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Relative abundance, size and age structure, and stock status of blue cod off south Otago in 2018

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Table of Contents

EXECUTIVE SUMMARY

Beentjes, M.P.; Fenwick, M. (2019). Relative abundance, size and age structure, and stock status of blue cod off south Otago in 2018.

New Zealand Fisheries Assessment Report 2019/14 47 p.

This report describes the results of the random-site potting survey for blue cod (*Parapercis colias*) off south Otago in April–May 2018. Estimates are provided for population abundance, size and age structure, sex ratio, total mortality (Z), and spawner biomass-per-recruit ratio.

The 2018 potting survey was the third in the south Otago time series, with previous surveys in 2010 and 2013. The 2010 survey was a dual random-site and fixed-site experimental survey in three of the six strata, and 2013 was a solely random-site survey in all six strata.

Forty-three random sites (6 pots per site, producing 258 pot lifts) at depths of 8–174 m in six strata off south Otago were surveyed. Mean catch rates of blue cod (all sizes) by stratum were 0.17–3.79 kg.pot^{-1}, with the lowest catch rates in stratum 4 (offshore south of Taieri Mouth) and highest catch rates in stratum 6 (offshore north of Taieri Mouth). The overall mean catch rate of blue cod for the survey was 1.52 kg.pot^{-1}, with a CV of 28.5%. Catch rates for recruited blue cod (30 cm and over) followed a similar pattern among strata as those for all blue cod; the overall mean catch rate for recruited cod was 1.18 kg.pot^{-1} (CV 32.2%). Of the 258 random-site pots, 145 (56%) had zero catch of blue cod. The sex ratios were 60–83% male across the six strata, and the overall weighted sex ratio was 68% male. The overall weighted mean length was 29.0 cm (range 14–56 cm) for males and 24.9 cm (range 8–49 cm) for females. The scaled length frequency distribution for males displayed two clear juvenile modes with peaks at about 14 cm and 22 cm, and a third less defined and wider mode centred round 33 cm. The female length distribution was similar, but the peaks were not as well defined and a few centimetres smaller than for males, reflecting the slower female growth.

Otolith thin-section ages from 326 males and 159 females were used to estimate the population age structure in 2018. The initial counts from each of the two otolith readers achieved 91% agreement, there was minimal bias between readers, and CV and average percent error were 1.1% and 0.8%, respectively. Von Bertalanffy growth parameters (L_∞, K, t_0) in 2018 were 64.9 cm, 0.086 yr^{-1}, -2.39 yr for males; and 50.7 cm, 0.109 yr^{-1}, and -1.88 yr for females. Sexed-based age-length-keys (one each for males and females) were used to estimate the population age composition. Ages in 2018 ranged from 1–21 years for males and 0–23 years for females, but most blue cod were 3–8 years old. The estimated population age distributions indicate that full selectivity to the potting method occurs at three years of age and older, with strong modes at three, five and eight years for both sexes, but particularly for males. The age distributions also exhibit weak modes for four-and seven-year-olds. The cumulative distribution plots of age frequency are similar for males and females and the mean ages were nearly the same at 5.0 years and 4.9 years, respectively. The traditional catch curve does not follow the ideal straight-line descending limb, suggesting that the assumption of constant recruitment had been violated to some extent, particularly for females, where some very weak and strong recruited year classes will have introduced error (and probably bias) into the Z estimate. Total mortality (Z) for age-at-full recruitment of six years (age at the minimum legal size for females) was estimated at 0.36 (95% confidence interval 0.24–0.50). Based on the default M of 0.14, estimated fishing mortality (F) was 0.22 and the associated spawner biomass-per-recruit ratio was 25.2% (95% confidence interval 17–44%).

There were no blue cod in the running ripe condition, suggesting that the survey took place either before or after the spawning peak.

Blue cod abundance (all and recruited) increased in 2013 followed by a marked decline in 2018. Given the confidence intervals, this decline is likely to be statistically significant. Only the 2018 survey has valid age estimates, so comparisons of age composition, total mortality (Z) and spawner-per-recruit ratios between surveys are not possible.

1. INTRODUCTION

This report describes the random-site potting survey of blue cod (*Parapercis colias*) off south Otago in April/May 2018. This is the third potting survey of blue cod off south Otago: a dual fixed and random-site experimental survey was carried out in 2010; and a solely random-site survey conducted in 2013 (Beentjes & Carbines 2011, Carbines & Haist 2014b).

1.1 South Otago blue cod fishery

Around the South Island, blue cod is the finfish species most frequently targeted and landed by recreational fishers (Ministry for Primary Industries 2017). The Quota Management Area (QMA) BCO 3 extends from the Clarence River, north of Kaikoura, to Slope Point in Southland (Figure 1). In BCO 3, recreational annual take was estimated at 119 t by a 2011–2012 panel survey (Wynne-Jones et al. 2014). Blue cod recreational catch in BCO 3 was the highest of any QMA (36% of total national recreational blue cod catch), with average daily catches of over 13 blue cod taken by 17% of respondents. This was supported by the National Blue Cod Strategy Report by MPI in 2017 (Ministry for Primary Industries 2017) in which recreational blue cod fishers were surveyed on-line nationally to gauge perceptions of the status of the New Zealand-wide blue cod fishery. Results from that survey ranked BCO 3 as the most important Quota Management Area in New Zealand for blue cod. Perceptions by respondents from Oamaru and Moeraki (Figure 1) ranked recreational bag limits as the major management issue, followed by localised depletion and fishing charter vessels, respectively. There are no reliable data to determine how the recreational blue cod catch is distributed within BCO 3, but north and south Otago are popular with recreational fishers as the Otago area offers relatively high catches, a bag limit of 30 blue cod (combined daily bag limit), and a minimum legal size of 30 cm. The two main access points for recreational fishers are Port Chalmers and Taieri Mouth, which are about 50 km apart and have permanent boat ramps (Figure 2). Limited access elsewhere is by launching from beaches.

The commercial catch from BCO 3 was about 40–50% higher than the estimated recreational catch with 166–183 t caught annually in the last seven years up to 2016–17 (Fisheries New Zealand 2018). Nearly all commercially landed blue cod in BCO 3 was caught by potting, and most of this was from Oamaru (Statistical Area 024), with much smaller amounts from Taieri Mouth (Statistical Area 026) and until the late 1990s from Kaikoura (Statistical Area 018) (Fisheries New Zealand 2018) (Figure 1).

1.2 South Otago bathymetry and substrate

The continental shelf off the south Otago coast is about 40 km wide but narrows to about 12 km off Otago Peninsula where it is incised by four relict canyons (Saunders, Papanui, Taiaroa, and Karitane Canyons) (Carter et al. 1985) (Figure 2). The main hydraulic feature is the warm saline Southland Current which originates from the Tasman Sea and travels through Foveaux Strait north-eastward along the continental shelf of the southern South Island (Carter et al. 1985). The Southland current is centred around 100 m depth off Otago with cooler neritic water inshore and the cold less saline sub-Antarctic water offshore of the slope. A frame-building bryozoan community forms a discrete band 25 km in length off the Otago Peninsula in 75 to 110 m depths (Batson & Probert 2000) (Figure 2). This area is thought to be important as habitat for invertebrate species and nursery grounds for commercially important finfish and shellfish including juvenile blue cod (Batson 2000).

The South Otago coast has considerable areas of foul ground compared to other parts of the New Zealand coastline, and trawling is limited to discrete areas between areas of foul. South Otago has substantial blue cod habitat such as biogenic reefs, both inshore and offshore, across a relatively flat sloping shelf, but also includes the heads of several canyons that form part of the Otago Canyon Complex. The survey area lies on the inner and mid continental shelf, which slopes gently away to the east, but also includes the heads of Saunders Canyon, and to a lesser extent Papanui Canyon, which form at about 200 m (Figure 2).

The sediments off south Otago have a mix of sand, gravel and rock areas distributed in patches with rock dominating inshore strata 1 and 2 (Figure 3). Stratum 3, at the head of Saunders Canyon, is predominantly sand with some gravel. There is no mud substrate within the survey area.

1.3 South Island blue cod potting surveys

Blue cod populations supporting South Island recreational fisheries are monitored using potting surveys. These surveys take place predominantly in areas where blue cod recreational fishing is common, but in some areas, including south Otago, there is substantial overlap between the commercial and recreational fishing grounds. Surveys are generally carried out every four years and provide data that can be used to monitor local relative abundance, size, age, and sex structure of geographically separate blue cod populations. The surveys provide a measure of the response of populations to changes in fishing pressure and management initiatives such as changes to the daily bag limit, minimum legal size, and area closures. One method to investigate the status of blue cod stocks is to estimate fishing mortality, the associated spawner-per-recruit ratio (SPR), and the Maximum Sustainable Yield (MSY) related proxy. The recommended Harvest Strategy Standard target reference point for blue cod (a low productivity stock) is $F_{45\%SPR}$ (Ministry of Fisheries 2011) — i.e., target fishing mortality should be at or below a level that reduces the spawner biomass to 45% of that if there was no fishing.

