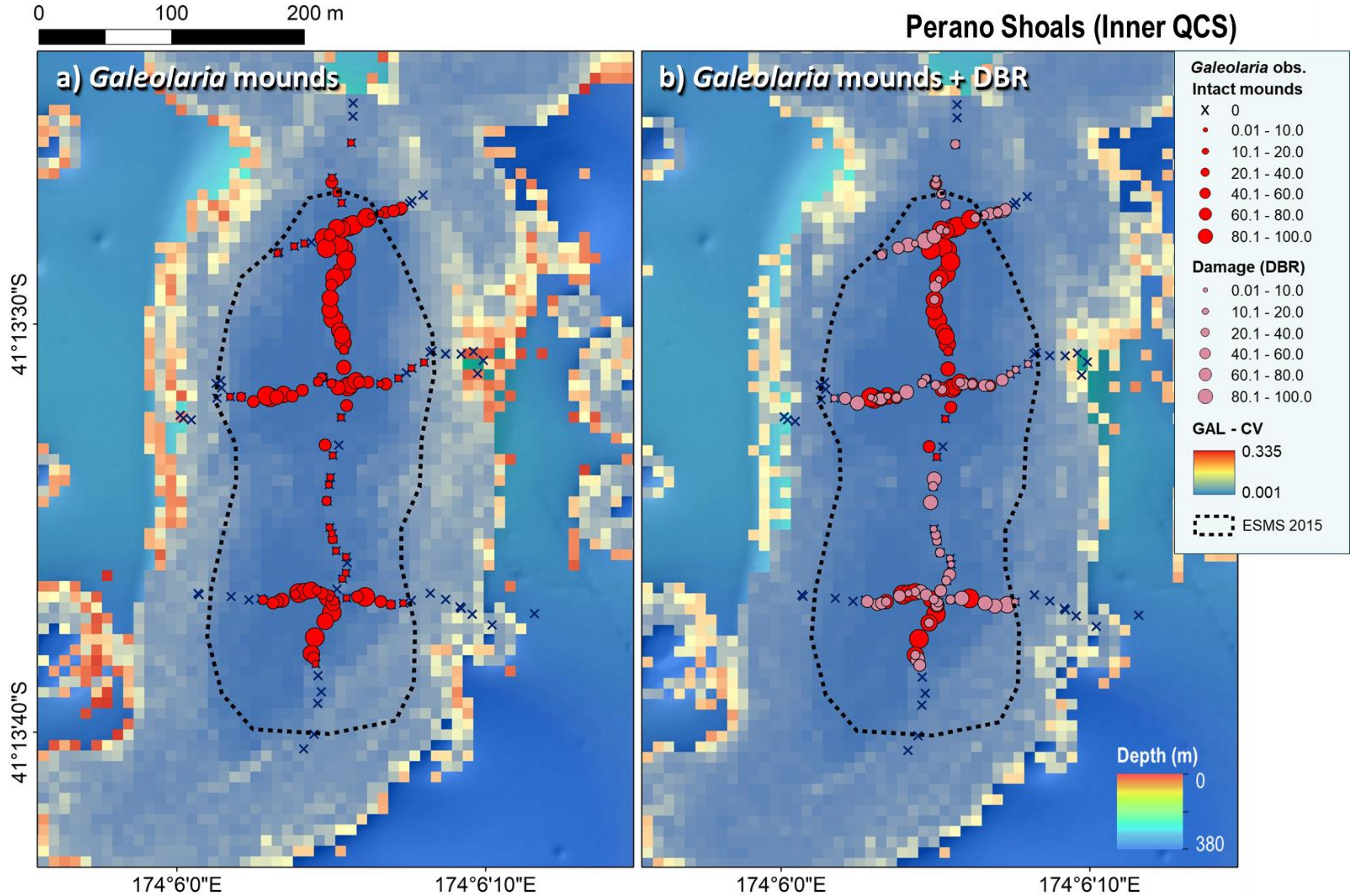

Figure 3-6: Precision of predicted habitat suitability of *Galeolaria hystrix* mounds across Perano Shoals, Inner QCS. GAL=*Galeolaria*; Observed (obs.) and precision of the predicted *Galeolaria* mound distributions for: a) Intact *Galeolaria hystrix* mounds; b) Intact and damaged (DBR= dead base and rubble) mounds. Red and mauve bubbles = observed intact and damaged bryozoan % cover, respectively (as per legend). Precision is presented as the CV (Cross-validation coefficient) of the predicted habitat suitability based on bootstrap resampling, and shown as a fraction (0–1), where blue=low uncertainty vs red=higher uncertainty. Overlaid on MBES grey-coloured hillshaded relief; Brown-shaded polygons=MBES rocky outcrop layer.

