Fisheries New Zealand

Tini a Tangaroa

Pāua abundance trends and population monitoring in areas affected by the November 2016 Kaikōura earthquake, December 2021 update

New Zealand Fisheries Assessment Report 2022/15

T.A. McCowan,
P. Neubauer

ISSN 1179-5352 (online)
ISBN 978-1-99-102693-4 (online)

May 2022

Te Kāwanatanga o Aotearoa

New Zealand Government

Disclaimer

Requests for further copies should be directed to:

Fisheries Science Editor
Fisheries New Zealand
Ministry for Primary Industries
PO Box 2526
Wellington 6140
NEW ZEALAND

Email: Fisheries-Science.Editor@mpi.govt.nz
Telephone: 0800 00 83 33

This publication is also available on the Ministry for Primary Industries websites at:
http://www.mpi.govt.nz/news-and-resources/publications
http://fs.fish.govt.nz go to Document library/Research reports

Please cite this report as:

McCowan, T.A.; Neubauer, P. (2021). Pāua abundance trends and population monitoring in areas affected by the November 2016 Kaikōura earthquake, December 2021 update. *New Zealand Fisheries Assessment Report 2022/15*. 20 p.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

McCowan, T.A.[1]; Neubauer, P.[2] (2022). Pāua abundance trends and population monitoring in areas affected by the November 2016 Kaikōura earthquake, December 2021 update.

***New Zealand Fisheries Assessment Report 2022/15.* 20 p.**

The November 2016 Kaikōura earthquake caused coastal uplift resulting in high pāua (*Haliotis iris*) mortality and extensive loss of critical pāua habitats. The uplift affected approximately 120 km of coastline that supports significant customary, recreational, and commercial pāua fisheries. There has been a closure of the pāua fishery from the Conway River in the south to Marfells Beach in the north (the 'closed area') since November 2016 to allow for recovery of affected pāua populations. The fishery was re-opened for the first time for a three month period on the 1st of December 2021.

Surveys monitoring pāua abundance and length-frequency have been undertaken annually for the last four years (since 2017), in the closed area (McCowan & Neubauer 2018, McCowan & Neubauer 2021). These surveys have employed a modified timed swim methodology to estimate site and area-wide (QMA) trends in pāua abundance and length frequency. Results from these surveys have shown an overall increase in adult biomass, and widespread juvenile recruitment, which supported the decision to re-open the fishery on the 1st of December 2021 for a period of three months.

The objective of this project was to monitor the abundance and length frequency of adult pāua populations to estimate biomass trends to inform management actions at the scale of the closed fishery until mid-2023. This was achieved by continuing to monitor baseline estimates of pāua abundance and length-frequency profiles at selected sites within the closed area since 2017 (McCowan & Neubauer 2018, McCowan & Neubauer 2021).

Data analysis followed methods outlined by McCowan & Neubauer (2021), namely using generalised linear mixed models. Additional diagnostics to those presented for previous surveys were inspected to ensure that the model adequately captured variation in survey data across various strata (e.g., survey strata, quota management areas, survey periods) and covariates. These efforts suggested that multi-modality in the response within survey sites is a key driver of high variability (CVs) in survey estimates, a feature that arises from patchiness of pāua distributions and is largely irreducible with limited survey effort.

During surveys undertaken from November 2020 to February 2021, 31 out of 35 established monitoring sites were re-surveyed. Analyses show that abundance of pāua (represented by estimated biomass per unit time effort (BPUE)) across all sites and at a fishery-wide scale have continued to increase during the most recent survey period. A notable increase in abundance between the third and fourth period may be indicative of the emergence of post-earthquake recruitment of small (<100 mm) pāua that are now visible during dive surveys. This is supported by length-frequency data in PAU 3; however incomplete surveying of sites and habitat related factors mean this is not as evident in PAU 7. There is high variability in abundance and recruitment trends across surveyed sites which could be attributed to site-specific variability in uplift and habitat related factors. Overall, current trends continue to support the criteria for fishery re-opening.

This project monitored pāua abundance across sites immediately prior to the re-opening of the fishery and resumed after the fishery closed on the 28th of February 2022 to assess the impacts of the three month fishing season on pāua abundance. BPUE derived from these surveys (in conjunction with fisheries dependent data) will be used as an index of abundance to inform a harvest control rule to allow for adaptive rebuilding of the fishery with ongoing fishing in the future.

[1] Pāua Industry Council, New Zealand.
[2] Dragonfly Data Science, New Zealand.

1. INTRODUCTION

1.1 The fishery closure

The November 2016 earthquake caused coastal uplift of up to 6 m along approximately 120 km of coastline from Spyglass Point in the south to Marfells Beach in the north. This resulted in mass mortality of a range of species that inhabit the diverse shallow sub-tidal and intertidal habitats affected by the uplift. Pāua (*Haliotis iris*) populations in particular were severely impacted, with mass mortality at all life stages and significant loss of critical habitats. 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 stages. An initial assessment of the amount of the pāua fishery that was lost to the uplift was estimated at 21% of previously fished areas (Neubauer 2017). This initial finding and general observations of pāua mortality and habitat loss resulted in the emergency closure of the pāua fishery from the Conway River in the south to Marfells Beach in the north ('the closed area') under section 16 of the Fisheries Act.

The closed area contains pāua fisheries of high importance to recreational, customary, and commercial stakeholders. It spans two pāua quota management areas (QMAs), PAU 7 (Marlborough), and PAU 3 (Kaikōura-Canterbury) that have historically accounted for 15 t of total allowable commercial catch (TACC) from PAU 7 and 47 t from PAU 3 (approximately 16% and 50% of each respective QMA TACC). 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 effective reductions serve to stop the spread of displaced fishing effort into the remaining open parts of these QMAs. In April 2021, PAU 3 was formally sub-divided into two new QMAs, PAU 3A and PAU 3B (with the Conway River as the boundary). This was to help facilitate the implementation of new management strategies upon re-opening of the closed area (PAU 3A).

1.2 Prior research

Following the earthquake and closure of the pāua fishery, the Ministry for Primary Industries (now Fisheries New Zealand) funded a range of projects to assess ecological impacts of the earthquake to inform future management options. Pāua were specifically included in projects undertaken by the University of Canterbury (monitoring juvenile pāua recruitment in the intertidal zone) and by the Pāua Industry Council Ltd. (monitoring the abundance of mature pāua).

McCowan & Neubauer (2018) estimated pāua abundance and length-frequency profiles at 35 sites in the closed area, and at an area-wide scale (QMA) to establish baselines for further monitoring. In a two year continuation of this project, re-surveying of initially surveyed sites showed an area-wide increase in pāua abundance, and evidence of post-earthquake recruitment into the shallow subtidal zone, with variability in trends between sites attributable to pre-earthquake abundance and the degree of uplift (McCowan & Neubauer 2021).

1.3 Fishery re-opening

In May 2021 the Kaikoura Marine Guardians submitted a proposal to the Minister to re-open the pāua fishery. This proposal was supported by previous results from this project and those from surveys monitoring juvenile pāua in the intertidal zone (Gerrity et al. 2020) which have illustrated an increasing abundance of mature adult pāua and area-wide post-earthquake recruitment. The proposal was drafted in consultation with all relevant fisheries and community stakeholders. This proposal was approved by the Minister for Ocean and Fisheries on 5th of October 2021, and the fishery was re-opened to all pāua fishing on the 1st of December 2021 for a period of three months.

1.4 Project objectives

This project is a three-year continuation of the monitoring established earlier by McCowan & Neubauer (2018) and continued by McCowan & Neubauer (2021) with the following objectives:

i. To complete pāua stock monitoring surveys to inform future management decisions at the scale of the earthquake fisheries closure in PAU 3 and PAU 7.
ii. To monitor the abundance and length-frequency of adult pāua populations to estimate biomass trends to inform management actions at the scale of the fishery closure until mid-2023.

Given the re-opening of the closed area to pāua fishing in December 2021, the primary purpose of these objectives is to inform management decisions relating to future adaptive management of the PAU 3A and PAU 7 East Coast fisheries.

2. METHODS

The general survey design for this project is the same as that employed in earlier assessments of pāua abundance in the closed area (McCowan & Neubauer 2018, McCowan & Neubauer 2021). However, changes have been made to data analyses and to how abundance is quantified. The following is a summary of the methodologies employed, and any applicable changes to the analyses are noted.

2.1 Site selection

Site selection was based on data-driven stratification. Sampling points were allocated only within strata representing areas relevant to the fishery.

Stratification procedure

Survey sites were selected from within strata of high, medium, and low fishery utilisation. Stratification was undertaken using all available data-logger data (industry collected GPS-referenced fine-scale catch and effort 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 1-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.

Assigning 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 (from approximately November to February), equating to approximately 30 dive days. Three sites (one in PAU 7 and two in PAU 3) were fixed to be aligned with intertidal juvenile pāua surveys being conducted by the University of Canterbury. Back-up 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 back-up sites. During initial baseline surveys, 35 sites (23 in PAU 3 and 12 in PAU 7) were surveyed (McCowan & Neubauer 2018). Over successive survey periods, attempts were made to re-survey these same sites to estimate longitudinal trends in pāua abundance at a site and an area-wide scale.

2.2 Sampling procedure

Dive surveys were conducted by a crew of three snorkel divers with commercial pāua diving experience. As much as possible, the same divers were used for surveys in each QMA to maintain consistency. At each sampling point a length 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. In previous surveys (i.e., McCowan & Neubauer 2018, McCowan & Neubauer 2021), each diver wore a GPS dive logger (‘turtle unit’) during the surveys to delimit the area swum to calculate pāua density estimates. However, due to issues with data quality from the turtle units, their use has not been continued in this project and a proxy for density (measurements per unit time effort, or MPUE) has been adopted (explained in detail under data analyses).

