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Tini a Tangaroa

Paua biomass estimates and population monitoring in areas affected by the November 2016 Kaikoura earthquake

New Zealand Fisheries Assessment Report 2018/54

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ISSN 1179-5352 (online)
ISBN 978-1-98-857129-4 (online)

November 2018

New Zealand Government

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EXECUTIVE SUMMARY

McCowan, T.A; Neubauer, P. (2018). Paua biomass estimates and population monitoring in areas affected by the November 2016 Kaikoura earthquake.

***New Zealand Fisheries Assessment Report 2018/54.* 24 p.**

The November 2016 Kaikoura earthquake caused extensive coastal uplift resulting in massive paua (*Haliotis iris*) mortality and loss of critical paua habitats. An immediate fisheries management response was the closure of the paua fishery across the uplifted area. The closed area spans portions of two paua quota management areas, the southern aspect of PAU 7 (Marlborough) and the northern aspect of PAU 3 (Kaikoura). The closed area historically accounted for approximately 60 t of annual commercial catch, and supports significant customary and recreational paua fisheries. The objective of this project was to estimate paua abundance and monitor paua populations in the earthquake-affected area to inform management decisions relating to the re-opening of the paua fishery. To estimate abundance, we developed novel methodologies using GPS dive loggers and underwater electronic callipers. We also established fixed monitoring points within surveyed areas to monitor discrete paua populations through time.

To allocate sampling effort, we devised a stratification scheme based on GPS dive logger data from the fishery. This allowed us to place sampling effort in areas that are relevant for the fishery. Our new survey method combined estimation of survey area from GPS units worn by pāua divers (turtle loggers) with estimates from a Bayesian model for the survey that integrates estimates of pāua detection probability. The integrated model allowed us to estimate pāua density with reasonable confidence. Uncertainty was relatively high (i.e., CVs were elevated) due to high within-stratum variance in pāua densities, as well as due to a thorough treatment of parameter uncertainty. Highest densities were found in the closed area of PAU 3, especially in areas of high and medium fishery use. Pāua densities were relatively uniform in PAU 7, which had lower densities over-all than areas in PAU 3.

We found that scaling density estimates to total biomass or abundance was difficult due to the lack of robust estimates of habitat area for pāua. In the absence of a defensible solution, we opted to calculate density only, and suggest that this quantity could be used to monitor change in the local pāua population. However, how useful the current survey and potential subsequent follow-up surveys will be to inform management will depend on the over-all science and management framework for the re-opening of the fishery.

1. INTRODUCTION

The Kaikoura earthquake of November 2016 caused significant coastal uplift of up to 6 m along approximately 100 km of the Kaikoura and southern Marlborough coastline. The uplift caused massive mortality in a range of sub-tidal and intertidal organisms that were exposed above the tide line. One of the most obvious casualties was paua (*Haliotis iris*), which suffered massive mortality over a range of critical life stages, as well as a loss of critical intertidal and sub-tidal habitats. As broadcast spawners, pāua rely on coralline algae covered boulders in less than 2 m depth for settlement and as habitat for the first few years of the pāua life cycle (McShane & Naylor, 1995). These depths are well within the range of what was uplifted along most of the coastline. A preliminary assessment of the loss to the pāua fishery estimated that 21% of previous fished areas (by biomass) were potentially lost as a result of the uplift (Neubauer, 2017). These observations and findings have caused great concern for the future of the pāua fishery in this region and resulted in the emergency closure under section 16 of the Fisheries Act, to pāua fishing in the area from Cape Campbell in the north to the Conway River in the South herewith known as 'the Closed Area'. This closure currently remains in force under section 11 of the Act.

The pāua fishery in the closed area is iconic to the region. It is one of the most accessible recreational pāua fisheries in the country, and is of customary significance with several mātaitai and taiāpure reserves. Commercially, the closed area spans two pāua quota management areas (QMAs), PAU 7 (Marlborough) and PAU 3 (Kaikoura-Canterbury). This area accounted for 15 t of annual commercial catch from PAU 7 and 47 t from PAU 3 (approximately 16% and 50% of the respective QMA's commercial catch). Following the closure, industry shelved approximately 50% of their annual catch entitlement (ACE) in PAU 3 (to prevent spread of effort into open areas). This shelving has been subsequently formalised by a 50% reduction in the TACC. In PAU 7 the industry shelved 12% of their (ACE) after the closure and this shelving is ongoing. These commercial catch reductions account for approximately $3 million in lost revenue from the paua fishery.

Following the emergency closure of the fishery the Ministry for Primary Industries (now Fisheries New Zealand) announced funding for a Kaikoura earthquake marine science package, to assess the ecological impact of the earthquake in order to inform future management options and allow for the recovery of biota and habitats in the region. Pāua were included as part of this research-funding package under two projects focusing on (1) recruitment (University of Canterbury) and (2) adult (spawning) biomass (Pāua Industry Council Ltd.).

The overall objective of this project is to complete stock monitoring surveys of the adult pāua population in order to inform management decisions at the scale of both the Kaikoura fisheries closure and the PAU 3 areas, with the specific objective being to monitor the abundance of adult paua populations to estimate biomass trends to inform management actions at the scale of the fishery closure area and at the scale of the PAU 3 area until mid-2018.

2. METHODS

We developed a novel stratification procedure and survey design in order to address shortcomings that have been identified in previous paua abundance/biomass survey designs (Cordue, 2009; Haist, (2010)). These surveys were based on timed swims, but subsequent simulation studies found that the relationship between timed swims and abundance may not be clear given the potential change in area surveyed between sites and surveys. Our new method was based on pāua dive-logger information that has been voluntarily collected by a subset of industry divers in both QMAs. We employed these devices to map the survey area and sampling intensity, in an effort to estimate pāua density in the closed area.

2.1 Site selection

Site selection was based on a data-driven stratification in order to assign only areas relevant to the fishery to survey strata. We then allocated sites within the identified fishery strata.

2.1.1 Stratification procedure

Survey sites were selected from within areas of high, medium and low fishery utilisation strata. The procedure for generating these strata relies on the assumption that commercial divers will, over time, harvest from available pāua habitat along the coast, and that the fishing intensity approximately reflects habitat quality and therefore pāua production.

Stratification was undertaken using all available data logger data from 2013–2016 from the Closed Area to calculate a utilisation density using two dimensional kernel-based smoothing of all available dive locations (Figure 1). The utilisation density was then intersected with the coastline to produce a 1D map of utilisation (Figure 2). The utilisation density was cut (within each QMA) at cumulative probability levels of 5–20% (low use), 20–80% (medium use), and 80–100% (high use), to define strata to frame sample allocation.

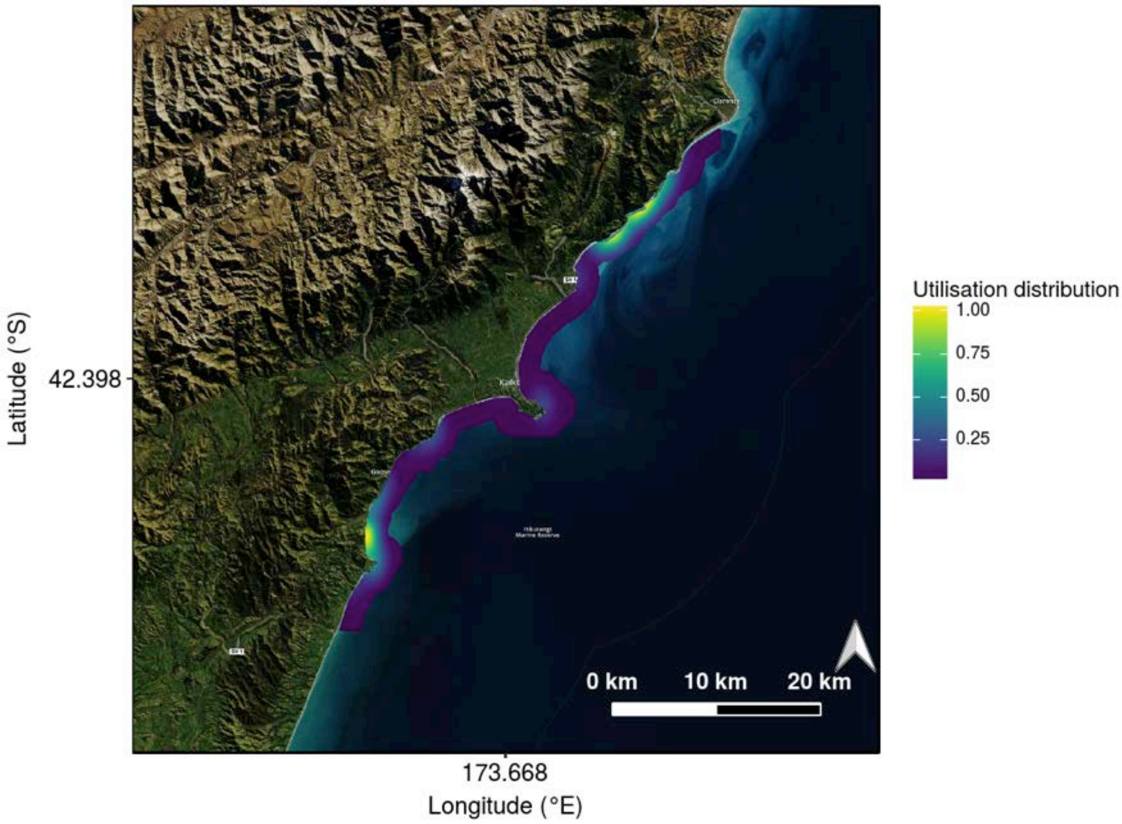


Figure 1: Estimated utilisation distribution in the closed area of PAU 3, estimated from available diver-logger data from the commercial pāua fishery from 2013–2016.

