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Recreational fishing effects on wadeable pāua populations along the Kaikōura coast, 2021–22

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EXECUTIVE SUMMARY

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***New Zealand Fisheries Assessment Report 2023/01*. 27 p.**

The 2016 Kaikōura earthquakes and uplift caused extensive damage to the marine ecosystem along 130 km of productive coastline. The disturbance resulted in widespread mortality of juvenile and adult blackfoot abalone (pāua, *Haliotis iris*) and damage to critical recruitment habitat, prompting an emergency closure of the commercial and recreational fisheries to allow recovery. During the 5-year closure, a strong rebuilding of shallow pāua populations occurred. Surveys of intertidal habitats showed significant increases in juvenile pāua densities, which reached peak abundance approximately three years after the closure began. A gradual build-up of adult and legal-sized pāua (≥ 125 mm shell length) in easily accessible areas was also documented, likely due to the prolonged reduction in shore-based harvesting.

On 1 December 2021, the fishery reopened for a 3-month season, during which an estimated 42 tonnes of pāua were harvested in the Kaikōura Marine Area by recreational fishers. We conducted surveys of pāua populations at 26 intertidal sites and 7 subtidal sites immediately before and after the 2021–22 season to quantify effects from fishing on wadeable pāua aggregations. These data, along with 5 years of data collected prior to the reopening, show changes to pāua abundance and size classes resulting from the harvest.

Shore-based surveys of intertidal pāua populations showed significant reductions of fished populations following the fishing season. Intertidal populations at 15 fished sites had a 66% decrease in legal-sized pāua abundance, with one site (Rakautara) declining by 92%. Across the 11 closed sites there was an overall decline of 42% in abundance of legal pāua, possibly an effect from legal customary and known illegal fishing. After the fishing season, the density of legal-sized pāua at fished sites had declined to the lowest level since surveys began in 2017, one year after the earthquakes. Size-frequency distributions showed non-significant changes in population structure, but fished sites shifted slightly toward smaller size classes after the fishing season.

Repeated timed dive surveys of shallow subtidal (2–3 m depth) habitats before and after the fishing season showed large reductions in pāua biomass in accessible fished areas. At four fished sites, there was a 74% reduction in legal-sized pāua biomass, compared with a 5% increase in biomass at three closed sites. At some fished sites the abundance of legal-sized pāua in shallow habitats had declined by up to 92%. Notable reductions in the abundance of sub-legal (< 125 mm) pāua in some areas may be indicative of illegal harvest or emigration outside the sample area. The size structure of subtidal fished populations shifted significantly towards smaller pāua following the season, and fished sites had a significant decrease in average shell size over the season (from 121 mm before to 110 mm after fishing), compared with closed sites (130 mm before to 132 mm after fishing).

This work highlights the sensitivity of accessible pāua populations in the Kaikōura Marine Area to intensive harvest and a vulnerability of shallow aggregations to localised depletion. The work establishes a baseline from which to gauge future changes to shallow pāua populations.

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1. INTRODUCTION

The November 2016 Kaikōura earthquakes and coastal uplift caused extensive damage to pāua (*Haliotis iris*) populations and critical habitats along 130 km of coastline, with widespread mortality of juvenile and adult pāua in a very productive fishery. The resulting emergency ban on all commercial and recreational pāua harvest lasted over 5 years, during which researchers from University of Canterbury documented a remarkable rebuilding of inshore populations (Schiel et al. 2019, Gerrity et al. 2020). Repeated surveys over 5 years showed rejuvenation of inshore habitats for recruiting pāua, a steady build-up of juvenile populations, and a significant increase in large, legal-sized pāua (≥ 125 mm shell length, SL) in very shallow habitats. The prolonged absence of shore-based fishing pressure, in combination with abundant high-quality recruitment habitat, resulted in the closest thing to a virgin fishery that many locals, commercial divers, and experienced scientists have witnessed in the area. On 1 December 2021, the Ministry for Oceans and Fisheries re-opened the area to commercial and recreational fishing for a 3-month period, during which an estimated recreational harvest of 42 tonnes (t) occurred. In this report, we summarise findings from our surveys designed to assess the effects of shore-based recreational fishing from this season.

Surveys were done before and after the 2021–22 pāua fishing season to quantify effects, document changes, and help inform future decisions on regulation. Two methods were used to achieve this in the low intertidal zone and in the shallow nearshore subtidal zone. In a continuation of a long-term data set started in 2017, quadrat surveys of intertidal habitats were completed at 26 sites to quantify the pre-opening and post-closure status of wadeable populations. These sites were distributed across the earthquake-affected coastline and included areas in PAU 3A (Kaikōura Marine Area) and PAU 7 management areas. Additional subtidal surveys before and after the fishing season at 7 sites in the Kaikōura Marine Area targeted aggregations of easily accessible or wadeable pāua. Survey data were used to assess changes in population structure, density, and biomass of legal-sized pāua, and shell lengths at sites open to recreational fishing and others that were closed. Note that some of the closed sites, while closed to recreational fishers, experienced a relatively low degree of customary or illegal fishing. Based on accounts by fisheries observers and considering that the customary catch allocation was 7 t and estimated recreational harvest was 42 t, it is reasonable to expect that ‘closed’ sites had significantly lower harvest than ‘fished’ sites open to the wider recreational sector.

It must be noted that it is very difficult, time-consuming, and expensive to attempt to determine the biomass of pāua populations over their entire coastal distribution. Pāua are patchy in their distribution, dependent on fine-scale features of habitat, and prone to high variances in estimates of numbers and biomass. Our approach was to choose accessible areas of nearshore reefs, mark their locations as precisely as possible, and count and measure pāua within them. Given swell and visibility conditions in the often-turbulent inshore waters, there is still variation in what can be counted and measured. Nevertheless, we are confident this approach yielded an accurate assessment of pāua abundance and size distribution before and after the fishing season across a variety of sites.

Recreational fishing pressure, especially during the December 2021–January 2022 holiday season, was very high, as indicated by Blue Water Marine (Holdsworth 2022) and also our own observations. Estimates of daily recreational pāua fishers were variable but often well into the hundreds, ranging as high as 839 per day (Holdsworth 2022). Fisheries officers and our research team observed various illegal fishing practices during the season, including one person collecting multiple bag limits for others, fishing in closed areas, etc., although these were not quantified. The great majority of fishing occurred within 100 m of the 52 identified areas where vehicle parking was available along the coastline.

The goal of this research was to quantify fishing impacts associated with shore-based, recreational fishers and assess how Kaikōura pāua populations responded to the resumption of fishing following a 5-year closure. Details of this work are presented in the following sections.

2. METHODS

2.1 Intertidal surveys

Thanks to funding from Fisheries New Zealand and the Ministry of Business, Innovation, and Employment, the University of Canterbury Marine Ecology Research Group has been collecting data on the recovery of intertidal pāua populations from the 2016 Kaikōura earthquakes since 2017. In October–November 2017, one year after the Kaikōura earthquakes, we established 26 sites across 12 rocky intertidal locations along the uplifted coastline. With multiple sites (2–3) within each location we aimed to account for localised variation in statistical models of ecosystem recovery (e.g., Alestra et al. 2020). The sites spanned the 130 km of coastline affected by the earthquakes, from Oaro in the south to Cape Campbell to the north (Figure 1). These sites were selected after consultation with local community members, fishers, and iwi on availability of pāua habitat (rocky reef and/or stable boulder fields). Popularity with fishers, accessibility, and ensuring a wide range of coastal uplift were also considered. Eleven sites had special management status, including marine reserve, rāhui, mātaitai, and taiāpure, and serve as relatively unfished 'closed' sites to compare with fished sites following the 2021–22 pāua season, although these areas did experience customary harvest throughout the 5-year closure (see Figure 1 for site details).

Within each site, twenty 1-m^2 (1 m × 1 m) quadrats were sampled in the low intertidal zone. Quadrats were placed in areas with suitable habitat for juvenile pāua (i.e., sandy areas and flat consolidated rock were avoided). In each quadrat, habitat features were recorded, all pāua were counted, and their maximum shell length (mm) measured using Vernier calipers (Figure 2). Sites were re-sampled every 6–12 months, with the last two sample events occurring just before and after the 2021–22 pāua fishing season. Across all sampling events, 3700 1-m^2 quadrats were sampled, and more than 22 000 pāua were counted and measured. These data provide a clear quantitative assessment of the structure of recovering pāua populations over 5 years of closure, and the effects of the 2021–22 pāua fishing season on intertidal populations. This is a large data set, and much can be ascertained about spatial and temporal trends in pāua population dynamics that are outside the scope of this report. Here we focus on broader trends that are relevant to the 2021–22 pāua fishing season.

2.2 Intertidal survey data analysis

Changes in density of pāua from different size classes (juveniles < 85 mm, adults 85–124 mm, legal $\geq$ 125 mm) were analysed using two-way PERMANOVA with Treatment (fished or closed) and Time (before or after fishery reopening) as factors (Anderson et al. 2008). Because we were interested in differences caused by fishing, we pooled data over sites to increase our power, to give n = 220 or 300 quadrats per sampling time for the fished and closed treatments, respectively. Note that PERMANOVA was used due to the high number of zeros in analyses, which can cause misleading results in traditional ANOVAs. To analyse population size structure, we first calculated the total number of pāua at each location within each site for every 5-mm shell length bin between 0 and 170 mm (i.e., there were 32 bins). We then calculated the cumulative percent of pāua in each size class at each site (n = 15 or 11 per time for the fished and closed treatments, respectively) and created a resemblance matrix using Euclidian distance (Virgin et al. 2019). Cumulative percent frequency data were plotted and analysed using PERMANOVA with Treatment and Time as fixed factors.

We did not know in 2017 which sites would eventually be opened or remain closed to fishing, and it was fortunate that there was a large number of sites in areas that would both be open and remain closed in 2021. However, it should be noted that the non-random selection of treatment (fished) and control (closed) sites is imperfect statistically. Also, the 'closed' sites were not entirely closed to all harvest, with some experiencing levels of customary harvest both during and after the 5-year emergency closure that are not quantified here. Based on the customary allocation (7 t) being comparatively low compared with recreational harvest estimates (42 t), and the fact that 4 of the closed sites are effectively closed to customary harvest (rāhui, marine reserve), it is nevertheless reasonable to assume that closed sites experienced significantly lower fishing pressure than fished sites.

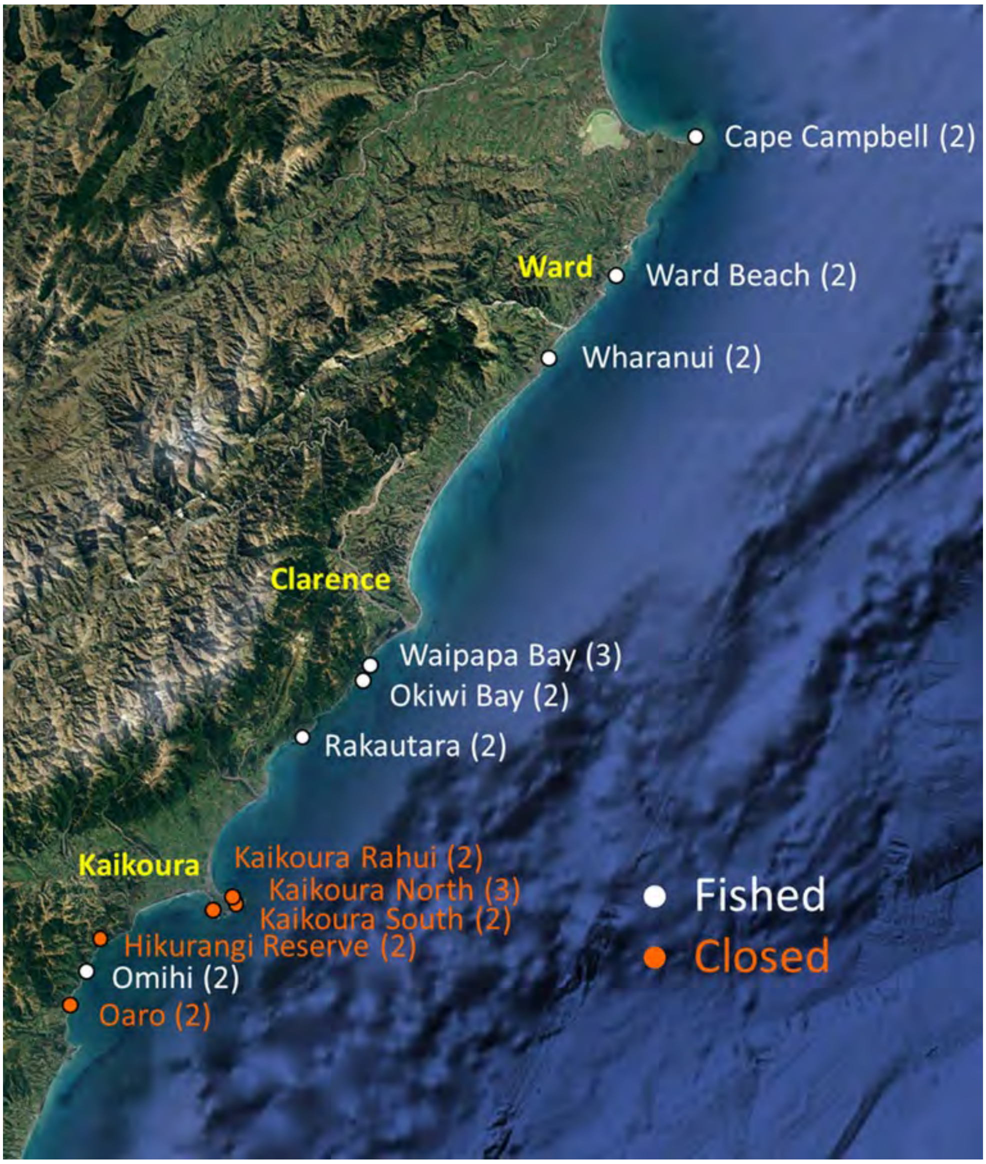


Figure 1: Map of intertidal locations surveyed since 2017. The number of sites per location is indicated in brackets, with 26 sites in total. All sites were closed to recreational and commercial fishing from November 2016 to December 2021. Fifteen of the sites were reopened to pāua fishing on 1 December 2021 (shown in white) and 11 remained closed to recreational fishing during the 2021–22 season (shown in orange).

