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Tini a Tangaroa

# Pāua abundance trends and population monitoring in areas affected by the November 2016 Kaikōura earthquake

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# EXECUTIVE SUMMARY

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The November 2016 Kaikōura earthquake caused coastal uplift that resulted in massive pāua (*Haliotis iris*) mortality and loss of critical pāua habitats. This has seen the ongoing closure of the pāua fishery along approximately 100 km of the coastline that supports significant customary, recreational, and commercial pāua fisheries (the 'closed area'). Commercially, the closed area spans portions of the PAU 7 and PAU 3 quota management areas (QMAs), which at the time of the closure had total allowable commercial catches of 93.6 t and 91.615 t, respectively. The closed area accounts for approximately 60 t of pre-earthquake commercial catch, approximately 15 t and 45 t from PAU 7 and PAU 3, respectively.

This project is a two-year continuation of initial work that was undertaken to estimate baseline pāua densities and length-frequency profiles at selected sites within the closed area (McCowan & Neubauer 2018). Initial estimates were made with novel methodologies using Global Positioning System turtle units and underwater electronic callipers. The objective of this project was to monitor changes in pāua abundance and length frequency (to assess recruitment), to ultimately inform fisheries management decisions at the scale of the closed area.

Of the initial 35 survey sites, 21 were successfully re-surveyed during the first survey period of this project (2018–2019), and 34 out of 35 were surveyed during the second survey period (2019–2020).

Initially an assessment was made of the appropriateness of using the number of measurements per unit effort (MPUE) as a proxy for pāua density to overcome issues with missing data from GPS dive units (originally used to delimit area to estimate density) and to enable the use of significantly larger data sets of measurements and counts of pāua at each site. The measurements per unit effort, as well as biomass per unit of survey effort (BPUE; number of measurements multiplied by the length-frequency distribution of measured pāua), correlated well ($R^2$=0.86) with density. Therefore, MPUE and BPUE were used as indices of changes in pāua density.

An overall increase in pāua abundance was observed at a QMA-wide level in both QMAs over the three survey periods. Increased abundance was generally more pronounced in PAU 7 than in PAU 3. In PAU 3, abundance trended downwards in the second survey period, which was likely due to the consistently poor survey conditions during the period, as well as a potential bias towards sampling sites with lower rates of increase. There was high variability in abundance trends across sites. This variability was in part related to variability in the amount of uplift at each site, because sites with a larger increase in abundance were those with less uplift. Variability in abundance trends across sites could also be linked to habitat related factors and pre-earthquake abundance. Comparison of length-frequency profiles across the three survey periods showed reasonably stable profiles in larger size classes (125–160 mm), with an increase in the number of individuals in the 80–100 mm size range in both QMAs which is likely to be indicative of post-earthquake recruitment. Recruitment signals were variable between sites due to differences in available recruitment habitat and variability in uplift.

At the time of publication, one likely pathway for the reopening and management of the closed area is via the recently approved PAU3 Fisheries Plan (PāuaMAC3 2021), which outlines criteria for when reopening of the fishery should be considered. Outcomes from this project indicate that these criteria have likely been met, and that reopening could be considered with future monitoring.

# 1. INTRODUCTION

## 1.1. Background

The November 2016 Kaikōura earthquake caused coastal uplift of up to 6 m along approximately 100 km of coastline stretching from Spyglass Point in the south to Marfells Beach in the north. This resulted in mass mortality of a range of species inhabiting the sub-tidal and intertidal range affected by the uplift. The amount of uplift was variable along the affected area and impacted a range of habitats that support important ecosystems and fisheries species. Pāua (*Haliotis iris)* was a severely impacted species that suffered mass mortality at all life stages and lost a significant amount of critical habitat. Of particular significance, was the loss of intertidal and shallow sub-tidal rocky reef habitats (previously in less than 2 m of water) that support initial settlement and juvenile life phases. Neubauer (2017) undertook a preliminary assessment of the amount of the pāua fishery area that was lost to the uplift and estimated that 21% of previously fished areas were lost. This finding and general observations of pāua mortality and habitat loss resulted in the emergency closure of the pāua fishery from Cape Campbell in the north to Conway River in the south (hereafter the 'closed area') under section 16 of the Fisheries Act. This closure currently remains in force under section 11 of the Act.

The pāua fishery in the closed area is of high importance to the region for recreational, customary, and commercial fisheries. The closed area spans two pāua quota management areas (QMAs), PAU 7 (Marlborough) and PAU 3 (Kaikōura-Canterbury) that previously accounted for 15 t of total allowable commercial catch (TACC) from PAU 7 and 47 t from PAU 3 (approximately 16% and 50% of the respective QMA's commercial catch). Since the closure there has been a formal reduction of 50% of the TACC in PAU 3, and an ongoing industry-initiated shelving of 12% of annual catch entitlement (ACE) in PAU 7. These reductions were to stop the spread of displaced effort into the remaining open parts of these QMAs. The reductions in catch from both QMAs equate to approximately $3 million in lost revenue annually from the pāua fishery (cumulatively, approximately $9 million at the time of publication).

## 1.2. Research response and previous work

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

In September 2018, the Pāua Industry Council Ltd. completed a project supported by this funding addressing the objective to complete stock monitoring surveys of the adult pāua population, to inform management decisions at the scale of both the Kaikōura fisheries closure and the PAU 3 areas, with the specific objective to monitor the abundance of adult pāua 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 (see McCowan & Neubauer 2018).

The main outcomes from this initial project were the development of a novel stratification and survey design to attempt to overcome the shortcomings associated with previous pāua abundance surveys (see below for summary of methods). These new methods enabled the establishment of baseline pāua density estimates and length-frequency profiles at 35 different sites spanning the earthquake affected area, as well as area-wide (QMA) baseline estimates.

## 1.3. Current project objectives

Funding for the continuation of this monitoring was made available in mid-2018 for a further two years of monitoring, with slightly modified project objectives:

i. To estimate abundance of pāua populations in the Kaikōura closed area and monitor changes,

ii. To monitor recruitment into the fishery by monitoring the length frequency of pāua in the Kaikōura closed area paying particular attention to newly recruited pāua (70–100 mm).

# 2. METHODS

The following is a summary of the methods used in the initial project described above and continued into the next two years of monitoring. For a full description of methods refer to McCowan & Neubauer (2018). A novel survey design was developed to overcome the issues associated with previously trialled, timed swim methodologies. The new methods were based on pāua 'data-logger' information to allocate sampling points in both QMAs and Global Positioning System (GPS) 'turtle units' to map the areas swum by survey divers to estimate pāua density at sites.

## 2.1 Site selection

Site selection was based on data-driven stratification to assign only areas relevant to the fishery to survey strata, and sampling points were then allocated within strata.

### 2.1.1 Stratification procedure

Survey sites were selected from within areas of high, medium, and low fishery utilisation strata. Stratification was undertaken using all available data-logger data from 2013 to 2016 from the closed area to calculate utilisation density using two-dimensional kernel-based smoothing of all available dive locations. The utilisation density was then intersected with the coastline to produce a one-dimensional map of utilisation (Figure 1). 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 for sample allocation.

### 2.1.2 Allocation of sampling points

A predetermined number of sampling points were allocated in each stratum, weighted towards more samples in high and medium use strata (Figure 1). The number of allocated sites was initially based on a realistic number of sites that could be surveyed over one season, equating to approximately 30 dive days. Three sites (one in PAU 7 and two in PAU 3) were pre-determined to be aligned with intertidal and juvenile pāua surveys being conducted by the University of Canterbury. Backup sites were also selected to give a sampling option when the primary site could not be surveyed due to poor diving conditions (i.e., swell over 1 m or visibility under 1 m). Based on the described criteria, 36 sites were allocated, with 12 primary sites in PAU 3 and 6 in PAU 7, with an equivalent number of backup sites.

## 2.2 Sampling procedure

Surveys were conducted by a crew of three snorkel divers with commercial pāua diving experience. As much as possible, the same divers were used within each QMA to maintain consistency. At each sampling point, an area of approximately 100 m was haphazardly delimited using float-lines or obvious geographical boundaries set by a neutral advisor so prior knowledge about pāua abundance could not be used by divers to bias the selection of the survey area within each site. Each area was roughly divided into three smaller areas and allocated to each diver to survey. Each diver wore a GPS dive logger ('turtle unit') during the surveys. Divers would swim and search for pāua for approximately 45 minutes. Divers measured the maximum shell length, marked, and logged every pāua seen using electronic underwater callipers. Measured pāua were marked with a yellow crayon so they were not re-measured. At the end of the initial survey, divers re-visited the area they had just surveyed to measure and log any pāua that were missed in the initial survey (those with no yellow mark). The data from this re-visit were used to estimate detection probability required for absolute density estimates. During each survey event (at each site), 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.

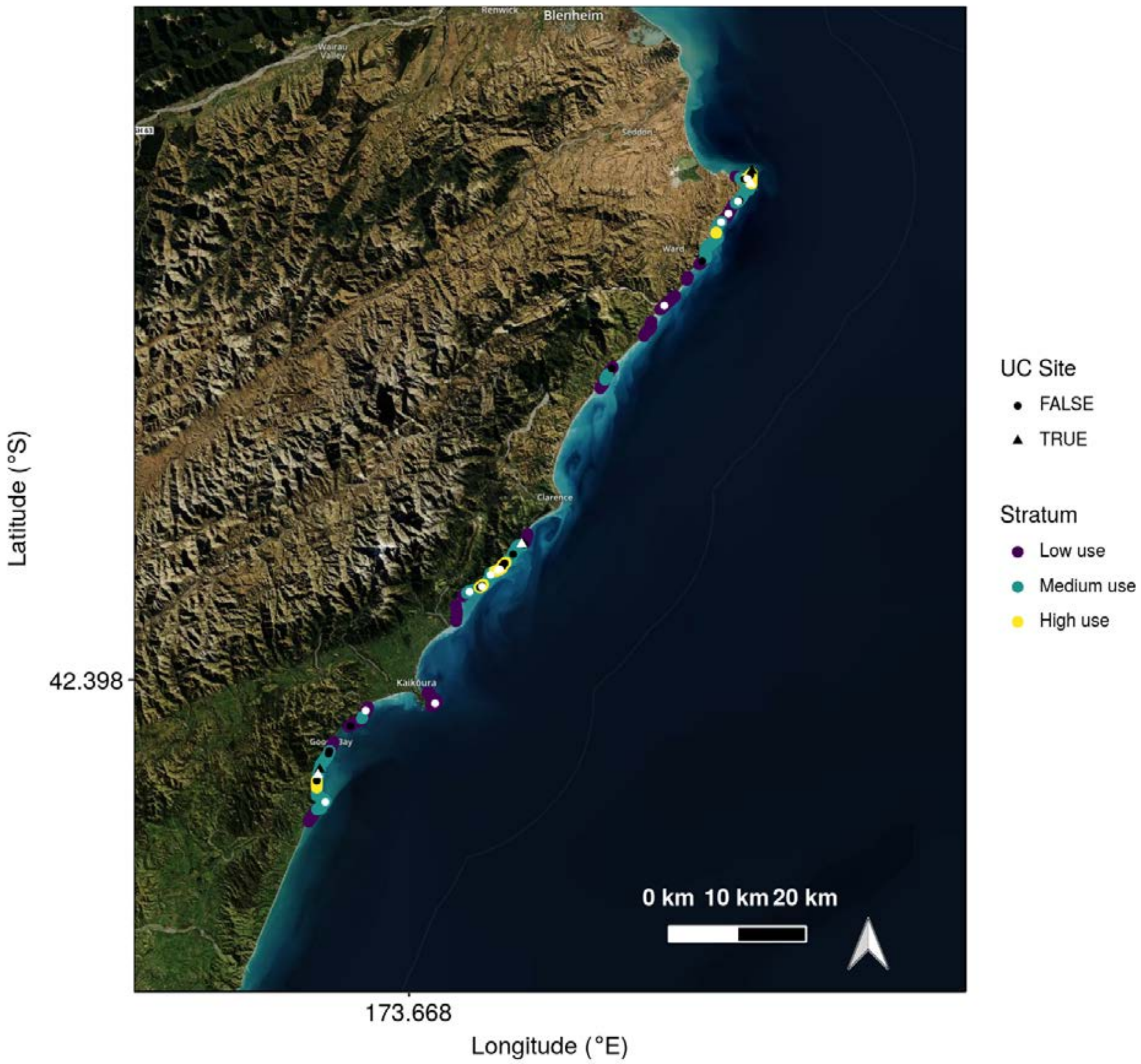


**Figure 1: Extracted fishery use strata, established from the utilisation density by intersecting the density with the coastline to produce a one-dimensional line and then dividing the cumulative one-dimensional use distribution into inter-quantile ranges as described in the text. Selected sites (black) as well as fall-back (secondary sites that were surveyed if initially selected sites could not be accessed due to poor conditions) points (white) for the Kaikōura 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.**

## 2.3 Data analyses

Survey data were aggregated from two data formats: dive location data, including time stamps from the turtle units, as well as pāua 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 points from the turtle units 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 unit 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 were discarded to minimise error from interpolated measurement positions.