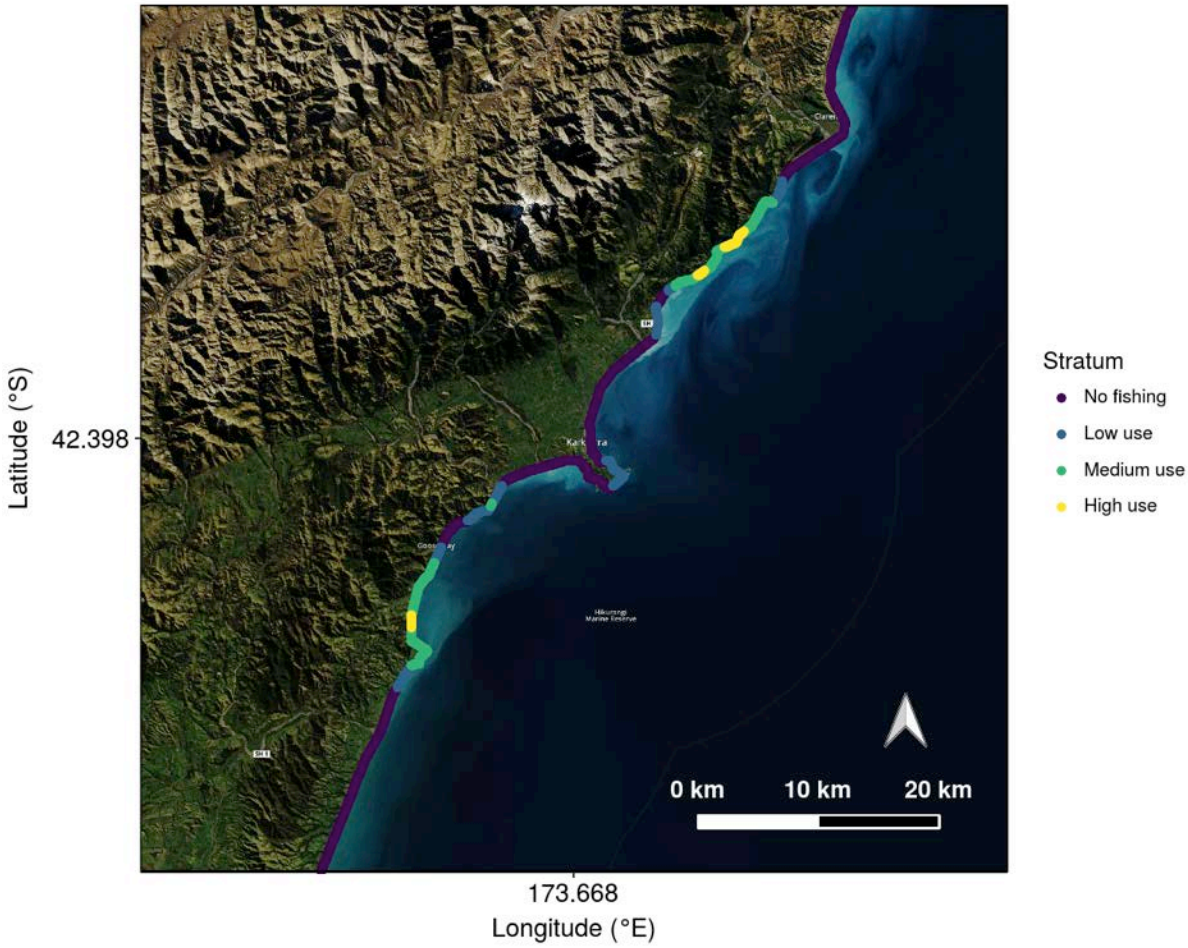


Figure 2: Extracted fishery use strata, established from the utilisation density in Figure 1 by intersecting the density with the coastline to produce a 1d line, and then dividing the cumulative 1-dimensional use distribution into inter-quantile ranges as described in the text.

2.1.2 Assigning sampling points

A predetermined number of sampling points were allocated in each stratum, with most samples allocated to high and medium use strata (Figure 3, Appendix 1). The number of sites was based on a realistic number of sites that could be surveyed over one season, equating to approximately 30 dive days. To be aligned with intertidal and juvenile pāua surveys being conducted by University of Canterbury, three sites (one in PAU 7 and two in PAU 3) were fixed. "Fall-back" sites were also selected to give a sampling option when the "primary site" could not be surveyed due to poor weather or visibility conditions (generally if visibility was under 1 m, or swell was over 1 m). Additional sites from initial pilot studies that trialled potential methodologies were also incorporated (Figure 3, Appendix 2). Based on the above criteria, we allocated a total of 36 sites, with 12 primary sites in PAU 3 and 6 primary sites in PAU 7, and an equivalent number of fall-back sites.

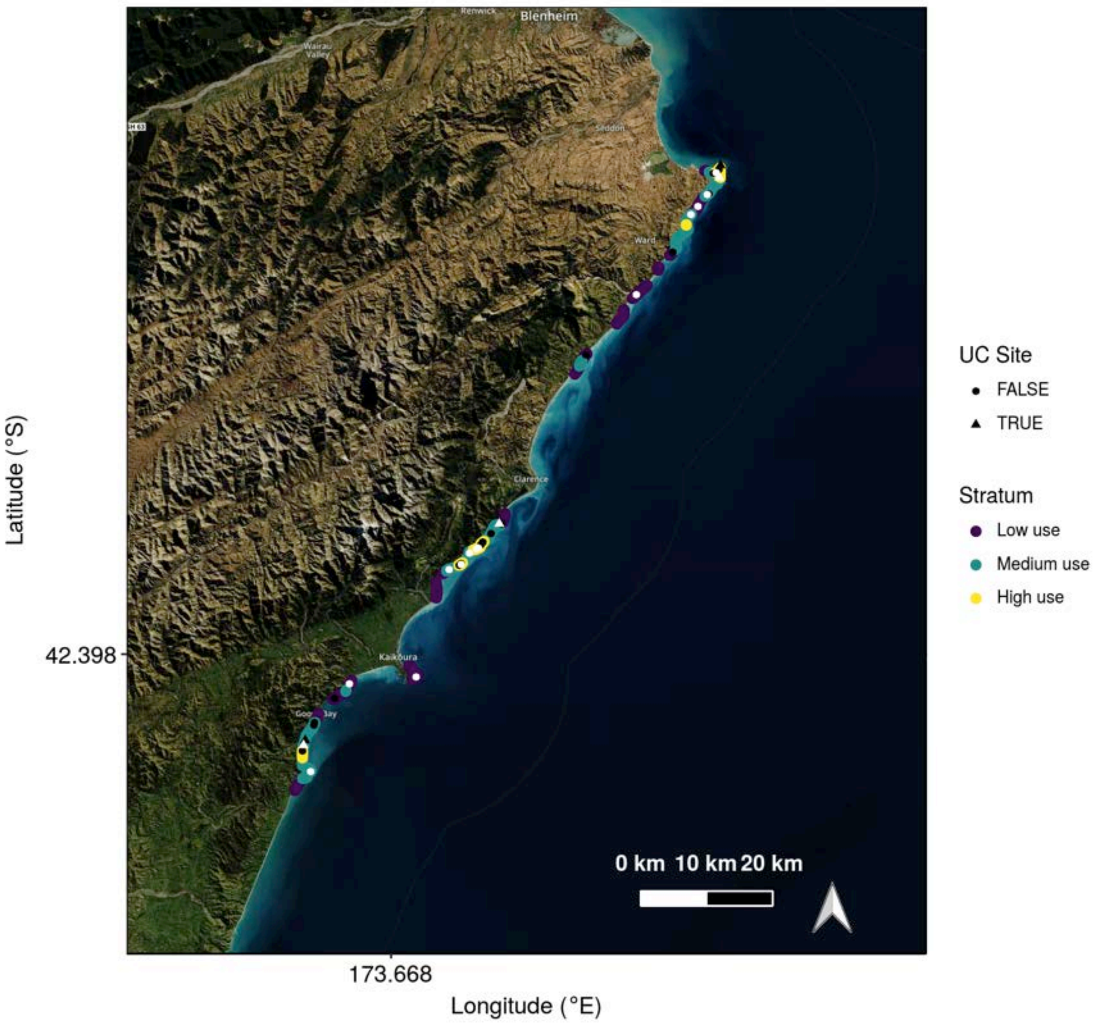


Figure 3: Selected sites (black) as well as fall-back points (white) for the Kaikoura pāua survey, in relation to fishery use strata. Note that many first-choice sites are nearly co-located with fall-back sites and therefore difficult to see. UC sites are those that were fixed to coincide with University of Canterbury sites for juvenile monitoring.

2.2 Sampling procedure

Surveys were conducted by a crew of three snorkel divers, who all had commercial pāua diving experience. As much as possible, we aimed to utilise the same dive crews within each QMA to ensure consistency. At each sampling point, an area of approximately 100 m was haphazardly delimited using float-lines or obvious geographical boundaries. These boundaries were set by the PIC scientist or another neutral advisor so prior knowledge about areas of high or low pāua abundance could not be used by survey divers to bias the selection of the survey area. Each area was roughly subdivided into three smaller areas and allocated to each diver to survey. All divers wore GPS dive loggers ('turtle units') during the surveys. Divers would swim and search as if they were actively looking for pāua for approximately 45 minutes. The divers measured and logged every pāua seen using underwater electronic callipers (Appendix 5, photograph 1). Measured pāua were marked with a yellow crayon so they would not be re-measured by any other diver.

At the end of the initial survey, divers were instructed to "zero" their callipers (close calliper to 0 mm and make several logs to indicate the end of, or change in survey event), and then the divers were asked to revisit the area they had just surveyed in order to measure and log pāua that were missed (with no yellow crayon mark) in the initial dive. This re-survey data was used to estimate detection probability required for density estimates.

During each survey event, estimates for visibility (m), swell (m), and codes for substrate type, weed coverage and ‘cryptic rating’ (a general rating for how difficult it was to find pāua) were recorded.

2.3 Establishment of monitoring points

Where possible within each sampling point, up to three discrete pāua aggregations were marked as monitoring points. The approximate centre of the aggregation was marked using approximately 60 cm of rebar with a yellow cattle ear-tag attached driven into the substrate (Photograph 1 and 2A, Appendix 5). At each point every pāua within a 5 m radius of the centre of the aggregation was measured as a reference for length frequency for ongoing monitoring.

2.4 Data analysis

Survey data was aggregated from two data formats: dive location data, including time-stamps from the turtle dive-loggers, as well as length, depth and time stamp from the electronic calliper measurements. These datasets were merged into a final dataset for analysis as follows:

- Calliper measurements that coincided with time-stamp and surface GPS point from the turtle loggers were assigned to that position.
- Calliper measurements that occurred between recorded surface GPS positions (i.e., measurements occurred while diving between two GPS positions) were assigned a linearly interpolated position.
- The turtle logger GPS sometimes does not record GPS positions for some period of time, presumably due to insufficient surface intervals. If such an interval without GPS positions was longer than 5 min, data from that site and diver was discarded to minimise error from interpolated measurement positions.