Figure 2: Photos from field surveys of wadeable intertidal pāua populations, which are typically dominated by juveniles that inhabit cryptic under-boulder habitat. The white squares in the upper left photo approximate 1-m^2 quadrats, 20 of which have been assessed at each of the 26 sites every 6–12 months since 2017. Pāua are measured using Vernier calipers to assess population structure (bottom left).

2.3 Subtidal surveys

The intertidal pāua population surveys provide detailed data on the rebuilding of predominantly juvenile pāua populations during a 5-year fishery closure, and the effects of fishing on large pāua that had accumulated intertidally. However, the majority of large, legal-sized adult pāua aggregations typically occur deeper down in shallow subtidal reef habitats (approx. 1–4 m depth). To assess the effects of the 2021–22 season on these aggregations, additional surveys were conducted in the immediate subtidal zone, in areas almost exclusively used by recreational fishers (commercial fishers target separate populations primarily accessible by boat and infrequently targeted by shore-based fishers).

Dive surveys recorded length-frequency distribution and biomass of wadeable and shallow dive-able (by snorkel) patches of large pāua before and after the fishing season. Initially 10 sites were selected, based on prior knowledge of easily-accessible aggregations of large pāua, but due to poor ocean conditions only 7 sites were re-surveyed following the fishing season. This included 4 sites open to recreational harvest (designated ‘fished’ in this report) sites and 3 relatively unfished (designated ‘closed’) sites (Figure 3). Site selection and resampling were constrained by logistics, including access, seawater visibility, etc. Sites prone to poor visibility and heavy swell were not resampled in the given time frame. For example, two ‘fished’ sites established in the northern portion of the coastline (Paparoa Point, Ward Beach) experienced strong swell and poor visibility and were not able to be resampled after the season. Furthermore, some ‘closed’ sites may have experienced some degree of customary or illegal harvest. These constraints and the potential biases that they impose should be considered when interpreting results.

At each of the 7 sites, a diver did a 90-minute survey in a well-defined area before and after the fishing season. To delineate the sample area, the diver entered the water and swam out directly east for 30 m, then dropped a weight with a buoy on it. Another weight with a buoy was dropped approximately 100 m north or south of the first buoy (Figure 4). A GPS point was taken on land directly perpendicular to each buoy so that the sample area could be re-established for a repeat survey. The diver then conducted a 90-minute snorkel survey within the sample area. The diver swam a U-shaped search pattern within the sample area, freediving down and measuring all pāua encountered using Zebratech underwater callipers, which recorded shell length and the depth below the sea surface (Figure 4). All pāua encountered were measured at-depth, and patches were marked with a Resene oil crayon to avoid double-counting. To account for variable tidal heights across dive days, individual depths were adjusted to 1.7 m mean high water spring tidal level using a tidal height calculator so that the depth distributions could be compared across sites. Each site was sampled before and after the 2021–22 pāua fishing season (September-November 2021 and March-May 2022, respectively). To optimise data quality, the same diver did all surveys, and surveys were not done if the visibility was below 2 m or if the swell was above 1.3 m.

Figure 3: **Site map of subtidal survey locations, with each location having one site. The white text indicates locations that would open for the 2021–22 pāua fishing season, and the orange text indicates a site that would remain closed to commercial or recreation fishing.**

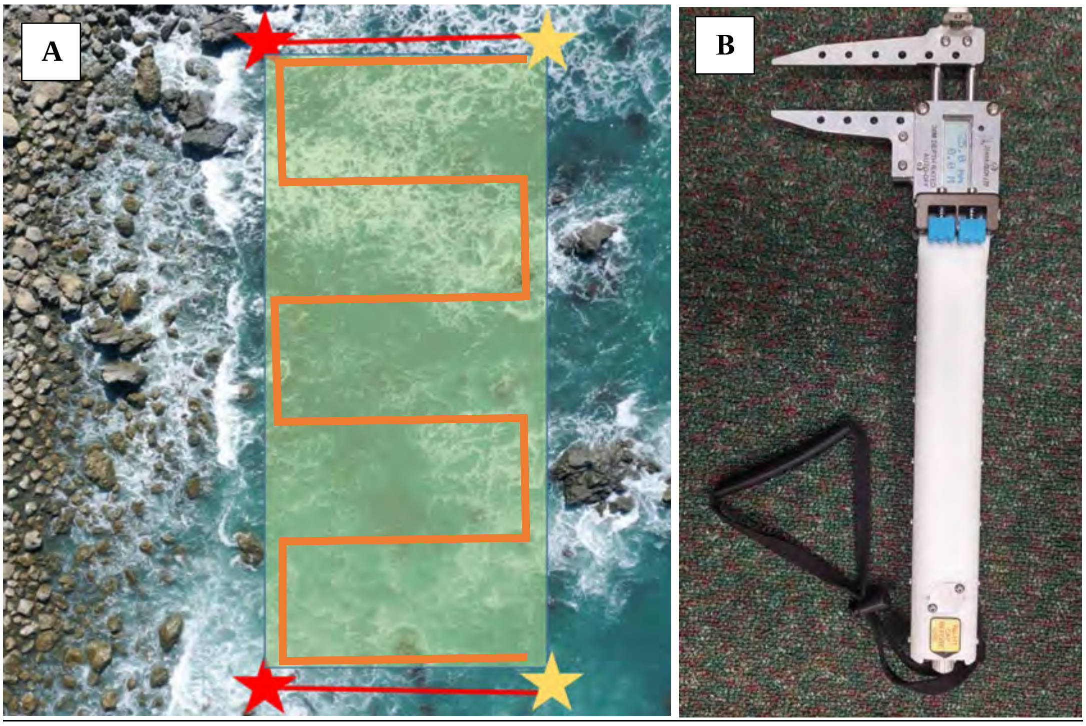


Figure 4: **A. Example of subtidal survey sample area. Red stars indicate GPS marks, yellow stars indicate location of buoys to delineate sample area. The red lines are 30 m long and the distance between the buoys is approximately 100 m. The entire sample area (approximated in green) at each site was surveyed by a diver swimming a U-shaped search pattern (orange line) and measuring all pāua encountered at depth. B. Underwater callipers by Zebratech used in subtidal sampling to record maximum shell length and individual depth.**

2.4 Subtidal data analysis

To visualise changes in length and depth distribution of the sampled populations, individual shell lengths and depths before and after the season were plotted. Biomass was calculated using a length-to-weight relationship established by Tom McCowan of the Pāua Industry Council. This relationship was based on pāua collected from sites around the Kaikōura Peninsula, which we feel are representative of our sample areas. The equation was a simple polynomial of $2E\text{-}05x^{3.3643}$, where x is length (in mm). The cumulative size frequency of populations before and after fishing were plotted, using shell length and biomass estimates described above. Differences in size frequency were analysed using PERMANOVA, as above. Shell lengths were also averaged across each site-treatment-time combination and analysed using a two-way ANOVA with Treatment and Time as factors to assess broader shell length patterns (Anderson et al. 2008).

3. RESULTS

3.1 Intertidal surveys

The time series collected since 2017 depicts patterns of population structure and pāua abundance at 26 intertidal sites and shows dynamic changes over the 5 years of fishery closure following the earthquakes (Figure 5). We documented a large increase in pāua abundance across sites between 2017 and 2019, driven mainly by a proliferation of juvenile pāua (< 85 mm shell length), which increased in mean density from (mean ± SE) 1.61 m^{-2} (± 0.15) to 6.34 m^{-2} (± 0.54) in that time (Table 1, Figure 5). This may correspond with a widespread synchronised spawning event triggered by the 2016 earthquake disturbance, and/or strong natural recruitment over the following three years (Figure 6). Four years after the earthquakes, a large proportion of juveniles in intertidal habitats began reaching adult size (≥ 85 mm SL), and the abundance of adults increased in shallow intertidal habitats. The abundance of legal-sized pāua is relatively low compared with the other size classes, as larger pāua tend to migrate to subtidal reefs.

The overall abundance of intertidal pāua peaked in 2019 and began either to stabilise or decline across sites, possibly a result of emigration to subtidal habitats by adults, intertidal habitats reaching carrying capacity, variable juvenile recruitment rates, or illegal or customary harvest. The last two sampling events were just before and just after the 2021–22 pāua season. Between these two events, there was a notable decline in the average density of all pāua across sites, with the sub-legal adult size class (85–124 mm) declining from 3.06 m^{-2} (± 0.26) to 1.99 m^{-2} (± 0.20). Legal-sized pāua (≥ 125 mm) density declined from 0.57 m^{-2} (± 0.09) to 0.22 m^{-2} (± 0.09) during this time across all open and closed sites. The average density of legal pāua decreased during the fishing season at almost all sites (closed and fished – see Appendix).

Table 1: Intertidal pāua density ±SE across size classes over time at all 26 sites including closed and fished sites. The red box indicates the sampling events just before and just after the 2021–22 pāua season.

	Years After Earthquake							
Size Class	**1**	**1.5**	**2**	**2.5**	**3**	**4**	**5**	**5.5**
Juvenile (<85mm)	1.61±0.15	2.92±0.31	3.80±0.34	6.00±0.47	6.34±0.54	3.57±0.35	2.22±0.22	1.71±0.19
Adult (85-124mm)	0.72±0.17	0.21±0.05	0.94±0.18	1.13±0.17	2.71±0.30	3.59±0.36	3.06±0.26	1.99±0.20
Legal (≥125mm)	0.27±0.09	0.06±0.03	0.26±0.09	0.11±0.04	0.36±0.12	0.64±0.14	0.57±0.09	0.22±0.09
ALL Sizes	2.60±0.28	3.18±0.32	5.01±0.43	7.27±0.51	9.41±0.66	7.80±0.57	5.85±0.39	3.92±0.30