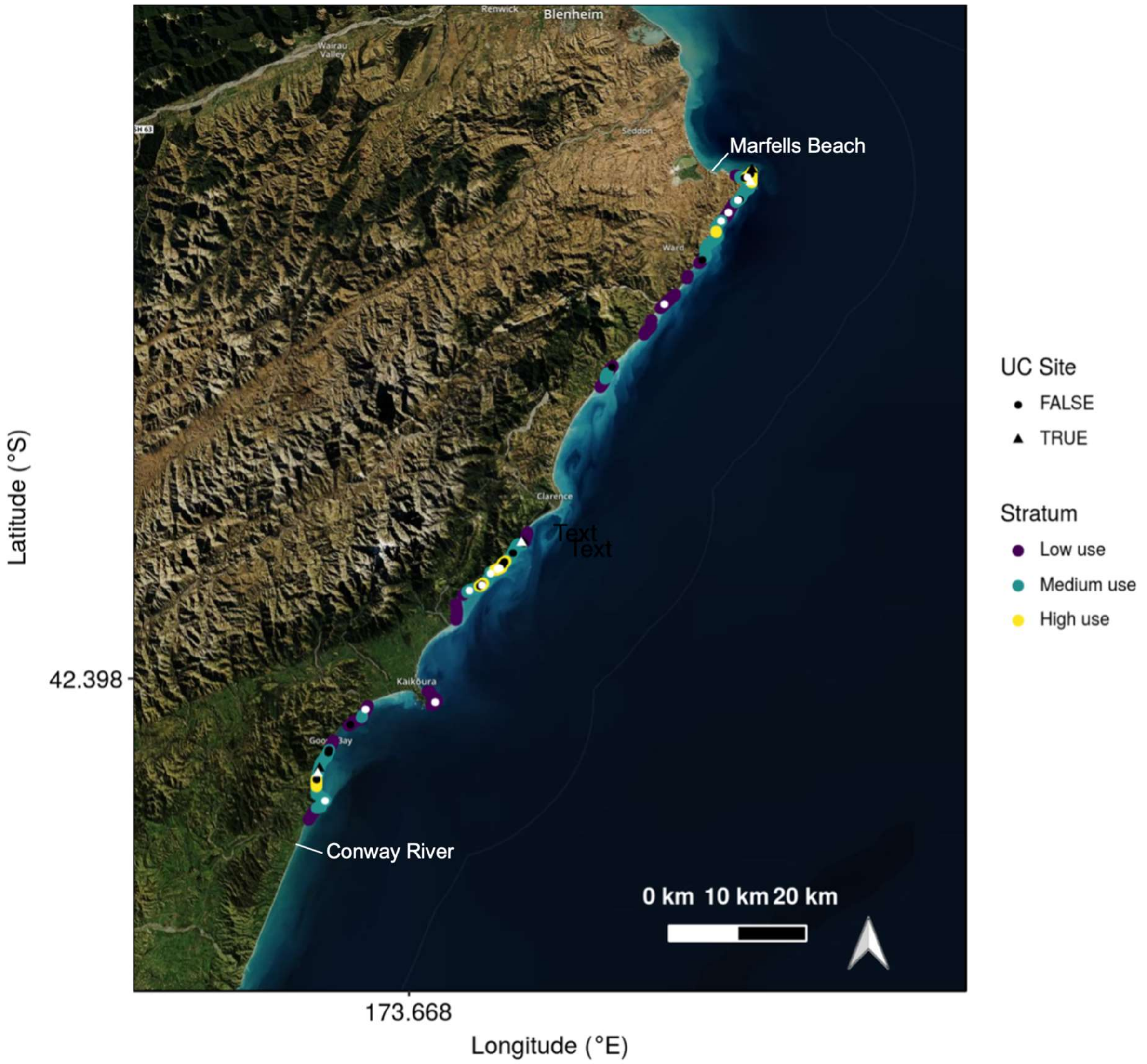

Figure 1: Extracted fishery use strata, established from the utilisation density by intersecting the density with the coastline to produce a 1-d line, and then dividing the cumulative 1-dimensional use distribution into inter-quantile ranges as described in the text. Selected sites (black) as well as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

Some sites additional to those allocated under the procedure described above were also surveyed. These sites were those of interest to commercial divers and were surveyed opportunistically when conditions were favourable at these sites, but not at those allocated under the sampling procedure. Data from these sites were kept and used for observational purposes (e.g., in recruitment detection) but were not included in overall analyses.

2.3 Data analyses

Earlier stages of this project developed a novel survey design to overcome some of the issues associated with previously trailed timed-swim methodologies for estimating pāua abundance. These methods relied on estimating pāua densities at allocated sites using a modified timed-swim design, using GPS 'turtle loggers' worn by divers to account for areas swum by divers. However, after the initial round of surveys, a number of problems were encountered with the overall design. In summary, these problems were due to a large amount of survey data having to be discarded due to missing GPS positions from dive loggers and difficulties in accurately estimating detection probability and up-scaling density estimates to absolute biomass (see McCowan & Neubauer 2021).

To address these issues, McCowan & Neubauer (2021) tested the number of measurements or estimated biomass per unit time effort (MPUE/BPUE) as a potential proxy for relative density differences, similar to catch per unit effort being used as a proxy for biomass in fisheries stock assessments. That analysis confirmed BPUE as a suitable predictor, showing an approximate 1:1 relationship between density and BPUE (slope=1.00, se = 0.06; Figure A-1).