The resulting dataset contains a row for each recorded pāua with GPS location, length, depth information as well as site-specific meta-data (visibility, swell, and habitat information).

A key feature of surveying potentially cryptic species such as pāua (but also birds, insects etc) is that at any given time, one might only count a subset of the actual population that resides within the allocated survey area. In that case, the true underlying abundance remains un-observed, and only a subset $N_{OBS} = pN$ of the N true individuals will be measured, with p the proportion of the true abundance counted. This data generating process can be modelled using a binomial distribution for observed counts, and a Poisson distribution for the latent (unobserved) true abundance.

The proportion of the true abundance that is generally observed can naturally vary with a number of factors, such as visibility and, the habitat type (e.g., amount of seaweed cover, or more generally habitat complexity). To estimate p, we require repeated surveys of the same area that allow us to quantify the proportion of pāua that were missed at each survey. This was achieved at most sites by a repeated swim of the area immediately following the initial survey (henceforth called a revisit, as opposed to a re-survey, which we define as a repeat survey on a different day).

The GPS tracks from the divers were then used to assess the number of pāua surveyed during the initial survey, and those surveyed in overlapping areas (i.e., in areas surveyed for both the initial survey as well as the second “revisit”; Figure 4). To define the polygon for each survey (initial and revisit), we fit a movement model to each time-series of GPS points using the ctmm R package (CITE). The package contains functionality to choose a parsimonious movement model from a suite of continuous-time movement models, and to estimate a utilisation density in space from the chosen model. In our case, a model was chosen for each path (i.e., each site, diver and survey/revisit combination). The utilisation density was then estimated using identical integration grids in space, with a 5-metre grid chosen as a compromise between computing requirements and precision. From the utilisation distributions, we estimated the 95% occurrence polygon in space (Figure 5), and used this to define the area for each path, as well as the overlap between the initial survey and the revisit.

With overlapping areas and pāua counts for each of the initial surveys and revisits at hand, we estimated the detection probability using $p_v=1-(1-p)^v$, where v is the number of visits (i.e., 1 for the initial survey, and 2 for the revisit). This amounts to assuming that pāua counts will asymptotically approach the true number of pāua in the surveyed area with an increasing number of revisits. In practice, we only needed a single revisit to estimate p and influences on covariates on p.

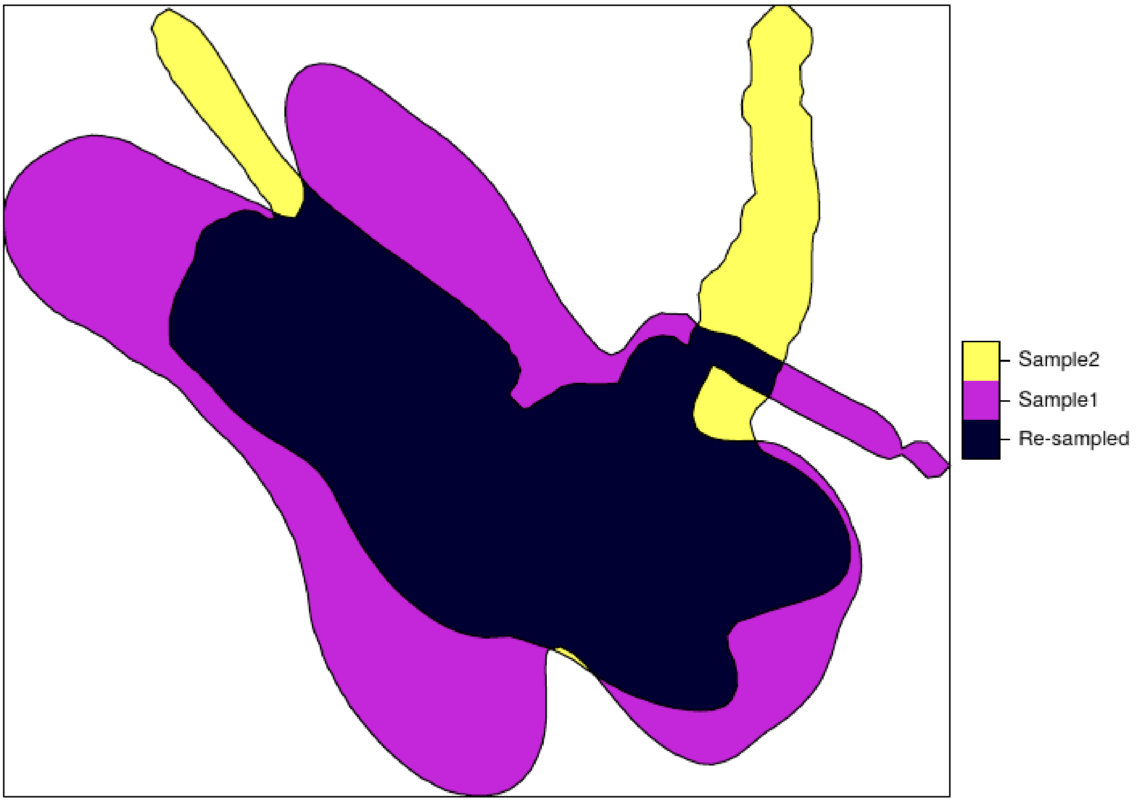


Figure 4: Schematic showing initial survey (Sample 1, pink) and revisit (Sample 2, yellow), with the overlapping area that was sampled twice shown in dark blue.

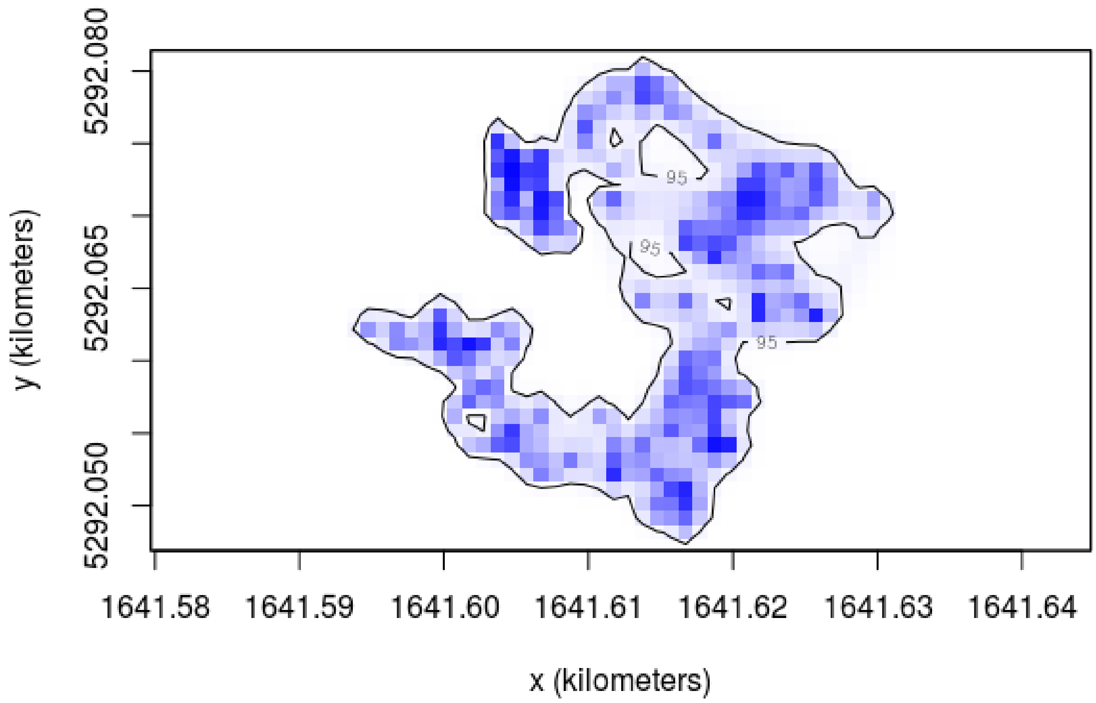


Figure 5: Estimated utilisation distribution for a single survey and diver, with the sampling intensity shown in blue on the integration grid.

Given that at each site, a non-standardised area was surveyed, we estimated an underlying density that determines N given the area surveyed as $N_{s,v}=\lambda_s A_{s,v}$, where λ_s is the density of pāua at site s, and $A_{s,v}$ is the surveyed area during visit v. We related the (log) density at each site to a stratum mean density μ_η, as well as a site random effect ν_s that captures variability among sites that is not captured at higher levels of the model (i.e., the binomial (B) or Poisson (P) models). The full model is then:

$$N_{OBS,s,\eta,v,d} \sim B\left(p_{s,v}, N_{s,\eta,d,v}\right)$$
$$N_{s,\eta,d,v} \sim P\left(\lambda_{s,\eta} \cdot A_{s,v}\right)$$
$$log\left(\lambda_{s,\eta}\right) = \mu_\eta + \nu_s$$
$$\nu_s \sim N(0, \sigma_s^2)$$
$$\mu_\eta \sim N\left(\mu, \sigma_\eta^2\right)$$
$$p_{s,v} = 1 - (1-p)^v$$
$$logit(p_s) = \tau + \beta \cdot X,$$

with τ the mean detection probability and β is a vector of regression coefficients that quantifies the impact of visibility, cryptic rating and depth of the logit of the detection probability.. However, we found that estimating a total area within each stratum is very sensitive to the definition of the area. For example, an initial attempt to estimate the area from the utilisation distribution used for stratification yielded results that were very strongly dependent on the smoothing length parameter of the smoothing kernel (here a bi-variate normal distribution). A short smoothing length (small variance of the kernel) yields a distribution that closely approximates available data-logger data, but ignores the potential of habitat beyond recorded positions. On the other hand, a large variance often includes areas that are not pāua habitat as the utilisation is smoothed across habitat types (e.g., beaches, deep areas). In the absence of a suitable solution to this problem (e.g., an independent habitat map), we refrained from extrapolating densities to total biomass.

3. RESULTS

3.1 General survey outcomes

Due to favourable diving conditions and efficient surveying times, more sites were surveyed than anticipated (both primary and fall-back). In PAU 3, 10 primary sites and 10 fall-back sites were sampled. In PAU 7, 3 primary sites and 5 fall-back sites were sampled. Further, due to access and logistical constraints in some remote sites, additional sites were surveyed haphazardly when crews were in an area where it was not possible to access sites further afield that day.

Our method of merging electronic calliper data with turtle-logger position data worked well when GPS information was accurately collected by the units, and did not contain major gaps in the GPS positions. However, in 40% of dive tracks (42 out of 104), gaps of more than 5 minutes prevented us from using the data for anything but descriptive statistics based on calliper data and/or "time in water" measures of survey effort (Figure 6,7).

