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Relative abundance, size and age structure, and stock status of blue cod off Motunau in 2020

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This report describes the results of the random-site blue cod (*Parapercis colias*) potting survey carried out off Motunau in January 2020. Estimates are provided for population abundance, size and age structure, sex ratio, total mortality (*Z*), and spawner biomass-per-recruit ratio. This is the third survey in the Motunau random-site survey time series, following those in 2012 and 2016.

Thirty-nine random sites (6 pots per site, producing 234 pot lifts) at depths of 5–57 m from three strata off Motunau were surveyed in January 2020 using the F.V. *Renegade*. Survey mean catch rate of blue cod (all sizes) was 2.07 kg pot^{-1} (coefficient of variation, CV 18.9%) and 0.95 kg pot^{-1} (CV 23.6%) for recruited blue cod (30 cm and over). Of the 234 pots, 32% had zero catch of blue cod. The overall weighted sex ratio was 74% male and mean lengths were 24.8 cm for males (range 10–43 cm) and 20.2 cm for females (range 10–39 cm). The survey length frequency distribution for males was unimodal and flat on top, whereas the female distribution was bimodal with peaks at about 15 cm and 23 cm. Age estimates were 1–10 years for males and 1–7 years for females. The estimated population age distributions showed strong modes at two, five, and seven years for both sexes, and a weak mode for six-year-olds. Mean age was 4.3 years for males and 3.6 years for females.

Chapman Robson total mortality (*Z*) for age-at-full recruitment of six years was estimated at 0.69 (95% confidence interval 0.46–0.96). Based on the default *M* of 0.17 (previously 0.14), estimated fishing mortality (*F*) was 0.52 and the associated spawner biomass-per-recruit (*SPR*) ratio was 21% (95% confidence interval 17–31%). The very high *Z* estimates and low *SPR* are indicative of overfishing.

There was no indication of spawning activity during the survey period, with virtually all fish either resting or maturing.

Time series analyses of the three random-site surveys indicate:

1) The all blue cod mean catch rates show a general decline over time and this was statistically significant.
2) The scaled length frequency distributions vary among years because blue cod from Motunau are heavily exploited with high proportions of pre-recruited juvenile fish, and hence distributions are especially influenced by strong and weak recruitment of cohorts to the population. Mean size overall, however, has declined for both sexes over time.
3) Modal progression of strong age classes was apparent and supports the ageing methodology based on counts of annual growth rings.
4) The all blue cod sex ratio was 71–76% male with no trends.
5) The proportion of pots with zero catch was 23–36% with no trend.
6) Notwithstanding the validity of the *Z* estimates, the spawner-per-recruit ratios were 22% in 2016 and 21% in 2020.

Motunau fixed-site surveys were carried out in 2005, 2008, 2012, and 2016; the latter two were conducted concurrently with random-site surveys. Notwithstanding the differences in catch rates that can be ascribed to the survey design (fixed- or random-site), there are strong indications that blue cod biomass has declined substantially between 2005 and 2020. The very high estimate of total mortality, truncated age composition, small size, and strongly skewed sex ratio toward males indicate that the blue cod population off Motunau has been heavily overfished.

1. INTRODUCTION

This report describes the results of the random-site blue cod (*Parapercis colias*) potting survey carried out off Motunau in January 2020. Estimates are provided for population abundance, size and age structure, sex ratio, total mortality (*Z*), and spawner biomass-per-recruit ratio. This is the third survey in the Motunau random-site survey time series, following those in 2012 and 2016 (Beentjes & Sutton 2017, Carbines & Haist 2018d). Fixed-site surveys were carried out in 2005, 2008, and concurrently with random-site surveys in 2012 and 2016 (Carbines & Beentjes 2006a, 2009, Carbines & Haist 2012b, Beentjes & Sutton 2017), but have been now been replaced by solely random-site surveys. All Motunau blue cod surveys were funded by Fisheries New Zealand.

1.1 Status of the north Canterbury blue cod stocks

Blue cod is the third most common recreational finfish species caught in New Zealand with a total catch of 292 t (nearly 600 000 fish) estimated during the 2017–18 panel survey involving face to face interviews with fishers (Wynne-Jones et al. 2019). Blue cod can be caught in a few metres deep to about 150 m in a range of habitats including reef edges, shingle/gravel, biogenic reefs, or sandy bottoms close to rocky outcrops. Quota Management Area (QMA) BCO 3 extends from the Clarence River, north of Kaikōura, to Slope Point in Southland (Figure 1), and within this area the 2017–18 recreational take of blue cod was estimated at 98 t (Wynne-Jones et al. 2014). Further, blue cod recreational catch in BCO 3 was the highest of any QMA (34% of total national recreational blue cod catch) with 18% of respondents reporting average daily catches of over 13 blue cod, and the most common method was by rod and line. This was supported by the National Blue Cod Strategy Report in 2017 (Ministry for Primary Industries 2017) where recreational blue cod fishers were surveyed on-line nationally to gauge perceptions of the status of the New Zealand wide blue cod fishery. Results from that survey ranked BCO 3 as the most important recreational blue cod Quota Management Area in New Zealand, in line with the 2017–18 panel survey. There are no reliable data to determine how the recreational blue cod catch was distributed within BCO 3, but Kaikōura and Motunau are important blue cod fisheries in north Canterbury (Hart & Walker 2004). The perception from the 2017 on-line survey was that at Kaikōura the three top issues of concern were the total allowable commercial catch (TACC), concentrated recreational effort on small areas, and recreational bag limits (Ministry for Primary Industries 2017).

The commercial catch from BCO 3 is about 40–50% higher than the recreational catch with 169–177 t caught annually in the five years up to 2018–19 (Fisheries New Zealand 2020). Nearly all commercially landed blue cod in BCO 3 were caught by cod potting (67%) or bottom trawl (22%) (NIWA, unpublished data, Large et al in prep). Most of the pot catch is from Statistical Area 024 (87%), off Oamaru, and the bottom trawl catch is spread throughout Statistical Areas 018, 020, 022, 024, and 026 (Figure 1).

Within the 'Kaikōura Marine Area' established in 2014, the minimum legal size (MLS) is 33 cm and the recreational daily bag limit (DBL) is six blue cod (Figure 2). For the rest of north Canterbury from Conway River to Waimakariri River including Motunau, the MLS was 30 cm and the DBL ten blue cod. The implementation of the National Blue Cod Strategy on 1 July 2020 resulted in regulatory changes to the MLS and DBL from Hurunui River to Rakaia River where the MLS was increased to 33 cm and the DBL was reduced to two blue cod per person. Further, the fish must be landed in a measurable state with a two-day accumulation limit. This area, that includes Motunau, was assigned a 'traffic light' colour of red by Fisheries New Zealand indicating that the blue cod stocks in this area are considered to be overfished. Outside these areas, in north Canterbury, the MLS is 33 cm and the DBL is 10 blue cod.

1.2 Blue cod potting surveys

South Island recreational blue cod fisheries are monitored using potting surveys. These surveys take place predominantly in areas where blue cod recreational fishing is common, but, in some areas, there is substantial overlap between the commercial and recreational fishing grounds, e.g., Foveaux Strait. Surveys are generally carried out every four years and provide data that can be used to monitor local relative abundance, size, age, and sex structure of geographically separate blue cod populations. The surveys provide a measure of the response of populations to changes in fishing pressure and management intervention, such as changes to the daily bag limit, minimum legal size, and area closures. In addition to Motunau, there are currently eight other South Island areas located in key recreational fisheries that are routinely surveyed: Marlborough Sounds, Kaikōura, Banks Peninsula, north Otago, south Otago, Foveaux Strait, Paterson Inlet, and Dusky Sound (Appendix 1).

One method to investigate the status of blue cod stocks is to estimate fishing mortality, the associated spawner-per-recruit ratio (*SPR*) and the Maximum Sustainable Yield (*MSY*) related proxy. The recommended Harvest Strategy Standard target reference point for blue cod (a low productivity stock) is $F_{45\%SPR}$ (Ministry of Fisheries 2011); i.e., target fishing mortality should be at or below a level that reduces the spawner biomass to 45% of that if there was no fishing.

1.3 Previous Motunau blue cod potting surveys

All potting surveys (except Foveaux Strait) originally used a fixed-site design, with predetermined (fixed) locations randomly selected from a limited pool of such sites (Beentjes & Francis 2011). The South Island potting surveys were reviewed by an international expert panel in 2009, which recommended that blue cod would be more appropriately surveyed using random-site potting surveys (Stephenson et al. 2009). A random site is any location (single latitude and longitude) generated randomly from within a stratum. Following this recommendation, all survey series began the transition to fully random survey designs with interim sampling of both fixed and random sites allowing comparison of catch rates, length and age composition, and sex ratios between the survey designs. Random sites were the only site type used in Foveaux Strait, and all other areas except Dusky Sound have now transitioned to solely random-site surveys.

Previous Motunau surveys were carried out in January 2005, 2008, 2012, and 2016 (Carbines & Beentjes 2006a, 2009, Carbines & Haist 2012b, Beentjes & Sutton 2017, Carbines & Haist 2018d).The first two surveys used only fixed sites, whereas in 2012 and 2016 concurrent fixed- and random-site surveys were carried out. The 2020 survey was the first solely random-site survey.

1.4 Objectives

Overall Objective

1. To estimate age structure and the relative abundance of blue cod (*Parapercis colias*) off north Canterbury

Specific objectives

1. To undertake a potting survey off north Canterbury to estimate relative abundance, size- and age-at-maturity, and sex ratio. Collect otoliths during the survey from pre-recruited and recruited blue cod.

2. To analyse biological samples collected from this potting survey.

3. To estimate the age structure and relative abundance of blue cod off Kaikōura.

4. To estimate the age structure and relative abundance of blue cod off Motunau.

5. To determine stock status of blue cod populations in this area and compare this with other previous surveys in this area and other survey areas.

The Kaikōura blue cod survey is reported by Beentjes & Page (2021).

In this report, the terms defined in the blue cod potting survey standards and specifications are used (Beentjes & Francis 2011, Beentjes 2019) (Appendix 2).

2. METHODS

2.1 Timing

The blue cod potting survey off Motunau was carried out by the National Institute of Water & Atmospheric Research Ltd (NIWA) from 13 to 21 January 2020 (eight days on the water), consistent with the previous survey dates and coinciding with the known spawning times in this region.

2.2 Consultation

The Motunau survey was supported and endorsed by Tuahiwi Marae and Motunau Marine Guardians.

2.3 Survey area

The survey area for the 2020 Motunau random-site survey was consistent with the previous surveys. The southern and northern boundaries were determined in 2004 based on discussions with local fishers, Fisheries New Zealand (formerly Ministry for Primary Industries), and the South Recreational Advisory Committee (Carbines & Beentjes 2006a). Fishers were given charts of the area and asked to mark discrete locations where blue cod are most commonly caught within the survey areas. The survey area was divided into three contiguous inshore strata, from Double Corner to Sail Rock, using the 30 m depth contour as the outer strata boundary (Figure 3). Each stratum was assumed to contain roughly random distributions of blue cod habitat and the total area (square kilometres) within each stratum was taken as a proxy for available habitat for blue cod.

2.4 Survey design

2.4.1 Allocation of sites

Simulations to determine the optimal allocation of random sites among the three strata were carried out using NIWA's Optimal Station Allocation Program (*allocate*) based on catch rate data from the 2012 and 2016 random-site surveys. Simulations were constrained to have a minimum of three sites per stratum and a CV (coefficient of variation) of no greater than 15%. The simulations indicated that 39 random sites were required to achieve the target CV.

A two-phase stratified random station design (Francis 1984) was used with 33 sites allocated to phase 1, and the remaining six available for allocation in phase 2, consistent with the proportion of phase 2 sites used in previous surveys (Table 1). The allocation of phase 2 stations was based on the mean pot catch rate (kg pot^{-1}) of all blue cod per stratum and optimised using the 'area mean squared' method of Francis (1984). In this way, stations were assigned iteratively to the stratum in which the expected gain is greatest, where expected gain is given by:

$$\textit{expected gain}_i = \textit{area}_i^{\,2}\ \textit{mean}_i^{\,2} \,/\, (n_i(n_i+1))$$

where for the ith stratum $mean_i$ is the mean catch rate of blue cod per pot, $area_i$ is the fishable stratum area, and n_i is the number of sets in phase 1. In the iterative application of this equation, n_i is incremented by 1 each time a phase 2 set is allocated to stratum i.

Random sites

A random site has a location (single latitude and longitude) generated randomly within a stratum (Beentjes 2019). Sufficient sites to cover both first and second phase stations were generated for each stratum using the NIWA random station generator program (*Rand_stn* v1.00-2014-07-21) with the constraint that sites were at least 800 m apart. From this list, the allocated number of random sites per stratum to be surveyed was selected in the order they were generated.

Pot configuration and placement for random sites is defined in the blue cod potting manual (Beentjes 2019). Consistent with previous random-site surveys in Motunau, systematic pot placement was used where the position of each pot was arranged systematically with the first pot set 200 m to the north of the site location and remaining pots set in a hexagon pattern around the site, at about 200 m from the site position. Where sites were too close to shore to accommodate the hexagon configuration, pots were set either side of the site along the shore 100 m apart.

2.4.2 Vessels and gear

The Motunau survey was conducted from F.V. *Renegade* (Registration number 135918), a Motunau-based commercial vessel owned and skippered by Mr Geoff Basher. Previous surveys in 2005 and 2008 used the F.V. *Navigator* and the 2012 survey used the F.V. *Legacy*, both also owned and skippered by Geoff Basher. The F.V. *Renegade* is equipped to set and lift rock lobster and blue cod pots with specifications: 13.5 m length, 12 t weight, aluminium monohull, powered by twin 450hp Yanmar Diesel Propulsion 292 jet units, with a maximum speed of 30 knots.

Six custom designed and built cod pots were used to conduct the survey (Pot Plan 2 given by Beentjes & Francis 2011). Pots were baited with 700 g of pāua (*Haliotis iris*) viscera in 'snifter pottles'. Bait was topped up or replaced after every lift. The same pot design and bait type were used in all previous surveys.

A high-performance, 3-axis (3D) acoustic Doppler current profiler (ADCP, RDI Instruments, 600 kHz) was deployed at each site. The ADCP recorded current flow and direction in 1-m depth bins above the seafloor as well as bottom water temperature.

2.4.3 Sampling methods

All sampling methods adhered strictly to the blue cod potting survey standards and specifications (Beentjes & Francis 2011, Beentjes 2019).

At each site, six pots were set and left to fish (soak) for a target period of one hour during daylight hours. As each pot was placed, a record was made of sequential pot number (1 to 6), latitude and longitude from GPS, depth, and time of day. After each site was completed, the next closest site in the stratum was sampled. The ADCP was deployed at the centre of each site prior to the setting of pots and recovered after the last pot of each set was lifted. The order that strata were surveyed depended on the prevailing weather conditions, with the most distant strata and/or sites sampled in calm weather. Following pot placement, the following environmental data were recorded: wind direction, speed, and force; air temperature and pressure; water clarity using secchi disc, sea condition and colour; swell height and direction; bottom type and contour; and surface water temperature. These variables and their units are defined in the potting manual (Beentjes 2019).

Pots were lifted aboard using the vessel's hydraulic pot lifter in the order they were set, and the time of each lift was recorded. The proportion of the bait remaining in the snifter pottle was recorded. Pots were then emptied, and the contents were sorted by species. Total catch weight per pot was recorded for each species to the nearest 10 g using 0–6/6–15 kg Marel motion compensating scales. The number of individuals of each species per pot was also recorded. Total length to the nearest centimetre below actual length, individual fish weight to the nearest 10 g, sex, and gonad maturity were recorded for all blue cod. Sagittal otoliths were removed from a representative length range of blue cod males and females over the available length range across all strata. To ensure that otolith collection was spread across the survey area, the following collection schedule was used: collect three otoliths per one-centimetre size class for each sex in strata 1 and 2 combined and in stratum 3, the largest stratum (Appendix 3).

Sex and maturity were determined by dissection and macroscopic examination of the gonads (Carbines 1998, 2004). Blue cod gonad staging was undertaken using the five stage Stock Monitoring method used on previous surveys. Gonads were recorded as follows: 1, immature or resting; 2, maturing (oocytes visible in females); 3, mature (hyaline oocytes in females, milt expressible in males); 4, running ripe (eggs and milt free flowing); 5, spent.

2.4.4 Data storage

The 2020 Motunau survey trip code was REN2001. At the completion of the survey, trip, station, catch, and biological data were entered into the *trawl* and *age* databases in accordance with their business rules and the blue cod potting survey standards and specifications (Beentjes & Francis 2011, Beentjes 2019). All analyses were carried out using data extracted from the *trawl* and *age* databases. Random sites were entered into attribute *stn_code*, prefixed with R (e.g., R1A, R2B, R3C). Random-site locations were also entered into *trawl* table *t_site*. Pot locations were entered in table *t_station* in attribute *station_no* (concatenating set number and pot number, e.g., 11 to 16 in set one, 21 to 26 for set two, etc.). In the *age* database, the *sample_no* is equivalent to *station_no* in the *trawl* database.

ADCP data were sent to the Fisheries New Zealand Research Database Manager.

2.4.5 Age estimates

Otolith preparation and reading

To assess reader competency in ageing before reading the 2020 survey otoliths, the two readers aged a subsample of 50 reference otolith preparations with the aim of achieving a score for Index of Average Percentage Error (IAPE) (Beamish & Fournier 1981) and mean coefficient of variation (CV) (Chang 1982) of below 1.50 % and 2.12 %, respectively (Walsh 2017).

Otolith preparation and reading

Preparation and reading of otoliths followed the methods of the blue cod age determination protocol (ADP) (Walsh 2017).

1. Blue cod otolith thin-section preparations were made as follows: otoliths were individually marked on their distal faces with a dot in the centrum using a cold light source on low power to light the otolith from behind. Five otoliths (from five different fish) were then embedded in an epoxy resin mould and cured at 50 ºC. Thin sections were taken along the otolith dorso-ventral axis through the centrum of all five otoliths, using a Struers Accutom-50 digital sectioning machine, with a section thickness of approximately 350 µm. Resulting thin section wafers were cleaned and embedded on microscope slides using epoxy resin and covered with a coverslip. Finally, these slides were oven cured at 50 ºC.
2. Otolith sections were read against a black background using reflected light under a compound microscope at a magnification of 40–100 times. Under reflected light, opaque zones appear light and translucent zones appear dark. Translucent zones were counted (ageing of blue cod otolith thin sections prior to 2015 counted opaque zones to estimate age).
3. Two readers initially read all otoliths without reference to fish length, sex, or previous age estimates.
4. When interpreting blue cod zone counts, both ventral and dorsal sides of the otolith were read, mainly from the core toward the proximal surface close to the sulcus.
5. The forced margin method was used: ‘Wide’ (a moderate to wide translucent zone present on the margin), October–February; ‘Line’ (an opaque zone in the process of being laid down or fully formed on the margin), March–April; ‘Narrow’ (a narrow to moderate translucent zone present on the margin), May–September.
6. Where between-reader counts differed, the readers rechecked the count and conferred until agreement was reached, unless the section was a grade 5 (unreadable) or damaged (removed from the collection).
7. Between-reader ageing precision was assessed by the application of the methods and graphical techniques documented by Campana et al. (1995) and Campana (2001); including APE (average percent error) and coefficient of variation.

