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Relative abundance, size and age structure, and stock status of blue cod (*Parapercis colias*) off north Otago in 2022

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This report describes the results of the random-site blue cod (*Parapercis colias*) potting survey carried out off north Otago in January 2022. Estimates are provided for population relative abundance, size and age structure, sex ratio, total mortality (Z), and fishing mortality (F). This was the third survey in the north Otago random-site survey time series with previous surveys in 2013 and 2018. The results of the 2022 survey are compared with the previous random-site surveys and also the four previous fixed-site surveys (2005, 2009, 2013, and 2018). In addition, four random sites were sampled in the proposed north Otago marine reserve (Te Umu Koau, D1) that, in part, overlaps with the main survey strata. Otolith thin section ages from 353 males and 174 females were used to estimate the population age structure. The initial counts from each of the two otolith readers achieved 93% agreement, there was minimal bias between readers, with a coefficient of variation (CV) and average percent error of 1.1% and 0.8%, respectively. Von Bertalanffy growth parameters (L_∞, K, t_0) were 55.1 cm, 0.15 yr^{-1}, -0.44 yr^{-1} for males; and 45.7 cm, 0.14 yr^{-1}, and -1.22 yr^{-1} for females.

Thirty-five random sites (6 pots per site, producing 210 pot lifts) at depths of 9–51 m from six strata were sampled. The survey blue cod mean catch rate was 1.89 kg pot^{-1} (CV 22%) for all blue cod and 1.16 kg pot^{-1} (CV 22%) for recruited blue cod (33 cm and over); 53% of pots had zero catch of blue cod. The overall weighted sex ratio was 77% male. The overall weighted mean length was 30.7 cm (range 15–55 cm) for males and 26.4 cm (range 16–45 cm) for females. Mean age was 5.4 years (1–30 years) for males and 5.8 years for females (2–20 years). The estimated population age distributions had strong modes at four, seven, and nine years for both sexes, but particularly for males, and weak modes for six- and eight-year-olds. There were indications of spawning activity during the survey period with about 3% of males and 9% of females maturing or running ripe; 30% of males were spent, suggesting that spawning had peaked prior to the survey.

Estimated total mortality (Z) for males for age-at-full recruitment of 7 years was 0.72 (95% confidence interval 0.50–0.98). Based on the default natural mortality (M) of 0.17, male F was 0.55 (95% confidence intervals 0.33–0.81), nearly four times higher than the target reference point of F=0.87M (F=0.15), indicating that the north Otago stock is overfished.

Survey abundance (total blue cod mean catch rate) declined by 49% between the 2013 and 2018 random-site surveys; this was statistically significant (t-test, $p < 0.01$). This was followed by a further 13% decline in abundance in 2022, which was not significant (t-test, $p > 0.05$). The length frequency distributions were generally similar among the three surveys, with any differences resulting from the relative numbers of the pre-recruited fish. Mean recruited length was higher in 2022 for both sexes although there was no trend across the random-site surveys. The proportion of pots with zero catch showed a progressive and steep increase from 35% in 2013 to 43% in 2018 to 54% in 2022. The sex ratio of blue cod from random sites showed a large increase from 68% male in 2013, to 75% in 2018, with little change in 2022, when it was 76% male. The age distributions display clear evidence of highly variable recruitment, with intermittent strong and weak year classes progressing through the fishery from 2018 to 2022.

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1. INTRODUCTION

This report describes the random-site potting survey of blue cod (*Parapercis colias*) relative abundance, population length/age structure, and stock status off north Otago in January 2022. This is the third random-site survey in the time series, with previous surveys in 2013 and 2018. Fixed-site surveys were carried out previously in 2005, 2009, and concurrently with the 2013 and 2018 random-site surveys (Carbines & Beentjes 2006b, 2011b, Carbines & Haist 2018b, Beentjes & Fenwick 2019a). The report also presents time series comparisons of these indices.

1.1 North Otago blue cod fishery

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 national panel survey involving face to face interviews with fishers (Wynne-Jones et al. 2019). Blue cod can be caught in a few metres to about 150 m depth, in a diverse range of habitats, including reef edges, shingle/gravel, biogenic reefs, or sandy bottoms close to rocky outcrops. The BCO 3 Quota Management Area (QMA) extends from the Clarence River, north of Kaikōura, to Slope Point in Southland (Figure 1). In BCO 3, recreational annual take was estimated at 98 t (Wynne-Jones et al. 2019), the highest of any QMA (33% of total national recreational blue cod catch). There are no reliable data to determine how the recreational blue cod catch was distributed within BCO 3; however, north Otago is becoming increasingly popular with recreational fishers as it offers relatively high catches and a bag limit of 10 blue cod compared with only two off the Canterbury area.

The area from Rakaia River to Taiaroa Heads (out to 12 nautical miles) is known as the 'North Otago Area' and on 1 July 2020, was assigned a 'traffic light' colour of orange by Fisheries New Zealand, as part of the National Blue Cod Management Plan. This indicates that the fishing pressure on blue cod stocks in this area is considered to be less sustainable than in the green areas, such as Southern and the Westland, but more sustainable than those in the red areas of Tasman and Canterbury. Orange areas have a daily bag limit of 10 blue cod and all South Island areas have a minimum legal size (MLS) of 33 cm.

The mean commercial catch from BCO 3 over the last 10 fishing years up to 2020–21 was 172 t, 76% higher than the most recent estimated annual recreational catch of 98 t (Wynne-Jones et al. 2019, Fisheries New Zealand 2022). About three-quarters of all commercially landed blue cod in BCO 3 is caught by potting, and 20% is caught by bottom trawling. The bulk of the potting catch was from north Otago (Statistical Area 024), with much smaller amounts from south Otago (Statistical Area 026) and, until the late 1990s, from Kaikōura Statistical Area 018 (Figure 1) (Holmes et al. 2022). Electronic reporting system (ERS) data show that blue cod off north Otago are caught offshore by commercial fishers from about 30 to 50 m depth in discrete areas (pers. comm., Tony Brett, Fisheries New Zealand), presumably associated with optimal blue cod habitat.

1.2 North Otago bathymetry and substrate

In north Otago, the two key recreational fishing areas for blue cod and many other species are Oamaru and Moeraki, which are about 30 km apart and provide access from boat ramps (Figure 2). North Otago has substantial blue cod habitat, such as biogenic reefs, both inshore and offshore, across a relatively flat sloping shelf. The survey area lies on the inner continental shelf, which slopes gently away to the east, terminating in the continental slope. The slope is characterised by a series of canyons forming part of Otago Canyon Complex extending from Oamaru to the Otago Peninsula (Figure 2). The sediments off north Otago have considerable areas of predominantly rock and gravel inshore, and sand and gravel offshore, providing ideal blue cod habitat (data from Bostock et al. 2019) (Figure 3).

1.3 Blue cod potting surveys

South Island recreational blue cod fisheries are monitored by Fisheries New Zealand using potting surveys. These surveys take place in the most important blue cod recreational fisheries, although there is substantial overlap between the commercial and recreational fishing grounds for some surveys, i.e., Foveaux Strait, north and south Otago. Surveys are generally carried out every four years to monitor local relative abundance, size, age, and sex structure of geographically separate blue cod populations supporting important recreational fisheries. 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 north Otago, there are currently eight other key recreational South Island fisheries surveyed: Marlborough Sounds, Kaikōura, Motunau, Banks Peninsula, south Otago, Paterson Inlet, Foveaux Strait, and Dusky Sound (see Appendix 1 for survey details and references).

All South Island potting surveys (except Foveaux Strait and south Otago) originally used a solely fixed-site design (Appendix 2, glossary of terms), with predetermined (fixed) locations randomly selected from a limited pool of such sites (Beentjes & Francis 2011, Beentjes 2019). Fixed sites represent 'good' fishing spots or locations where blue cod were known to be abundant. 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 (Beentjes & Francis 2011, Beentjes 2019). Following this recommendation, surveys transitioned to a fully random-site design with interim sampling of both fixed and random sites allowing comparison of catch rates, length and age composition, and sex ratios between the two survey designs. Random sites were used as the only site type in Foveaux Strait, and all other surveys including north Otago have now transitioned to the fully random survey design, with the exception of Dusky Sound.

Previous north Otago surveys were carried out in 2005, 2009, 2013, and 2018 (Carbines & Beentjes 2006b, 2011b, Carbines & Haist 2018b, Beentjes & Fenwick 2019a). The first two surveys used only fixed sites, whereas the 2013 and the 2018 surveys included concurrent fixed- and random-site surveys. The 2022 survey was the first solely random-site survey carried out in north Otago and this survey time series has now fully transitioned to the random-site design (Table 1).

1.4 Stock status of north Otago blue cod

Tagging experiments indicate that blue cod have a restricted home range (Rapson 1956, Mace & Johnston 1983, Mutch 1983, Carbines & McKenzie 2001, Carbines & McKenzie 2004) and that stocks of this species are likely to consist of many largely independent sub-populations within Fisheries Management Areas (FMA) (Carbines 2004). This suggests that blue cod are susceptible to localised and serial depletion within an FMA. However, blue cod are not genetically distinct around the New Zealand mainland (Gebbie 2014), indicating that some genetic mixing is occurring on a wider geographical scale than within the restricted home range indicated by tagging studies.

Monitoring the sex ratio of these cod populations is particularly important because blue cod are protogynous hermaphrodites with some (but not all) females changing into males as they grow, and the largest fish in the populations are invariably males (Carbines 2004). In heavily fished blue cod populations, sex ratios skewed towards males are often observed (Beentjes & Carbines 2009, Beentjes 2021, Beentjes & Miller 2021, Beentjes et al. 2022a). This is thought to result from the removal of the inhibitory effect of large males and a consequent higher rate (and possibly earlier onset) of sex change by primary females (Beentjes & Carbines 2005, Beentjes 2021).

The standard method of assessing the stock status of blue cod in north Otago by Fisheries New Zealand was to estimate fishing mortality (F) and the associated spawner-biomass-per-recruit ratio (SPR), which was used as a proxy for B_{MSY} (maximum sustainable yield biomass) (Beentjes et al. 2018, Fisheries New Zealand 2022). Spawner-biomass-per-recruit is defined as the expected lifetime contribution to the spawning biomass for the average recruit to a fishery. The recommended Harvest Strategy Standard maximum sustainable yield 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 (the total weight of sexually mature fish in the stock) to 45% of that if there was no fishing.

However, the Fisheries New Zealand Stock Assessment Plenary meeting on 18 July 2022 agreed that the standard *SPR* is not appropriate as a target reference point for blue cod in Marlborough Sounds because few females currently grow large enough to recruit to the fishery, and the standard spawner-per-recruit approach does not model blue cod sex change dynamics (Beentjes et al. 2022b). The Plenary also recommended F=0.87M (natural mortality) as an alternative B_{MSY} proxy target reference point or overfishing threshold for Marlborough Sounds blue cod based on the study of Zhou et al. (2012), where Z (total mortality) and F are estimated from the male-only age composition in the population. In both cases, the age at full recruitment was taken as the male average age at minimum legal size plus one year to ensure that more than 50% of males are recruited to the fishery.

Following the presentation of the 2022 north Otago survey results to the Inshore Finfish Working Group (8 December 2022), and based on the same rationale as for Marlborough Sounds, the working group agreed that *SPR* is not appropriate as a target reference point for north Otago blue cod. Hence *SPR* analyses for the 2022 north Otago survey are not presented in this report; F of males was, instead, compared with the target reference point of F=0.87M.

1.5 Objectives

This is the final reporting requirement for Fisheries New Zealand research project BCO2021-03.

Overall Objective

To estimate relative abundance, maturity state, sex ratio, and age structure of blue cod (*Parapercis colias*) between Oamaru and Shag Point.

Specific objectives

1. To undertake a potting survey between Oamaru and Cornish Head (BCO 3) to estimate relative abundance, age structure, size- and age-at-maturity, and sex ratio, and collect otoliths from pre-recruited and recruited blue cod.
2. To analyse biological samples collected from the potting survey.
3. To determine stock status of blue cod populations in this area and compare to other surveys.

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

2. METHODS

2.1 Timing and survey area

A potting survey off north Otago was carried out by the National Institute of Water & Atmospheric Research Ltd (NIWA) from 6 to 23 January 2022, the timing of which was consistent with previous surveys.

The original 2005 survey area was defined after discussions with local fishers, Fisheries New Zealand (previously Ministry of Fisheries), and the South Recreational Advisory Committee (Carbines & Beentjes 2006b). Fishers were given charts of the area and asked to mark discrete locations around north Otago where blue cod were commonly caught. The survey area was divided arbitrarily into three inshore (strata 1, 2, and 4) and two offshore strata (strata 3 and 5) between Oamaru and Bobby’s Head (Figure 2). The outer boundaries of the inshore and offshore strata were defined approximately by the 30 m and 50 m depth contours, respectively. In subsequent surveys, including the 2022 survey, the same five strata were surveyed as well as an additional inshore stratum to the south (Stratum 6, Bobby’s Head to Cornish Head) (Figure 2). Each stratum was assumed to contain roughly random distributions of blue cod habitat and the total area (in square kilometres) within each stratum was taken as a proxy for available habitat for blue cod. Strata were defined before seabed substrate sediment maps were available (Figure 3).

While the survey was in progress, Department of Conservation requested that the proposed north Otago marine reserve (Te Umu Koau, D1) be included in 2022 survey, with the aim of providing data on blue cod population status, before and after the marine reserve introduction (Figure 2). The marine reserve polygon overlaps parts of existing strata 4, 5, and 6. Fisheries New Zealand agreed to the request and provided additional resources for this work.

Hereafter, the proposed marine reserve is referred to as the marine reserve (MR).

2.2 Survey design

2.2.1 Allocation of random sites

Simulations using NIWA's Optimal Station Allocation Program (*allocate*, Francis 2006) were carried out using catch rates from the 2018 random-site survey to determine the optimal allocation of sites among the 6 strata. 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 informed the allocation within strata and indicated that about 35 random sites were required to achieve a CV of 15%.

The 2022 random-site survey used a two-phase stratified random station design (Francis 1984) with 31 sites allocated to phase 1 and the remaining four available for phase 2, consistent with the proportion of phase 2 sites used in 2013 and 2018 (Table 2).

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 was greatest, where expected gain is given by:

$$expected\ gain_i = area_i^{\ 2}\ mean_i^{\ 2} / (n_i(n_i+1))$$

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.

A random site has a location (single latitude and longitude) generated randomly within a stratum (Beentjes & Francis 2011, 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 & Francis 2011, Beentjes 2019). The 2022 random-site surveys in north Otago used systematic pot placement, 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.

Marine reserve sites

Four additional sites were generated randomly within the MR polygon, of which, by chance, three were outside the main survey strata and one was marginally inside the seaward boundary of stratum 4. There was no phase 2 component to the MR survey. There were four main survey sites that by chance, fell within the MR polygon, and these were included in the data set for the MR analyses, bringing the total to eight sites. Conversely, MR sites were not included in the main survey analyses data set.

2.2.2 Vessels and gear

The 2022 survey was carried out using the Wellington-based NIWA inshore research vessel *Ikatere.* The R.V. *Ikatere* is an aluminium-alloy catamaran with a length of 13.9 m, beam of 4.85 m, equipped with 322 Hamilton water-jet units, and powered by twin Cummins QSC engines rated at 500 HP, capable of

25 knots cruising speed. The *Ikatere* was skippered by Richard Leppard. This is the first time this vessel has been used for the north Otago survey (Table 1).

Six custom designed and built cod pots were used to conduct the survey (Pot Plan 2 given by Beentjes 2019). Pots were baited with 700 g of pāua viscera in 'snifter pottles' and replaced after every lift. The same pot design and bait were used in all previous north Otago blue cod potting 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.

2.2.3 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 order that strata were surveyed depended on the prevailing weather conditions, with the most distant or offshore strata and/or sites sampled in calm weather. 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. After 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 millimetre, 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, three otoliths per 1 cm size class for each sex were targeted in strata 1, 2, and 3 combined, and the same for strata 4, 5, and 6 combined (Appendix 3). In addition, to ensure that adequate numbers of large and small fish and females were included, otoliths were collected from all blue cod under 18 cm, all males over 46 cm, and all females over 37 cm.

Sex and maturity of blue cod 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 (SM) 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.

2.2.4 Data storage

The 2022 north Otago survey trip code was IKA2201. At the completion of the survey, trip, station, catch, and biological data were entered into the *trawl* database in accordance with the business rules and the blue cod potting survey standards and specifications (Beentjes 2019). All catch rate, and length and sex-based analyses were from data extracted from the *trawl* database. Catch-at-age analyses were based on the ageing results provided by the otolith readers and, at the completion of the catch-at-age analyses, after any possible errors in the age and length data were identified and corrected, age data were entered into the *age* database. Random sites were entered into attribute *stn_code*, prefixed with R (e.g., R1A, R2B).

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, or 31 to 36, etc.). In the *age* database the *sample_no* is equivalent to *station_no* in the *trawl* database.

ADCP data were sent to the Research Database Manager in spreadsheet format.

2.2.5 Age estimates

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 °C. 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 °C.
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.

2.2.6 Data analyses

Analyses of catch rates, sex ratios, scaled length distribution, catch-at-age, and Z and *F* estimates (males only), were carried out and are presented for the 2022 random-site survey.

Analyses of catch rates and coefficients of variation (CV), 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 and age distribution and mean length (i.e., using data extracted from t_lgth in the *trawl* database).

Unless otherwise specified, the methods below refer to analyses using data collected from the 35 sites within the main survey strata.