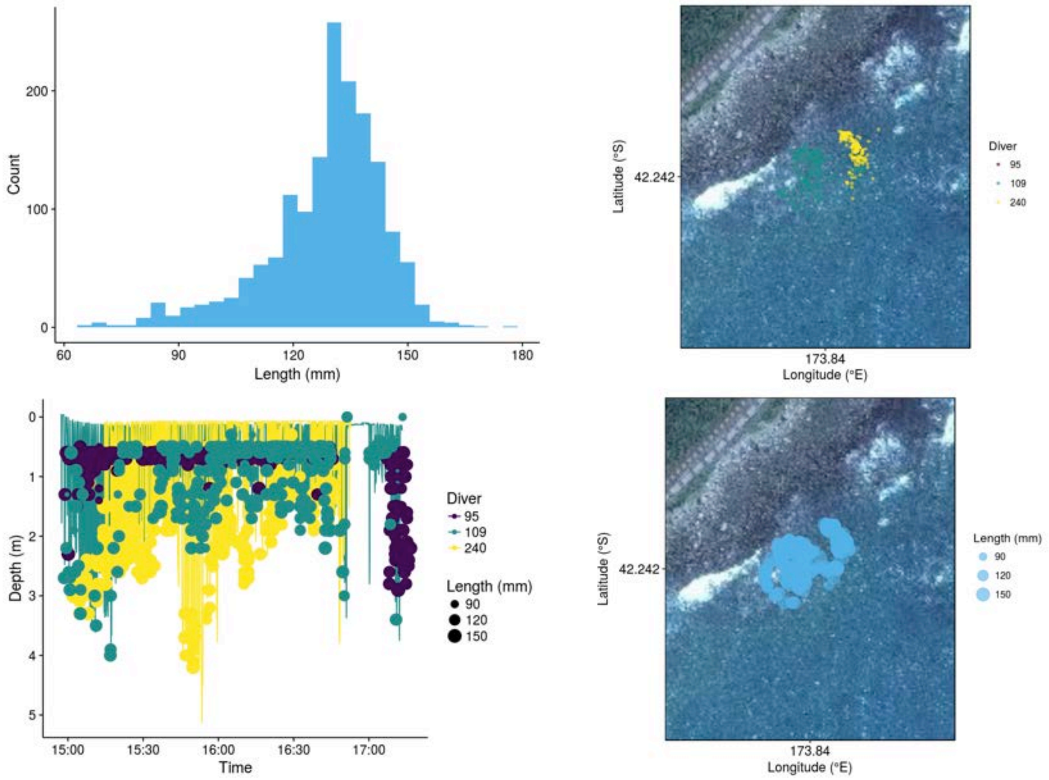


Figure 6: Example of survey data from a single site with high pāua density. Measured lengths (top left), GPS recorded positions (top right), depth profile from turtle-logger (lines) and measurement depths from callipers (points; bottom left), and assigned locations of pāua measurements by combining GPS data with calliper measurements. Note that there are no recorded GPS positions for the diver with turtle-logger number 95.

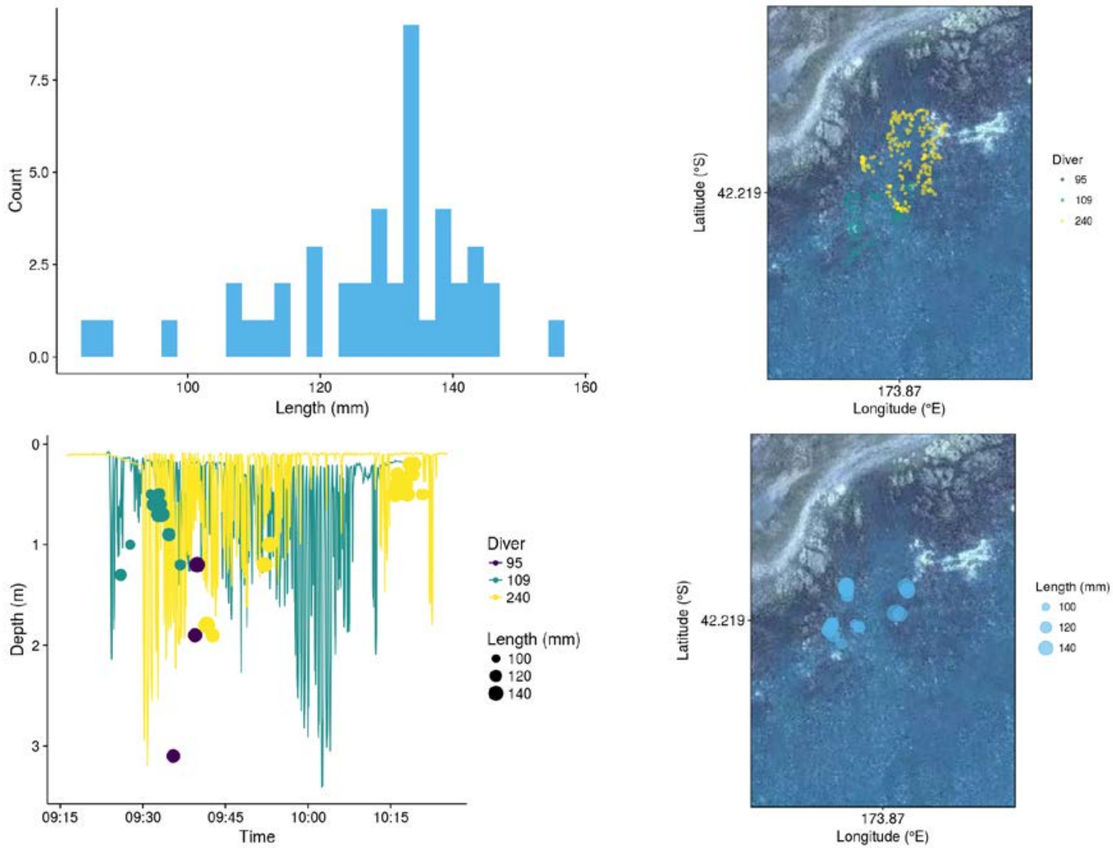


Figure 7: Example of survey data from a single site with low pāua density. Measured lengths (top left), GPS recorded positions (top right), depth profile from turtle-logger (lines) and measurement depths from callipers (points; bottom left), and assigned locations of pāua measurements by combining GPS data with calliper measurements. Note that there are no recorded GPS positions for the diver with turtle-logger number 95.

3.2 Descriptive statistics

Pāua were mostly found in aggregations, preferentially in shallow water (Figures 8,9). This was not just the case for small pāua but also for large individuals (i.e., above 120 mm), although smaller individuals (below 100 mm) showed a strongly decreasing trend with depth.

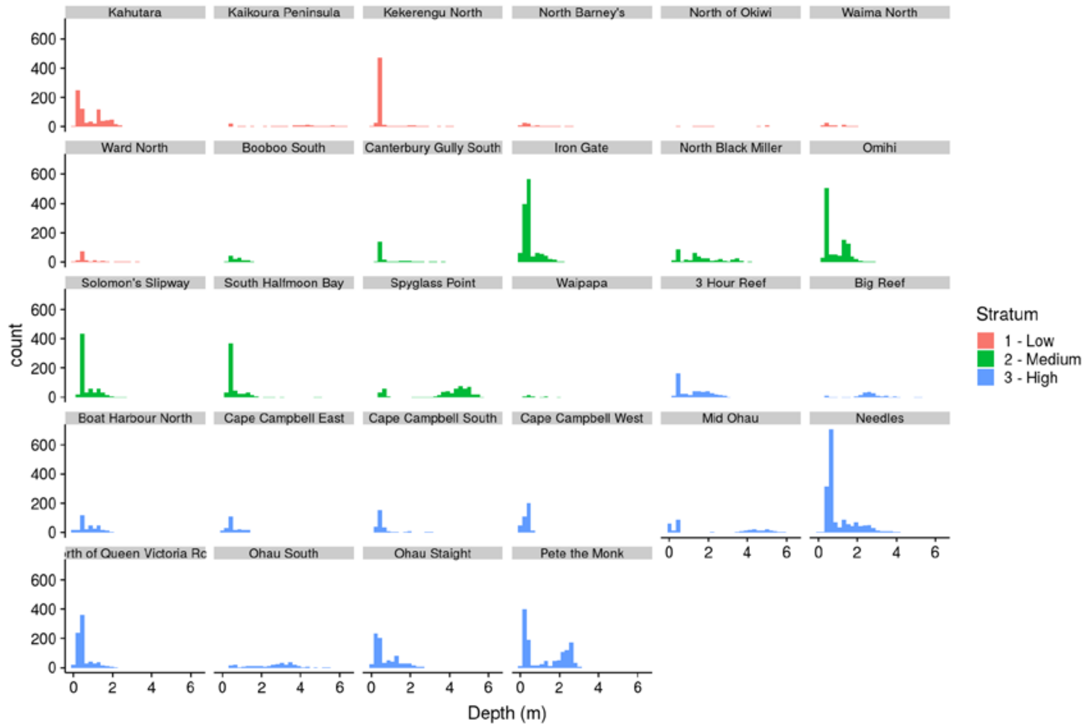


Figure 8: Number of pāua measured as a function of depth at each site, with sites ordered by stratum (low, medium and high-use areas).