Trends between surveys were then assessed using a Bayesian generalised linear mixed model to estimate: i) the over-all survey year effect, ii) a survey year within stratum (high/medium/low-use), iii) a survey year within QMA effect, and iv) a survey year within site effect. We used a truncated normal distribution to model the error in the (square root-transformed) response variable, with truncation to exclude negative numbers from the support of the error distribution. We also included predictors for potential nuisance variables (swell, visibility, depth, and cryptic rating) to remove potentially confounding effects (e.g., those that would affect detection probability). 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)
```

Additional diagnostics to those presented for previous surveys were inspected to ensure that the model adequately captured variation in survey data across various strata (e.g., survey strata, QMAs, survey periods) and covariates. For continuous covariates (here depth and cryptic rating as the two most influential variables), diagnostics were calculated as errors of posterior predictive means (residuals) which were plotted against the covariates to inspect for potentially non-linear relationships. For model strata, we plotted posterior predictive densities against raw densities to ensure that the model captures variability within all model strata.

3. RESULTS

3.1 General survey outcomes

The first round of surveys undertaken during the initial project (McCowan & Neubauer 2018) resulted in 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 haphazardly 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 distributions were made across all of these sites (as well other descriptive statistics).

The continuation of the project over the last three years has seen three more rounds of surveys attempted across all initially surveyed sites; 21 out of 35 sites were re-surveyed during the second survey period, 34 out of 35 during the third, and 31 out of 35 during the fourth, most recent survey period. Over these years, incomplete coverage of sites was due to consistently poor survey conditions (large swell or poor visibility) during the survey period and/or logistical constraints.

3.2 Pāua abundance trends

Figure 2 shows raw pāua abundance data expressed in measurements per hour by individual divers across sites within different fisheries use strata. This shows that the number of pāua counted by each diver at each site was consistently variable across all survey periods. While there is a general trend of increasing number of pāua measured across all four survey periods, there is no obvious link between abundance trends and fishery use strata (see Figure 3).

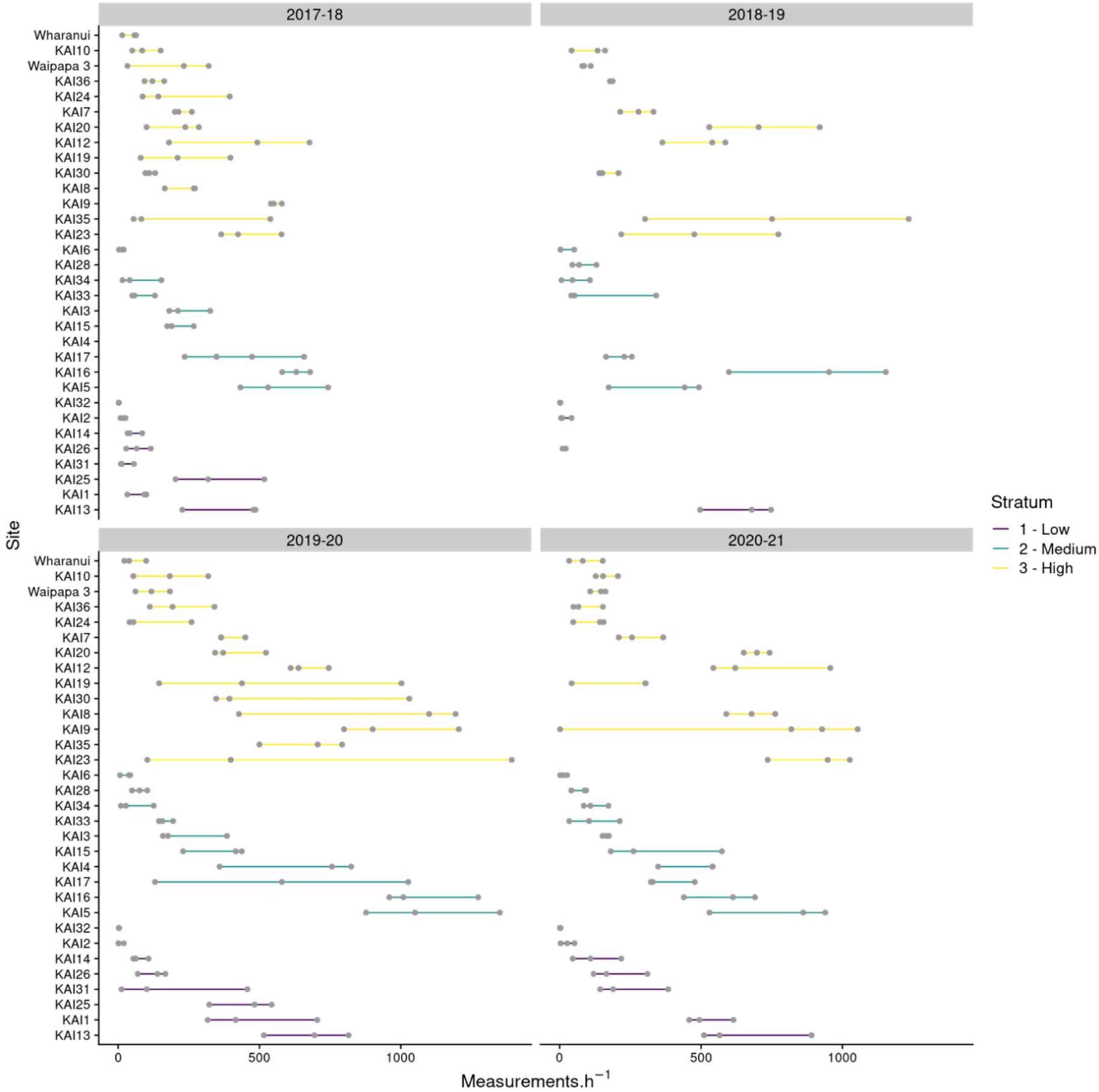

Figure 2: Numbers of pāua counted per hour at each site across four survey periods, with points indicating results from individual divers, and lines showing the range. Colour indicates the survey stratum.

Measurement data shown in Figure 2 were used to model BPUE as proxy of pāua density. Models on square-root-transformed data had adequate fits (Figure A-2). Estimates of coefficients are shown in Figure A-3). Coefficients for confounding variables were close to expectation, with lower visibility, higher cryptic rating, depth, and swell leading to less measurements/biomass per unit time (Figures A-4 to A-7), noting that surveys only took place when conditions were acceptable for diving (i.e., swell less than 2 m).