2.2.6.1 Catch rates

The catch rate (kg pot^{-1}) estimates were pot-based and the CV estimates were set-based (Beentjes & Francis 2011). Catch rates and 95% confidence intervals (± 1.96 standard error) were estimated for all blue cod and for recruited blue cod (33 cm and over). Catch rates of recruited blue cod were based on the sum of the weights of individual recruited fish, which on the 2022 survey, were all weighed. The stratum areas (km^2) shown in Table 2 were used as the area of the stratum (A_t) when scaling catch rates (equations 3 and 5 of Beentjes & Francis 2011). Catch rates are presented by stratum and overall. Catch rates were estimated for individual strata and for all strata combined.

2.2.6.2 Length-weight parameters

The length-weight parameters a_k, b_k from the 2022 north Otago random-site survey 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. The following equation:

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

calculates the expected weight (g) for a fish of sex k and length l (cm) in the survey catch.

2.2.6.3 Growth parameters

Separate von Bertalanffy growth models (von Bertalanffy 1938) were fitted to the 2022 north Otago survey length-age data by sex 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.

2.2.6.4 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 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 areas are given in Table 2, and the sex-specific length-weight parameter estimates were from the 2022 north Otago survey data.

Length and age frequencies were calculated as numbers of fish from equations 7, 8, and 9 of Beentjes (2019). The length and age frequencies in this report are expressed as proportions by dividing by total numbers.

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

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

2.2.6.5 Sex ratios, mean length, and mean age

Sex ratios (expressed as percentage male) and mean lengths were calculated for the stratum and survey using equations 10 and 11 of Beentjes (2019) from the stratum or survey scaled length frequencies. Mean ages were calculated analogously from the scaled age frequencies. Sex ratios were also estimated for recruited blue cod (33 cm and over), and overall survey 95% confidence intervals around sex ratios were generated from the 300 length frequency bootstraps.

2.2.6.6 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 years 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 using only male ages, and a Z estimate was output for males only. Fishing mortality was estimated from the results of the Chapman-Robson analyses and the current default estimate of M (i.e., $F = Z–M$), assumed to be 0.17, revised from 0.14 in 2019 (Doonan 2020). Sensitivity analyses of F were carried out for M values 20% above and below the default (0.14 and 0.20).

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 investigate how well Z is being estimated. This is particularly important when there are not many age classes, and there is potential for strong or weak year classes to introduce bias.

2.2.6.7 Condition factor

Fulton's condition factor (K) (Nash et al. 2006) was estimated for blue cod as follows:

$$K = 100w/l^3$$

where l is the total length (centimetres) and w is the fish weight (grams).

2.2.6.8 Analyses of marine reserve survey

With the exception of the total mortality, the same analyses as described above were carried out for the MR, using the catch and length frequency data for the four dedicated MR sites, plus the four main survey sites that fell within the MR polygon (i.e., sites R4H, R6A, R6B, and R6C). In addition, the MR analyses used the length-weight coefficients and growth parameters from the main survey. Although 57 otoliths were collected from the 67 blue cod caught in the four dedicated MR sites, these were not aged, and ages from the main survey were applied to length data for the eight sites inside the MR to estimate catch-at-age and total mortality.

2.2.6.9 Analyses of previous north Otago surveys

For previous north Otago surveys in 2005, 2009, 2013, and 2018, catch rates, scaled length composition, and sex ratios were analysed previously using the analytical methods in the potting manual (Beentjes 2019), described above, to ensure comparability with earlier analyses and/or research providers. During the 2022 survey analyses, previous survey catch rates were re-estimated for recruited fish 33 cm and over, the MLS since July 2020 (previously 30 cm).

No ageing analyses of the 2005, 2009, or 2013 surveys were carried out because, although blue cod otoliths were collected and aged from these surveys, the ageing interpretation was not compliant with the

ADP for blue cod and therefore assigned ages may not be accurate and/or consistent with those from the 2018 and 2022 surveys.

To allow valid comparison of Z and F estimates between 2018 and 2022 random-site surveys, both carried out on age compositions determined using the age-determination protocol, the 2018 random-site survey analyses were updated as follows: Z and F were estimated for males only, with male age-at-full recruitment equivalent to age at the 2018 MLS (30 cm) plus one year, and using the default M value of 0.17 (previously 0.14).

3. RESULTS

3.1 2022 random-site survey

3.1.1 Sites surveyed and catch

Thirty-five random sites (6 pots per site, producing 210 pot lifts) from six strata off north Otago were surveyed in January 2022 (Table 2, Figure 4). Depths sampled were 9–51 m (mean = 27.5 m). Thirty-one sites were sampled in phase 1 and four in phase 2. An example of the systematic pot placement configuration for random sites is shown in Figure 5.

A total of 505.9 kg of blue cod (1048 fish) was taken, comprising 90.2% by weight of the catch of all species on the survey (Table 3A). Bycatch species included six teleost fishes, as well as octopus, brittle star, and starfish. The most abundant teleost bycatch species, by number, were leatherjacket (*Meuschenia scaber*), tarakihi (*Nemadactylus macropterus*), banded wrasse (*Notolabrus fucicola*), and scarlet wrasse (*Pseudolabrus miles*) (Table 3A).

3.1.2 Blue cod catch rates, length, and sex ratio

Mean catch rates (kg pot^{-1}) of blue cod (all blue cod, and 33 cm and over) are presented by stratum and overall for the 2022 random-site survey (Table 4, Figure 6). Mean catch rates of blue cod (all sizes) by stratum were 0.06–3.5 kg pot^{-1} with the lowest in stratum 2 (inshore south of Oamaru) and the highest in stratum 4 (inshore between Moeraki and Bobby’s Head) (Table 4, Figure 6). The all-blue-cod survey catch rate was 1.89 kg pot^{-1} with a CV of 22.0%. Catch rates for recruited blue cod (33 cm and over) generally followed the same pattern among strata as for all blue cod and overall the catch rate was 1.16 kg pot^{-1} (CV 22.1%) (Table 4, Figure 6). Of the 210 random-site pots, 113 (53%) had zero catch of blue cod. The catch rates (kg site^{-1}) of blue cod are also presented by site for the 2022 random-site survey and show that the largest catch was in stratum 4 (Figure 7).

All 1048 blue cod caught on the survey were measured for length and weighed, and all but 10 small fish (under 16 cm) were sexed (Table 5). The sex ratios were 66–85% male across the six strata and the overall weighted sex ratio was 77% male (Table 5). Length range was 15–55 cm for males and 16–45 cm for females. Weighted mean length was 30.7 cm for males and 26.3 cm for females, and, although the scaled length frequency distributions varied among the strata, males and females tended to show similar shapes within strata (Figure 8). There was only one blue cod caught in stratum 2 (inshore off Oamaru), and males were dominant in all strata.

3.1.3 Age and growth

Otolith thin-section ages from 353 males and 174 females collected from the 2022 random-site survey were used to estimate the population age structure from north Otago in 2022 (Table 6). 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 9). There is a large range in length-at-age, particularly for males, which grow faster than females. Most of the fish over 10 years of age are female, although the oldest two fish were males (27 and 30 years of age).

The 2022 north Otago survey von Bertalanffy growth parameters (L_∞, K, t_0) were 55.1 cm, 0.15 yr^{-1}, - 0.44 yr^{-1} for males; and 45.7 cm, 0.14 yr^{-1}, and -1.22 yr^{-1} for females. The von Bertalanffy curves for 2018 and 2022 were similar, although both sexes attained a greater asymptotic length in 2022 (Figure 10).
Between-reader comparisons are presented in Figure 11. The first counts of the two readers showed 93% agreement, with a CV of 1.13% and average percent error (IAPE) of 0.8%.

The length-weight parameters from the 2022 north Otago survey were a = 0.006787 and b = 3.2370 (N = 794, range = 15–55 cm) for males; and a = 0.006463 and b = 3.2523 (N = 242, range = 16–45 cm) for females.

3.1.4 Spawning activity

Gonad stages of blue cod from random sites sampled in the January 2022 north Otago survey are presented for all fish combined (Table 7). There were some indications of spawning activity during the survey period with about 3% of males and 9% of females maturing or running ripe. Thirty percent of males were spent, suggesting that spawning may have peaked prior to the survey. The majority of fish were immature or resting (stage 1).

3.1.5 Population length and age composition

The scaled length frequency and age distributions for the 2022 north Otago random-site survey are shown for all strata combined, as histograms and as cumulative frequency line plots for males, females, and both sexes combined (Figure 12). The scaled length frequency distribution for males was unimodal, slightly skewed to the right, with a strong peak at about 27 cm and an overall mean length of 30.8 cm (Figure 12). The female distribution showed a strong mode with a peak at about 25 cm and a smaller mode with a peak at about 41 cm, and an overall mean length of 26.4 cm (Figure 12). The cumulative distribution plots of length frequency were similar in shape between sexes, but the female plot was steeper and to the left, reflecting the smaller size overall, with few fish over 35 cm length. The mean weighted coefficients of variation (MWCVs) around the length distributions were 31% for males and 46% for females.

Age estimates of blue cod were 1–30 years for males and 2–20 years for females, but most males and females were 3–9 years old (Figure 12). The estimated population age distributions indicated almost knife-edge selectivity to the potting method at three years with strong modes at four, seven, and nine years for both sexes, but particularly for males. The age distributions also exhibited weak modes for six- and eight-year-olds. The cumulative distribution plots of age frequency are almost identical for males and females and the mean ages were similar (males 5.4 years, females 5.3 years) (Figure 12Figure 12). The MWCVs around the age distributions were 18% for males and 30% for females, indicating a good representation of the overall male population age structure, but less so for females.

3.1.6 Total mortality estimates (*Z* and *F*)

Chapman-Robson total male mortality estimates (Z) and 95% confidence intervals for the 2022 random-site survey are given for a range of recruitment ages (5–10 y) in Table 8. Age at full recruitment (*AgeR*), was assumed to be equal to the average age at which males reached the MLS of 33 cm, plus one year (i.e., 7 years of age) (see growth curve in Figure 9). The male CR Z for *AgeR* of seven years for north Otago in 2022 was 0.72 yr^{-1} (95% confidence interval of 0.50–0.98) (Table 8).

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 of seven years, is shown for diagnostic purposes (Figure 13). The natural log of numbers-at-age did not display the traditional shape characterised by smooth ascending and descending limbs, but had an intermediate domed portion, suggesting that the assumption of constant recruitment had been sufficiently violated to detract from the results to some degree (Figure 13). Although the CR estimation is less sensitive to age classes with few fish, very strong and weak recruited year classes will have introduced some error (and probably bias) into the Z estimate, which was reflected in the wide 95% confidence intervals around Z (Table 8).

Male mortality parameters (CR *Z* and *F*) at three values of *M*, and age at full recruitment of seven years are shown in Table 9. Based on the default *M* of 0.17, male estimated fishing mortality (*F*) was 0.55 (95% confidence intervals 0.33–0.81).

3.1.7 Condition factor

Fulton's median condition factor (*K*) for the 2022 north Otago survey by strata is presented as a boxplot (Figure 14). There was some variation among strata, with median condition highest in strata 4 and 5 between Shag Point and Moeraki. The mean condition factor for 2022 was 1.52 (standard error 0.005), similar to 2018, but lower than the mean for three previous surveys (Figure 15).

3.1.8 North Otago random-site survey time series (2013, 2018, and 2022)

Survey abundance (=all blue cod mean catch rate) declined by 49% between 2013 and 2018, with no overlap in the confidence intervals; this was statistically significant (t-test, $p < 0.01$) (Figure 16 and Figure 17). This was followed by a 13% decline in abundance in 2022, which was not statistically significant (t-test, $p > 0.05$) from the 2018 value. These declines were mirrored in all strata except stratum 3 (Figure 16).

The length frequency distributions were similar for the three years, with the main differences occurring in the relative numbers of the pre-recruited fish (Figure 18). Mean recruited length was higher in 2022 for both sexes, although there was no trend in mean recruited length across the fixed- and random-site surveys (Figure 19).

The proportion of pots with zero catch from random sites shows a progressive and steep increase from 35% in 2013, to 43% 2018, and to 54 % in 2022 (Figure 20).

The sex ratio of all-blue cod from random sites shows a large increase from 68% male in 2013, to 75% in 2018, with little change in 2022, when it was 76% male (Figure 21).

3.1.9 North Otago fixed-site survey time series (2005, 2009, 2013, and 2018)

The results of the fixed-site surveys (2005, 2009, 2013, and 2018) are summarised in Appendix 4.

3.2 2022 marine reserve random-site survey

An analysis of the results of the survey within the proposed marine reserve is presented here with a view to comparing this with future surveys in this stratum if this becomes legislated as a marine reserve.

Four dedicated sites (4 pots per site, producing 24 pot lifts) were sampled in the marine reserve with no phase 2 sites allocated Table 2, Figure 4). Depths sampled were 32–40 m (mean = 37 m). A total of 32.5 kg of blue cod were caught from these four sites (Table 3B).

The following results include the data from these four dedicated sites, plus the four sites from the main survey, that, by chance, were also within the MR stratum (see Figure 4). A total of 98.8 kg of blue cod (256 fish) was taken, comprising 88.1% by weight of the catch of all species in the MR (Table 3C). Bycatch species included two teleost fishes (leather jacket and scarlet wrasse), as well as octopus.

The mean catch rates in the MR stratum were 2.06 kg pot^{-1} (CV of 31.2%) and 1.0 kg pot^{-1} (CV 30.7%) for all blue cod (all sizes) and recruited blue cod (33 cm and over), respectively (Table 4). Of the 48 random-site pots, 21 (44%) had zero catch of blue cod.

All 256 blue cod caught in the MR were measured for length, weighed, and sexed (Table 5). The sex ratio was 74% male (Table 5). Mean length was 28.6 cm (15–44 cm) for males and 24.3 cm (18–41 cm) for females. Mean age was 4.8 years (1–10 years) for males and 4.4 years (2–16 years) or females. The scaled length frequency and age distributions were similar to those for the main survey area (Figure 22).

4. DISCUSSION

4.1 General

The 2022 north Otago potting survey was the third random-site survey in the time series of relative abundance and population structure of blue cod from this area, after previous surveys in 2013 and 2018, and was the first exclusively random-site survey. The first two random-site surveys were carried out concurrently with fixed-site surveys and, before this, the 2005 and 2009 surveys were exclusively fixed-site designs. Differences in catch-rate trends for equivalent strata between the 2013 and 2018 fixed and random surveys suggest that there is no suitable way of quantitatively linking the fixed-site series with the random-site series. Accordingly, the random-site surveys provide a separate time series that will become more informative with each successive survey. The four fixed-site surveys have nevertheless indexed the marked decline in abundance that occurred after 2009, also reflected in the progressive increase in the proportion of empty pots over time (see Figure 17 and Figure 20).

Although length and age structures, and sex ratios were similar between the overlapping north Otago fixed- and random-site surveys in 2013 and 2018, the differences in these survey designs are shown in the generally lower abundance indices and the higher proportion of empty pots for random sites (see Figure 18 and Figure 21). Although size distributions can sometimes vary, catch rates tend to be higher in fixed- than random-site surveys throughout the South Island waters, such as in Marlborough Sounds and off Kaikōura, Motunau, Banks Peninsula, and south Otago (Beentjes & Fenwick 2017, Beentjes & Sutton 2017, Beentjes & Page 2018, Beentjes et al. 2018, Beentjes & Fenwick 2019b). The likely reason for this is that fixed sites were selected as locations where blue cod were known to be abundant, whereas random sites can fall anywhere within a stratum, including on marginal habitat.

4.2 Blue cod habitat

Sediment sampling stations (*n* = 30 000) collected predominantly on the New Zealand continental shelf have been used to build sediment distribution maps that are now freely available online in the New Zealand Oceanographic Data Network (see Figure 3) (Bostock et al. 2019). The sediment maps of north Otago show how sand, mud, and rock are distributed within the six north Otago strata and may be useful for re-stratifying future surveys, with the caveat that these represent extrapolations from a limited number of sampling grabs. The north Otago coastline and inner shelf occupied by the strata are characterised by rock inshore, transitioning into gravel, and then sand outside 30 m (see Figure 3). There is little mud, with the exception of a small patch in stratum 6. Highest catch rates were in stratum 4, which is dominated by rock and gravel, followed by strata 5 and 3, which are dominated by sand (see Figure 6 and Figure 7). A multivariate analysis may determine if sediment type is related to catch rates, but this could be limited by the paucity of sediment sampling sites used to build the sediment distribution maps in this area. High-resolution multibeam seabed surveys were carried out by the Department of Conservation off north Otago in 2020 and these surveys could potentially be used to provide quantitative data on seabed structure for this purpose. The north Otago survey abundance estimates, length and age distributions, and sex ratio were weighted (scaled) by the area of each stratum. Scaling by stratum area assumes that the size of each stratum is directly proportional to the amount of blue cod habitat, although it is likely that some strata (and parts thereof) will have higher proportions of habitat suited to blue cod than others.

4.3 Survey precision

The survey CV around relative abundance (catch rates) was not specified in the project objectives for the 2022 north Otago survey, but a CV of around 15% is generally targeted and this is what the survey was optimised to achieve. The achieved CV of 22% was higher than those from previous random-site surveys (14% for both 2013 and 2018), most likely a result of declining catch rates and the increase in zero pot-catches. The 2022 survey CV indicates that the survey design and number of sites used (40 sites) were appropriate for north Otago random-site surveys, but it seems likely that more sites will be required on the next survey to achieve a CV of 15%, particularly if abundance continues to decline.

4.4 Age composition and cohort progression

The 2018 and 2022 age distributions both display evidence of highly variable recruitment, with intermittent strong and weak year classes moving through the fishery over time, typical of blue cod from all areas where surveys have been conducted (Figure 23). Further, the strong and weak year classes in 2018 have progressed through to 2022, retaining the same relative cohort strengths, i.e., strong 3- and 5-year-old cohorts have grown to strong 7- and 9-year-old age classes. Similarly, weak 4-, 6-, and 7-year-old cohorts have grown to weak 8-, 10-, and 11-year-old age classes (Figure 23). This finding reinforces the confidence in the blue cod ageing methodology and the consistency achieved by the two readers over time. It also suggests that the same sub-populations of blue cod off north Otago have been sampled in subsequent surveys and that these surveys are monitoring the age composition effectively.