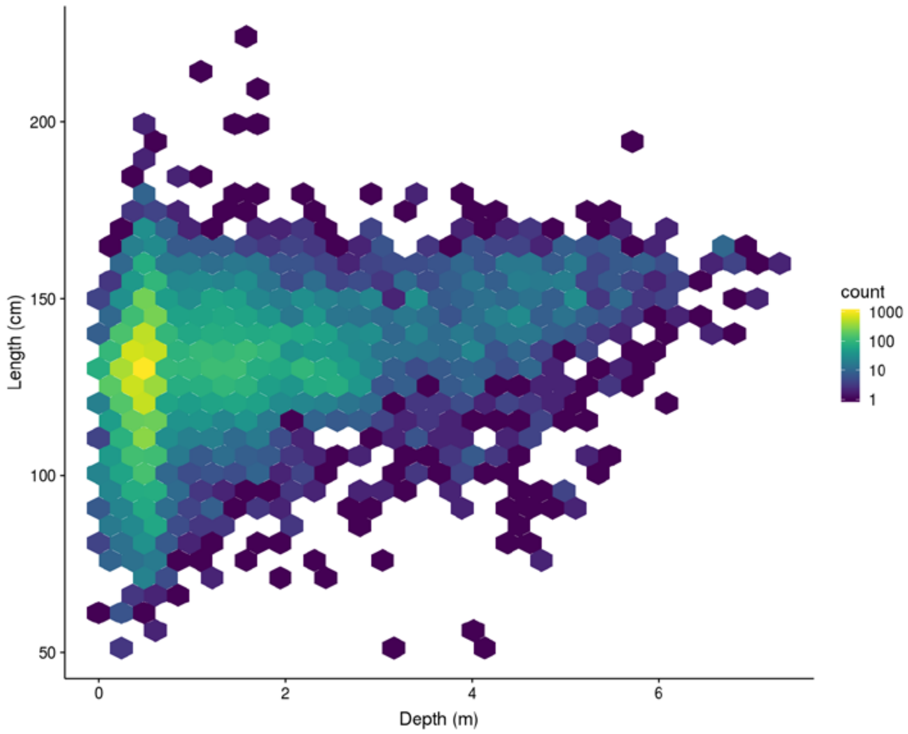


Figure 9: Pāua length binned and plotted against measurement depth, with colour indicating the number of pāua within each hexagonal bin.

Although high count rates were preferentially observed in high use strata, they also occurred in low-use strata (Figure 10). However, at most low-use strata, densities were substantially and consistently lower than at sites in medium or high-use strata. In all strata there was substantial within and among site variability in numbers of pāua counted per unit time.

In contrast to variability in number surveyed per hour, pāua length distributions were far more consistent among high-use stratum sites compared to low use stratum sites (Figure 11), with sites in intermediate use strata showing intermediate variability.

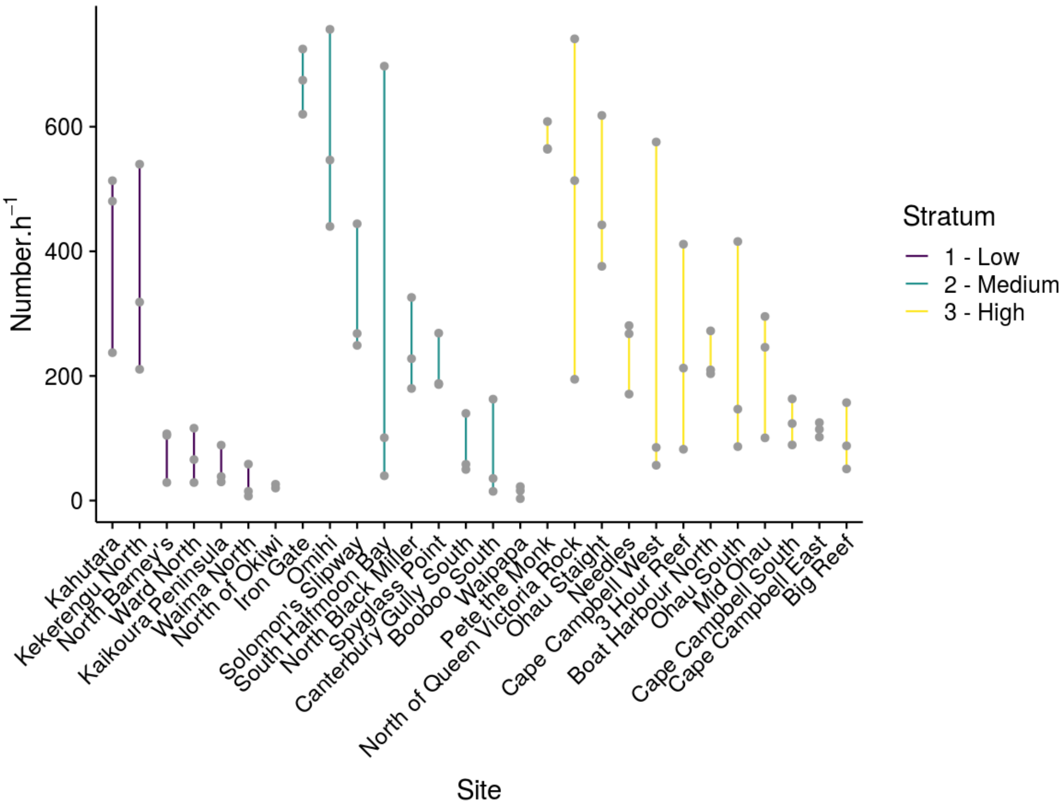


Figure 10: Numbers of pāua counted per hour at each site, with points indicating results from individual divers, and lines showing the range. Colour indicates the survey stratum.

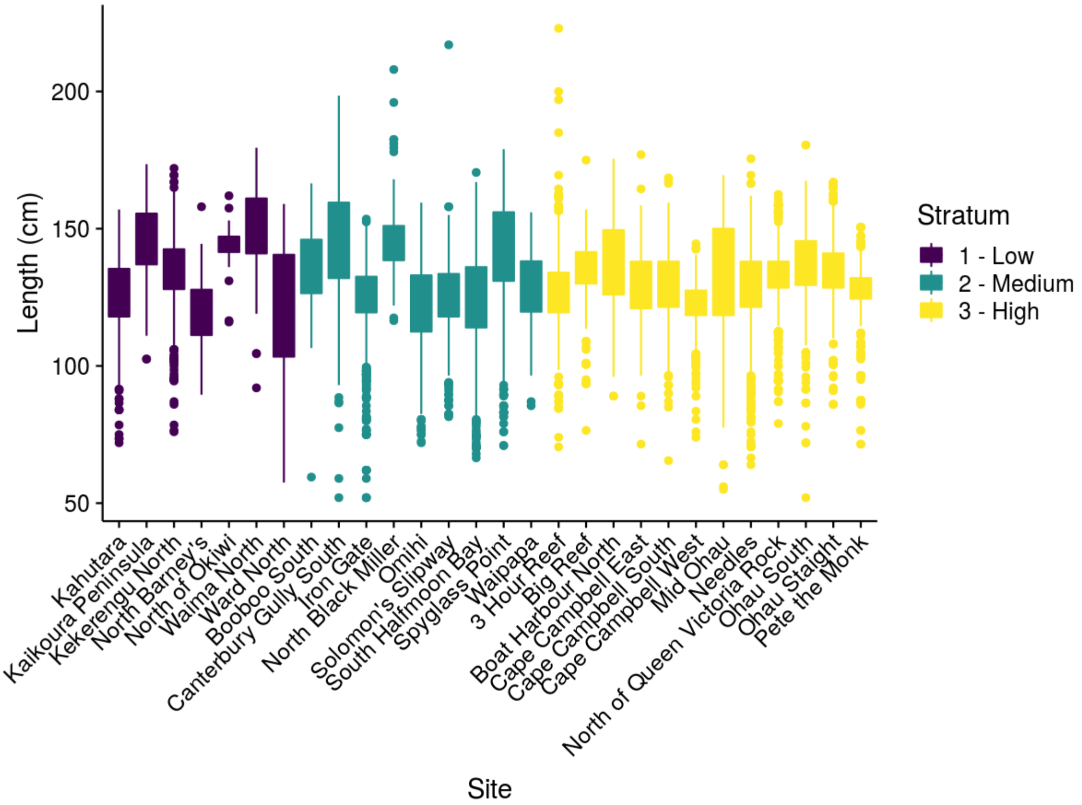


Figure 11: Boxplot of pāua length distributions found at survey sites. Colour indicates the survey stratum.

3.3 Data modelling and density estimates

The survey model produced qualitatively good fits to data (Figure 12), and showed that detection probability could be estimated within the model from the repeat visit survey design. Mean detection probability was estimated at around 0.75 at average co-variate conditions (Figure 13). More cryptic habitat led to lower detection probability, whereas most pāua are missed in shallow areas according to the positive effect of depth on detection probability (Figure 13). Visibility had surprisingly no detectable effect on detection probability.

Estimated pāua density varied from a mean of 0.028 pāua per m^2 (geometric mean; 95% confidence interval (CI) [0.009; 0.08]) in PAU 7, to a high of 0.11 per m^2 (CI [0.049; 0.27]) in PAU 3 (Figure 15). In PAU 7, the high use stratum had the highest densities, with low densities found in both the medium use and low use strata. Over-all, densities estimated for PAU 7 were substantially lower than those estimated for PAU 3, where the medium use stratum had the highest mean densities. Estimated geometric CVs are relatively high (between 48.5 and 76.7%), reflecting considerable variability in densities among sites within strata. The over-all mean density μ is estimated at 0.052 pāua per m^2 (CI [0.028; 0.103]), with a geometric CV of 0.400 and an arithmetic CV of 0.345.

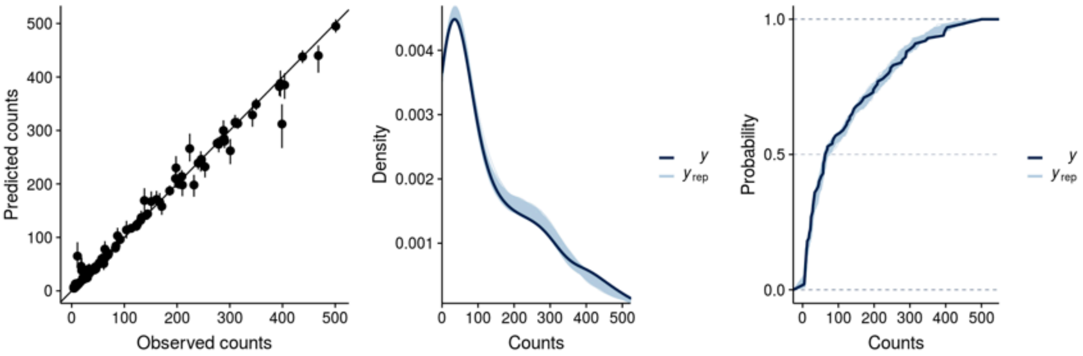


Figure 12: Comparisons between observed data and the posterior predictive distribution for observations. The left panel compares observed data and predictions for individual data points (counts), the middle panel compares the empirical density for the observed data with the predicted densities from individual MCMC draws, showing that the latter encompass the observed density, the right panel shows the same but plotted as cumulative probabilities.