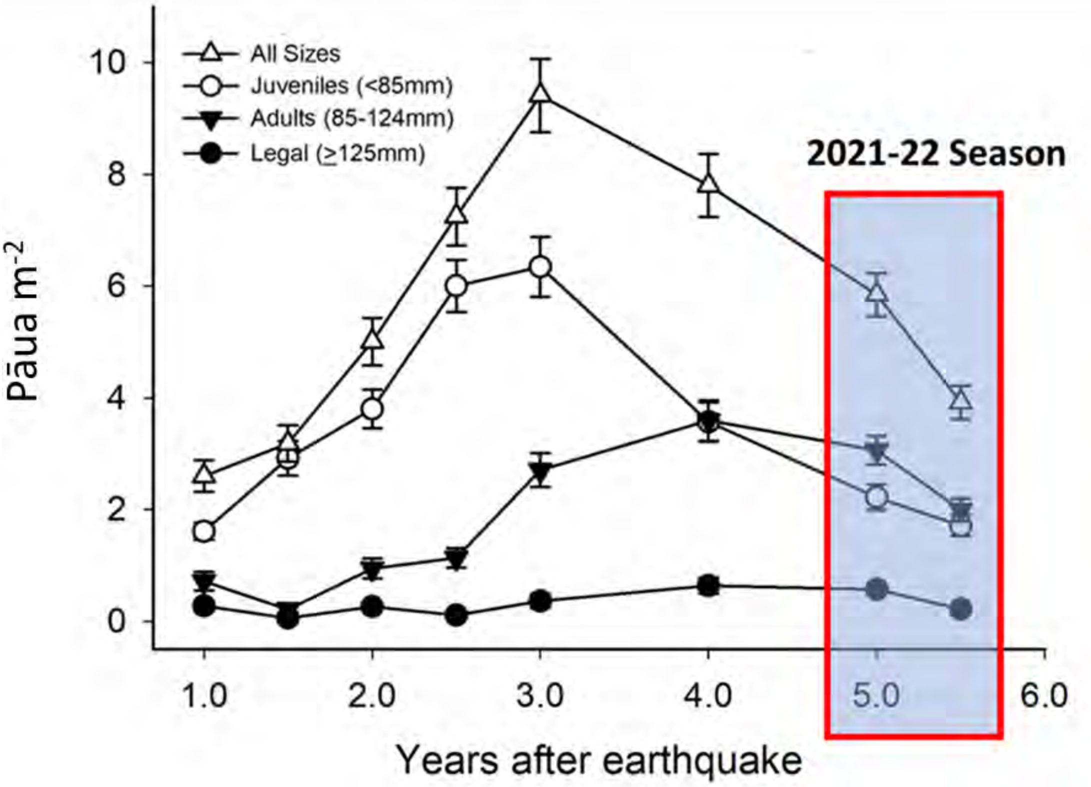


Figure 5: Time series depicting the average densities (pāua m^{-2}) of juvenile (< 85 mm), sub-legal adult (85–124 mm), legal adults (≥ 125 mm), and all sizes of pāua across all 26 intertidal sites, including those open and closed to recreational fishing in 2021–22. The red box indicates the two sampling events before and after the 2021–22 pāua season. Average abundance of all sizes increased greatly from 2017 to 2019, then began to stabilise or decline.

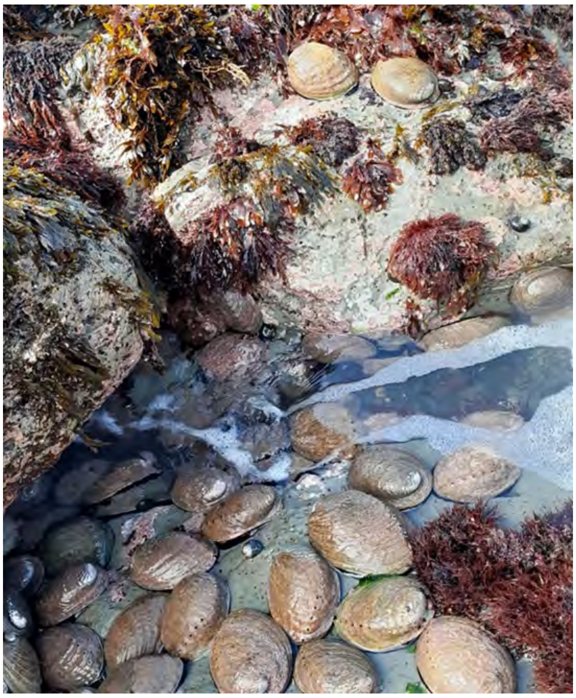


Figure 6: **The first 3 years after the earthquakes and fishery closure showed a great increase in the intertidal abundance of juvenile pāua across sites.**

One of the most notable changes recorded over the 5-year fishery closure was a steady build-up of large, legal-sized ($\geq$ 125 mm SL) pāua in shallow intertidal habitats (Figure 7). This zone is vulnerable to continual shore-based fishing pressure and is usually occupied mainly by sub-legal pāua. However, in the prolonged absence of harvesting, and as sub-legal pāua grew to harvestable size, legal pāua began to accumulate intertidally. The greatest increase in legal pāua density occurred across the sites that would eventually be reopened to fishing, with an increase of 0.39 m^{-2} ($\pm$ 0.16) to a peak of 0.92 m^{-2} ($\pm$ 0.22) in 2020 (Figure 8). Sites that would remain closed typically had populations dominated by juveniles and did not show a noticeable increase in large pāua during the closure (Figures 8 and 9, Table 2). The reasons for the relatively low abundance of legal pāua accumulating in the closed sites are unknown for certain, but may be a result of customary harvest at some sites (especially Oaro) and occasional illegal take which occurred over the 5-year closure.

Over the 2021–22 fishing season, the mean density of legal-sized pāua at fished sites decreased from 0.84 m^{-2} ($\pm$ 0.13) to 0.29 m^{-2} ($\pm$ 0.07), a 66% reduction (Figure 9). Across the closed sites, the mean density of legal pāua decreased from 0.19 m^{-2} ($\pm$ 0.11) to 0.11 m^{-2} ($\pm$ 0.06), a 42% reduction. At all fished sites, the post-fishing season densities were the lowest for legal-sized pāua recorded since the surveys began, although similar to levels recorded 1–2 years after the earthquakes (Figure 8, Table 2). The decline at fished sites was significantly greater than that at closed sites. PERMANOVA analysis showed that although density decreased at both fished and closed sites, there was a significant Time*Treatment interaction, indicating that pāua density decline was greater at fished sites (Pseudo-F = $5.18_{1,1038}$ $p<0.001$).

Figure 7: During the 5-year fishery closure, a significant build-up of large legal-sized pāua in shallow intertidal habitats was documented. Some sites began to resemble virgin fisheries. The majority of the pāua in this photo, taken at Rakautara prior to the 2021 reopening, were ≥ 125 mm.

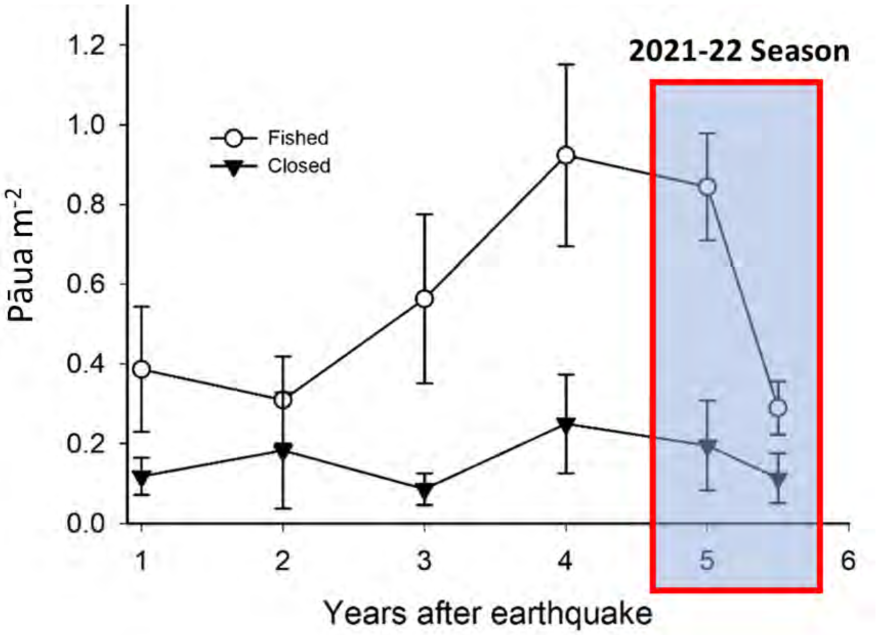


Figure 8: Intertidal legal-sized (≥ 125 mm) pāua density (pāua m^{-2}) over time at 11 closed sites and 15 fished sites (sites that would open for harvest in 2021). The red box indicates the two sampling events before and after the 2021–22 pāua season. In the first 5 years following the earthquakes, the abundance of legal-sized pāua more than doubled at sites that would become open to harvest and remained stable at closed sites. The 2021 fishing season showed a 42% decline in the average density of legal-sized pāua at closed sites, and a 66% decline at fished sites, resulting in the lowest average density recorded at fished sites since the surveys began in 2017.

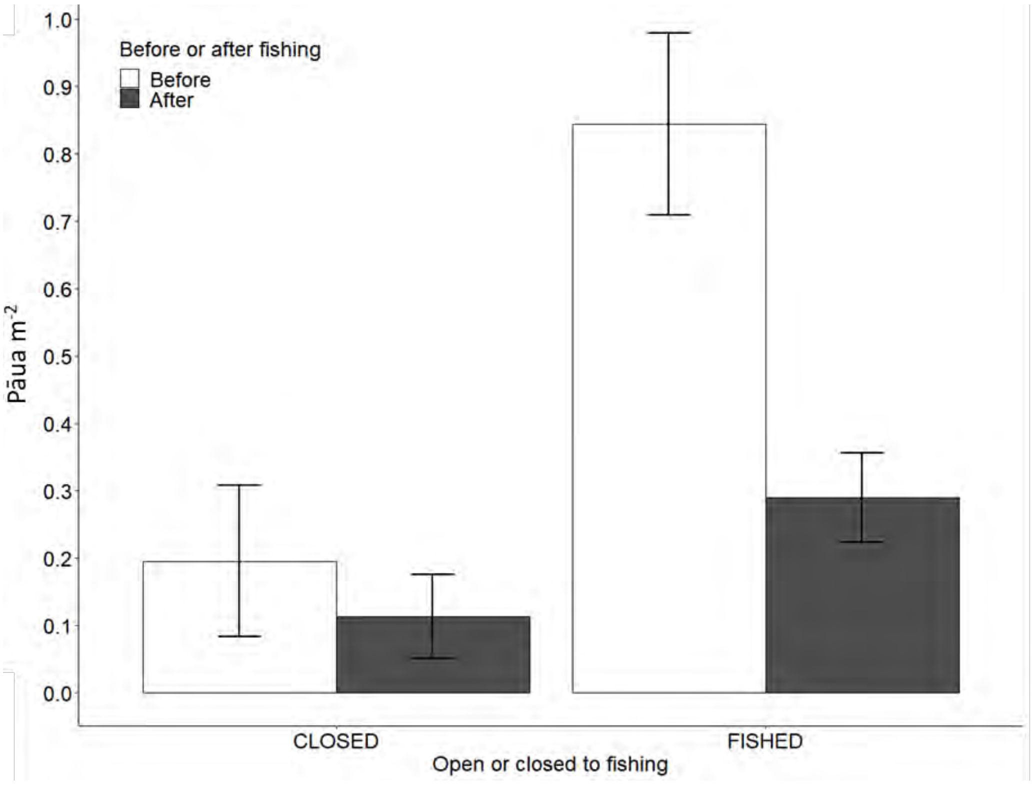
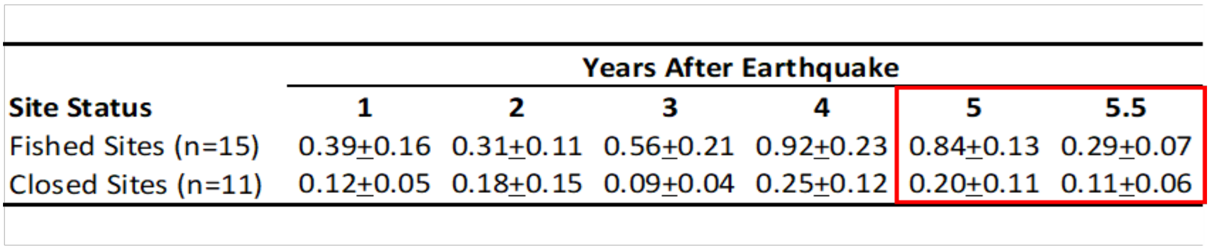


Figure 9: **Average intertidal density of legal-sized pāua in closed (left bars) and fished (right bars) sites before (white) and after (dark grey) (± SE) the 2021–22 season. At the 11 closed sites, density decreased 42% from 0.19 m^{-2} (± 0.11) to 0.11 m^{-2} (± 0.06) and at the 15 fished sites density decreased 66% from 0.84 m^{-2} (± 0.13) to 0.29 m^{-2} (± 0.07). PERMANOVA results indicate that the change in pāua density over time was significantly greater at fished sites compared with closed sites.**

Table 2: **Intertidal legal adult (≥ 125 mm) pāua density ± SE across 15 fished and 11 closed sites over time. Note that all sites were closed to recreational and commercial fishing from years 1–5, but experienced some degree of legal customary harvest during the 5-year closure. Years 5 and 5.5 represent the periods just before and just after the 2021–22 pāua season, respectively, indicated with a red box.**



	Years After Earthquake					
Site Status	**1**	**2**	**3**	**4**	**5**	**5.5**
Fished Sites (n=15)	0.39±0.16	0.31±0.11	0.56±0.21	0.92±0.23	0.84±0.13	0.29±0.07
Closed Sites (n=11)	0.12±0.05	0.18±0.15	0.09±0.04	0.25±0.12	0.20±0.11	0.11±0.06

Shell lengths of legal-sized pāua were converted to biomass for utility to fishery managers, who typically work with biomass. Across the 11 closed intertidal sites, the total biomass of legal pāua was 13.5 kg over the 220 m^2 of habitat sampled (0.061 kg m^{-2}) before the season and 7.8 kg (0.035 kg m^{-2}) after the season, a decrease of 42% (Figure 10). Across the 15 fished intertidal sites the biomass was 69.6 kg over the 300 m^2 of habitat sampled (0.232 kg m^{-2}) before the season and 22.5 kg (0.075 kg m^{-2}) after the season, a 68% decline (Figure 10). Note that while the sample area for these surveys is consistent between sample events (20 m^2 per site in the same general area), the quadrat placement is haphazard, not permanent, so some degree of spatial variability is expected. These biomass figures may seem low, but they only represent a very small area of much larger reefs (closed Sites = 220 m^2 of reef sampled, fished Sites = 300 m^2 of reef sampled). Nevertheless, these randomised quadrats are representative of the reefs that were subsampled over broad sample area (30 km of coast covered on foot).