In addition to south Otago, there are currently eight other South Island areas located in key recreational fisheries that are surveyed by Fisheries New Zealand: Kaikoura (Carbines & Beentjes 2006a, 2009, Beentjes & Page 2017, 2018, Carbines & Haist 2018d); Motunau (Carbines & Beentjes 2006a, 2009, Beentjes & Sutton 2017, Carbines & Haist 2018d); Banks Peninsula (Beentjes & Carbines 2003, 2006, 2009, Beentjes & Fenwick 2017, Carbines & Haist 2017b); north Otago (Carbines & Beentjes 2006b, 2011, Carbines & Haist 2018b, Beentjes & Fenwick 2019); Foveaux Strait (Carbines & Beentjes 2012, Carbines & Haist 2017a, Beentjes et al. 2019); Paterson Inlet (Carbines 2007, Carbines & Haist 2014a, 2018a); Dusky Sound (Carbines & Beentjes 2006a, 2009, Beentjes & Page 2016); and the Marlborough Sounds (Blackwell 1997, 1998, 2002, 2006, 2008, Beentjes & Carbines 2012, Beentjes et al. 2017, Beentjes et al. 2018).

1.4 Potting survey design

All South Island potting surveys, except Foveaux Strait, originally used a fixed-site design, with predetermined (fixed) locations randomly selected from a limited pool of such sites (Beentjes & Francis 2011). The South Island potting surveys were reviewed by an international expert panel in 2009, which recommended that blue cod would be more appropriately surveyed using random-site potting surveys (Stephenson et al. 2009). A random-site is a location (single latitude and longitude) generated randomly from within a stratum (Beentjes & Francis 2011). Following this recommendation, all survey series are in transition to a fully random survey design with the interim sampling of both fixed and random sites allowing comparison of catch rates, length and age composition, and sex ratios between the survey designs. Random sites were the only site type used in all the Foveaux Strait surveys, and there has been a transition to solely random-site surveys in south Otago (2013 survey), Kaikoura (2017 survey), and Paterson Inlet (2018 survey). For other areas, the most recent surveys included both fixed and random sites.

1.5 Objectives

This report fulfils the final reporting requirement for Fisheries New Zealand Research Project BCO2017/05.

Overall Objective

To estimate relative abundance, maturity state, sex ratio, and age structure of blue cod (*Parapercis colias*) between Otago Peninsula and the Catlins.

Specific objectives

1. To undertake a potting survey between Otago Peninsula and the Catlins (BCO 3) to estimate relative abundance, age structure, size- and age-at-maturity, 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 survey areas.

2. METHODS

In this report we use the terms defined in the blue cod potting survey standards and specifications (Beentjes & Francis 2011) (Appendix 1).

2.1 2018 survey timing and area

A random-site potting survey of south Otago was carried out by NIWA from 4 April – 5 May 2018. The survey was consistent with start dates of previous surveys, but finished earlier.

The survey area for the 2018 south Otago random-site survey was identical to that for the 2013 survey (Figure 2). There are six strata: two are contiguous with the coast in depths less than about 30 m, three are offshore between Otago Peninsula and the Clutha River Mouth in depths from about 30 to 70 m, and there is one deeper isolated stratum in depths of 100–200 m directly east of Otago Peninsula on the edge of Saunders Canyon. These strata were defined after discussions with local recreational and commercial fishers in 2009 and are assumed to be areas where blue cod were most abundant, and where they have historically been targeted. 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).

2.2 2018 survey design

2.2.1 Allocation of sites

Simulations to determine the optimal allocation of random sites among the six strata were carried out using catch rate data from the 2013 random-site survey and NIWA's Optimal Station Allocation Program (*allocate*). Simulations were constrained to have a minimum of three sites per stratum and a CV (coefficient of variation) of no greater than 15%. The simulations indicated that 48 random sites were required to achieve the target CV of 15%.

The 2018 survey had a two-phase stratified random station design (Francis 1984) with 43 sites allocated to phase 1, and the remaining five available for phase 2, consistent with the proportion of phase 2 sites used in previous surveys (Table 1). However, no phase 2 was carried out because of weather and vessel availability issues.

Random sites

A random site has a location (latitude and longitude) generated randomly within a stratum (Beentjes & Francis 2011). Sites 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). Random-site surveys used systematic pot placement, 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.

2.2.2 Vessels and gear

Two vessels were used to carry out the survey. The northern part of the survey used the Otakou based fishing vessel F.V. *Triton* (registration number 7515) skippered by Mr Neil McDonald. The *Triton* is a 12.6 m length wood/fibreglass monohull, and powered by a Ford diesel 120 hp engine with propeller propulsion. The same vessel and skipper were used on the 2013 survey. For sites closer to Taieri Mouth, which is only navigable at mid to high tide because of the sand bar, the F.V *Chivalier* (registration number 901254) skippered by My John Pile was used. The *Chivalier* is a 13 m length fibreglass monohull, powered by a 500 hp Volvo Penta engine with propeller propulsion. Both skippers have considerable experience in commercial blue cod potting.

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

A high-performance, 3-axis (3D) acoustic Doppler current profiler (ADCP, RDI Instruments, 600 kHz) was deployed at each site. The ADCP records current flow and direction in 1 m depth bins above the seafloor as well as bottom water temperature. ADCP was not deployed in 13 of the 43 sampled sites, including all six stations in stratum 3 where sets were deep and ocean currents strong.

2.2.3 Sampling methods

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

At each site, six pots were set and left to fish (soak) for a target period of one hour during daylight hours. As each pot was placed, a record was made of sequential pot number (1 to 6), latitude and longitude from GPS, depth, and time of day. After each site was completed, the next closest site in the stratum was sampled. The ADCP was deployed at the centre of each site prior to the setting of pots and recovered after the last pot of each set was lifted. The order that strata were surveyed depended on the prevailing weather conditions, with the most distant strata and/or sites sampled in calm weather.

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. Pots were then emptied, and the contents sorted by species. Total catch weight per pot was recorded for each species to the nearest 10 g using 0–6/6–15 kg Marel motion compensating scales. The number of individuals of each species per pot was also recorded. Total length to the nearest centimetre below actual length, individual fish weight to the nearest 10 g, sex and gonad maturity were recorded for all blue cod. Sagittal otoliths were removed from a representative length range of blue cod males and females over the available length range across all strata. To ensure that otolith collection was spread across the survey area, the following collection schedule was used – collect three otoliths per 1 cm size class for each sex in stratum 3 (offshore deep), and in strata 1, 2, 4, 5 and 6 combined

(Appendix 2). Sex and maturity were determined by dissection and macroscopic examination of the gonads (Carbines 1998, 2004).

Blue cod gonad staging was undertaken using the five stage Stock Monitoring (SM) method used on previous surveys. Gonads were classified 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 2018 south Otago survey trip codes were TRI1802 and CHV1801. 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 & Francis 2011). All catch rate, 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); the numerical character identifies the stratum and the alpha character the site. 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). In the *age* database the *sample_no* is equivalent to *station_no* in the *trawl* database.

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 ºC. Thin sections were taken along the otolith dorso-ventral axis through the centrum of all five otoliths, using a Struers Accutom-50 digital sectioning machine, with a section thickness of approximately 350 µm. Resulting thin section wafers were cleaned and embedded on microscope slides using epoxy resin and covered with a coverslip. Finally, these slides were oven cured at 50ºC.
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 dark. Translucent zones were counted (ageing of blue cod otolith thin sections prior to 2015 counted opaque zones to estimate age).
3. Two readers read all otoliths without reference to fish length.
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 in Campana et al. (1995) and Campana (2001); including APE (average percent error) and coefficient of variation (CV).

2.2.6 Data analyses

Analyses of catch rates, sex ratios, scaled length distribution, catch-at-age, total mortality (*Z*) estimates, and spawner-per-recruit were carried out.

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). Fish length was recorded to the nearest millimetre on the survey, but following standard protocol, all lengths were rounded down to the nearest centimetre for analyses of the scaled length distribution, and mean length (i.e., using data extracted from t_lgth in the *trawl* database).

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 (30 cm and over). Catch rates of recruited blue cod were based on the sum of the weights of individual recruited fish which were all weighed on the survey. The stratum areas (km^2) shown in Table 1 were used as the area of the stratum (A_t) when scaling catch rates (equations 3 and 5 in 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 2018 south Otago survey were used in the following equation:

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

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

2.2.6.3 Growth parameters

Separate von Bertalanffy growth models (von Bertalanffy 1938) were fitted to the 2018 south 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 area (km^2) shown in Table 1 was taken as the area of the stratum (A_t), and the length-weight parameter estimates are from the 2018 south Otago survey data for males and females separately.

Length and age frequencies were calculated as numbers of fish from equations 7, 8, and 9 of Beentjes & Francis (2011). 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 age using equation 12 of Beentjes & Francis (2011). That is, simulated data sets were created by resampling (with replacement) sets from each stratum, and fish from each set (for length and sex information); and also fish from the age-length-sex data that were used to construct the age-length key.

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

2.2.6.5 Sex ratios, and mean length and age

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

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 (= natural mortality M + fishing mortality F). This assumes that recruitment and mortality are constant, that all recruited fish are equally vulnerable to capture, and that there are no age estimation errors.

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

A traditional catch curve was also plotted from the natural log of catch (numbers) against age and a regression line fitted to the descending curve from age at full recruitment. Although the Z estimate from the traditional catch curve was not used in further analyses, it provides a comparison for the CR estimate of Z. This is useful as a diagnostic to identify situations where there are not many age classes, and variable recruitment strength introduces bias.