Growth estimates indicate that males are on average nearly 6-years-old and females nearly 8-years-old when they reach the current MLS of 33 cm in north Otago, although this was about a year younger before July 2020 when the MLS was 30 cm. The relatively high age at recruitment, combined with the truncated nature of these age compositions with few fish older than 10 years of age (maximum age is 31 years), concentrates the fishing pressure on just a few cohorts, some of which are poorly represented. In 2018, the fishery was largely reliant on the 5-year-old males and 8-year-old male and female age classes, whereas, in 2022, it was the 7-year-old males and 9-year-old males and females. Lightly fished populations, such as those offshore from Banks Peninsula, have a much broader age structure, with a better representation of older age classes that contribute to the fishery (Beentjes et al. 2022a). Comparison of age compositions from blue cod potting surveys off the east coast South Island from Kaikōura to south Otago have been shown to have similar age structures with the same strong and weak year classes present (Beentjes 2021).

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 more than a few kilometres from their tagging location. Blue cod off east coast South Island are therefore likely to consist of largely independent sub-populations. 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 2021). These events will have impacted localised spawning and survival of eggs, larvae, and juvenile fish.

4.5 Sex change and sex ratio

The 2022 north Otago overall sex ratio of blue cod favours males at a ratio of about three to one and, for recruited fish 33 cm and over, it is closer to 90% male (see Table 5). This finding was consistent across the previous fixed- and random-site north Otago surveys (see Figure 21). Sex ratios tend to favour males in heavily exploited blue cod populations, and despite the north Otago abundance declining markedly between 2009 and 2013, and 2013 to 2022 (see Figure 17), the sex ratio has remained stable and male dominated.

Blue cod are sequential protogynous hermaphrodites with some (but not all) females changing into males as they grow (sex change) (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 2021). 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). North Otago blue cod population sex and size structure is consistent with 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, Marlborough Sounds, and inshore Banks Peninsula, 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, Beentjes et al. 2022a). In contrast, in Foveaux Strait, Dusky

Sound, and offshore Banks Peninsula, sex ratios tend to be more balanced (Beentjes & Page 2016, Beentjes et al. 2019, Beentjes et al. 2022a), suggesting that fishing pressure is less intense in these areas. 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 (Beentjes & Carbines 2005, Beentjes 2021). 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. Fishing nevertheless appears to result in fewer and smaller females, which will have a large impact on egg production.

4.6 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 proxy for F_{MSY} is $F_{45\%SPR}$. As discussed in Section 1.4, the Inshore Finfish Working Group (8 December 2022) agreed that *SPR* is not appropriate as a target reference point for north Otago blue cod and, instead, recommended F=0.87M as an overfishing threshold (Zhou et al. 2012), where Z and F are estimated from the male-only age composition in the population.

The 2022 north Otago random-site survey Z for males, where M = 0.17, and age at full recruitment is 7 years of age, was 0.72, with a resulting F of 0.55 (95% confidence intervals 0.33–0.81) (see Table 9).

Relative to the target reference point of F=0.15 (F=0.87M), the estimated F of 0.55 in 2022 was nearly four times higher than this target, indicating that the stock has been overfished.

The 2018 estimates of Z and F for males were 0.46 and 0.29 (95% confidence intervals 0.15–0.44), respectively (Table 9). The lower Z and F than in 2022, to some extent, are because of the lower age at recruitment in 2018, when the MLS was 30 cm, compared with 33 cm in 2022. The estimated F of 0.29 was nearly two times higher than this target, indicating that the stock was overfished in 2018.

The finding that blue cod were over-exploited in 2018 and 2022 using the target reference point F=0.87M, is consistent with a trend of declining abundance and a progressive increase in pots with zero catch (see Figure 17 and Figure 21).

4.7 Reproductive condition

All five north Otago blue cod surveys (fixed and random) were carried out in January, with the exception of 2013, which extended into mid-February, so reproductive status is temporally comparable. All five surveys show indications of spawning activity for both sexes, with a variable but declining trend in the proportions in the mature and running-ripe conditions, particularly for males (Figure 24). Blue cod are serial or batch-spawners with a protracted spawning period that can extend from June to January, with peak spawning occurring later in southern latitudes (Beer et al. 2013). During the spawning period, individuals spawn multiple times (Pankhurst & Conroy 1987), and it seems likely they will transition between the mature and running-ripe conditions during this period. Often in blue cod populations, there are higher proportions of females than males in the combined mature/running-ripe conditions, and this is also the case for north Otago (Figure 24). This is possibly related to the reproductive strategy where a large male will hold a territory, attracting multiple females. The north Otago surveys occurred during the known protracted spawning period and the high proportions of males in the spent condition suggests that spawning had passed its peak (see Table 7). The reason for the temporal decline in the proportions of spawning condition fish are unknown, but may be related to environmental shifts, inherent variation in the timing of peak spawning, or to the decline in abundance (Figure 24). The poorer condition factor of blue cod in 2018 and 2022 compared with earlier surveys may, in part, be related to spawning state (see Figure 15).

4.8 Management implications

The high historic catch rates, MLS of 30 cm, and a bag limit of 30 fish (or blue cod) up to July 2020, had made north Otago attractive to blue cod fishers and there is strong anecdotal evidence of a large increase in effort from recreational and charter vessels at Moeraki in recent years. Anecdotal reports of fishers arriving in Moeraki with trailer freezers to accommodate the blue cod catch from a trip are common. Displacement of recreational fishing effort from Canterbury to north Otago is known to have occurred in recent years because of low catch rates around inshore Banks Peninsula combined with lower daily bags limits and larger MLS at Motunau and Kaikōura before July 2020. Even with the current bag limit of 10 blue cod per day and MLS of 33 cm in the north Otago area (Rakaia River to Taiaroa Heads), this is still less restrictive than the Canterbury area (Hurunui River to Rakaia River) where only 2 blue cod per day can be taken. Hence the incentive to concentrate fishing effort in north Otago remains strong.

Without spatial and temporal information on recreational fishing effort in north Otago, it is difficult to gauge impacts on this blue cod population. While the fishing mortality is high relative to natural mortality and the age structure is severely truncated, the length frequency distributions show no indications of declining size or lack of smaller recruiting fish.

The most recent fishery characterisation and catch per unit effort (CPUE) analyses for BCO 3 up to 2017–18 showed that about 75% of the commercial catch in BCO 3 is taken from Statistical Area 024, virtually all by cod potting, the northern part of which includes the north Otago survey area (see Figure 1) (Holmes et al. 2022). The CPUE index for the cod potting method was taken as representative of the southern Statistical Areas 024 and 026 and showed no trend over the time series. The electronic reporting system data on spatial distribution of commercial blue cod potting catch in Statistical Area 024 in 2020–21 and 2021–22, indicate that catches overlap with the survey strata (Fisheries New Zealand, unpublished data) and are concentrated over those areas where survey catch rates are highest. The stability of the CPUE is not consistent with the potting survey trend of declining abundance.

5. POTENTIAL RESEARCH

Research is needed into understanding the factors that control sex change in blue cod, to better interpret survey sex ratios and trends.

A multivariate analysis such as Generalised Linear Models could be used to routinely standardise blue cod potting survey abundance indices and potentially allow linkage between fixed- and random-site surveys. Predictor variables could include survey design (fixed or random), ADCP outputs (current strength and direction, bottom temperature), strata, depth, bottom contour, bottom type, sediment type, water clarity, multibeam seafloor descriptive variables, surface water temperature, tide state, bycatch, etc.

While not strictly a research priority, the ADCP data collected on blue cod potting surveys do not have an appropriate database where they can be archived and easily extracted. Data are currently archived in proprietary software files (.cnv, .ad2cp), and in a customised version in Matlab format with corrections made for magnetic declination to the compass data. Resources are required to investigate and extract the most appropriate ADCP summary metrics (for example, mean bottom water temperature, mean current direction and speed) that can be archived appropriately (for example in the *trawl* database) and assigned to each pot and/or site from potting surveys.

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9. TABLES AND FIGURES

Table 1: Fixed- and random-site blue cod potting survey time series in north Otago, including the 2022 survey. See Figure 2 for locations of strata. Survey dates include only fishing days. MR, proposed marine reserve (Te Umu Koau, D1).

Year	Strata	Survey Design	Vessel	Skipper	Survey date	Research provider
2005	1–5	Fixed	F.V. *Suzanne*	John Pile	12–27 Jan 2005	NIWA
2009	1–6	Fixed	F.V. *Nimbus*	John Pile	16–30 Jan 2009	NIWA
2013	1–6	Fixed and Random	F.V. *Triton*	Neil McDonald	21 Jan–18 Feb 2013	Saltwater Research
2018	1–6	Fixed and Random	F.V. *Triton*	Neil McDonald	7–29 Jan 2018	NIWA
2022	1–6 MR	Random	R.V. *Ikatere*	Richard Leppard	7–23 Jan 2022	NIWA

Table 2: Effort and catch data for the 2022 north Otago random-site blue cod potting survey. MR, proposed marine reserve (Te Umu Koau, D1).

	Area		*N* sets (sites)			Catch (blue cod)		Depth (m)	
Stratum	(km^2)	Site type	Phase 1	Phase 2	*N* pots (stations)	*N*	kg	Mean	Range
1	153.1	Random	7		42	150	84.2	18.0	9–32
2	243.5	Random	3		18	1	1.0	20.2	18–24
3	149.9	Random	5	1	36	221	100.2	36.7	30–44
4	115.9	Random	5	3	48	370	168.0	23.4	11–33
5	200.1	Random	8		48	193	113.8	43.1	37–51
6	54.3	Random	3		18	113	38.7	27.4	13–32
Total	916.8		31	4	210	1 048	505.9	27.5	9–51
MR	91.5	Random	4		24	67	32.5	36.8	32–40

Table 3: Total catch and numbers of blue cod and bycatch species caught on the 2022 north Otago random-site blue cod potting survey (A), the 4 dedicated sites in the proposed marine reserve (B), and the four dedicated sites in the proposed marine reserve plus four main survey sites that were inside the marine reserve polygon (C). Percent of the catch by weight is also shown. MR, proposed marine reserve.

(A)

		Main survey			
Common name	Species	Code	Number	Catch (kg)	% Catch
Blue cod	*Parapercis colias*	BCO	1 048	505.9	90.15
Leatherjacket	*Meuschenia scaber*	LEA	101	31.2	5.56
Banded wrasse	*Notolabrus fucicola*	BPF	13	9.4	1.68
Scarlet wrasse	*Pseudolabrus miles*	SPF	13	6.3	1.12
Common octopus	*Octopus maorum*	OCT	2	6.0	1.07
Tarakihi	*Nemadactylus macropterus*	NMP	30	0.9	0.16
Brittle star	Ophiuroid	OPH	14	0.8	0.14
Starfish	Asteroidea	ASR	1	0.5	0.09
Blue moki	*Latridopsis ciliaris*	MOK	1	0.1	0.02
Southern bastard cod	*Pseudophycis barbata*	SBR	1	0.1	0.02
Totals			1 224	561.2	

(B)

		MR (4 dedicated sites)			
Common name	Species	Code	Number	Catch (kg)	% Catch
Blue cod	*Parapercis colias*	BCO	67	32.5	91.29
Leatherjacket	*Meuschenia scaber*	LEA	1	2.0	5.62
Scarlet wrasse	*Pseudolabrus miles*	SPF	2	1.1	3.09
Totals			70	35.6	

(C)

		MR (8 sites)			
Common name	Species	Code	Number	Catch (kg)	% Catch
Blue cod	*Parapercis colias*	BCO	256	98.8	88.06
Leatherjacket	*Meuschenia scaber*	LEA	31	8.8	7.84
Scarlet wrasse	*Pseudolabrus miles*	SPF	6	2.6	2.32
Common octopus	*Octopus maorum*	OCT	1	2.0	1.78
			294	112.2	

Table 4: Mean catch rates for all blue cod and recruited blue cod (33 cm and over) from the 2022 north Otago random-site blue cod potting survey. Catch rates are also shown for the four dedicated sites in the proposed marine reserve plus four main survey sites that were inside the marine reserve polygon. Catch rates are pot-based, and s.e. and CV are set-based. s.e., standard error; CV coefficient of variation. MR, proposed marine reserve.

				All blue cod			Recruited blue cod ≥ 33 cm		
Stratum	Site type	Sites (N)	Pot lifts (N)	Catch rate (kg pot^{-1})	s.e.	CV (%)	Catch rate (kg pot^{-1})	s.e.	CV (%)
1	Random	7	42	2.00	0.91	45.6	1.46	0.65	44.0
2	Random	3	18	0.06	0.06	100.0	0.06	0.06	100.0
3	Random	6	36	2.78	0.81	29.0	1.76	0.57	32.6
4	Random	8	48	3.50	2.07	59.2	1.62	0.87	53.8
5	Random	8	48	2.37	1.13	47.7	1.59	0.83	52.1
6	Random	3	18	2.15	0.82	38.1	1.01	0.38	37.3
Overall		35	210	1.89	0.42	22.0	1.16	0.26	22.1
MR sites	Random	8	48	2.06	0.64	31.2	1.00	0.31	30.7

Table 5: Descriptive statistics for blue cod caught on the 2022 north random-site blue cod potting survey, and the proposed marine reserve (MR). Outputs are raw for each stratum and weighted overall. Sex ratio is also given for recruited blue cod (33 cm and over). The MR outputs include catch from the four dedicated sites in the proposed marine reserve, plus four main survey sites that were inside the marine reserve polygon. m, male; f, female; u, unsexed. –, no data.

		Length (cm)				Percent male	
Stratum	Sex	N	Mean	Minimum	Maximum	All blue cod	Recruited ≥ 33 cm
1	m	123	32.6	18.6	46.5	82.1	89.7
	f	27	28.7	19.8	41.5		
2	m	1	42.1	42.1	42.1	–	–
	f	–	–	–	–	–	–
3	m	144	30.2	16.2	55.0	66.0	80.8
	f	75	26.9	16.3	45.4		
	u	2	15.2	14.4	15.9		
4	m	283	30.5	15.9	52.9	78.4	94.5
	f	79	26.5	18.3	44.7		
	u	8	11.5	5.5	15.9		
5	m	164	32.4	20.3	48.9	84.9	94.7
	f	29	28.0	20.8	41.9		
6	m	81	28.1	14.9	43.6	71.9	100
	f	32	23.4	17.9	32.5		
Overall	m	796	30.7	14.9	55.0	76.8	90.6
	f	242	26.3	16.3	45.4		
	u	10	12.0	5.5	15.9		
MR (8 sites)	m	189	28.6	14.9	43.6	74.0	96.3
	f	67	24.3	17.9	40.8		

Table 6: Blue cod otolith ageing data used in the catch-at-age, and mortality estimates for the 2022 north Otago random-site blue cod potting survey.

		Length of aged fish (cm)		Age (years)	
Survey	No. otoliths	Minimum	Maximum	Minimum	Maximum
Male	353	14	55	1	30
Female	174	16	45	2	20
Total	527	14	55	1	30

Table 7: Gonad stages (%) of male and female blue cod from the north Otago random-site blue cod potting survey in January 2022. Gonad stages: 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	43.7	23.4	0.3	2.9	29.8	796
Females	76.4	12.4	7.4	1.7	2.1	242

Table 8: Chapman-Robson total mortality estimates (*Z*) and 95% confidence intervals of male blue cod for the 2018 and 2022 north Otago random-site blue cod potting surveys. *AgeR*, age at full recruitment.

				95% CIs	
Survey	Site type	*AgeR*	*Z*	Lower	Upper
2022	Random	5	0.42	0.30	0.57
	Random	6	0.44	0.31	0.61
	Random	7	0.72	0.50	0.98
	Random	8	0.51	0.34	0.71
	Random	9	0.94	0.56	1.42
	Random	10	0.24	0.14	0.37
2018	Random	5	0.52	0.36	0.71
	Random	6	0.46	0.32	0.61
	Random	7	0.53	0.36	0.73
	Random	8	1.04	0.71	1.40
	Random	9	0.56	0.38	0.77
	Random	10	0.68	0.43	1.01

Table 9: Mortality (Chapman Robson *Z* and *F*) point estimates at three values of *M* for male blue cod from the 2022 north Otago random-site potting survey. Age at recruitment = 7 years (age at which males reach minimum legal size of 33 cm, plus one year. *F* values are also given for the default *M* (0.17) and the 95% confidence interval *Z* values. Results are also given for the 2018 survey for males where *M* = 0.17 and age at recruitment = 6 years (age at which males reach minimum legal size of 30 cm, plus one year). *F*, fishing mortality; *M*, natural mortality; *Z*, total mortality; LowerCI, lower 95% confidence interval; UpperCI, upper 95% confidence interval.