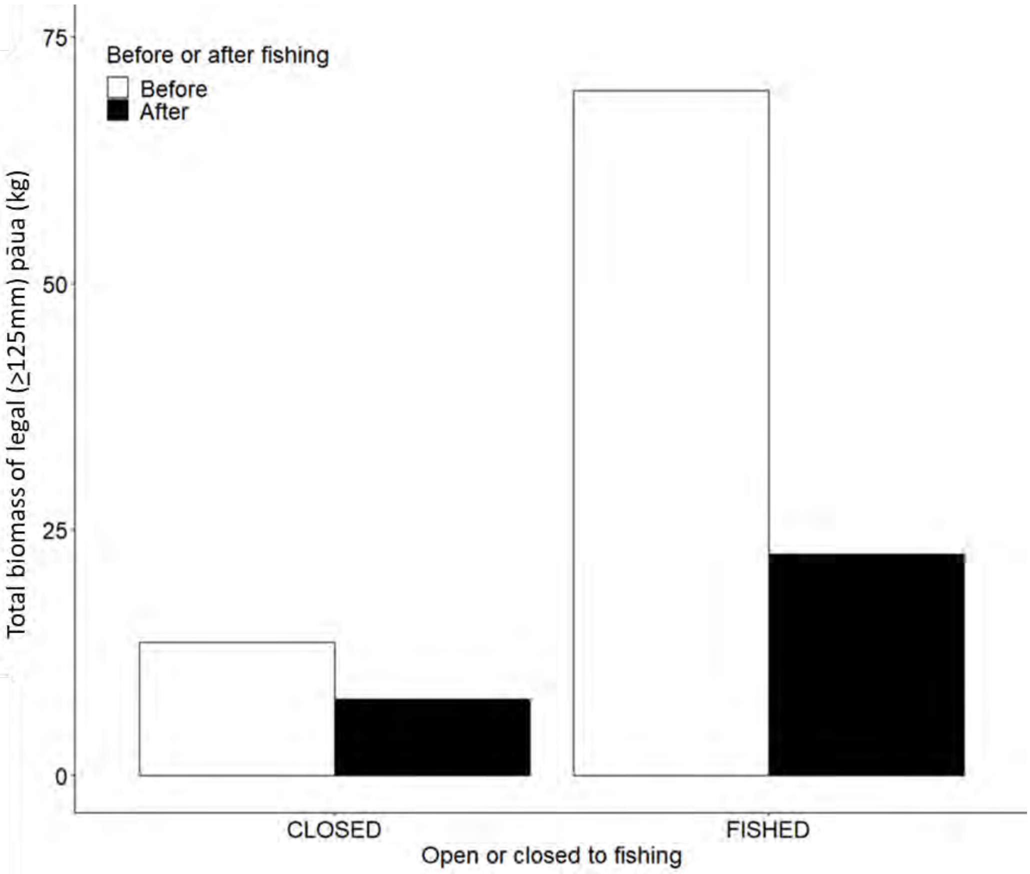


Figure 10: Changes in intertidal total biomass of legal (≥ 125 mm) pāua found in quadrats across all 11 closed sites (left bars) and 15 fished sites (right bars) before (white) and after (black) the 2021–22 fishing season. At the 11 closed sites biomass decreased 42% from 13.5 kg to 7.8 kg (or from 0.061 kg m^{-2} to 0.035 kg m^{-2}), and at the 15 fished sites, biomass decreased 68% from 69.6 kg to 22.5 kg (or 0.232 kg m^{-2} to 0.075 kg m^{-2}). Note that while the sample area for these surveys is consistent between sample events (20 m^2 per site), the quadrat placement is haphazard, not permanent, so some degree of spatial variability is expected.

Although changes in intertidal abundance of legal-sized pāua due to the 2021–22 fishing season were significant, overall changes in population size structure were non-significant. There was no significant effect of Fishing or Time on cumulative percent of pāua in different size classes (Treatment*Time Pseudo-$F_{1,46} = 0.54$, $p = 0.578$; Figure 11). The 11 closed sites had a greater abundance of juveniles prior to the fishery reopening and did not have a high proportion of large legal pāua in the intertidal habitats even after the 5-year fishery closure. Across the 15 fished sites, a slight shift in population structure towards smaller individuals occurred over the fishing season, but this was not statistically different than the shift seen at closed sites (Figure 11). It is important to reiterate that this population is largely dominated by juvenile size classes due to the nature of the habitat type and tidal zone. Therefore, the significant drop in abundance of legal-sized pāua described earlier did not result in a noticeable shift in overall demography, since the larger size classes made up a very small proportion of the whole population. Additional length-frequency distributions (in Figures A.2 and A.3 in the Appendix), give a better indication of proportional changes to the largest size classes at fished and closed intertidal sites, whereby the size classes ≥ 125 mm at fished sites were greatly reduced after fishing compared with at closed sites.

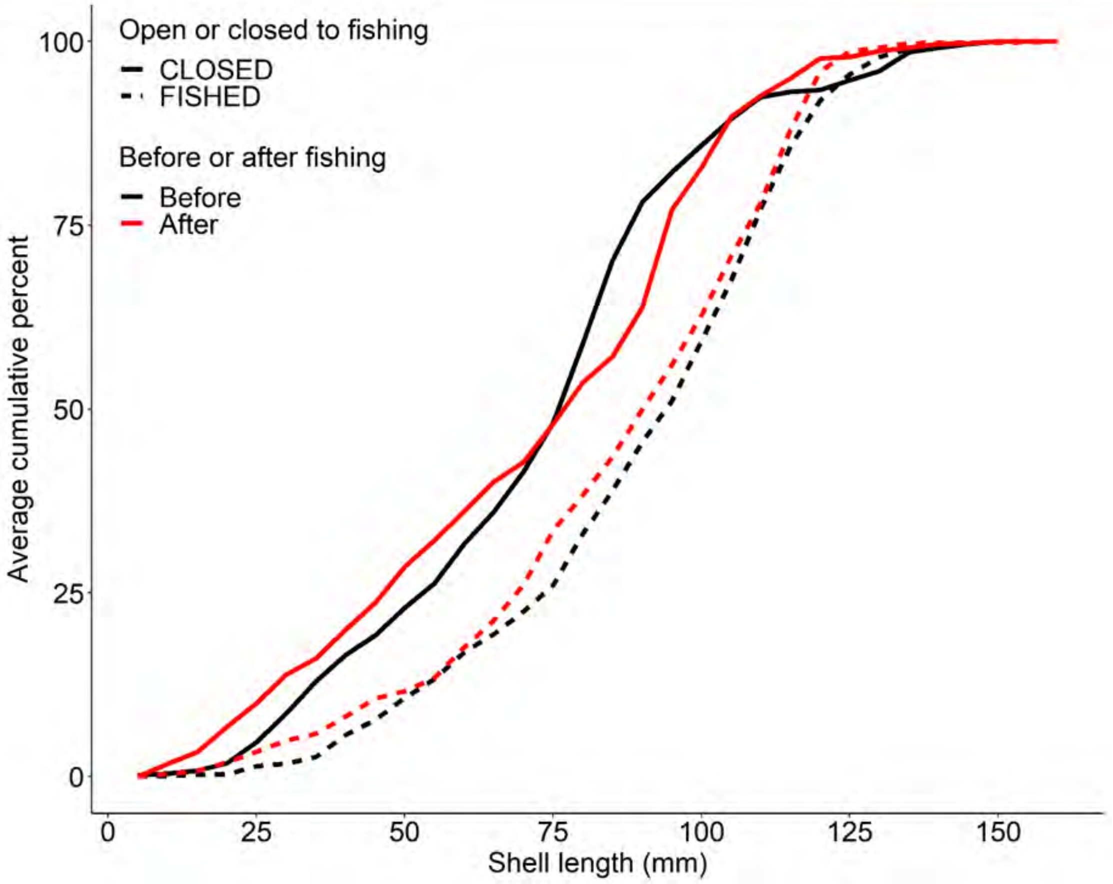


Figure 11: Intertidal cumulative length-frequency distribution of pāua populations at closed (solid line) and fished (dotted line) before (black) and after (red) the 2021–22 fishing season. The population size structure shifted slightly at fished sites to smaller individuals, but no obvious shift occurred at closed sites. Closed intertidal sites generally had smaller pāua before and after the fishing season than did fished sites (although this trend was opposite in subtidal results below).

3.2 Subtidal surveys

Seven subtidal sites were sampled before and after the fishing season, including 4 fished and 3 closed sites. Here, scatterplots of all individual shell measurements (y-axis) across depth (x-axis) show before vs. after comparisons of closed (Figure 12) and fished sites (Figure 13). The red line shows the recreational minimum legal size (MLS) of 125 mm. Closed sites showed little difference before and after the fishing season, as indicated by the general overlapping of sizes between the two surveys (Figure 12). Fished sites showed a notable downward shift in size after the fishing season, which was particularly evident to 2 m depth (Figure 13). The prevalence of very large pāua (135–160 mm) decreased after fishing, especially in depths shallower than 2 m. Not all legal pāua were harvested, and many just sub-legal individuals remained after the season ended.

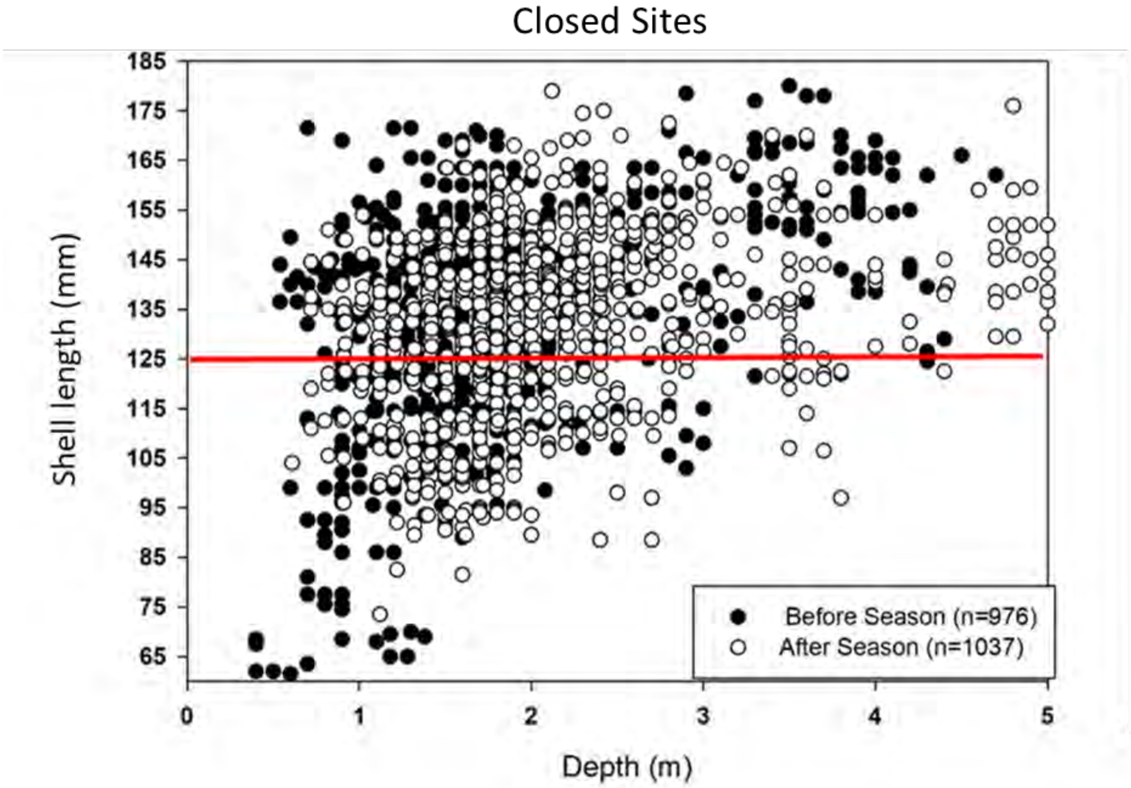


Figure 12: Subtidal depth distribution of all shell measurements taken before (black dots) and after (white dots) the 2021–22 fishing season for three closed sites. The red horizontal line indicates the 125 mm minimum legal size for recreational fishers.