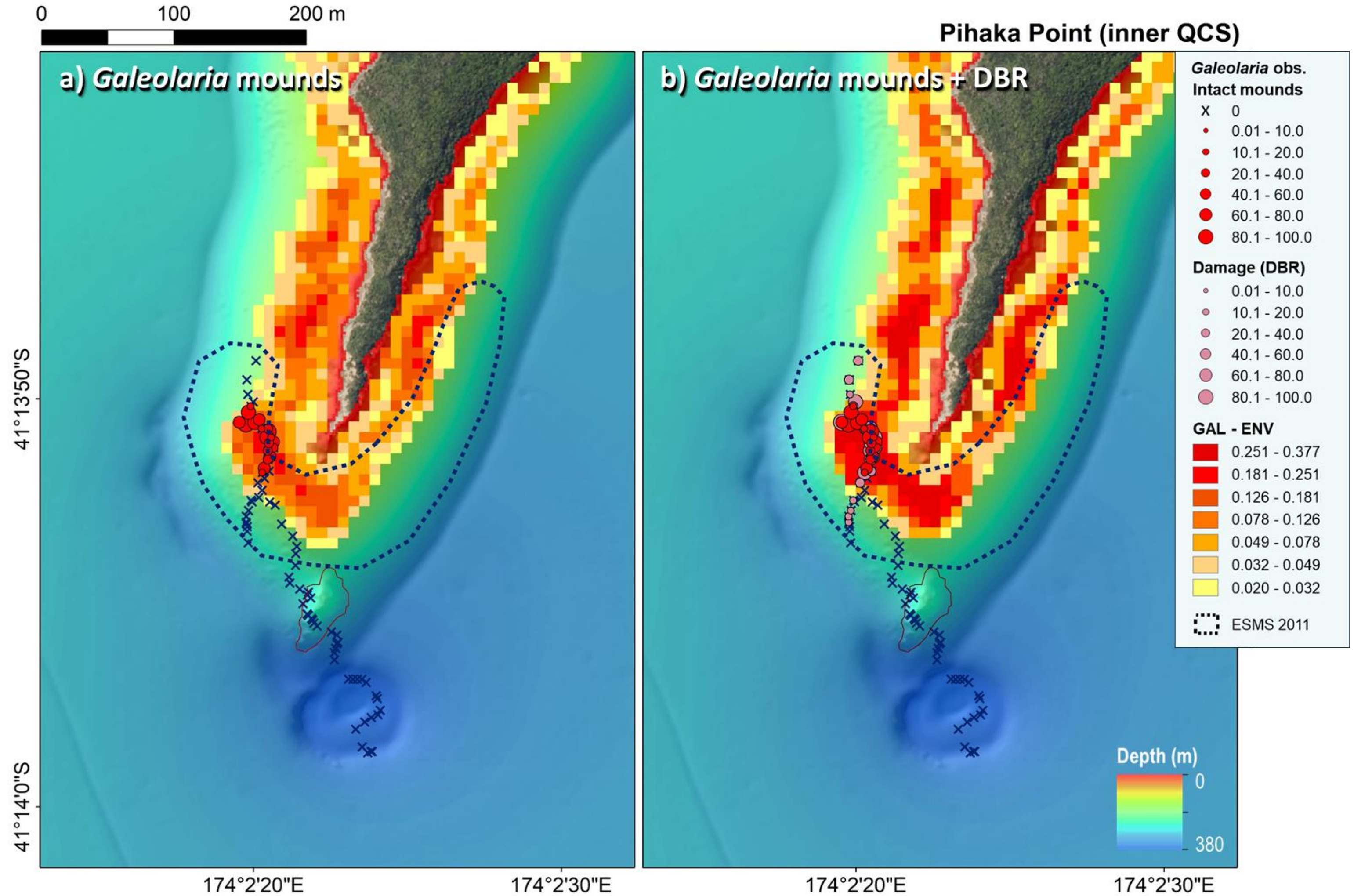

Figure 3-7: Predicted habitat suitability of *Galeolaria hystrix* mounds across Pihaka Point, Inner QCS. GAL=*Galeolaria*; Observed (obs.) and predicted *Galeolaria* mound distributions for: a) Intact *Galeolaria hystrix* mounds; b) Intact and damaged (DBR= dead base and rubble) mounds; Red and mauve bubbles = observed intact and damaged bryozoan % cover, respectively (as per legend); Graduated prediction colours (from blue to red, as shown in legend) indicate the fraction of predicted % cover (0–1); Overlaid on 2-m resolution MBES bathymetry; Brown lined-polygon=drawn boundary of the Deep-reef at Pihaka.

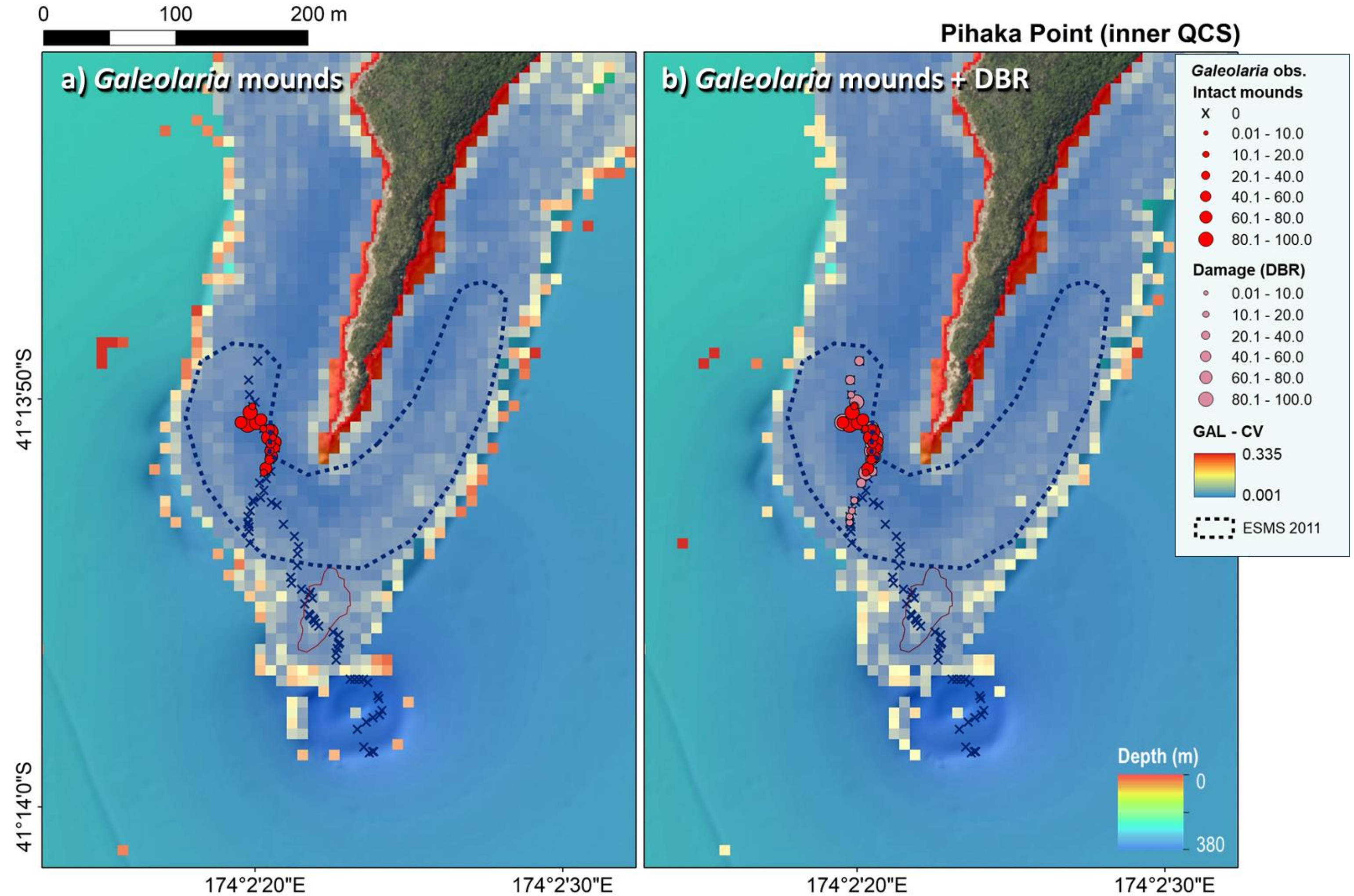

Figure 3-8: Precision of predicted habitat suitability of *Galeolaria hystrix* mounds across Pihaka Point, Inner QCS. GAL=*Galeolaria*; Observed (obs.) and precision of the predicted *Galeolaria* mound distributions for: a) Intact *Galeolaria hystrix* mounds; b) Intact and damaged (DBR= dead base and rubble) mounds. Red and mauve bubbles = observed intact and damaged bryozoan % cover, respectively (as per legend). Precision is presented as the CV (Cross-validation coefficient) of the predicted habitat suitability based on bootstrap resampling, and shown as a fraction (0–1), where blue=low uncertainty vs red=higher uncertainty. Overlaid on 2-m resolution MBES bathymetry; Brown lined-polygon=drawn boundary of the Deep-reef at Pihaka.