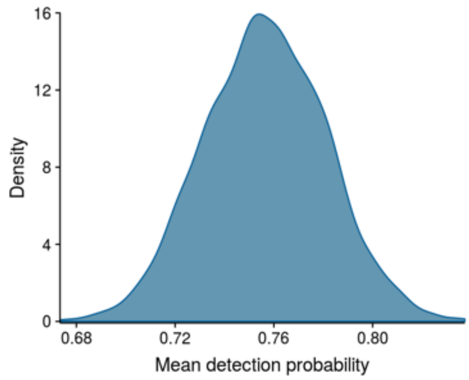


Figure 13: Posterior distribution for the mean detection probability, estimated a mean depth, 2.5 m visibility and a cryptic rating of 4.5 out of 10.

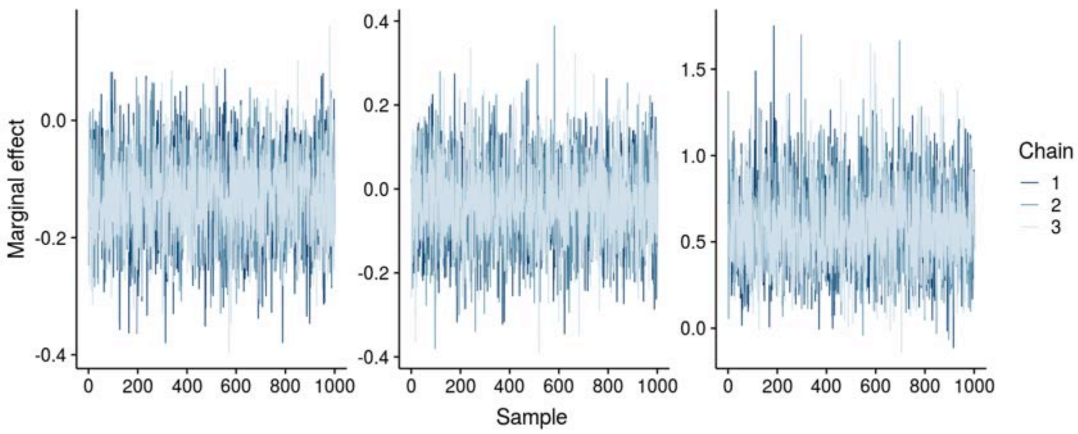


Figure 14: Markov chain trace-plots for MCMC samples for the vector of regression coefficients determining the effect of the cryptic habitat rating (left), visibility (middle) and depth (right) on detection probability.

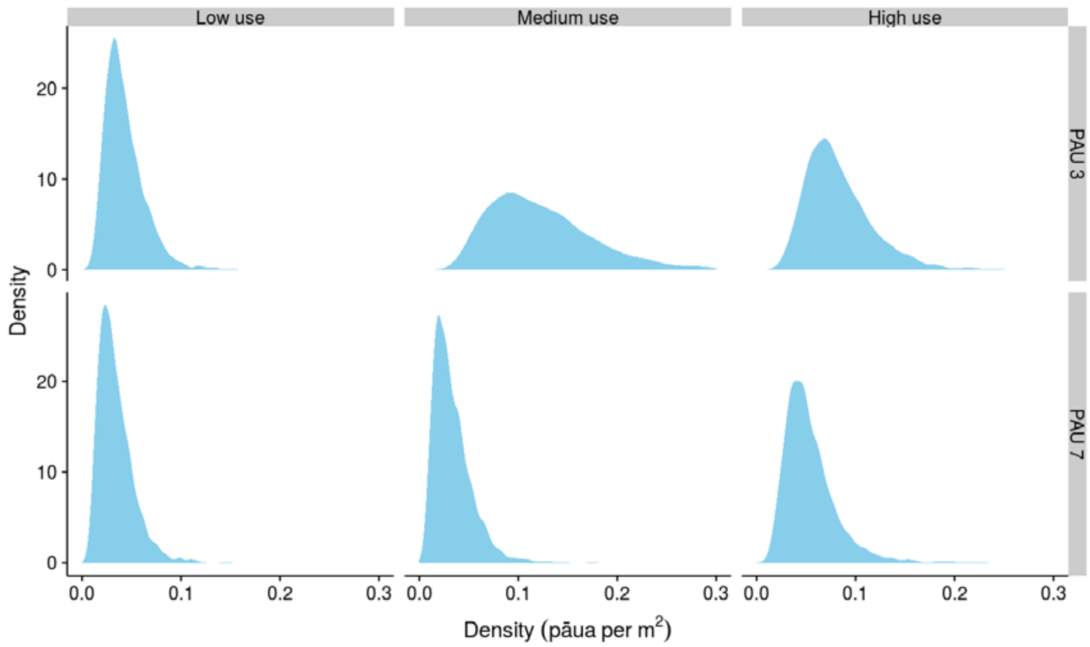


Figure 15: Estimated posterior distribution for pāua densities in low, medium and high use strata in PAU 3 and PAU 7.

3.4 Survey observations

During dive surveys high variability in paua abundance was observed across all sites surveyed. This variability could be attributed to the status of the fishery pre-earthquake, the amount of uplift, the shoreline gradient, and general 'patchiness' of paua distribution in relation to pre-determined sampling points.

The establishment of monitoring points allowed us to detect ongoing loss of habitat in some areas. For example one monitoring point near Queen Victoria Rock was completely covered with sediment during a six-month period over winter (see Photograph 2 in Appendix 5) and a site north of Paparoa Point was completely covered with fine sediment resulting from a large slip following Cyclone Gita.

We observed unusual behaviour from juvenile pāua (approximately 50 mm) near Ohau Point. In several locations we observed juvenile pāua in aggregations under boulders in habitat that is usually associated with larger emergent pāua (over 90 mm) (see Photograph 3 in Appendix 5). It is suspected that fine sediments from road works and slips may be filling in cryptic habitats in these areas forcing juveniles out into more exposed habitats.

3.5 Monitoring points

Eighty-three discrete monitoring points were established throughout survey sites. Within the time frames of this project, we were able to re-survey 30 of these points (Appendix 3). Length-frequency distributions of paua at different survey times for these points are displayed in Appendix 4. We observed relatively stable length-frequency distributions between survey times across many monitoring points (e.g., KAI17B), although some points showed notable decreases or a complete absence of paua on re-survey (e.g., KAI6A). This shows the potential utility of these monitoring points for monitoring the abundance of discrete populations through time.

4. DISCUSSION

The method developed here provides density estimates by directly quantifying the habitat surveyed from GPS loggers and relating this to an estimated abundance in the survey area. CVs may appear high compared to other, more traditionally used survey methods such as design-based estimators. The relatively high CV reflects both the variability in density that is evident among sites even within strata, as well as uncertainty estimated for all aspects of the survey. Therefore, our model-based method may provide a more reliable estimate of the true CV compared to design based methods which ignore some sources of uncertainty (e.g., uncertainty in selectivity, efficiency etc). Despite high CVs, meaningful changes in mean density trends should provide a picture of changing abundance in the closed area, and the temporal trends in mean density could help inform future management decisions for the fishery.

Density could be used as an indicator in empirical control rules or other management tools that could be used in guiding management of the pāua fishery in the closed area. However, it will be more difficult to integrate this measure with management based on more traditional fisheries advice tools, such as stock assessments. As this measure is only relative until it is scaled by some area to a total biomass, it only provides an index of relative abundance that will be difficult to scale to total biomass in a stock assessment in the absence of other information such as catch. However, since we also recorded size, future work could look at using density estimates (converted to kilograms) above the minimum legal size directly as an extension of the CPUE time series in a stock assessment, under the assumption that catchability does not change between fishing and survey activity. To the extent that experienced pāua divers conducted the survey work, this may indeed be a reasonable assumption. However, this possibility is highly speculative at this point.

Another possibility to integrate the current survey estimates with model-based advice, would be to scale density to total biomass. As explained above, we did not attempt this here as we deemed measures of habitat area that we could come up with as arbitrary and unverifiable. However, it may be possible to determine habitat area using other methods than the ones trialled here (i.e., from turtle-logger data). One such method may be using drone footage with suitable sensors/cameras in conjunction with automated habitat classification (e.g., https://vimeo.com/278990869). This would allow extrapolation of density to biomass, and direct comparison with stock-assessment estimates, and estimation of suitable catch limits given management objectives.

The main limitation of our approach is currently the sporadic failure to obtain GPS data from the turtle loggers, which renders a large portion of the data useless for density estimation. We recommend that future surveys include a pilot survey to better understand the GPS problems and mitigate these if possible (e.g., by introducing a mandatory surface time between dives to allow the GPS module to acquire position data). Improved GPS positioning could greatly improve the cost-effectiveness of the survey method, and decrease CVs by having more useable data.

5. MANAGEMENT IMPLICATIONS

The survey presented here provides a snapshot of pāua density in the closed area of the Kaikoura region pāua fishery. On its own, this survey will be difficult to use to inform management decisions, unless it is scaled to total biomass in a meaningful way. However, by repeating the survey, it may be possible to track changes in the local pāua population.

6. ACKNOWLEDGMENTS

This project was funded by Fisheries New Zealand project KAI2016-07. We acknowledge Fisheries New Zealand, and in particular Rich Ford for support during this project. We thank Tim McLeod, Pat Reid, Barry Chandler, Shayne Cuff, Phil Richardson and Jason Ruawai for their services during dive surveys. In particular we acknowledge the logistical and boat support of Tim McLeod, Phil Richardson and Jason Ruawai. We acknowledge Reyn Naylor (NIWA) for his advisory role in this project. We thank David Schiel and members of the University of Canterbury Marine Ecology Lab and Robyn Dunmore (Cawthron Institute) for their collaboration with aligning sites for surveys across various projects. We also thank North Canterbury Transport Infrastructure Recovery (NCTIR) for allowing site access and for providing health and saftey support during surveys.

7. REFERENCES

Cordue, P.L. (2009). Analysis of PAU5A dive survey data and PCELR catch and effort data. Working document for Ministry of Fisheries Shellfish Fishery Assessment Working Group 2009/65. 44 p. (Unpublished report held by Fisheries New Zealand.)

Haist, V. (2010). Paua research diver survey: review of data collected and simulation study of survey method. *New Zealand Fisheries Assessment Report 2010/38*.

McShane P.E.; Naylor, J.R. (1995). Small-scale spatial variation in growth, size at maturity, and yield- and egg-per recruit relations in the New Zealand abalone *Haliotis iris*. *New Zealand Journal of Marine and Freshwater Research 29 (4)*: 603–612.

Neubauer, P. (2017). Area lost to the paua fishery from the November 2016 Kaikoura earthquake, 7 p. (Unpublished report held by Fisheries New Zealand.)