Overall pāua density, as approximated by BPUE, has increased steadily between the first and last survey periods, with a notable increase between third and fourth survey periods (Figure 4). Although the estimates are uncertain, median estimates suggest an approximate increase of 50% in pāua abundance between the initial and final survey periods. Increases were predominantly driven by increases in low- and high-use strata (Figure 3). Trends in BPUE were similar in PAU 7 relative to PAU 3 (Figure 5), although BPUE has remained substantially higher in PAU 3 than that in PAU 7. While there was a general trend of increasing abundance over survey periods across both QMAs, and across sites of different amounts of uplift, there was high variability in trends at individual sites (Figure 6).

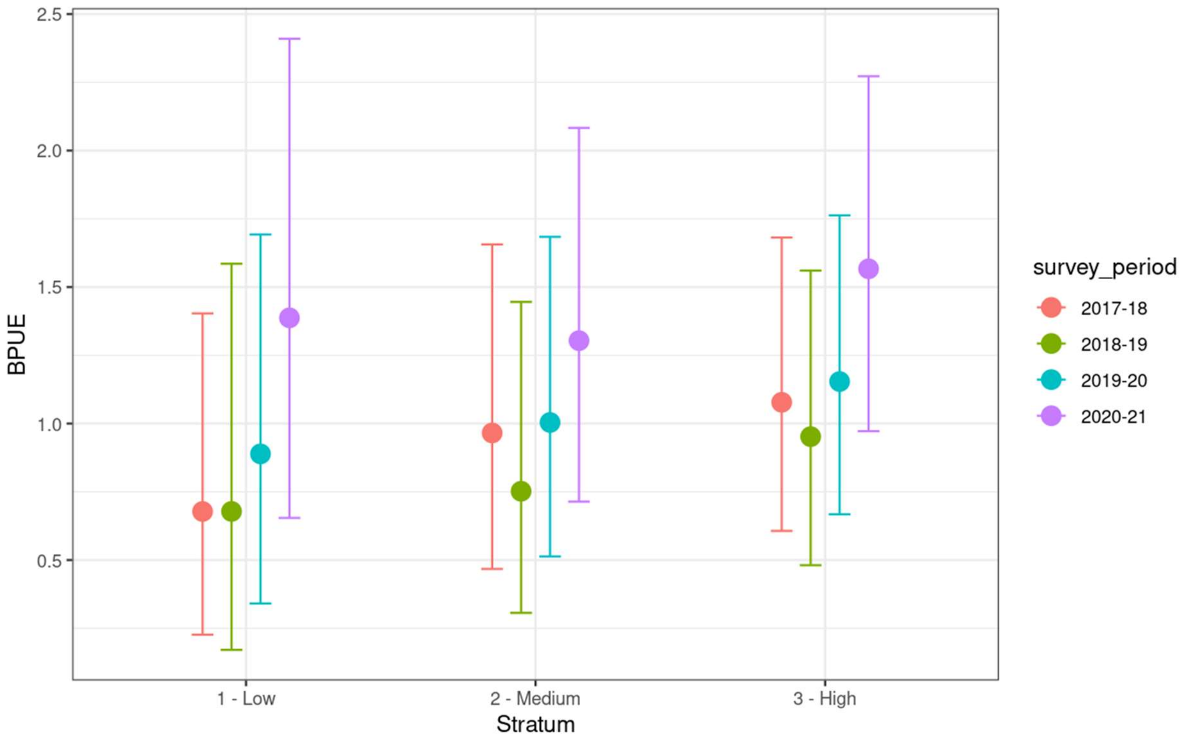

Figure 3: Marginal trend (relative to a geometric mean of 1) in biomass per unit effort (BPUE) across survey years and strata from the BPUE model after accounting for confounding variables.

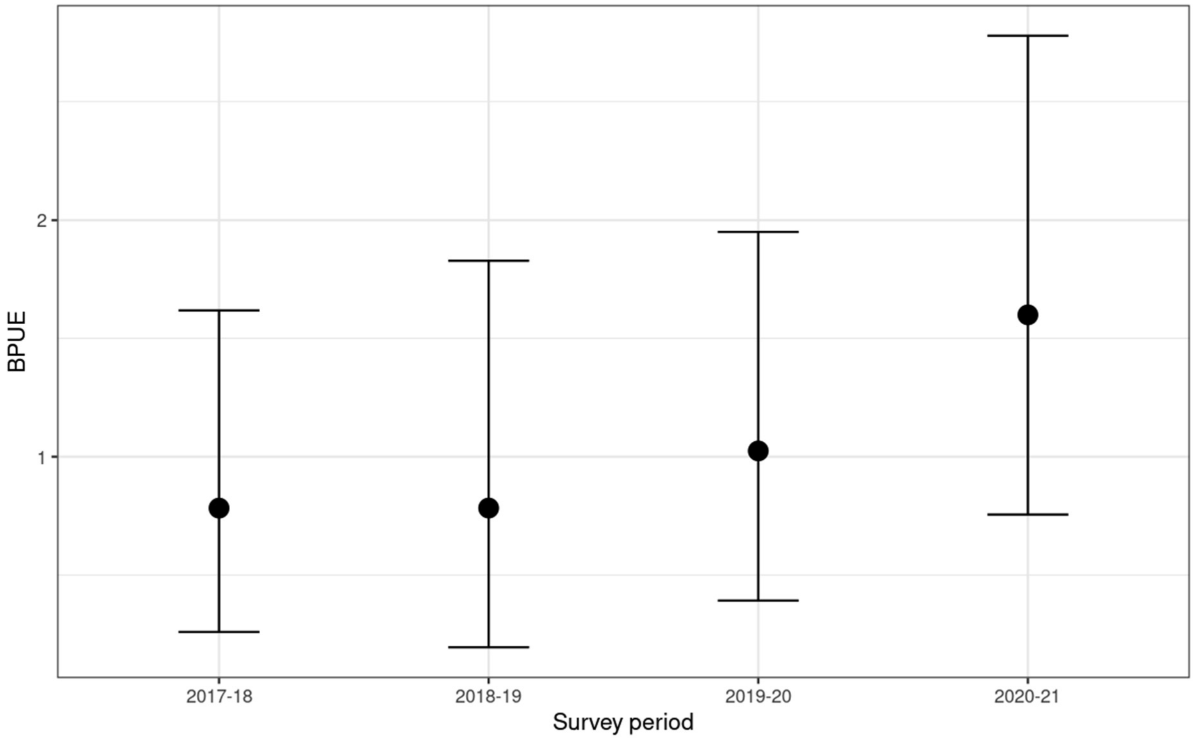

Figure 4: Marginal trend (relative to a geometric mean of 1) in biomass per unit effort (BPUE) across survey years from the BPUE model after accounting for confounding variables.

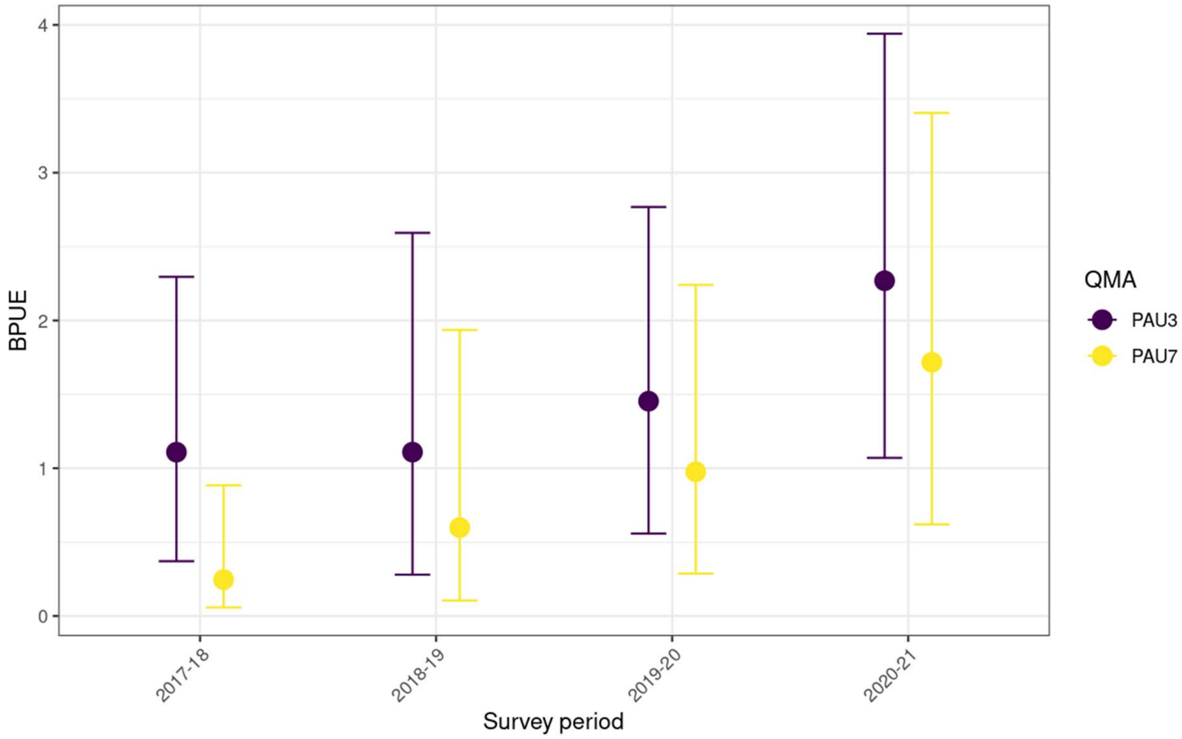

Figure 5: Marginal trend (relative to a geometric mean of 1) in biomass per unit effort (BPUE) across survey years for QMAs PAU 3 and PAU 7 from the BPUE model after accounting for confounding variables.

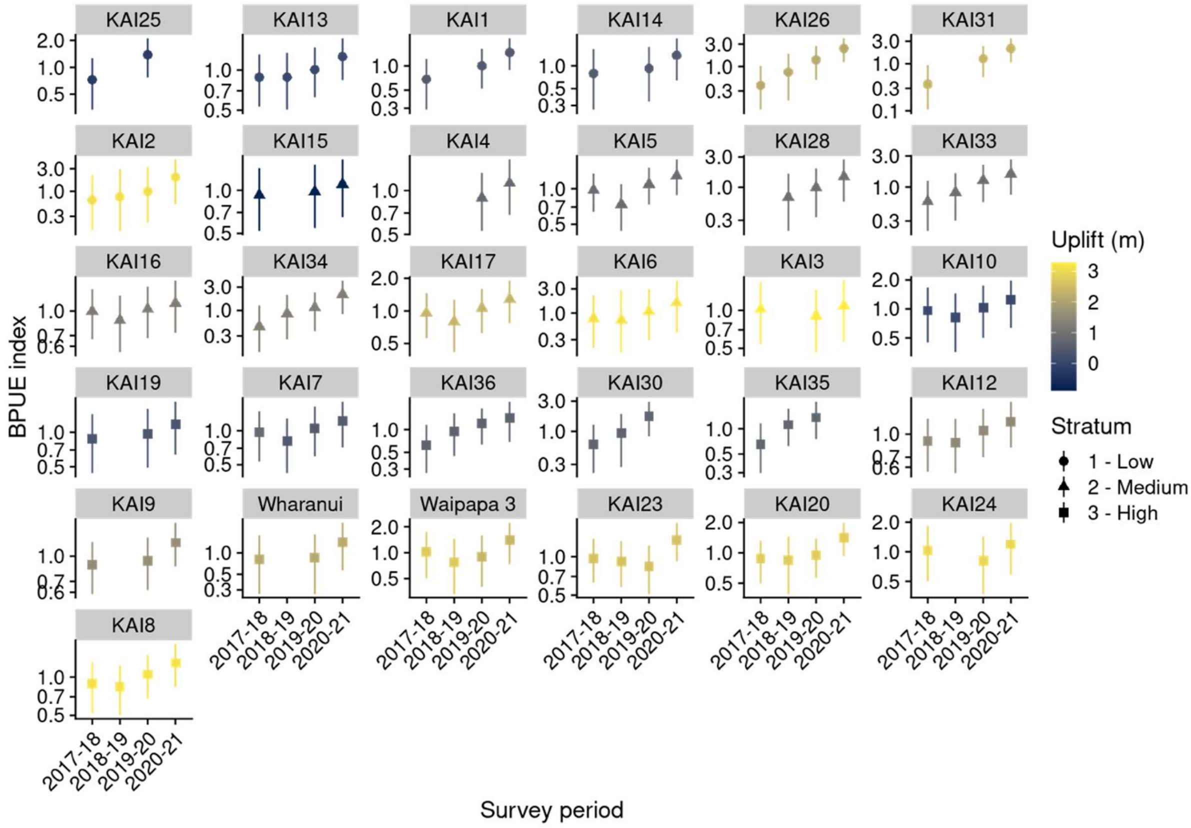

Figure 6: Marginal trend (relative to a geometric mean of 1 at each site) in biomass per unit effort (BPUE) across survey years for QMAs PAU 3 and PAU 7 from the BPUE model after accounting for confounding variables.

Model diagnostics suggested that multi-modality in the response within survey sites is a key driver of high variability (CVs) in survey estimates (Figures A-2–A-5). Although the model itself fits the data by introducing sufficient residual variation (Figure A-2), it appears to do so to accommodate the strong multi-modality in the data that is not explained by the model covariates or stratification. Especially the medium-use stratum (Figure A-3) as well as the most recent survey (Figure A-4) had highly multi-modal distributions. PAU 3 also showed a more multi-modal distribution overall than PAU 7, which had a more dominant mode at smaller biomass per unit time estimates (Figure A-5). However, this feature stems from within site variability (Figure 2) rather than variability among sites within strata and is therefore not easily reducible by further stratification. In addition, there was no evidence that a non-linear effect of covariates could have caused multi-modality (Figures A-6 & A-7).

3.3 Length-frequency observations (recruitment patterns)