2.2.6.7 Spawner-per-recruit estimates

A spawner-per-recruit analysis for 2018 was conducted using CASAL (Bull et al. 2005). The calculations involved simulating fishing with constant fishing mortality (F), and estimating the equilibrium spawning biomass per recruit (SPR) associated with that value of F (Beentjes & Francis 2011). The %SPR for that F is then simply that SPR, expressed as a percentage of the equilibrium SPR when there is no fishing (i.e., when F = 0, and %SPR =100%).

Input parameters used in SPR analyses

Growth parameters	von Bertalanffy growth parameters and length-weight coefficients are from the 2018 south Otago survey:

Parameter	Males	Females
K (yr^{-1})	0.086176	0.109737
t_0 (yr)	-2.39531	-1.88134
L_∞ (cm)	64.8848	50.7019
a	0.004727	0.005480
b	3.3418	3.3006

Natural mortality	default assumed to be 0.14. Sensitivity analyses were carried out for M values 20% above and below the default (0.11 and 0.17).
Maturity	the following maturity ogive was used: 0, 0, 0, 0.1, 0.4, 0.7, and 1; where 10% of blue cod are mature at 4 years old and all are mature at 7 years.
Selectivity	selectivity to the fishery (recreational/commercial) is described as knife-edge equal to age-at-MLS calculated from the 2018 south Otago survey von Bertalanffy model. The south Otago recreational MLS is 30 cm and selectivity was 4.8 years for males and 6.3 years for females.
Fishing mortality (F)	fishing mortality was estimated from the results of the Chapman-Robson Z analyses and the assumed estimate of M (i.e., $F = Z–M$). The Z value was for age-at-full recruitment (6 years for females).
Maximum age	assumed to be 31 years.

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

The SPR estimates are based on age at recruitment equal to the MLS for females, in this case six years.

2.3 Analyses of 2010 and 2013 south Otago surveys

The 2010 and 2013 south Otago surveys (trip_codes TRI1001 and TRI1302) were re-analysed as part of this report to ensure consistency and compliance with the analytical methods in the potting manual (Beentjes & Francis 2011). All analyses used survey data extracted from the Fisheries New Zealand *trawl* database. Catch rates of recruited blue cod were based on the sum of the weights of individual fish 30 cm and over, estimated from the respective 2010 and 2013 survey's published length-weight coefficients (Beentjes & Carbines 2011, Carbines & Haist 2018c). No ageing analyses of these two previous surveys were carried out because although blue cod were aged from these surveys, ageing was not compliant with the ADP for blue cod (Walsh 2017) and therefore ages cannot be assumed to be accurate.

3. RESULTS

3.1 2018 random-site survey

Forty-three random sites (6 pots per site, producing 258 pot lifts) from six strata in south Otago were surveyed from 5 April–5 May 2018 (Table 1, Figure 4). Depths sampled were 8–174 m (mean = 55.0 m). All 43 sites were sampled in phase 1; there was no phase 2 component because allocated vessel days had been used, and further the skipper did not show up on the last allocated day of the survey. An example of the systematic pot placement configuration for random sites is shown in Figure 5.

3.1.1 Catch and catch rates

A total of 465 kg of blue cod (1050 fish) was taken, comprising 78.6% by weight of the catch of all species on the survey (Table 2). Bycatch species included nine teleost fishes, as well as carpet shark, octopus, and other invertebrates. The most abundant bycatch species was brittle stars (Ophiuroidea) comprising 16.3% of the catch weight.

Mean catch rates (kg.pot^{-1}) of blue cod (all blue cod, and recruited blue cod 30 cm and over) are presented by stratum and overall (Table 3, Figure 6). Mean catch rates of blue cod (all sizes) by stratum were 0.17–3.79 kg.pot^{-1} with the lowest catch in stratum 4 (offshore south of Taieri Mouth) and highest catch rate in stratum 6 (offshore north of Taieri Mouth) (Table 3, Figure 4). The overall survey catch rate was 1.52 kg.pot^{-1} with a CV of 28.5%. Catch rates for recruited blue cod followed a similar pattern among strata as for all blue cod, and the overall survey catch rate was 1.18 kg.pot^{-1} (CV 32.2%) (Table 3, Figure 6). Of the 258 random-site pots, 145 (56%) had zero catch of blue cod.

3.1.2 Biological and length frequency data

Of the 1050 blue cod caught, all were measured for length, weighed, and sexed (Table 4). The sex ratios were 60–83% male across the six strata and the overall weighted sex ratio was 68% male (Table 4). Length was 14–56 cm for males and 8–49 cm for females. In strata 1–5 there were too few fish to assess the shape of the scaled length frequency distributions, although in stratum 4 there were no recruited fish (30 cm and over) and a small mode of juvenile fish was apparent (Figure 7). Stratum 6 comprised 43% and 46% of the scaled numbers of males and females, respectively for the survey and the scaled length frequency distributions were unimodal overall except for a strong juvenile mode centred around 20–23 cm, particularly for males (Figure 7).

3.1.3 Age and growth

Otolith section ages from 326 males and 159 females were used to estimate the population age structure from south Otago in 2018 (Table 5). 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 8). There is a large range in length-at-age, particularly for males; and males generally grow faster and comprise most of the largest fish. The growth rates for all three surveys are similar by sex up to about age 5, after which they tend to diverge (Figure 8). The estimated mean length at maximum age (L_∞) is implausibly high for males, likely a result of low numbers of fish older than about 12 years.

Between-reader age comparisons are presented in Figure 9. The first counts of the two readers showed 91% agreement, and overall there was no bias between readers with a CV of 1.1% and average percent error (APE) of 0.8%.

3.1.4 Spawning activity

Gonad stages of blue cod sampled on the south Otago survey in April to early May 2018 are presented for all fish combined (Table 6). There were few indications of spawning activity during the survey period with no fish in the running ripe condition and few in the ripe condition, suggesting that the survey took place after the spawning peak.

3.1.5 Population length and age composition

The scaled length frequency and age distributions for the 2018 south 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 10).

The scaled length frequency distribution for males displayed two clear juvenile modes with peaks at about 14 cm and 22 cm, and a third less defined and wider mode centred round 33 cm (Figure 10). Male mean length was 29 cm. The female distribution was similar, but the peaks were not as well defined and a few centimetres less than for males, reflecting the slower growth. There were also relatively fewer larger female fish and the mean length was 24.9 cm (Figure 10). The cumulative distribution plots of length frequency reflect these differences showing that male distributions have a longer right-hand tail. The mean weighted coefficients of variation (MWCVs) around the length distributions were 35% and 49% for males and females, respectively.

The 2018 survey age estimates were 1–21 years for males and 0–23 years for females, but most males and females were 3–8 years old (Figure 10). The estimated population age distributions indicate that while fish as young as 0–2 years old are entering the pots, full selectivity to the potting method appears to be at about three years of age or older, with strong modes at three, five and eight years for both sexes, but particularly for males. The age distributions also exhibit weak modes for four-and seven-year-olds. The cumulative distribution plots of age frequency are similar for males and females and the mean ages were nearly the same at 5.0 years and 4.9 years, respectively (Figure 10). The MWCVs around the age distributions were 23% for males and 40% for females, indicating a good representation of the overall population age structure for males, but not females.

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

Chapman-Robson total mortality estimates (Z) and 95% confidence intervals are given for a range of recruitment ages (5–10 y) in Table 7. Age-at-full recruitment (AgeR) is assumed to be six years, equal to the age at which females reach the MLS of 30 cm. In 2018 the CR Z for AgeR of six years was 0.36 (95% confidence interval of 0.24–0.50).

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 six years, is shown for the 2018 survey for diagnostic purposes (Figure 11). The natural log of numbers-at-age does not follow the ideal straight-line descending limb, suggesting that the assumption of constant recruitment had been sufficiently violated to introduce bias, particularly for females (Figure 11). Although the CR estimation is less sensitive to age classes with few fish, some very weak and strong recruited year classes will have introduced error (and probably bias) into the Z estimate, which is reflected in the 95% confidence intervals around Z (see Table 7).

Mortality parameters (CR Z and F, and M) and spawner-per-recruit (SPR) estimates at three values of M and age at full recruitment of six years are shown for the 2018 survey in Table 8. Based on the default M of 0.14, estimated fishing mortality (F) was 0.22 and associated spawner-per-recruit was 25.2% (Figure 12). At the 2018 levels of fishing mortality, the expected contribution to the spawning biomass over the lifetime of an average recruit is reduced to 25% of the contribution in the absence of fishing. The 95% confidence interval around the 2018 SPR ratio using the default *M* was 17–44% (Table 8).

3.2 South Otago random-site surveys time series (2010, 2013, 2018)

Mean catch rates (kg.pot^{-1}) for all blue cod and recruited blue cod by stratum for the three random-site surveys are presented in Figure 13. The 2010 survey included only three of the six strata (1, 3 and 6). The pattern of catch rates in 2010 and 2013 amongst the three common strata (1, 3 and 6), were similar, with the highest catch rates being from stratum 6 and the lowest in stratum 1 (see Figure 4 for strata locations). The catch rate pattern in 2018 changed from that in 2013 with large relative declines in strata 3, 4 and 5. Overall, whether comparing survey catch rates from the three common strata (1, 2 and 3), or for all strata surveyed in each year, blue cod abundance (all and recruited) increased in 2013 followed by a marked decline in 2018 (Figures 13 and 14). Given the confidence intervals for both strata comparisons, this decline is likely to be statistically significant.