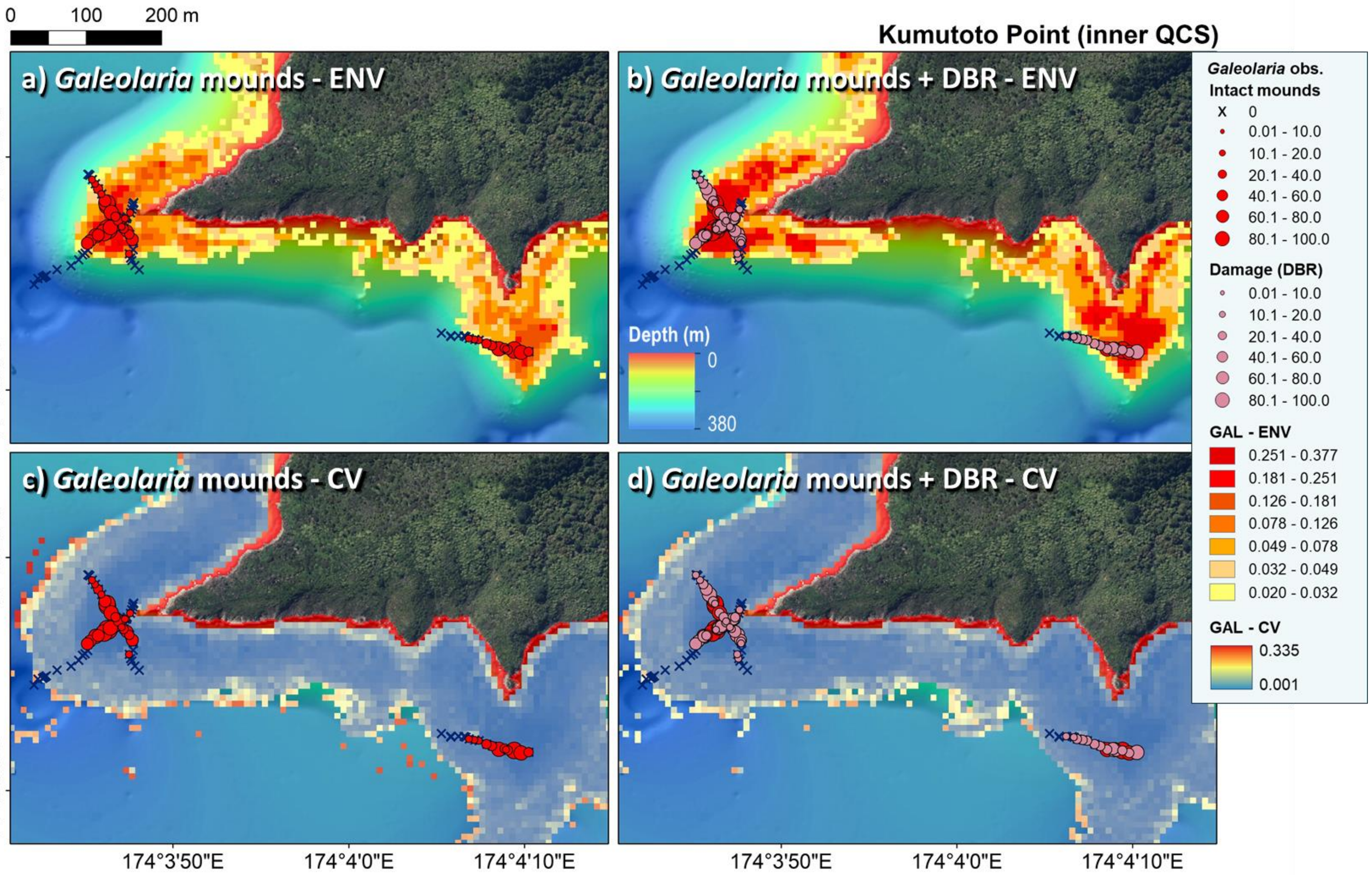

Figure 3-9: Predicted habitat suitability of *Galeolaria hystrix* mounds across Kumutoto Point, Inner QCS. a-b) predicted distributions (ENV) and c-d) Precision of predicted distributions (CV) for Intact *Galeolaria hystrix* mounds (left-images) and Intact and damaged mounds (DBR= dead base and rubble) (right-images); Red and mauve bubbles = observed intact and damaged bryozoan % cover, respectively (as per legend); a-b) Graduated ENV colours (from blue to red, as shown in legend) indicate the fraction of predicted % cover (0–1); while c-d) Precision is presented as the CV (Cross-validation coefficient) of the predicted habitat suitability based on bootstrap resampling, and shown as a fraction (0–1), where blue=low uncertainty vs red=higher uncertainty. Overlaid on 2-m resolution MBES bathymetry.