APPENDIX 1

Table of outputs of random sampling point allocation showing site number, fishery stratum, latitude and longitude, set, University of Canterbury site alignment, QMA and given site name

Number	Stratum	Long	Lat	Set	UC	QMA	Site name
1	Low	173.5633712	-42.45866928	1	No	PAU3	KAI 1
2	Low	173.8733874	-42.21937922	1	No	PAU3	KAI 2
3	Med	173.8533483	-42.23234568	1	No	PAU3	KAI 3
4	Med	173.5244718	-42.49521111	1	No	PAU3	KAI 4
5	Med	173.5256506	-42.4916748	1	No	PAU3	KAI 5
6	Med	173.87156	-42.21767	1	Okiwi 1	PAU3	KAI 6
7	High	173.50856	-42.51617	1	Oaro 1	PAU3	KAI 7
8	High	173.8380243	-42.24413336	1	No	PAU3	KAI 8
9	High	173.7979462	-42.27360258	1	No	PAU3	KAI 9
10	High	173.503254	-42.53057417	1	No	PAU3	KAI 10
11	High	173.834488	-42.24766967	1	No	PAU3	KAI 11
12	High	173.7944099	-42.27596012	1	No	PAU3	KAI 12
13	Low	173.5904829	-42.43863021	2	No	PAU3	KAI 13
14	Low	173.7142536	-42.42920006	2	No	PAU3	KAI 14
15	Med	173.518578	-42.55886462	2	No	PAU3	KAI 15
16	Med	173.7755496	-42.28185396	2	No	PAU3	KAI 16
17	Med	173.8132702	-42.25945736	2	No	PAU3	KAI 17
18	Med	173.86862	-42.21899	2	Okiwi 2	PAU3	KAI 18
19	High	173.50537	-42.52287	2	Oaro 2	PAU3	KAI 19
20	High	173.8285942	-42.25238474	2	No	PAU3	KAI 20
21	High	173.7979462	-42.27478135	2	No	PAU3	KAI 21
22	High	173.8285942	-42.25238474	2	No	PAU3	KAI 22
23	High	173.8262366	-42.25356351	2	No	PAU3	KAI 23
24	High	173.8297729	-42.25238474	2	No	PAU3	KAI 24
25	Low	174.0293988	-41.98620117	1	No	PAU7	KAI 25
26	Low	174.190448	-41.84420081	1	No	PAU7	KAI 26
27	Med	174.2657775	-41.73510297	1	No	PAU7	KAI 27
28	Med	174.2571189	-41.76367622	1	No	PAU7	KAI 28
29	High	174.2761677	-41.72990784	1	No	PAU7	KAI 29
30	High	174.27926	-41.72412	1	Cape Campbell 1	PAU7	KAI 30
31	Low	174.1229113	-41.90307901	2	No	PAU7	KAI 31
32	Low	174.2372042	-41.78099333	2	No	PAU7	KAI 32
33	Med	174.2545214	-41.76454207	2	No	PAU7	KAI 33
34	Med	174.2242164	-41.79224946	2	No	PAU7	KAI 34
35	High	174.2709726	-41.73423712	2	No	PAU7	KAI 35
36	High	174.27688	-41.7409	2	Cape Campbell 2	PAU7	KAI 36

APPENDIX 2

JAGS Model used to estimate density for each stratum

```
model{
  for (s in 1:N_SITES){
  # Site specific detection probability given Visibility and cryptic rating
    logit(p_obs[s]) = p_mu + beta_vis*VIS[s] +beta_crypt*CRYPT[s]
# Site specific random effect for density
    n_site_fx[s] ~ dnorm(0,1/n_site_sd)
  }
  for (i in 1:N) {
# Detection probability for each observation depends on revisit status (GRID_INT)
    det_prob[i] = 1-(1-p_obs[SITE[i]])^(GRID_INT[i])
    latent_d[i] = n_mu[QMASTRATUM[TA[i]]] + n_site_fx[SITE[i]]+  beta_depth*DEPTH[TA[i]]
    latent_mu[i] = exp(latent_d[i])*AREA[TA[i]]
    latent_n[i] ~ dpois(latent_mu[i])
    N_OBS[i] ~ dbinom(det_prob[i],latent_n[i])
  }

  ### PRIORS ###
  p_mu ~ dnorm(1,1)

  #random effect
  n_site_sd ~ dgamma(1,2)

  for (i in 1:6){
# Stratum/QMA combinations
    n_mu[i] ~ dnorm(n_mu_mu,1/n_mu_sd)
    }
  n_mu_mu ~ dnorm(-2.5 ,2)
  n_mu_sd ~ dgamma(1 ,2)

  # regression coeffs
  beta_vis ~ dnorm(0,2)
  beta_crypt ~ dnorm(0,2)
  beta_depth ~ dnorm(0,5)

}
```

APPENDIX 3

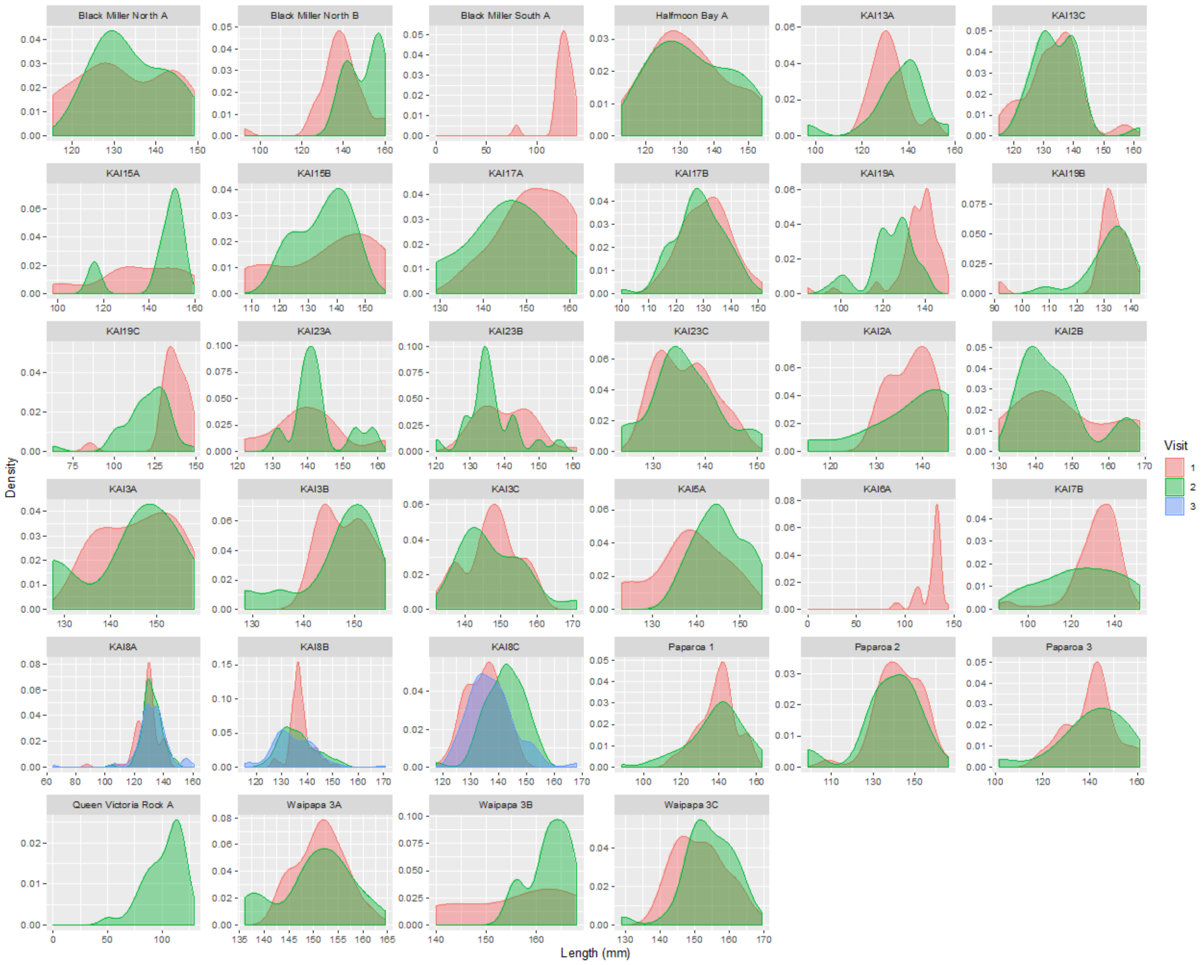
Table summarising monitoring point locations, date of establishment and re-survey dates