2.4.6 Data analyses

Analyses of catch rates, sex ratios, scaled length distribution, catch-at-age, *Z* estimates, and spawner-per-recruit were carried out and are presented for the Motunau 2020 random-site survey.

Analyses of catch rates and coefficients of variation, length-weight parameters, scaled length and age frequencies and CVs, sex ratios, mean length, and mean age were carried out using the equations documented in the blue cod potting survey standards and specifications (Beentjes & Francis 2011, Beentjes 2019). Fish length was recorded to the nearest millimetre on the survey, but, following standard protocol, all lengths were rounded down to the nearest centimetre for analyses of the scaled length distribution and mean length (i.e., using data extracted from t_lgth in the *trawl* database). Length was also rounded down when producing the age-length-keys for catch-at-age analyses, and for estimating von Bertalanffy parameters.

2.4.6.1 Catch rates

The catch rate (kg pot^{-1}) estimates were pot-based and the CV estimates were set-based (Beentjes & Francis 2011, Beentjes 2019). Catch rates and 95% confidence intervals (± 1.96 standard error) were estimated for all blue cod and for recruited blue cod (30 cm and over). Catch rates of recruited blue cod were based on the sum of the weights of individual recruited fish. The stratum areas shown in Table 1 were used as the area of the stratum (A_t) when scaling catch rates (equations 3 and 5 given by Beentjes & Francis 2011). Catch rates are presented by stratum and overall.

2.4.6.2 Length-weight parameters

The length-weight parameters a_k, b_k from the 2020 Motunau survey were used in the following equation:

$$w_{lk} = a_k l^{b_k}$$

This calculates the expected weight (g) for a fish of sex k and length l (cm) in the survey catch. These parameters were calculated from the coefficients of sex-specific linear regressions of log(weight) on log(length) using all fish for which length, weight, and sex were recorded: b_k is the slope of the regression line, and log(a_k) is its y-intercept.

2.4.6.3 Growth parameters

von Bertalanffy growth models (von Bertalanffy 1938) for each sex were fitted to the 2020 Motunau survey length-age data as follows:

$$L_t = L_\infty(1 - \exp^{-K[t - t_0]})$$

where L_t is the length (cm) at age t, L_∞ is the asymptotic mean maximum length, K is a constant (growth rate coefficient), and t_0 is hypothetical age (years) for a fish of zero length. Because there were so few fish older than seven years in the 2020 and previous random-site surveys in 2012 and 2016, the resulting L_∞ growth parameters were unrealistically large and not representative of the true growth trajectory. Hence, von Bertalanffy growth models were fitted to the combined length and age data from the last three Kaikōura surveys (2015, 2017, and 2019) where older fish were present, to provide more representative growth parameters for input into spawner per recruit analyses. Growth was first compared for all three Kaikōura and two Motunau surveys to justify this approach.

2.4.6.4 Scaled length and age frequencies

Length and age compositions were estimated using the NIWA program Catch-at-Age (Bull & Dunn 2002). The program scales the length frequency (LF) data by the area of the stratum, number of sets in each stratum, and estimated catch weight determined from the length-weight relationship of individual fish. The latter scaling should be negligible or very close to one if all fish caught during the survey were measured (which they were) and if the actual weight of the catch is close to the estimated weight of the catch. The stratum area shown in Table 1 was taken as the area of the stratum (A_t), and the length-weight parameter estimates are from the 2020 Motunau survey data for males and females separately.

Length and age frequencies were calculated as numbers of fish from equations 7, 8, and 9 of the manual (Beentjes & Francis 2011, Beentjes 2019). The length and age frequencies are expressed as proportions by dividing by total numbers.

Bootstrap resampling (300 bootstraps) was used to calculate CVs for proportions- and numbers-at-length and at-age using equation 12 of the manual (Beentjes & Francis 2011, Beentjes 2019). That is, simulated data sets were created by resampling (with replacement) sets from each stratum and fish from each set (for length and sex information); and also fish from the age-length-sex data that were used to construct the age-length key.

Catch-at-age was estimated using a single age-length-key (ALK) (2020 Motunau age data) for each sex applied to the length data from the entire survey area. Scaled length frequency and age frequency proportions are presented, together with CVs for each length and age class, and the mean weighted coefficients of variation (MWCVs).

2.4.6.5 Unsexed fish

All blue cod caught during the 2020 Motunau survey were sexed.

2.4.6.6 Sex ratios, and mean length and age

Sex ratios (expressed as percentage male) and mean lengths, for the stratum and survey, were calculated using equations 10 and 11 of Beentjes & Francis (2011) from the stratum or survey scaled LFs. Mean ages were calculated analogously from the scaled age frequencies. Sex ratios were also estimated for recruited blue cod (30 cm and over), and overall survey 95% confidence intervals around sex ratios were generated from the 300 LF bootstraps. The proportion of fish of recruited size was estimated from the scaled LFs.

2.4.6.7 Total mortality estimates

Total mortality (*Z*) was estimated from catch-curve analysis using the Chapman-Robson estimator (CR) (Chapman & Robson 1960). Catch curve analyses measure the sequential decline of cohorts annually. The CR method was shown to be less biased than the simple regression catch curve analysis (Dunn et al. 2002). Catch curve analysis assumes that the right-hand descending part of the curve declines exponentially and that the slope is equivalent to the total mortality Z ($M + F$). This assumes that recruitment and mortality are constant, that all recruited fish are equally vulnerable to capture, and that there are no age estimation errors.

Estimates of CR total mortality, *Z*, were calculated for age-at-recruitment values of 5 to 10 y using the maximum-likelihood estimator (equation 13 of Beentjes & Francis 2011). Variance (95% confidence intervals) associated with *Z* was estimated under three different parameters of recruitment, ageing error, and *Z* estimate error (equations 14 to 18 of Beentjes & Francis (2011)). Catch-at-age distributions were estimated separately for males and females and then combined, hence providing a single *Z* estimate for the population.

A traditional catch curve was also plotted from the natural log of catch (numbers) against age and a regression line fitted to the descending curve from age-at-full recruitment. Although the *Z* estimate from the traditional catch curve was not used, it provides a diagnostic tool to illustrate how well data conform to the assumptions made for estimating *Z* from age structure. This is particularly important when there are not many age classes, with potential for strong or weak year classes to introduce bias.

2.4.6.8 Spawner-per-recruit estimates

Spawner-per-recruit analyses were conducted using CASAL (Bull et al. 2005). The calculations involved simulating fishing with constant fishing mortality (*F*) and estimating the equilibrium spawning biomass per recruit (*SPR*) associated with that value of *F* (Beentjes & Francis 2011). The %*SPR* for that *F* is then simply that *SPR*, expressed as a percentage of the equilibrium *SPR* when there is no fishing (i.e., when $F = 0$, and %*SPR* =100%). To allow valid comparison between years (i.e., 2016 and 2020) the spawner-per-recruit ratios for the 2016 survey were reanalysed using the default *M* value of 0.17 which was previously 0.14. For the 2016 survey the von Bertalanffy growth parameters and length-weight coefficients used in the spawner-per-recruit calculations were taken from the 2015 Kaikōura survey (Beentjes & Sutton 2017).

Input parameters used in 2020 survey *SPR* analyses

Growth parameters — von Bertalanffy growth parameters are from the combined length and age data from the 2015, 2017, and 2019 Kaikōura surveys and length-weight coefficients are from the 2020 Motunau survey:

Parameter	Males	Females
K (yr^{-1})	0.1238	0.1479
t_0 (yr)	-0.8799	-1.2099
L_∞ (cm)	56.6	43.3
a	0.010698	0.010906
b	3.1138	3.1069

Natural mortality — default assumed to be 0.17, revised from 0.14 in 2019 (Doonan 2020). Sensitivity analyses were carried out for *M* values 20% above and below the default (0.14 and 0.20).

Maturity — the following maturity ogive was used: 0, 0, 0, 0.1, 0.4, 0.7, and 1; where 10% of blue cod are mature at 4 years old and all are mature at 7 years.

Selectivity — selectivity to the fishery (recreational/commercial) is described as knife-edge equal to age-at-MLS calculated from the von Bertalanffy models from the 2015, 2017, and 2019 Kaikōura surveys' length and age data combined. The Motunau recreational MLS was 30 cm at the time of the survey and selectivity was 5.2 years for males and 6.8 years for females.

Fishing mortality (*F*) — fishing mortality was estimated from the results of the Chapman-Robson analyses and the assumed estimate of *M* (i.e., $F = Z–M$). The *Z* value was for age-at-full recruitment (6 years for females).

Maximum age — assumed to be 31 years.

To estimate *SPR* the CASAL model uses the Baranov catch equation which assumes that *M* and *F* are occurring continuously throughout the fishing year, i.e., instantaneous natural and fishing mortality.

The *SPR* estimates are based on age at recruitment equal to the MLS for females, in this case 6 years. Age-at-full recruitment of 7 could not be used because there were no females older than 7 years.

2.4.6.9 The GLM model on environmental data

The influence of environmental variables on blue cod survey pot catch rates were investigated using a forward stepwise Generalised Linear Model (GLM) (McCullagh & Nelder 1989), with the individual pot catch (log-normal transformation) modelled as the response variable. Zero pot catches were assigned a nominal value of 0.01 kg. Data from the three fixed-site and three random-site Motunau surveys were included in the analyses (2008, 2012, 2016, and 2020). The 2005 fixed-site survey was not included because there were no environmental data collected on this survey.

The predictor variables used in the model were fishing year (= survey), site_type (fixed or random) stratum, depth, time of day, tide status, bottom contour, bottom type, sea colour, sea condition, water clarity (secchi disc), swell height, cloud cover, moon phase, barometric pressure, surface water temperature, wind speed, latitude, and longitude. Fixed-site and random-site surveys carried out at the same time (2012 and 2016) were treated as single surveys, with site_type used as a predictor. Variables were treated as categorical, except depth, water clarity, wind speed, barometric pressure, surface water temperature, latitude, longitude, and moon phase which were all entered as continuous variables. The variable 'bait' (percentage bait left when hauled) was only recorded in the last two surveys (2017 and 2019) so could not be used in the GLM model.

The variable 'time of day' of pot set was assigned to categories as follows:

0600–0800	morning_early
0801–1000	morning_mid
1001–1200	morning_late
1201–1400	afternoon_early
1401–1600	afternoon_mid
1601–1800	afternoon_late
1801–2000	evening_early
2001–2200	evening_late

The 'tide status' at each pot was determined using the NIWA tide forecasting model which provides the tide height for a given position, date, and time of day. Tide height was then assigned to the following six categories: high-tide, high-receding, low-receding, low-tide, low-incoming, and high-incoming.

The stepwise fitting method began with a basic model in which fishing year (survey) was the only predictor and iteratively included predictors until there was insufficient improvement in the model. For all analyses, the improvement in the residual deviance, i.e., (new deviance - old deviance) / (saturated deviance - null deviance) and termed R^2, was used as the criterion for including predictors. At each step, the predictor giving the greatest improvement in R^2 was included, providing that its inclusion resulted in an improvement in R^2 of at least 0.5%.

2.4.6.10 Analyses of 2012 Motunau survey

In the previous report (Beentjes & Sutton 2017) catch rates, scaled length frequencies, and sex ratios were estimated for the 2012 Motunau survey (carried out by Saltwater Research), consistent with the potting survey standards and specifications (Beentjes & Francis 2011, Beentjes 2019). At that time the data for the 2012 survey had not been loaded into the Fisheries New Zealand *trawl* database, nor had the report been published, and hence analyses were carried out from raw data provided to NIWA on a spreadsheet. Catch rates of recruited blue cod were based on the sum of the weights of individual fish 30 cm and over. These were estimated from the 2015 Kaikōura survey length-weight coefficients because no individual fish weights were then available for the 2012 Motunau survey. Catch rates, scaled length frequencies, and sex ratios for the 2012 survey have not been re-estimated using data extracted from the *trawl* database. Although blue cod otoliths were collected and aged from the 2012 and previous surveys, the ageing is considered to be invalid because it was not carried out using the methods of the blue cod ADP (Walsh 2017).

The spawner-per-recruit ratios for the 2016 survey were re-estimated using M of 0.17 and selectivity based on the 2015 Kaikōura survey von Bertalanffy (VB) growth curve. Previous analyses for 2016 used M of 0.14 and the selectivity based on 2016 Motunau VB curve in which L_∞ growth parameters were unrealistically large and not representative of the true growth trajectory.

3. RESULTS

3.1 Motunau 2020 random-site survey

Thirty-nine random sites were sampled (6 pots per site, producing 234 pot lifts) from three strata off Motunau (Table 1, Figure 4). Depths sampled were 5–57 m (mean = 23 m). Thirty-three sites were carried out in phase 1 and six in phase 2, all in stratum 3.

3.1.1 Catch and catch rates

A total of 569.3 kg of blue cod (2158 fish) was taken from the three strata, comprising 90.3% by weight of the catch of all species on the survey (Table 2). Bycatch species included ten teleost fishes, as well as octopus. The three most abundant bycatch species, by number, were leatherjacket (*Meuschenia scaber*), spotty (*Notolabrus celidotus*), and scarlet wrasse (*Pseudolabrus miles*).

Mean catch rates (kg pot^{-1}) of blue cod (all blue cod, and 30 cm and over) are presented by stratum and overall (Table 3, Figure 5). Mean catch rates of blue cod (all sizes) by stratum were 1.41–4.54 kg pot^{-1} with highest catch rates in stratum 1 and lowest in stratum 3 (Table 3, Figure 5). The all-blue-cod survey catch rate was 2.07 kg pot^{-1} with a CV of 18.9%. Catch rates for recruited blue cod (30 cm and over) followed the same pattern among strata as for all blue cod, and the recruited blue cod survey catch rate was 0.95 kg pot^{-1} (CV 23.6%) (Table 3, Figure 5). Of the 234 random-site pots, 76 (32%) had zero catch of blue cod.

3.1.2 Biological and length frequency data

Of the 2158 blue cod caught, all were sexed, measured for length, and weighed (Table 4). The sex ratios were 71–76% male across the three strata and the overall area-weighted sex ratio was 74% male (Table 4). Length ranges were 10–43 cm for males and 10–39 cm for females, and the overall weighted mean length was 24.8 cm for males and 20.2 cm for females. The scaled length frequency distributions were generally similar for each sex among the three strata, although in stratum 1 there were proportionally fewer larger males, reflected in the lower mean length (Figure 6).

3.1.3 Age and growth

Otolith section ages from 167 males and 102 females collected from the 2020 Motunau random-site survey were used to estimate the population age structure (Table 5). The length-age data are plotted and the von Bertalanffy model fits and growth parameters (K, t_0, and L_∞) are shown for males and females separately (Figure 7). There is a large range in length-at-age particularly for males; and males grow faster and are the largest and oldest fish. The 2016 and 2020 fitted von Bertalanffy curves are similar, but the L_∞ values are not representative of the true growth because older fish, which normally sit on the flat part of the curve, are absent (Figure 7). These growth parameters are unsuitable for the *SPR* analyses and instead the combined length-age data for the 2015, 2017, and 2019 Kaikōura surveys were used because these data have a good representation of older males and females (Figure 8).

The two readers achieved CV and IAPE scores below the targets when ageing 50 otoliths from the blue cod reference collection (Table 6). Between-reader comparisons of the 2020 Motunau survey otoliths are presented in Figure 9. The first counts of the two readers showed 97% agreement, and overall there was no bias between readers with a CV of 0.53% and an IAPE of 0.38%.

3.1.4 Spawning activity

Gonad stages of blue cod sampled in the early January 2020 are presented by sex for the survey overall (Table 7). There was no indication of spawning activity during the survey period with virtually all fish either resting or maturing.

3.1.5 Population length and age composition

The scaled length frequency and age distributions for the 2020 Motunau random-site survey are shown as histograms for all strata combined and as cumulative frequency line plots for males, females, and both sexes combined (Figure 10).

The scaled length frequency distribution for males is unimodal, flat on top with no clear peaks, and the overall mean length is 24.8 cm. The female distribution appears to be bimodal with peaks at about 15 cm and 23 cm, and an overall mean length of 20.2 cm (Figure 10). The female cumulative distribution plots of length frequency are much steeper than males, reflecting the virtual absence of females larger than 30 cm (Figure 10). Indeed, the proportions of all fish that were recruited (30 cm and over) were 25.9% for males and 2.1% for females by number. The mean weighted coefficients of variation around the length distributions were 26% for males and 33% for females.

Age of blue cod was 1–10 years for males and 1–7 years for females, but most males were aged between 2 and 7, and females between 2 and 5 (Figure 10). The estimated population age distributions indicate virtually knife-edge selectivity to the potting method at two years and show relatively strong modes at two, five, and seven years, and a weak mode for six-year-olds for both sexes. The cumulative distribution plots of age frequency are generally similar for both sexes with slight differences stemming from males having a higher proportion of older fish (Figure 10). Further, the mean age of females was less than that of males (4.3 for males and 3.6 years for females). The MWCVs around the age distributions were 22% for males and 26% for females, indicating a good representation of the overall population age structure.

3.1.6 Total mortality estimates (*Z*) and spawner-per-recruit (*SPR*)

Chapman-Robson total mortality estimates (*Z*) and 95% confidence intervals are given for a range of recruitment ages (5–7 y) in Table 8. Estimates above seven, the maximum age for females, could not be generated. Age-at-full recruitment (AgeR) is assumed to be equal to the age at which females reach the MLS of 30 cm, which is close to seven years (6.8 years). Six years was used instead because the *Z* estimates around age seven are implausible. The CR *Z* for AgeR of six years is 0.69 (95% confidence interval of 0.46–0.96).

The traditional catch curve based on log catch (numbers) plotted against age with a regression line fitted to the descending limb from age-at-full recruitment is shown for diagnostic purposes (Figure 11). The age at full recruitment is taken as 6 years, but for females 5 years is used because the model is unable to generate a plot above this age. The low numbers of fish and age classes older than the recruited age has influenced the slope of the regression line and probably the validity of *Z* to some extent. However, the combined male and female plot seems plausible, reflecting very high total mortality.