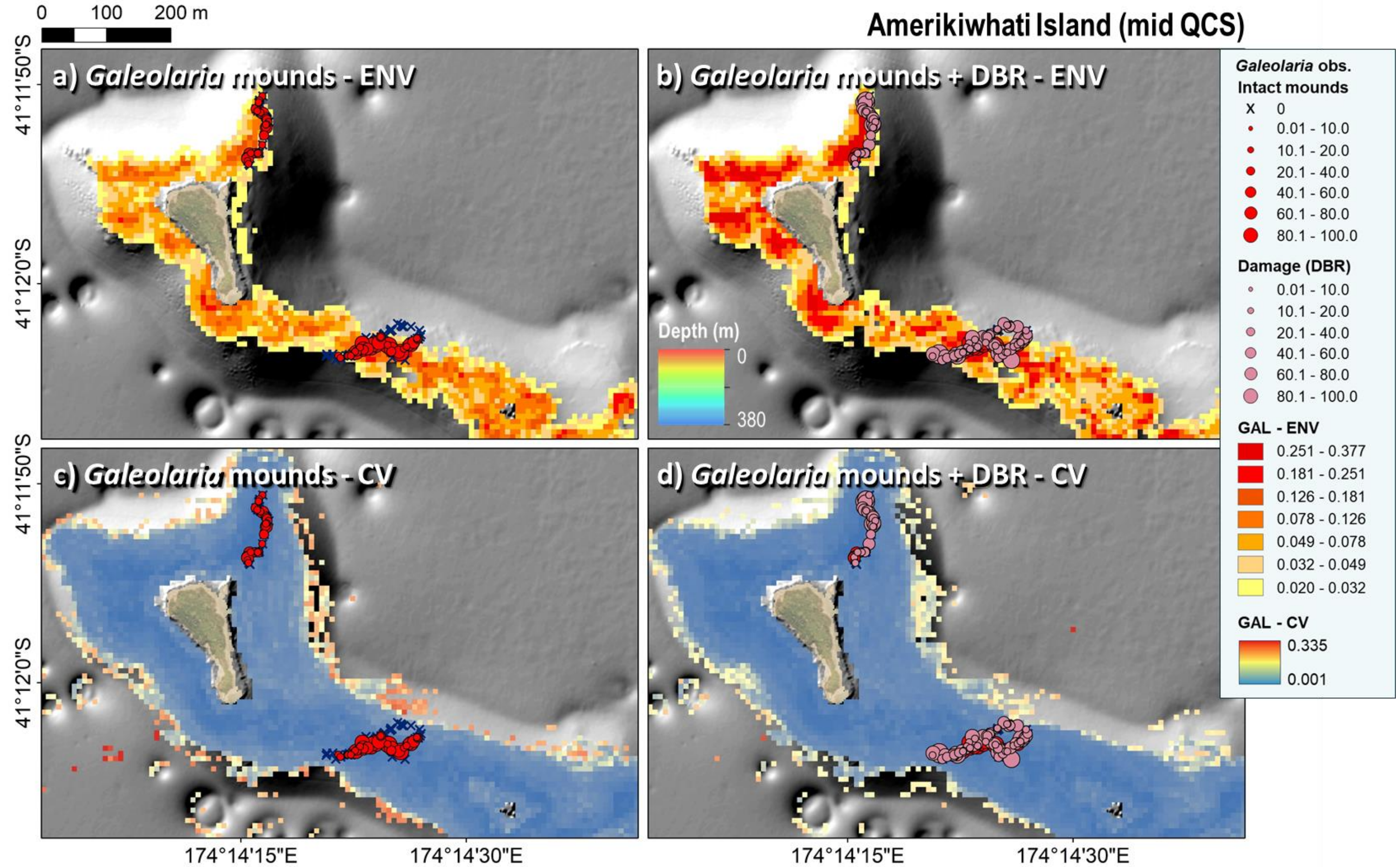

Figure 3-10: Predicted habitat suitability of *Galeolaria hystrix* mounds across Amerikiwhati Island, mid QCS. a-b) predicted distributions (ENV) and c-d) Precision of predicted distributions (CV) for Intact *Galeolaria hystrix* mounds (left-images) and Intact and damaged mounds (DBR= dead base and rubble) (right-images); Red and mauve bubbles = observed intact and damaged bryozoan % cover, respectively (as per legend); a-b) Graduated ENV colours (from blue to red, as shown in legend) indicate the fraction of predicted % cover (0–1); while c-d) Precision is presented as the CV (Cross-validation coefficient) of the predicted habitat suitability based on bootstrap resampling, and shown as a fraction (0–1), where blue=low uncertainty vs red=higher uncertainty. Overlaid on grey hillshaded relief.

3.1.3 Predicted distributions for bryozoan mounds

Model performance and predictive success for bryozoans was good at broad-spatial scales, with the model effectively predicting bryozoan mounds (or bryo-reefs) along the outer bank at the entrance to QCS: specifically across the Duck Pond, channel entrances and deeper outer channels of QCS (Table 3-1; Figure 3-11 and Figure 3-12). However, at finer-spatial scales across the entrance to QCS, model performance and predictive success was lower than expected (Figure 3-13, Figure 3-14), as compared to the hand-drawn ArcGIS bryo-reef polygons that provide good delineation of patchy bryo-reef areas at scales of ≥ 2 m (blue and red dotted polygons: Figure 3-15). The main explanatory variables for % cover of bryozoan mounds in all three models were very similar (Table 3-6), with depth, seafloor rugosity (VRM), and near-bottom current speed accounting for a combined mean percent influence of >70%, while spatial autocorrelation (RAC) accounted for ~16-18% (depending on the model). However, the main explanatory variables for the 'presence/absence of bryozoan mounds' was RAC (~37-47%), near-bottom current speed (~19-23%) and depth (13-17%) (Table 3-7). While depth and near-bottom currents are important in both models, the importance of RAC was notably higher in the presence-absence compared to the '%cover' models. This indicates that while both models identified bryozoans patch reefs were locally structured with fine-scale spatial autocorrelation (as would be expected due to the natural patchiness of this habitat-forming species within a matrix of sandy-muds), the % cover data provides more independent information. Surprisingly, seafloor classification (numerical variable representing the combinations of seafloor the hardness and sediment composition) was the least influential of the key variables (~6-13% influence across both models) (Table 3-6 and Table 3-7). Similarly, rugosity was also much less influential than expected - although its relative influence varied between models (i.e., higher in % cover models - indicative of a linear increase in % cover with higher rugosity), (Table 3-6 and Table 3-7).

Table 3-6: Bryozoan mounds - % cover models. Mean percent influence from 100 bootstrap model runs, ordered from most to least influential environmental variables in the ensemble model.

Environmental variable	RF	BRT	Ensemble
Depth	24.21	26.52	25.36
Seafloor rugosity (VRM)	22.06	26.11	24.09
Near-bottom current speed	22.83	23.87	23.35
RAC	18.32	16.83	17.58
Seafloor classification	12.57	6.67	9.62

Table 3-7: Bryozoan mounds - presence/absence models. Mean percent influence from 100 bootstrap model runs, ordered from most to least influential environmental variables in the ensemble model.

Environmental variable	RF	BRT	Ensemble
RAC	37.66	47.17	42.42
Near-bottom current speed	22.52	19.48	21.00
Depth	17.22	13.59	15.41
Seafloor classification	11.21	11.10	11.15
Seafloor rugosity (VRM)	11.38	8.66	10.02