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

For the initial analysis of this type of data from the 2018 survey (McCowan & Neubauer 2018), the observed densities were scaled up to total biomass within strata by i) estimating detection probability in each habitat and ii) scaling estimated densities to strata. Briefly, to estimate density, the survey area for each diver and site was estimated as the 95% occurrence polygon in space from diver GPS tracks (Figure 2). Repeated swims of each area were used to estimate detection probability (i.e., the probability that a pāua would be counted given that it had not previously been counted and given recorded habitat characteristics). For details of the methodology, refer to McCowan & Neubauer (2018).

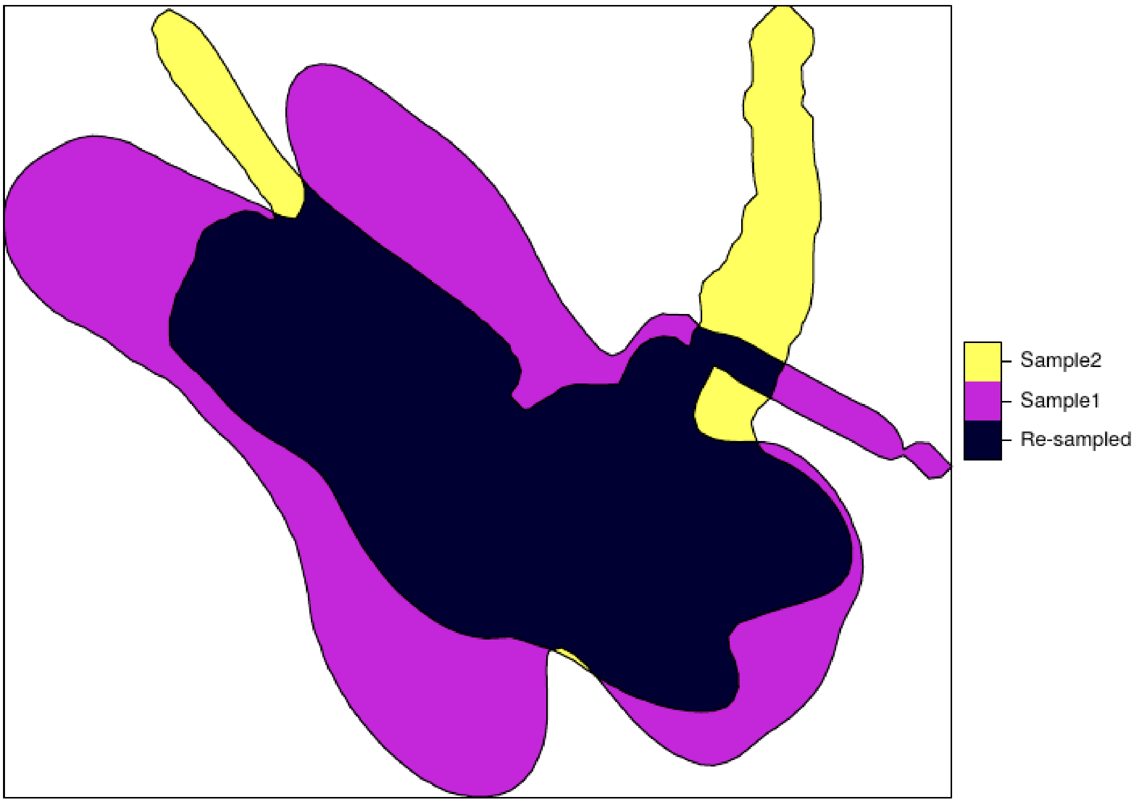


**Figure 2: Schematic showing initial survey (Sample 1, purple) and revisit (Sample 2, yellow), with the overlapping area that was sampled twice shown in dark blue.**

After the first round of surveys, however, a number of problems with the overall design led to changes in the analyses for the survey data:

- A large amount of data was discarded for each of the surveys because of missing GPS positions, despite careful application of the data loggers (Table 1). There are a range of possible causes (discussed by McCowan & Neubauer 2018), however, no applicable remedy was found for this problem.
- The model used to estimate density led to high uncertainty due to the inherent statistical difficulty in precisely estimating the detection probability from a relatively small number of surveys.
- Scaling from densities to overall biomass, though desirable, 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) yielded a distribution that closely approximates available data-logger data but ignores the potential of habitat beyond recorded positions. A large variance often includes areas that are not pāua habitat because 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), the densities were not extrapolated to total biomass; thus, the analysis used a proxy for relative density, not an absolute density estimate.

**Table 1: Diver-site combinations by survey year: amount and percent of data retained after removing data with missing GPS positions.**

| Survey | Diver sites | Retained | Percent retained |
|---|---|---|---|
| 2017–18 | 87 | 52 | 60 |
| 2018–19 | 57 | 34 | 60 |
| 2019–20 | 92 | 62 | 67 |

To circumvent these issues, the number of measurements per unit time effort (MPUE) was used as a potential proxy for relative density differences, similar to the use of catch per unit effort (CPUE) as a proxy for biomass in fisheries stock assessments. To test the relationship between MPUE and density, a Bayesian linear regression was run with diver as a random effect and depth, visibility, and habitat cryptic rating as predictors. This model confirmed MPUE as a suitable predictor, showing an approximate 1:1 relationship between density and MPUE ($\rho$=1.00, se = 0.06; Figures 3, A-1). The results were nearly identical between MPUE and BPUE, but BPUE was used for further analyses for consistency with management measures based on biomass.

Trends between surveys were then assessed using a Bayesian generalised linear mixed model to estimate i) the overall survey year effect, ii) a survey year within stratum effect (high/medium/low use), iii) a survey year within QMA effect, and iv) a survey year within site effect. A truncated normal distribution was used to model the error in the (square root-transformed) response variable, with truncation to exclude negative numbers from the support of the error distribution. Predictors for potential nuisance variables (swell, visibility, depth, and cryptic rating) were also included to remove potentially confounding effects (e.g., those that would affect detection probability). In addition, the role of uplift in determining survey patterns was investigated by fitting a model with a survey period within the uplift interaction term. However, this effect was omitted from the final model to estimate trends so as not to estimate these effects as marginal effects with respect to uplift (i.e., at some mean uplift) but as conditional on actual uplift. Survey site, diver, and survey period within site were estimated as random effects; all other parameters were specified as fixed effects. The full model may be written in the R package *brms* (Bürkner 2018) as:

```
sqrt(BPUE) ~ depth + visibility + cryptic_rating + stratum*survey_period + survey_period*QMA +
survey_period:uplift + (1|diver) + (1|site_code) + (1|site_code:survey_period)
```

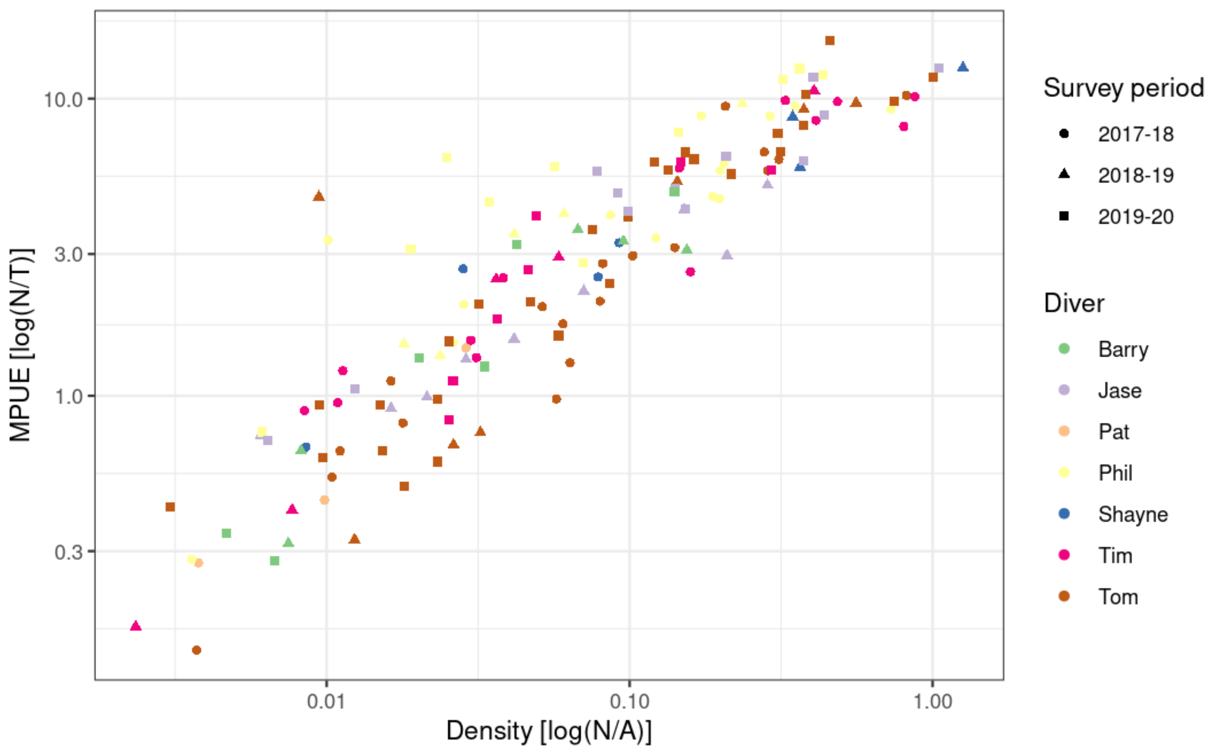


**Figure 3: Relationship between density in (log) individuals per unit area, and measurements per unit time (MPUE), for the three different survey periods (shapes) and divers (colours).**

## 3. RESULTS

### 3.1 General survey outcomes

The first round of surveys undertaken during the initial project (described above) saw a total of 35 sites surveyed (23 in PAU 3 and 12 in PAU 7). The number of sites surveyed initially was higher than the proposed number of 'primary' sites because favourable survey conditions and efficient surveying times enabled several 'back-up' sites to be surveyed in both QMAs. Further, due to access and logistical constraints in some remote sites, additional sites were surveyed opportunistically with sites allocated haphazardly in space when crews were in the area and where it was not possible to access sites further afield that day. Baseline estimates of pāua density and length frequency were made for all these sites (as well other descriptive statistics).

The continuation of the project over the next two years saw two more rounds of surveys attempted across all initially surveyed sites. During the second round of surveys (summer 2018–19), 21 out of 35 sites were re-surveyed. This was due to consistently poor survey conditions during this period, with consistently higher than usual swell and poor visibility. On several occasions, surveys were abandoned because conditions prevented accurate surveying. During the third and most recent round of surveys, 34 of 35 sites were able to be re-surveyed.