Survey	Site type	*M*	*Z*	*F*	Estimate
2022	Random	0.14	0.72	0.58	Point
	Random	0.17	0.72	0.55	Point
	Random	0.20	0.72	0.52	Point
	Random	0.17	0.50	0.33	LowerCI
	Random	0.17	0.98	0.81	UpperCI
2018	Random	0.17	0.46	0.29	Point
	Random	0.17	0.32	0.15	LowerCI
	Random	0.17	0.61	0.44	UpperCI

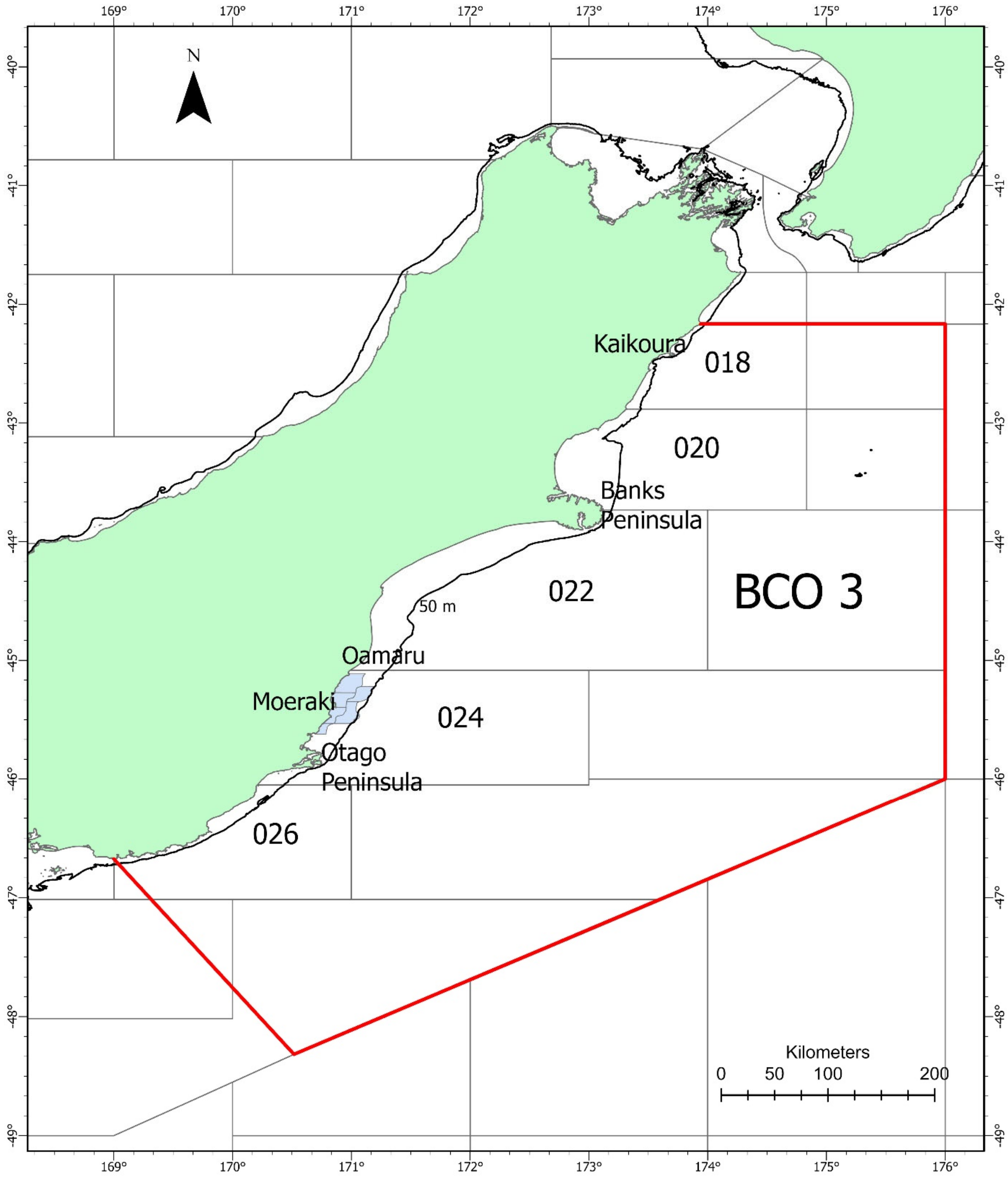

Figure 1: Blue cod Quota Management Area BCO 3 (red border) and main statistical areas. The north Otago potting survey strata (light blue shading) are shown off Moeraki. The 50-m depth contour is shown.

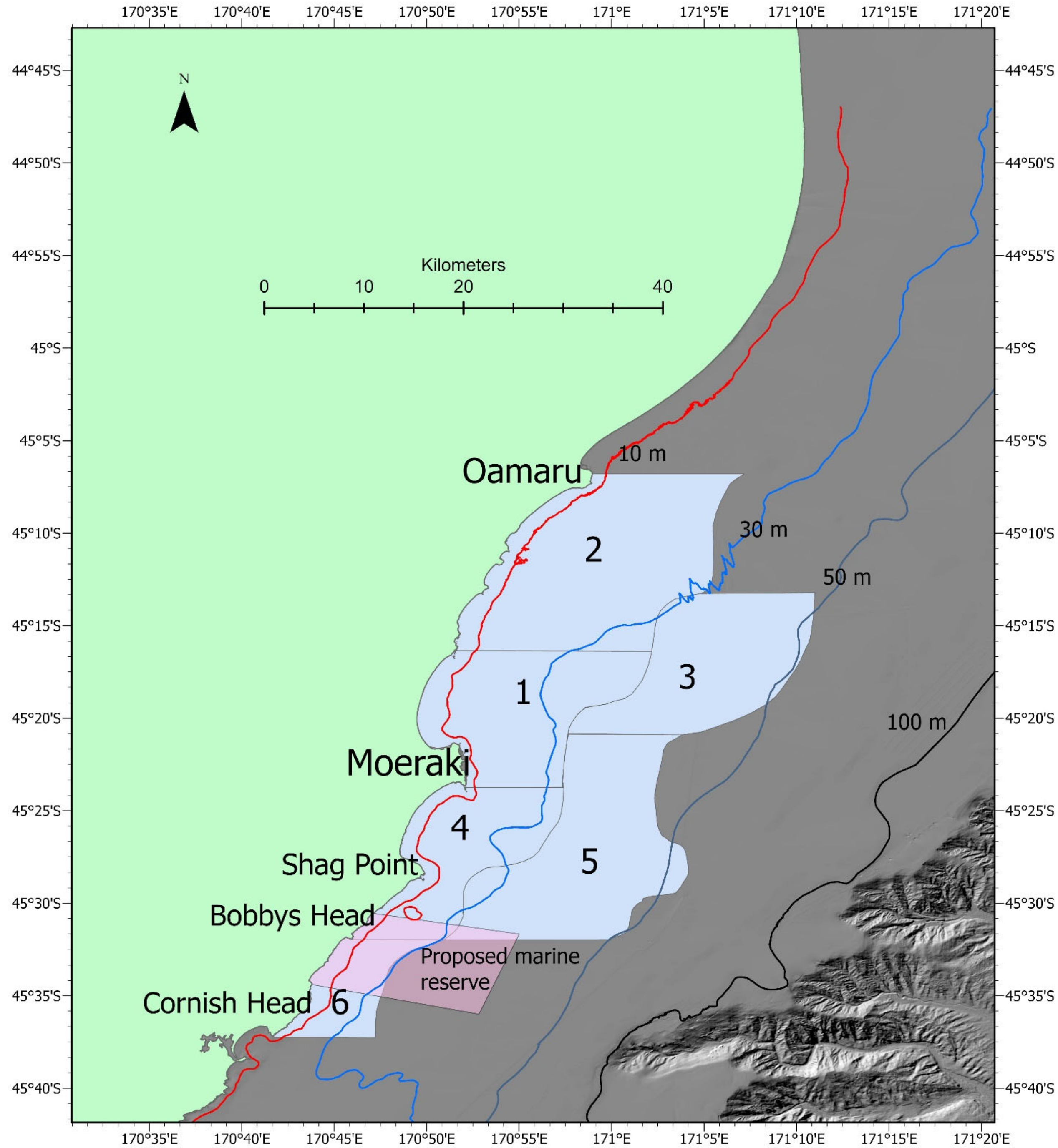

Figure 2: North Otago blue cod survey strata, bathymetry contours, and hillshade view of the seafloor based on the NIWA Digital Terrain Model (DEM) of the 25-m gridded data set (3x vertical exaggeration). The proposed marine reserve (Te Umu Koau, D1) is also shown, overlaying strata 4, 5, and 6.

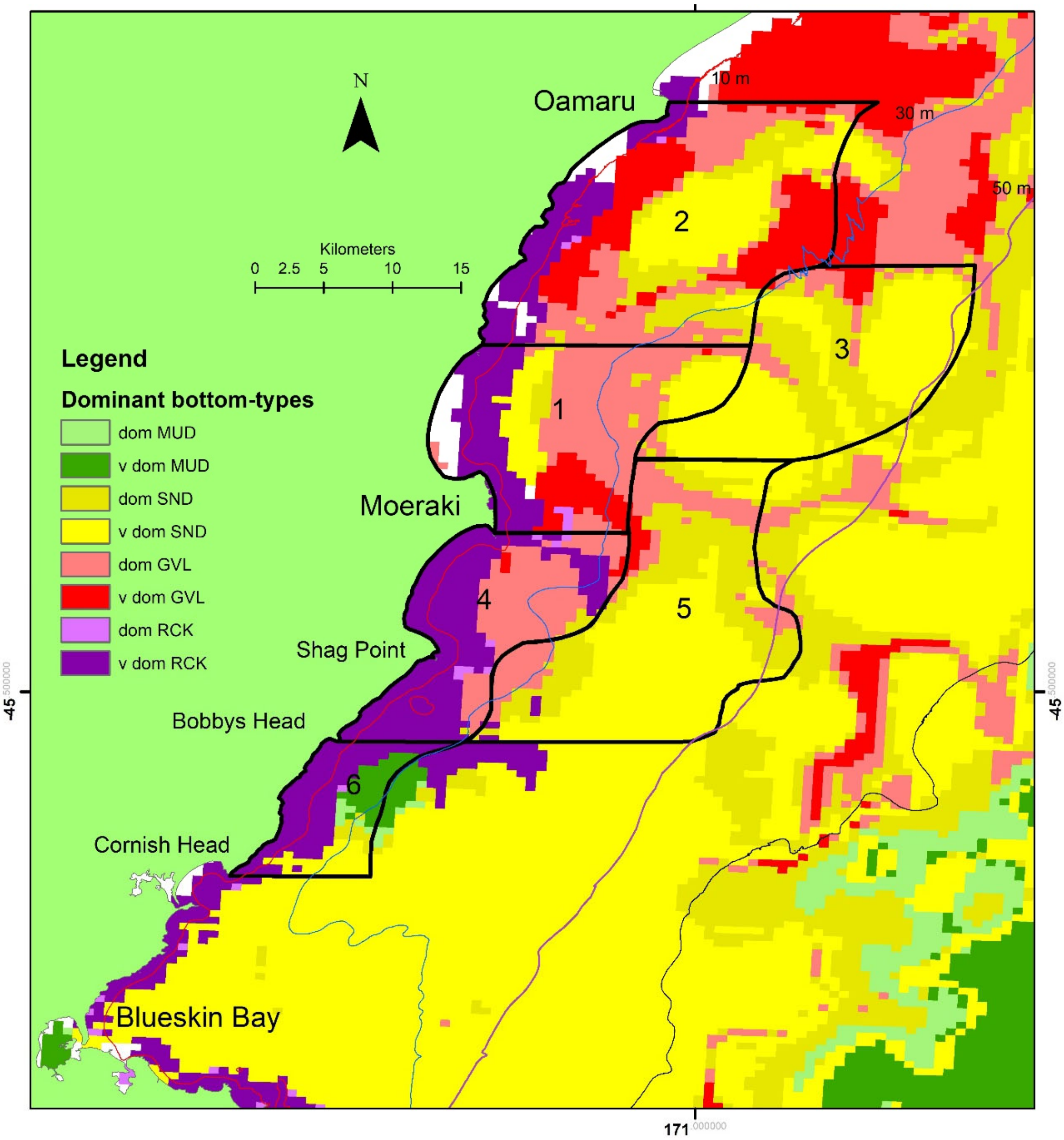

Figure 3: North Otago blue cod survey strata, bathymetry contours, and dominant seafloor substrate types (data from Bostock et al. 2019). Dom, dominant; v dom, very dominant; MUD, mud; SND, sand; GVL, gravel; RCK, rock.

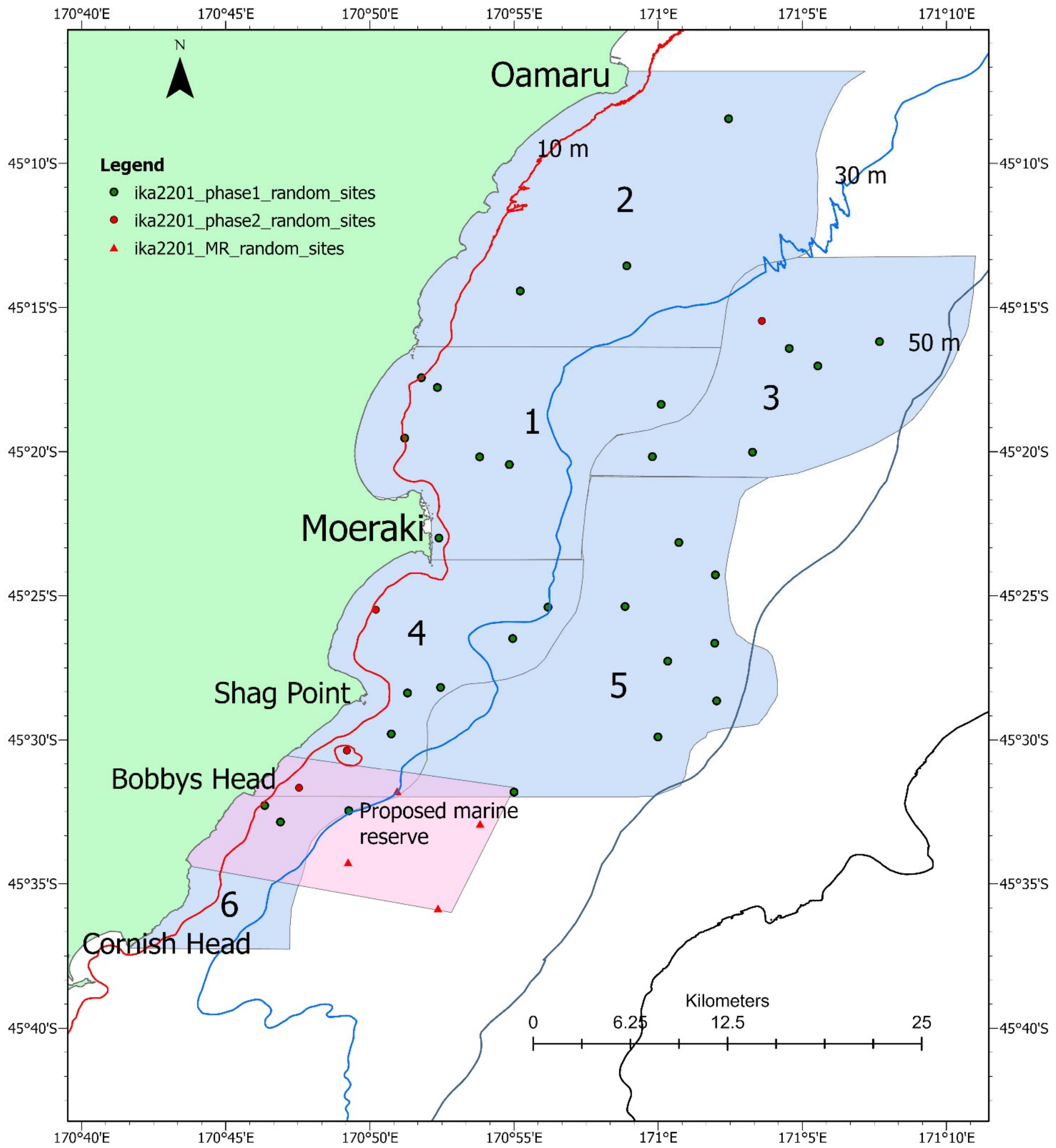

Figure 4: Strata and site positions for the North Otago 2022 random-site blue cod potting survey. The proposed marine reserve (Te Umu Koau, D1) stratum, and four additional site positions within this stratum are also shown (red triangles).