The scaled length frequency distributions and mean length of all blue cod from the three random-site surveys were generally similar in that they have corresponding modes, but the strength of the modes varies, i.e., all years have a pre-recruit mode about 22–25 cm, but in 2013 it dominates the distributions (Figure 15). The 2013 survey also has proportionately more large recruited fish than the other years, shown clearly by the cumulative distributions (Figure 15). Similarly, recruited mean length was larger in 2013, and for males this was statistically significant with no overlap in confidence intervals (Figure 16).

The sex ratio for the three random-site surveys was 57–68% male for all blue cod, and 73–86% male for recruited blue cod, with no clear trend (Figure 17).

The proportion of pots with zero catch for the three random-site surveys ranged from 34–56% with a clear increasing trend (Figure 18).

Only the 2018 survey has valid age estimates, so comparisons of age composition, total mortality (*Z*) and spawner-per-recruit ratios among surveys are not possible.

3.3 Comparison of fixed and random-site surveys in 2010

In 2010 the catch rates of all blue cod from fixed sites are more than double those for random sites, with no overlap in confidence intervals (see Figure 14). The CVs were similar at 17% and 18%, for fixed and random site surveys respectively, and highest catch rates in both surveys were in stratum 6 (see Beentjes & Carbines 2011).

The length frequency distributions in 2010 were different between fixed and random sites with fixed sites having a higher proportion of larger fish and fewer smaller fish (see Figure 15). Mean length of recruited fish, however, was not different (see Figure 16).

Sex ratios were much the same between survey types in 2010 with 74% and 67% male for fixed and random site surveys, respectively (Figure 17).

The proportion of pots with zero catch was identical (34%) for fixed and random site surveys in 2010 (Figure 18).

The 2010 survey also compared pot placement (directed and systematic) and found no meaningful differences in catch rates, regardless of pot placement, for either fixed or random site surveys (Beentjes & Carbines 2011).

4. DISCUSSION

4.1 General

The 2018 south Otago random-site potting survey was the third survey in the time series of relative abundance and population structure of blue cod from this area, with previous surveys in 2010 and 2013. The 2010 survey was a dual random-site and fixed-site experimental survey in three of the six strata, and 2013 was a solely random-site survey in all six strata.

4.2 Blue cod habitat and abundance

Sediment samples (*n* = 30 000 stations) 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. 2018). The sediment maps of south Otago show how sand, mud, gravel and rock are distributed within and around the six strata. Within the survey strata, substrates are patchy with rock dominating the inshore strata (1 and 2), and a mix of sand and gravel with some rock occurring offshore (strata 4–6). The deep stratum 3 in 100–200 m is mostly sand with some gravel between Saunders and Papanui Canyons (see Figure 2).

South Otago offers substantial and varied blue cod habitat, both inshore, offshore on the mid shelf (30 to 75 m), and also in deep water out to 200 m at the head of the Saunders Canyon. The area off the south Otago coast is a highly dynamic oceanic environment with a narrow continental shelf incised with many canyons, and complex water current and water mass regimes that include inshore neritic water, the fast flowing, warm, saline Southland Current, bounded offshore by cooler and less saline sub-Antarctic water (Carter et al. 1985, Chiswell 1996). The seafloor is rugged and characterised by large areas of foul ground that provides substantial and varied blue cod habitat. The strata boundaries were originally based, to a large extent, on where blue cod were thought to be most abundant, and where they were targeted. Stratum 3 is the deepest of any area surveyed for blue cod in any of the South Island surveys and demonstrates the wide depth distribution of blue cod from near shore out to 200 m.

The relative abundance of blue cod across the six survey strata in 2013[1] showed that the largest catches were offshore and sets with zero catch were virtually all confined to the inshore strata (Figure 19). In 2018, however, the distinction between inshore and offshore catch size was not evident, and the zero catches were also not confined to the inshore (Figure 20). The differences between these two surveys may be partly explained by the much lower catch rates and higher incidence of zero catches in the 2018 survey (see Figures 14 and 18). The catch rate distributions in both years show no clear association between habitat type and abundance (Figures 19 and 20, see Figure 3). The sediment maps, however, are only approximations based on extrapolations from the nearest historic sediment sampling stations and most likely do not fully reflect the dynamic nature of sediment shifts. A more detailed analyses of habitat type by pot location in real time is required to determine if a relationship exists between habitat type and blue cod abundance. For example, underwater video at selected sites during the 2013 south Otago potting survey showed some preference by small and large fish for specific habitats (Carbines & Haist 2018c). It is clear, however, that off the south Otago coast, blue cod occupy a broad variety of seafloor types from rock through to sand, across a wide depth range.

[1] 2010 survey catch rate distribution was not plotted because random sites were not assigned codes in the *trawl* database and joining catch with location of the random site was problematical. Further only three strata were surveyed in 2010.

4.3 Survey precision

The survey CV around relative abundance estimates (catch rates) was not specified in the project objectives for the 2018 south Otago survey, but a CV of around 15% is generally targeted in blue cod surveys. The achieved CV of 28% in 2018 (from 43 sites) was higher than desired and higher than the previous full random-site survey in 2013 (20% from 40 sites). The high CV may have been reduced if a phase 2 component had been carried out, but more likely this was because of the lower abundance of blue cod in 2018 and the increase in zero catches. The 2018 CV of 28% indicates that the number of sites should be increased for future surveys if a lower CV is desired.

4.4 Age structure and genetic mixing

Growth estimates from the 2018 survey indicate that males are on average 5-years-old, and females nearly 6-years-old when they reach the current MLS of 30 cm in south Otago (see Figure 8). Hence the abundance of 5-year-old fish (5+) in 2018 suggests that the 2012 year-class can be expected to provide a strong pulse of recruitment to the south Otago fishery over the next few years (see Figure 10). The partially selected 2014 (3+) year class appears to be very strong and most likely will result in another pulse of recruitment to the fishery in a few years' time. The south Otago fishery is currently dominated by the 2011 and 2009 year-classes (ages 6+ and 8+) (see Figure 10).

The south Otago blue cod age structure is similar to that from the east coast South Island areas that have been surveyed from 2015 to 2018 (Banks Peninsula, Kaikoura, Motunau, and north Otago) which have all displayed a strong 2012 year-class and a weak 2011 year-class (Beentjes & Fenwick 2017, Beentjes & Page 2017, Beentjes & Sutton 2017, Beentjes & Fenwick 2019). These findings indicate that blue cod on the east coast South Island are prone to variable recruitment with intermittent pulses of strong and weak year classes, a characteristic not evident in Foveaux Strait (Beentjes et al. 2019). The consistent age pattern on the northeast and southeast coast of the South Island suggests that the 2012 spawning event was more successful than average and/or that natural mortality was low, possibly a result of favourable environmental conditions along the east coast South Island. Blue cod tend to have a restricted home range (Rapson 1956, Mace & Johnston 1983, Mutch 1983, Carbines & McKenzie 2001, Carbines & McKenzie 2004) and stocks are likely to consist of largely independent sub-populations. However, there is no evidence that blue cod are genetically distinct around the New Zealand mainland (Gebbie 2014), suggesting that mixing is occurring on a wider geographical scale than within the mainly restricted home range indicated by some tagging studies. Tagging studies in Dusky Sound and Foveaux Strait have shown that while most blue cod move very little from the tagging location, some have been recaptured many kilometres away (Carbines & McKenzie 2001, Carbines & McKenzie 2004). Similarly, a recent tagging study of blue cod at Kaikoura showed that most returns were from locations close to the site of release, but one tag was reportedly recaptured off Kapiti Island eight months after release (Emma Kearney, University of Otago, pers. comm.). Mechanisms for genetic mixing are unknown, but clearly some blue cod do undertake large movements.

4.5 Sex change and sex ratio

The 2018 south Otago blue cod survey sex ratio was 68% male (see Table 4), a value reasonably consistent across all three random-site surveys (see Figure 17). The proportion male tends to increase with length, with females often dominating at lengths below about 20 cm to 30 cm (Figure 21). The large spikes in Figure 21 reflect low numbers of fish at small and large sizes.

Blue cod are protogynous hermaphrodites with some (but not all) females changing into males as they grow (Carbines 2004). In areas where fishing pressure is known to be high, such as Motunau, inshore Banks Peninsula, and the Marlborough Sounds, the sex ratios are strongly skewed towards males, contrary to an expected dominance of females resulting from selective removal of the larger final phase male fish (Beentjes & Carbines 2003, 2006, Carbines & Beentjes 2006a, Beentjes & Carbines 2012, Beentjes & Sutton 2017). Beentjes & Carbines (2005) suggest that the shift towards a higher proportion of males in heavily fished blue cod populations may be caused by removal of the inhibitory effect of large males, resulting in a higher rate (and possibly earlier onset) of sex change by primary females. Recent experimental studies have indicated that in the protogynous hermaphroditic tuskfish (*Choerodon schoenleinii*), this process may be density dependent, with the degree of male to female tactile stimulation regulating the extent of sex change from females to males (Sato et al. 2018). Sex change is more likely to occur at low levels of behavioural interaction between a dominant male and a female. The male-dominated sex ratio in south Otago indicates that this population is heavily fished, consistent with high estimates of fishing mortality and low spawner biomass per recruit ratio (see below).

4.6 Reproductive condition

The 2013 and 2018 south Otago random-site blue cod surveys were carried out in April/May, while the 2010 survey went into early June, so reproductive status is temporally comparable between surveys. There were no indications of spawning activity for either sex on any of the three surveys. 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 ripe and running-ripe conditions during this period. Often there are higher proportions of females than males in the combined ripe/running-ripe conditions, possibly related to the reproductive strategy where a large male will hold a territory, attracting multiple females. The virtual absence of ripe or running-ripe fish in any of the south Otago surveys suggests that these surveys in April to early June took place after the spawning season.