### 3.2 Pāua abundance trends

Figure 4 shows raw pāua abundance data expressed in measurements per hour by individual divers across sites within different fishery use strata. This shows that the number of pāua counted by each diver at each site was consistently variable for all survey periods. Although there is a general trend of increasing numbers of pāua measured for all three survey periods, there is no obvious link between abundance trends and fishery use strata (also see Figure 6).

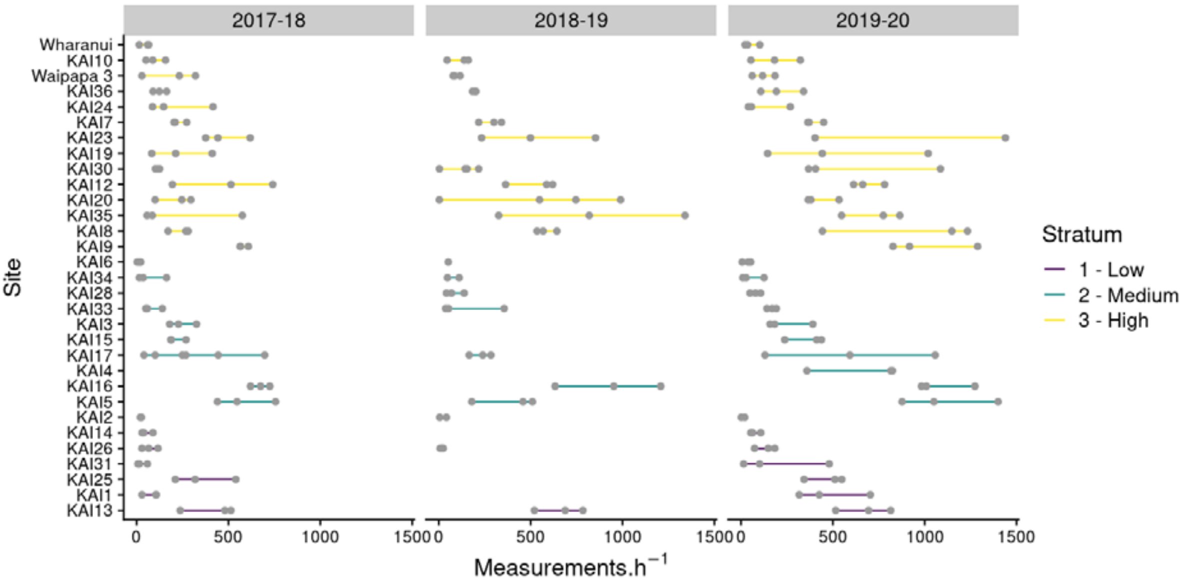


**Figure 4: Numbers of pāua counted per hour at each site across three survey periods, with points indicating results from individual divers and lines showing the range. Colour indicates the survey stratum.**

Measurement data shown in Figure 4 were used to model MPUE/BPUE as a proxy of pāua density. Models on square-root transformed data had adequate fit (Figure A-2), and MPUE and BPUE models provided near identical estimates of coefficients (Figures A-3, A-4). Coefficients for confounding variables were close to expectations, with lower visibility, higher cryptic rating, and depth leading to less measurements/biomass per unit time (Figures A-5 to A-7), and a less notable effect of swell (Figure A-8); note that surveys only took place when conditions were acceptable for diving (i.e., swell was under 2 m).

Overall, pāua density, as approximated by BPUE, increased slightly between the first and last survey year, with lower BPUE estimated for the 2018–19 survey year (Figure 5). Although the estimates are uncertain, median estimates suggest an approximate increase of 25% in density in the last survey period over the initial survey in 2017–18. Increases were largely driven by increases in low and high use strata (Figure 6), with a slight decrease in BPUE in medium use strata over the surveys. Increases in BPUE were also substantially larger in PAU 7 relative to PAU 3 (Figure 7). Nevertheless, BPUE in PAU 3 remained substantially higher than that in PAU 7, with nearly 50% higher BPUE in PAU 3 in the last survey period, despite an increase in BPUE of nearly 50% in PAU 7.

BPUE was also determined based on the amount of uplift at each site (Figure 8). This relationship shows that increase in abundance was lower at sites that experienced high uplift compared with those that experienced lower uplift (Figure 9). Although there was a general trend of increasing abundance over survey periods for both QMAs, and for sites of different amounts of uplift, there was high variability in trends at individual sites (Figure 9).

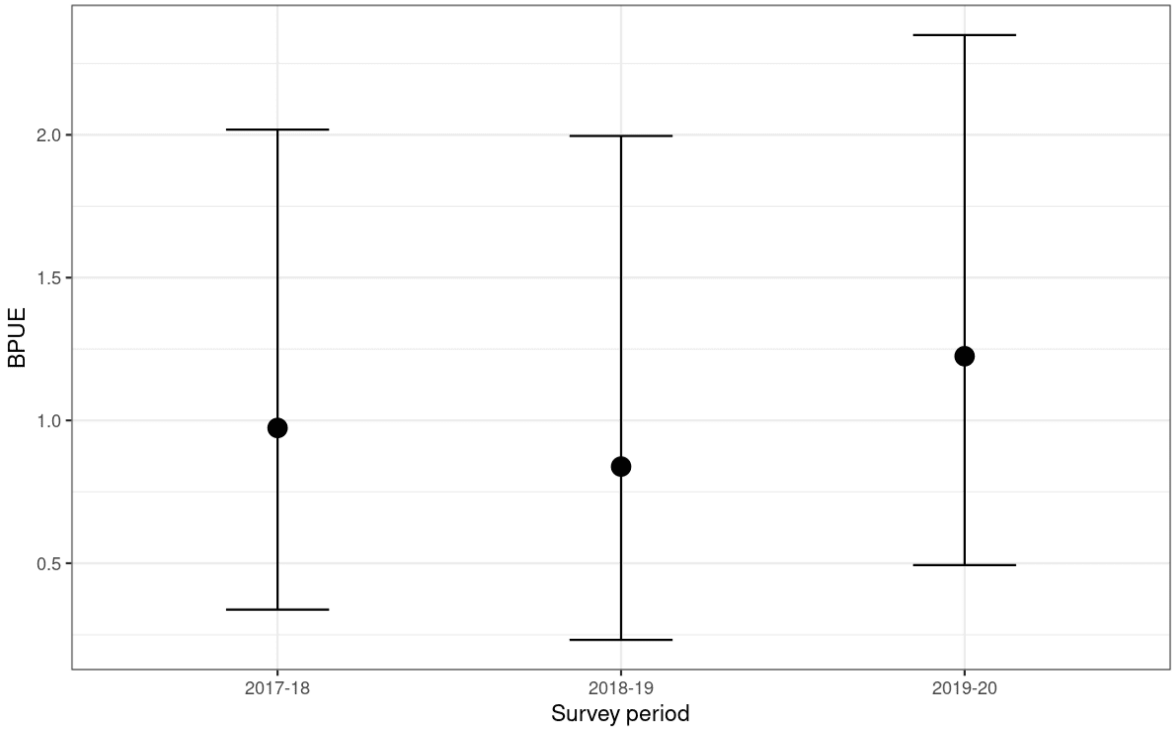


**Figure 5: Marginal trend (relative to a geometric mean of 1) in biomass per unit effort (BPUE) across survey years from the BPUE model after accounting for confounding variables. Error bars show 95% confidence intervals.**

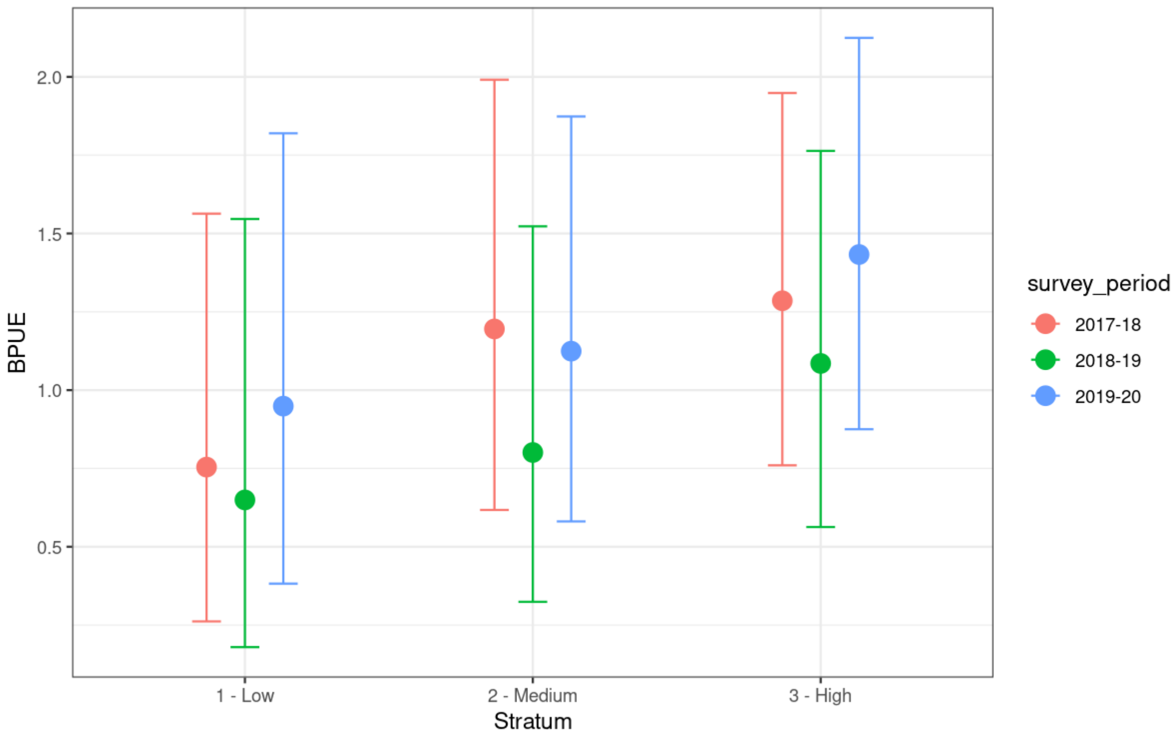


**Figure 6: Marginal trend (relative to a geometric mean of 1) in biomass per unit effort (BPUE) for survey years and strata from the BPUE model after accounting for confounding variables. Error bars show 95% confidence intervals.**

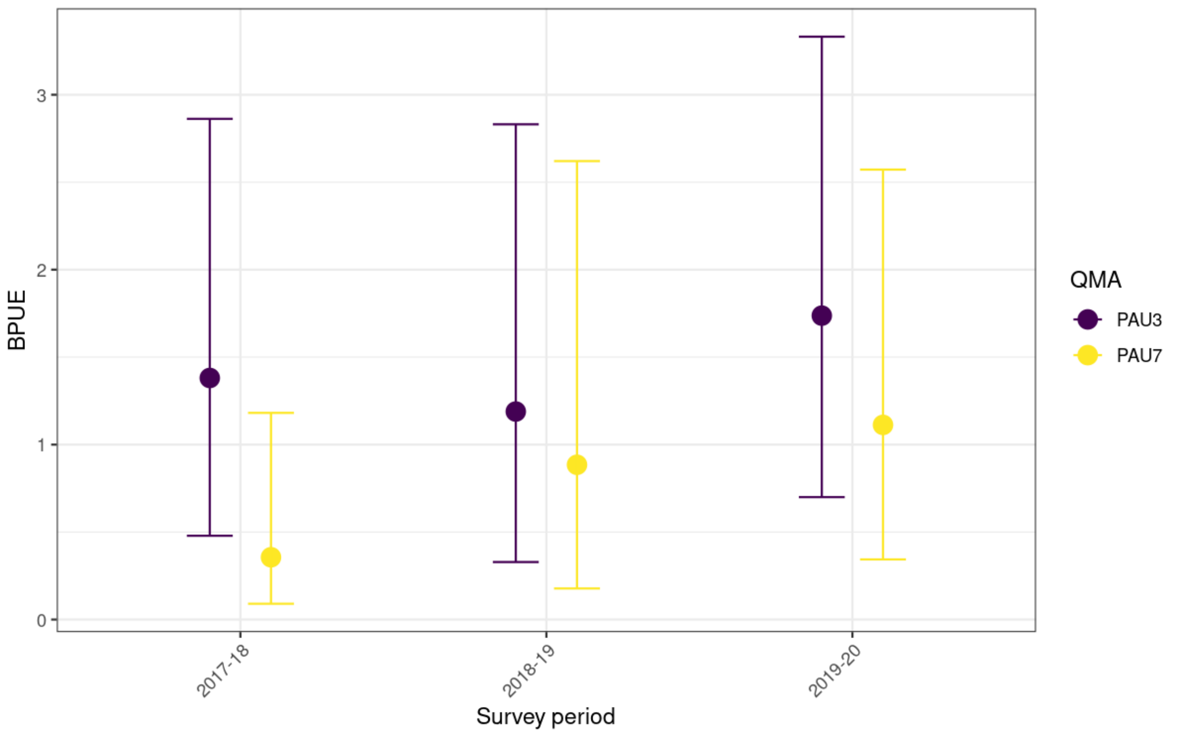


**Figure 7: Marginal trend (relative to a geometric mean of 1) in biomass per unit effort (BPUE) for survey years for QMAs PAU 3 and PAU 7 from the BPUE model after accounting for confounding variables. Error bars show 95% confidence intervals.**