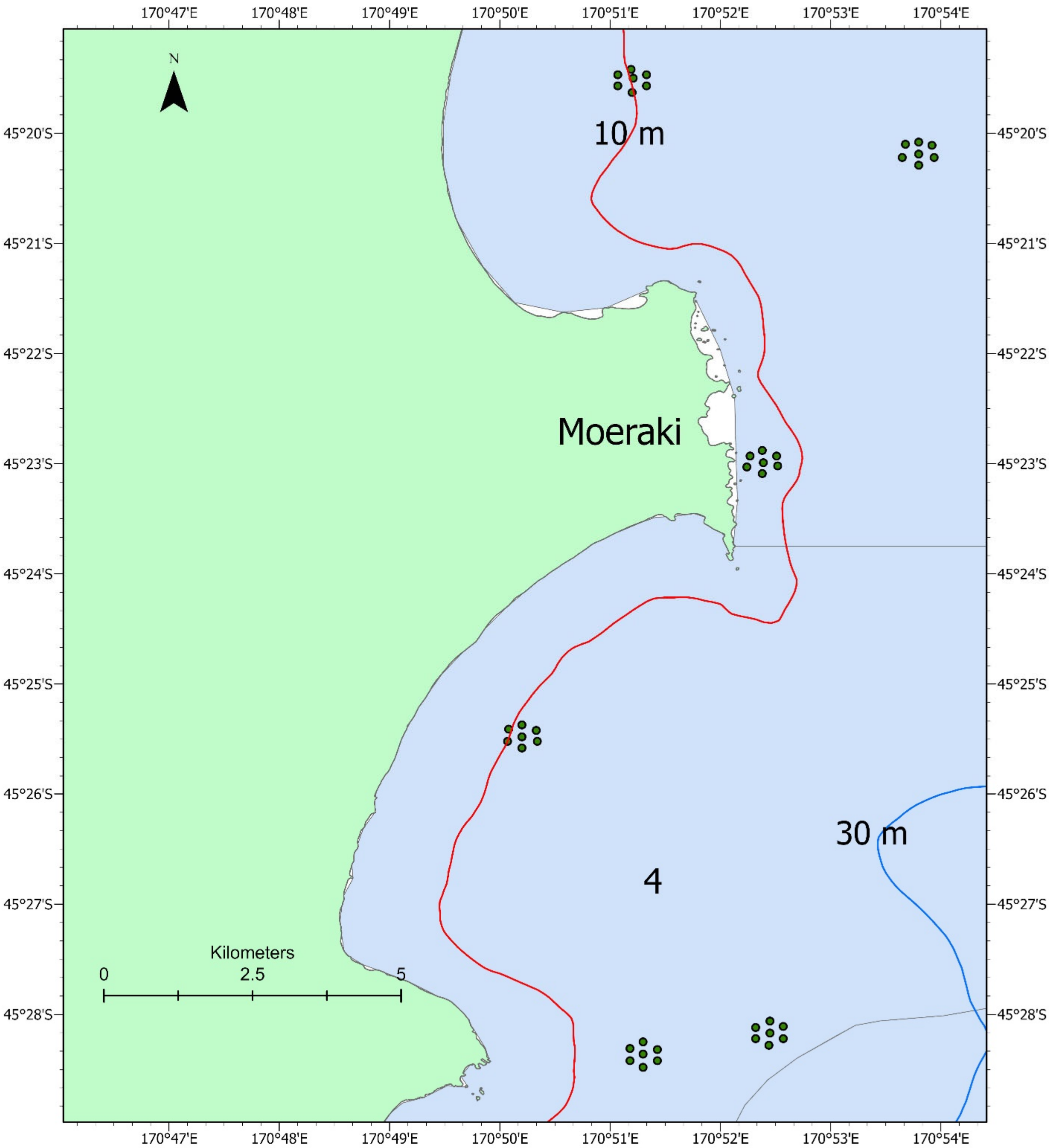

Figure 5: Site and pot positions for the 2022 north Otago random-site blue cod potting survey in strata 1 and 4, demonstrating how the six pots were placed systematically around the random site positions.

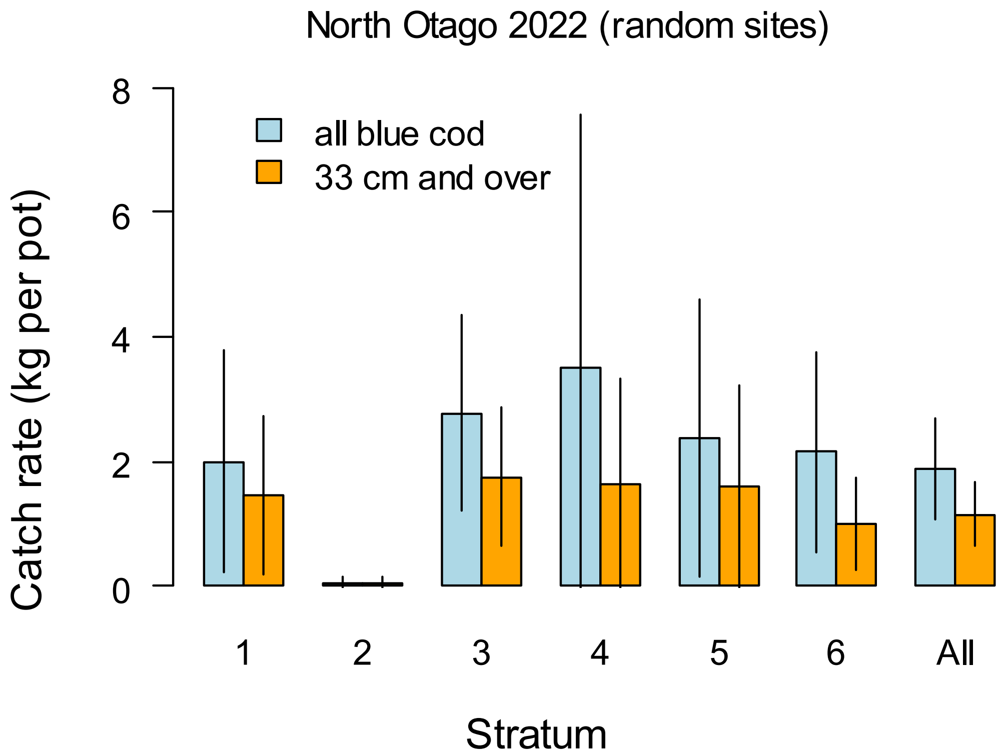

Figure 6: Catch rates (kg pot^{-1}) of all blue cod and recruited blue cod (33 cm and over) by strata, and overall for the 2022 north Otago random-site survey. Error bars are 95% confidence intervals.

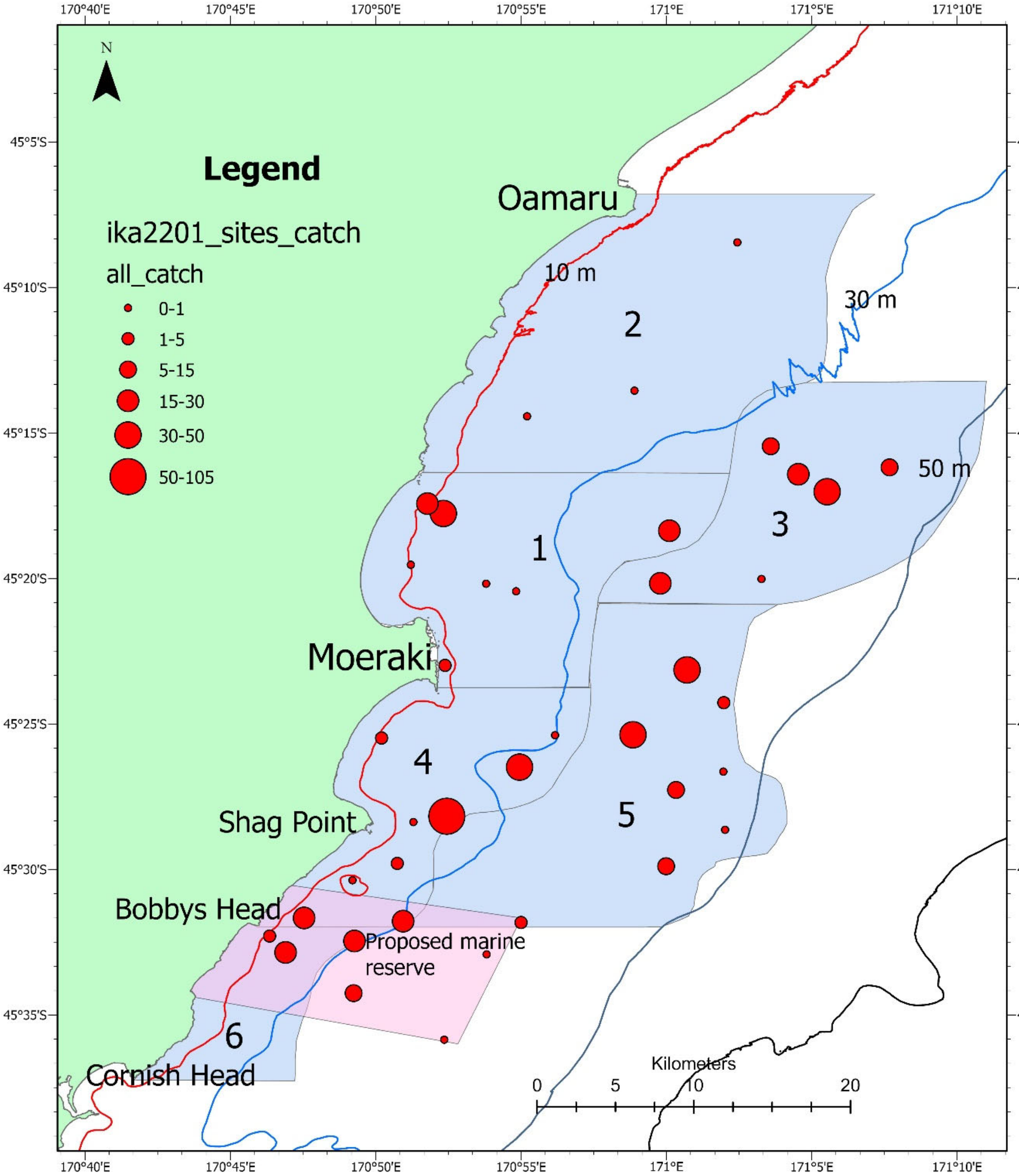

Figure 7: Strata and site positions showing relative blue cod catch rates (kg pot^{-1}) for the north Otago 2022 random-site blue cod potting survey. The proposed marine reserve (Te Umu Koau, D1) stratum and four additional site positions within this stratum are also shown.

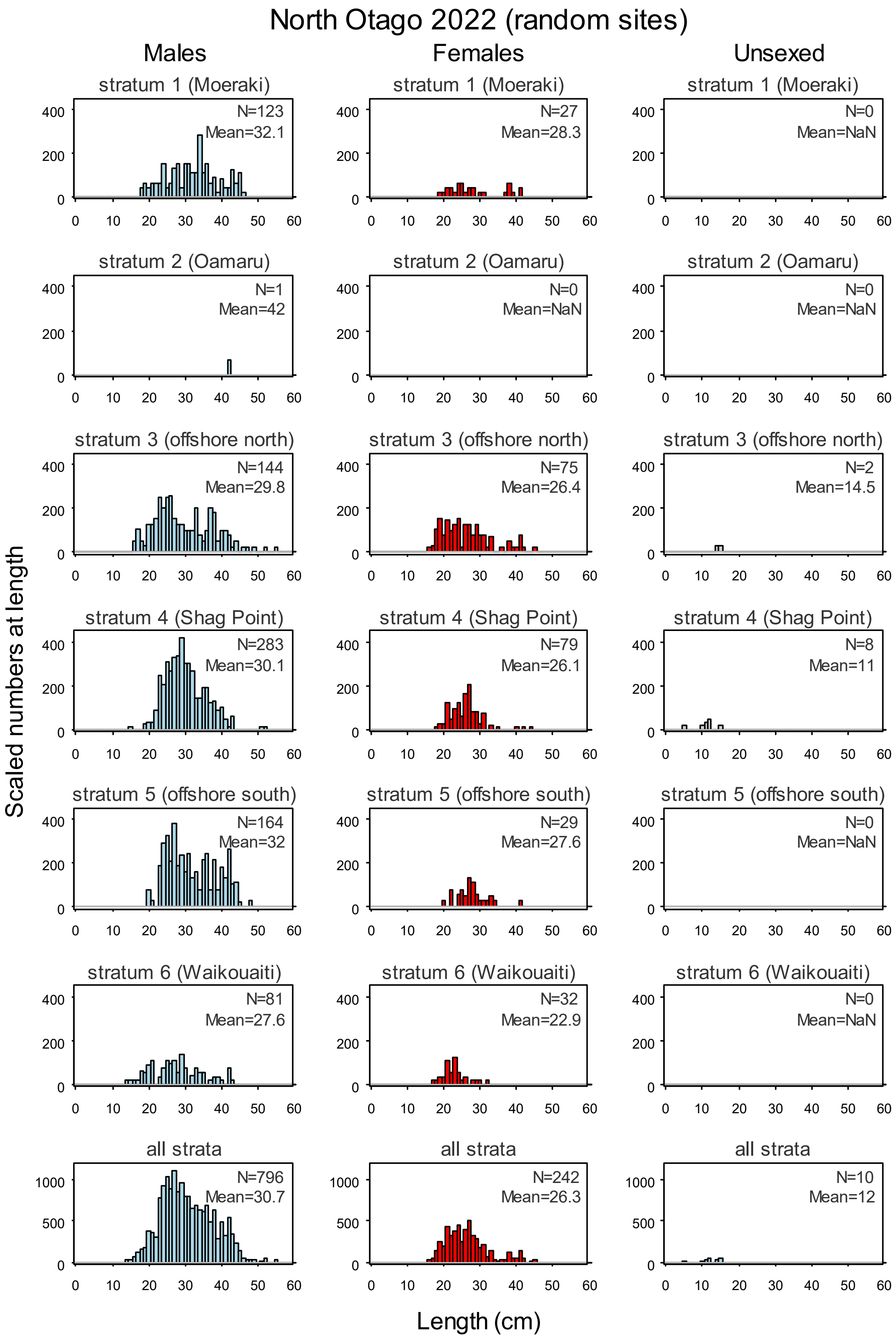

Figure 8: Scaled length frequency distributions of blue cod by strata and overall, for the 2022 north Otago random-site potting survey. N, sample numbers; Mean, mean length (cm). Scaled numbers are relative, but non-informative.

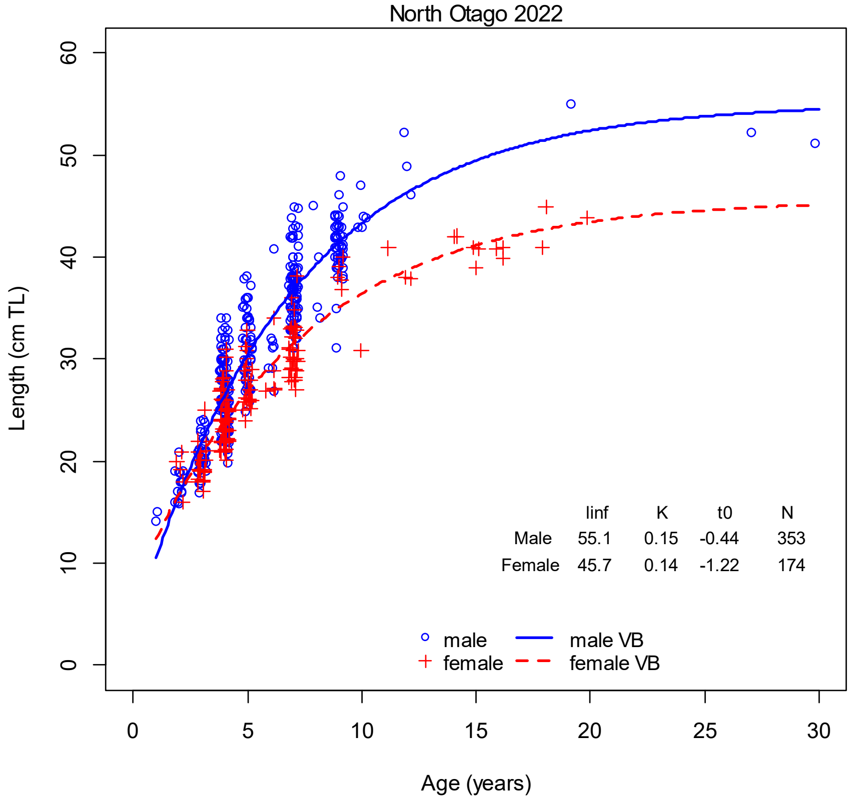

Figure 9: Observed blue cod age-length data by sex for the 2022 north Otago random-site survey, with von Bertalanffy (VB) growth models fitted to the data. *Linf*, average size at the maximum age (cm); *K*, Brody growth coefficient (yr^{-1}); *t0*, age when the average size is zero (y).

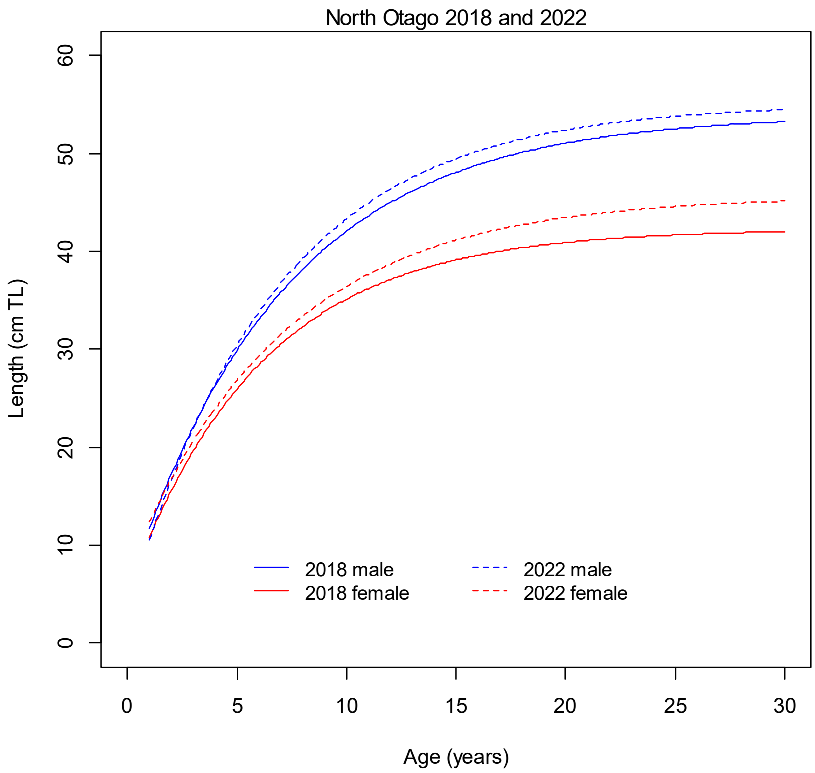

Figure 10: von Bertalanffy growth models fitted to the 2018 and 2022 blue cod survey age and length data.