4.7 Stock status and management implications

The *Harvest Strategy Standard* (Ministry of Fisheries 2011) 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. 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 $\mathrm{F_{MSY}}$ is the level of spawner-per-recruit $\mathrm{F_{\%SPR}}$ (Ministry of Fisheries 2011). Blue cod is categorised as an exploited species with low productivity (on account of complexities of sex change) and the recommended default proxy for F_{MSY} is $F_{45\%\mathrm{SPR}}$.

The 2018 south Otago random-site survey Z estimate was 0.36, F was 0.22 and the SPR estimate (M value of 0.14, and age at full recruitment of 6 years) was $F_{25.2\%\mathrm{SPR}}$ ($F_{17\%–44\%\mathrm{SPR}}$, 95% CI), indicating that the expected contribution to the spawning biomass over the lifetime of an average recruit was reduced to 25% of the contribution in the absence of fishing (see Figure 15). These results suggest that the level of exploitation (F) of south Otago blue cod stocks in 2018 was above the F_{MSY} target reference point of $F_{45\%\mathrm{SPR}}$ (i.e., the stock was over-exploited). Stock status before 2018 cannot be determined because there is no valid ageing for the 2010 and 2013 surveys.

As well as the exploitation rate being well above the F_{MSY} target reference point, from 2013 to 2018 the catch rates in south Otago declined by four-fold, recruited mean length of males declined, and the proportion of zero catch pots increased. These are all indications of increasing exploitation and declining abundance and size.

The high historic catch rates, MLS of 30 cm and a bag limit of 30 fish (or blue cod) has made north Otago attractive to blue cod fishers and there is strong anecdotal evidence of a large increase in effort at Moeraki in recent years, from both recreational and charter vessels. Displacement of recreational fishing effort from Canterbury to south Otago is also likely 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 Kaikoura. Without information on recreational fishing effort, however, it is difficult to gauge impacts on the stock status. For example, the 2018 low abundance in south Otago may be a result of sustained poor recruitment over several years, although there are no reliable ageing data before 2018 to verify this. Otoliths from previous surveys could be re-aged using the age determination protocol for blue cod (Walsh 2017).

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7. TABLES AND FIGURES

Table 1: Effort and catch data for the 2018 south Otago random-site blue cod potting survey.

	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	154.9	Random	4		24	133	77.6	23.6	10–46
2	245.4	Random	4		24	54	25.1	14.1	8–27
3	177.9	Random	6		36	75	52.8	128.1	100–174
4	426.2	Random	12		72	133	12.2	50.3	38–64
5	196.6	Random	5		30	39	24.2	52.4	45–63
6	251.3	Random	12		72	616	273.1	61.3	41–77
Total	1452.3	Random	43	0	258	1 050	465	55.0	8–174

Table 2: Total catch and numbers of blue cod and bycatch species caught on the 2018 south Otago random-site blue cod potting survey. Percent of the catch by weight is also shown.

		Random sites			
Common name	Species	Code	Number	Catch (kg)	% catch
Blue cod	*Parapercis colias*	BCO	1 050	465.0	78.56
Brittle star	Ophiuroidea	OPH	1 650	96.9	16.37
Common octopus	*Octopus maorum*	OCT	2	8.1	1.37
Banded Wrasse	*Notolabrus fucicola*	BPF	8	6.1	1.03
Tarakihi	*Nemadactylus macropterus*	NMP	39	4.7	0.79
Southern bastard cod	*Pseudophycis barbata*	SBR	2	3.2	0.54
Carpet shark	*Cephaloscyllium isabella*	CAR	1	2.3	0.39
Scarlet wrasse	*Pseudolabrus miles*	SPF	2	1.6	0.27
Sea perch	*Helicolenus percoides*	SPE	2	0.9	0.15
Starfish	Asteroidea	ASR	4	0.8	0.14
Leatherjacket	*Meuschenia scaber*	LEA	3	0.8	0.14
Red cod	*Pseudophycis bachus*	RCO	2	0.5	0.08
Blue moki	*Latridopsis ciliaris*	MOK	1	0.5	0.08
Crab	Decapod	CRB	3	0.3	0.05
Hermit crab	Paguridae	PAG	2	0.1	0.02
Yellow cod	*Parapercis gilliesi*	YCO	2	0.1	0.02
			2 773	591.9	100

Table 3: Mean catch rates for all blue cod, and recruited blue cod (30 cm and over) from the 2018 south Otago random-site blue cod potting survey. Catch rates are pot-based, and s.e. and CV are set-based. s.e., standard error; CV coefficient of variation; NA, not applicable.

		All blue cod			Recruited blue cod ≥ 30 cm		
Stratum	Pot lifts (N)	Catch rate (kg.pot^{-1})	s.e.	CV (%)	Catch rate (kg.pot^{-1})	s.e.	CV (%)
1	24	3.23	3.23	100	2.81	2.81	100
2	24	1.05	0.73	70.1	0.76	0.60	79.1
3	36	1.47	0.69	47.3	1.33	0.66	49.8
4	72	0.17	0.11	63.0	0.00	0.00	NA
5	30	0.81	0.49	60.7	0.79	0.48	61.3
6	72	3.79	1.15	30.3	2.77	1.04	37.4
Overall	258	1.52	0.43	28.5	1.18	0.38	32.2

Table 4: Descriptive statistics for blue cod caught on the 2018 south Otago random-site blue cod potting survey. Mean lengths are raw for each stratum, and weighted overall. Sex ratio is also given for recruited blue cod (30 cm and over). m, male; f, female; u, unsexed; –, no data.; *, length is suspect.

	Random site survey						
			Length (cm)			Percent male	
Stratum	Sex	N	Mean	Minimum	Maximum	All blue cod	Recruited blue cod ≥ 30 cm
1	m	110	32.8	24.8	49.7	82.7	86.5
	f	23	29.6	23.3	33.9		
	u	–	–	–	–		
2	m	36	31.5	20.8	45.0	66.5	91.4
	f	18	26.6	21.2	42.8		
	u	–	–	–	–		
3	m	46	32.6	21.9	53.1	61.6	64.5
	f	29	35.8	19.9	49.5		
	u	–	–	–	–		
4	m	79	19.4	12.5	27.9	59.7	no recruited fish
	f	54	18.6	8.5	26.5		
	u	–	–	–	–		
5	m	28	32.4	14.3	*61.9	72.4	68.7
	f	11	35.0	27.3	42.2		
	u	–	–	–	–		
6	m	411	29.8	14.1	56.5	66.7	84.8
	f	205	24.3	13.4	42.8		
	u	–	–	–	–		
Overall	m	710	29.0	14.1	56.5	68.4	82.4
	f	340	24.9	8.5	49.5		
	u	–	–	–	–		

Table 5: Otolith ageing data used in the catch-at-age, Z estimates and SPR analyses for the 2018 south Otago random-site blue cod potting survey.

		Length of aged fish (cm)		Age (years)	
Survey	No. otoliths	Minimum	Maximum	Minimum	Maximum
Total	485	8	56	0	23
Male	326	14	56	1	21
Female	159	8	49	0	23

Table 6: Percentages of blue cod (by sex) in each gonad stages from the south Otago random-site blue cod potting survey in April–early May 2018. 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	49.2	1.0	0.1	0.0	49.7	710
Females	89.7	2.1	0.0	0.0	8.2	340

Table 7: Chapman-Robson total mortality estimates (*Z*) and 95% confidence intervals for blue cod from the random-site 2018 south Otago random-site blue cod potting survey. AgeR, age at full recruitment.

		95% CIs	
AgeR	*Z*	Lower	Upper
5	0.46	0.31	0.62
6	0.36	0.24	0.50
7	0.36	0.26	0.48
8	0.44	0.29	0.60
9	0.31	0.20	0.45
10	0.40	0.25	0.60

Table 8: Mortality parameters (Chapman Robson *Z*, *F* and *M*) and spawner-per-recruit ($F_{SPR\%}$) point-estimates at three values of *M* for blue cod from the 2018 south Otago random-site blue cod potting survey. The mortality parameters and spawner-per-recruit estimates are also given for the default *M* (0.14) and the 95% confidence interval values of Z. AgeR = 6, where AgeR is the age at which females reach MLS of 30 cm. *F*, fishing mortality; *M*, natural mortality; *Z*, total mortality; LowerCI, lower 95% confidence interval; UpperCI, Upper 95% confidence interval.