Estimates of mortality parameters (CR *Z* and *F*, and *M*) and spawner-per-recruit (*SPR*) ratios at three values of *M* and age at full recruitment of six years are shown in Table 9. Based on the default *M* of 0.17 (previously 0.14), estimated fishing mortality (*F*) was 0.52 and associated spawner-per-recruit ratio was 21.4% (Figure 12). At the 2020 levels of fishing mortality, the expected contribution to the spawning biomass over the lifetime of an average recruit is reduced to 21% of the contribution in the absence of fishing. The 95% confidence interval around the *SPR* ratios was 17–31% (Table 9). The revised spawner-per-recruit ratios for the 2016 random-site survey using *M* of 0.17 was 22.2%.

3.2 Motunau random-site survey time series (2012, 2016, 2020)

Mean catch rates (kg pot^{-1}) for all blue cod and recruited blue cod for each of the three random-site surveys are presented in Figure 13. The relative differences in catch rates among strata are generally preserved over time; i.e., catch rates were consistently highest in stratum 1 and lowest in stratum 3. The survey mean of all blue cod catch rates shows a slight decline over time, but there was no statistically significant difference between mean catch rates in 2012 and 2020 (two sample t-test, p=0.19) (Figure 13).

The scaled length frequency distributions vary among years because blue cod from Motunau are heavily exploited with high proportions of pre-recruited juvenile fish, and hence distributions are especially influenced by strong and weak recruitment of cohorts to the population (Figure 14). Mean size overall, however, has declined for both sexes over time.

The sex ratio for all surveys was 72–76% male for all blue cod, and 96–97% male for recruited blue cod, with no trend (Figure 15). There are also no differences in sex ratio between strata, or within strata over time (Figure 16).

Age compositions can be validly compared only for the 2016 and 2020 random-site surveys (Figure 17) because blue cod ageing from the 2012 random-site survey was carried out before the new age determination protocol was developed. The 3-year-old age class in 2016 progressed through to a strong 7-year-old age class for both sexes in 2020. Similarly, the strong 5- and 6-year-old male age classes progressed to 9- and 10-year-old age classes in 2020, but for females these age classes are not present and likely to have been fished out (Figure 17). Similarly, the relatively weak 4-year-old age class in 2016 is not present in 2020. These results indicate that modal progression of strong year classes is apparent and supports the ageing methodology based on counts of annual growth rings.

Chapman Robson total mortality estimates (*Z*) are similar in 2016 and 2020 and both are very high with correspondingly low *SPR* ratio estimates (see Figure 12) both well below the target of 45% ($F_{45\%SPR}$).

The proportion of pots with zero catch for the three random-site surveys ranged from 23–36% with no clear trend (Figure 18).

3.3 The GLM model on environmental data

The results of the stepwise GLM indicated that 36% of the variability in the survey pot catch rates could be explained by the ten variables (Table 10). Longitude explained 17% of the variability with the next four variables combined explaining 14% (bottom contour, site type, time of day, and sea colour). The relationships between blue cod pot catch and the predictor variables are shown in Figure 19. Site type explains the difference between survey designs and shows that overall, the median catch from fixed sites was much greater than for random sites. Some of these variables are likely to be correlated, such as depth and sea colour, and the weather-related variables wind speed, swell height, and sea condition.

4. DISCUSSION

4.1 General

The 2020 Motunau random-site potting survey was the third in the time series of relative abundance and population structure of blue cod from this area, after previous random-site surveys in 2012 and 2016. Fixed-site surveys were carried out in 2005 and 2008 and then concurrently with the random-site surveys in 2012 and 2016. The fixed-site surveys were discontinued after the 2016 survey because the random-site design was deemed to be more accurate, statistically robust, and more likely to represent the entire blue cod population (Stephenson et al. 2009). Differences in catch rates between fixed- and random-site surveys, and the finding that the random-site surveys caught slightly larger blue cod (Beentjes & Sutton 2017), suggest that there is no suitable way of quantitatively linking the fixed-site with the random-site series. Notwithstanding the differences in catch rates that can be ascribed to the survey design (fixed or random), there are strong indications that blue cod biomass has declined substantially between 2005 and 2020 (Figure 20). Future analyses could use a GLM to standardise catch rates from fixed- and random-site surveys by offering site type to the model as a predictor and hence utilising the entire five survey time series (see Table 10).

The abundance estimates and length and age distributions are weighted (scaled) by the area of each stratum in this survey. Scaling by area assumes that the size of each stratum is directly proportional to the amount of blue cod habitat (i.e., it is assumed to be a proxy for habitat); however, this is probably not always the case given the discrete nature of areas of foul and biogenic habitat.

4.2 Catch rates and survey precision

The target CV around relative abundance (catch rates) was not specified for the 2020 Motunau survey, but a CV of around 15% is generally targeted and simulations were carried out to estimate effort required to achieve this level of precision. The 19% CV achieved for the 2020 random-site survey was 4% above this target, with previous CVs of 19% and 27% for 2012 and 2016. Effort was increased from 21 sites in 2012 and 2016, to 39 sites in 2020 to reduce CVs. The achieved CV of 19% in 2020 indicates that the survey design and number of sites used are adequate, but the latter could be increased, especially if biomass continues to decline and catches by site become more variable.

4.3 Cohort progression

Motunau

Cohort progression of blue cod age classes off Motunau is apparent from 2016 to 2020, showing both nominally strong and weak year classes (see Figure 17). The progression and relative strength of the

2012 year class (i.e., 3 years old in 2016 and 7 years old in 2020), suggests that this year class was exceptionally strong with the expectation that, as it recruits fully to the recreational and commercial fisheries, these will have been enhanced. Growth estimates indicate that males would be on average 5 years old and females 7 years old when they reached the previous MLS of 30 cm (increased to 33 cm on 1 July 2020) in this area (see Figure 8). Hence, the faster growing 2012 year class males will have fully recruited to the fishery in 2018 and females in 2020. There were, however, no indications of a commensurate increase in all blue cod or recruited abundance in the 2020 survey, probably because, apart from two strong male cohorts (5- and 7-year-olds), other cohort strengths are comparatively weak and there are fewer older age classes. This suggests that for abundance to increase substantially, a number of strong recruitment pulses is required to offset those from the poor to average years, and the population needs time to recover by reducing fishing pressure on recruiting cohorts. Indeed only 2% of female blue cod were over the previous 30 cm MLS. The increase in MLS to 33 cm and reduction in the daily bag limit to two fish from July 2020 will have reduced exploitation rate of this population allowing the stock to rebuild.

Other areas

The strong blue cod 2012 year class (3-year-olds) and the weak 2011 year class (4-year-olds) observed in Motunau in January 2016 (see Figure 17) were also present in the age compositions from Kaikōura in 2015, Banks Peninsula in 2016, and north and south Otago in 2018 (Beentjes & Fenwick 2017, Beentjes & Sutton 2017, Beentjes & Fenwick 2019a, 2019b, Beentjes 2020). The recruitment patterns for the Kaikōura surveys in 2015, 2017, and 2019 (Beentjes & Page 2021) are most similar to those of nearby Motunau and indicate that the closer the populations are to each other, the more similar are their patterns in recruitment strength. This consistent recruitment strength pattern suggests that the 2012 spawning event and/or survival of subsequent life-history stages off the east coast of the South Island was more successful than average. Blue cod have a restricted home range (Rapson 1956, Mace & Johnston 1983, Mutch 1983, Carbines & McKenzie 2001, Govier 2001, Carbines & McKenzie 2004, Rodgers & Wing 2008) with only small numbers of blue cod travelling any distance from their tagging location. Blue cod off Kaikōura, Motunau, Banks Peninsula, and Otago are therefore likely to consist of largely independent sub-populations. However, there is no evidence that blue cod are genetically distinct around the New Zealand mainland (Gebbie 2014); this suggests that egg or larval dispersion coupled with the occasional larger scale movements of individuals are sufficient to prevent genetic isolation occurring. Hence, the strong and weak year classes often common off the east coast South Island are more likely to be regulated by fisheries-independent environmentally driven events acting at the scale of the east coast of the South Island or wider (Beentjes 2020). These events will have impacted localised spawning and survival of eggs, larvae, and juvenile fish.

4.4 Sex change and sex ratio

In all three random-site surveys, sex ratio strongly favoured males and ranged from 72 to 76% male. Sex ratios of blue cod favouring females tend to be less common, particularly in exploited blue cod populations. Blue cod are sequential protogynous hermaphrodites with some (but not all) females changing into males as they grow (sex reversal) (Carbines 2004). Blue cod are a diandric species where males either develop directly from the undifferentiated state without sex inversion (primary males) or begin life as female and become male following sex inversion (secondary males) (Reinboth 1980, Beentjes 2020). The monandric condition is where life always begins as female and males develop only through sex inversion; this occurs in six Australian reef species of the same genus as blue cod (*Parapercis* spp.) (Stroud 1982). Kaikōura blue cod population sex and size structure is consistent with this diandric reproductive strategy with both small males and large females present in the population. In areas where fishing pressure is known to be high, such as Motunau, inshore Banks Peninsula, and the Marlborough Sounds, the sex ratios are strongly skewed towards males which is contrary to an expected dominance of females resulting from selective removal of the larger male fish (Beentjes & Carbines 2003, 2006, Carbines & Beentjes 2006a, Beentjes & Carbines 2012, Beentjes & Sutton 2017). In contrast, in Foveaux Strait, offshore Banks Peninsula, and particularly Dusky Sound, females are dominant, suggesting that fishing pressure is less intense (Beentjes & Carbines 2009, Carbines & Beentjes 2012, Beentjes & Page 2016). Beentjes & Carbines (2005) suggest that the shift towards a higher proportion of males in more heavily fished blue cod populations may be caused by removal of the possible inhibitory effect of large males, resulting in a higher rate (and possibly earlier onset) of sex change by females. The reduced levels of behavioural interaction between males and females has been shown to lead to enhanced sex inversion in other protogynous fish species (Fishelson 1970, Robertson 1972, Warner 1984, Sato et al. 2018). Factors affecting sex change and sex ratios in blue cod are not well understood.

4.5 Stock status

The *Harvest Strategy Standard* specifies that a Harvest Strategy should include a fishery target reference point, and that this may be expressed in terms of biomass or fishing mortality (Ministry of Fisheries 2011). The most appropriate target reference point for blue cod is F_{MSY}, which is the amount of fishing mortality that results in the maximum sustainable yield. The recommended proxy for F_{MSY} is the level of spawner-per-recruit $F_{\%SPR}$ (Ministry of Fisheries 2011). Blue cod is categorised as an exploited species with low productivity (on account of complexities of sex change) and the recommended default proxy for F_{MSY} is $F_{45\%SPR}$.

The 2016 and 2020 random-site survey *SPR* ratio estimates were $F_{22\%SPR}$, and $F_{21\%SPR}$ indicating that the expected contribution to the spawning biomass over the lifetime of an average recruit was reduced to below a quarter of the contribution in the absence of fishing (see Figure 12). The level of exploitation (*F*) of Motunau blue cod stocks therefore greatly exceeds the F_{MSY} target reference point of $F_{45\%SPR}$ and the *SPR* ratios are well below the target of 45%. Indeed, the age distributions of blue cod from the 2016 and 2020 Motunau surveys are so truncated that growth could not be accurately modelled using the von Bertalanffy growth curve, which requires some larger and older fish to estimate a sensible length at infinity parameter (see Figure 7).

4.6 Reproductive condition

There were no indications of spawning in January 2020, consistent with the previous four surveys all carried out at the same time of year (Carbines & Beentjes 2006a, 2009, Carbines & Haist 2012b, Beentjes & Sutton 2017) (Table 7). Given that some spawning activity is consistently observed in Kaikōura one month earlier, spawning may take place before January in Motunau.

4.7 Concluding remarks

In summary, blue cod abundance and mean size off Motunau have declined over the fifteen years from 2005 to 2020, notwithstanding the differences that can be ascribed to the survey design (fixed or random). The very high estimate of total mortality, truncated age composition, small size, and strongly skewed sex ratio toward males indicate that the blue cod population off Motunau has been heavily overfished. Further, given the small size of blue cod in this area, nearly all females and most males caught will be of sub-legal size (less than 33 cm from 1 July 2020), and this is likely to result in substantial mortality through catch and return of undersize fish. The smaller size of blue cod at Motunau compared with blue cod at Kaikōura (90 km to the north) was first evident from a recreational survey of private fishers and charter boats from north Canterbury in 2003 (Hart & Walker 2004).

Displacement of recreational fishing effort from the Marlborough Sounds to Kaikōura and Motunau is likely to have occurred since at least 2008 with the restrictions on blue cod fishing in the Marlborough Sounds[1]. Further, the establishment of the Kaikōura Marine Area in 2014 with a larger MLS (33 cm compared with 30 cm) and lower daily bag limit (6 compared with 10) than in Motunau at that time may also have further increased effort in the Motunau blue cod fishery. The north Canterbury area that includes Motunau was assigned a 'traffic light' colour of red by Fisheries New Zealand in 2020

[1] Closure of the inner Marlborough Sounds to all blue cod fishing in October 2008; a slot limit of 30 to 35 cm and a DBL of 2 blue cod in April 2011; and from 20 December 2015, a MLS of 33 cm and DBL of 2 blue cod within the period 20 December to 31 August.

indicating that the blue cod stocks in this area are considered to be overfished. The increase in MLS and reduced DBL in July 2020 were introduced as a fisheries intervention to reduce fishing pressure and aid stock recovery.

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6. REFERENCES

Beamish, R.J.; Fournier, D.A. (1981). A method for comparing the precision of a set of age determinations. *Canadian Journal of Fisheries and Aquatic Sciences 38*: 982–983.

Beentjes, M.P. (2019). Blue cod potting surveys: standards and specifications: Version 2. *New Zealand Fisheries Assessment Report 2019/21*. 62 p.

Beentjes, M.P. (2020). Age structure, recruitment variation, and sex ratio in blue cod (*Parapercis colias*) subpopulations in New Zealand. *New Zealand Journal of Marine and Freshwater Research, DOI: 10.1080/00288330.2020.1825000*

Beentjes, M.P.; Carbines, G.D. (2003). Abundance of blue cod off Banks Peninsula in 2002. *New Zealand Fisheries Assessment Report 2003/16*. 25 p.

Beentjes, M.P.; Carbines, G.D. (2005). Population structure and relative abundance of blue cod (*Parapercis colias*) off Banks Peninsula and in Dusky Sound, New Zealand. *New Zealand Journal of Marine and Freshwater Research 39*: 77–90.

Beentjes, M.P.; Carbines, G.D. (2006). Abundance of blue cod off Banks Peninsula in 2005. *New Zealand Fisheries Assessment Report 2006/1*. 24 p.

Beentjes, M.P.; Carbines, G.D. (2009). Abundance, size and age composition, and mortality of blue cod off Banks Peninsula in 2008. *New Zealand Fisheries Assessment Report 2009/25*. 46 p.

Beentjes, M.P.; Carbines, G.D. (2011). Relative abundance, size and age structure, and stock status of blue cod off south Otago in 2010. *New Zealand Fisheries Assessment Report 2011/42*. 60 p.

Beentjes, M.P.; Carbines, G.D. (2012). Relative abundance, size and age structure, and stock status of blue cod from the 2010 survey in Marlborough Sounds, and review of historical surveys. *New Zealand Fisheries Assessment Report 2012/43*. 137 p.

Beentjes, M.P.; Fenwick, M. (2017). Relative abundance, size and age structure, and stock status of blue cod off Banks Peninsula in 2016. *New Zealand Fisheries Assessment Report 2017/30*. 81 p.

Beentjes, M.P.; Fenwick, M. (2019a). Relative abundance, size and age structure, and stock status of blue cod off north Otago in 2018. *New Zealand Fisheries Assessment Report 2019/07*. 55 p.

Beentjes, M.P.; Fenwick, M. (2019b). Relative abundance, size and age structure, and stock status of blue cod off south Otago in 2018. *New Zealand Fisheries Assessment Report 2019/14*. 47 p.

Beentjes, M.P.; Francis, R.I.C.C. (2011). Blue cod potting surveys: standards and specifications. Version 1. *New Zealand Fisheries Assessment Report 2011/29*. 47 p.

Beentjes, M.P.; Michael, K.; Pallentin, A.; Parker, S.; Hart, A. (2017). Blue cod relative abundance, size and age structure, and habitat surveys of Marlborough Sounds in 2013. *New Zealand Fisheries Assessment Report 2017/61*. 110 p.

Beentjes, M.P.; Miller, A. (2020). Relative abundance, size and age structure, and stock status of blue cod in Paterson Inlet in 2018. *New Zealand Fisheries Assessment Report 2020/12*. 52 p.

Beentjes, M.P.; Miller, A.; Kater, D. (2019). Relative abundance, size and age structure, and stock status of blue cod in Foveaux Strait in 2018. *New Zealand Fisheries Assessment Report 2019/13*. 52 p.

Beentjes, M.P.; Page, M. (2016). Relative abundance, size and age structure, and stock status of blue cod in Dusky Sound in 2014. *New Zealand Fisheries Assessment Report 2016/42*. 51 p.