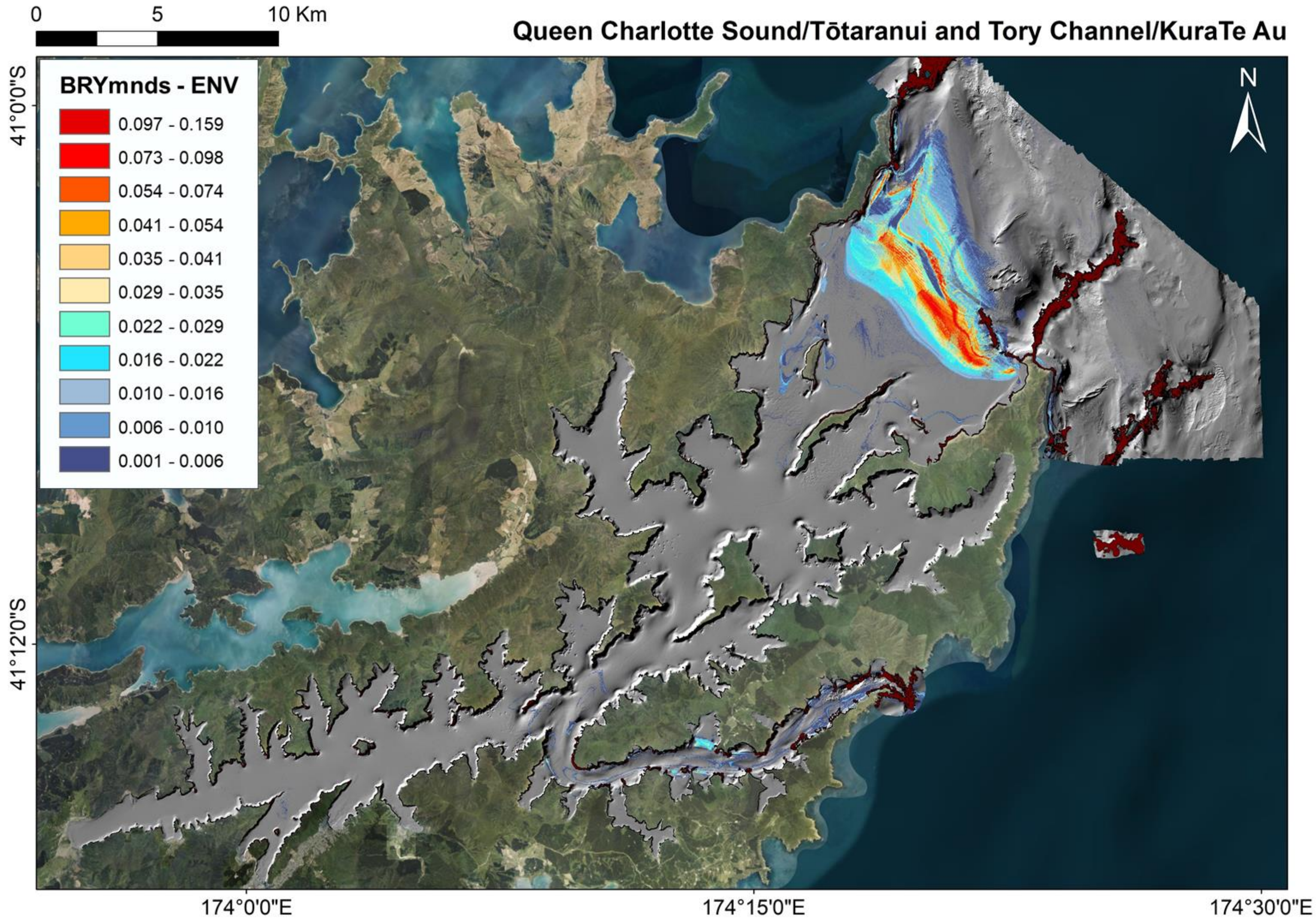

Figure 3-11: Predicted habitat suitability of Bryozoan mounds. BRYmnds=Bryozoan mounds, where ENV=environmental predictions; Graduated ENV colours (from blue to red, as shown on the scale-bar) indicate the fraction of predicted % cover (0–1). Overlaid on MBES grey-coloured hillshaded relief; Brown-shaded polygons=MBES rocky outcrop layer.

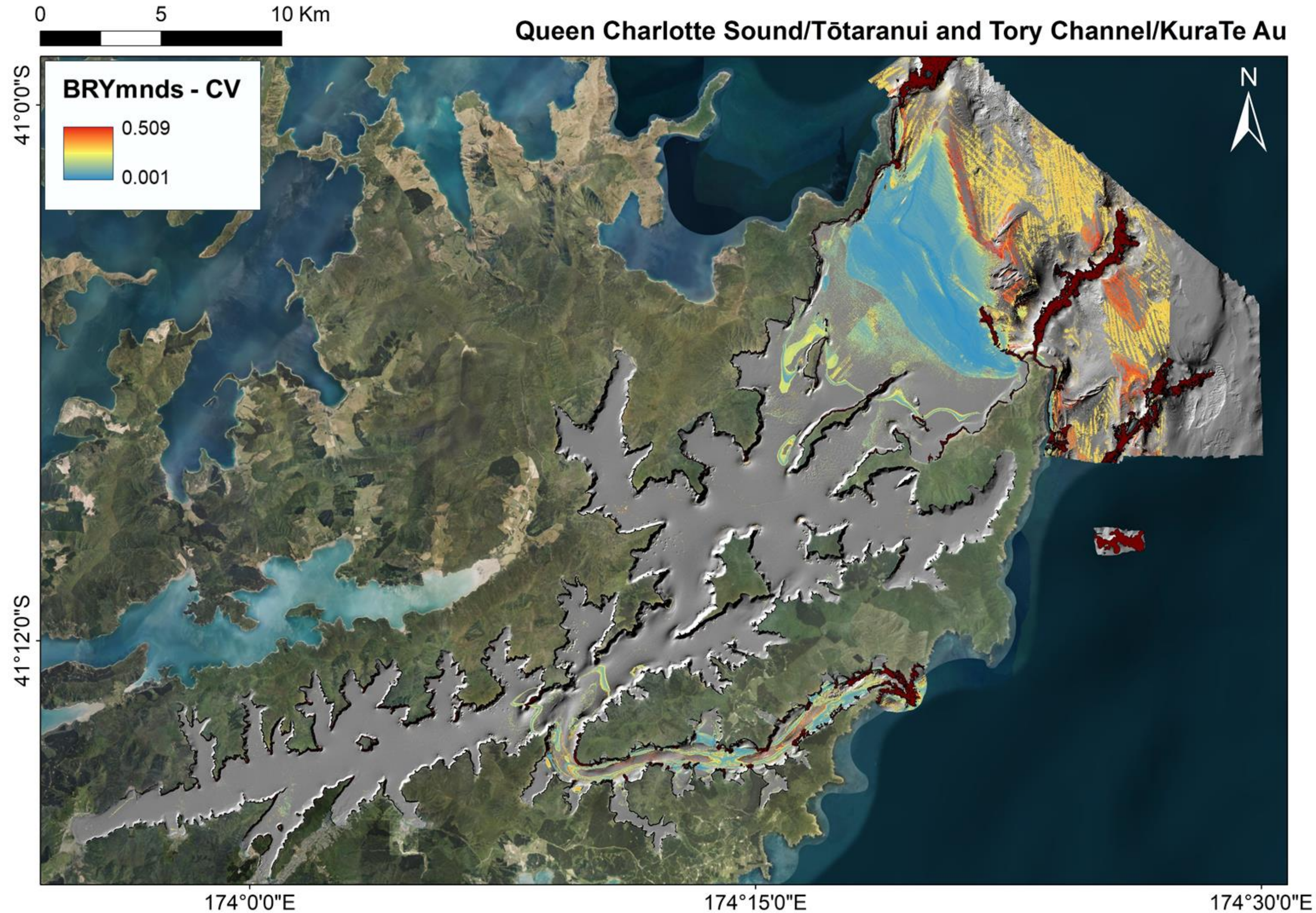

Figure 3-12: Precision of predicted habitat suitability of Bryozoan mounds. BRYmnds=Bryozoan mounds. Precision is presented as the CV (Cross-validation coefficient) of the predicted habitat suitability, based on bootstrap resampling, and shown as a fraction (0–1), where blue=low uncertainty vs red=higher uncertainty. Overlaid on MBES grey-coloured hillshaded relief. Brown-shaded polygons=MBES rocky outcrop layer.