Length frequencies of pāua were analysed across all sites and survey periods to make size class and recruitment observations at QMA levels (Figure 7). In PAU 3, length-frequency profiles have been reasonably stable across the larger size classes (125–150 mm) across all survey periods, whereas in PAU 7 there has been an observable shift in mode across survey periods, with more large pāua (>140 mm) in the most recent survey period (Figure 8). In the smaller size classes, there has been an increase in the number of emergent pāua recruits over the last two survey periods relative to the initial baseline survey in 2017 in PAU 3. The same trend does not occur in PAU 7, with a lower number of emergent size classes observed during the most recent survey period. These observations are most evident in Figure 9, showing frequency profiles of pāua of different size classes (compared with relative densities in Figure 8). Figure 9 also shows that overall numbers of pāua measured in PAU 7 were significantly lower in the most recent survey period which is due to three high density sites not being able to be surveyed due to unfavourable dive conditions. In Figures 8 and 9, vertical lines on the plots mark 125 mm, 135 mm, and 145 mm as visual references for consideration of proportions of pāua over these sizes for minimum harvest size considerations.

Figure 10 shows the length-frequency profiles of pāua over all survey periods at each site, with the x-axis showing pāua less than 100 mm, which helps to visualise post-earthquake recruitment patterns 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 being measured at each site.

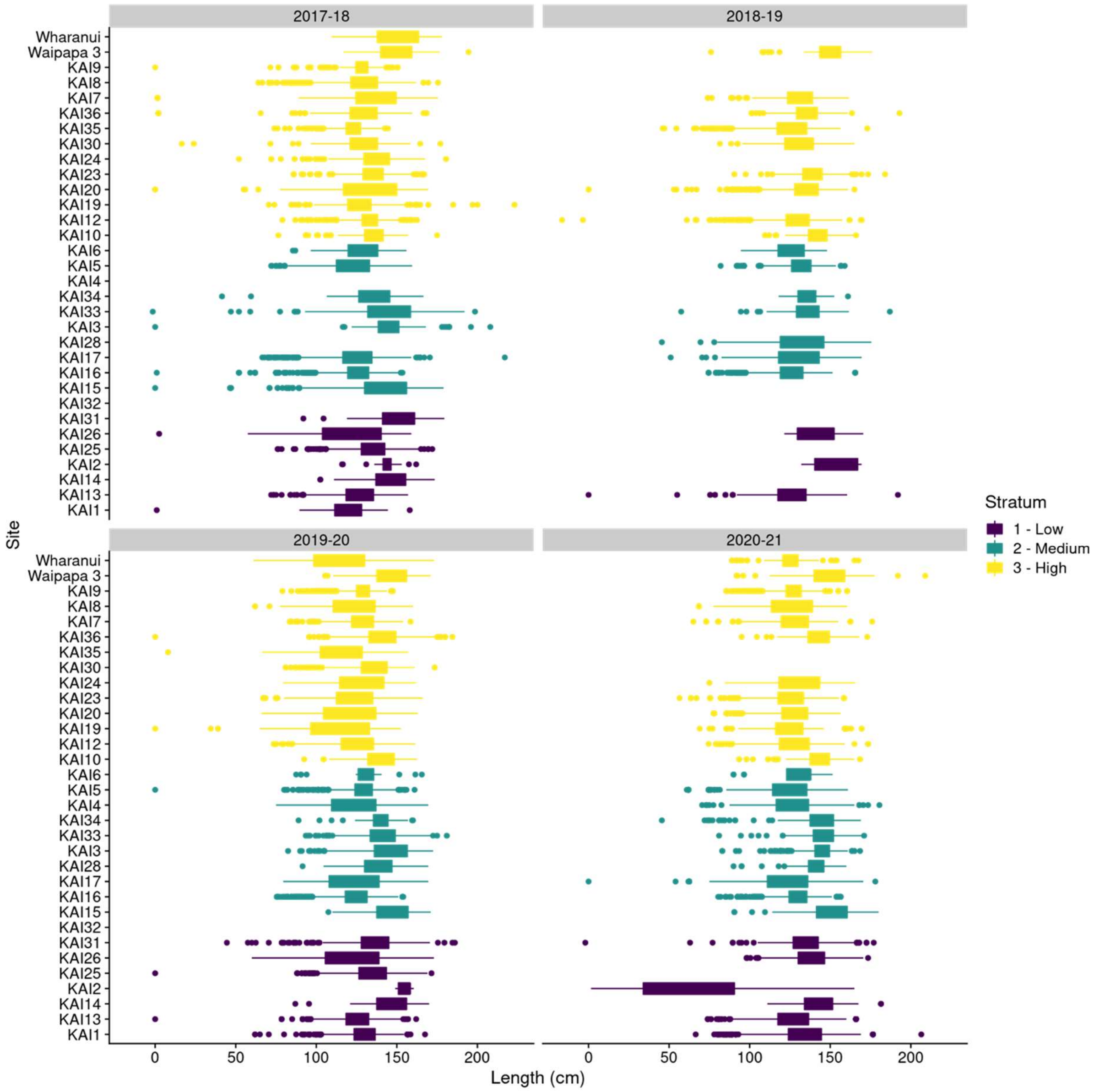

Figure 7: Boxplot of pāua length distributions found at survey sites over four survey periods. Colour indicates the survey stratum.

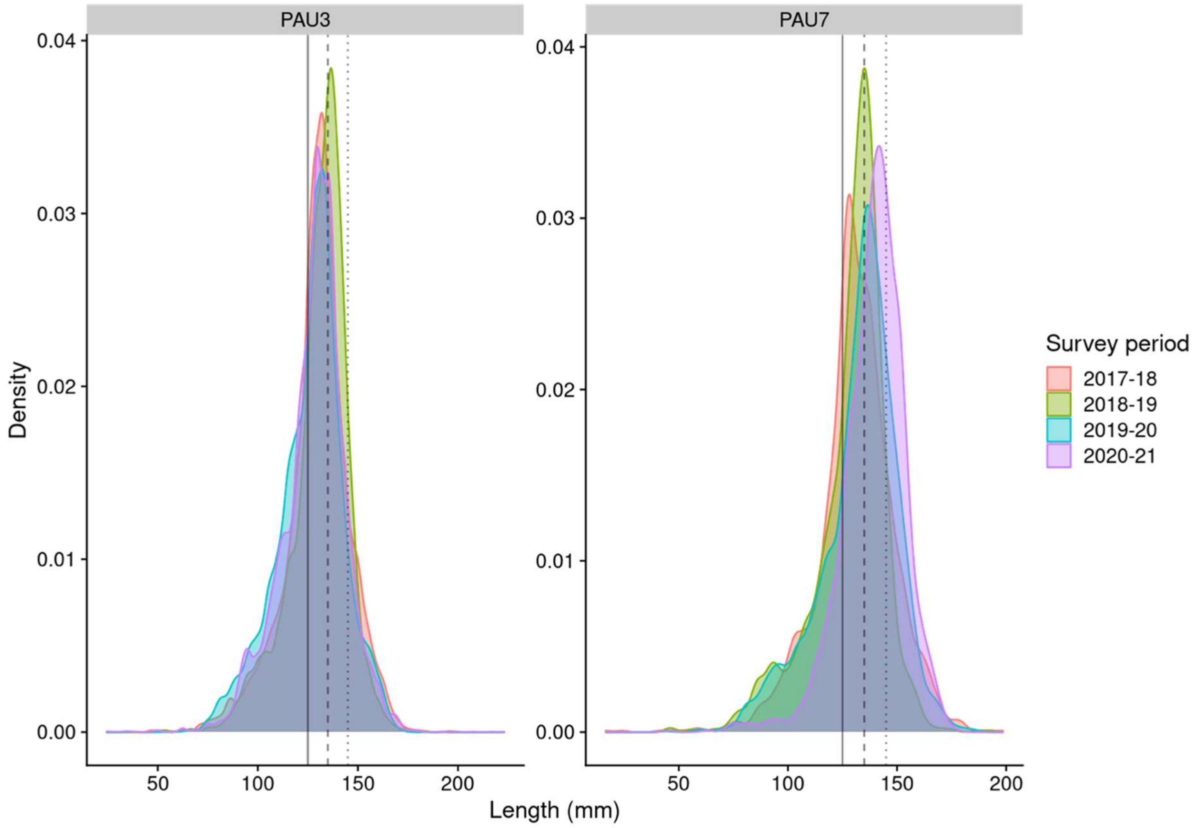

Figure 8: **Length-frequency profiles (as relative densities) for all pāua measured over four survey periods in PAU 3 and PAU 7. Vertical lines show the legal size of 125 mm (MLS; solid line), 135 mm (dashed line), and 145 mm (dotted line).**

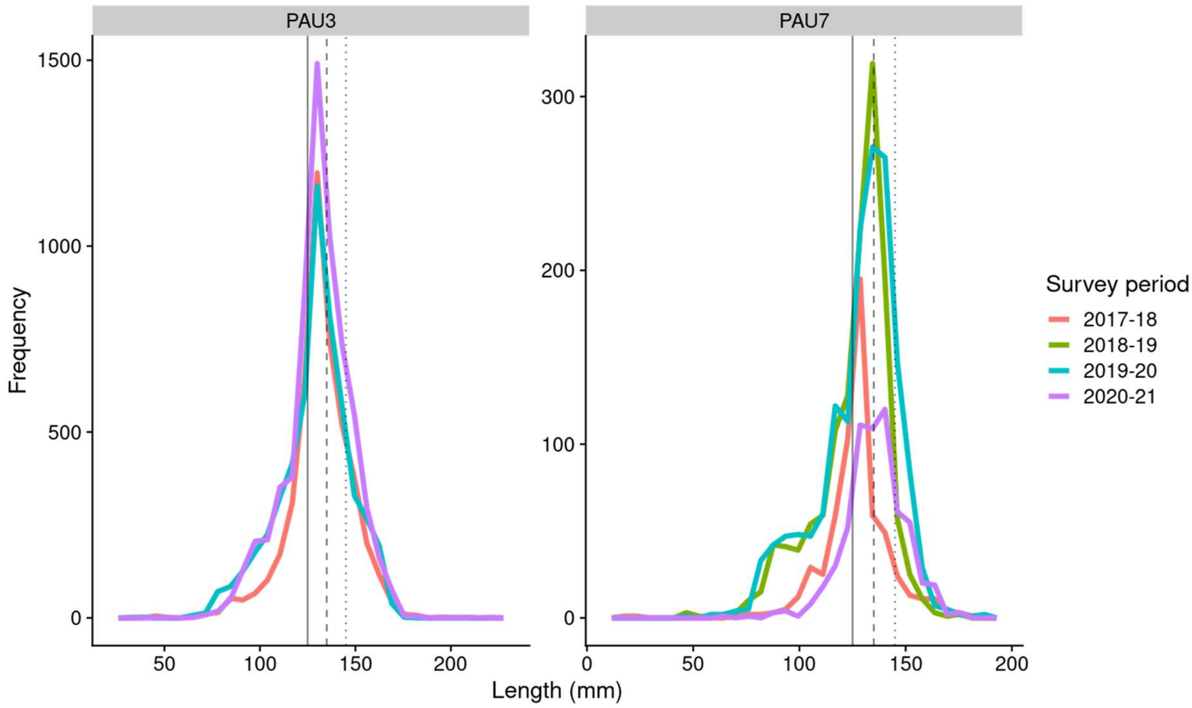

Figure 9: **Length-frequency profiles (as frequency) for all pāua measured over four survey periods in PAU 3 and PAU 7. Vertical lines show the legal size of 125 mm (MLS; solid line), 135 mm (dashed line), and 145 mm (dotted line).**

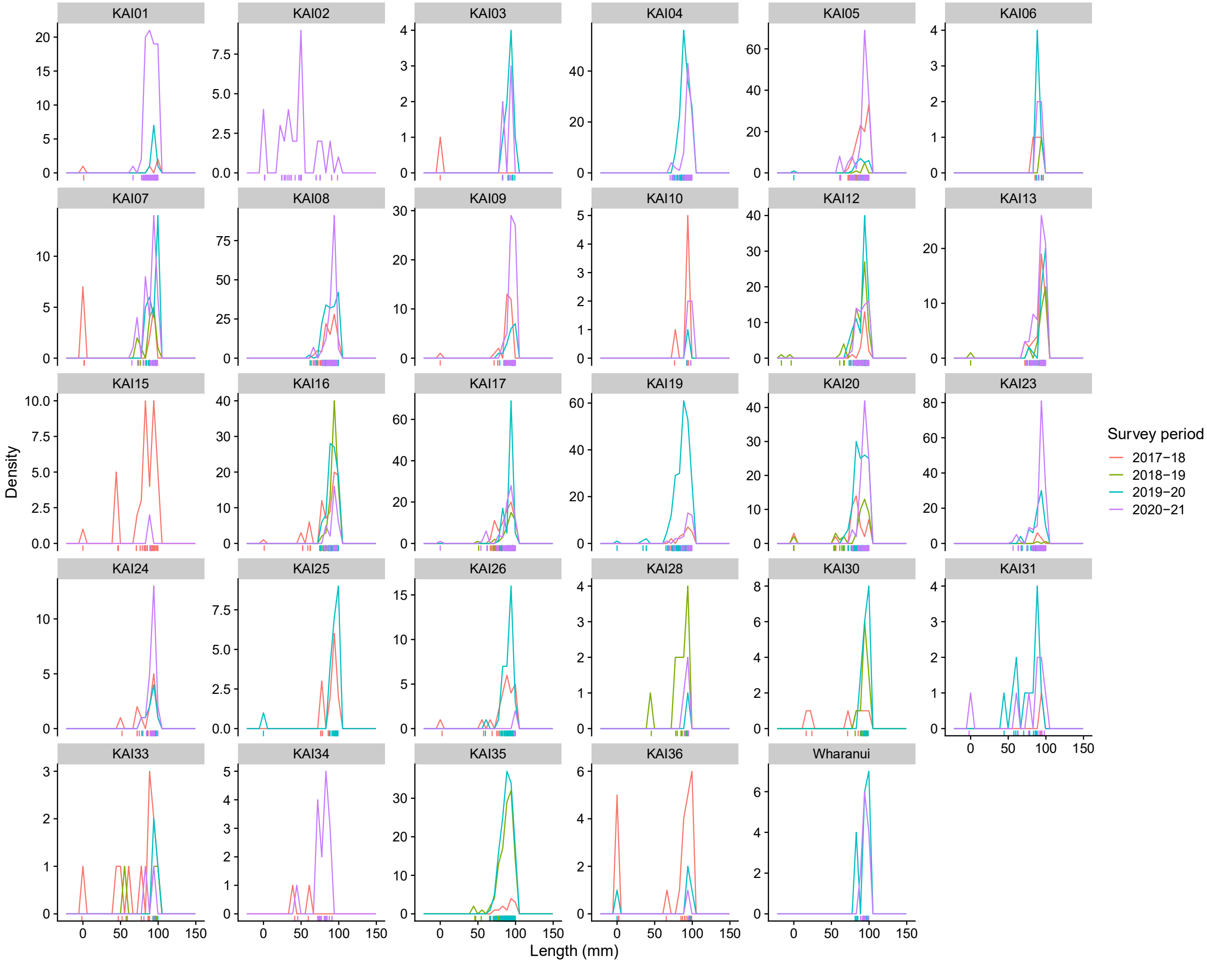

Figure 10: Length-frequency profiles (by number of pāua measured) for individual sites surveyed over four survey periods. X-axis shows only individuals less than 100 mm.

4. DISCUSSION

4.1 The fishery re-opening

After more than four years of closure to pāua fishing, the Kaikōura Marine Guardians drafted a proposal for the re-opening of the pāua fishery in April 2021. This proposal adopted criteria from the PāuaMAC3 Fisheries Plan for consideration of re-opening, when a "widespread emergence of post-earthquake recruits is observed across the fishery; and a sustained increase in pāua biomass is observed across the fishery". Previous results from this project (McCowan & Neubauer 2018 and McCowan & Neubauer 2021) supported these criteria, resulting in the subsequent approval of the proposal by the Minister, with re-opening to occur on the 1st of December 2021 for a period of three months. At this stage, the pāua fishery would have been closed for five years after the earthquake along this coastline.