Beentjes, M.P.; Page, M. (2017). Relative abundance, size and age structure, and stock status of blue cod off Kaikoura in 2015. *New Zealand Fisheries Assessment Report 2017/16*. 54 p.
Beentjes, M.P.; Page, M. (2018). Relative abundance, size and age structure, and stock status of blue cod off Kaikoura in 2017. *New Zealand Fisheries Assessment Report 2018/37*. 44 p.
Beentjes, M.P.; Page, M. (2021). Relative abundance, size and age structure, and stock status of blue cod off Kaikōura in 2019. *New Zealand Fisheries Assessment Report 2021/27*. 46 p.
Beentjes, M.P.; Page, M.; Sutton, C.; Olsen, L. (2018). Relative abundance, size and age structure, and stock status of blue cod from the 2017 survey in Marlborough Sounds, and review of historical surveys. *New Zealand Fisheries Assessment Report 2018/33*. 103 p.
Beentjes, M.P.; Sutton, C. (2017). Relative abundance, size and age structure, and stock status of blue cod off Motunau in 2016. *New Zealand Fisheries Assessment Report 2017/17*. 54 p.
Blackwell, R.G. (1997). Abundance, size composition, and sex ratio of blue cod in the Marlborough Sounds, September 1995. *NIWA Technical Report 88*. 52 p.
Blackwell, R.G. (1998). Abundance, size and age composition, and yield-per-recruit of blue cod in the Marlborough Sounds, September 1996. *NIWA Technical Report 30*. 47 p.
Blackwell, R.G. (2002). Abundance, size and age composition of recruited blue cod in the Marlborough Sounds, September 2001. Final Research Report for Ministry of Fisheries Research Project BCO2001/01. (Unpublished report held by Fisheries New Zealand, Wellington.)
Blackwell, R.G. (2005). Abundance and size composition of recruited blue cod in the Marlborough Sounds, September 2005. Final Research Report for the Ministry of Fisheries Research Project BCO2003/01. (Unpublished report held by Fisheries New Zealand, Wellington).
Blackwell, R.G. (2008). Abundance and size composition of recruited blue cod in the Marlborough Sounds, September 2007. Final Research Report for Ministry of Fisheries Research Project BCO2006/01 24 p. (Unpublished report held by Fisheries New Zealand, Wellington.)
Bull, B.; Dunn, A. (2002). Catch-at-age: User Manual v1.06.2002/09/12. NIWA Internal Report 114. 23 p. (Unpublished report held in NIWA Library, Wellington.)
Bull, B.; Francis, R.I.C.C.; Dunn, A.; McKenzie, A.; Gilbert, D.J.; Smith, M.H. (2005). CASAL (C++ algorithmic stock assessment laboratory): CASAL user manual v2.07-2005/08/21. *NIWA Technical Report 127*. 272 p.
Campana, S.E. (2001). Accuracy, precision, and quality control in age determination, including a review of the use and abuse of age validation methods. *Journal of Fish Biology 59*: 197–242.
Campana, S.E.; Annand, M.C.; McMillan, J.I. (1995). Graphical and statistical methods for determining the consistency of age determinations. *Transactions of the American Fisheries Society 124*: 131–138.
Carbines, G.; Haist, V. (2012a). Relative abundance, size structure, and stock status of blue cod off Banks Peninsula in 2012. Presentation to the SINS WG. SIN-WG-2012/23. (Unpublished report held by Fisheries New Zealand, Wellington.)
Carbines, G.; Haist, V. (2012b). Relative abundance, size structure, and stock status of blue cod off North Canterbury (Kaikoura & Motunau) in 2011/12. SINS WG Report 2012-24 (Unpublished report held by the Ministry for Primary Industries, Wellington.)
Carbines, G.; Haist, V. (2014). Relative abundance, size and age structure, and stock status of blue cod in Paterson Inlet of BCO 5 in 2010. *New Zealand Fisheries Assessment Report 2014/14*. 49 p.
Carbines, G.; Haist, V. (2017a). Relative abundance, population structure, and stock status of blue cod in the Foveaux Strait in 2014. Experimental evaluation of pot catchability and size selectivity. *New Zealand Fisheries Assessment Report 2017/63*. 61 p.
Carbines, G.; Haist, V. (2017b). Relative abundance, size and age structure, and stock status of blue cod off Banks Peninsula in 2012. *New Zealand Fisheries Assessment Report 2017/37*. 126 p.
Carbines, G.; Haist, V. (2018a). Relative abundance, population structure, and stock status of blue cod in Paterson Inlet in 2014. Concurrent fixed and random site potting surveys. *New Zealand Fisheries Assessment Report 2018/09*. 59 p.
Carbines, G.; Haist, V. (2018b). Relative abundance, population structure, and stock status of blue cod off north Otago in 2013. Concurrent fixed and random site potting surveys. *New Zealand Fisheries Assessment Report 2018/07*. 58 p.

Carbines, G.; Haist, V. (2018c). Relative abundance, population structure, and stock status of blue cod off south Otago in 2013. Estimates of pot catchability and size selectivity. *New Zealand Fisheries Assessment Report 2018/08*. 69 p.
Carbines, G.; Haist, V. (2018d). Relative abundance, size and age structure, and stock status of blue cod off Kaikoura and north Canterbury in 2011–12. Comparisons of potting survey designs and estimates of pot catchability and size selectivity. *New Zealand Fisheries Assessment Report 2018/06*. 97 p.
Carbines, G.D. (1998). Blue cod age validation, tagging feasibility and sex inversion. Final Research Report for Ministry of Fisheries Project SOBCO4. 74 p. (Unpublished report held by Fisheries New Zealand, Wellington.)
Carbines, G.D. (2004). Age, growth, movement and reproductive biology of blue cod (*Parapercis colias*-Pinguipedidae): Implications for fisheries management in the South Island of New Zealand. Unpublished Ph.D. thesis, University of Otago, Dunedin, New Zealand. 224 p.
Carbines, G.D. (2007). Relative abundance, size, and age structure of blue cod in Paterson Inlet (BCO 5), November 2006. *New Zealand Fisheries Assessment Report 2007/37*. 31 p.
Carbines, G.D.; Beentjes, M.P. (2003). Relative abundance of blue cod in Dusky Sound in 2002. *New Zealand Fisheries Assessment Report 2003/37*. 25 p.
Carbines, G.D.; Beentjes, M.P. (2006a). Relative abundance of blue cod off north Canterbury in 2004–2005. *New Zealand Fisheries Assessment Report 2006/30*. 26 p.
Carbines, G.D.; Beentjes, M.P. (2006b). Relative abundance of blue cod off North Otago in 2005. *New Zealand Fisheries Assessment Report 2006/29*. 20 p.
Carbines, G.D.; Beentjes, M.P. (2009). Relative abundance, size and age structure, and mortality of blue cod off north Canterbury (BCO 3) in 2007–08. *New Zealand Fisheries Assessment Report 2009/37*. 56 p.
Carbines, G.D.; Beentjes, M.P. (2011a). Relative abundance, size and age structure, and stock status of blue cod in Dusky Sound, Fiordland, in 2008. *New Zealand Fisheries Assessment Report 2011/35*. 56 p.
Carbines, G.D.; Beentjes, M.P. (2011b). Relative abundance, size and age structure, and stock status of blue cod off north Otago in 2009. *New Zealand Fisheries Assessment Report 2011/36*. 57 p.
Carbines, G.D.; Beentjes, M.P. (2012). Relative abundance, size and age structure, and stock status of blue cod in Foveaux Strait in 2010. *New Zealand Fisheries Assessment Report 2012/39*. 66 p.
Carbines, G.D.; McKenzie, J. (2001). Movement patterns and stock mixing of blue cod in Southland (BCO 5). Final Research Report for Ministry of Fisheries Research Project BCO9702. 16 p. (Unpublished report held by the Ministry for Primary Industries, Wellington.)
Carbines, G.D.; McKenzie, J. (2004). Movement patterns and stock mixing of blue cod in Dusky Sound in 2002. *New Zealand Fisheries Assessment Report 2004/36*. 28 p.
Chang, W.Y.B. (1982). A statistical method for evaluating the reproducibility of age determination. *Canadian Journal of Fisheries and Aquatic Sciences 39*: 1208–1210.
Chapman, D.G.; Robson, D.S. (1960). The analysis of a catch curve. *Biometrics 16*: 354–368.
Doonan, I. (2020). Stock assessment of blue cod (*Parapercis colias*) in BCO 5 using data to 2019. *New Zealand Fisheries Assessment Report 2020/14*. 48 p.
Dunn, A.; Francis, R.I.C.C.; Doonan, I.J. (2002). Comparison of the Chapman-Robson and regression estimators of Z from catch-curve data when non-sampling stochastic error is present. *Fisheries Research 59*: 149–159.
Fishelson, L. (1970). Protogynous sex reversal in the fish *Anthias squamipinni*s (Teleostei, Anthiidae) regulated by presence or absence of male fish. *Nature 227*: 90–91.
Fisheries New Zealand (2020). Fisheries Assessment Plenary, May 2020: stock assessments and stock status. Compiled by the Fisheries Science and Information Group, Fisheries New Zealand, Wellington, New Zealand. 1746 p.
Francis, R.I.C.C. (1984). An adaptive strategy for stratified random trawl surveys. *New Zealand Journal of Marine and Freshwater Research 18*: 59–71.
Gebbie, C.L. (2014). Population genetic structure of New Zealand blue cod *(Parapercis colias*) based on mitochondrial and microsatellite DNA markers. 89p. MSc. thesis, Victoria University of Wellington.

Govier, D. (2001). Growth and movement of Blue Cod (*Parapercis colias*) in Paterson Inlet, Stewart Island, New Zealand (Thesis, Master of Science). University of Otago. Retrieved from http://hdl.handle.net/10523/2967.

Hart, A.M.; Walker, N.A. (2004). Monitoring the recreational blue cod and sea perch fishery in the Kaikoura - North Canterbury area. *New Zealand Fisheries Assessment Research Report 2004/45*. 30 p.

Large, K.; Bian, R; Beentjes, M. (in prep). Characterisation and standardised CPUE of the blue cod (*Parapercis colias*) commercial fishery in BCO 3 up to 2017–18 fishing year. New Zealand Fisheries Assessment Report.

Mace, J.T.; Johnston, A.D. (1983). Tagging experiments on blue cod (*Parapercis colias*) in the Marlborough Sounds, New Zealand. *New Zealand Journal of Marine and Freshwater Research 17*: 207–211.

McCullagh, P.; Nelder, J.A. (1989). Generalised linear models. Chapman & Hall, London.

Ministry for Primary Industries (2017). National Blue cod Strategy. Summary Report of results and feedback. (http://www.mpi.govt.nz/news-and-resources/publications/). 153 p.

Ministry of Fisheries (2011). Operational guidelines for New Zealand's harvest strategy standard (Revision 1). 78 p. (Unpublished report held by Fisheries New Zealand, Wellington.)

Mutch, P.G. (1983). Factors influencing the density and distribution of the blue cod (*Parapercis colias*) (Pisces: Mugilodae). Unpublished MSc thesis, University of Auckland, New Zealand. 76 p.

Rapson, A.M. (1956). Biology of the blue Cod (*Parapercis colias* Forster) of New Zealand. Unpublished Ph.D. Thesis, Victoria University, Wellington, New Zealand. p53.

Reinboth, R. (1980). Can sex inversion be environmentally induced? *Biology of Reproduction 22*: 49–59.

Robertson, D.R. (1972). Social Control of Sex Reversal in a Coral-Reef Fish. *Science 177*: 1007–1009.

Rodgers, K.L.; Wing, S.R. (2008). Spatial structure and movement of blue cod *Parapercis colias* in Doubtful Sound, New Zealand, inferred from delta C-13 and delta N-15. *Marine Ecology Progress Series 359*: 239–248.

Sato, T.; Kobayashi, M.; Takebe, T. et al. (2018). Induction of female-to-male sex change in a large protogynous fish, *Choerodon schoenleinii*. *Marine Ecology 39:e12484*: 1–8.

Stephenson, P.; Sedberry, G.; Haist, V. (2009). Expert review panel report. Review of blue cod potting surveys in New Zealand. Draft 14 May 2009. BCOREV-2009-22, 14 p. (Unpublished report held by Fisheries New Zealand, Wellington.)

Stroud, G.J. (1982). The taxonomy and biology of fishes of the genus *Parapercis* (Teleostei: Mugiloididae) in Great Barrier Reef waters. 428 p. PhD thesis, James Cook University, Australia

von Bertalanffy, L. (1938). A quantitative theory of organic growth. *Human Biology 10*: 181–213.

Walsh, C. (2017). Age determination protocol for blue cod (*Parapercis colias*). *New Zealand Fisheries Assessment Report 2017/15*. 34 p.

Warner, R.R (1984). Mating behavior and hermaphroditism in coral reef fishes. *American Scientist 72*: 128–136.

Wynne-Jones, J.; Gray, A; Heinemann, A.; Hill, L.; Walton, L. (2019). National Panel Survey of Marine Recreational Fishers 2017–18. *New Zealand Fisheries Assessment Report 2019/24*. 104 p.

Wynne-Jones, J.; Gray, A.; Hill, L.; Heinemann, A. (2014). National Panel Survey Of Marine Recreational Fishers 2011–12: Harvest Estimates. *New Zealand Fisheries Assessment Report 2014/67*. 139 p.

7. TABLES

Table 1: Effort and catch data for the 2020 Motunau blue cod potting survey.

								Random sites	
	Area		*N* sets (sites)		*N* pots	Catch (blue cod)		Depth (m)	
Stratum	(km^2)	Site type	Phase 1	Phase 2	(stations)	*N*	kg	Mean	Range
1	41.3	Random	10		60	899	272.4	25.9	10–37
2	66.9	Random	10		60	555	135.8	25.0	11–35
3	176.1	Random	13	6	114	704	161.1	20.3	5–33
Total	284.3	Random	33	6	234	2 158	569.3	22.9	5–37

Table 2: Total catch and numbers of blue cod and bycatch species caught on the 2020 Motunau random-site potting survey. Percent of the catch by weight is also shown.

Common name	Species	Code	Number	Catch (kg)	% catch
Blue cod	*Parapercis colias*	BCO	2 158	569.3	90.32
Leatherjacket	*Meuschenia scaber*	LEA	71	26.9	4.27
Common octopus	*Octopus maorum*	OCT	4	7.9	1.25
Banded wrasse	*Notolabrus fucicola*	BPF	14	7.4	1.17
Scarlet wrasse	*Pseudolabrus miles*	SPF	16	6.4	1.02
Hairy conger	*Bassanago hirsutus*	HCO	1	6.0	0.95
Spotty	*Notolabrus celidotus*	STY	35	4.9	0.78
Tarakihi	*Nemadactylus macropterus*	NMP	3	0.6	0.10
Girdled wrasse	*Notolabrus cinctus*	GPF	2	0.5	0.08
Hagfish	*Eptatretus cirrhatus*	HAG	1	0.2	0.03
Triplefin	*Gilloblennius* spp.	GIL	3	0.1	0.02
Yellow-eyed mullet	*Aldrichetta forsteri*	YEM	1	0.1	0.02
Totals			2 309	630.3	100

Table 3: Mean catch rates for all blue cod and recruited blue cod (30 cm and over) from the 2020 Motunau random-site potting survey. Catch rates are pot-based, and s.e. and CV are set-based. s.e., standard error; CV coefficient of variation.

			All blue cod			Recruited blue cod		
Stratum	Site type	Pot lifts (N)	Catch rate (kg pot^{-1})	s.e.	CV (%)	Catch rate (kg pot^{-1})	s.e.	CV (%)
1	Random	60	4.54	1.71	37.7	2.41	1.12	46.5
2	Random	60	2.26	0.63	28.0	1.12	0.43	38.8
3	Random	114	1.41	0.42	30.0	0.55	0.19	34.4
Overall	Random	234	2.07	0.39	18.9	0.95	0.22	23.6

Table 4: Descriptive statistics for blue cod caught on the 2020 Motunau random-site blue cod potting survey. Outputs are raw for each stratum and weighted for the survey overall. Sex ratio is also given for recruited blue cod (30 cm and over). m, male; f, female.

				Length (cm)			Percent male	
Stratum	Site type	Sex	No.	Mean	Minimum	Maximum	All blue cod	Recruited
1	Random	m	680	26.7	12	41	75.5	97.7
		f	219	21.2	13	33		
2	Random	m	392	24.8	10	42	70.7	98.1
		f	163	19.3	10	38		
3	Random	m	536	23.8	10	43	76.1	96.0
		f	168	20.4	13	39		
Overall	Random	m	1 608	24.8	10	43	74.5	97.3
		f	550	20.2	10	39		

Table 5: Otolith ageing data used in the catch-at-age, *Z* estimate, and *SPR* analyses for the 2020 Motunau survey.

		Length of aged fish (cm)		Age (years)	
Survey	No. otoliths	Minimum	Maximum	Minimum	Maximum
Male	167	10	43	1	10
Female	102	10	34	1	7
Total	269	10	43	1	10

Table 6: **Reader comparison scores determined from ageing 50 randomly selected blue cod reference otolith samples ranging in age from 2 to 23 years. IAPE, Index of Average Percentage Error; CV, mean coefficient of variation.**

	IAPE (%)	**CV (%)**	**Agreed age (%)**	**Pass/Fail**
Target	1.50	2.12	–	–
Reader 1	1.48	2.09	80	Pass (1st attempt)
Reader 2	1.40	1.98	82	Pass (1st attempt)

Table 7: Gonad stages of all blue cod by sex from the Motunau survey in early January 2020. 1, immature or resting; 2, maturing (oocytes visible in females); 3, mature (hyaline oocytes in females, milt expressible in males); 4, running ripe (eggs and milt free flowing); 5, spent.

	Gonad stage (%)					
Sex	1	2	3	4	5	*N*
Males	25.1	73.9	0.7	0.0	0.3	1 608
Females	84.2	15.6	0.0	0.0	0.2	550

Table 8: Chapman-Robson total mortality estimates (*Z*) and 95% confidence intervals of blue cod for the 2020 Motunau random-site potting survey. AgeR, age-at-full recruitment (years). Estimates above seven, the maximum age for females, could not be generated

		95% CIs	
AgeR	*Z*	Lower	Upper
5	0.74	0.49	1.04
6	0.69	0.46	0.96
7	2.34	1.34	3.3

Table 9: Mortality parameters (CR *Z* and *F*, and *M*) and spawner-per-recruit ($F_{SPR\%}$) estimates at three values of *M* for age at full recruitment (AgeR) of 6 years for blue cod from the 2020 Motunau random-site potting survey. Note that selectivity to the fishery for females at MLS was 6.8 years, but AgeR of 7 years was not used because this was also the maximum age for females. AgeR is the age at which females reach MLS of 30 cm. *F*, fishing mortality; *M*, natural mortality; *Z*, total mortality. LowerCI, lower 95% confidence interval; UpperCI, upper 95% confidence interval.

AgeR	*M*	*Z*	*F*	$F_{\%SPR}$	Estimate
6	0.14	0.69	0.55	16.6%	Point
6	0.17	0.69	0.52	21.4%	Point
6	0.20	0.69	0.49	26.5%	Point
6	0.17	0.46	0.29	31.0%	LowerCI
6	0.17	0.69	0.52	21.4%	Point
6	0.17	0.96	0.79	16.9%	UpperCI

Table 10: Predictor variables, degrees of freedom, and R^2 values from the GLM stepwise regression analysis on the dependent variable pot catch. Variables are shown in the order of acceptance by the model with associated cumulative R^2 value. Surveys in the analyses were the three fixed-site (2008, 2012, 2016) and three random-site Motunau surveys (2012, 2016, and 2020). The 2005 fixed-site survey was not included because there were no environmental data collected on this survey.