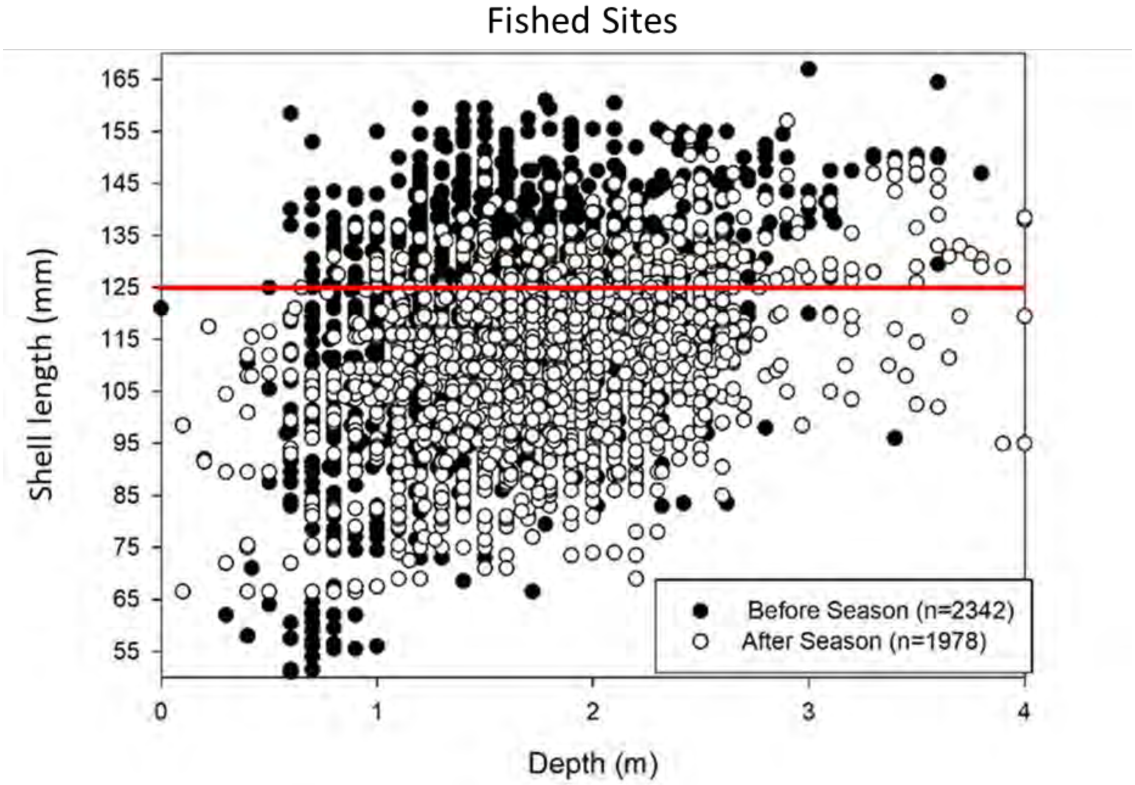


Figure 13: Subtidal depth distribution of all shell measurements taken before (black dots) and after (white dots) the 2021–22 fishing season for four fished sites. The red horizontal line indicates the 125 mm minimum legal size for recreational fishers.

The most evident change in pāua distribution occurred at Rakautara, where the majority of legal pāua were harvested (Figure 14). Here, there was a nearly complete 'fishing down' of pāua to the MLS. This site is located in one of the most heavily fished areas along the coast (Holdsworth 2022) and may represent an extreme example of recreational fishing effects.

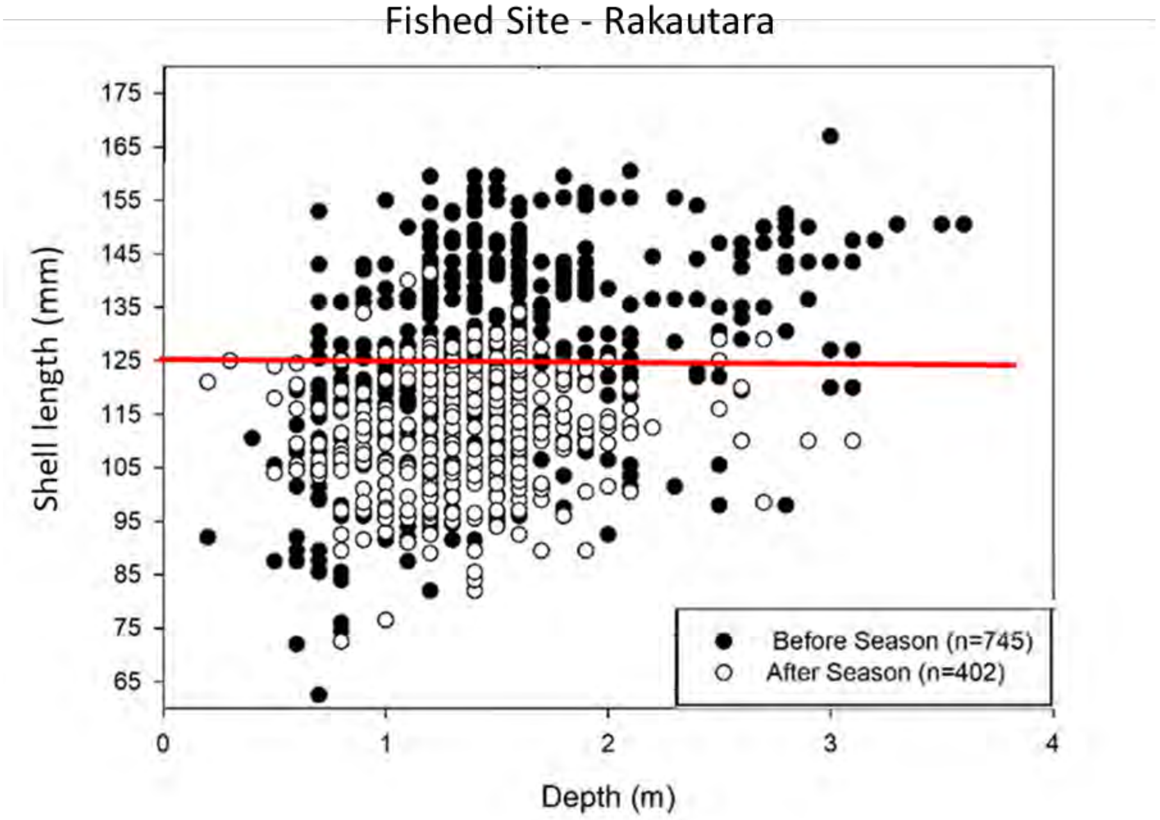


Figure 14: Subtidal depth distribution of all shell measurements taken before (black dots) and after (white dots) the 2021–22 fishing season at the Rakautara site.

The shell lengths of sampled pāua were converted to biomass. In assessing the total biomass of all pāua measured across all sites, there was a slight increase of 4.5% from 292 kg to 305 kg at closed sites, but a 40% decrease from 529 kg to 315 kg at fished sites (Figure 15). Most of this change in biomass was due to changes in abundance of legal-sized pāua. Across the 3 closed sites, the total biomass of legal pāua was 249 kg before the season and 261 kg after the season, an increase of 5% (Figure 16). Across the 4 fished sites, the biomass of legal pāua was 369 kg before the season and 97 kg after the season, a 74% decline (Figure 16). Note that while the sample area for these surveys was carefully delineated, and measures were taken to optimise data quality, some variability due to sampling logistics must be expected. Also, due to the irregularity of the sampling area from rocky features (e.g., boulders and reef promontories) and therefore varying seafloor topography, it would not be accurate to convert these data to a density because the precise area of the reefs sampled could not be calculated. Nevertheless, the two-dimensional area (length-width) was constant between samples.

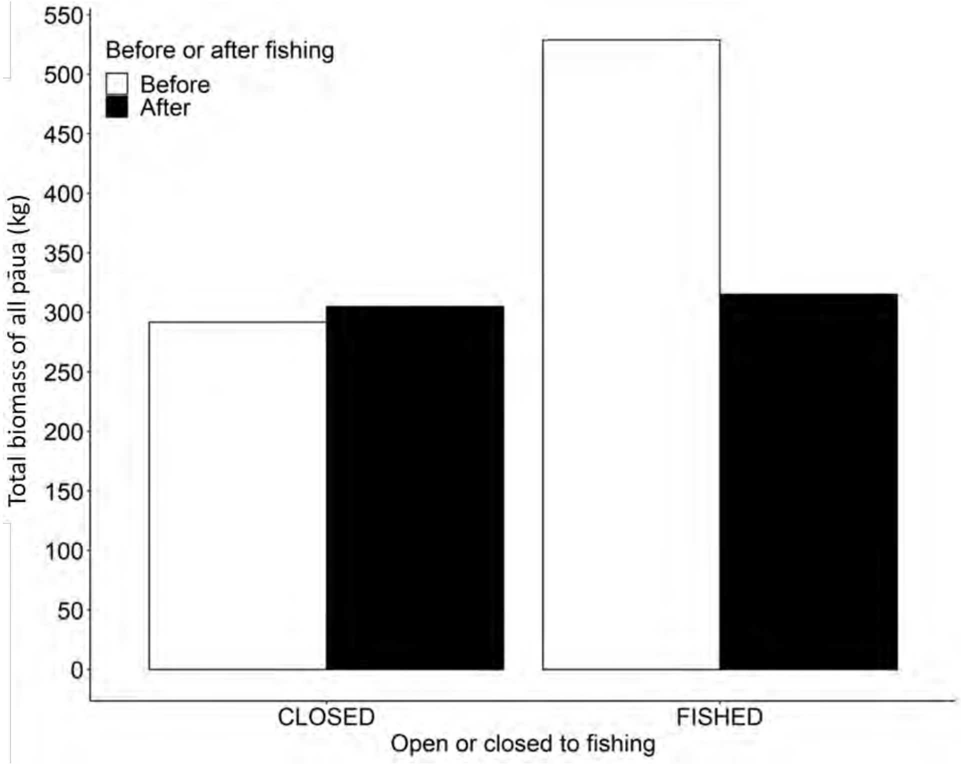


Figure 15: Total subtidal biomass (all sizes included) of pāua measured during 90-minute dive surveys in the three closed (left bars) and four fished (right bars) sites before (white) and after (black) the 2021–22 fishing season. Total biomass increased by 4.5% at closed sites and decreased by 40% at fished sites.