This proposal leading to the pivotal decision to re-open the closed area to pāua fishing was made immediately after the completion of the fourth round of surveys presented in this report, but before data analyses had been undertaken. The results presented in this report further support those used to inform the re-opening and provide further time series of abundance trends for ongoing monitoring, but they will not have direct application to management decisions at this time.

4.2 Abundance trends

Abundance trends represented by BPUE over survey period showed a continued increase in abundance in pāua in both PAU 3 and PAU 7 QMAs over the fourth year of monitoring (Figures 4 and 6). This trend provides continuing evidence of sustained increase in pāua biomass being observed across the fishery, further supporting the criteria for re-opening.

Overall pāua abundance, as represented by BPUE, has increased notably since the last survey period. In PAU 3 this could be explained by the sustained abundance of larger pāua (> 125 mm), and an increase in abundance in smaller pāua (< 100 mm). Pāua in the < 100 mm size classes are most likely to be post-earthquake recruits, that have emerged into more open habitats and are now detectable in dive surveys. In PAU 7, increases in BPUE could be explained by increasing abundance of large pāua growing through to larger size classes (> 130 mm); however, this does not appear to be due to significant increases in recruitment of emergent pāua (Figures 8 and 9).

There is notable variability in abundance trends between sites (Figure 6). This could be attributed to variability in the amount of uplift at sites and habitat related factors which make it harder to detect pāua of smaller size classes during dive surveys. Trends in some sites show that abundance may be starting to plateau (e.g., KAI33, KAI36), suggesting these sites may be close to their maximum carrying capacity for pāua within the habitats surveyed. Results from planned surveys over the next two years will assist in determining this. Figure 6 also indicates that sites that experienced higher uplift have shown weaker positive abundance trends than lower uplift sites. This is expected, because monitoring in sites with little to no uplift is really showing a 'marine reserve' effect, rather than population recovery post-earthquake.

Variability in abundance and uplift across sites has been considered by PāuaMAC3 in the development of their management tools with the re-opening, formalised in their 2021–2022 annual operating plan. Specifically, catch spreading has been implemented to take fishing effort away from areas with higher uplift and lower pāua abundance.

Differences in overall abundance over survey periods between PAU 3 and PAU 7 are likely to be attributable to pre-earthquake stock status, where it is anecdotally accepted that PAU 7 was under high fishing pressure relative to PAU 3. Abundance in PAU 7 measured by the most recent survey period may also be lower than expected due to two high abundance sites (KAI30 and KAI35) not being able to be surveyed due to poor conditions.

4.3 Recruitment patterns