Predictors	Df	R^2
Survey year	3	0.069
longitude	1	0.174
Bottom contour	4	0.234
Site type	1	0.270
Time	7	0.295
Sea colour	6	0.315
Depth	1	0.329
Tide state	5	0.338
Swell height	2	0.347
Sea condition	6	0.356
Wind speed	1	0.361

8. FIGURES

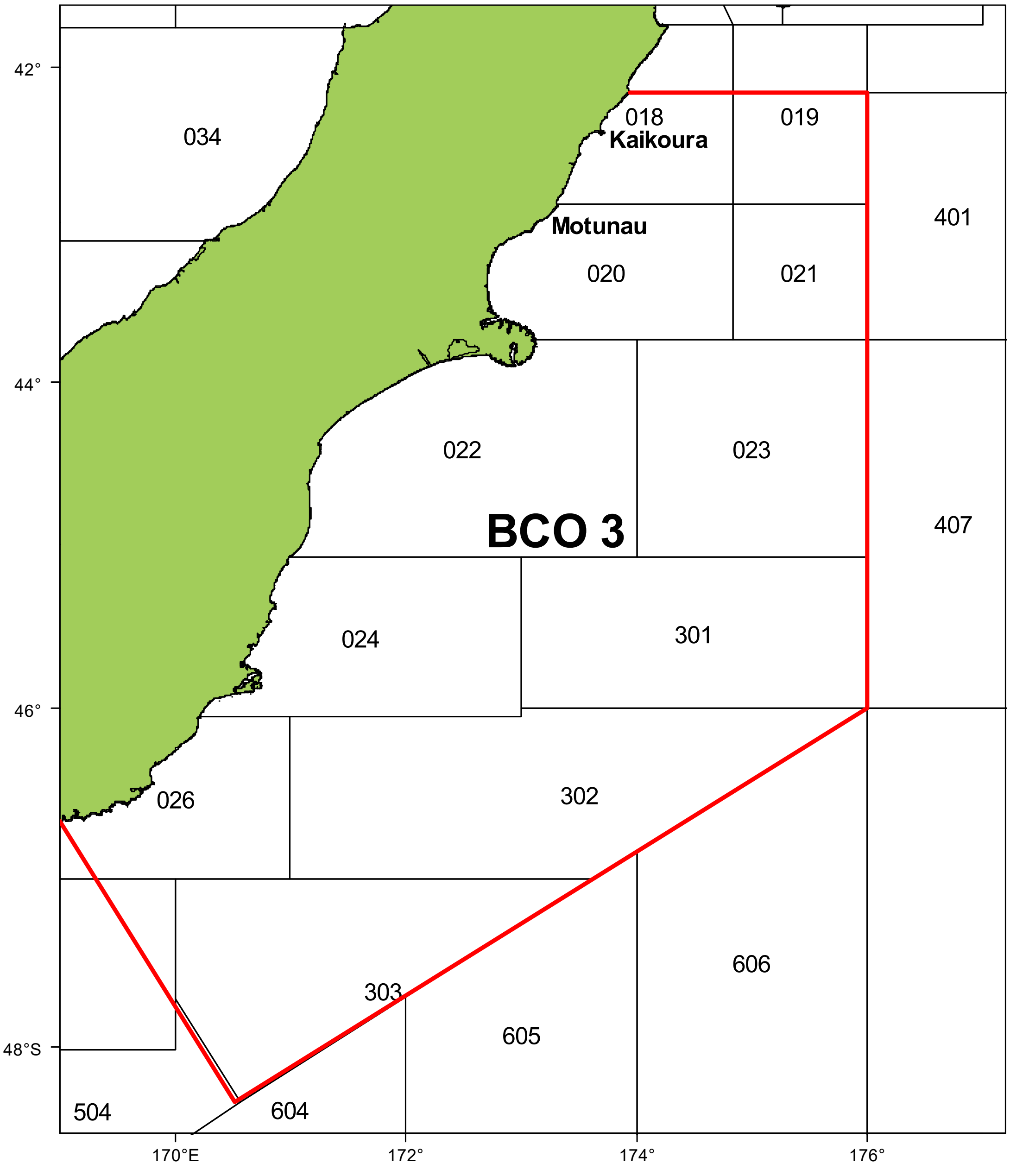

Figure 1: Blue cod Quota Management Area BCO 3 (red border) and statistical areas. The north Canterbury potting survey locations of Kaikōura and Motunau are shown.

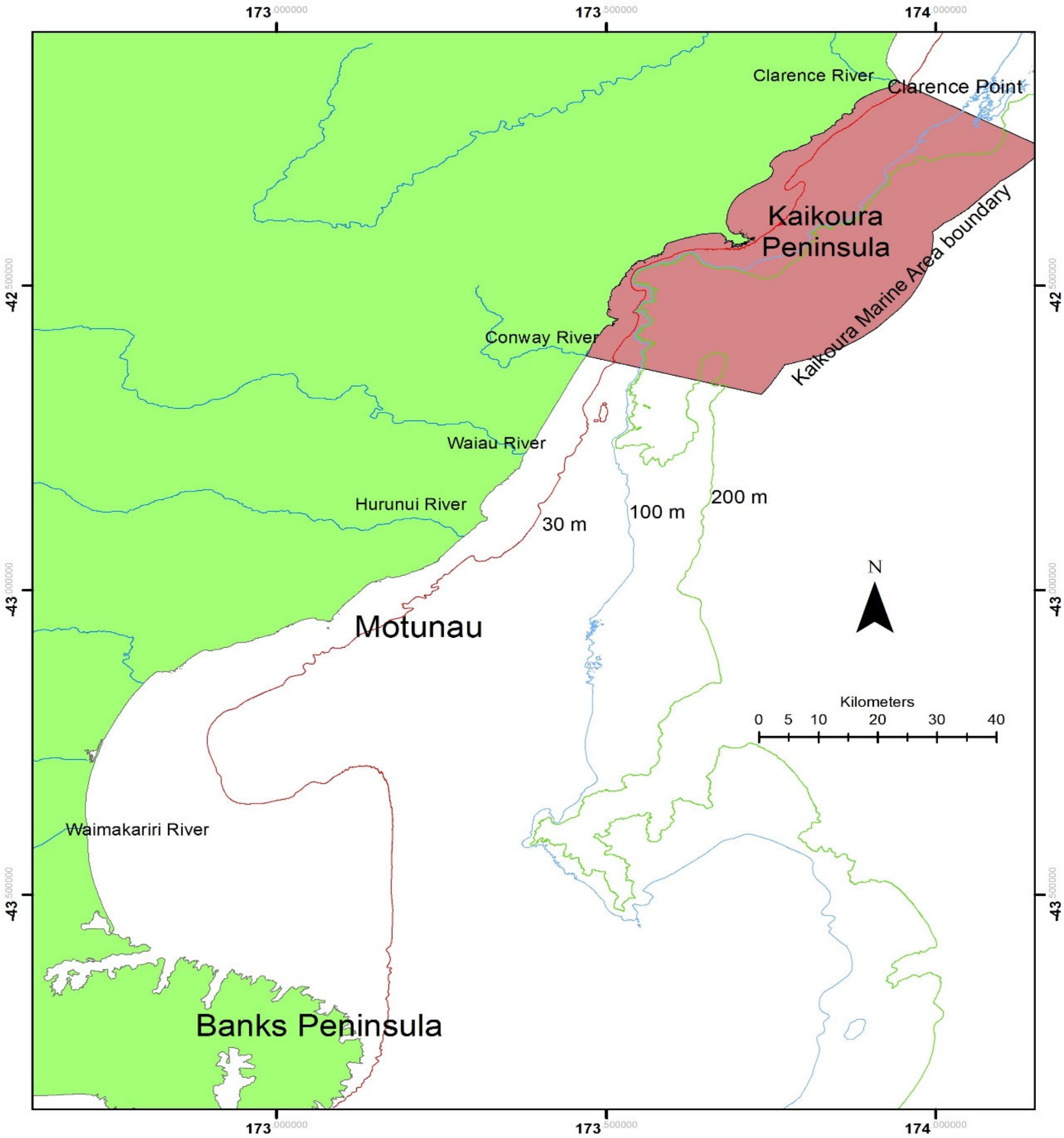

Figure 2: Map of north Canterbury coastline showing locations of Motunau and the Kaikōura Marine Area.

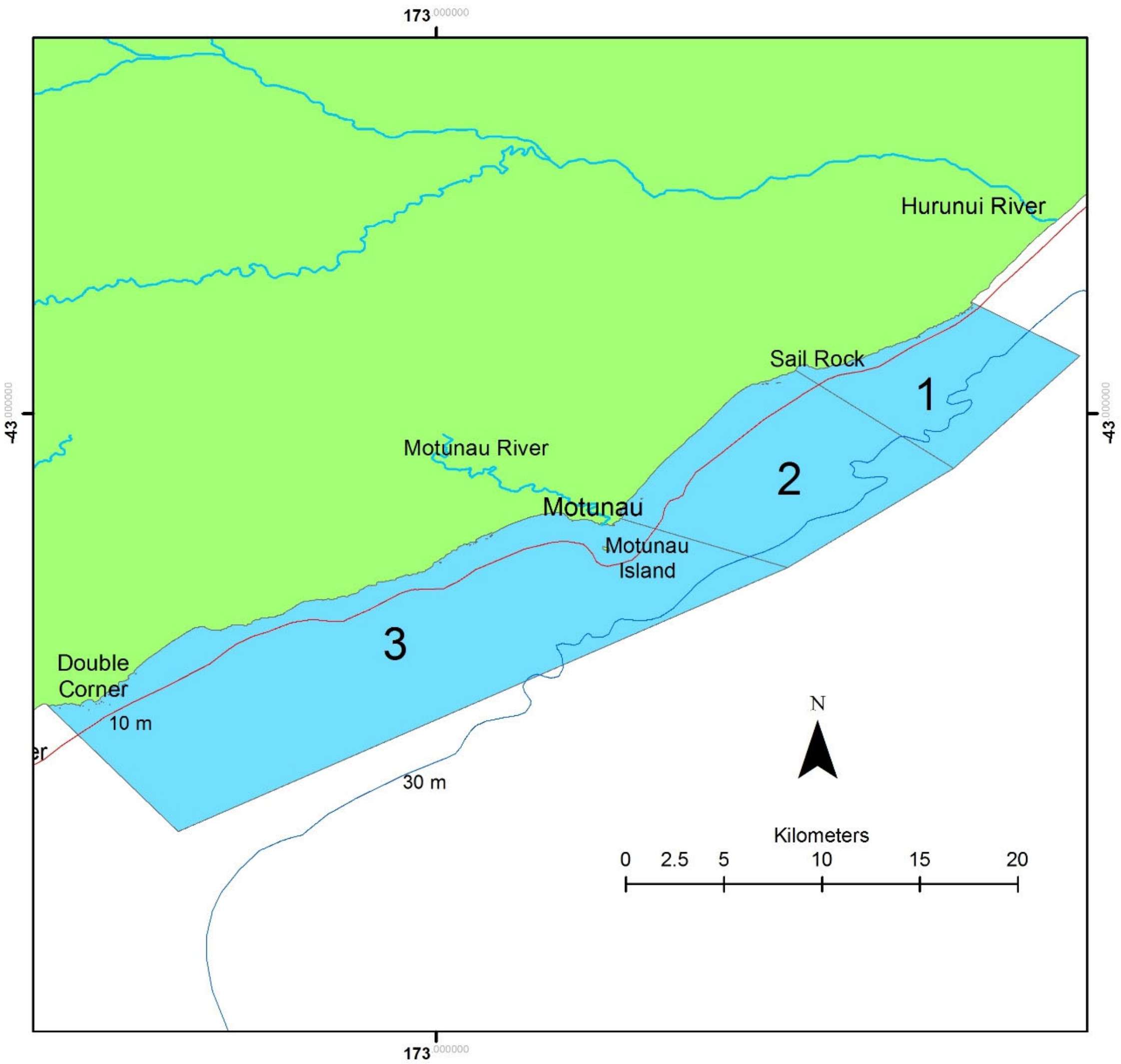

Figure 3: Map of Motunau blue cod potting survey strata (1, 2, and 3). The 10 m and 30 m depth contours are also shown.

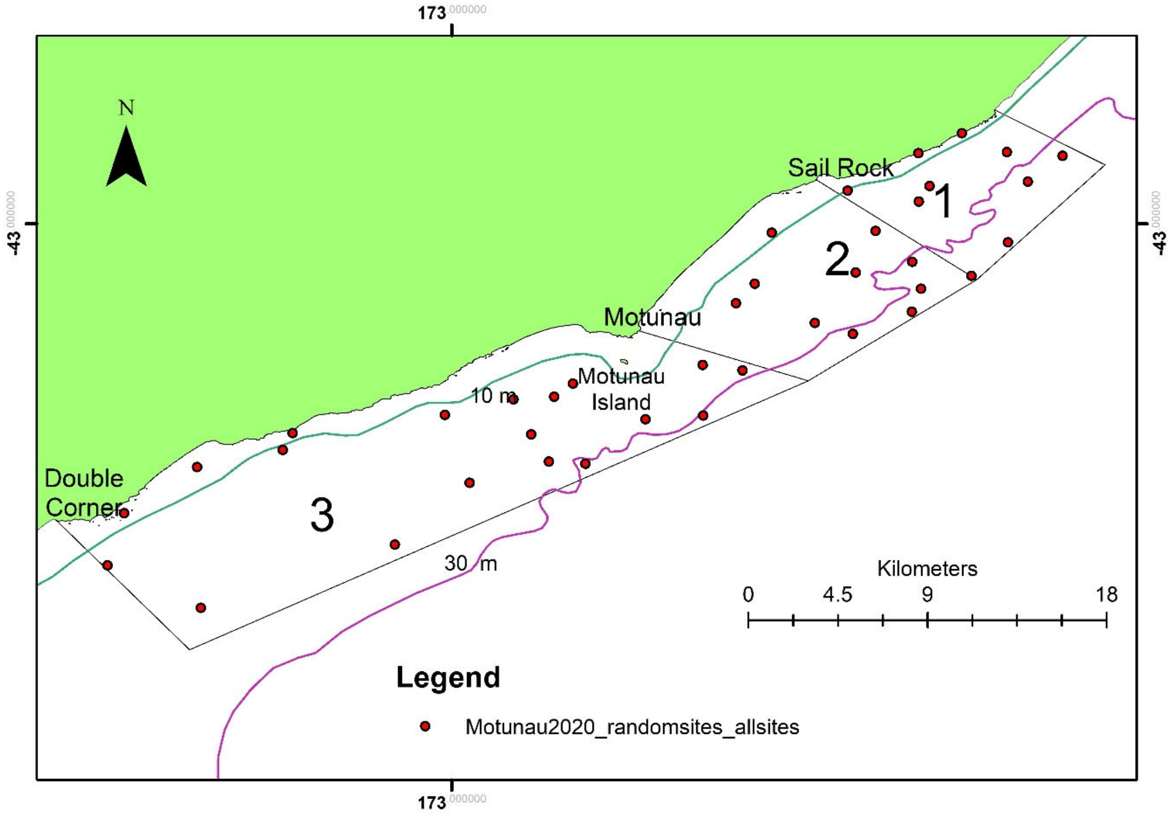

Figure 4: Map of Motunau strata and sites sampled during the 2020 blue cod random-site potting survey.

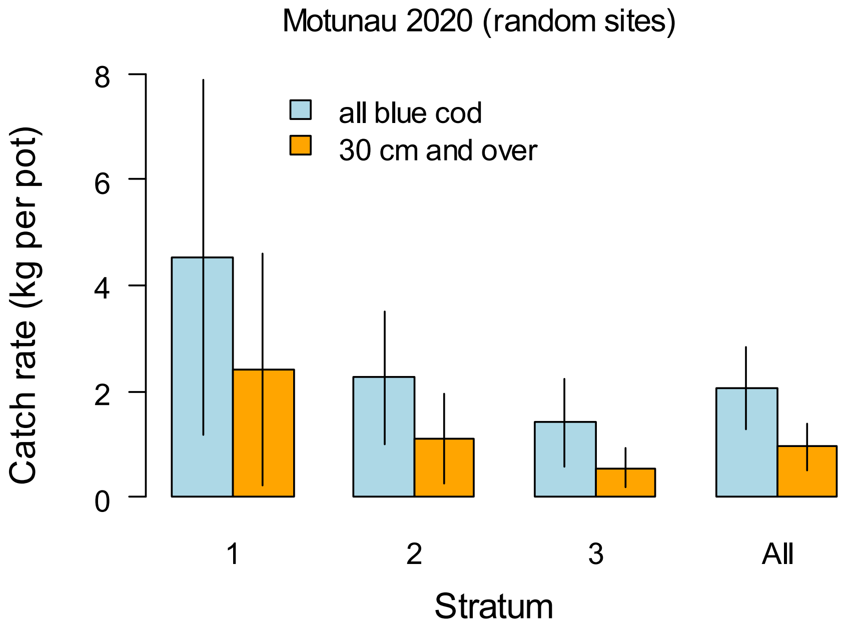

Figure 5: Catch rates (kg pot^{-1}) of all blue cod and recruited blue cod (30 cm and over) for the 2020 Motunau random-site potting survey. Error bars are 95% confidence intervals. See Figure 3 for location of strata.