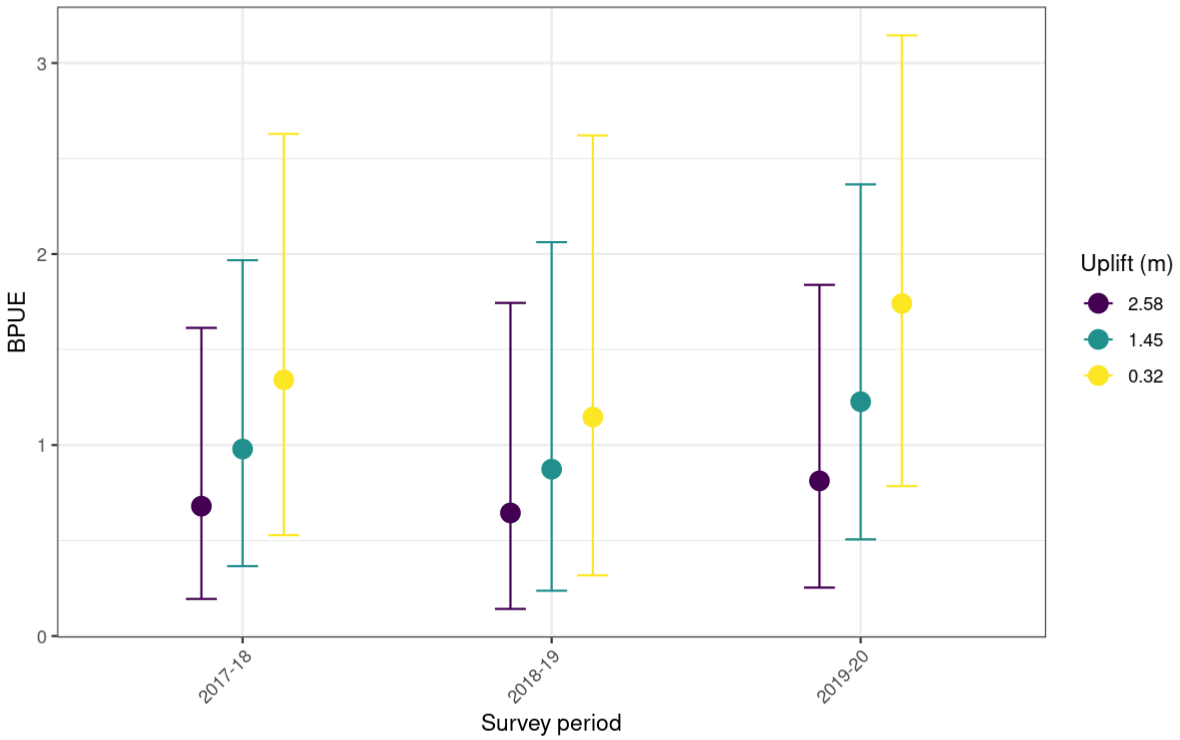


**Figure 8: Marginal trend (relative to a geometric mean of 1) in biomass per unit effort (BPUE) for survey years as a function of uplift from the BPUE model after accounting for confounding variables. Error bars show 95% confidence intervals.**

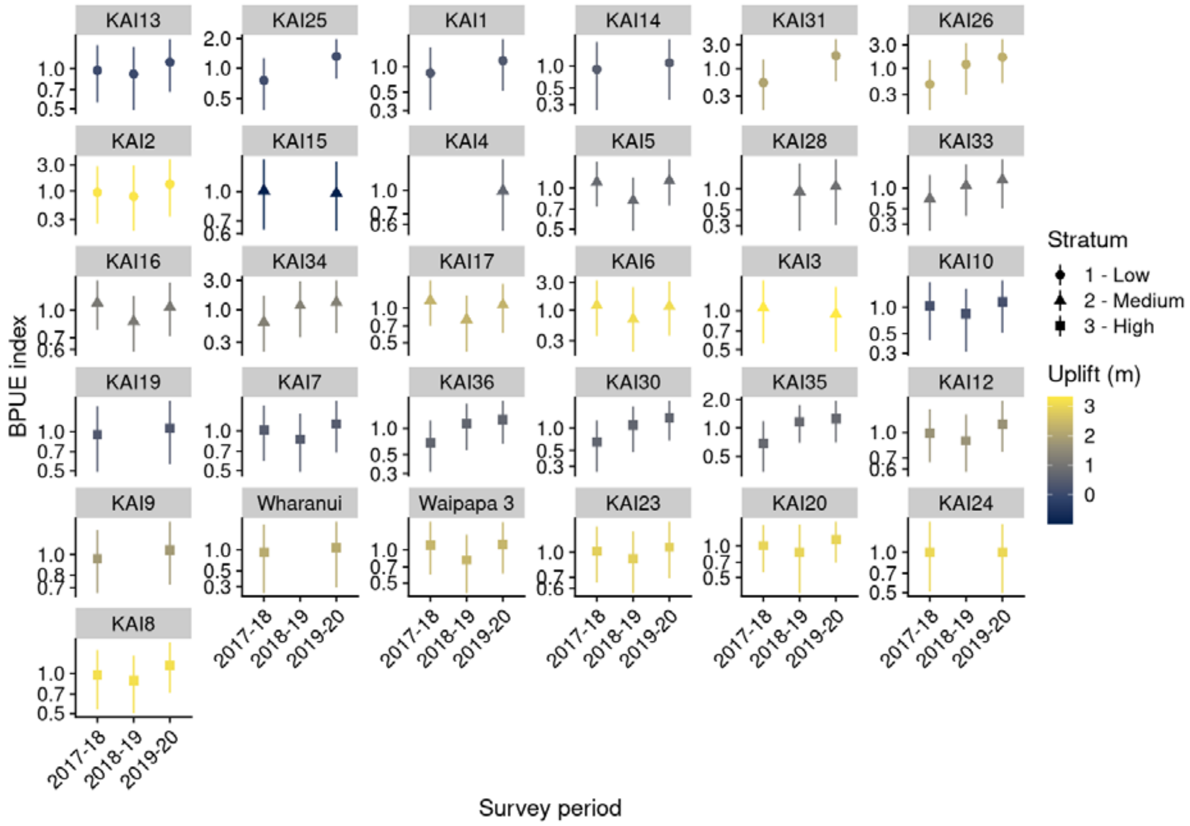


**Figure 9: Marginal trend (relative to a geometric mean of 1 at each site) in biomass per unit effort (BPUE) for survey years for PAU 3 and PAU 7 sites from the BPUE model after accounting for confounding variables. Error bars show 95% confidence intervals.**

## 3.3 Length-frequency observations (recruitment patterns)

Length frequencies of pāua were analysed across all sites and survey periods to make observations about recruitment at site and QMA levels. An overall increase in the range of pāua sizes was observed at all sites over the three survey periods (Figure 10). Length-frequency profiles for pāua measured across all sites show comparable patterns in both PAU 3 and PAU 7 (Figure 11). Relative frequencies in both QMAs are reasonably stable in larger size classes (125–150 mm) for the three survey periods. Changes in length-frequency profile at a QMA level are more pronounced when presented as numbers of pāua at length (rather than relative frequency) as shown in Figure 12, because the changing number of pāua surveyed in each period can be visualised. The larger BPUE increase in overall abundance in PAU 7 is reflected in an increase in all size classes in that QMA, whereas the more moderate increase in PAU 3 relates predominantly to smaller and intermediate size classes (under 140 mm). In both QMAs, there is a notable increase in the number of pāua in smaller size classes (70–100 mm) in the third survey period (also present in the second round of surveys in PAU 7). The length-frequency profiles shown in Figures 11 and 12 are also useful to inform possible minimum harvest sizes (MHS) when pāua fishing resumes. Figures 11 and 12 show the current minimum legal size (MLS) of 125 mm, as well as 135 mm and 145 mm to help visualise the proportion of pāua larger than these potentially larger MHS.

The relative increase in the numbers of smaller size classes is more pronounced in PAU 3 (Figure 13). Figure 13 shows changes in length frequency (by number) over the three survey periods, where the x-axis shows pāua less than 100 mm. This helps visualise the changes in abundance of post-earthquake recruits at each site.

As with general patterns with pāua abundance across QMAs, trends in length-frequency profiles are subject to considerable variation between sites. Differences are most apparent in the changes in abundance of pāua in smaller size classes (70–100 mm), and the overall number of pāua measured at each site (also reflected in figures showing change in abundance).

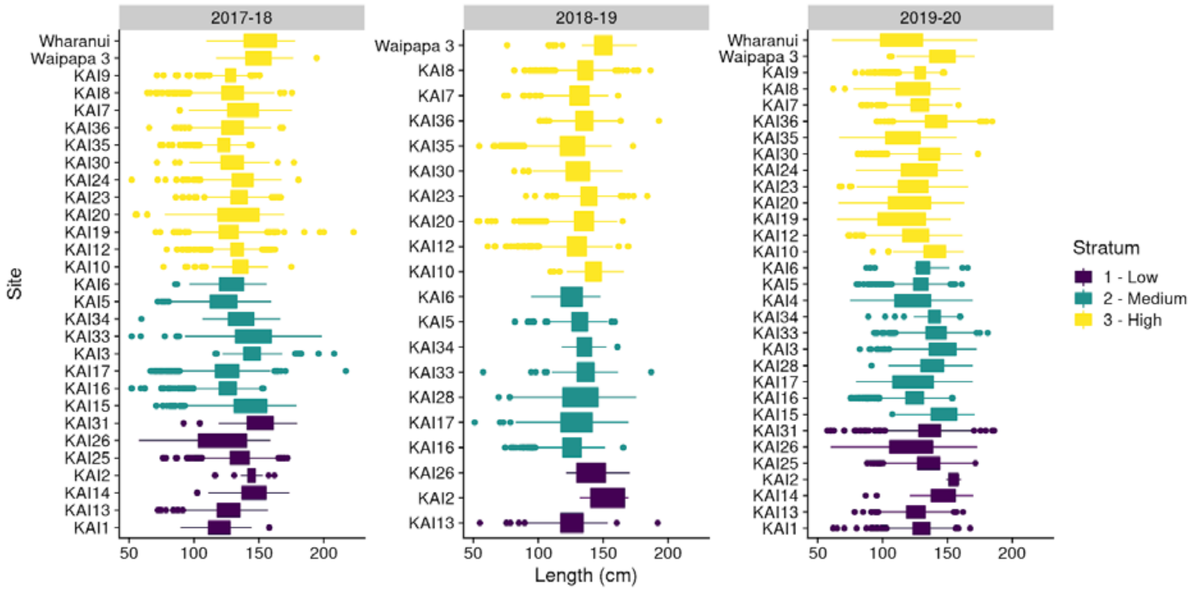


**Figure 10: Boxplot of pāua length distributions found at survey sites over three survey periods. Colour indicates the survey stratum.**