Length-frequency profiles (Figures 8 and 9) illustrate that PAU 3 has maintained a relatively stable length-frequency profile of mature pāua over the four survey periods. In PAU 7 there is evidence of a modal shift to larger mature pāua across survey periods. This could be explained by the pre-earthquake stock status of PAU 7 relative to PAU 3 (described above), and the growth of pāua into larger size classes in PAU 7 following the closure, where pāua are anecdotally known to grow larger. In Figure 9 the apparent decrease in frequency of pāua of all size classes in the latest survey period can be explained by the inability to survey two high abundance sites in PAU 7 during this period.

Figure 9 shows that there has been a detectable pulse of post-earthquake recruitment in PAU 3, with an increase in abundance in pāua in smaller size classes (< 100 mm) in the last two survey periods. This pattern is not evident to the same extent in PAU 7 where there is a low abundance of post-earthquake recruits in the last survey period. This is likely to be due to the inability to survey sites that have shown high abundance of < 100 mm pāua in previous surveys in PAU 7 due to poor survey conditions. Further, smaller pāua are easier to detect during dive surveys in small to medium boulder habitats more typical of PAU 3, rather than large boulder and gutter type habitats typical of PAU 7. The variability in post-earthquake recruitment across sites (Figure 10) can be attributed to these habitat factors and is also illustrative of the fine-scale annual variability in recruitment known to occur in pāua generally (Wilson

& Schiel 1995). Overall, post-earthquake recruitment pulses in the last two years can be observed across the majority of sites, meaning these results continue to support one of the agreed criteria for re-opening, that "widespread emergence of post-earthquake recruits is observed across the fishery".

5. MANAGEMENT IMPLICATIONS

Previous results from monitoring surveys were used to support the decision to re-open the fishery on the 1st of December 2021 for three months. Although the results from the most recent round of surveys were not considered for this, they show continued positive trends in abundance and recruitment and are an important point in the time series for ongoing monitoring.

Further surveys of established monitoring sites were undertaken in October–November 2021, to establish abundance status at individual sites and at the QMA level immediately before re-opening on the 1st of December (dive conditions allowing). With the closure of the fishing season on 28 February 2022, further surveys will assist to determine the ongoing status of the fishery and assist in management decisions in future seasons. It is intended that BPUE will be used as an index of abundance (in conjunction with fisheries dependent data) to inform management procedures governed by a harvest control rule, to allow for the adaptive rebuild of the commercial fishery through following seasons.

6. ACKNOWLEDGEMENTS

This project was funded by Fisheries New Zealand project PAU2020-02. We acknowledge Fisheries New Zealand, and in particular Rich Ford for support during the early stages 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 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.

7. REFERENCES

Burkner, P. (2018). Advanced bayesian multilevel modelling with the R package brms. *The R Journal 10*: 395–411.

Gerrity, S.; Alestra, T.; Fischman, H.S.; Schiel, D.R. (2020). Earthquake effects on abalone habitats and populations in southern New Zealand. *Marine Ecology Progress Series 656*: 153–161.