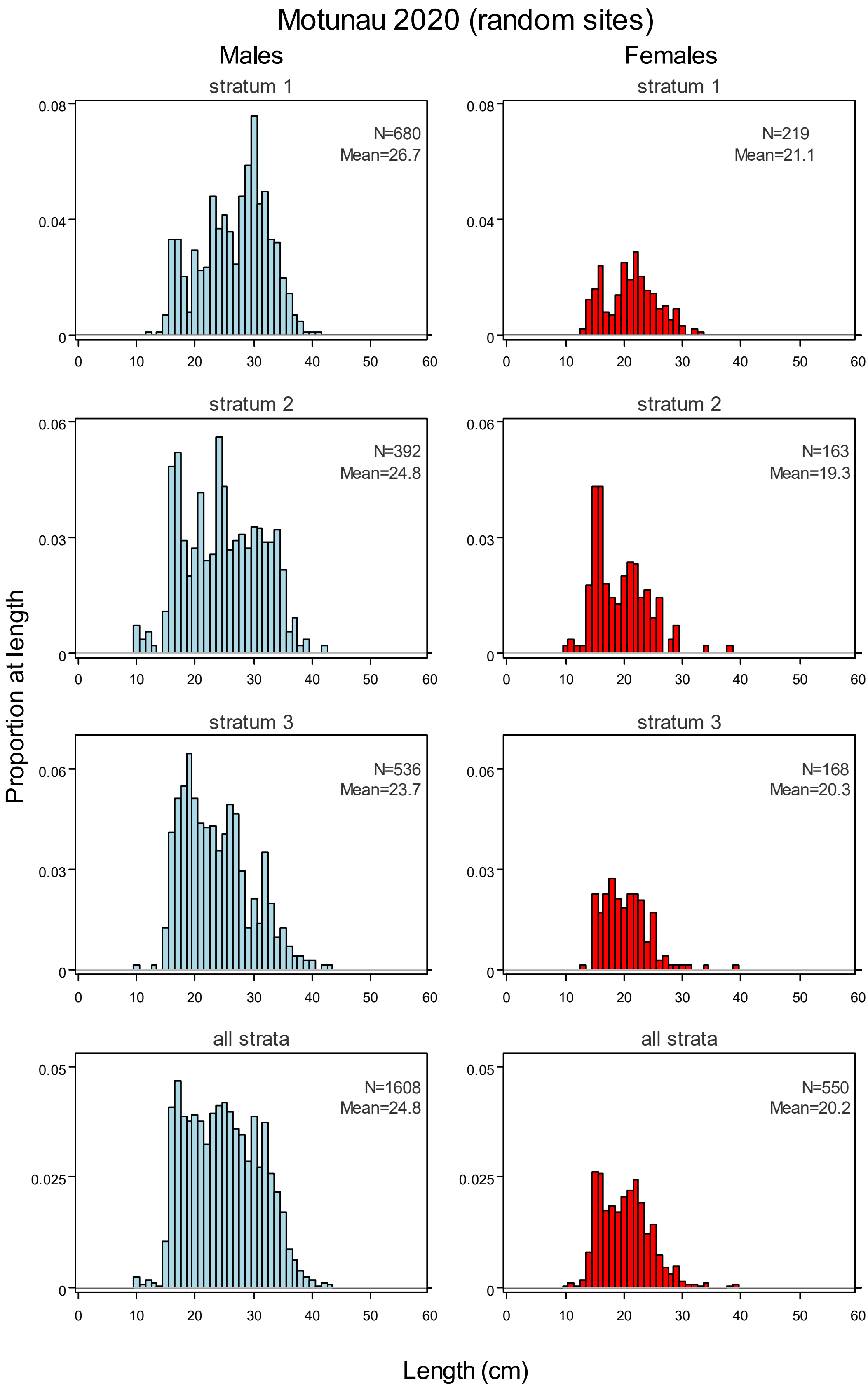

Figure 6: Scaled length frequency distributions by strata and overall for the 2020 Motunau random-site potting survey. N, sample numbers; Mean, mean length (cm). Proportions sum to one within each stratum.

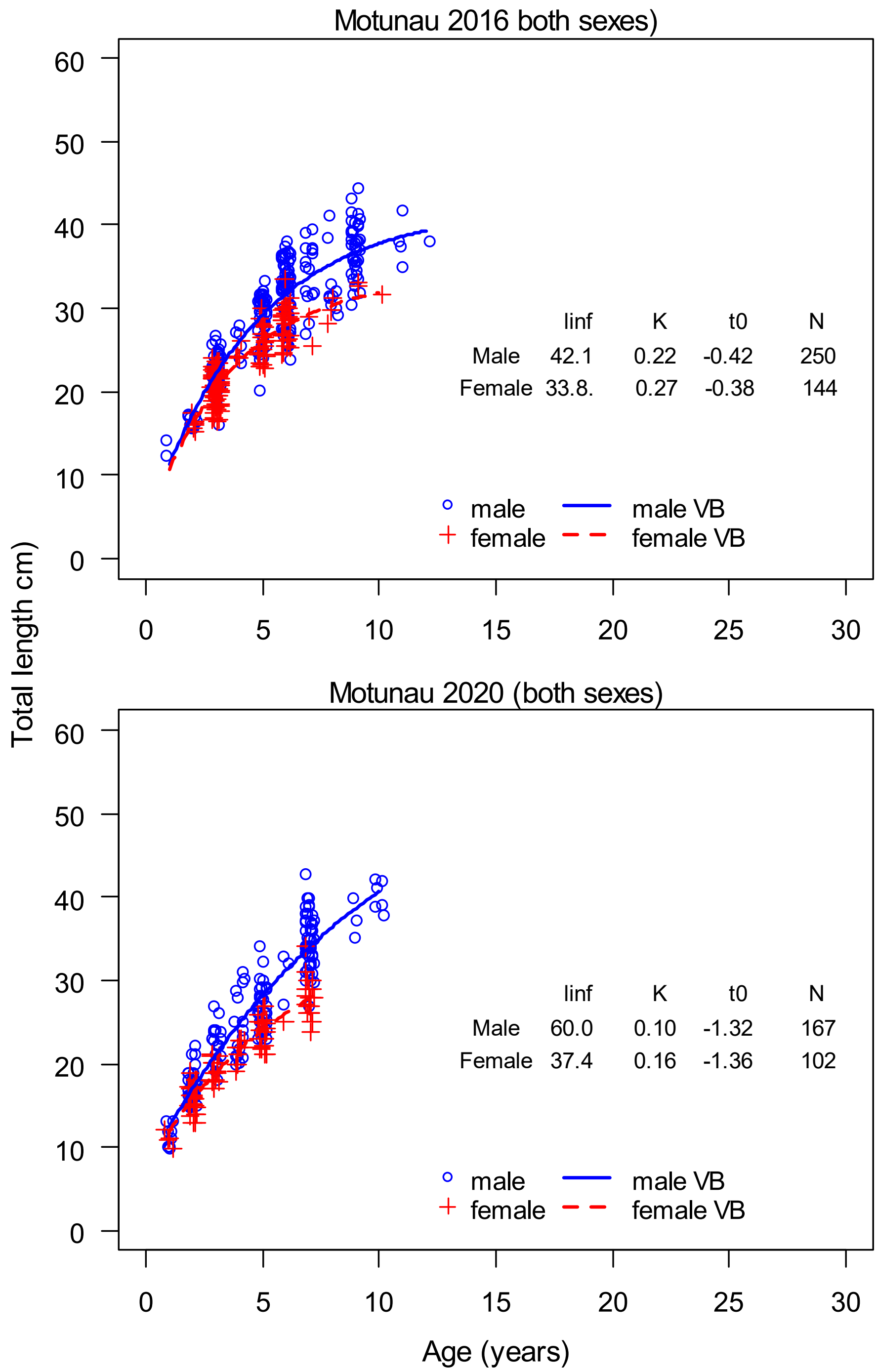

Figure 7: Observed blue cod age and length data by sex for the 2016 and 2020 Motunau blue cod potting surveys with von Bertalanffy (VB) growth models fitted to the data.

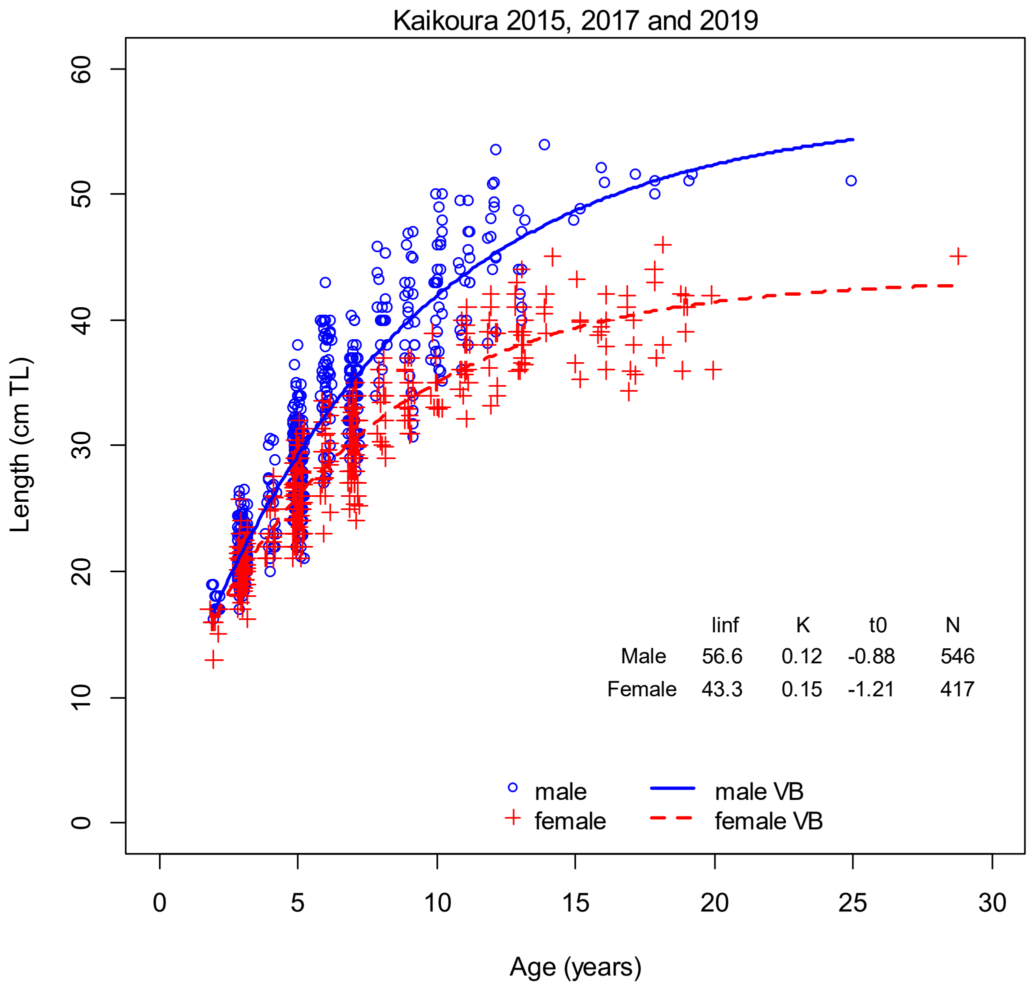

Figure 8: von Bertalanffy (VB) growth models fitted to the blue cod age and length data by sex for the 2015, 2017, and 2019 Kaikōura blue cod potting surveys. These VB parameters were used in the estimation of the Motunau spawner-per-recruit ratio in 2020.

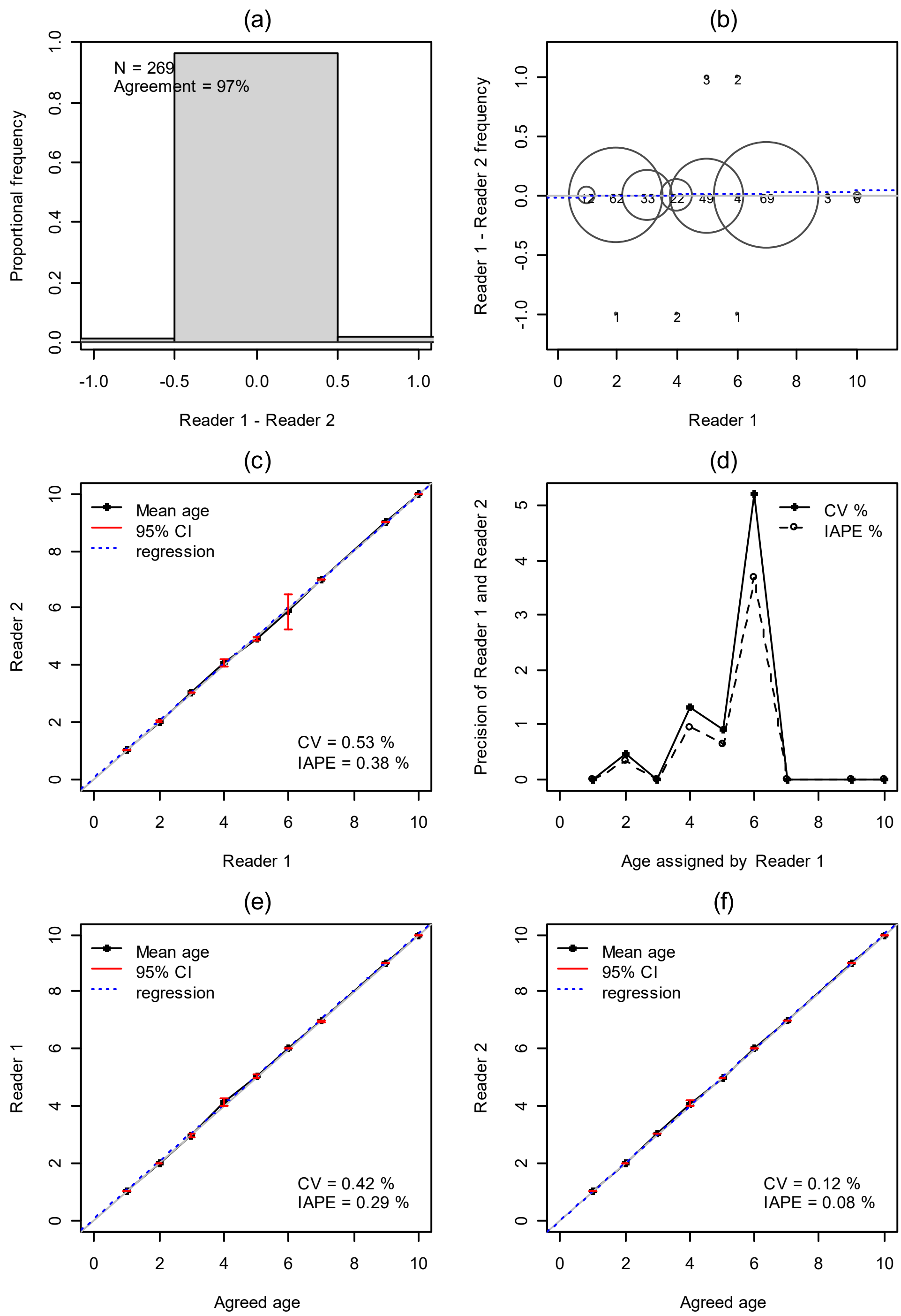

Figure 9: Blue cod age otolith reader comparison plots between reader 1 and reader 2 for the 2020 Motunau survey: (a) histogram of age differences between two readers; (b) difference between reader 1 and reader 2 as a function of the age assigned by reader 1, where the numbers of fish in each age bin are annotated and proportional to circle size; (c) age bias plot, showing the correspondence of ages between reader 1 and reader 2 for all ages; (d) precision of readers; (e and f) reader age compared with agreed age. In b, c, e, and f, solid lines show perfect agreement, dashed lines show the trend of a linear regression of the actual data.

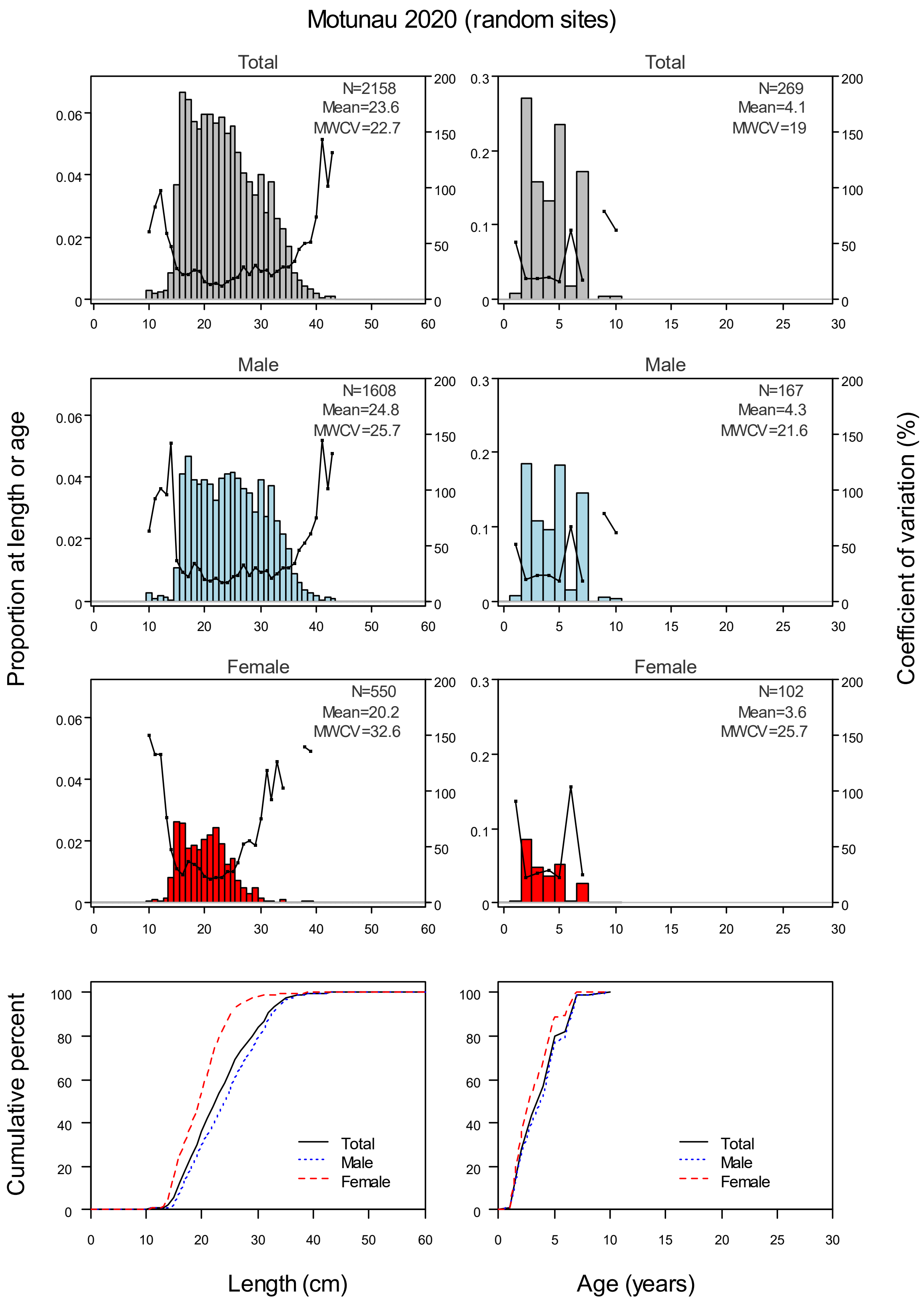

Figure 10: Scaled length and age frequency histograms, and cumulative distributions for total, male, and female blue cod for all strata in the 2020 Motunau random-site blue cod potting survey. The coefficients of variation are shown as lines plots for individual length and age. N, sample size; MWCV, mean weighted coefficient of variation (%).