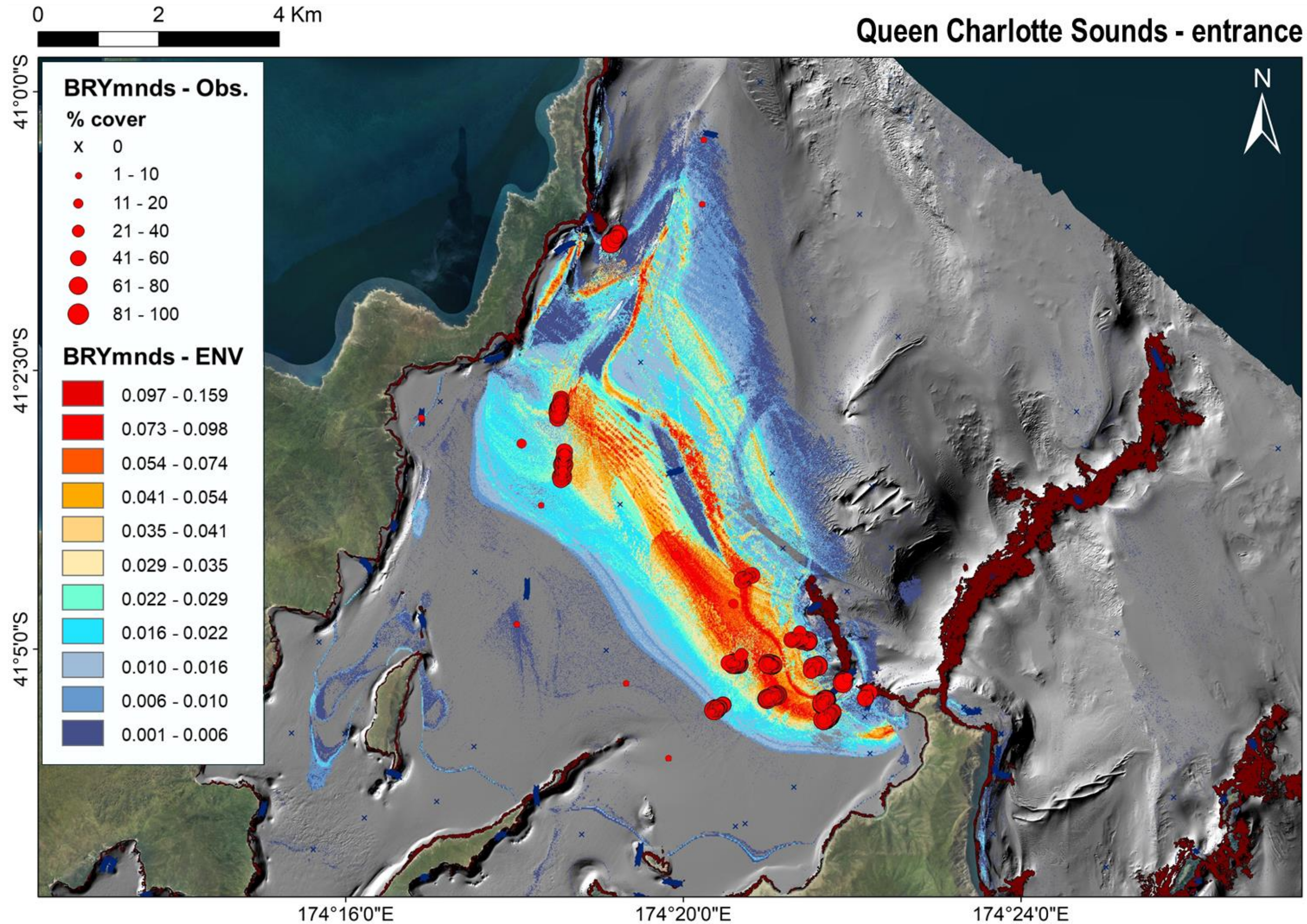

Figure 3-13: Predicted habitat suitability of Bryozoan mounds (Zoomed in) at the entrance to Queen Charlotte Sound (QCS). BRYmnds=Bryozoan mounds, with OBS=observations and ENV=environmental predictions; Red bubbles = observed bryozoan % cover (as per legend); Graduated ENV colours (from blue to red, as shown in legend) indicate the fraction of predicted % cover (0–1); Overlaid on MBES grey-coloured hillshaded relief; Brown-shaded polygons=MBES rocky outcrop layer.

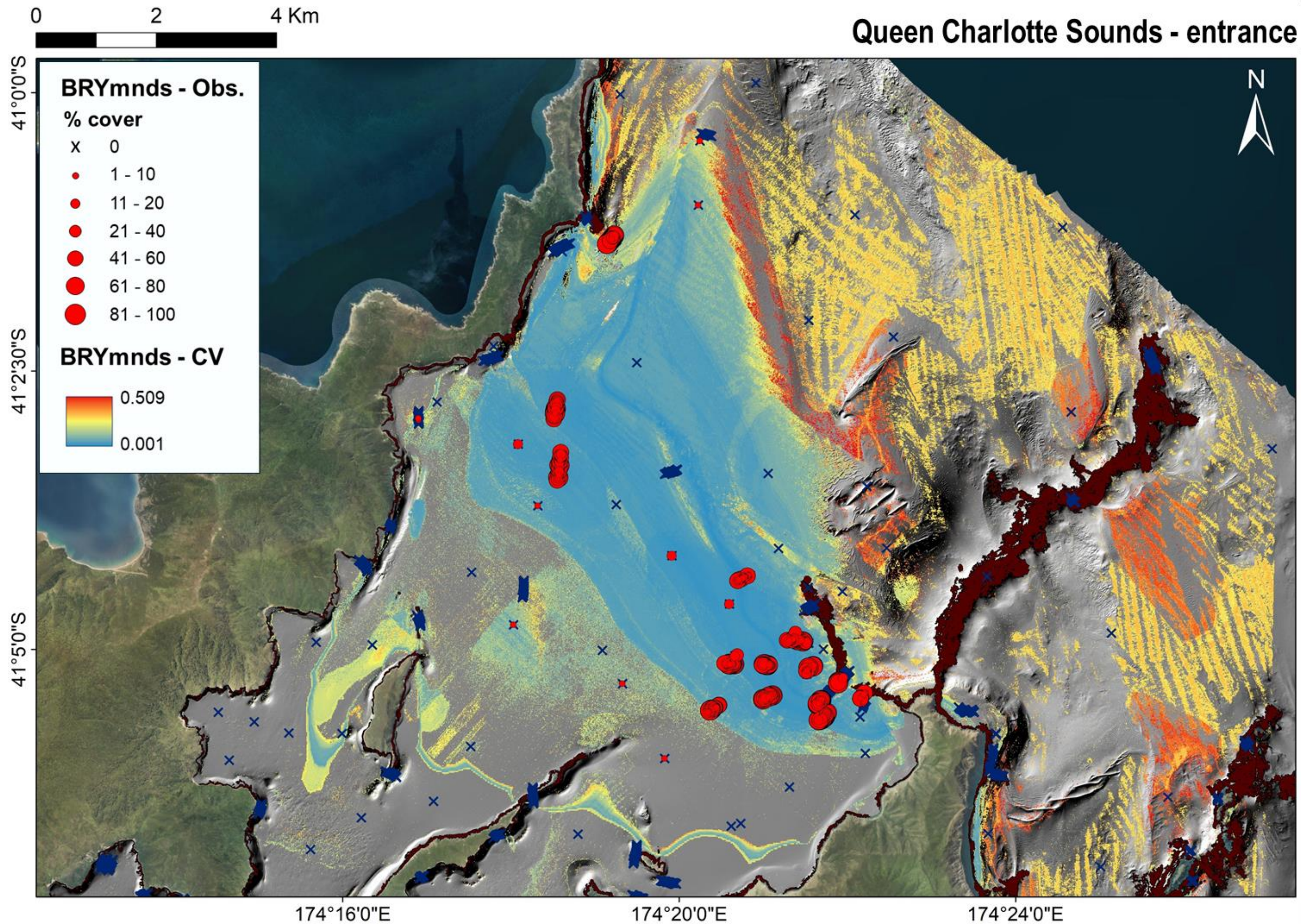

Figure 3-14: Precision of predicted habitat suitability of Bryozoan mounds (<u>Zoomed in</u>) at the entrance to Queen Charlotte Sounds (QCS). BRYmnds=Bryozoan mounds. Precision is presented as the CV (Cross-validation coefficient) of the predicted habitat suitability based on bootstrap resampling, and shown as a fraction (0–1), where blue=low uncertainty vs red=higher uncertainty. Red bubbles = observed bryozoan % cover (as per legend); Overlaid on MBES grey-coloured hillshaded relief; Brown-shaded polygons=MBES rocky outcrop layer.