M	*Z*	*F*	$F_{\%SPR}$	Estimate
0.11	0.36	0.25	$F_{17.6}$	Point
0.14	0.36	0.22	$F_{25.2\%}$	Point
0.17	0.36	0.19	$F_{33.7\%}$	Point
0.14	0.24	0.10	$F_{44.5\%}$	LowerCI
0.14	0.50	0.36	$F_{16.7\%}$	UpperCI

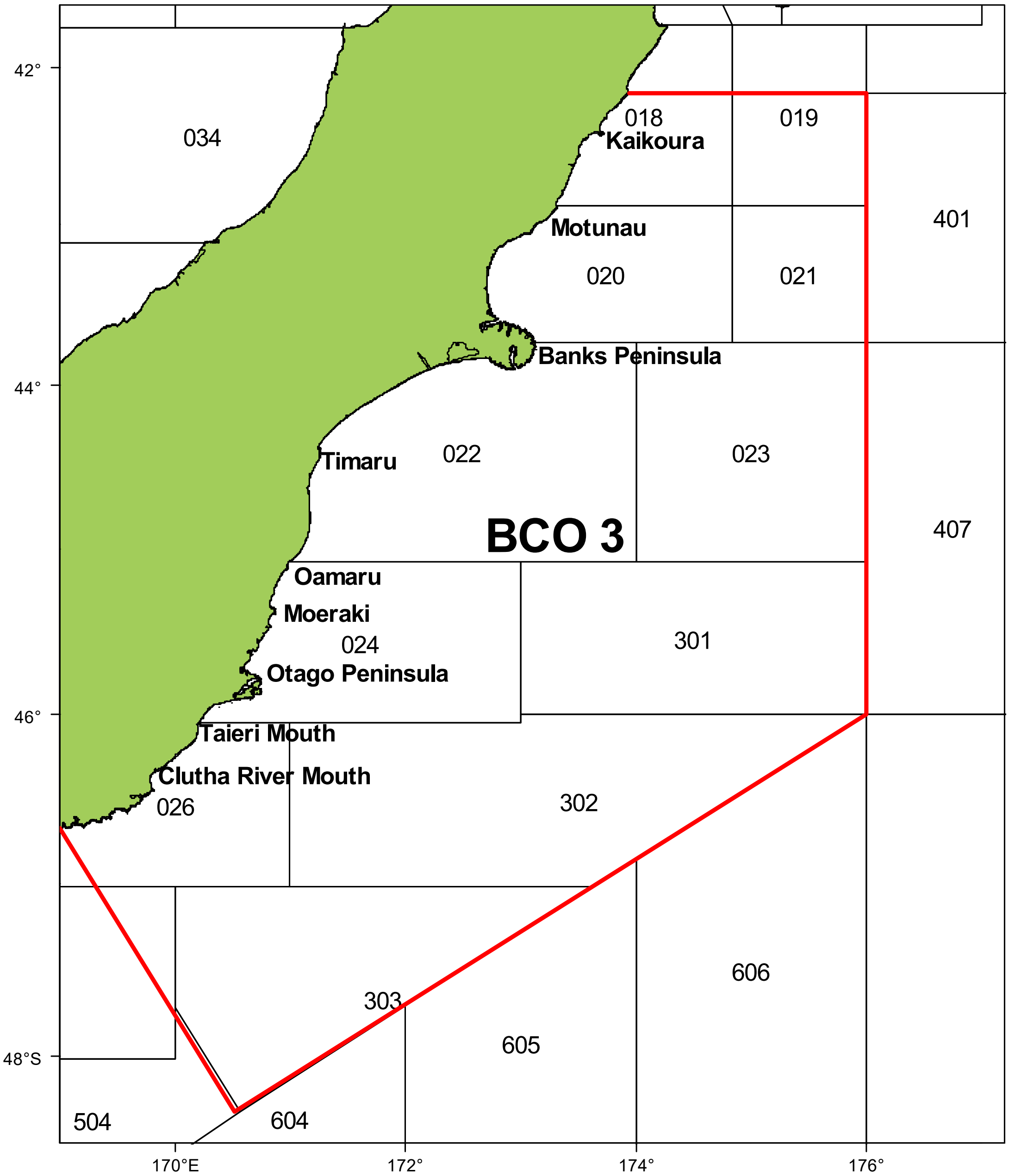

Figure 1: Blue cod Quota Management Area BCO 3 (red border) and statistical areas. The south Otago survey area is from Otago Peninsula to Clutha River Mouth.

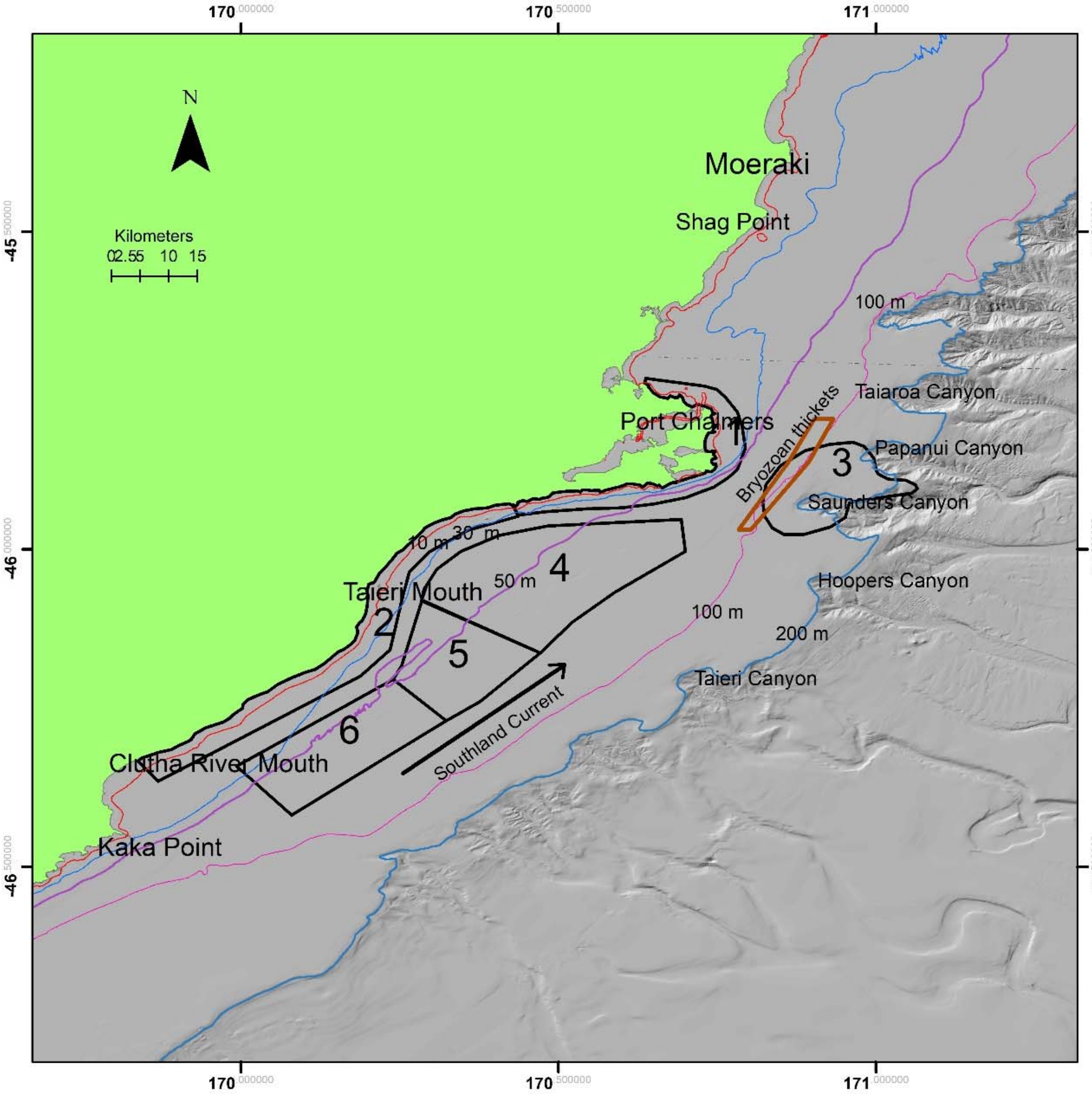

Figure 2: South Otago blue cod survey strata, bathymetry contours, and hillshade view of the seafloor based on the NIWA Digital Terrain Model (DEM) of the 25 m gridded data-set (3× vertical exaggeration).