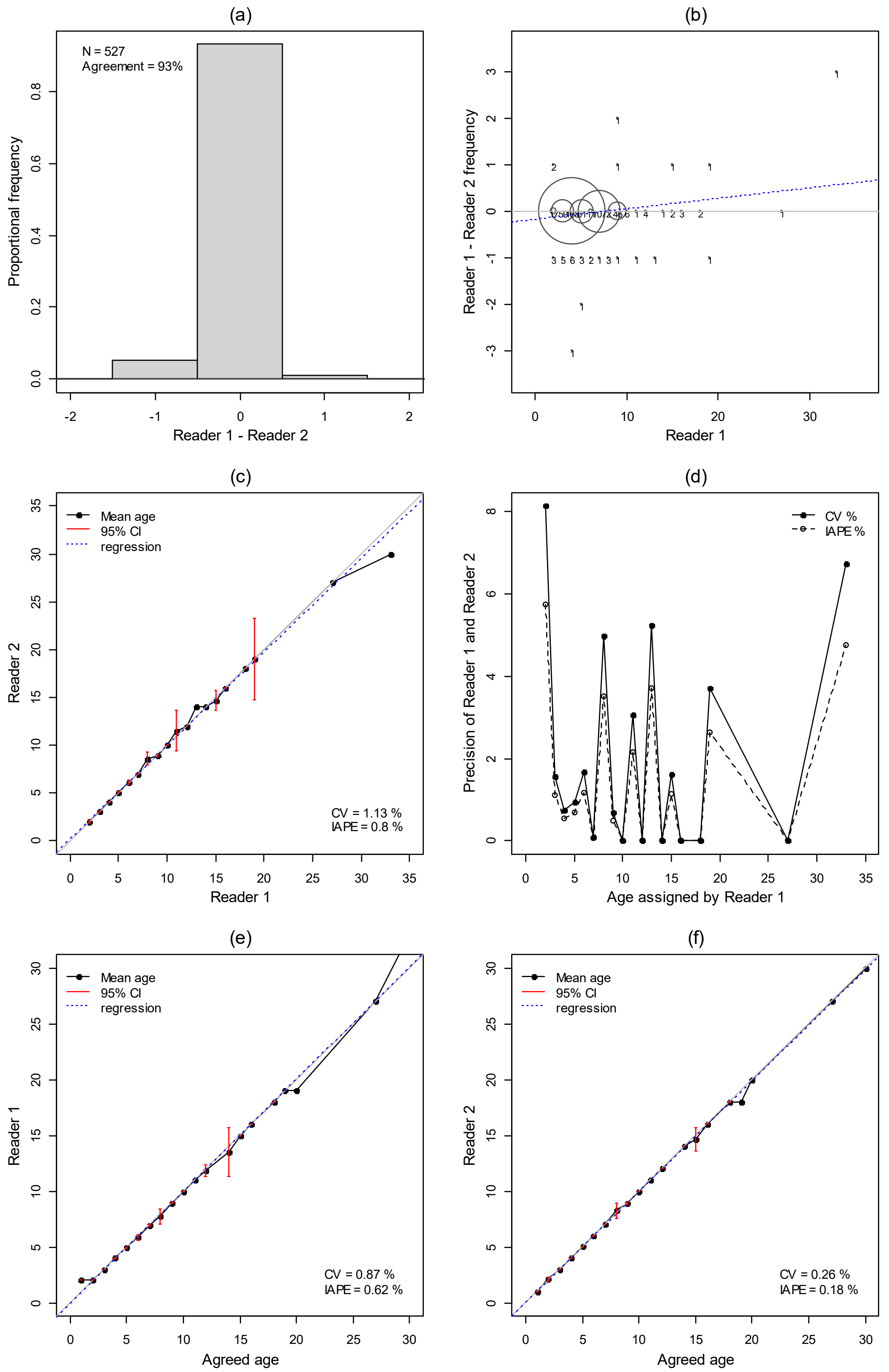

Figure 11: Blue cod age otolith reader comparison plots between reader 1 and reader 2 for the 2022 north Otago survey: (a) histogram of age differences between two readers; (b) difference between reader 1 and reader 2 as a function of the age assigned by reader 1, where the numbers of fish in each age 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 panels b and c, solid lines show perfect agreement, dashed lines show the trend of a linear regression of the actual data.

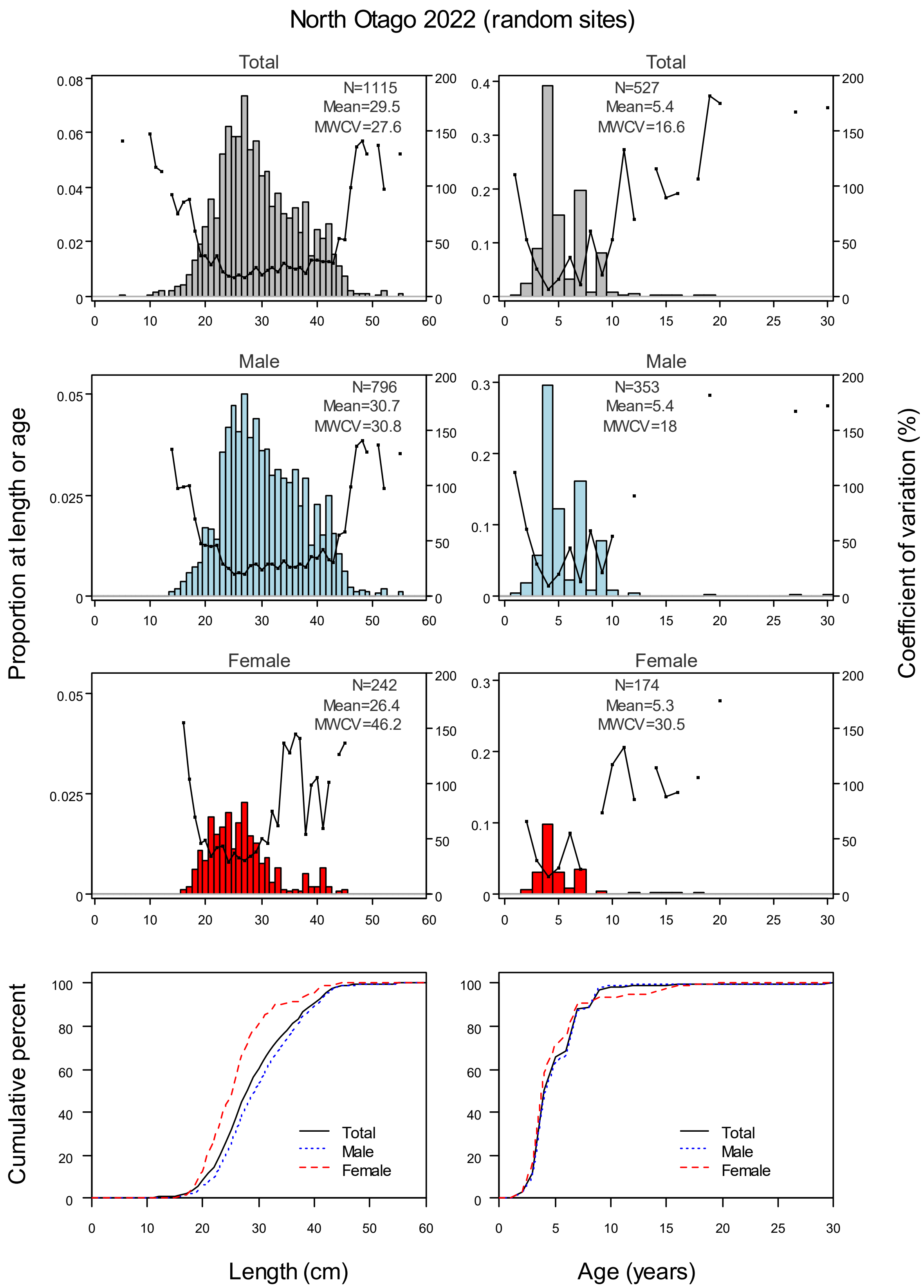

Figure 12: Scaled length frequency, age frequency, and cumulative distributions for total, male, and female blue cod for all strata in the 2022 north Otago random-site blue cod potting survey. N, sample size; MWCV, mean weighted coefficient of variation (%).

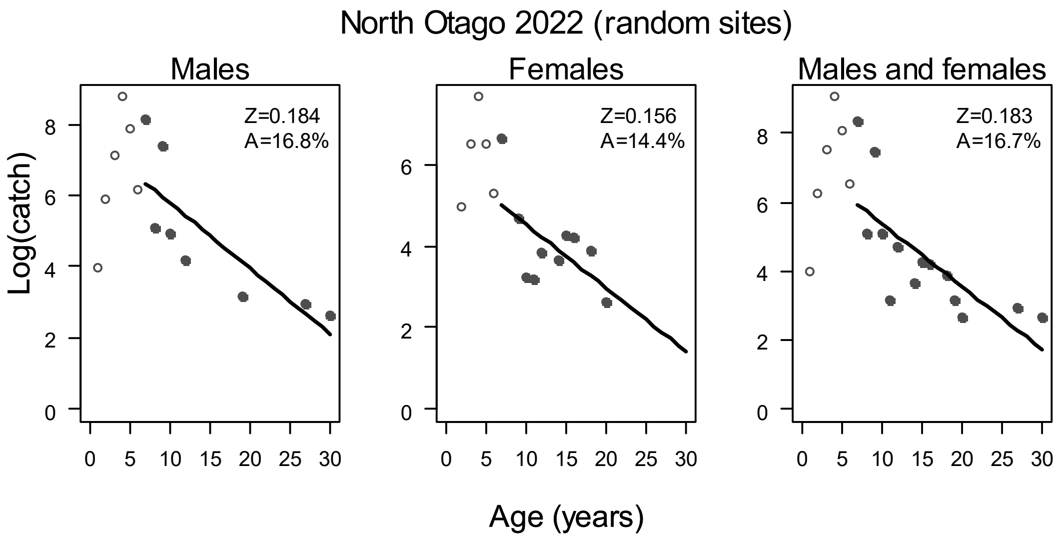

Figure 13: Catch curves (natural log of catch numbers versus age) for the 2022 north Otago random-site survey. The regression line is plotted from age at full recruitment of 7 years (i.e., dark points on the graph). *Z*, instantaneous total mortality; *A*, the annual mortality rate or the proportion of the population that suffers mortality in a given year.

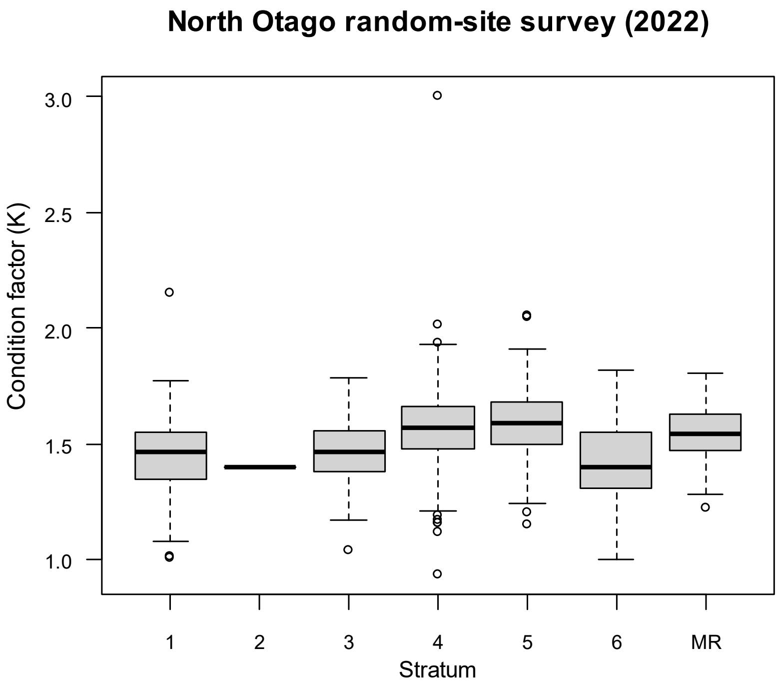

Figure 14: Box plot of Fulton's condition factor (*K*) for blue cod on the north Otago 2022 random-site potting survey by strata. Data shown are the minimum and maximum (whiskers), 25th and 75th percentiles (shaded box), median (dark line), and outliers (open circles). See Figure 2 for location of strata.

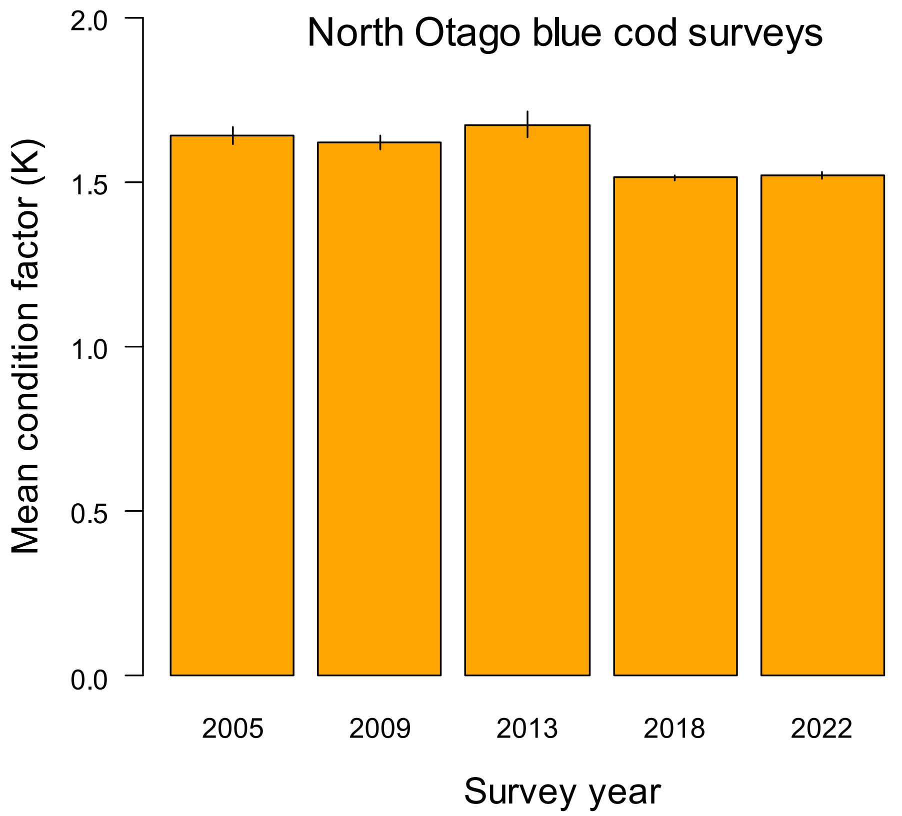

Figure 15: Mean Fulton's condition factor (*K*) for blue cod from the north Otago potting surveys. Error bars are 95% confidence intervals.

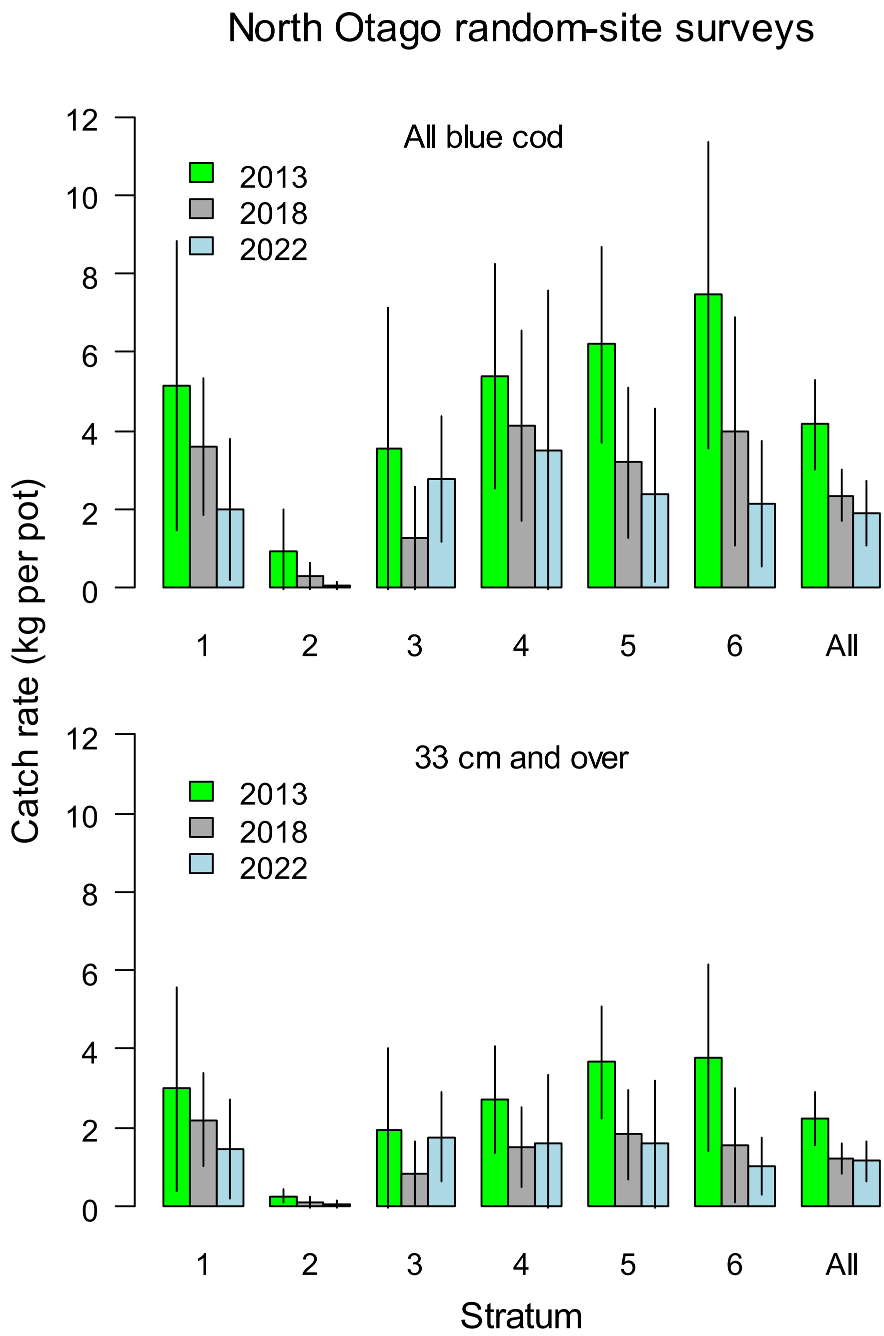

Figure 16: Strata and overall survey catch rates (kg pot^{-1}) of all blue cod and recruited blue cod (33 cm and over) for north Otago random-site potting surveys in 2013, 2018, and 2022. Error bars are 95% confidence intervals.