McCowan, T.; 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.

McCowan, T.; Neubauer, P. (2021). Pāua abundance trends and population monitoring in areas affected by the November 2016 Kaikōura earthquake. *New Zealand Fisheries Assessment Report 2021/26*. 23 p.

Neubauer, P. (2017). Area lost to the pāua fishery from the November 2016 Kaikoura earthquake. 7 p. (Report to the Ministry for Primary Industries, held by Fisheries New Zealand.)

Wilson, N.H.F.; Schiel, D.R. (1995). Reproduction of two species of abalone (*Haliotis iris* and *H. australis*) in southern New Zealand. *Marine and Freshwater Research 46*: 629–637.

APPENDIX A – MODEL FIT AND SUPPLEMENTARY PLOTS

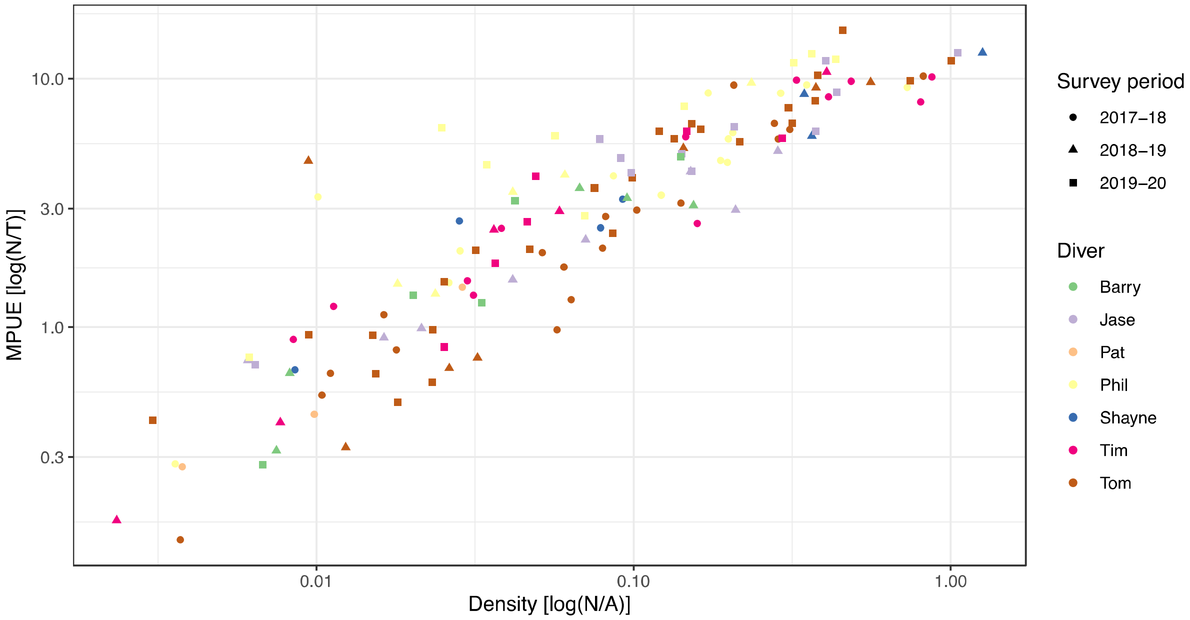

Figure A-1: Relationship between density in (log) individuals per unit area, and measurements per unit time (MPUE), for the three different survey periods (shapes) and divers (colours).

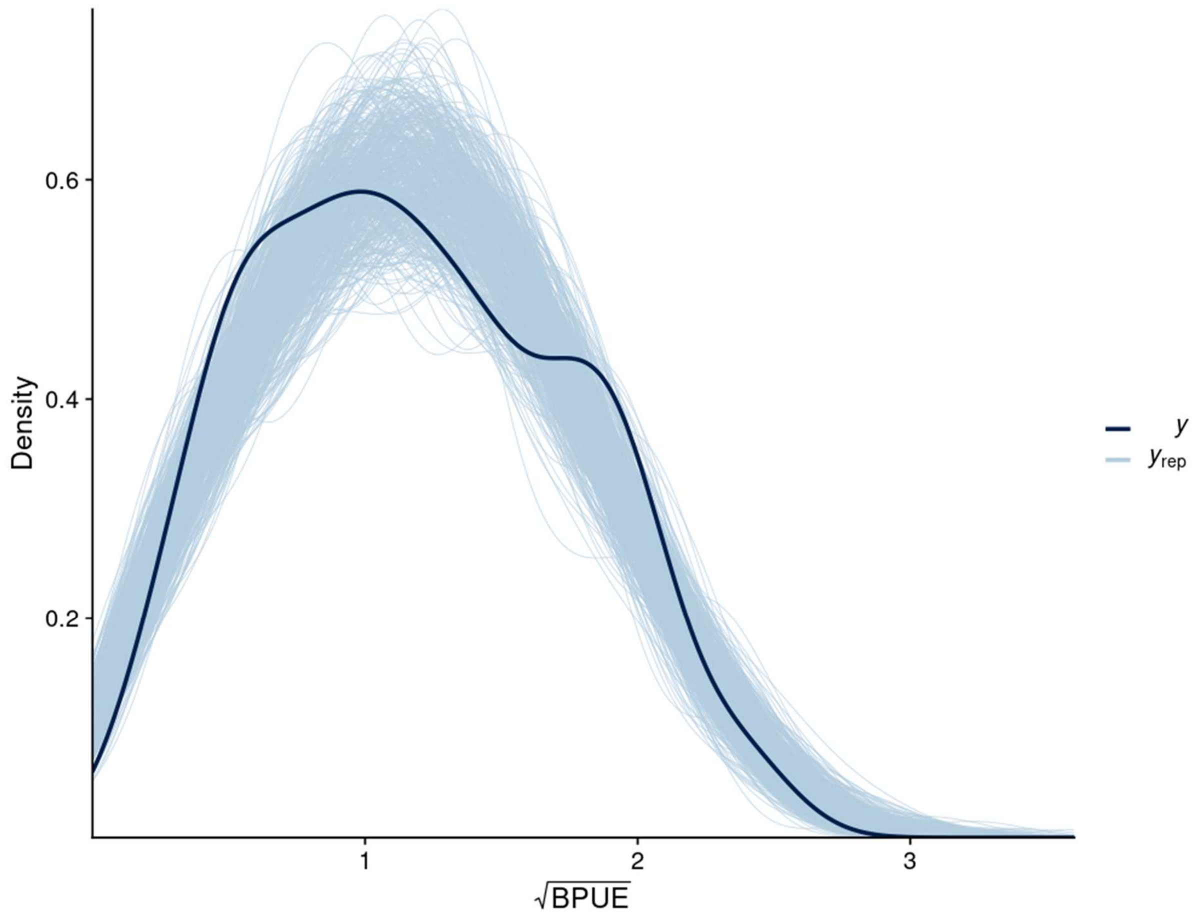

Figure A-2: Model fit for the model relating biomass per unit effort (BPUE) to predictors, as assessed by draws from the posterior predictive distribution (blue lines) compared with the empirical density for density data (black line).

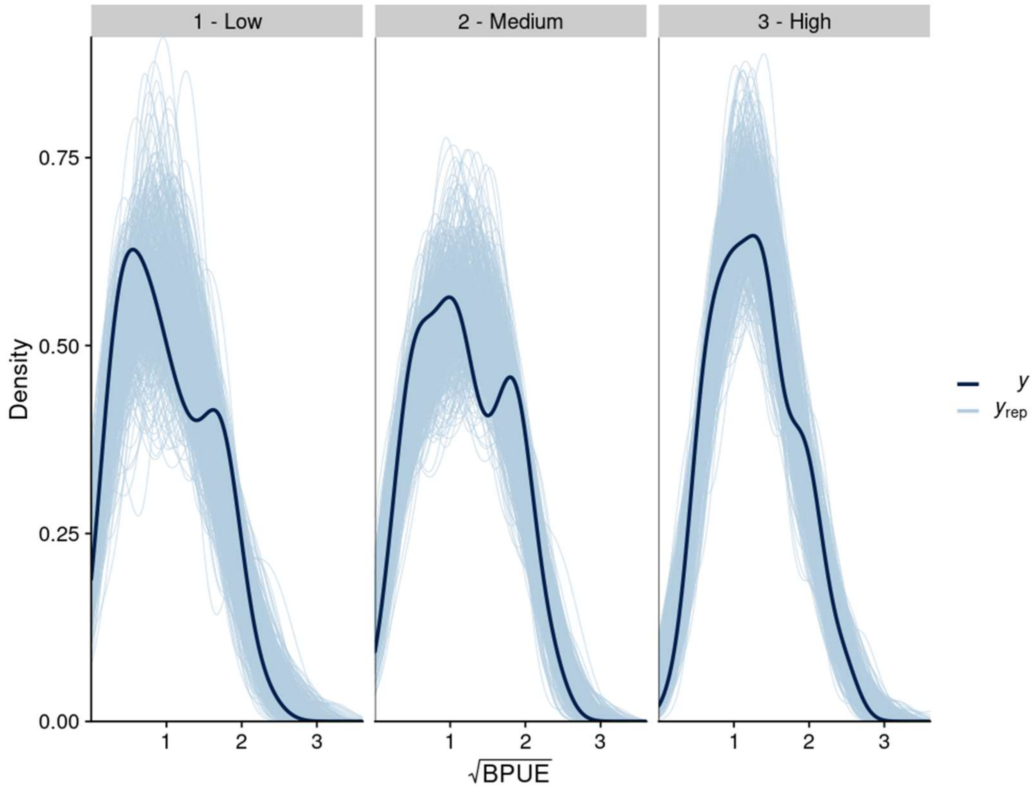

Figure A-3: Model fit by survey stratum for the model relating biomass per unit effort (BPUE) to predictors, as assessed by draws from the posterior predictive distribution (blue lines) compared with the empirical density for density data (black line).

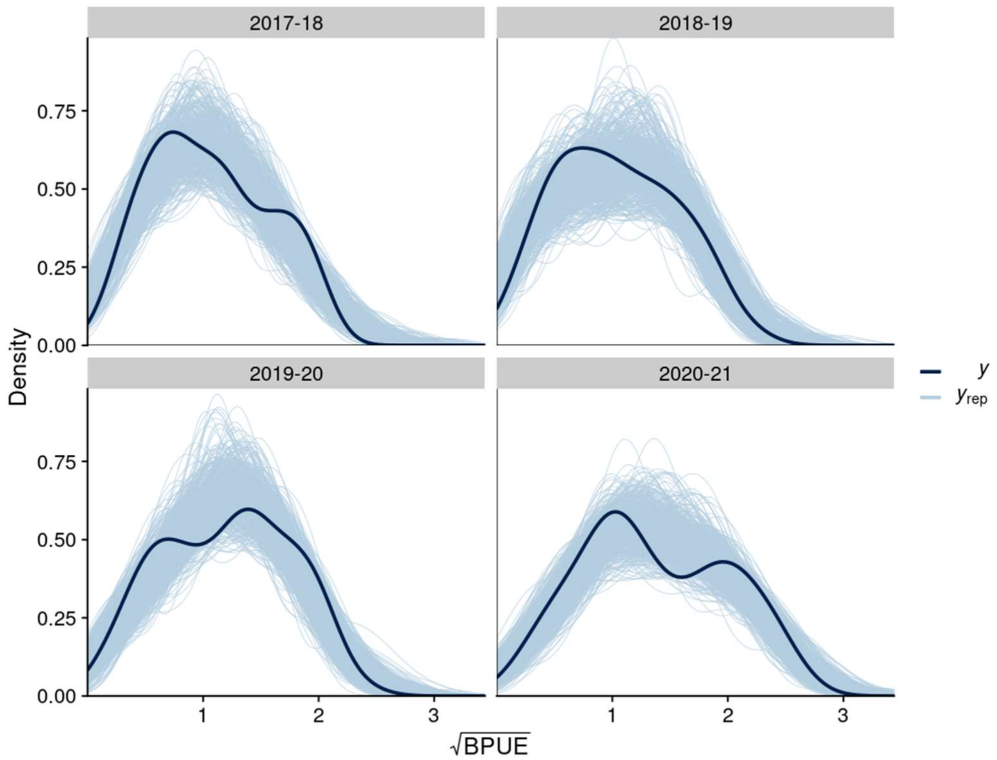

Figure A-4: Model fit by survey period for the model relating biomass per unit effort (BPUE) to predictors, as assessed by draws from the posterior predictive distribution (blue lines) compared with the empirical density for density data (black line).

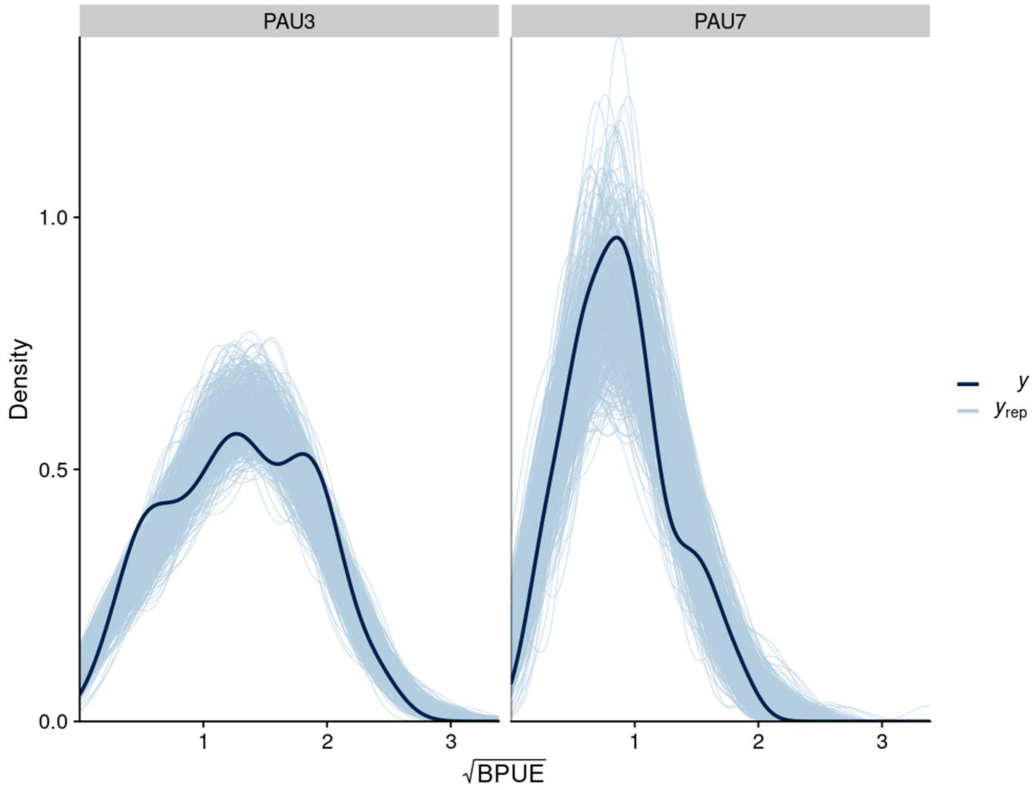

Figure A-5: Model fit by QMA for the model relating biomass per unit effort (BPUE) to predictors, as assessed by draws from the posterior predictive distribution (blue lines) compared with the empirical density for density data (black line).

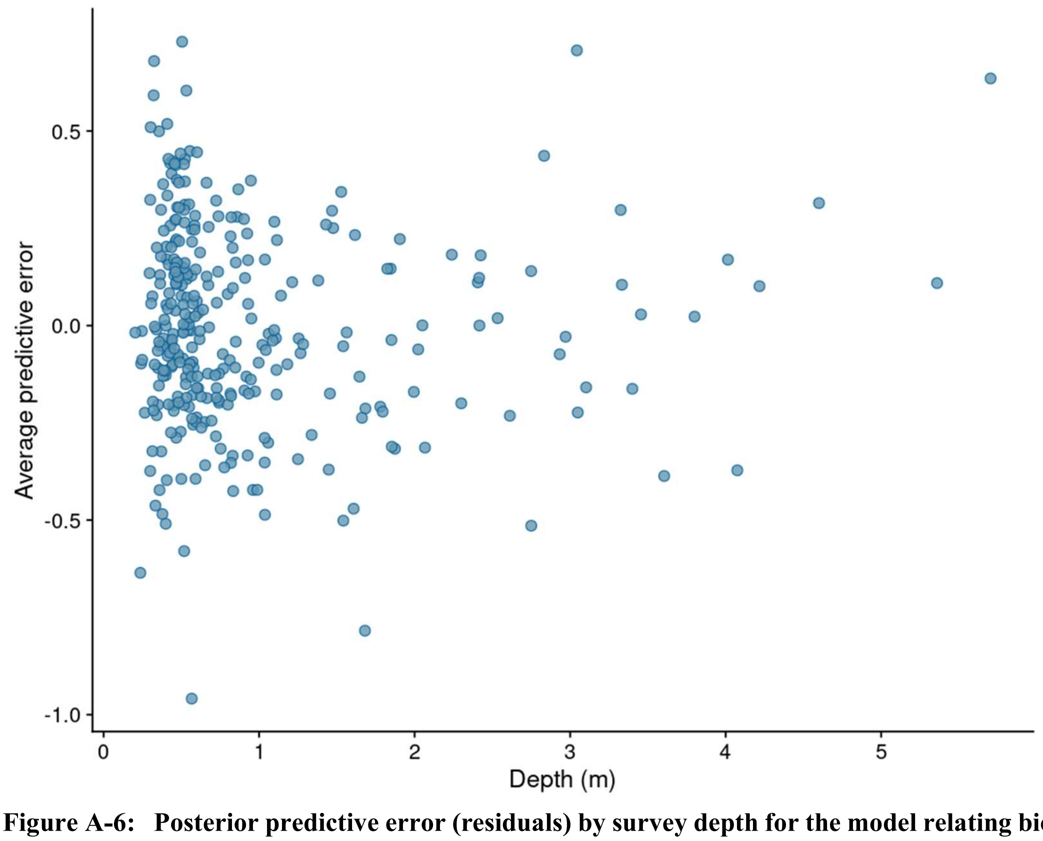

Figure A-6: Posterior predictive error (residuals) by survey depth for the model relating biomass per unit effort (BPUE) to predictors.

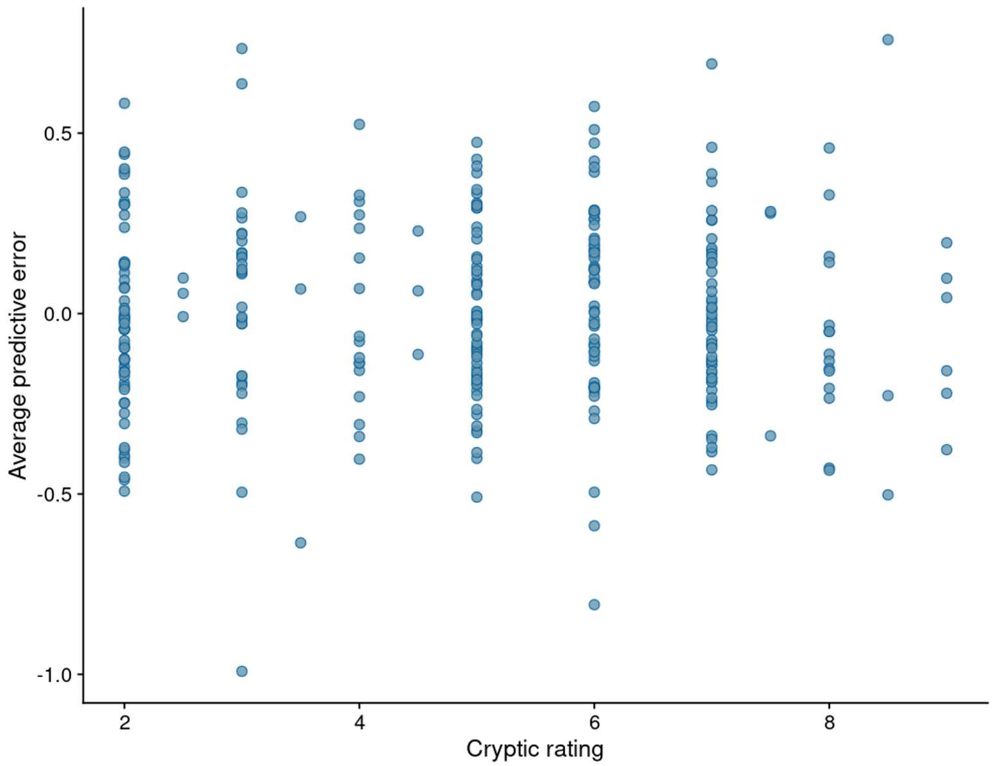

Figure A-7: Posterior predictive error (residuals) by survey Cryptic rating (1-10 scale) for the model relating biomass per unit effort (BPUE) to predictors.

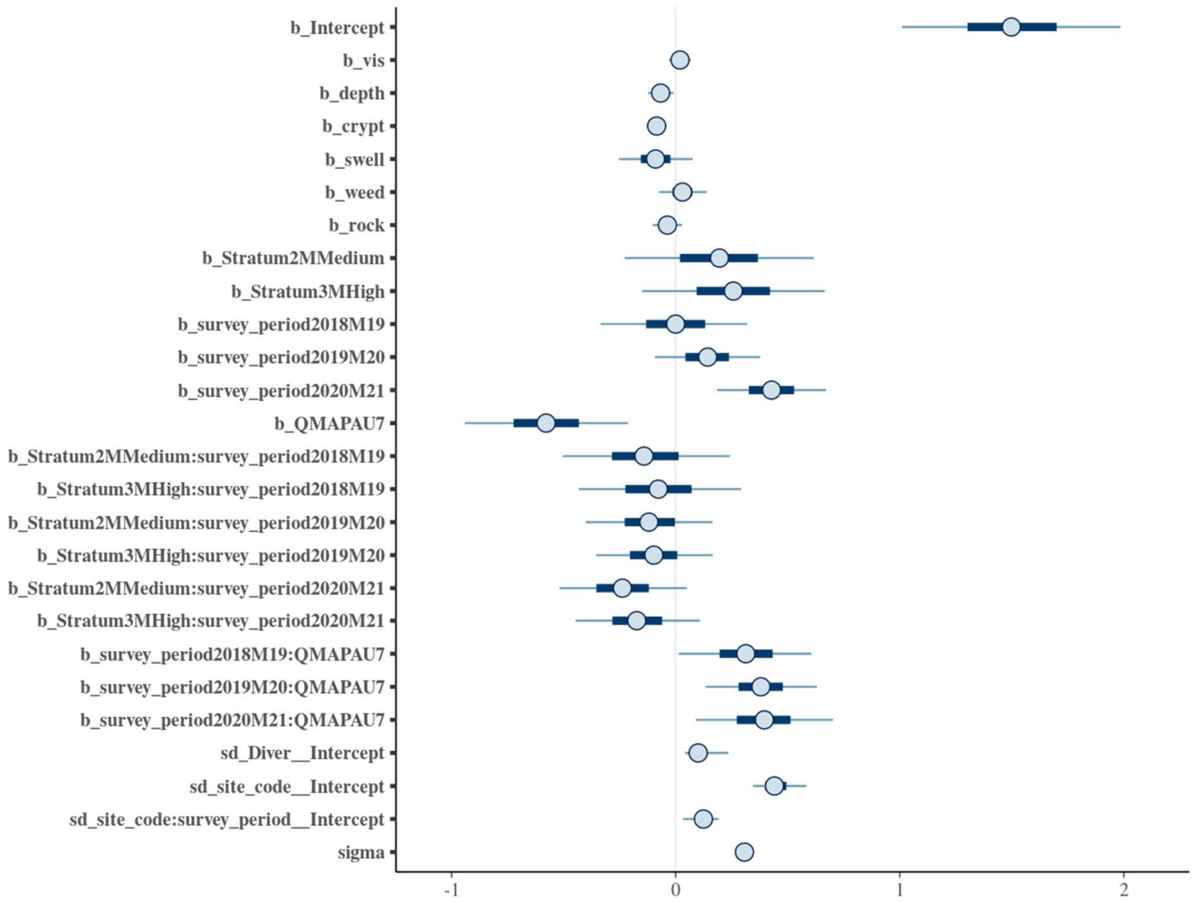

Figure A-8: Estimated coefficients in the biomass per unit effort (BPUE) model.

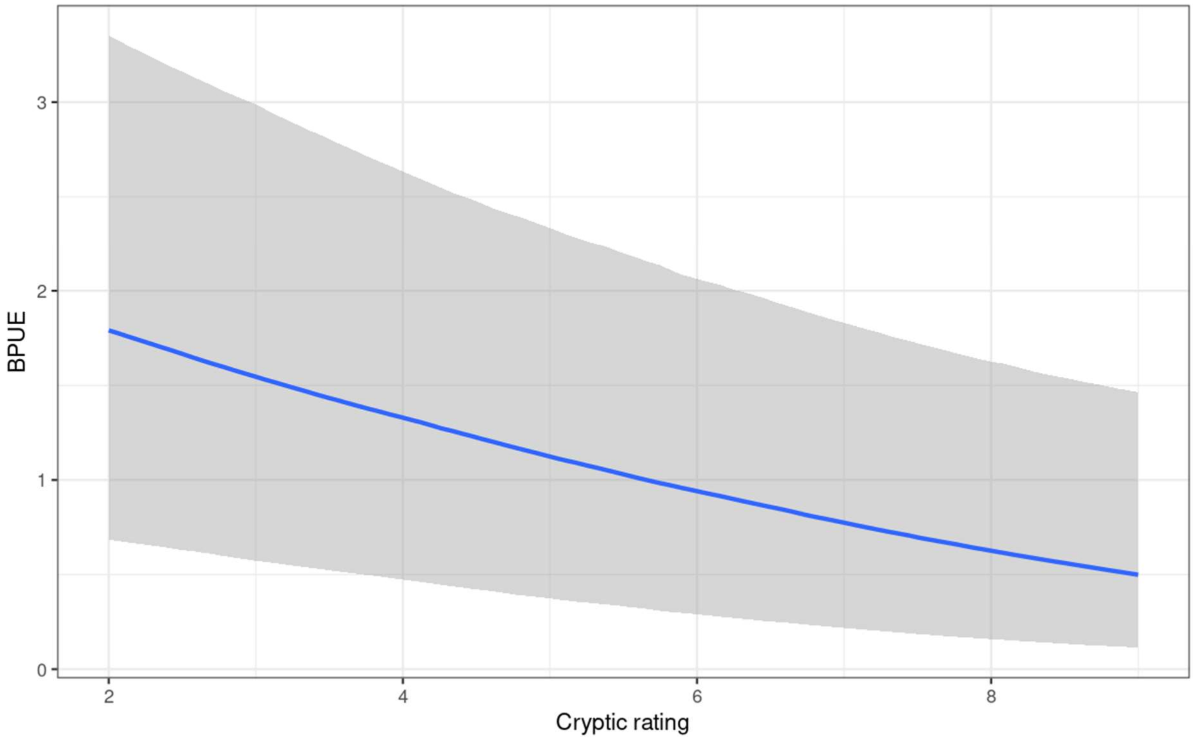

Figure A-9: Effect of cryptic rating in the biomass per unit effort (BPUE) model, as assessed by its marginal impact on BPUE.

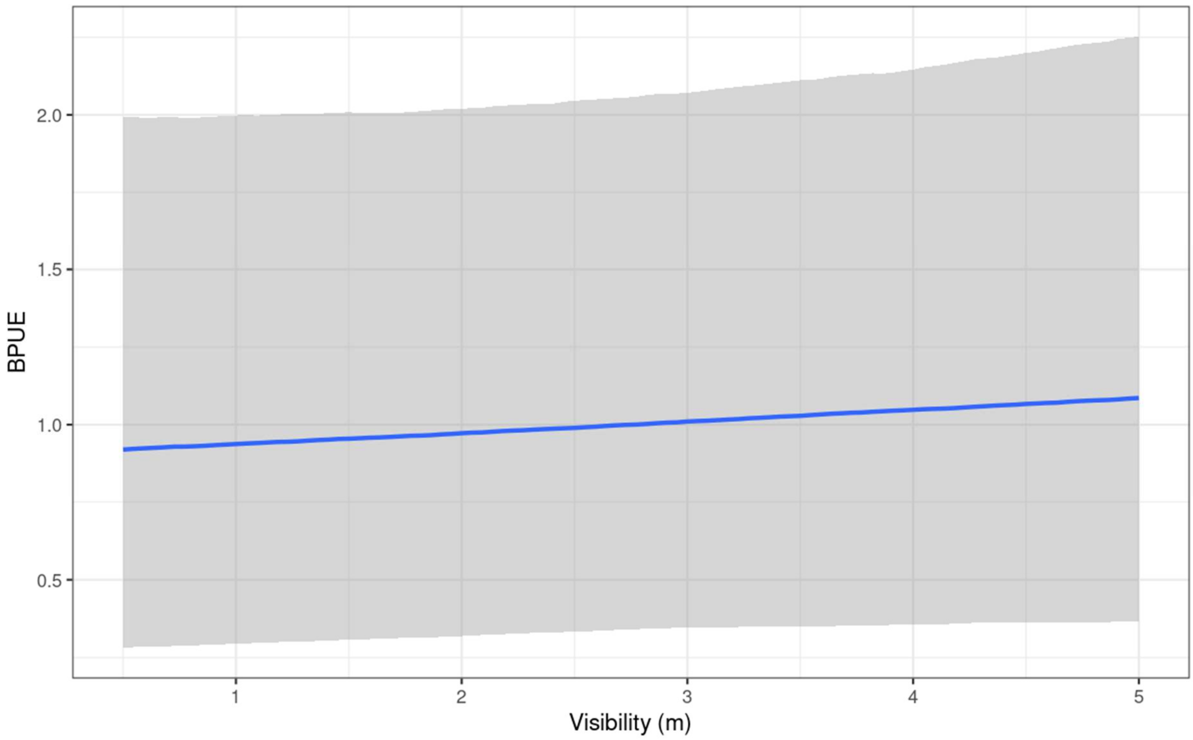

Figure A-10: Effect of visibility in the biomass per unit effort (BPUE) model, as assessed by its marginal impact on BPUE.

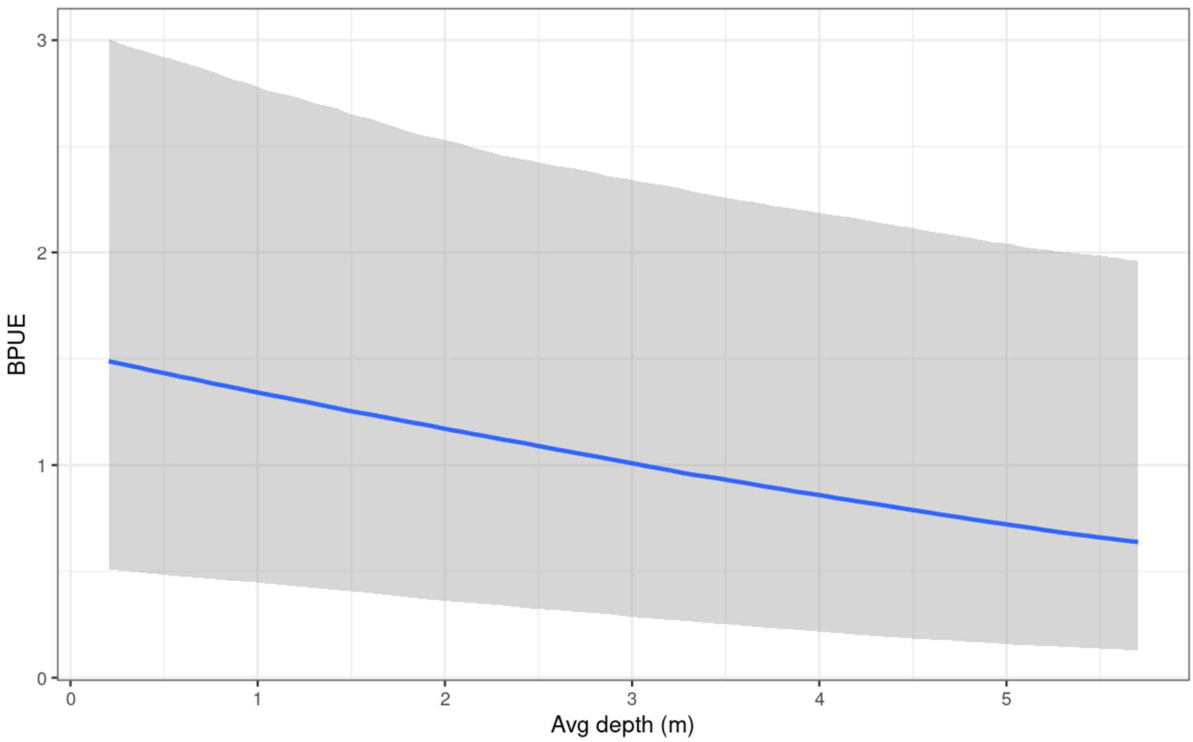

Figure A-11: Effect of depth in the biomass per unit effort (BPUE) model, as assessed by its marginal impact on BPUE.

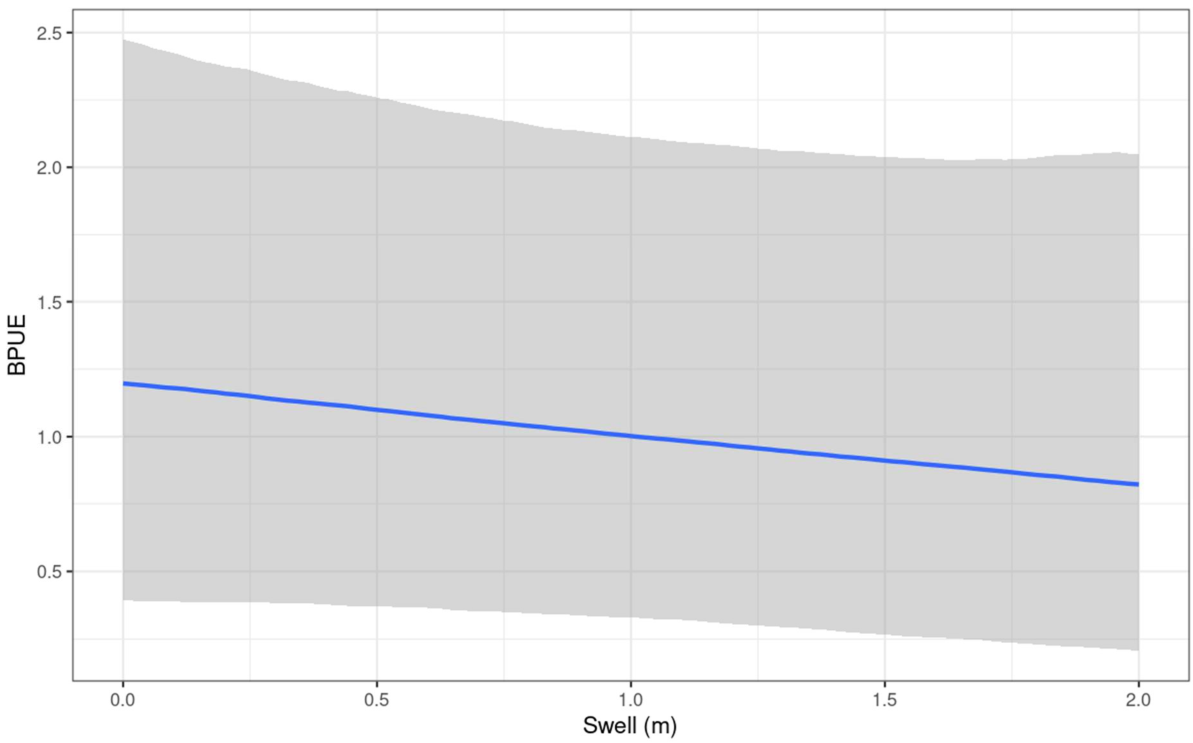

Figure A-12: Effect of swell in the biomass per unit effort (BPUE) model, as assessed by its marginal impact on BPUE.