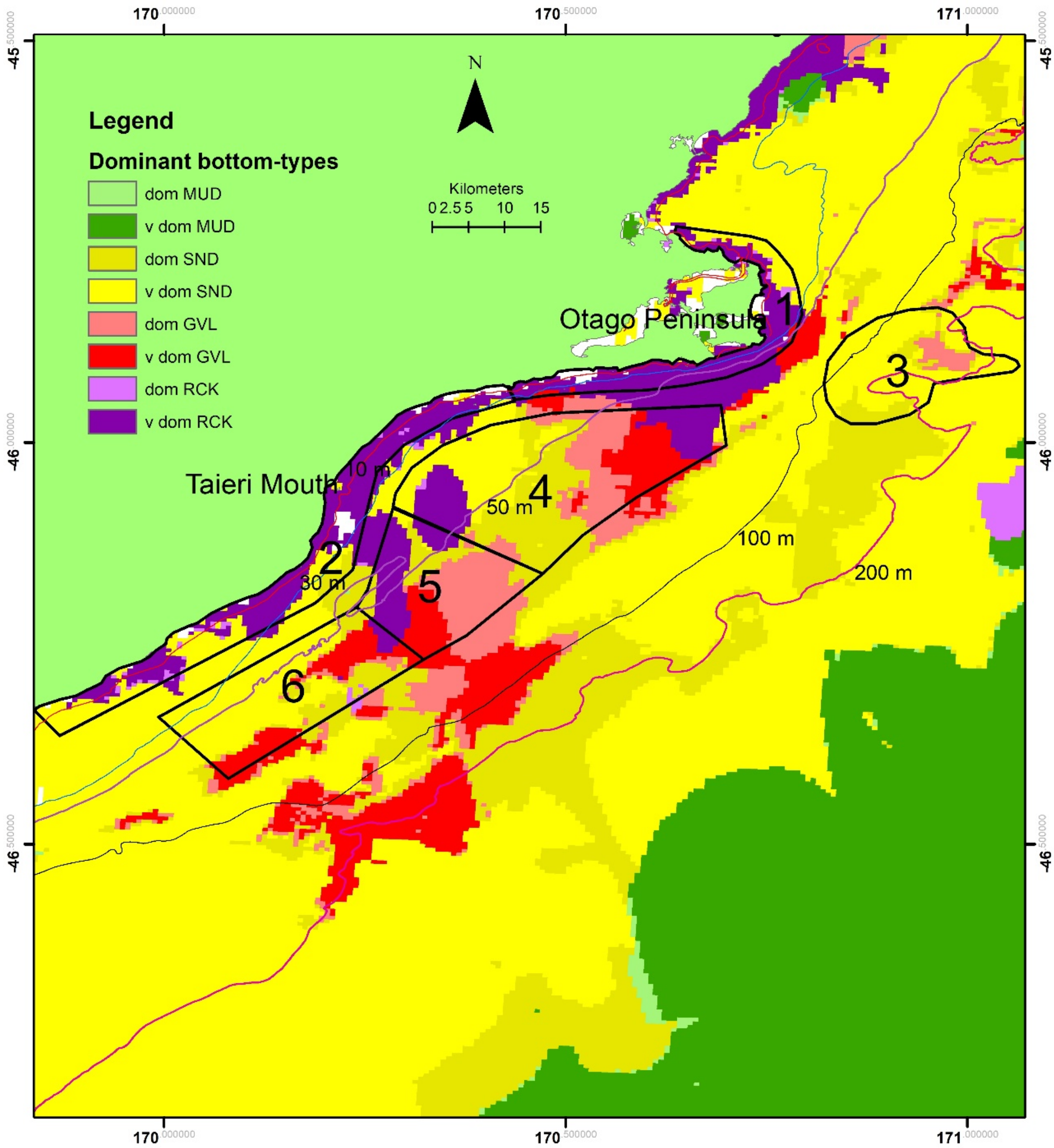

Figure 3: South Otago blue cod survey strata, bathymetry contours, and dominant sea floor substrate types (data from Bostock et al. 2018). Key: dom, dominant; v dom, very dominant; MUD, mud; SND, sand; GVL, gravel; RCK, rock.

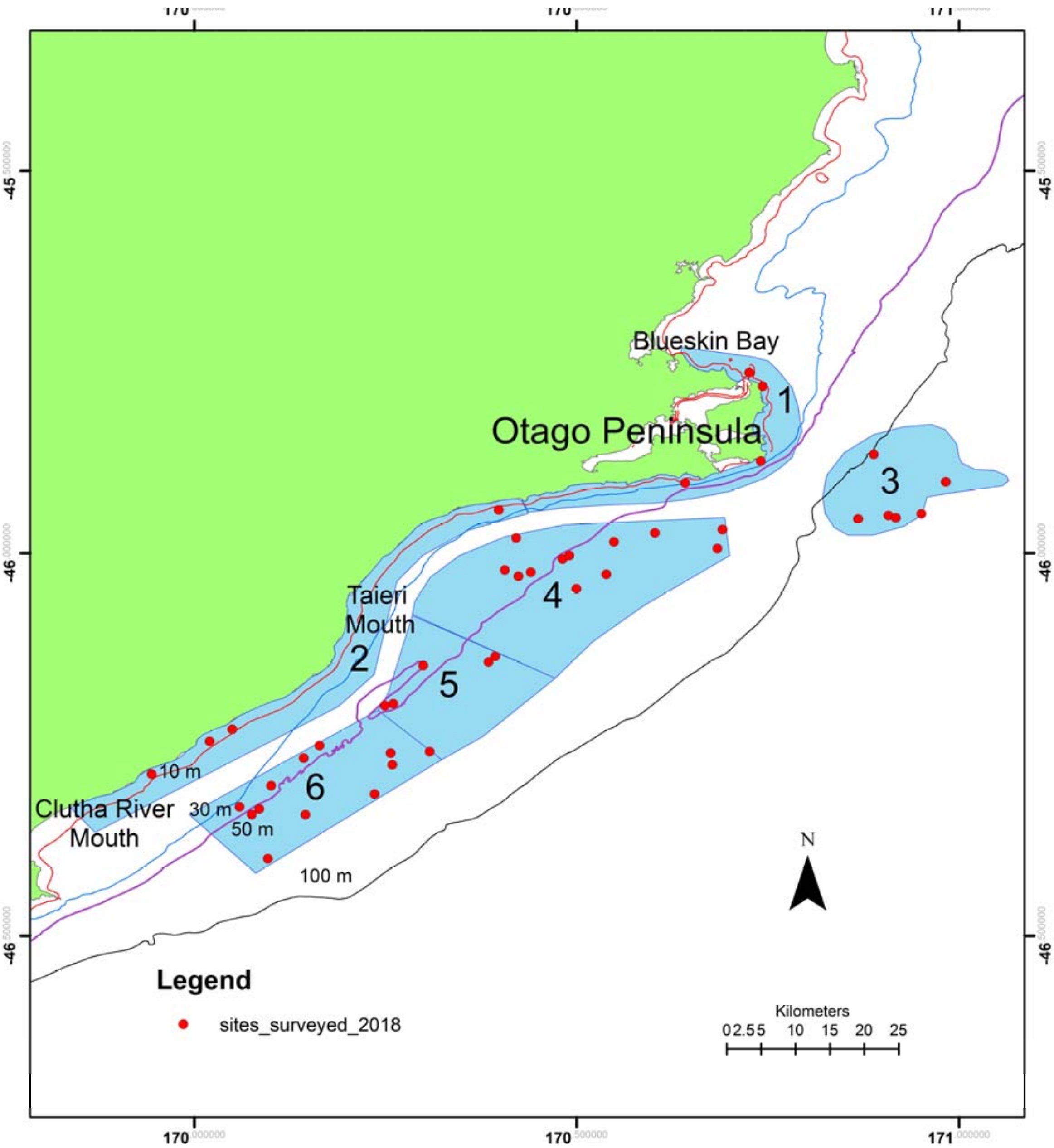

Figure 4: Stratum and site positions for the 2018 south Otago random-site blue cod potting survey.

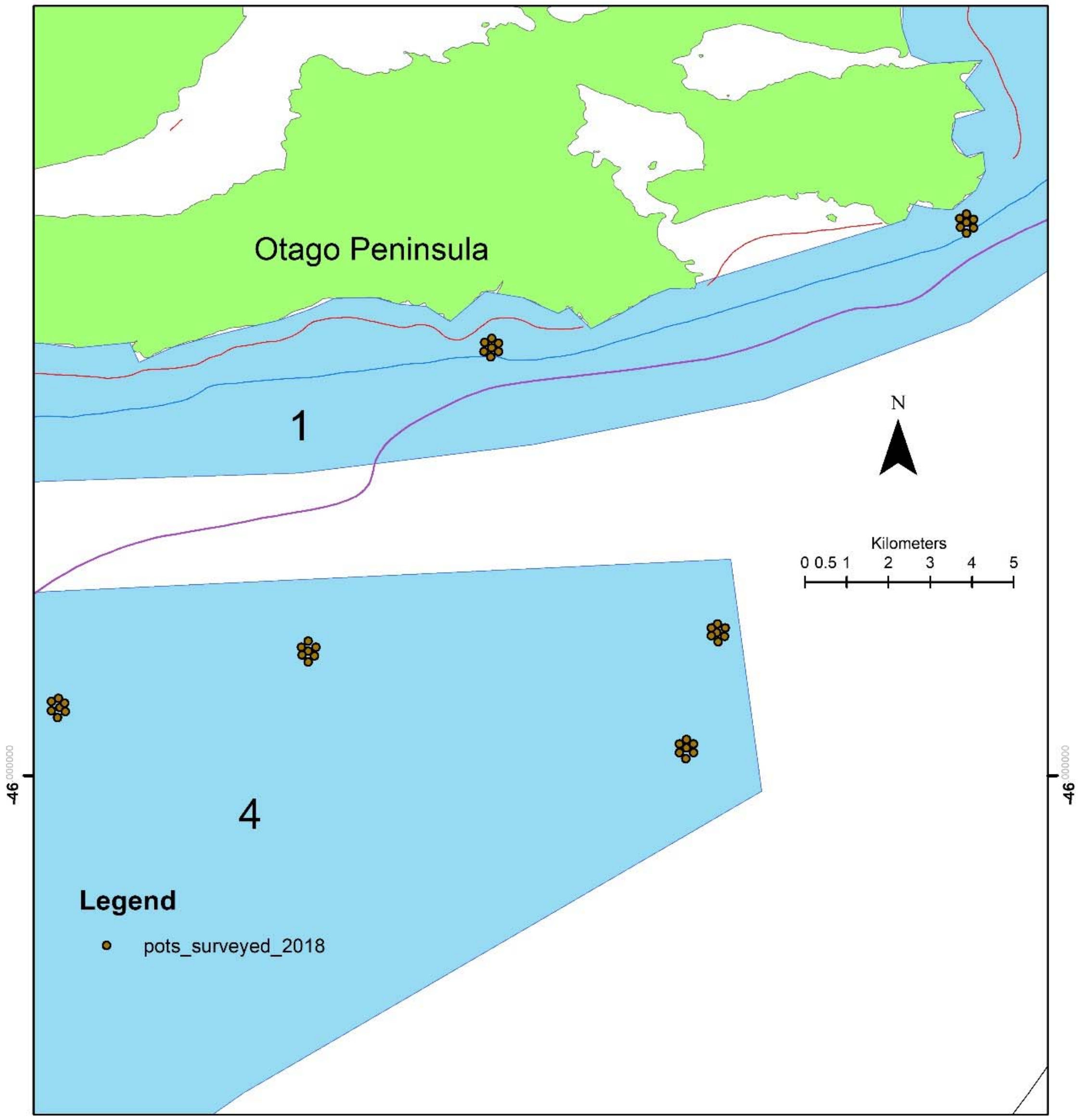

Figure 5: Site and pot positions for the 2018 south Otago random-site blue cod potting survey in strata 1 and 4, shown to demonstrate how pots were placed around the sites.