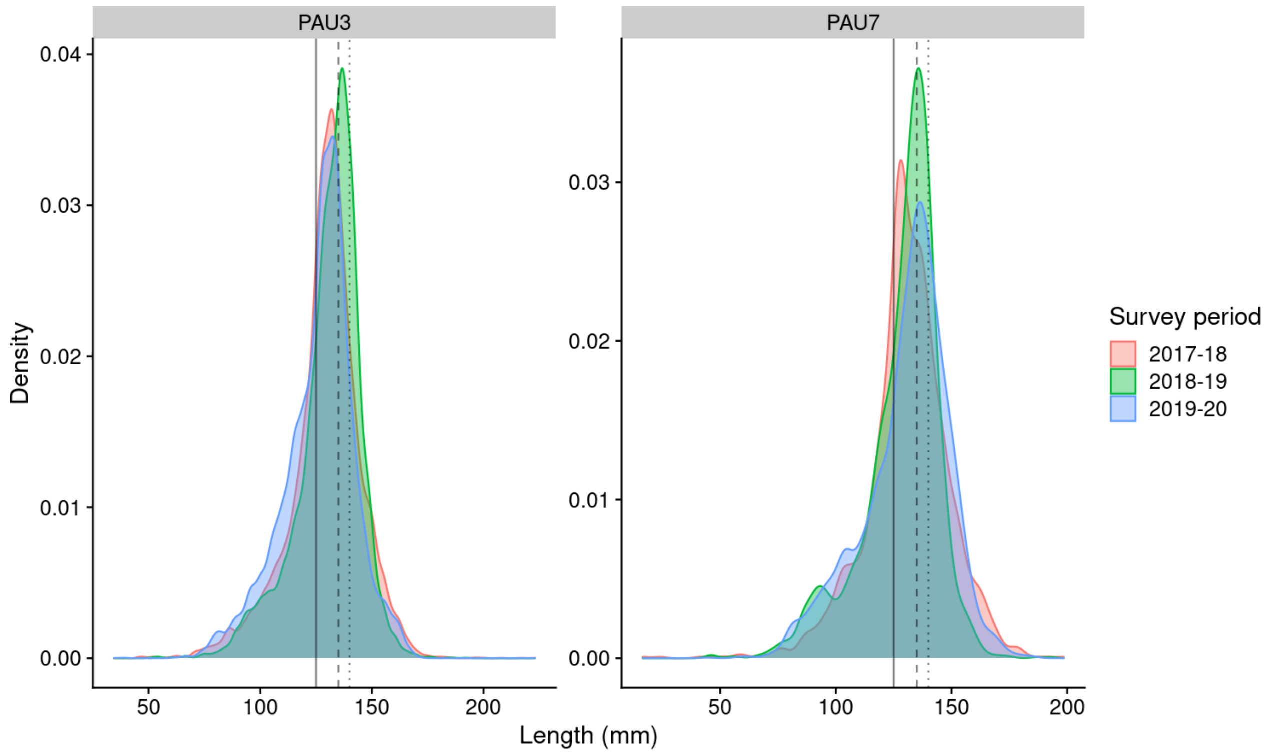


**Figure 11: Length-frequency profiles (as relative densities) for all pāua measured over three survey periods in PAU 3 and PAU 7. Vertical lines show the legal size of 125 mm (MLS; solid line), 135 mm (dashed line), and 140 mm (dotted line).**

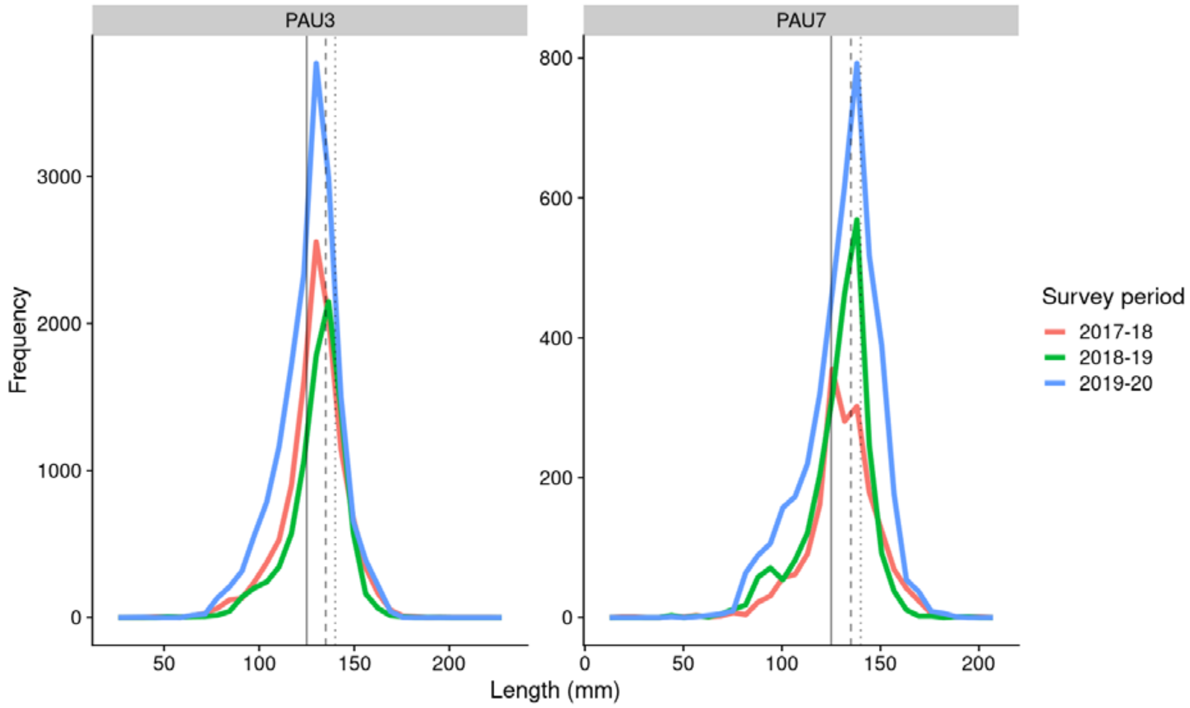


**Figure 12: Length-frequency profiles (as frequency) for all pāua measured over three survey periods in PAU 3 and PAU 7. Vertical lines show the legal size of 125 mm (MLS; solid line), 135 mm (dashed line), and 140 mm (dotted line).**

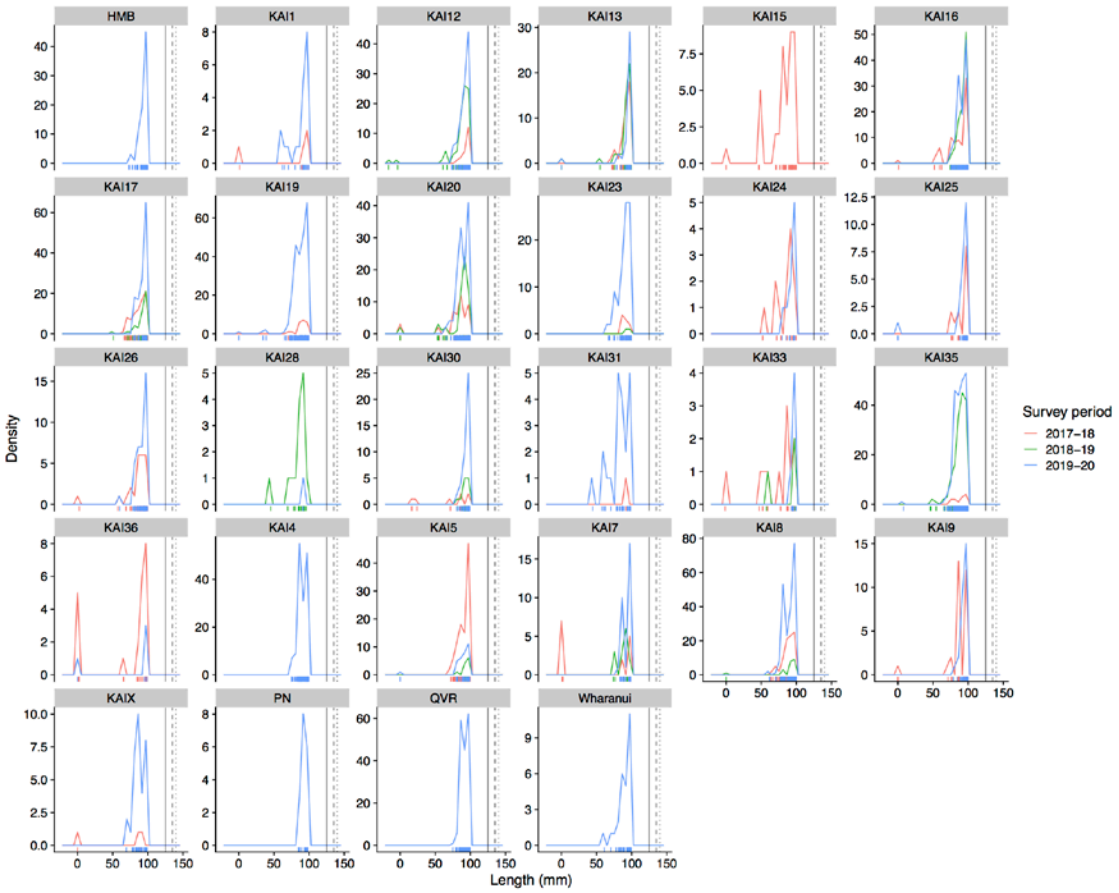


**Figure 13: Length-frequency density (by number of pāua measured) for individual sites surveyed over three survey periods. X-axis shows only individuals less than 100 mm.**

### 3.4 Depth of pāua measurement

Although the number of pāua measured generally increased across all size classes, there is no notable difference in the depths at which pāua were measured (Figure 14). There was a dominant mode of pāua at shallow depths of under 2 m, which may have resulted partly from divers pressing the measurement button at the surface rather than at depth. Few pāua were sampled beyond depths of 4 m.

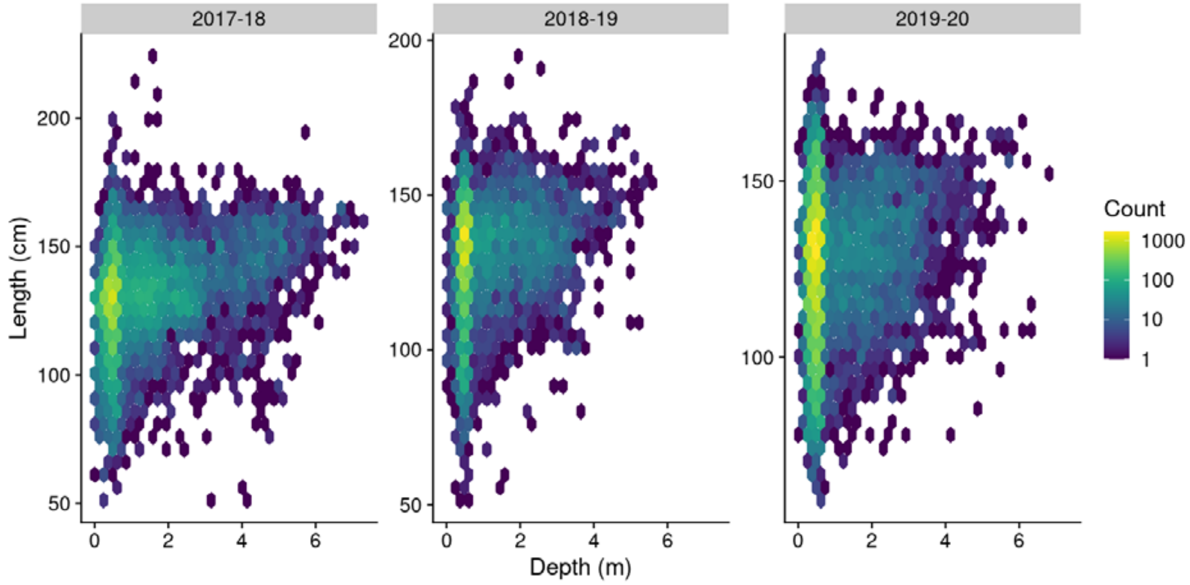


**Figure 14: Pāua length binned and plotted against measurement depth over three survey periods, with colour indicating the number of pāua within each hexagonal bin (on a logarithmic scale).**

## 4. DISCUSSION

### 4.1 Links to proposed reopening mechanisms

The primary purpose of this project was to obtain information about pāua population abundance trends and size structure (recruitment) to inform decisions about reopening the pāua fishery and subsequent management approaches. It is therefore important to discuss the surveys in the light of the (proposed) mechanisms and strategies for how the reopening may occur. At the time of publication, there are two relevant and related proposals for the reopening of the closed area; the proposal to subdivide the PAU 3 fishery, and the PAU3 Fisheries Plan.