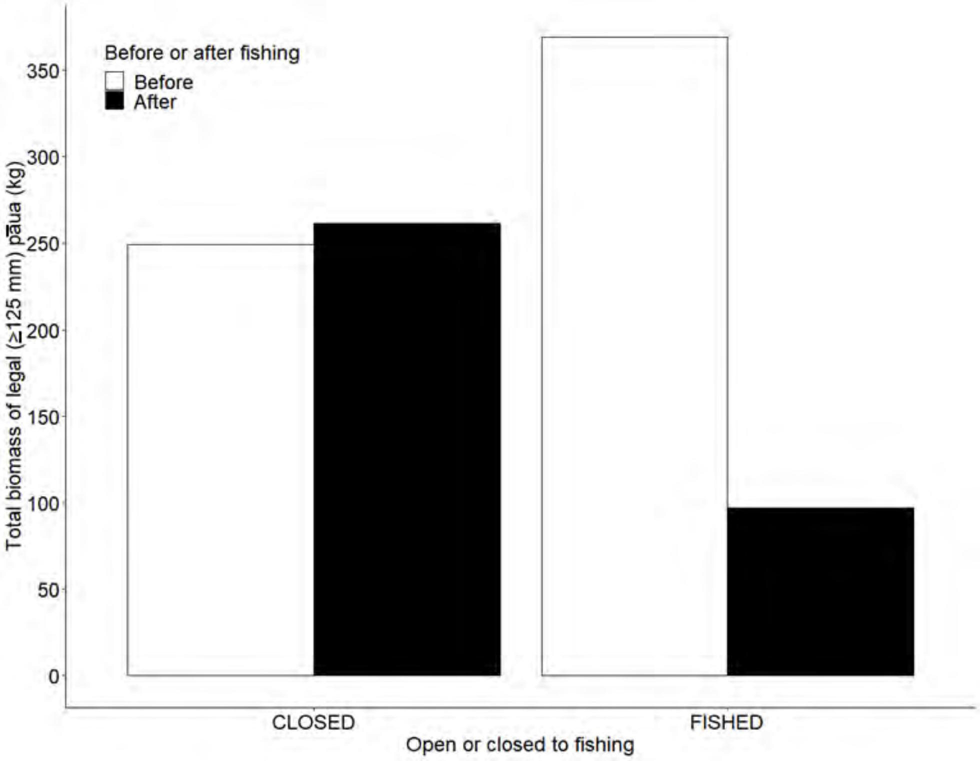


Figure 16: Total subtidal biomass of legal pāua (≥ 125 mm) measured during 90-minute dive surveys in three closed (left bars) and four fished (right bars) sites before (white) and after (black) the 2021–22 fishing season. Total biomass increased 5% from 249 kg to 261 kg at closed sites and decreased 74% from 369 kg to 97 kg at fished sites.

Shifts in population size structures (summarised in Figure 17) were evident in the cumulative length-frequency distribution of pāua at fished and closed sites before and after the fishing season. In general, closed sites had a higher proportion of larger pāua to begin with, perhaps a legacy of their protected status in special areas (especially Kaikōura rāhui sites which have been closed to all harvest for 20+ years). Closed sites experienced a slight shift towards smaller individuals after the fishing season, indicating either temporal variability (e.g., emigration) or that legal customary or illegal harvest had occurred. The fished sites showed a shift in population structure, with a pronounced decrease in the proportion of larger individuals after fishing. This decrease is significant as shown by the Treatment*Time interaction (Pseudo-$F_{1,10}$ = 6.45, p = 0.018). Fished sites had significantly greater proportions of smaller individuals after the fishing season compared with closed sites.

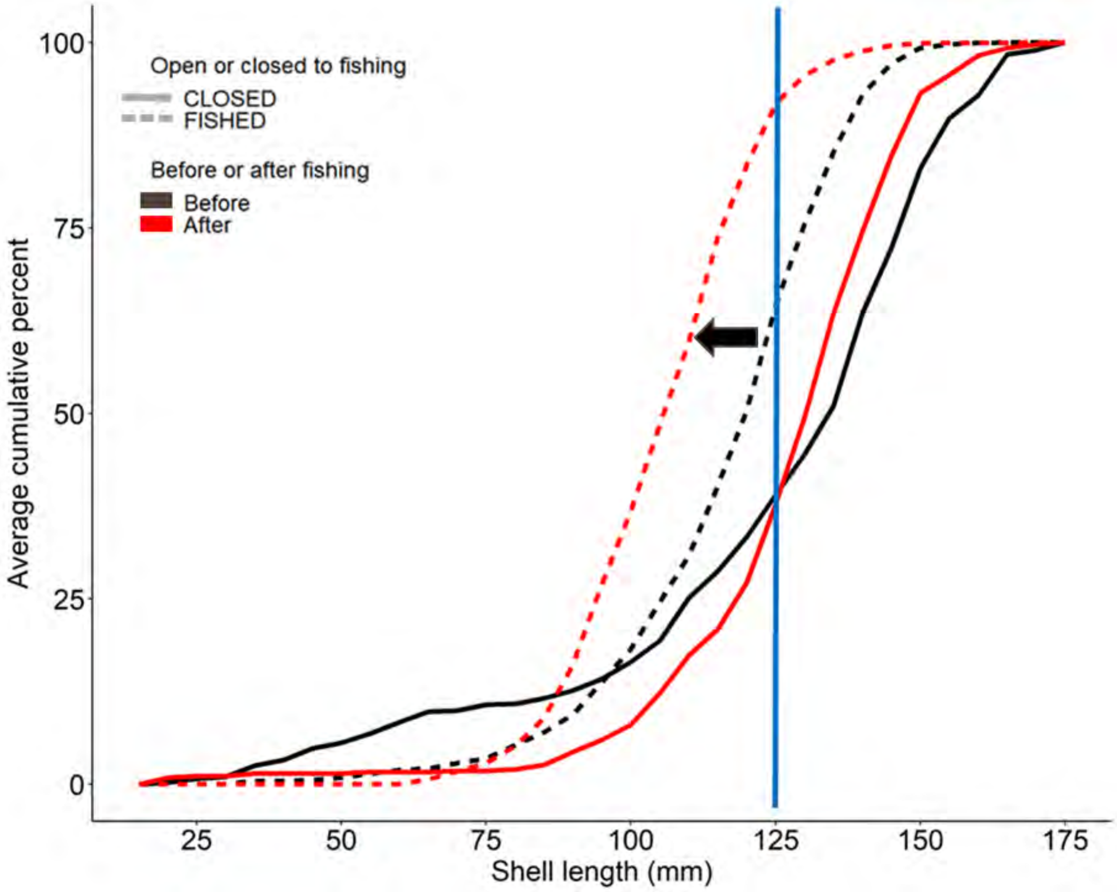


Figure 17: **Subtidal cumulative length-frequency distribution at closed (solid line) and fished (dotted line) before (black) and after (red) the 2021–22 season. The vertical blue line indicates the 125 mm shell length (MLS). Unfished sites had higher proportions of large pāua to begin with. Fished sites showed a notable shift in population structure towards smaller individuals (indicated with black arrow).**

Fishing effects are also illustrated by the significant reduction in the average shell length at fished sites compared with closed sites (significant Treatment*Time interaction, Pseudo-$F_{1,1005}$ = 7.86, p = 0.019; Figure 18). Mean shell length at closed sites was larger to begin with, at 130.57 mm (± 0.83), and did not change significantly after the fishing season (131.96 mm ± 0.61). At fished sites, however, average shell size was 121.34 mm (± 0.41) before and 109.99 mm (± 0.35) after the fishing season.

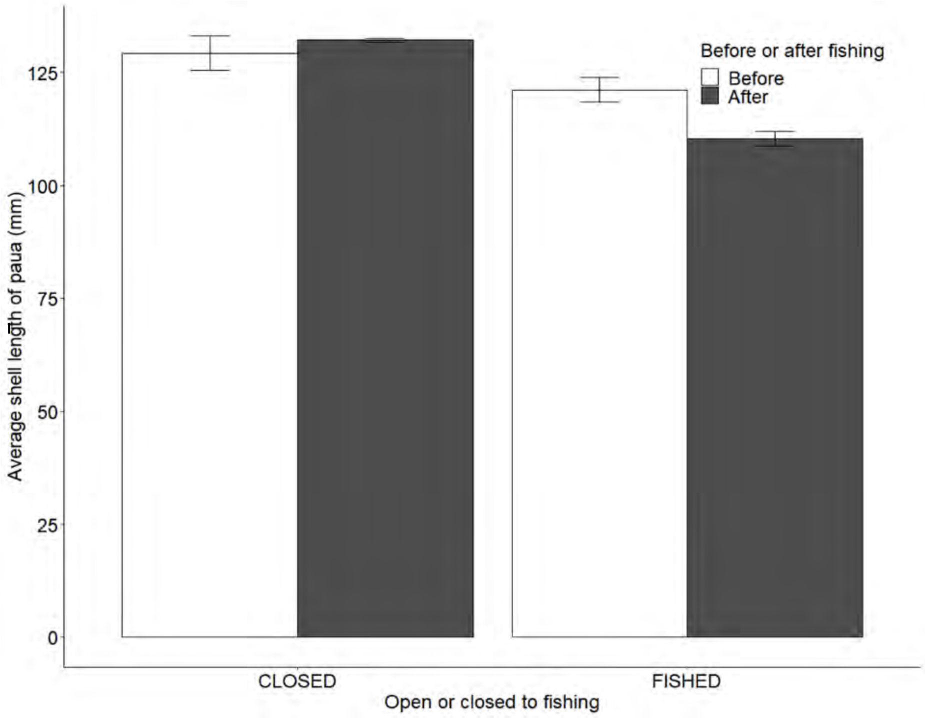


Figure 18: Average shell length (± SE) of all pāua measured at subtidal closed (left bars) and fished (right bars) subtidal sites before (white) and after (dark grey) the 2021–22 fishing season. Average shell length did not change significantly at closed sites (130.57 ± 0.83 mm before, 131.96 ± 0.61 mm after) but did decline significantly at fished sites (121.34 ± 0.41 mm before and 109.99 ± 0.35 mm after).

3.3 Notable observations

At the four subtidal fished sites that were surveyed, there were clear signs of a high harvest of pāua, evidenced by dense patches of pāua 'scars' (Figure 19A). However, in areas that were more difficult to access, such as dangerous surge channels or areas with consistent wave impact, dense patches of large pāua often remained and few scars were seen (Figure 19B). These relatively unfished patches will likely be important contributors to future spawning events, but they may also become more susceptible to harvest if more accessible patches are depleted.

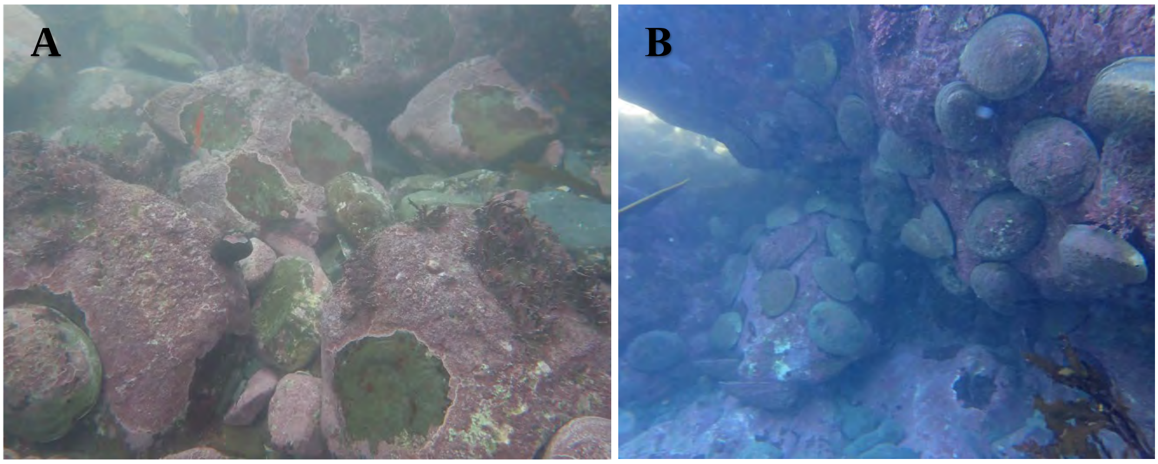


Figure 19: A. Some accessible areas were completely absent of legal-sized pāua after the fishing season, with numerous bare scars on the rocks where pāua previously had been (photo: Rakautara). B. Other open areas, such as Omihi, were not heavily harvested, probably due to their difficult access in large swell areas.

During our dive surveys after the fishing season closed, a variety of metal tools that were presumably lost by recreational fishers were found in fished areas. These included screw drivers, paint scrapers, and serrated garden tools (Figure 20). The survey by Blue Water Marine estimated that nearly 35 000 pāua were handled and returned by recreational fishers (Holdsworth 2022). Considering that pāua lack blood clotting factors and are particularly susceptible to mortality from being cut or punctured by harvest tools, the use of inappropriate tools may result in high levels of non-harvest mortality. Note that commercial divers are unlikely to handle many undersized pāua or cause lethal damage when fishing.

Figure 20: A number of sharp metal harvest implements were found discarded or lost at popular recreational sites, including paint scrapers, flat-head screw drivers, and this serrated garden tool found at Rakautara.

Throughout the 5 years of fishery closure, and during the 2021–22 fishing season, illegal harvesting practices were observed by our research team, who spend much time in the field. This included non-customary harvesting during the 5-year closure, harvesting in closed areas during the fishing season, harvest of evidently undersized pāua, single fishers harvesting multiple limits for non-fishers, and the discarding of undersized pāua in areas where they were unlikely to survive. Numbers of fishers entering the Hikurangi Marine Reserve were as high as 50 per hour, as noted by local Department of Conservation rangers[2]. After the fishing season we saw several piles of dead pāua discarded near State Highway 1 (Figure 21), presumably by fishers who were at risk of being caught by a fisheries officer. Illegal harvest is very difficult to quantify but may constitute a considerable addition to total harvest estimates.