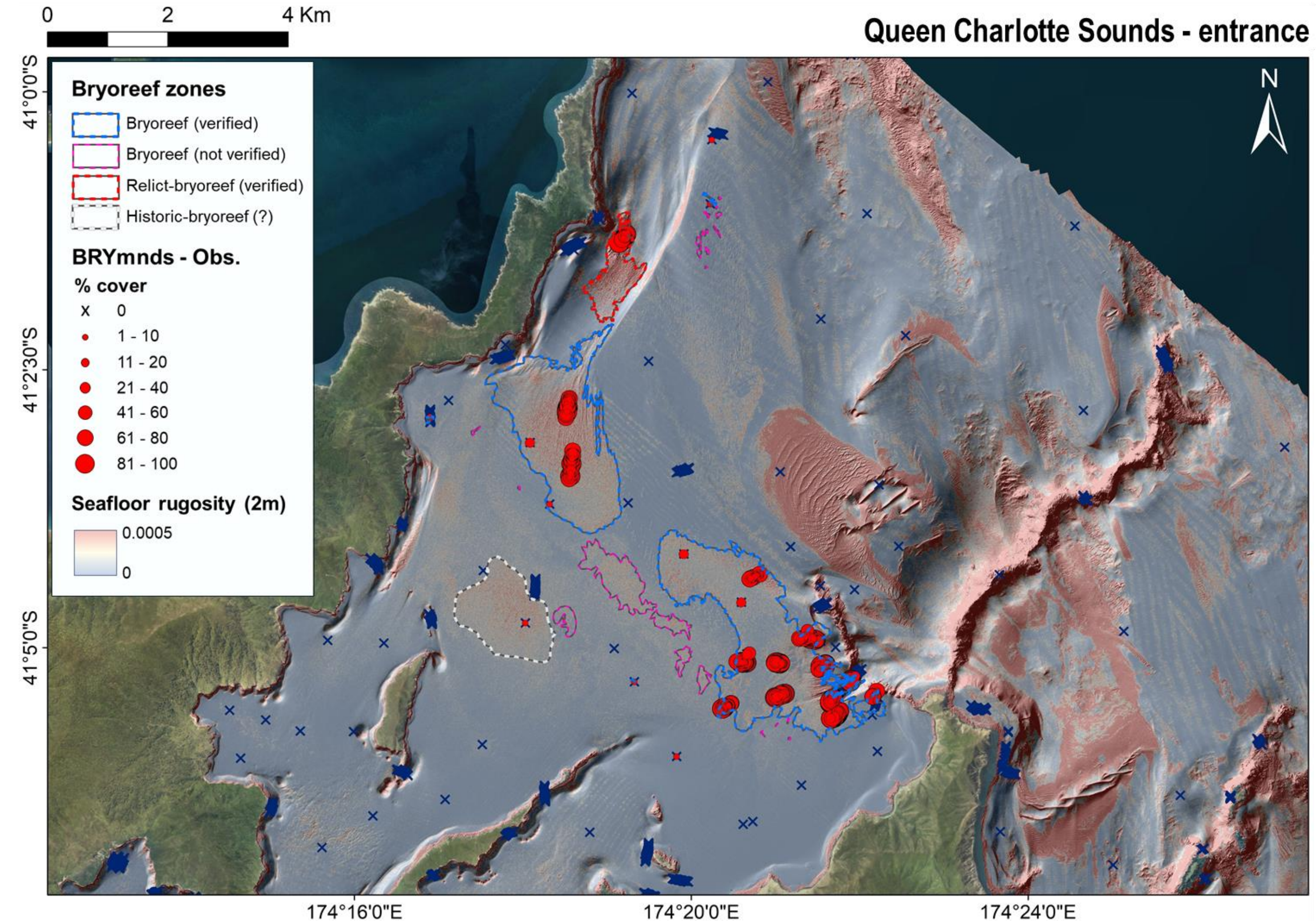

Figure 3-15: Location of the bryzoan patch reef (bryo-reef) zones (Zoomed-in) at the entrance to Queen Charlotte Sound. Polygons were drawn in ArcGIS based on observed reefs associated with combined features of backscatter, rugosity, hillshaded relief and seafloor classification layers. Red bubbles = bryozoan % cover (as per legend); Four zones types (colours depicted in legend) are delineated: Blue dashed polygon-lines = Intact living bryo-reef zones validated by observational data; red dashed polygon-lines = relict reef in entrance channel (also verified by observational data). Background: Seafloor rugosity (semi-transparent) enhanced to show areas of higher rugosity (red-brown) compared to even seafloor areas (darkened blue), overlaid on hillshaded relief.

4 Discussion/summary

Management of benthic marine habitats and their biological communities is generally hampered by a lack of comprehensive spatial information, particularly in depths not easily accessible to divers (>20 m). This was particularly true for the Marlborough Sounds which relied mostly on nearshore diving and snorkelling surveys in depths ≤20 m (as described in Davidson et al. 2011; 2015), prior to the continuous multibeam swath mapping surveys and extensive data-intensive tow-video ground-truth surveys (described in Neil et al. 2018a,b, and Anderson et al. 2020b, respectively). Continuous mapped cover of the seafloor across QCS, TC and adjacent Cook Strait (Neil et al. 2018a,b) provide essential new knowledge on the shape and structure of the seafloor within the HS51 survey area, while the high density, spatially extensive ground-truthing surveys (Anderson et al. 2020b) provide a wealth of new information on the known distribution of both bryozoan and *Galeolaria* mounds. These studies have identified a diversity of marine life that provides essential ecosystems services, supporting coastal fisheries, that in turn are also vulnerable to anthropogenic impacts and environmental change.

In this project, we used habitat suitability modelling to predictively map distributions of two significant habitat-forming species: Bryozoan and *Galeolaria* mounds. We found that the distribution, occurrence and % cover of these taxon can be explained by and predicted using existing environmental variables, including bathymetry, bathymetry-derived variables (such as slope, seafloor classification and rugosity), near-bottom currents and spatial-derived indices (distance to headland and reef) - although the predictive strengths of these variables varied between the taxon/groups. In addition to providing the first quantitative and full-coverage maps of these habitat-forming taxa across the HS51 survey extent, the predicted distribution maps for *Galeolaria* mounds and the revised bryozoan patch-reef polygons provide delineation of these significant habitats across the survey area (albeit mostly constrained to QCS), and as such provide MDC with an extremely valuable new tool to aid in the management and conservation of the Marlborough Sounds.