#### 4.1.1 The PAU 3 subdivision proposal

As a result of the earthquake and subsequent closure there are now two distinct parts of the PAU 3 fishery: the area south of the Conway River, and the area north of the Conway River that is currently closed to pāua fishing (the southern aspect of the closed area). There has been a 50% reduction in the TACC in PAU 3 (to 45.8 t), which is currently only caught south of the Conway River. The proposal regarding the subdivision suggests subdividing the PAU 3 QMA (e.g., into PAU 3 North and PAU 3 South) to allow sustainability concerns to be better managed in the new smaller QMAs, to give the fishery in the north time to rebuild while supporting the sustainable use of the southern portion of the fishery. The creation of a new PAU 3 North would require the setting of a new TACC once the fishery is reopened. The request to subdivide the QMA has been made by PAU 3 quota owners. This proposal has been consulted with all relevant stakeholders and has been made available for public submissions, and the proposal is currently awaiting final approval by the Minister of Fisheries. Subdivision of the PAU 3 fishery is seen as a critical precursor to the implementation of the PAU3 Fisheries Plan discussed below.

### 4.1.2 The PAU3 Fisheries Plan (and reopening strategy)

The Minister for Ocean and Fisheries recently approved the PAU3 Fisheries Plan (hereafter 'the Plan') submitted by the PāuaMAC3 industry association. On the assumption that the QMA subdivision is approved, the Plan outlines key strategies for the maintenance of a sustainable PAU 3 South fishery and to enable the PAU 3 North fishery to be rebuilt. The Plan also contains strategies to guide the reopening and subsequent management of the PAU 3 North fishery. Key strategies of the PAU3 Fisheries Plan that relate to this project are given in appendix 1 of the Plan. These key strategies will be referred to later in this discussion. The strategy for the reopening and subsequent management of the PAU 7 section of the closed area will reflect that outlined in the Plan for PAU 3. The only difference will be the mechanism for how commercial catch limits are re-established because this will be through the release of shelving rather than the assignment of a new TACC.

## 4.2 Abundance trends

Since the establishment of baseline estimates of site-level pāua density in 2017–2018, a further two years of monitoring have shown an overall increase in pāua biomass at a QMA level in both PAU 3 and PAU 7. A notable aspect of the trend in PAU 3 (Figure 8) (and also reflected in other effects e.g., when sites are grouped by amount of uplift) is the slight decrease in abundance during the second survey period. This is likely to be due to the consistently poor survey conditions that were experienced during the second survey period. Although there was an attempt to standardise estimates for swell and visibility, the influence of these effects may have been greater than was able to be accounted for within the standardisation model. Further, only 13 of 23 initially surveyed sites in PAU 3 were able to be surveyed during this period, so there may have been potential bias towards sites which showed lower increases in abundance.

The other obvious difference between PAU 3 and PAU 7 in Figure 7 is the lower estimated abundance in PAU 7 for the three survey periods, but a greater increase in overall abundance across periods. The lower overall abundance in PAU 7 is likely to be a reflection of the status of the fishery (relative to PAU 3) before the earthquake closure. It is generally agreed by harvesters in the respective QMAs that the biomass in PAU 7 had reduced notably in recent years prior to the earthquake, whereas the PAU 3 fishery was in a healthy state pre-earthquake. The relative status of the fisheries pre-earthquake could also help explain the larger increase in abundance in PAU 7, because in PAU 3 there are more sites of very high abundance where the habitat may have reached carrying capacity thus hindering further increase in abundance.

Although overall trends in abundance have been positive across the three survey periods, there is variation in trends between sites (Figure 9). Variation between these sites can be related to the amount of uplift at each site and habitat related factors that support recruitment and/or increase in pāua abundance. For example, Waipapa 3 is a high uplift site that is mainly shelf and gut type habitat not typically associated with good recruitment, and new recruits are not generally observed until they are completely emergent (larger than approximately 100 mm). At this site the lack of increase in abundance suggests that the same pāua were measured for each survey, and new recruits have not yet been observed to increase the biomass. By contrast, KAI1 (North of Barney's Rock) is a low uplift site with good juvenile and adult boulder habitat that has seen a steady increase in abundance over the two surveys undertaken here.

Abundance trends also appear to have been influenced by the amount of uplift associated with specific sites (Figure 8). Sites that experienced higher uplift (over 2.53 m) showed a much lower increase in abundance compared with sites which experienced lower uplift (under 0.25 m). This observation is intuitive and is likely to be due to the higher mortality (of all life stages) and larger loss of habitat (in particular recruitment habitat under 2 m) experienced at sites with higher uplift. Although pāua in lower uplift sites are naturally increasing in abundance after relatively little disturbance, higher uplift sites are more likely to be waiting for the re-establishment of recruitment pathways to start increasing in abundance, which is also dependent on the re-establishment of appropriate juvenile and settlement habitats. This outcome suggests that spatial management based on the amount of uplift along the coast may be a sensible approach when the fishery is reopened, e.g., opening areas of low to medium uplift and maintaining closures in areas of high uplift.

Despite variability in trends overall, 26 out of 31 sites (see Figure 9) display an overall increase in abundance over three survey periods, with the remaining sites showing no change or very minor decreases. These findings would generally support the second criterion for the Minister to consider reopening the fishery, contained within strategy 2.2.2 of the recently approved PAU3 Fisheries Plan (Appendix B), i.e., that “A sustained increase in pāua biomass is observed across the fishery”.

## 4.3 Recruitment patterns

In fisheries, recruitment is the addition of individuals of a certain size or reproductive stage to a population. In the context of this project, recruitment is defined as the addition of newly emergent juveniles to the population (as detected by dive surveys). This phase corresponds to pāua of approximately 70–100 mm and is generally associated with the onset of maturity. Growth data from tagging studies, and recent mark recapture analyses of reseeds in the Kaikōura area, indicate that newly recruited pāua are approximately 3 years old (Gerrity et al. 2020 observed growth rates in reseeded pāua of up to 28 mm per year over two years). This is important in the wider context of this study because it suggests that newly emergent recruits are likely to be from spawning events that happened after the earthquake (November 2016).

Figures 12 and 13 show that there has been an observable increase in the number of post-earthquake recruits (70–100 mm) in sites in both QMAs. Site-specific recruitment is more easily observed where length frequency is plotted by number where the x-axis shows only pāua counted in this newly emergent size class (under 100 mm) (Figure 12). Figure 12 illustrates that there is an obvious pulse in recruitment in two thirds (21 of 30) of sites where length-frequency data were collected for the three survey periods. These findings are also supported by intertidal surveys monitoring juvenile pāua abundance by the University of Canterbury, where pulses in juvenile size classes are seen consistently at survey sites (Gerrity et al. 2020).

As discussed above, with regard to abundance trends across sites, observations about recruitment also generally support the first criterion for the Minster to consider reopening the fishery contained within strategy 2.2.1 of the recently approved PAU3 Fisheries Plan (Appendix B), that “Widespread emergence of post-earthquake recruits is observed across the fishery”.

## 4.4 Depth distribution

From Figure 14 it can be seen that although the overall numbers of pāua across all size classes have increased over time, there is no evidence that pāua are being found deeper with time. This suggests that after the uplift, pāua generally retained their position, rather than moving out into deeper habitats. This has some potential implications for management because it means pāua are generally still in shallower waters (under 6 m) making them easily accessible to fishing (in particular, recreational fishing). It also means that, although significant shallow subtidal habitat has been lost, there is no evidence of pāua moving out to deeper “new” habitats.

However, there are some potential biases with regards to these inferences. Site areas were delimited by GPS marks or obvious geographic markers (rocks) before each survey, meaning that divers were generally restricted from surveying areas deeper than previous years. This means that pāua could be moving into deeper habitats and be missed in successive surveys. Also, there were instances where pāua were measured and counted on the bottom, but, for safety and practical reasons, the buttons were pushed and data registered at the surface and thus a depth of 0–1 m was recorded. This occurred more frequently in areas of very high densities.

Further, the fishery along most of the closed area was historically considered to be a ‘shallow’ fishery where commercial divers would not regularly dive deeper than 6 m (J. Ruawai, 2020, pers comm.).

## 4.5 Ongoing monitoring

Ongoing monitoring (including with the re-introduction of fishing) is included as a key strategy in the PAU3 Fisheries Plan (Strategy 2.1, see appendix 1). At the initial presentation of results to the Fisheries New Zealand Shellfish Working Group on the 17th of August 2020, there was agreement that measurements/biomass per unit effort (M/BPUE) was an acceptable proxy for estimated density for monitoring individual sites. The adoption of M/BPUE as an index of abundance simplifies the methods by removing the need to incorporate correct turtle unit usage into survey methods, meaning that more sites could be surveyed in a given day.

Further surveys undertaken in parallel with the potential reopening of the fishery, with increased numbers of survey sites, will create a better picture of the whole fishery in both QMAs. Further surveys of an increased number of sites will also enable specific areas of interest to be targeted for monitoring with the reintroduction of fishing, e.g., areas that are close to newly built ‘safe stopping areas’ on the new road, which essentially serve as recreational fishing access points. An increased number of sites will also enable more sites to be targeted towards higher fishery use areas, as well as those that experienced high uplift and have been shown to exhibit slower recovery rates.

# 5. MANAGEMENT IMPLICATIONS

Outcomes from this project can be used to guide decisions relating to the timing of reopening and subsequent management of the earthquake-affected parts of the PAU 3 and PAU 7 fisheries. These outcomes, after three years of monitoring, suggest the criteria within the PAU3 Fisheries Plan for the Minister to consider reopening the fishery have been met, i.e., there is widespread emergence of post-earthquake recruits and a sustained increase in biomass observed across the fishery.

Outcomes from this work can also guide management following the reopening of the fishery. For example, parts of the fishery that experienced higher uplift have been slower to increase in abundance than lower uplift sites. This would be one obvious way to spatially manage the fishery, e.g., allow fishing in medium to low uplift areas and keep high uplift areas closed until they show adequate recovery. This would also necessitate ongoing monitoring that could potentially be targeted towards higher uplift sites and high use areas (e.g., new recreational fishing access points). Ongoing monitoring could also complement fisheries dependent data (CPUE) after commercial fishing recommences. These data sets could ultimately inform a harvest control rule to enable the TACC to be adjusted annually.