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[2] Radio New Zealand (04 January 2022) Dozens spotted taking pāua from marine reserve near Kaikōura. Dozens spotted taking pāua from marine reserve near Kaikōura | RNZ News

Figure 21: A pile of dead, discarded pāua found near the side of State Highway 1 near Rakautara in December 2021. These legal-sized pāua were likely abandoned by a poacher who was over the bag limit and saw a fisheries officer or other official approaching. Poaching was also witnessed in the Hikurangi Marine Reserve and in the Oaro Taiāpure during and after the 2021–22 fishing season.

4. DISCUSSION

4.1 Intertidal surveys

During the 5-year fishery closure, a widespread build-up of juvenile and adult sized pāua occurred at the intertidal sites. Peak abundance of juveniles occurred 3 years after the earthquake disturbance. The emergence of a large cohort in 2019 may be attributed to a synchronised spawning event triggered by the earthquakes and subsequent tsunami, a phenomenon documented in other haliotid populations (e.g., Onitsuka et al. 2007). The increase in juvenile pāua abundance may also partially reflect commercial enhancement efforts initiated by the Pāua Industry Council and PauaMAC3, who organised the release of 170 000 hatchery-reared ‘seed’ pāua in 2018 to speed recovery of the fishery. Multi-year studies by our research team have found that these seeding events can account for about 12% of the pāua population at enhancement sites such as Omihi (Gerrity, unpublished data). It is important to consider that the recruitment seen in the years immediately following the earthquakes may have been anomalously high. Future reproduction and juvenile recruitment events, especially after the resumption of pāua harvest, may be considerably reduced. Any effects from harvesting a large spawning biomass on juvenile demography will not be detectable for 2–3 years after the season closes. This is about the time it takes for a cohort to settle from larvae, grow, and emerge from cryptic habitats where they can more readily be surveyed and quantified. At this stage, there are still high abundances of juveniles from previous reproduction episodes.

After the 2019 peak in abundance, a decline in pāua density in all size classes occurred prior to the fishery reopening. This is likely due to a combination of habitats reaching their carrying capacity, emigration of crowded pāua into deeper, more favourable habitats, effects from customary or illegal fishing, or natural variability in reproduction and recruitment over the years, which is typical in shellfish populations. Subtidal surveys showed the presence of numerous ‘emergent’ pāua (70–100 mm) with clean shells that appeared to have recently moved into the adult habitats (Figures 12, 13, and 22). A continuation of this survey work will provide more information on the temporal changes in these dynamic populations.

Figure 22: Emergent pāua, identified by smaller size and clean shells without algal crust growth, mixed in with large adults in shallow subtidal habitats. Emergent pāua predominately migrate from juvenile intertidal habitats.

During the 5-year closure, the abundance of legal-sized pāua increased significantly at several sites that would eventually reopen to recreational fishing in 2021, but rapidly decreased back to post-earthquake levels after 3 months of fishing. Although the population was in gradual decline after the 2019 peak prior to the reopening, a statistically significant effect from fishing was detected. Sites easily accessible from State Highway 1 such as Omihi and Rakautara had few, if any, legal pāua remaining in intertidal habitats after the fishing season. The remaining intertidal biomass of legal pāua at our study sites was found almost exclusively at the more inaccessible reefs, suggesting that accessibility is a main driver of harvest along this coastline.

Despite the decline in legal pāua abundance across sites, high abundances of sub-legal pāua and smaller juvenile size classes, including recently settled recruits (< 25 mm) were commonly found among cryptic habitats. These juvenile and sub-legal adult populations are the product of high spawning biomass and good reproduction, juvenile recruitment, and survival during the 5-year closure. Future recruitment classes will likely be reduced if adult biomass gets sequentially ‘fished down’.

4.2 Subtidal surveys

Dive surveys of wadeable patches of pāua showed strong effects of the 2021–22 fishing season. The biomass of legal-sized pāua declined by 74% at fished sites, while the biomass recorded at closed sites increased by 5%. The most striking example of fishing effects was seen at Rakautara, where the population was fished down nearly to the recreational MLS of 125 mm SL, a 92% decrease in legal biomass. This site falls within one of the busiest access points, with Blue Water Marine estimating 3000 recreational fishers over the 3-month season (Holdsworth 2022). This example highlights the importance of an informed minimum legal size requirement, which ensures that an adequate proportion of the spawning biomass remains despite high fishing pressure. Pāua are broadcast spawners and require proximity of males and females for fertilisation, and the importance of patch size and connectivity between spawning aggregations for the sustainability of abalone fisheries is well documented (e.g., McShane 1995, Babcock & Keesing 1999). At this stage, it is unknown how effective the 125 mm recreational size limit is in protecting the reproductive potential of populations, or whether it is advisable to move to a higher size limit as have the commercial fishers, who fish at a minimum of 130 mm in the Kaikōura management area and 135 mm at several areas within this area. Many tools that the commercial sector use to avoid localised depletion and the fragmentation of spawning patches, namely catch-spreading and voluntary increases in MLS, are likely not used by recreational fishers in a cohesive way. Maintaining a viable and connected spawning biomass along the Kaikōura coast will be an essential challenge in ensuring the long-term viability of the fishery.

The demography of subtidal populations surveyed here was measurably affected by fishing. At fished sites, the population structure shifted significantly towards smaller individuals, and the average shell size decreased significantly. These detectable changes in the demography after 3 months of fishing further illustrate the sensitivity of these populations to acute harvest over relatively short periods.

Despite evident ‘fishing down’ of larger pāua, some difficult-to-access areas appeared to have been barely harvested. It is likely that more remote stretches of coastline north of Kaikōura that have poor accessibility to shore-based fishers, and consistent poor visibility, were less harvested than the sites we surveyed. We are therefore unable to extrapolate our findings to the wider Kaikōura coastline, some of which is inaccessible to most amateur fishers. The ease of access (both in terms of access from the road and typical sea conditions of a site) was likely a main driver to the extent to which reefs were depleted. This highlights that accessible areas take the brunt of harvest pressure and are particularly vulnerable to localised depletion.

4.3 Conclusion

These data show that the initial season had immediate and measurable effects on pāua populations that were readily accessible along the Kaikōura Marine Area and southern portion of PAU 7. This emphasizes the vulnerability of the fishery to intensive short-term amateur fishing. Our findings are unsurprising when considering estimates of fishing pressure and harvest for the season (Holdsworth 2022; Shane Orchard, University of Canterbury, unpublished data) which showed that the recreational harvest exceeded its allowance by about 37 t. At 3 pāua per kilogram, this represents more than 110 000 pāua removed in excess of the designated recreational allocation. This can be viewed in terms of the total life history of pāua, which take a minimum of 6–7 years to reach a legally harvestable size of 125 mm. Such harvest entails a substantial time period for replenishment. Now that the build-up of easily accessible pāua is largely reduced, the level of recreational fishing that is sustainable in the long term needs addressing.

Despite evidence of localised depletion in some wadeable areas, other difficult-to-access areas maintain good spawning biomass and an abundance of sub-legal adults and juveniles. These surviving patches may become more susceptible to harvest as easily-accessible areas are ‘fished down’.

This work adds to an important quantitative time series of pāua population structure and abundance across a diverse suite of sites, and serves as a reference point to gauge future changes to the fishery.

5. POTENTIAL RESEARCH

A continuation of this research would clarify spatial and temporal trends in the pāua populations along the Kaikōura coastline, and better differentiate the effects of recreational fishing. A continuation of intertidal population surveys will help quantify the effects of the 2021–22 fishing season on juvenile recruitment dynamics in the near future. The addition of more subtidal sites to better represent the spatial variability along the earthquake-affected coastline, and capture a wider range of accessibility of the fishery by shore-based fishers, would allow for a broader assessment of fishing effects along the coastline.

6. ACKNOWLEDGEMENTS

This work was completed under Fisheries New Zealand project SEA2021-07. We thank Fisheries New Zealand for funding this work as well as other research programmes, which have provided essential background information on wider ecosystem impacts and recovery from the earthquakes. Thanks to John Holdsworth of Blue Water Marine, who was generous in sharing his work and observations during the pāua season. Thanks to the Pāua Industry Council, Storm Stanley, Jeremy Cooper, and Tom McCowan for collaboration and support of this work and broader research. Thanks to Tommaso Alestra, Spencer Virgin, and Thomas Falconer for survey design, fieldwork, and statistical analysis. Thanks to Jason Ruawai of Kaikōura for ongoing support and assistance. Thanks to Shane Orchard for additional work on the fishery reopening. Thanks to those who reviewed this report, including Ian Tuck, Paul Creswell, Marine Pomarède, and Philip Heath, who gave constructive feedback and showed genuine interest.

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8. APPENDIX

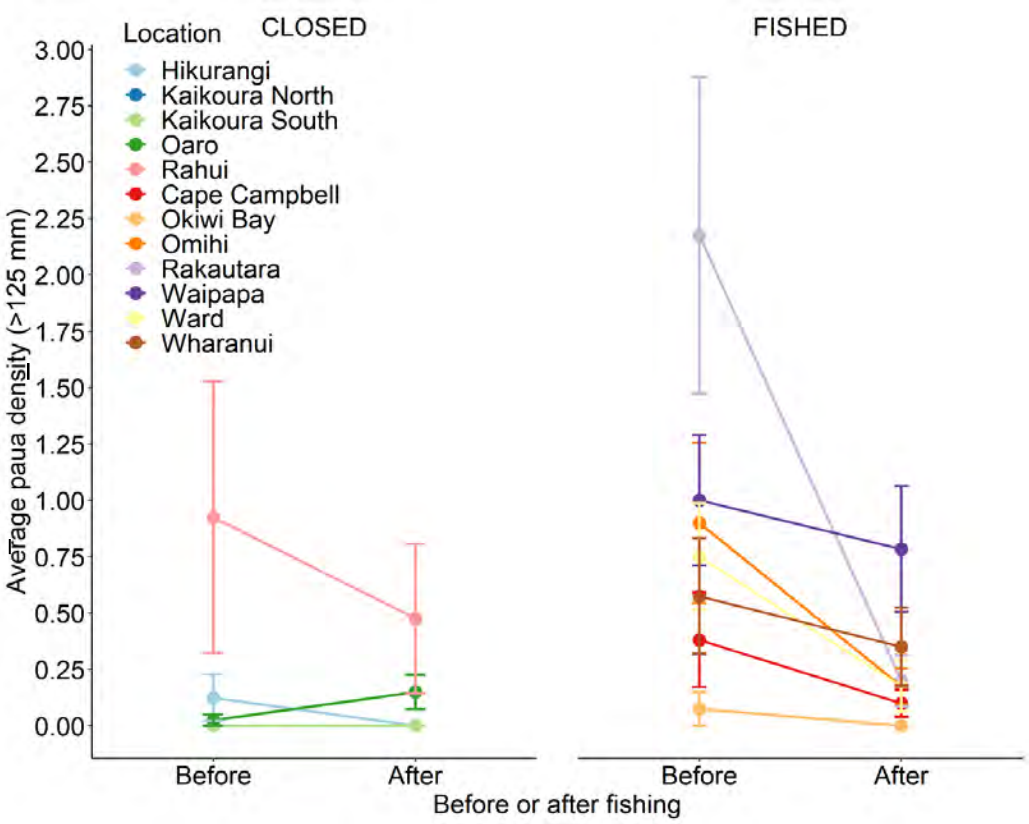

Figure A.1: Average density of legal (>125 mm) pāua (pāua m^{-2}) before and after fishing at closed (left) and fished (right) intertidal locations. Each location has 2 sites, except for Waipapa, which has 3 sites.