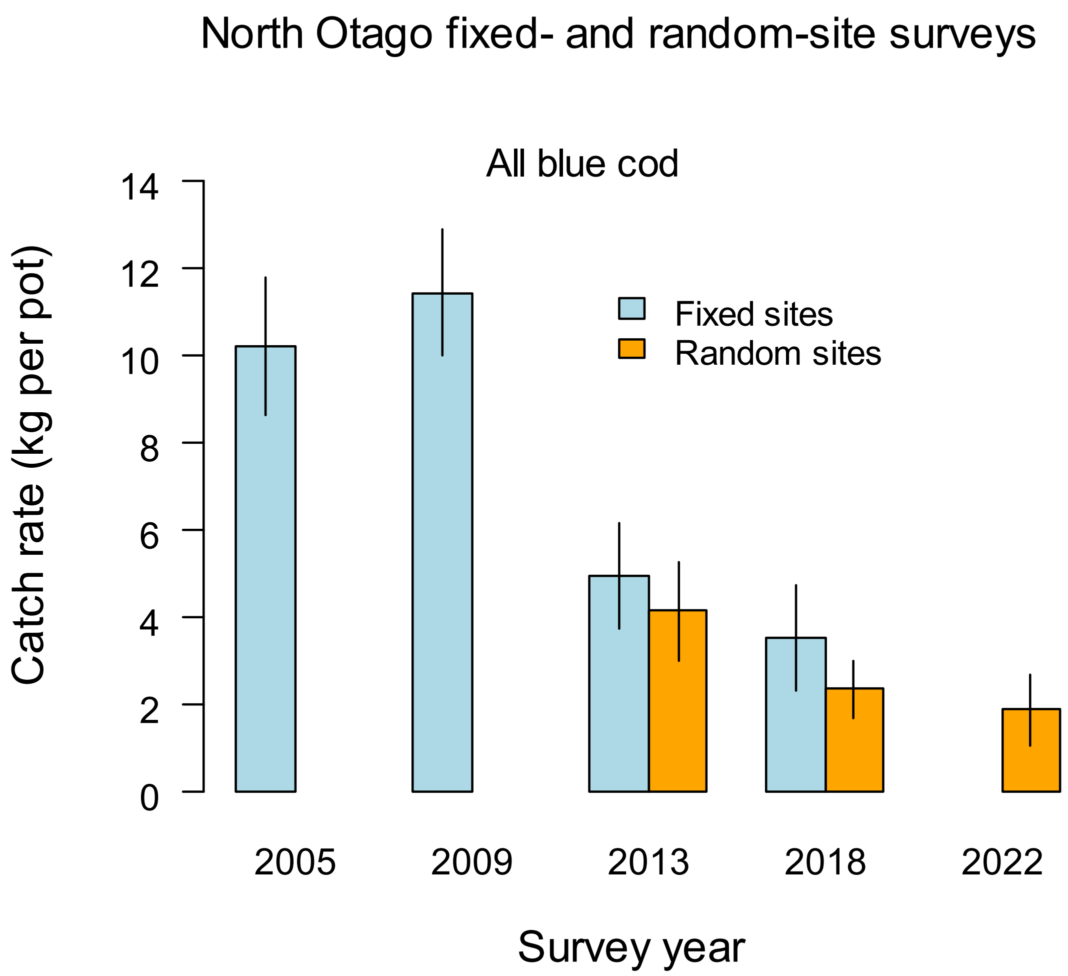

Figure 17: Overall survey catch rates (kg pot^{-1}) of all blue cod for north Otago fixed-site surveys in 2005, 2009, 2013, and 2018; and random-site surveys in 2013, 2018, and 2022. Error bars are 95% confidence intervals.

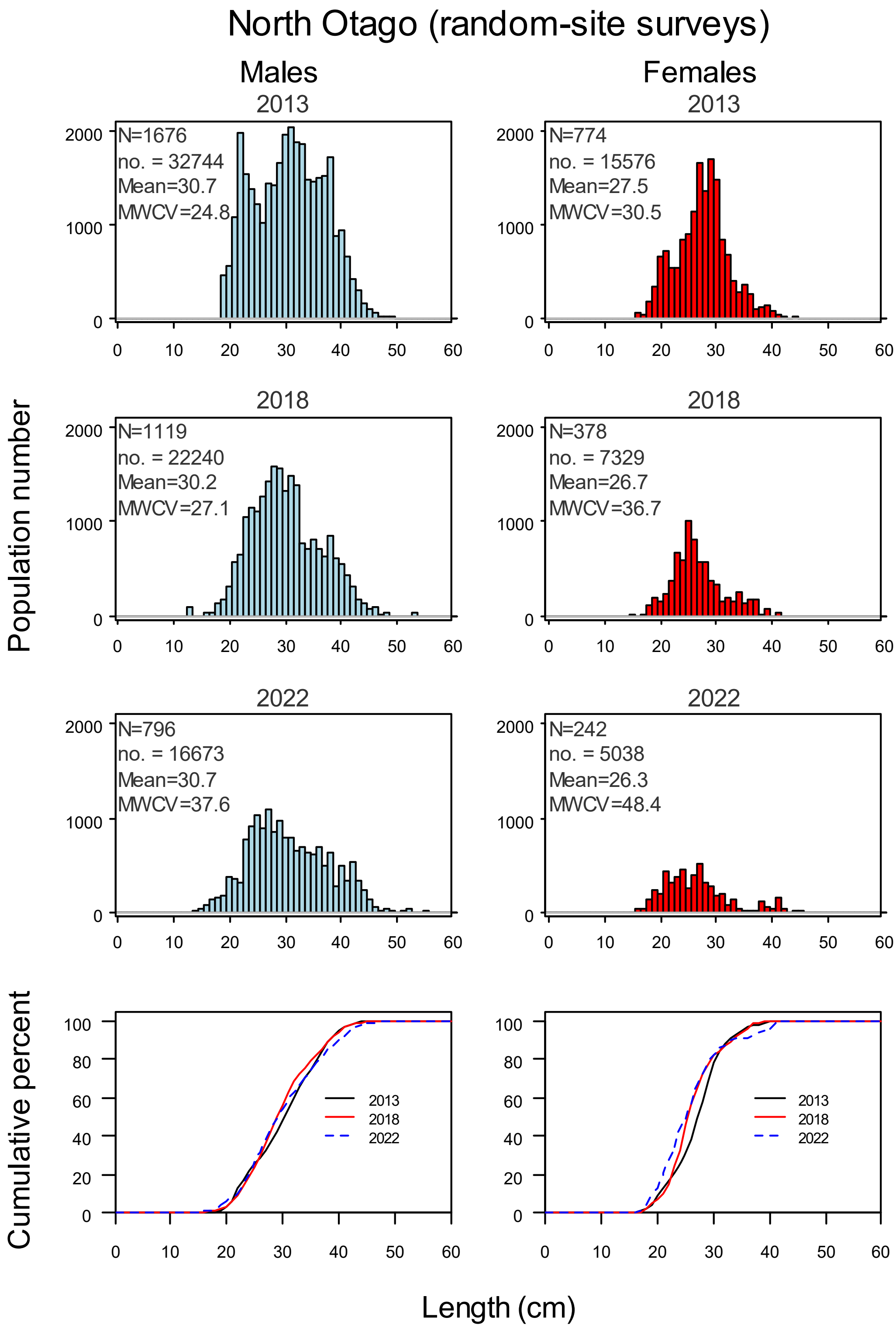

Figure 18: Scaled length frequency and cumulative distributions for male and female blue cod from north Otago random-site blue cod potting surveys in 2013, 2018, and 2022. Scaled numbers are relative, but non-informative. N, sample numbers; no, population number; Mean, mean length (cm); MWCV, mean weighted coefficient of variation (%).

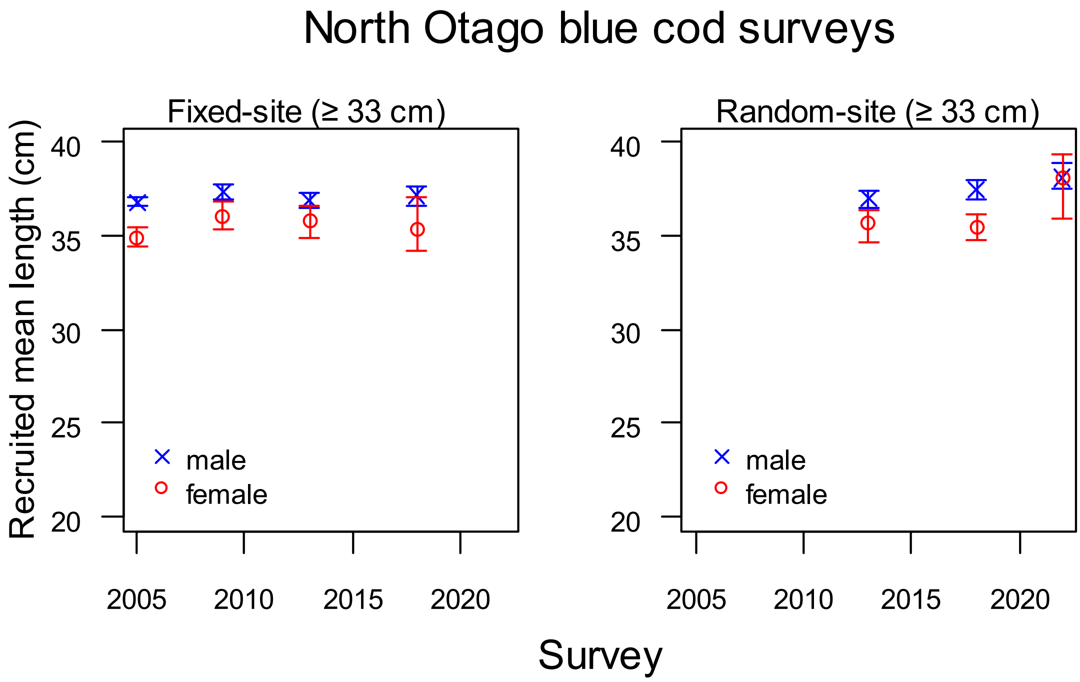

Figure 19: Recruited mean length and 95% confidence intervals for male and female blue cod from north Otago fixed-site potting surveys in 2005, 2009, 2013, and 2018 (left panel); and random-site potting surveys in 2013, 2018, and 2022 (right panel). Surveys from 2009 onward include stratum 6.

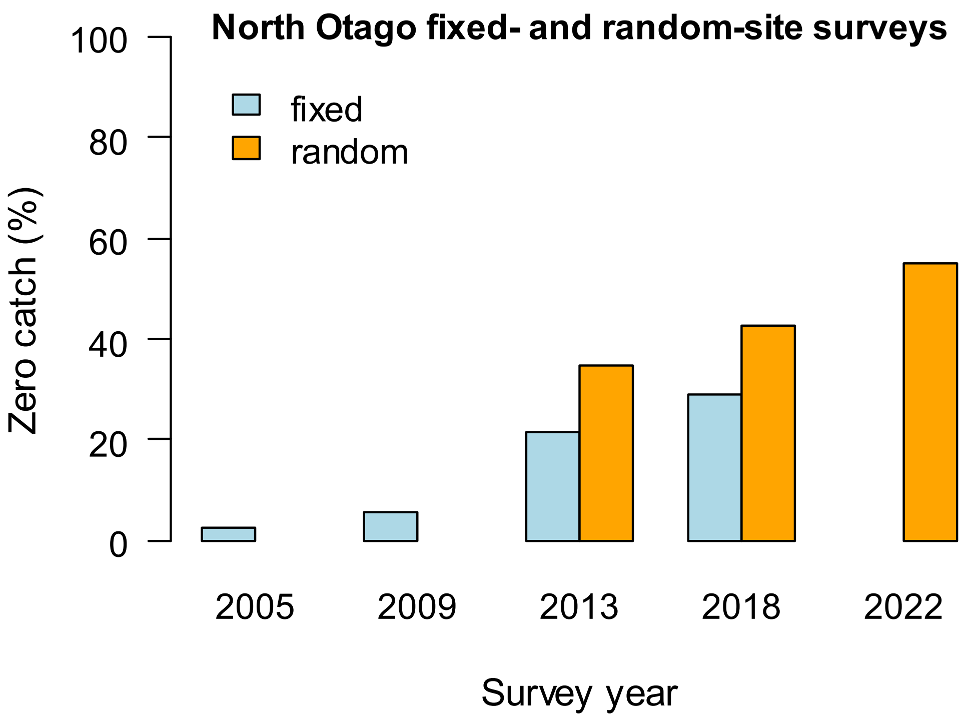

Figure 20: Percent of pots with zero catch of blue cod for the north Otago fixed-site surveys in 2005, 2009, 2013, and 2018; and random-site surveys in 2013, 2018, and 2022. Surveys from 2009 onward include stratum 6.

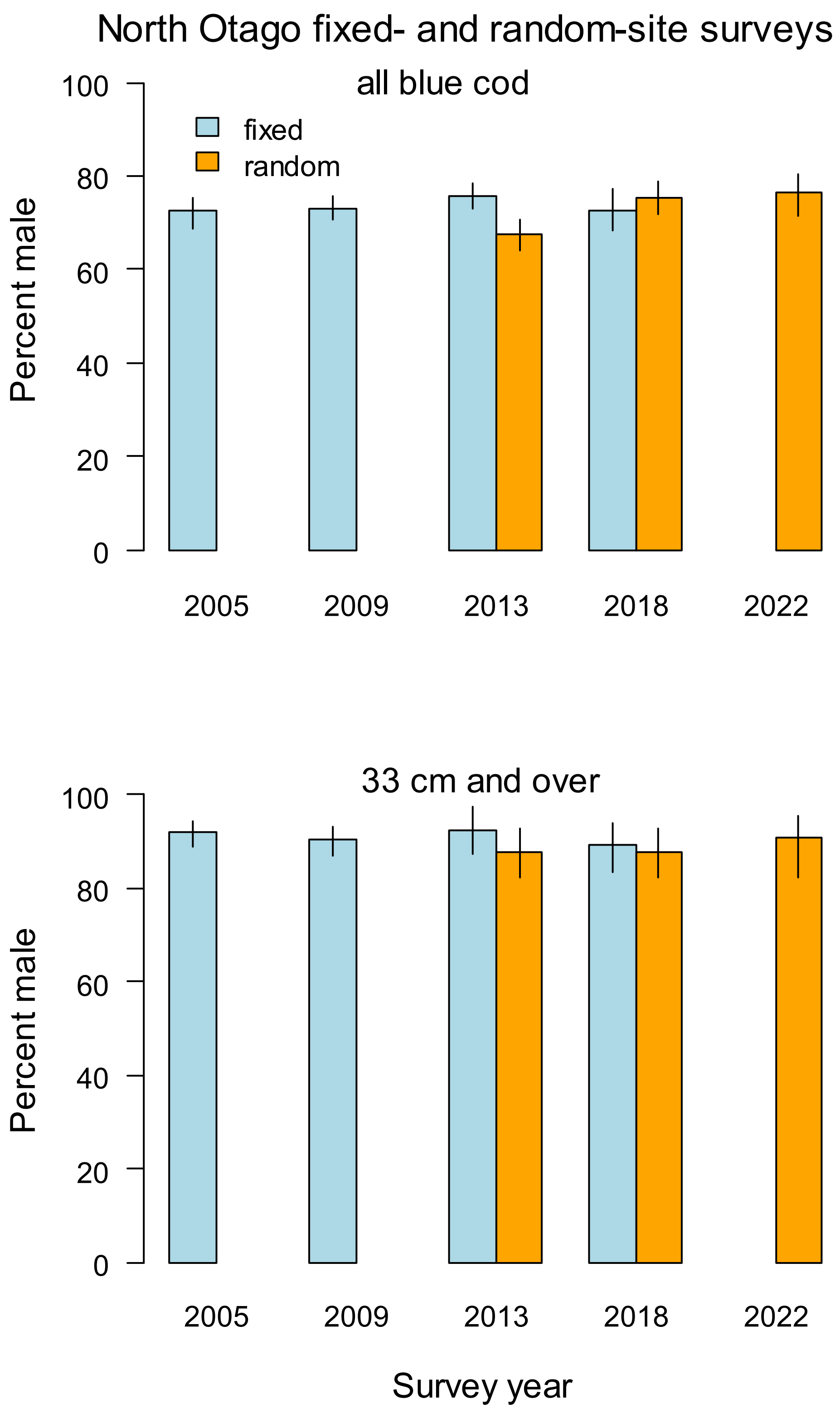

Figure 21: Proportion of males in the north Otago fixed-site potting surveys in 2005, 2009, 2013, and 2018; and random-site potting surveys 2013, 2018, and 2022. Surveys from 2009 onward include stratum 6.