Site	Site Code	Latitude	Longitude	Established	Revisit 1	Revisit 2
Paparoa	Paparoa 1	42.2376	173.843067	14/01/17	6/04/18	
Paparoa	Paparoa 2	42.237633	173.843217	14/01/17	6/04/18	
Paparoa	Paparoa 3	42.23785	173.843833	14/01/17	6/04/18	
Needles	KAI8A	42.24133	173.83987	14/01/17	31/10/17	28/03/18
Needles	KAI8B	42.24145	173.83997	14/01/17	31/10/17	28/03/18
Needles	KAI8C	42.24154	173.84024	14/01/17	31/10/17	28/03/18
Waipapa	KAI6A	42.21864	173.86964	1/11/17	6/04/18	
Ohau South	KAI24A	42.24914	173.83017	1/11/17		
Ohau South	KAI24B	42.24882	173.83035	1/11/17		
Spyglass Point	KAI15A	42.55698	173.51634	2/11/17	29/03/18	
Spyglass Point	KAI15B	42.55719	173.51625	2/11/17	29/03/18	
Big Reef	KAI10A	42.53111	173.50684	2/11/17		
Big Reef	KAI10B	42.53104	173.50716	2/11/17		
Omihi	KAI5A	42.48706	173.52786	2/11/17	29/03/18	
Kahutara	KAI13A	42.43916	173.58798	3/11/17	29/03/17	
Kahutara	KAI13B	42.43926	173.58763	3/11/17		
Kahutara	KAI13C	42.43943	173.58772	3/11/17	29/03/17	
Iron Gate	KAI16A	42.27828	173.77875	4/11/17		
Iron Gate	KAI16B	42.27834	173.77969	4/11/17		
Queen Victoria Rock	Queen Victoria Rock A	42.27761	173.78252	27/05/17	1/11/17	
Black Miller South	Black Miller South A	42.23062	173.8502	24/05/17	28/03/18	
Black Miller North	Black Miller North A	42.22926	173.85118	25/05/17	28/03/18	
Black Miller North	Black Miller North B	42.22993	173.85326	25/05/17	28/03/18	
Halfmoon Bay	Halfmoon Bay A	42.25694	173.81123	27/05/17	28/03/18	
North of Queen Victoria Rock	KAI12A	42.27568	173.78949	4/11/17		
North of Queen Victoria Rock	KAI12B	42.27542	173.78972	4/11/17		
North of Queen Victoria Rock	KAI12C	42.27542	173.790007	4/11/17		
South Halfmoon Bay	KAI17A	42.26142	173.81259	5/11/17	28/03/18	
South Halfmoon Bay	KAI17B	42.26107	173.81236	5/11/17	28/03/18	
Ohau Staight	KAI23A	42.25256	173.82175	5/11/17	28/03/18	
Ohau Staight	KAI23B	42.25246	173.82162	5/11/17	28/03/18	
Ohau Staight	KAI23C	42.25245	173.82147	5/11/17	28/03/18	
3 Hour Reef	KAI19A	42.52256	173.50649	4/12/17	29/03/18	
3 Hour Reef	KAI19B	42.52263	173.50675	4/12/17	29/03/18	
3 Hour Reef	KAI19C	42.52278	173.50657	4/12/17	29/03/18	
Solomon's Slipway	KAI17A	42.51545	173.50909	4/12/17		
Solomon's Slipway	KAI17B	42.51546	173.50956	4/12/17		
Solomon's Slipway	KAI17C	42.51556	173.50947	4/12/17		
Boat Harbour North	KAI7A	42.49419	173.52197	4/12/17	29/03/18	
Boat Harbour North	KAI7B	42.49459	173.52162	4/12/17	29/03/18	
Kaikoura Peninsula	KAI14A	42.42852	173.71397	4/12/17		
Rakautara	KAIXA	42.2691	173.80336	5/12/17		
Rakautara	KAIXC	42.26888	173.80286	5/12/17		
Mid Ohau	KAI20A	42.25037	173.82619	5/11/17		

Mid&Ohau&	KAI20B&	42.25082&	173.82628&	5/11/17&		
Mid&Ohau&	KAI20C&	42.25052&	173.82663&	5/11/17&		
North&Black&Miller&	KAI3A&	42.23011&	173.85433&	5/11/17&	6/04/18&	
North&Black&Miller&	KAI3B&	42.23025&	173.85439&	5/11/17&	6/04/18&	
North&Black&Miller&	KAI3C&	42.22996&	173.85529&	5/11/17&	6/04/18&	
North&of&Okiwi&	KAI2A&	42.21608&	173.87268&	6/11/17&	3/04/18&	
North&of&Okiwi&	KAI2B&	42.21663&	173.87315&	6/11/17&	3/04/18&	
Waipapa&3A&	Waipapa&3A&	42.20995&	173.87784&	6/11/17&	6/04/18&	
Waipapa&3B&	Waipapa&3B&	42.21034&	173.87811&	6/11/17&	6/04/18&	
Waipapa&3C&	Waipapa&3C&	42.21059&	173.87828&	6/11/17&	6/04/18&	
Waipapa&2A&	Waipapa&2A&	42.20435&	173.87857&	6/11/17&		
Waipapa&2B&	Waipapa&2B&	42.20428&	173.87859&	6/11/17&		
Waipapa&2C&	Waipapa&2C&	42.20416&	173.87835&	6/11/17&		
Kekerengu&North&	KAI25A&	41.99716&	174.010607&	11/12/17&		
Kekerengu&North&	KAI25B&	41.99707&	174.01605&	11/12/17&		
Kekerengu&North&	KAI25C&	41.99701&	174.01618&	11/12/17&		
Waima&North&	KAI31A&	41.90043&	174.12845&	11/12/17&		
Waima&North&	KAI31B&	41.90103&	174.12773&	11/12/17&		
Waima&North&	KAI31C&	41.90173&	174.12726&	11/12/17&		
Wharanui&	Wharanui&A&	41.93544&	174.09339&	11/12/17&		
Wharanui&	Wharanui&B&	41.93511&	174.09395&	11/12/17&		
Wharanui&	Wharanui&C&	41.93615&	174.09297&	11/12/17&		
Canterbury&Gully&South&	KAI33A&	41.76293&	174.25588&	12/12/17&		
Canterbury&Gully&South&	KAI33B&	41.763&	174.25541&	12/12/17&		
Canterbury&Gully&South&	KAI33C&	41.76283&	174.25496&	12/12/17&		
Canterbury&Gully&North&	KAI28A&	41.76229&	174.25667&	12/12/17&		
Canterbury&Gully&North&	KAI28B&	41.7626&	174.25672&	12/12/17&		
Canterbury&Gully&North&	KAI28C&	41.76219&	174.2569&	12/12/17&		
Ward&North&	KAI26A&	41.84235&	174.19008&	25/01/18&		
Ward&North&	KAI26B&	41.84157&	174.18993&	25/01/18&		
Booboo&South&	KAI34A&	41.7875&	174.22809&	25/01/18&		
Booboo&South&	KAI34B&	41.78798&	174.22734&	25/01/18&		
Booboo&South&	KAI34C&	41.78783&	174.22754&	25/01/18&		
Cape&Campbell&East&&	KAI30A&	41.72592&	174.27779&	13/02/18&		
Cape&Campbell&East&&	KAI30B&	41.72571&	174.278&	13/02/18&		
Long&Point&South&	KAIZA&	41.81656&	174.20848&	12/02/18&		
Long&Point&South&	KAIZB&	41.81647&	174.20891&	12/02/18&		
Cape&Campbell&South&	KAI36A&	41.740037&	174.27707&	14/02/18&		
Cape&Campbell&South&	KAI36B&	41.7405&	174.27724&	14/02/18&		
Cape&Campbell&South&	KAI36C&	41.74082&	174.27692&	14/02/18&		
Cape&Campbell&West&	KAI35A&	41.72421&	174.27577&	14/02/18&		

APPENDIX 4

Length-frequency plots for paua populations at fixed monitoring points at different times (up to 3 visits to the same site). Y-axis is frequency and x-axis is size (mm).

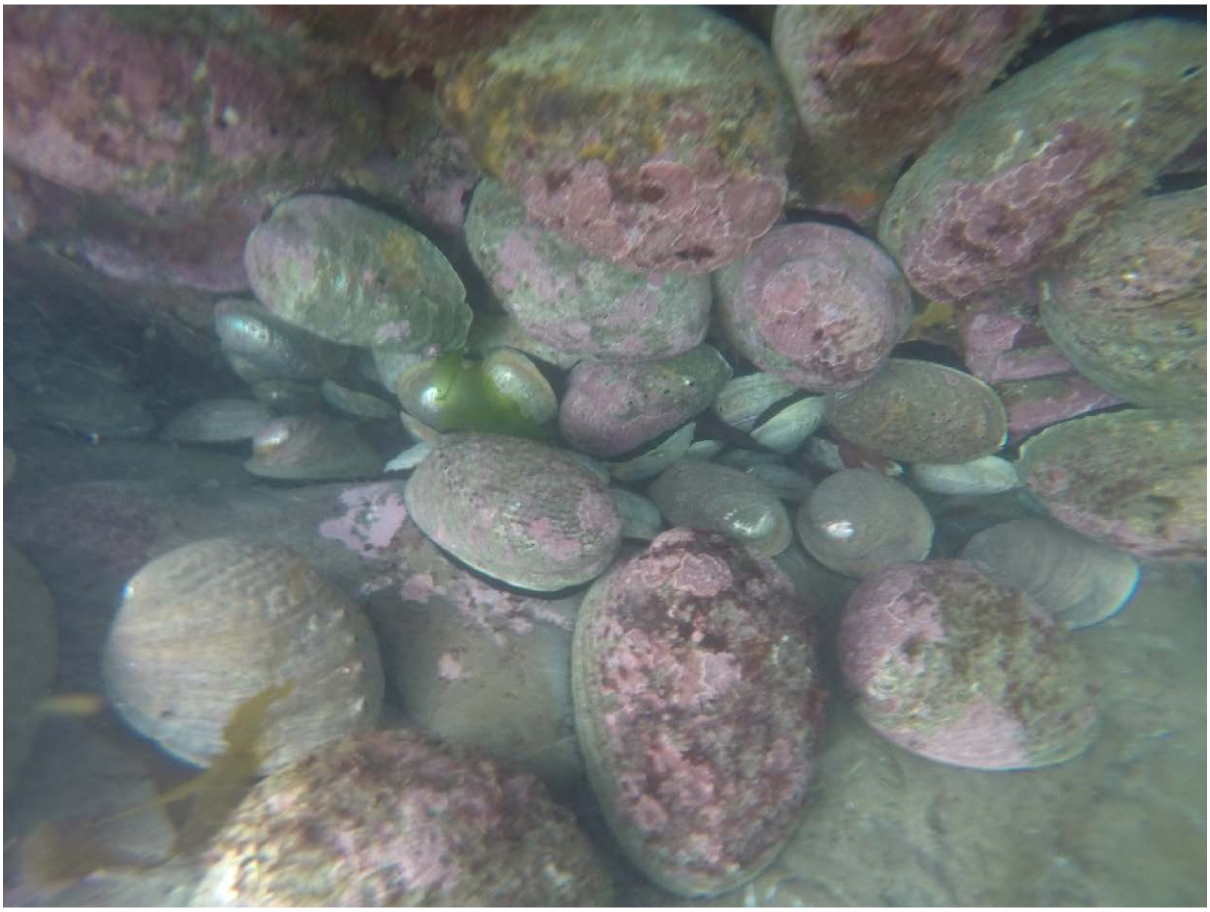


APPENDIX 5

Photographs

Photograph 1: Monitoring point marked with re-bar and eartag showing underwater electronic callipers used for measuring paua. Note yellow crayon mark on paua indicating that it has been measured.

Photograph 2: Photograph A shows the establishment of a monitoring point in the shallow sub-tidal zone near Queen Victoria Rock (-42.277528°, 173.781965°) on 27 May 2017. Photo B shows a person standing on the same GPS location on 1 November 2018, showing significant influx of sediment.



Photograph 3: Aggregation of adult (over 100 mm) paua and juvenile (under 90 mm) paua in boulder habitat near Ohau Point (-42.268619°, 173.803071°). It is uncharacteristic to find juvenile paua exposed in boulder habitats.