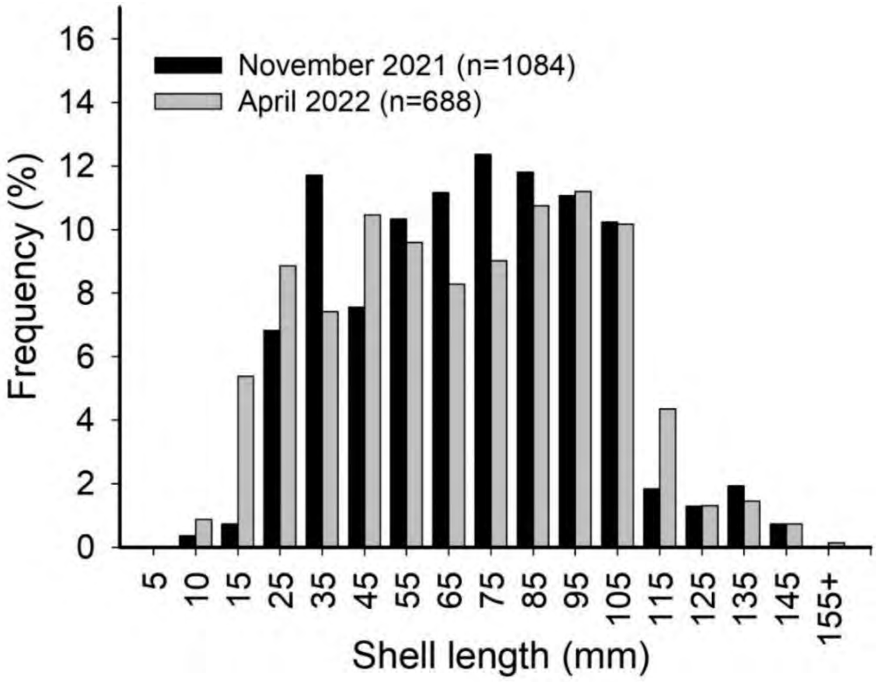

Figure A.2: Length-frequency distribution of intertidal pāua measured at 11 closed sites before (black bars), and after (grey bars) the 2021–22 fishing season.

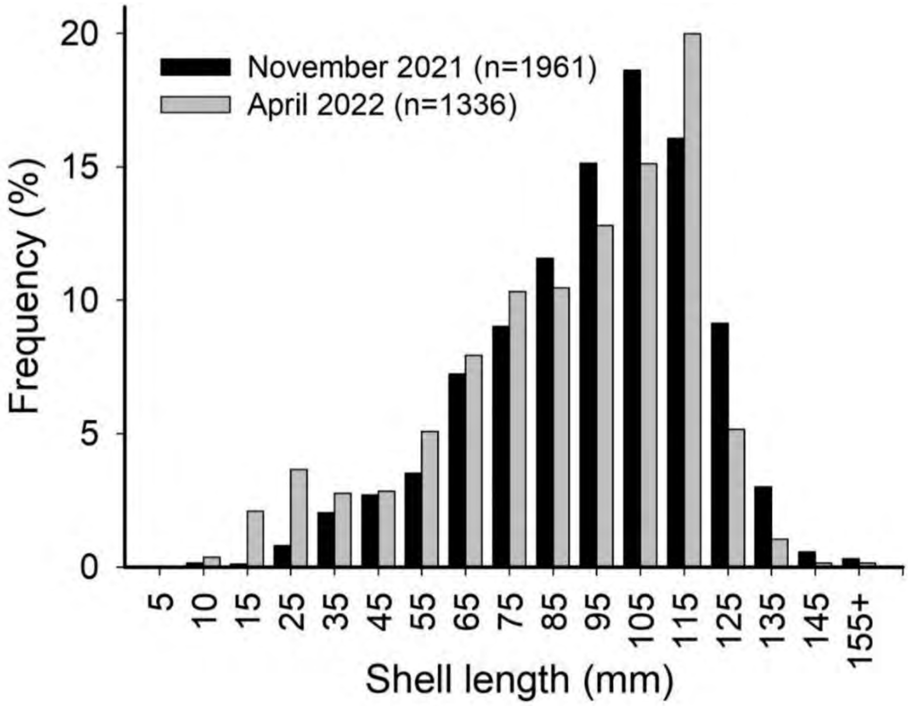

Figure A.3: Length-frequency distribution of intertidal pāua measured at 15 fished sites before (black bars) and after (grey bars) the 2021–22 fishing season.

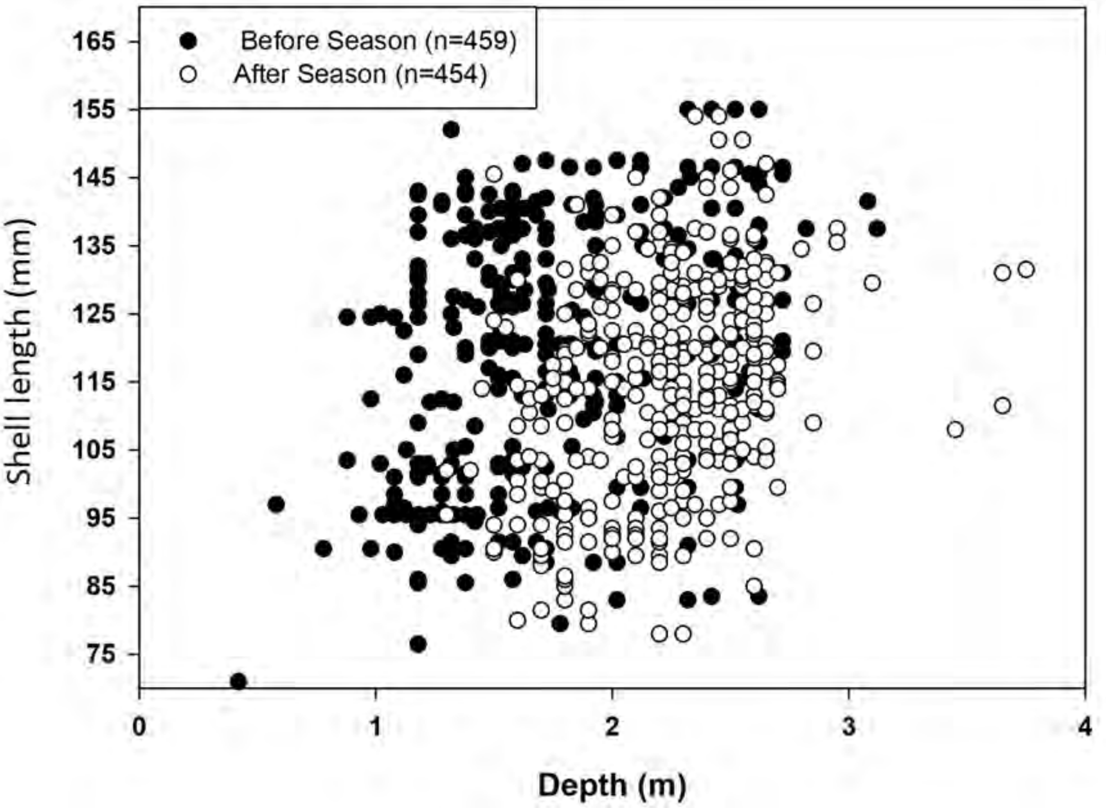

Figure A.4: North Paia (fished subtidal site) scatterplot showing individual shell measurements of all pāua measured at depth, before (black dot) and after (white dot) the 2021–22 season.

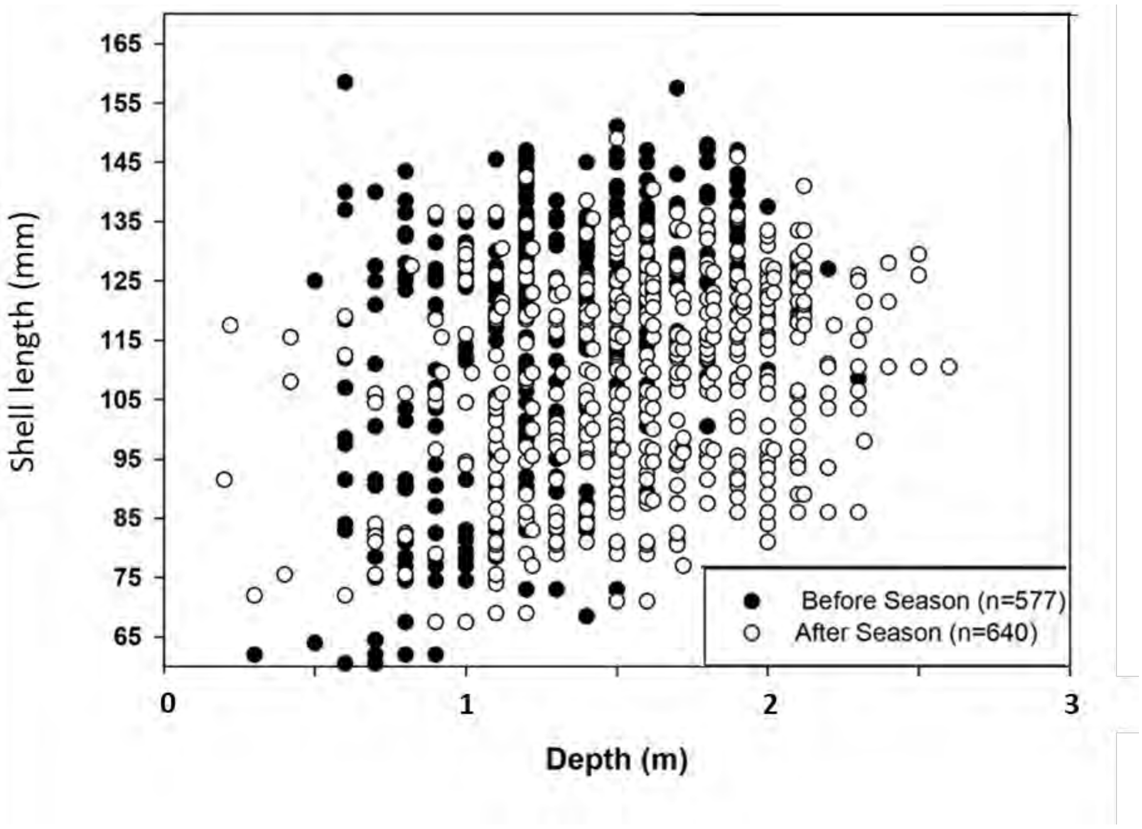

Figure A.5: Paia Point (fished subtidal site) scatterplot showing individual shell measurements of all pāua measured at depth, before (black dot) and after (white dot) the 2021–22 season.

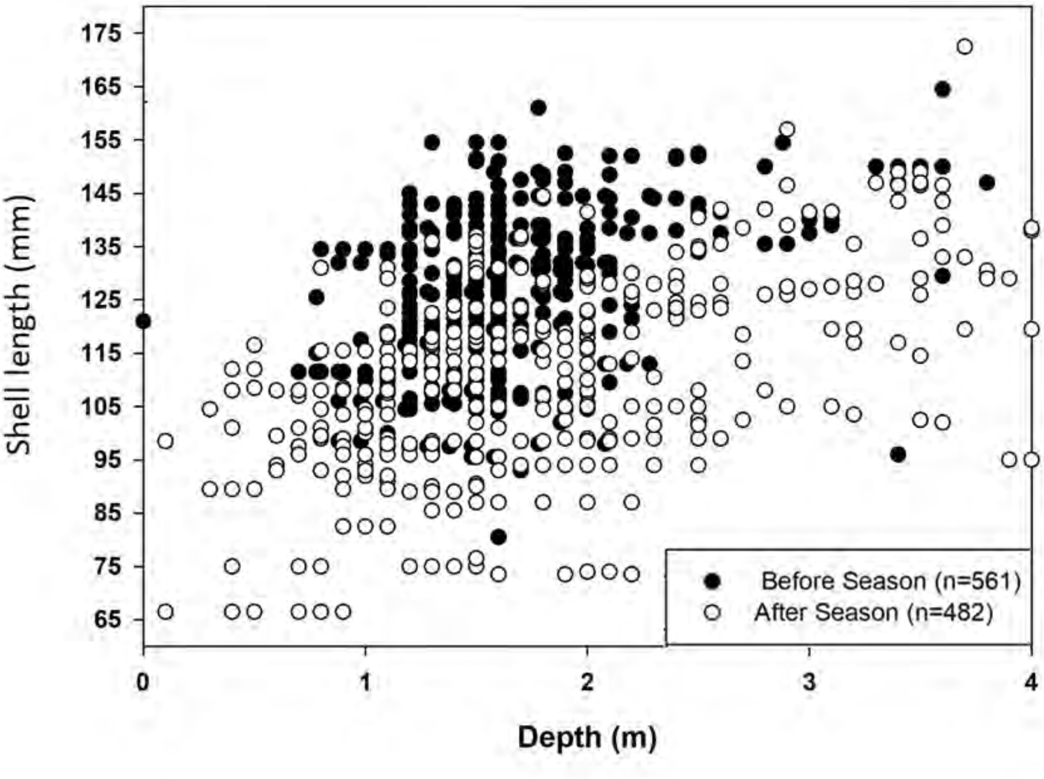

Figure A.6: Boat Harbour (fished subtidal site) scatterplot showing individual shell measurements of all pāua measured at depth, before (black dot) and after (white dot) the 2021–22 season.