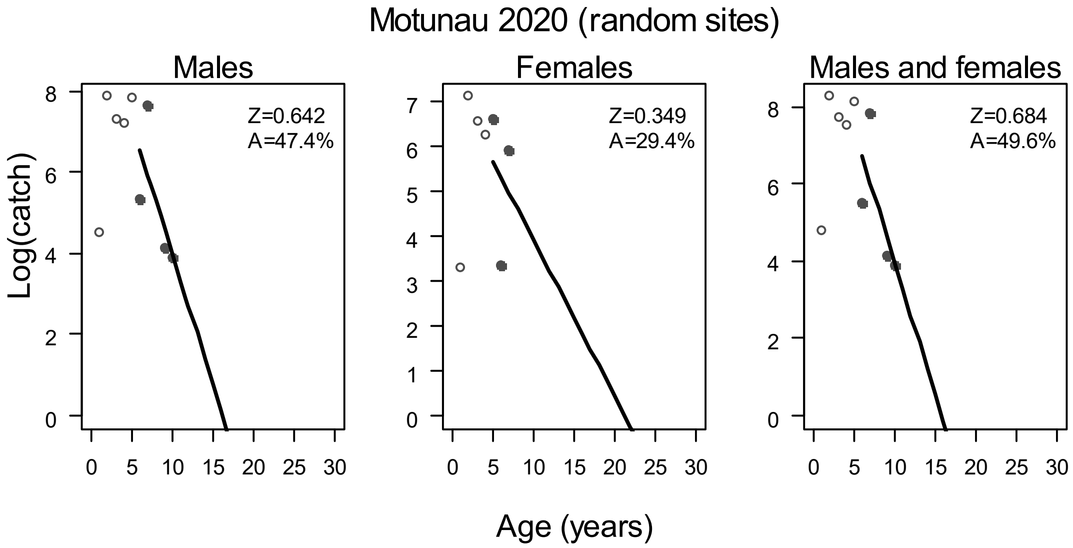

Figure 11: Motunau 2020 random-site blue cod potting survey catch curve (natural log of catch numbers versus age). The regression line is plotted from age at full recruitment of 6 years, but for females 5 years is used because the model is unable to generate a plot above this age (i.e., dark points on the graph). Z, instantaneous total mortality; A, the annual mortality rate or the proportion of the population that suffers mortality in a given year.

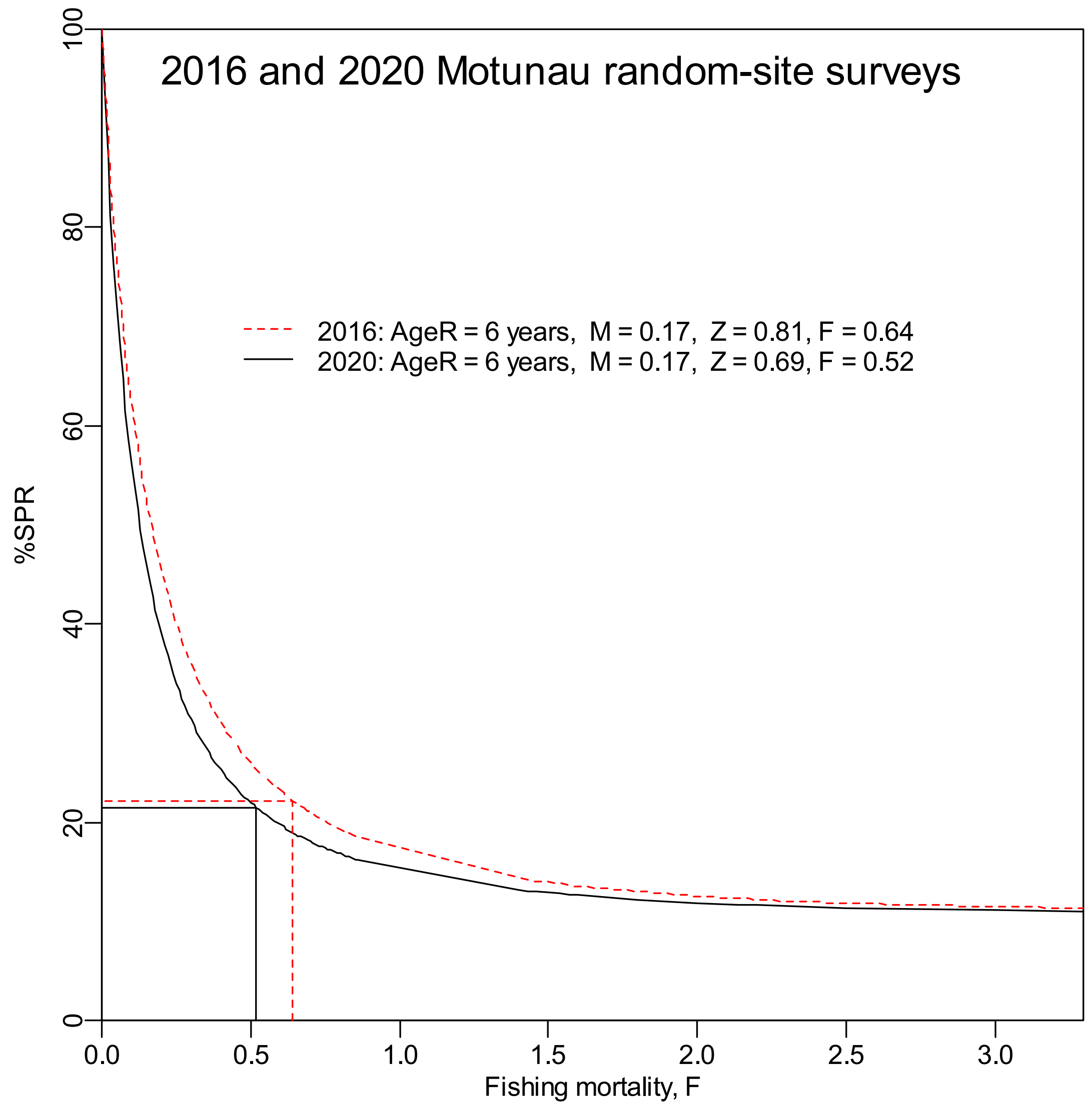

Figure 12: Blue cod spawner-per-recruit (*SPR*) as a function of fishing mortality (*F*) for Motunau random-site potting surveys in 2016 and 2020. The %*SPR* was 22.2% in 2016 and 21.4% in 2020. Age at full recruitment (AgeR = 6 years) and selectivity in 2016 were based on the 2015 Kaikōura survey von Bertalanffy growth curve. In 2020 age at full recruitment (AgeR = 6 years) and selectivity were based on the combined 2015, 2017, and 2019 Kaikōura surveys von Bertalanffy growth curve (see text for explanation).

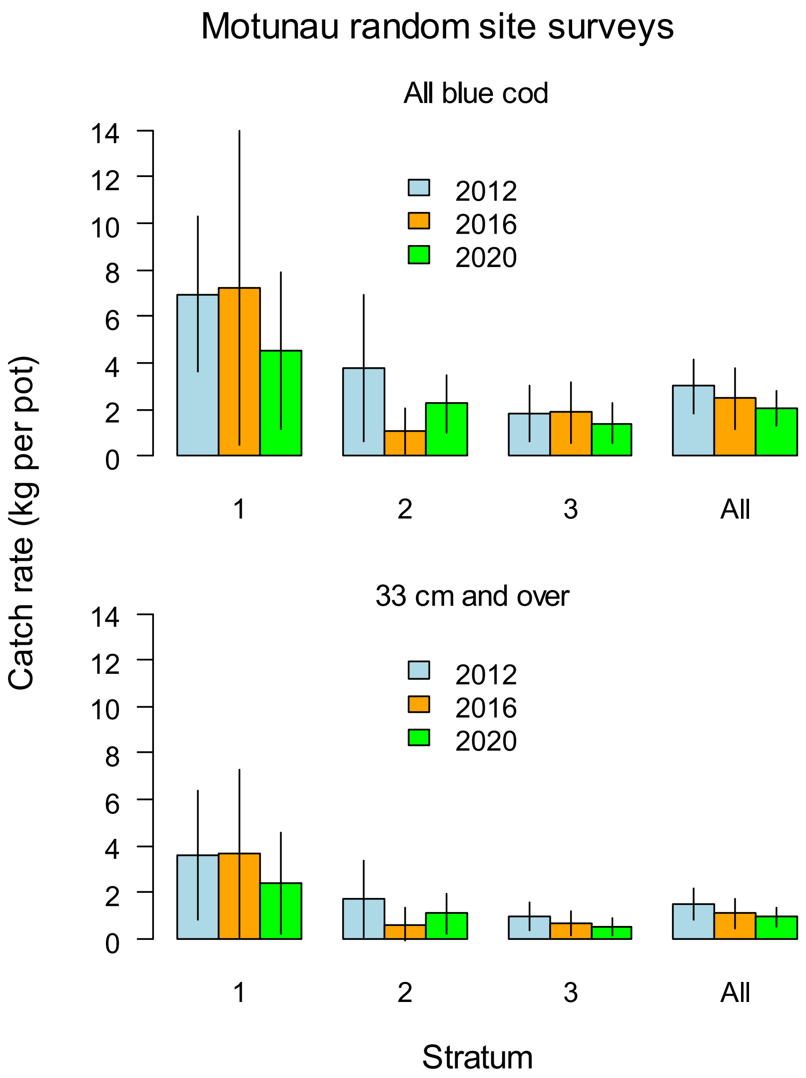

Figure 13: Catch rates (kg pot^{-1}) of all blue cod (top panel) and for recruited blue cod (30 cm and over, bottom panel) for the Motunau random-site potting surveys in 2012, 2016, and 2020. Error bars are 95% confidence intervals.

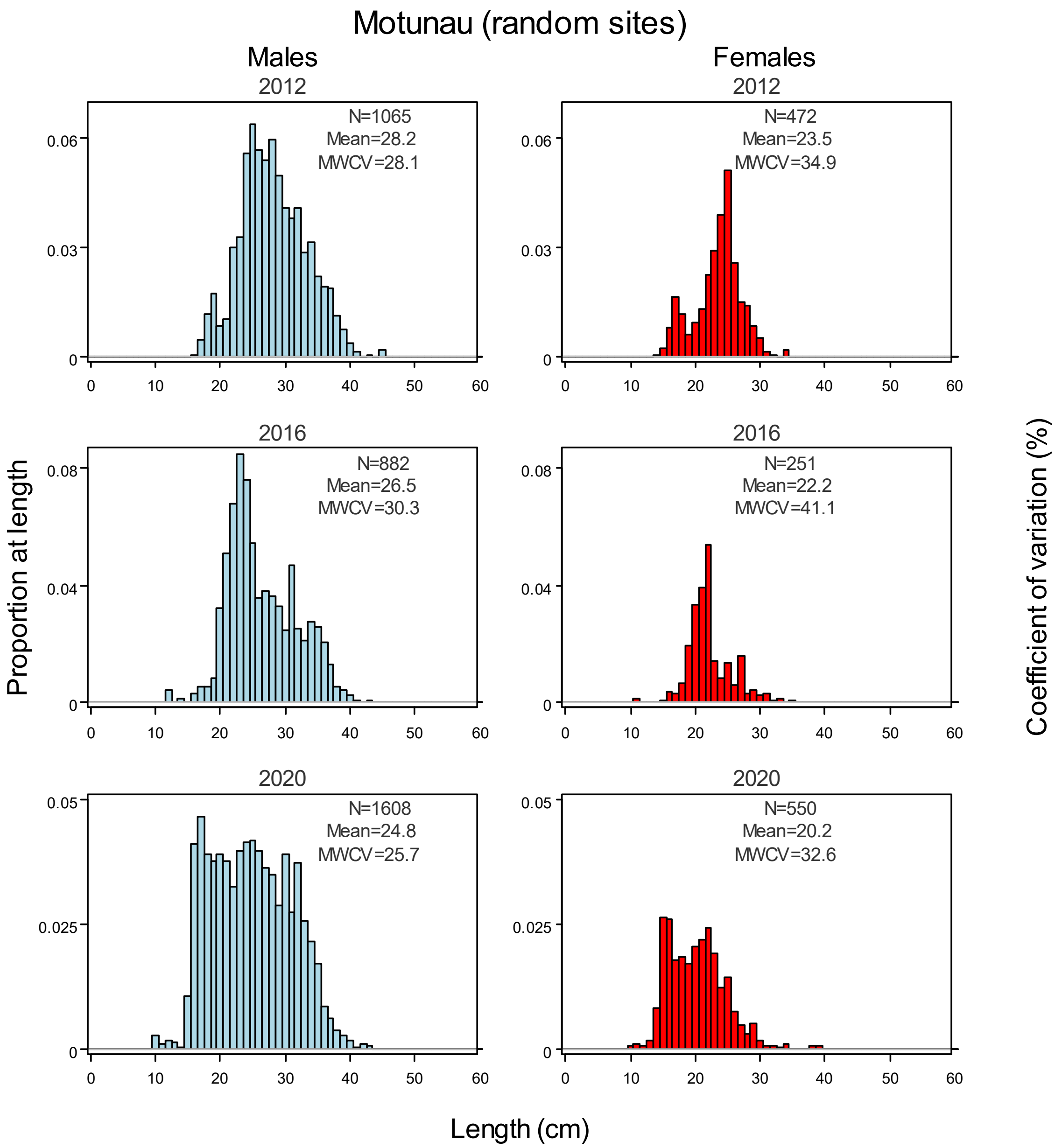

Figure 14: Scaled length frequencies for male and female blue cod from Motunau random-site blue cod potting surveys in 2012, 2016, and 2020.

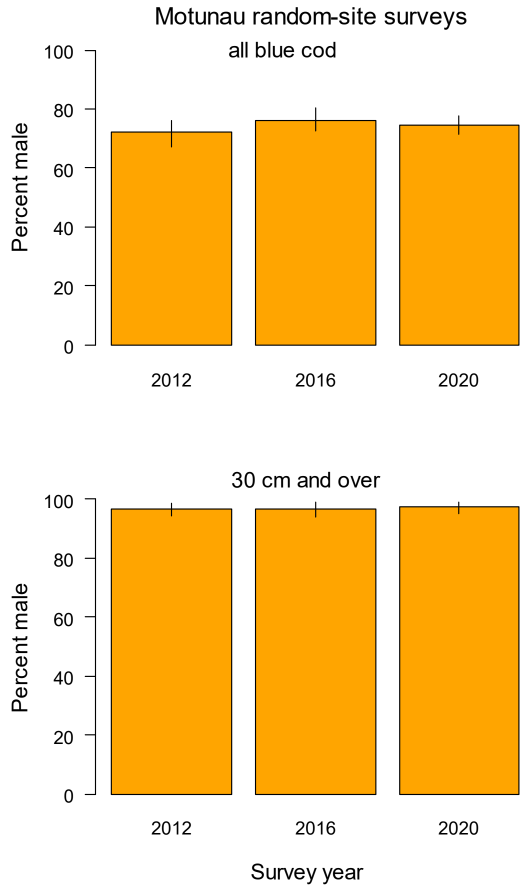

Figure 15: Sex ratio (percent male) of scaled length frequencies of all blue cod (top panel) and recruited blue cod (30 cm and over, bottom panel) for the Motunau random-site potting surveys in 2012, 2016, and 2020. Error bars are 95% confidence intervals.

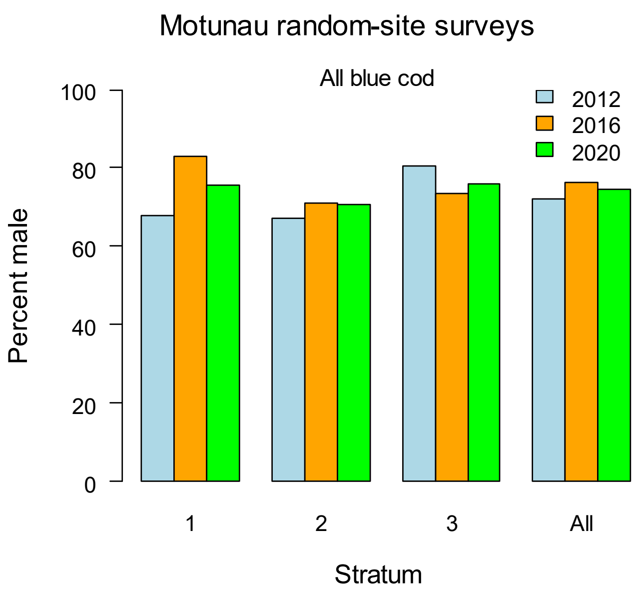

Figure 16: Sex ratio (percent male) of scaled length frequencies of all blue cod by strata for the Motunau random-site potting surveys in 2012, 2016, and 2020.

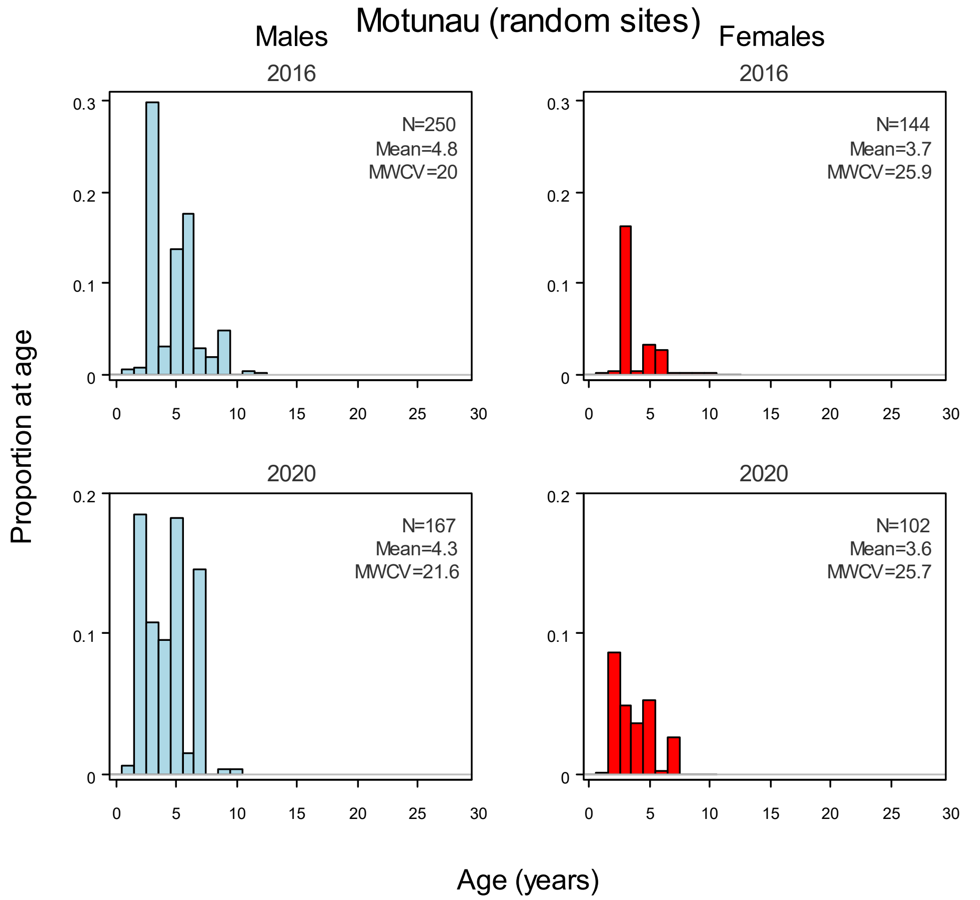

Figure 17: Scaled age frequency distributions for male and female blue cod for all strata in the 2016 and 2020 Motunau random-site blue cod potting surveys. N, sample size; no, population number; Mean, mean length (cm); MWCV, mean weighted coefficient of variation (%).