# 6. ACKNOWLEDGMENTS

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## APPENDIX A – MODEL FIT AND SUPPLEMENTARY PLOTS

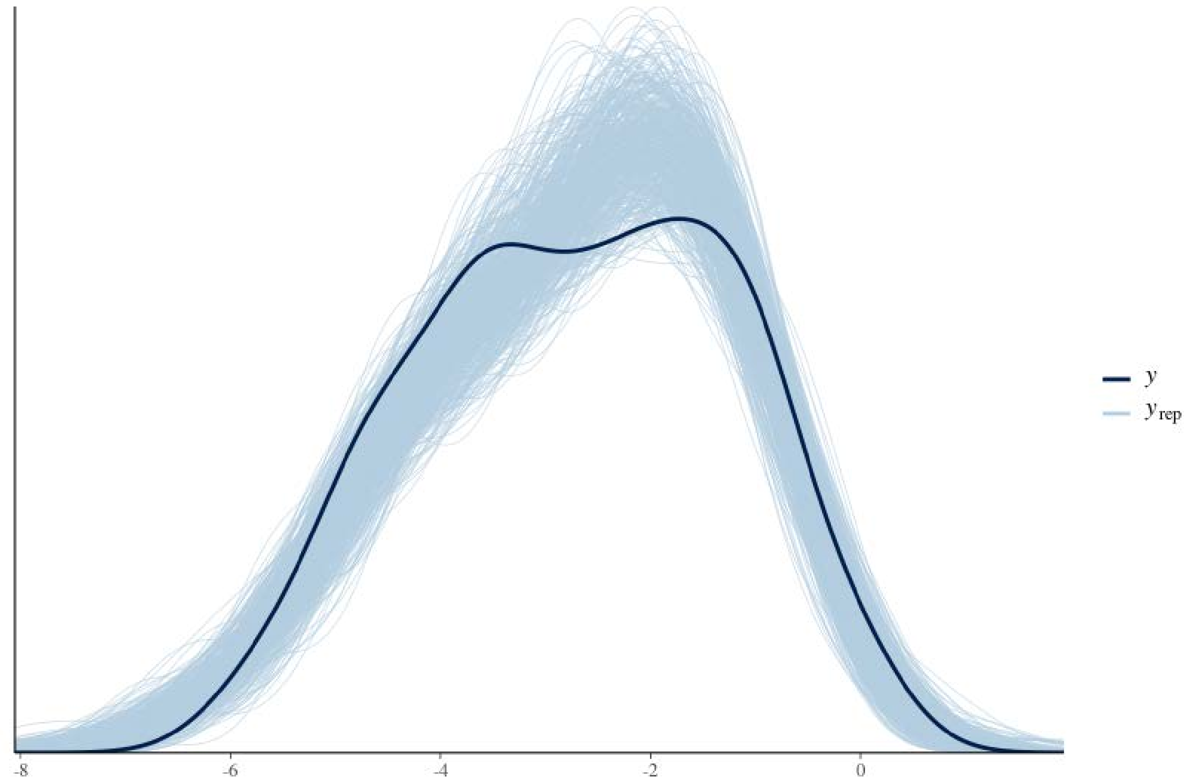


**Figure A-1: Model fit for the model relating density and measurements per unit effort (MPUE), as assessed by draws from the posterior predictive distribution (blue lines) compared with the empirical density for density data (black line).**

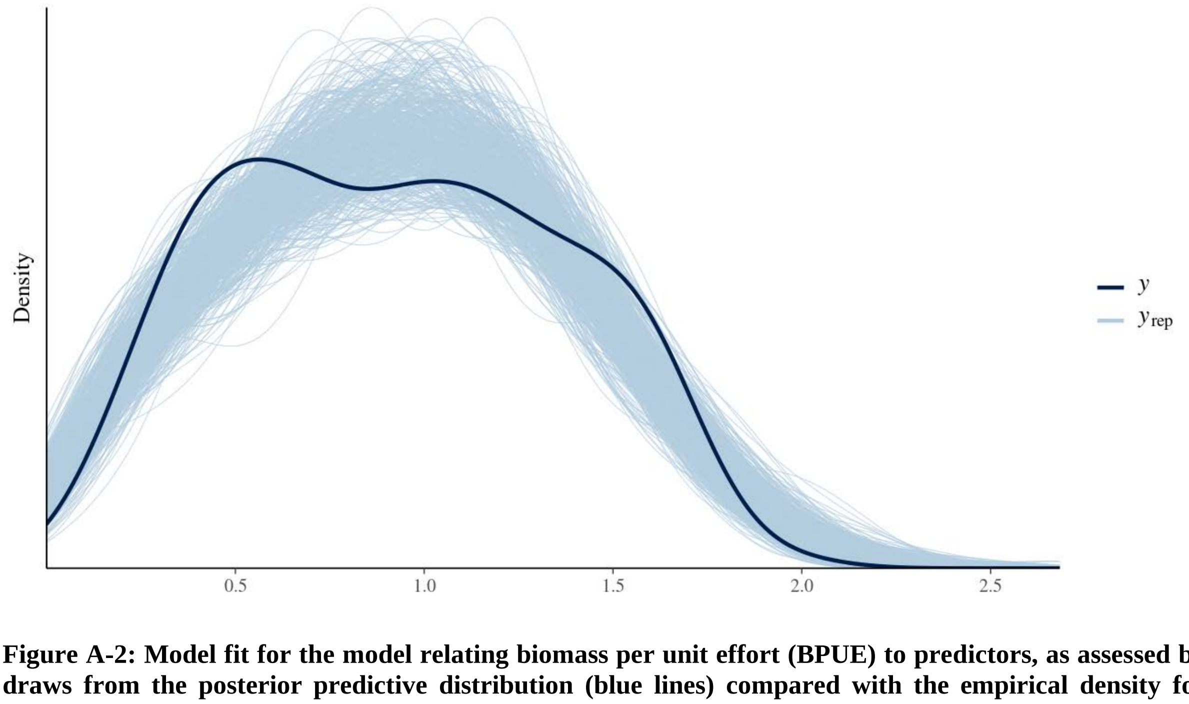


**Figure A-2: Model fit for the model relating biomass per unit effort (BPUE) to predictors, as assessed by draws from the posterior predictive distribution (blue lines) compared with the empirical density for density data (black line).**

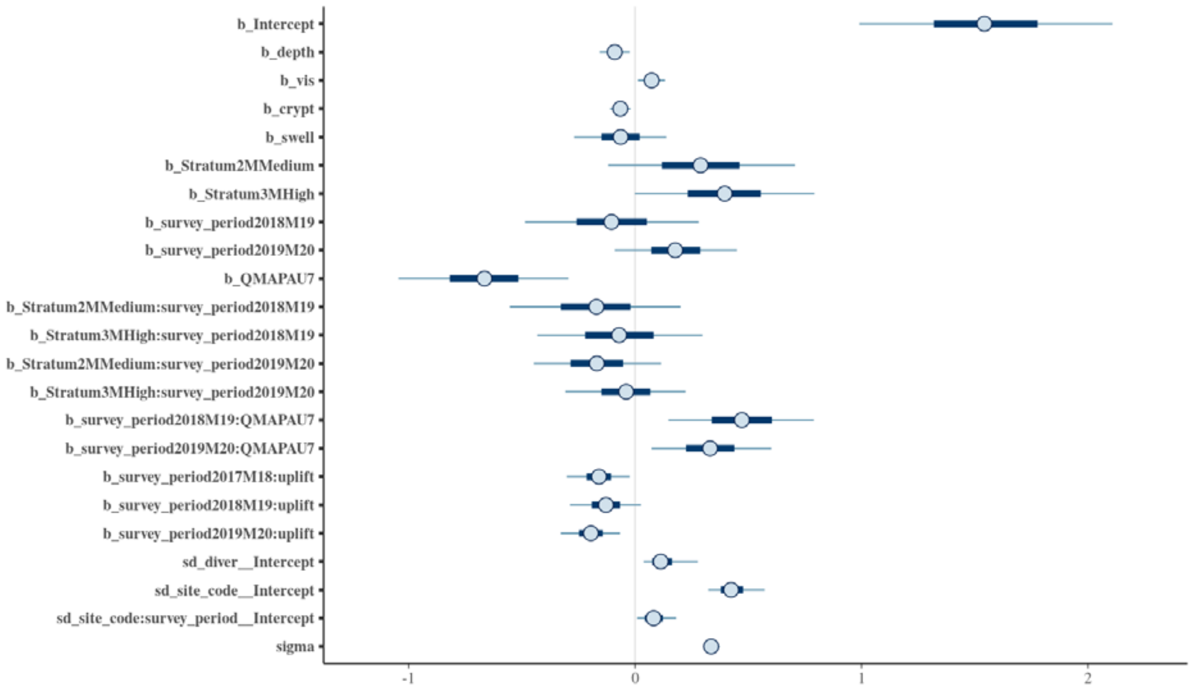


**Figure A-3: Estimated coefficients in the biomass per unit effort (BPUE) model. Note the similarity (near identical estimates) to the MPUE model in Figure A-4.**

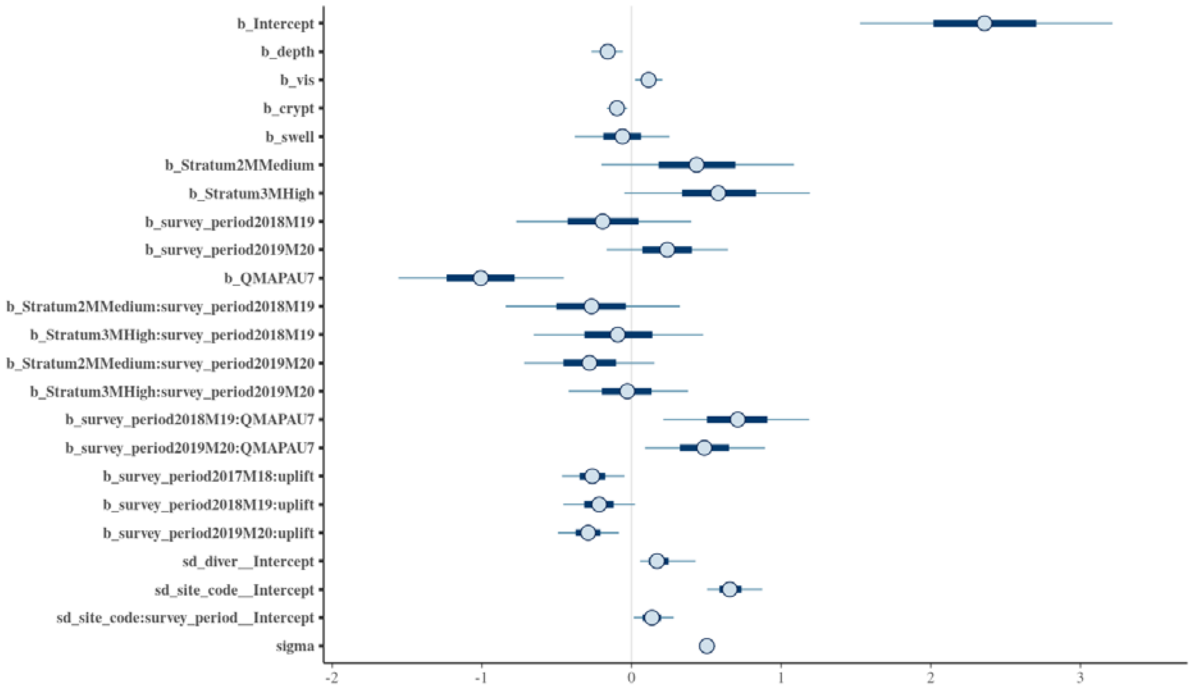


**Figure A-4: Estimated coefficients in the measurements per unit effort (MPUE) model. Note the similarity (near identical estimates) to the BPUE model in Figure A-3.**