4.1 Distribution of *Galeolaria* mounds

HS models reliably predicted the distribution of Galeolaria mounds, for both intact and damaged mound types, over broad-spatial scales (i.e., distribution across the entrance to QCS within the broader HS51 survey area), and at finer-spatial scales across known sites. While the intact-only ensemble model closely matched the observed *Galeolaria* mound distributions, the combined model provided additional information that more accurately described the habitat suitable of *Galeolaria* mound habitats. The threshold cut off of 0.02 was a good-fit across the scale of the survey, and for intact-mounds, but contracted the outer boundary of some edge-damaged sites. We would therefore recommend that both the predicted and observed distributions of mounds be used to determine the outer boundaries of damaged sites.

The predicted versus observed distributions of intact and combined mounds at zoomed-in example sites (i.e., Perano Shoals, Pihaka and Kumutoto Points and around Amerikiwhati Island) identified that the *Galeolaria* models were extremely good at predicting the % cover and extent of *Galeolaria* mounds and as such will provide MDC with an extremely valuable tool in helping to manage and conserve these unique habitat-forming species.

4.2 Distribution of Bryozoan mounds

HS models reliably predicted the distribution of bryozoan mounds (within bryo-reefs zones) over broad-spatial scales (i.e., distribution across the entrance to QCS within the broader HS51 survey area), but at finer-spatial scales across the entrance to QCS these models were less reliable at accurately delineating finer-scale boundaries of patchy bryozoan mounds (termed bryo-reef zones in Anderson et al. 2020b). Video observations overlaid on environmental raster layers identified that bryozoan patch reefs were associated with local increases in rugosity and higher reflectivity sediments at fine scales (i.e., m's to 10's of m's) depicting raised hard patch-reefs interspersed by low rugosity soft sandy muds (Anderson et al. 2020b). ArcGIS polygons delineating patchy bryo-reef zones were drawn around areas of higher fine-scale rugosity and seafloor hardness (based on these visual-associations), and appear to provide good delineation of patchy bryo-reef zones at the scale of ≥ 2 m. Although other 'non-verified' bryo-reef zones (pink and grey dotted polygons in Figure 3-15) would require further ground-truthing verification.

Given that within the bryozoan patch reef zone, rugosity and seafloor hardness are simply a function of vertical height and the hard structure of the bryozoan mounds – it would be expected they be excellent predictors of fine-scale distributions of bryozoan mounds in the HS models. The lower than expected influence of seafloor classification and rugosity may simply be a function of reducing data resolution from 2 x 2 m down to the 8 x 8 m grid-cell size (due to analytical constraints). Depth and near-bottom current did not vary notably at fine-scales, but instead represented broader-scale spatial gradients important in predicting bryzoan mound distributions over large scales. Consequently, averaged values for depth and currents at the 8 x 8 m scale would unlikely have much of an effect on model precision across these finer-scale bryo-reef zones (i.e., QCS entrance). In contrast, averaging rugosity and seafloor classification (SC) may have in effect cancelled out (i.e., homogenised) any fine-scale variability in these two variables - by simply averaging low SC and rugosity values associated with the matrix of sandy muds, with higher SC and hardness values associated with the high-reflectivity bryozoan reefs. These averaged values in combination with the other modelled variables have still successfully distinguished this region as having moderate-high probability of bryozoan patch-reef occurrence and abundance compared to habitats further south or out in Cook Strait, but has not successfully predicted the finer-scale patchiness of these habitats or the likely boundaries of these patch reef areas. However, these finer-scale boundaries are captured in the hand-drawn ArcGIS bryo-reef zone polygons in Figure 3-15. As a result, we would recommend that the combination of large scale modelling and the hand-drawn reef polygons be used to inform management decisions.

4.3 Recommendations for future research

4.3.1 *Galeolaria* mounds

The predicted distributions of 'intact' mounds and 'intact and damaged' *Galeolaria* mounds accurately predicted both the broad-scale distributions and fine-scale boundaries relative to observed distributions of *Galeolaria* mound fields. However, these models also predicted intact and damaged *Galeolaria* mounds in other sites that have not yet been surveyed (i.e., non-verified). The next step would be to verify these newly predicted sites and determine whether boundaries between *Galeolaria* mounds and adjacent non-mound habitats are accurate, with new ground-truthing observational data, particularly those unverified sites predicted to have higher % cover over larger localised areas. Any new observations should also identify the % cover of intact versus damaged *Galeolaria* mounds. Any new observational data could then in turn be used to improve the precision of these models.

4.3.2 Bryozoan mounds

In the current HS models, an 8 x 8 m cell-grid size (25 million cells) for each continuous environmental dataset was used, as the original 2 x 2 m resolution (650 million cells) were computationally too large to analyse for the entire survey area. Although the 8 x 8 m models accurately predicted both the broad and fine-scale *Galeolaria* mound distributions and the broad scale bryozoan distributions, it did not accurately delineate the finer-scale boundaries of 'bryo-reef zones' (i.e., as compared with the 'drawn bryo-reef zone polygons' and observed bryozoans).

In order to improve the fine-scale predictive success of the bryozoan HS models, we would recommend that fine-scale modelling be undertaken on the full data density (original 2 x 2 m cell-grid size) over a much smaller spatial area, specifically targeting the bryo-reef zones around entrance to QCS (i.e., the area immediately north of Long Island out to the boundary to Cook Strait). This higher resolution information over a small areas would still need to be balanced to ensure the overall cell size of the model was no larger than approx. 25 million grid-cells (approx. analytical upper limit).

4.3.3 Other taxa

The development of these models now paves the way to predictively map the distributions of other benthic taxa across the HS51 survey area. With the pre-requisite that 1) there is adequate observational data available for that taxon/group (e.g. as described in Anderson et al. 2020b), and 2) that there is some likely/expected association with the continuous environmental variables available to the model).

4.3.4 Broader-scales

These existing models can be applied to other Marlborough Sounds areas. As new continuous-cover environmental layers (e.g. from new multibeam echo-sounder [MBES] surveys) become available for other areas across the Marlborough Sounds (e.g. the newly planned MBES mapping of the Pelorus Sounds, Outer Sounds, and D'Urville Is.), these HS models (trained on the HS51 survey area) could be used to predict *Galeolaria* and bryozoan mound distributions out across these other regions beyond QCS. However, this would require the same suite of continuous-cover variables (e.g. bathymetry, backscatter, sediment composition, currents (NB: near-bottom current speed already exist: Broekhuizen et al. 2015) to be available for the extended regions. Predicted distributions for these other regions, could then be validated using NIWA's existing broad-scale tow-video survey observations for those regions (along with any new observational data). These additional observational data could subsequently be used to fine-tune the HS models performances for improved precision across the broader Marlborough Sounds management region.

5 Acknowledgements

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