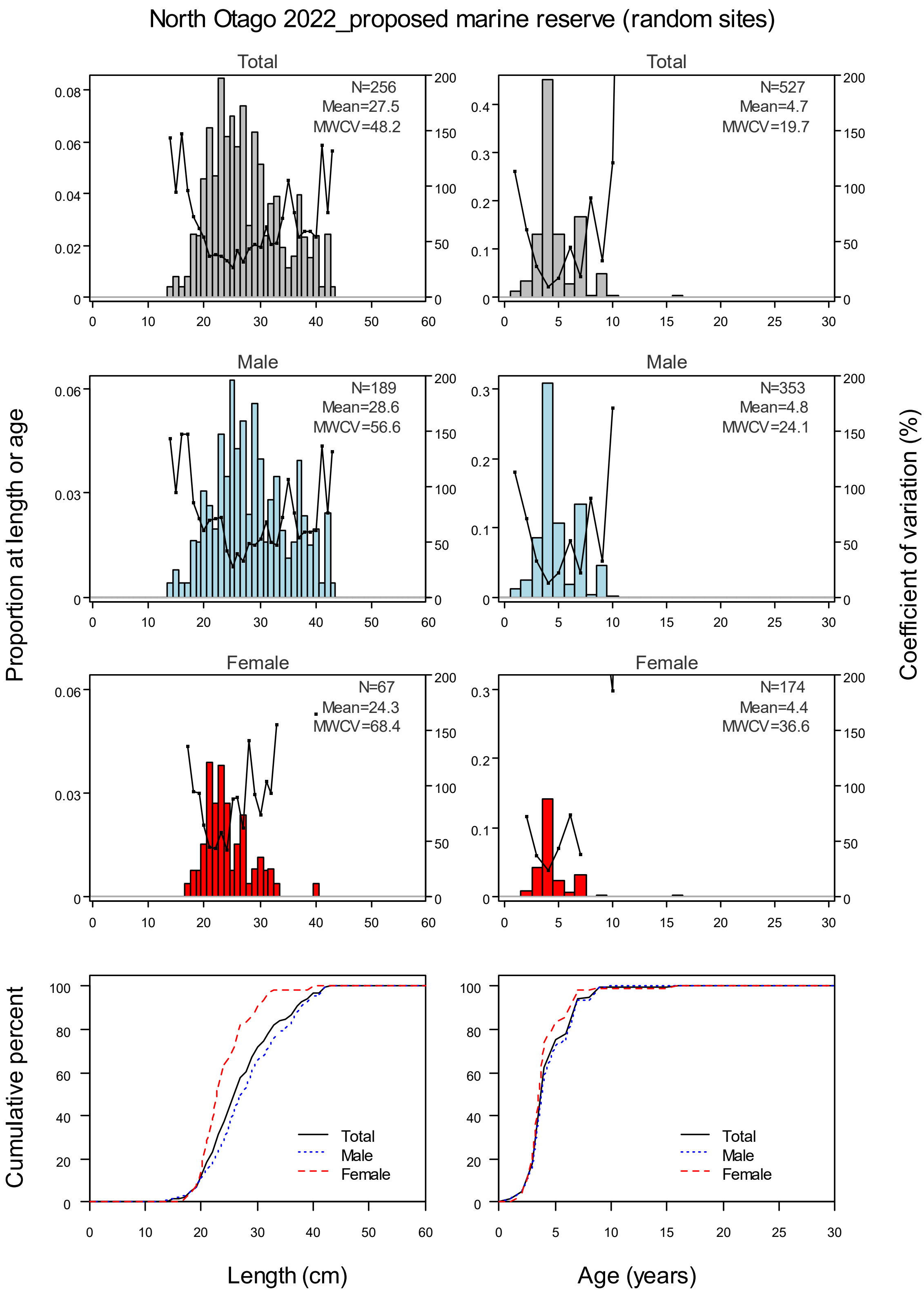

Figure 22: Scaled length frequency, age frequency, and cumulative distributions for total, male, and female blue cod for the 2022 potting survey of the proposed marine reserve. The plots include data from the four dedicated sites in the proposed marine reserve, plus four main survey sites that were inside the marine reserve polygon. N, sample size; MWCV, mean weighted coefficient of variation (%).

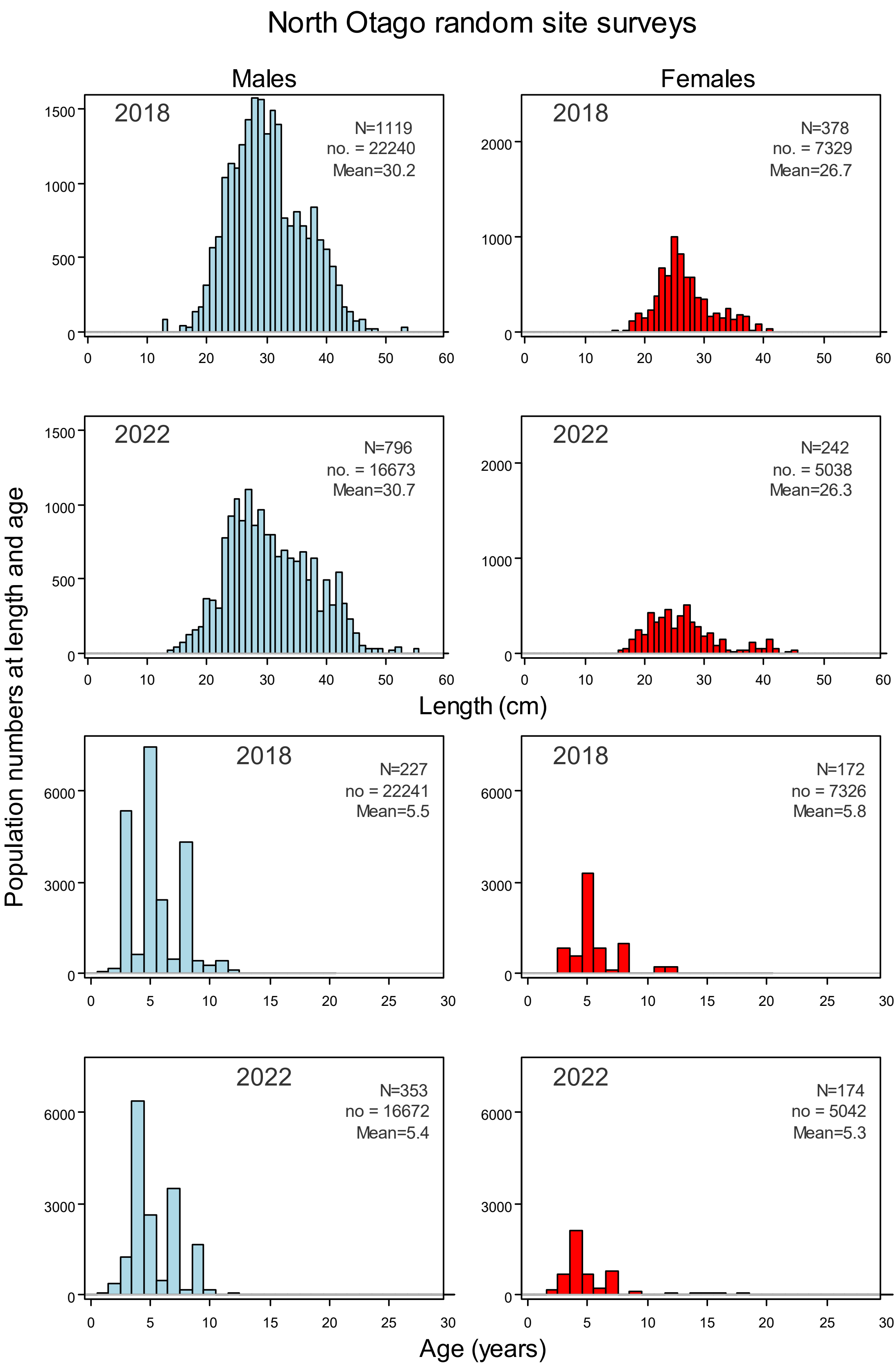

Figure 23: Scaled length and age frequency distributions for male and female blue cod for the 2018 and 2022 random-site blue cod potting surveys. Scaled numbers are relative, but non-informative. N, sample size; no, population number; Mean, mean length (cm).

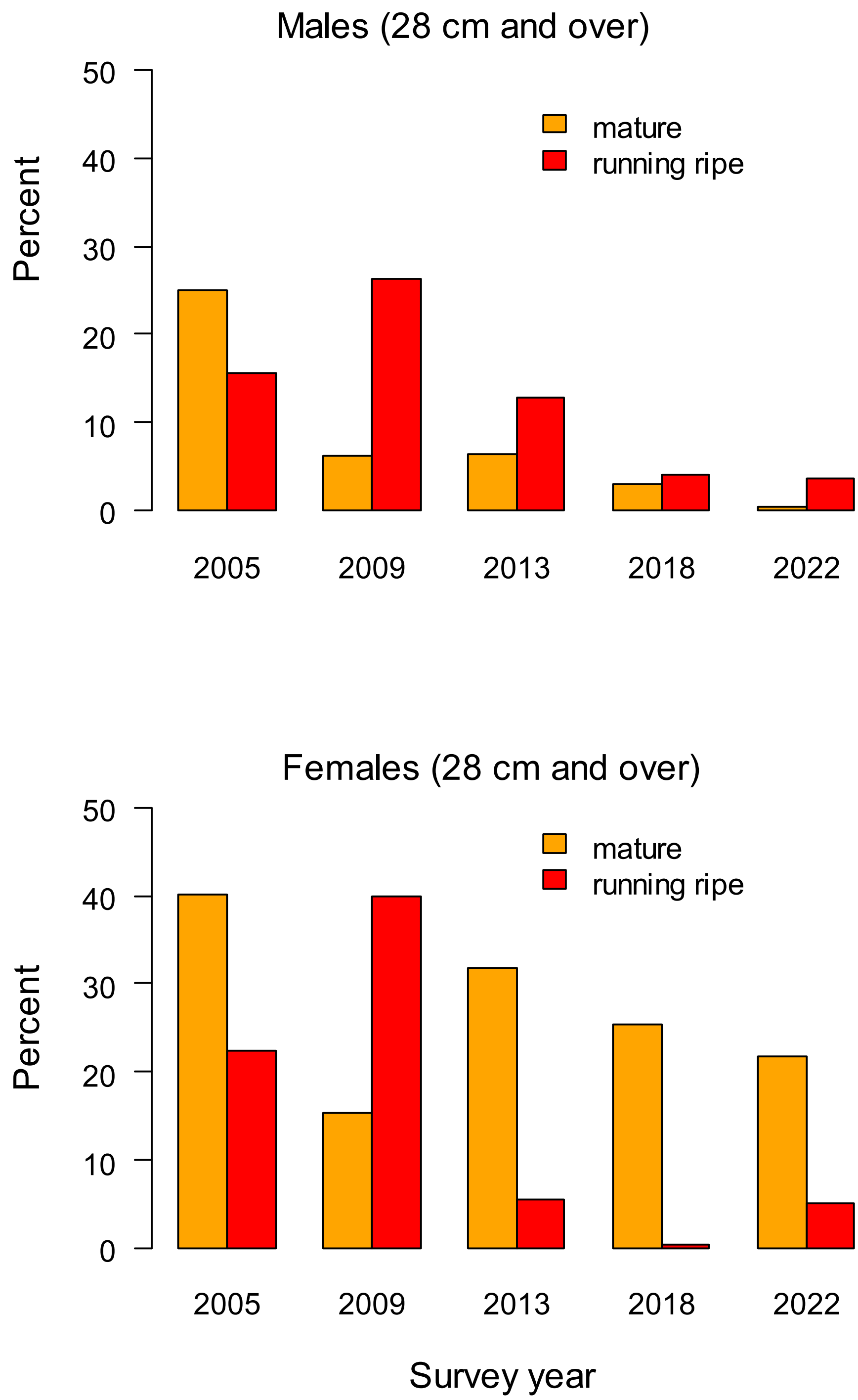

Figure 24: Percent of male and female blue cod in the 'mature' or 'running ripe' reproductive condition from North Otago blue cod potting surveys. All data combined for fixed and random-site surveys before 2022. Only fish considered to be mature (28 cm and over, from Fisheries New Zealand 2022), are included in these plots.

10. APPENDICES

Appendix 1: Fisheries New Zealand blue cod potting surveys carried out for 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, 2008	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)
	2021	Random-site	Systematic	(Beentjes et al. 2022b)
Kaikōura	2004, 2007	Fixed-site	Directed	(Carbines & Beentjes 2006a, 2009)
	2011, 2015	Fixed-site and Random-site	Directed and systematic	(Carbines & Haist 2012, 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 2012, Beentjes & Sutton 2017)
	2020	Random-site	Systematic	(Beentjes & Miller 2021)
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)
	2021	Random-site	Systematic	(Beentjes et al. 2022a)
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)
	2022	Random-site		This report
South Otago	2010	Fixed-site and Random-site	Directed and systematic	(Beentjes & Carbines 2011)
	2013, 2018, 2022	Random-site	Systematic	(Carbines & Haist 2018c, Beentjes & Fenwick 2019b), 2022 survey report pending
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 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 (1–6 or 1–9) in the order they are placed during a set. In the north Otago survey, six pots were 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 echosounder 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 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. A site may be specified as a latitude and longitude or a section of coastline (for the latter, the latitude and longitude at the centre of the section is used).
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 and aged from the 2022 north Otago random-site blue cod survey for males and females, by stratum and length class. An additional 57 otoliths were collected from the proposed marine reserve, but these were not aged.

	Males							Females						
	Strata							Strata						
Length (cm)	1	2	3	4	5	6	Male totals	1	2	3	4	5	6	Female totals
14						1	1							
15						1	1							
16			2			1	3			1				1
17			3			1	4						1	1
18	2		2			3	7			4	1		1	6
19	3		1	1		2	7	1		4	2		2	9
20	2		3	1	3	3	12	1		1	1	1	2	6
21	3		3	2	1	3	12	2		3	3		3	11
22	3		3	3			9	2		3	3	3	3	14
23	3		3	3	3	2	14	1		3	2		4	10
24	3		3	3	3	3	15	3		3	3	2	2	13
25	1		3	3	3	3	13	3		1	3	3	1	11
26	3		3	3	3	3	15	1		4	3	2	2	12
27	2		3	3	3	3	14	2		3	3	3		11
28	4		3	3	3	2	15	2		3	3	3	1	12
29	2		3	3	3	3	14			3	3	2	1	9
30	2		2	4	2	3	13	1		3	2	1	1	8
31	3		3	3	3		12	1		3	3	1		8
32	3		3	3	3	2	14			1		1	1	3
33	3		3	2	3	3	14			3	1	2		6
34	3		3	3	3	3	15					1		1
35	3		2	3	3	3	14				1			1
36	3		3	2	3		11			1				1
37	3		3	3	3	1	13	1						1
38	3		3	3	3	2	14	3		2				5
39	1		2	3	3	2	11	1		1				2
40	3		3	3	3	1	13			1	1			2
41	1		2	3	3		9	2		3		1		6
42	2	1	3	1	2	3	12			1	1			2
43	3		1	3	3	1	11							
44	3		2		3		8				1			1
45	3				1		4			1				1
46	1		1				2							
47			1				1							
48					1		1							
49			1				1							
50														
51				1			1							
52			1	1			2							
53														
54														
55			1				1							
Totals	7	1	81	69	70	58	353	27		56	40	26	2	174

Appendix 4: Summary of fixed-site surveys.

North Otago fixed-site surveys time series (2005, 2009, 2013, and 2018)

The addition of stratum 6 to the surveys from 2009 onward has made little difference to the survey overall catch rates estimated by including or excluding stratum 6 and, hence, 2005 has been included in the time series, despite not including stratum 6.

Catch rates among strata were similar in 2005 and 2009 when abundance was similar; however, in 2013 and 2018, the pattern changed among strata and between these two years. There was a clear and marked decline in the survey abundance between 2009 and 2013, with no overlap in the confidence intervals, and abundance remained low in 2018 (see Figure 18).

The scaled length frequency distribution shapes were similar for the 2005 and 2009, but changed in 2013 and again in 2018, with the latter having relatively fewer larger fish than earlier surveys. Although mean length of all-blue cod declined over time, for recruited blue cod (30 cm and over before July 2020), there was no trend (not shown, see Beentjes & Fenwick 2019a).

The proportion of pots with zero catch for all fixed-site surveys increased steeply on each successive survey from 2% in 2005 to 29% in 2018 (see Figure 21).

The overall sex ratio for all fixed-site surveys was 72–76% male for all blue cod and 85–86% male for recruited blue cod, with no trends (see Figure 22)

Comparison of concurrent fixed- and random-site surveys in 2013 and 2018

The catch rates from fixed-site surveys were generally higher across strata and slightly higher overall than for random-site surveys, but with overlapping confidence intervals (see Figure 18). The CVs and associated confidence intervals were not noticeably different between survey types with 2013 CVs of 13% and 14%, and 2018 CVs of 18% and 14% for fixed- and random-site surveys, respectively. The patterns of catch rates across strata were also similar for both survey types in 2013 and 2018.

There were only slight differences in the length distributions in 2013 and 2018 between fixed- and random-site surveys (not shown, see Beentjes & Fenwick 2019a).

The proportion of pots with zero catch was markedly higher for random-site surveys, with proportions of 22% and 34% in 2013, and 29% and 43% in 2018 for fixed- and random-site surveys, respectively (see Figure 21)

Sex ratios were largely the same between survey types, with proportions of male in 2013 of 76% and 68%, and in 2018, of 73% and 75% for fixed- and random-site surveys, respectively (see Figure 22).

Valid age data are available only for the 2018 fixed-site survey because on the previous surveys, ageing was not carried out in accordance with the blue cod ADP. Age distributions were similar for the 2018 fixed- and random-site surveys to the extent that total mortality, fishing mortality, and spawner-biomass-per-recruit ratios were identical for age-at-recruitment of seven years and M of 0.14 (not shown, see Beentjes & Fenwick 2019a).