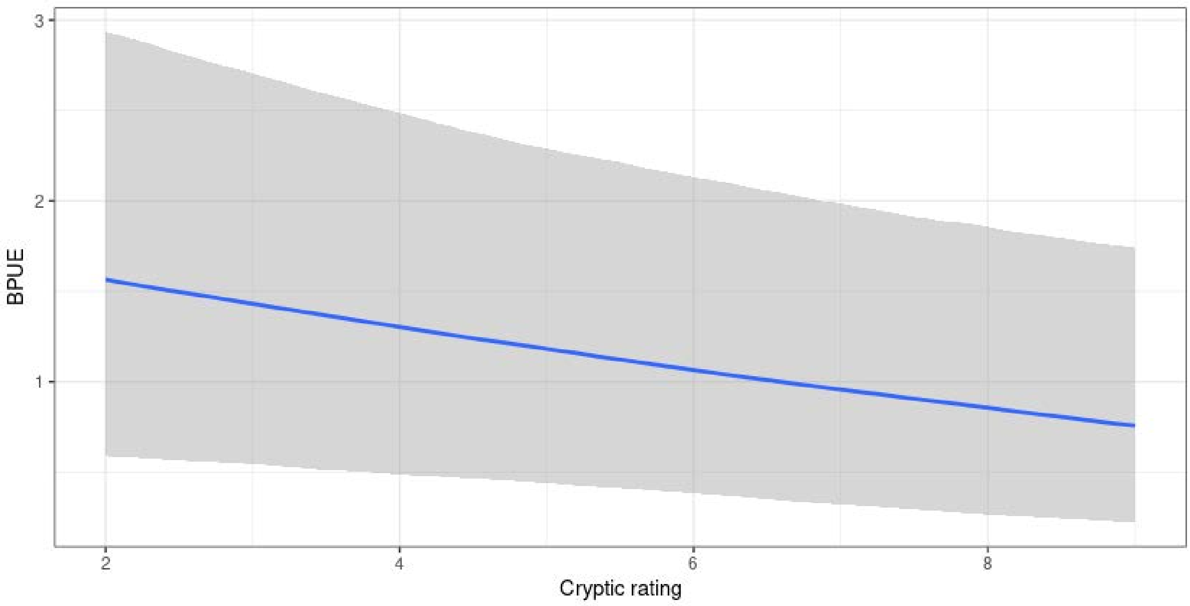


**Figure A-5: Effect of cryptic rating in the biomass per unit effort (BPUE) model, as assessed by its marginal impact on BPUE.**

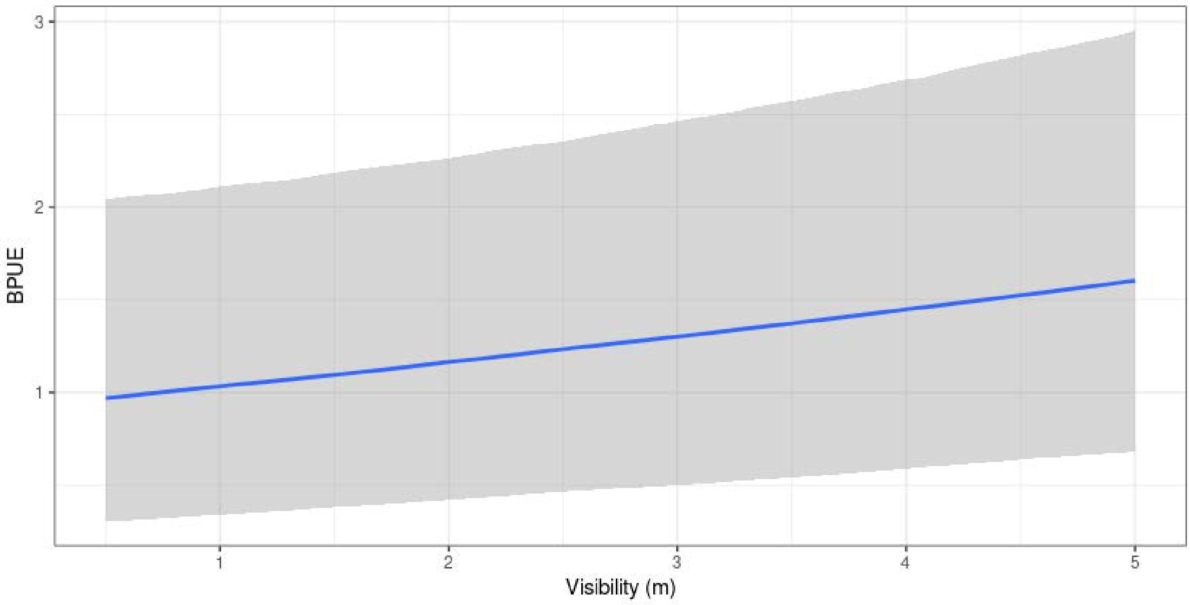


**Figure A-6: Effect of visibility in the biomass per unit effort (BPUE) model, as assessed by its marginal impact on BPUE.**

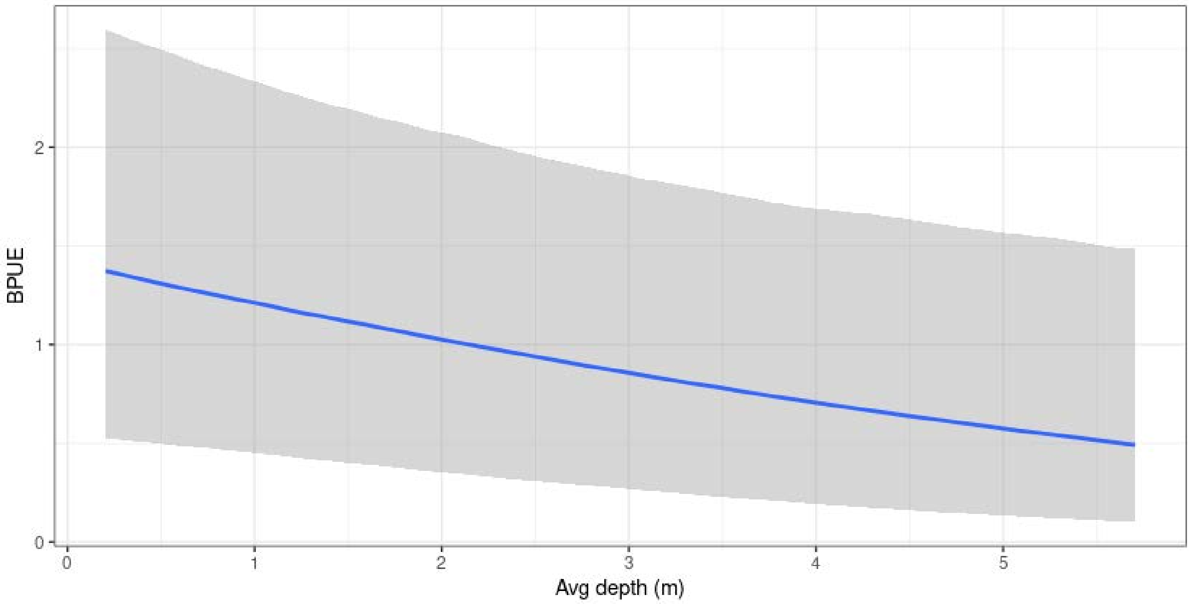


**Figure A-7: Effect of depth in the biomass per unit effort (BPUE) model, as assessed by its marginal impact on BPUE.**

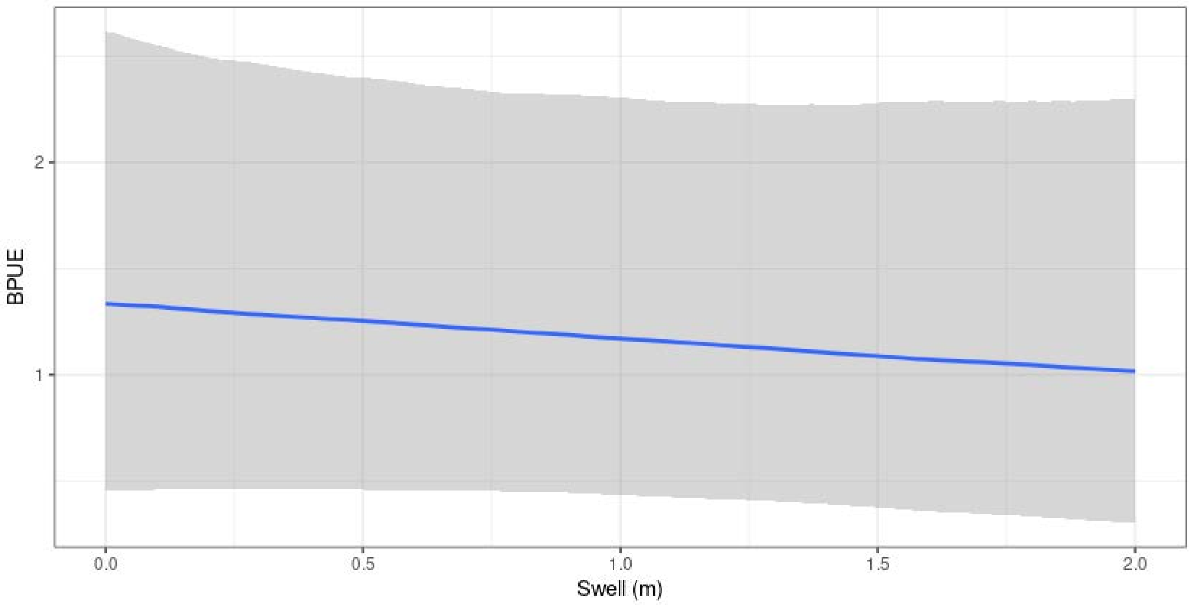


**Figure A-8: Effect of swell in the biomass per unit effort (BPUE) model, as assessed by its marginal impact on BPUE.**

## APPENDIX B – KEY STRATEGIES OF THE PAU3 FISHERIES PLAN

**Strategy 2.1** Monitor the status of the fishery including by

2.1.1 Undertaking annual pāua stock monitoring surveys to collect data on site-specific and fishery-scale pāua density and length frequency estimates with the section 11 closed area; and

2.1.2 Supporting work by the University of Canterbury to estimate juvenile abundance in intertidal habitats.

**Strategy 2.2** Reopen (Ministerial decision) Recommend to the Minister of Fisheries that PAU3-N should be reopened to commercial pāua harvesting when the following performance standards are achieved, based on research and monitoring reviewed by the Fisheries New Zealand Shellfish Working Group.

2.2.1 Widespread emergence of post-earthquake recruits is observed across the fishery; and

2.2.2 A sustained increase in pāua biomass is observed across the fishery.

**Strategy 2.3** Initial TAC and TACC (Ministerial decisions). Recommend to the Minister of Fisheries that prior to reopening the section 11 closure, the Minister should, in relation to new QMA PAU3-N:

2.3.1 Set a TACC that provides for an initial level of commercial utilisation:

- Either at approximately 50% of the commercial catch previously taken from the closed area;
- Or at an alternative level recommended by the Fisheries New Zealand Shellfish Working Group as being appropriate to enable information to be collected from the fishery to inform future management decisions while ensuring sustainability.

2.3.2 Set a customary allowance based on actual customary catch and reflecting aspirations for customary harvest, a recreational allowance that is proportional to the TACC, and a TAC that is the sum of the TACC and all allowances.

**Strategy 2.4** Adaptive rebuild programme. Adopt the following management measures during the adaptive rebuild phase:

2.4.1 Safeguard spawning biomass by setting a Minimum Harvest Size (MHS), where possible, in the range of 135 mm to 140 mm.

2.4.2 Spread commercial fishing effort and catch across the 10 statistical areas in PAU3-N, using estimates of pāua habitat availability, density and length frequency, supplemented by diver-provided information, and scaled to the observed level of recruitment in each area.

2.4.3 Collect comprehensive, fine-scale data to inform future management decisions, including:

- Catch and location data (from Fisheries New Zealand's mandatory electronic reporting and geospatial position reporting system);
- Commercial length frequency data (from the shell sampling programme, see strategy 3.1.3);
- Population length frequency data (from dive surveys);
- Additional data, if necessary, as recommended by the Fisheries New Zealand Shellfish Working Group.

2.4.4 Use a harvest control rule (HCR) to inform recommendations on commercial harvest levels, and review and if necessary adjust the HCR on an annual basis in response to stakeholder input and advice from the Shellfish Working Group.

2.4.5 (Ministerial decision) Recommend to the Minister of Fisheries that the PAU3-N TAC and TACC should be reviewed and, if necessary adjusted, on an annual basis until the stock is at or above the target level of biomass.