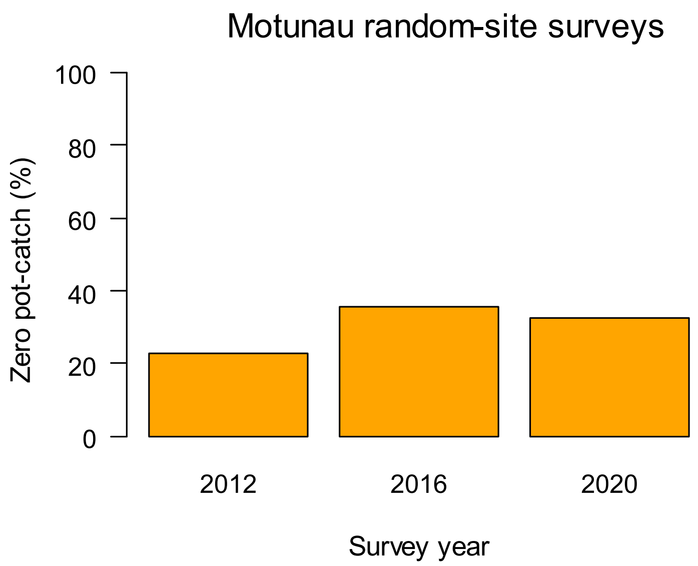

Figure 18: Proportion of pots with zero blue cod catch for the Motunau random-site potting surveys in 2012, 2016, and 2020. N= 126, 126, and 234 pots for each survey, respectively.

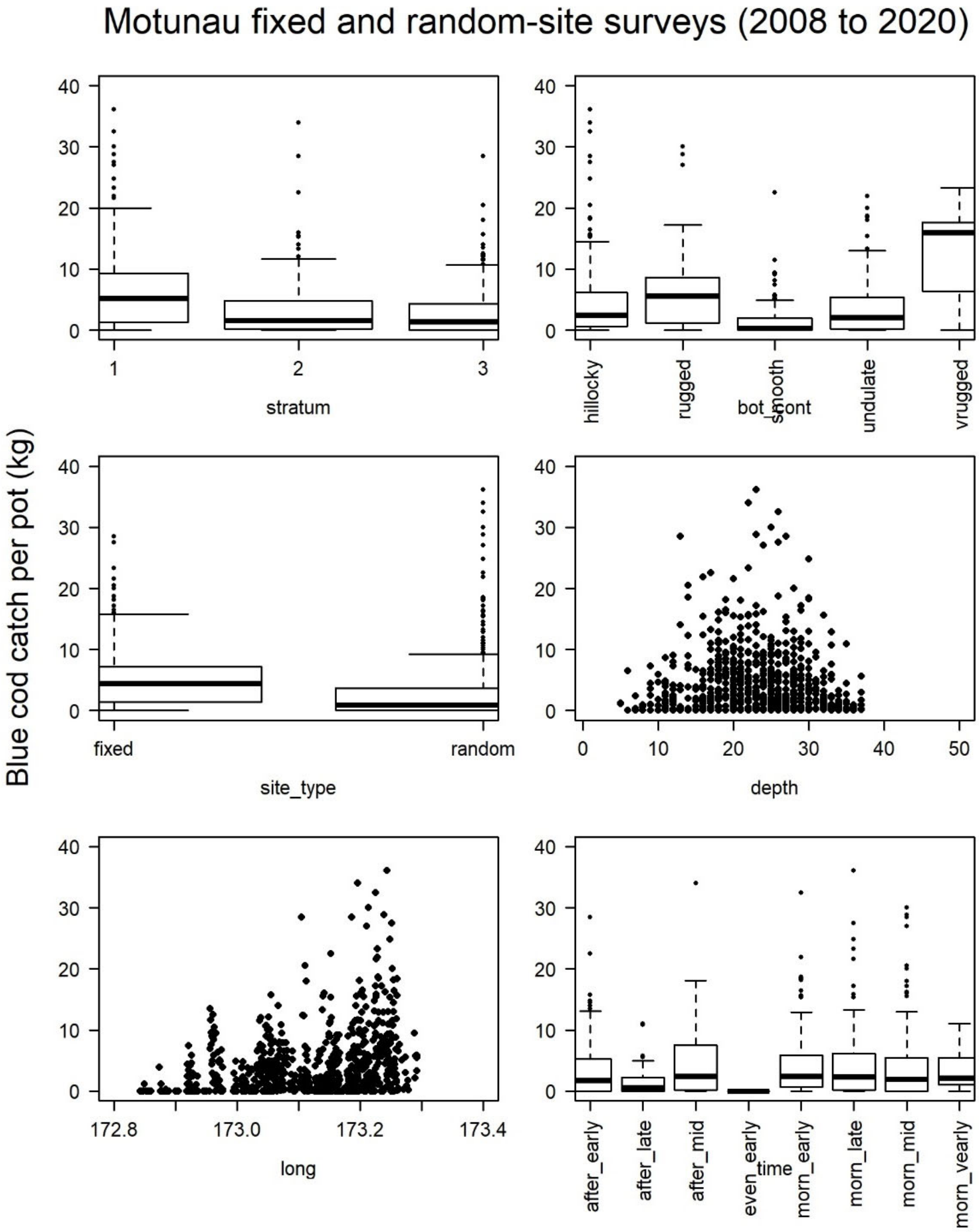

Figure 19: Blue cod catch (kg) against predictor variables in the GLM. Box (whisker plots for categorical predictor variables, and scatter plots for continuous variables). Stratum is also shown although it was not accepted by the model. Data are for the Motunau fixed-site and random-site surveys in 2008, 2012, 2016, and 2020. For box and whisper plots the dark horizontal line is the median, the top and bottom of the box are the interquartiles (25% and 75%), and error bars are 95th percentile range. The points represent outliers. **[Continued on next page]**

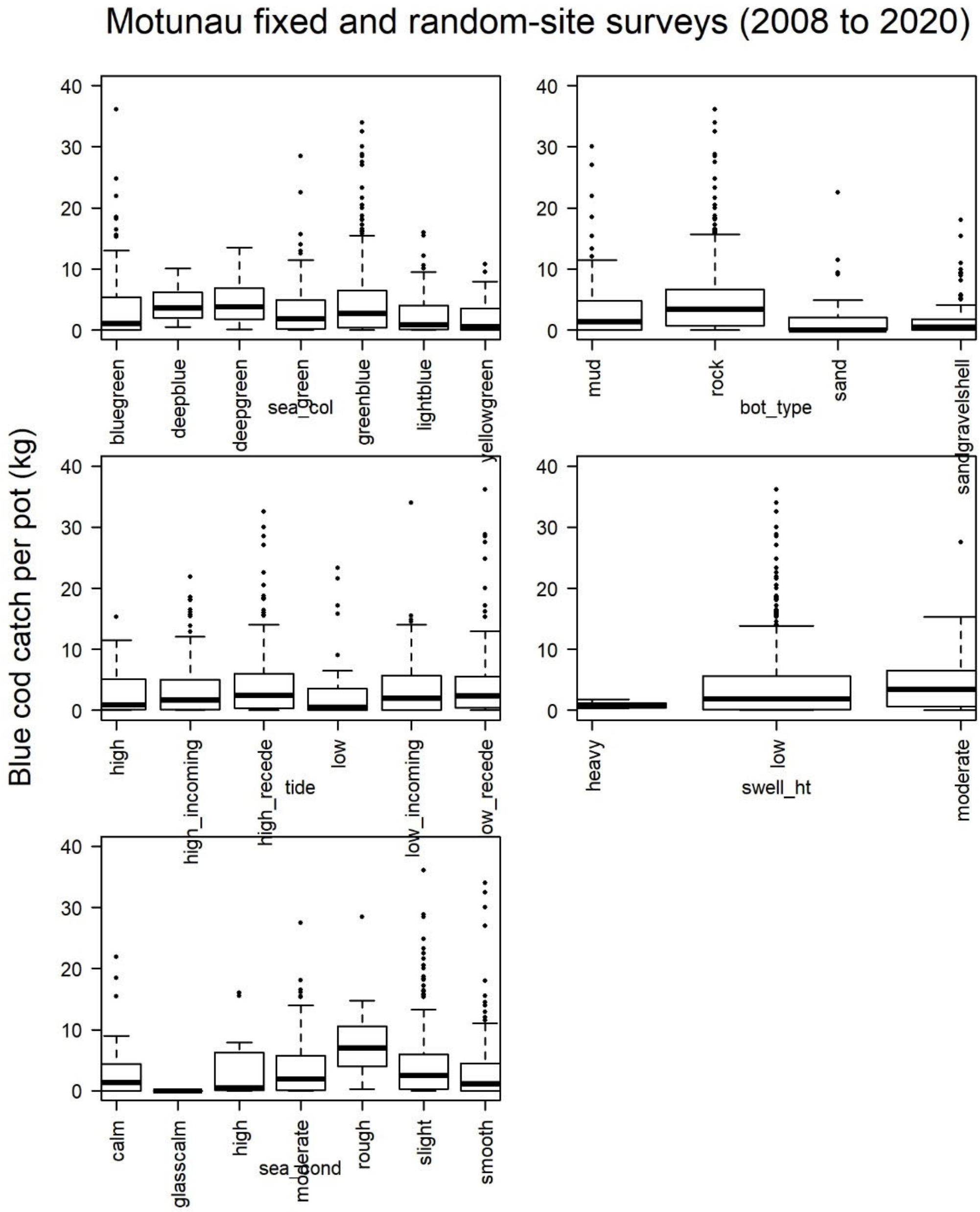

Figure 19: — *continued*.

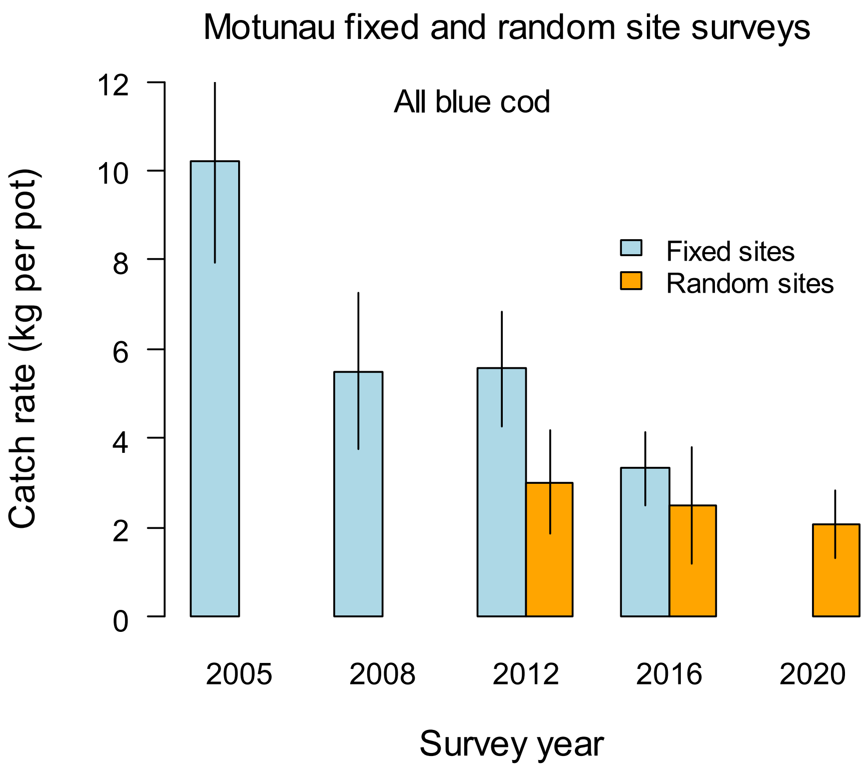

Figure 20: Catch rates (kg pot^{-1}) of all blue cod for the Motunau fixed-site potting surveys in 2005, 2008, 2012, and 2016 and random-site surveys in 2012, 2016, and 2020. Error bars are 95% confidence intervals

9. APPENDICES

Appendix 1: Blue cod potting surveys carried out for Fisheries New Zealand in nine South Island recreational fisheries. See Appendix 2 for definitions of fixed-site and random-site surveys and directed and systematic pot placement.

Survey area	Survey year	Survey design type	Pot placement	References
Marlborough Sounds	1995, 1996, 2001, 2004, 2007	Fixed-site	Directed	(Blackwell 1997, 1998, 2002, 2005, 2008)
	2010	Fixed-site and partial Random-site	Directed and systematic	(Beentjes & Carbines 2012)
	2013	Fixed-site and Random-site	Directed and systematic	(Beentjes et al. 2017)
	2017	Fixed-site and Random-site	Directed and systematic	(Beentjes et al. 2018)
Kaikōura	2004, 2007	Fixed-site	Directed	(Carbines & Beentjes 2006a, 2009)
	2011, 2015	Fixed-site and Random-site	Directed and systematic	(Carbines & Haist 2012a, Beentjes & Page 2017)
	2017	Random-site	Systematic	(Beentjes & Page 2018)
	2019	Random-site	Systematic	(Beentjes & Page 2021)
Motunau	2005, 2008	Fixed-site	Directed	(Carbines & Beentjes 2006a, 2009)
	2012, 2016	Fixed-site and Random-site	Directed and systematic	(Carbines & Haist 2012a, Beentjes & Sutton 2017)
Banks Peninsula	2002, 2005, 2008	Fixed-site	Directed	(Beentjes & Carbines 2003, 2006, 2009)
	2012	Fixed-site and Random-site	Directed and systematic	(Carbines & Haist 2017b)
	2016	Fixed-site and Random-site	Directed and systematic	(Beentjes & Fenwick 2017)
North Otago	2005, 2009	Fixed-site	Directed	(Carbines & Beentjes 2006b, 2011b)
	2013, 2018	Fixed-site and Random-site	Directed and systematic	(Carbines & Haist 2018b, Beentjes & Fenwick 2019a)
South Otago	2010	Fixed-site and Random-site	Directed and systematic	(Beentjes & Carbines 2011)
	2013, 2018	Random-site	Systematic	(Carbines & Haist 2018c, Beentjes & Fenwick 2019b)
Foveaux Strait	2010, 2014, 2018	Random-site	Systematic	(Carbines & Beentjes 2012, Carbines & Haist 2017a, Beentjes et al. 2019)
Paterson Inlet	2006	Fixed-site	Directed	(Carbines 2007)
	2010, 2014	Fixed-site and Random-site	Directed and systematic	(Carbines & Haist 2014, 2018a)
	2018	Random-site	Systematic	(Beentjes & Miller 2020)
Dusky Sound	2002, 2008	Fixed-site	Directed	(Carbines & Beentjes 2003, 2011a)
	2014	Fixed-site and Random-site	Directed and systematic	(Beentjes & Page 2016)

Appendix 2: Glossary of terms used in this report (modified from Beentjes & Francis 2011). See the potting survey standard and specifications for more details.

Fixed site	A site that has a fixed location (single latitude and longitude or the centre point location of a section of coastline) in a stratum and is available to be used repeatedly on subsequent surveys in that area. The fixed sites used in a particular survey are randomly selected from the list of all available fixed sites in each stratum. Fixed sites are sometimes referred to as index sites or fisher-defined sites and were defined at the start of the survey time series (using information from recreational and commercial fishers)
Pot number	Pots are numbered sequentially (1 to 6 or 1 to 9) in the order they are placed during a set. In the Marlborough Sounds nine pots are used.
Pot placement	There are two types of pot placement: **Directed**–the position of each pot is directed by the skipper using local knowledge and the vessel SONAR to locate a suitable area of reef/cobble or biogenic habitat. **Systematic**–the position of each pot is arranged systematically around the site or along the site for a section of coastline. For the former site, the position of the first pot is set 200 m to the north of the site location and remaining pots are set in a hexagon pattern around the site, at about 200 m from the site position.
Random site	A site that has the location (single latitude and longitude) generated randomly within a stratum, given the constraints of proximity to other selected sites for a specific survey.
Site	A geographical location near to which sampling may take place during a survey. A site may be either fixed or random (see below). A site may be specified as a latitude and longitude or a section of coastline (for the latter, use the latitude and longitude at the centre of the section).
Site label	An alphanumeric label of no more than four characters, unique within a survey time series. A site label identifies each fixed site and also specifies which stratum it lies in. Site labels are constructed by concatenating the stratum code with an alpha label (A–Z) that is unique within that stratum. Thus, sites within stratum 2 could be labelled 2A, 2B, and sites in stratum 3 could be labelled 3A, 3B etc. Site labels for random sites are constructed in the same way but prefixed with R (e.g., R4A, R4B etc).
Station	The position (latitude and longitude) at which a single pot (or other fishing gear such as ADCP) is deployed at a site during a survey, i.e., it is unique for the trip.
Station number	A number which uniquely identifies each station within a survey. The station number is formed by concatenating the set number with the pot number. Thus, pot 4 in set 23 would be *station_no* 234. This convention is important in enabling users of the *trawl* database to determine whether two pots are from the same set. Note that the set numbers for potting surveys are not recorded anywhere else in the *trawl* database.

Appendix 3: Numbers of otoliths collected during the 2020 Motunau survey for males and females, by strata and length class. Lgth, length.

Lgth (cm)	Stratum 1	2	3	Male totals	Stratum 1	2	3	Female totals
10		3		3		1		1
11		1		1		2		2
12	1	1		2		1		1
13		1	1	2		1	1	2
14					3			3
15		3	3	6	2	1	4	7
16	2	3	3	8	2	2	3	7
17	2		3	5	1	3	5	9
18	2	1	3	6		3	3	6
19	1	1	3	5	2	1	3	6
20	2	1	3	6	2	1	2	5
21	3	1	3	7	2	3	3	8
22		2	3	5	2	2	3	7
23	2	2	3	7	3		3	6
24	2	2	4	8	3		2	5
25	2	1	3	6	2	2	3	7
26	2		3	5	2	2		4
27	2	2	3	7	2		3	5
28	2	1	2	5	2	1	1	4
29	2		3	5	1	1	1	3
30	2	1	4	7	1		1	2
31	2	1	3	6			1	1
32	3		4	7				
33	2	1	3	6				
34	4	2	3	9		1		1
35	3	1	2	6				
36	3		2	5				
37	2	2	2	6				
38	2		2	4				
39	1	2	2	5				
40	1		2	3				
41	1			1				
42		1	1	2				
43			1	1				
Totals	53	37	77	167	32	28	42	102