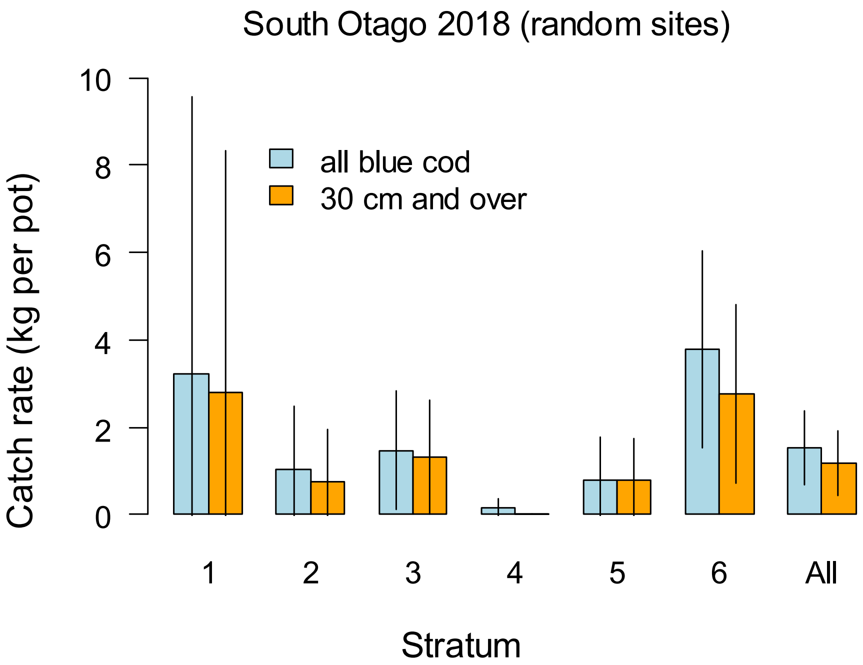

Figure 6: Catch rates (kg.pot^{-1}) of all blue cod and recruited blue cod (30 cm and over) by strata, and overall for the 2018 south Otago random site survey. Error bars are 95% confidence intervals.

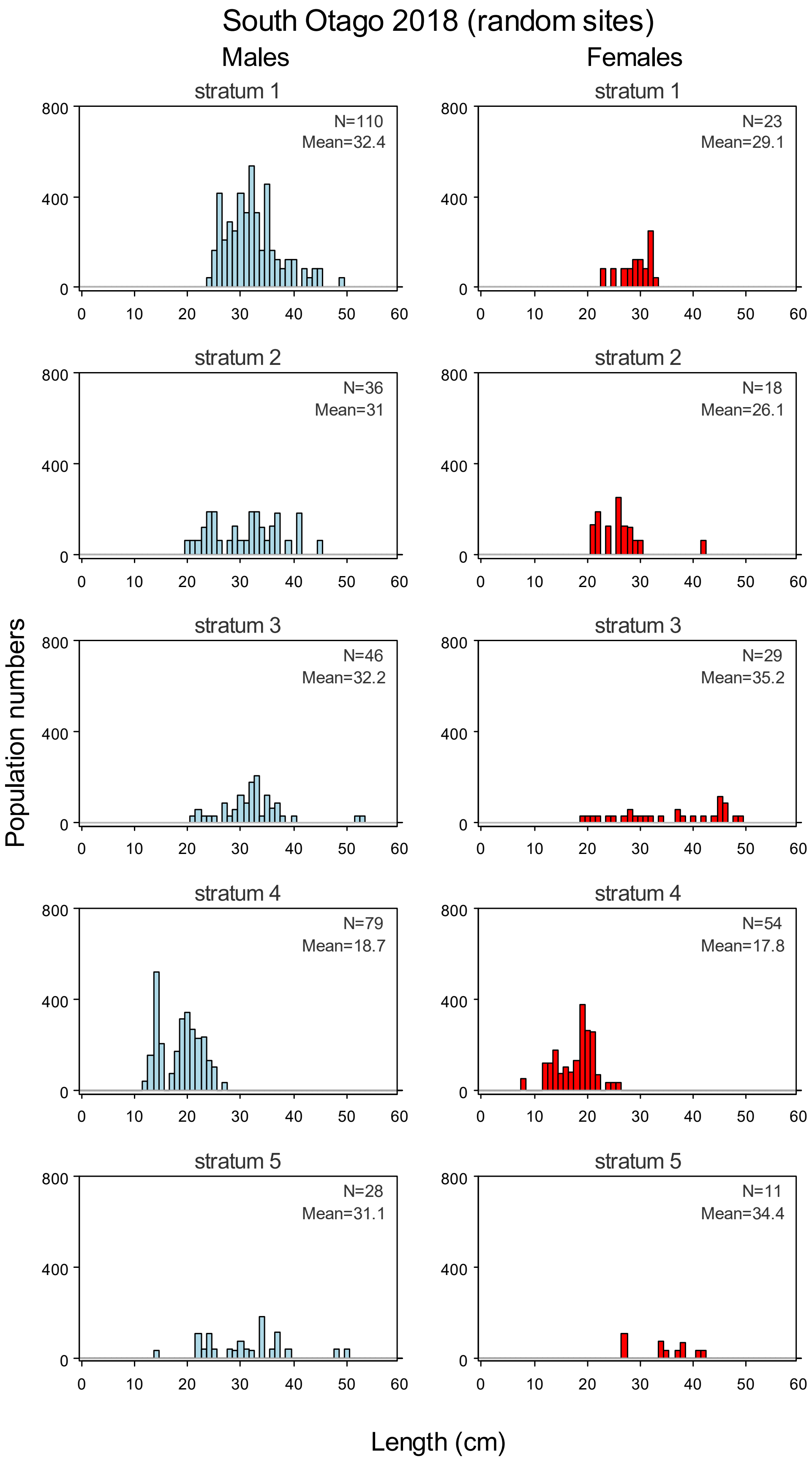

Figure 7: Scaled length frequency distributions by stratum and overall for the 2018 south Otago random-site potting survey. N, sample numbers; Mean, mean length (cm). Scale on the *y*-axis is different for the 'all strata' plot.

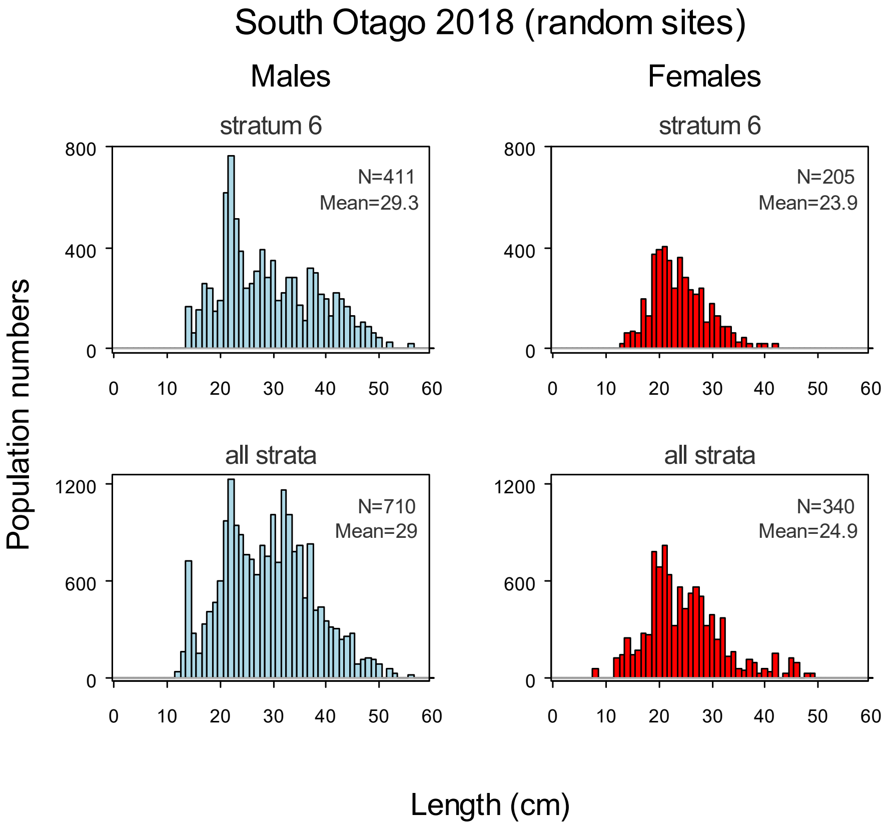

Figure 7 – *continued*

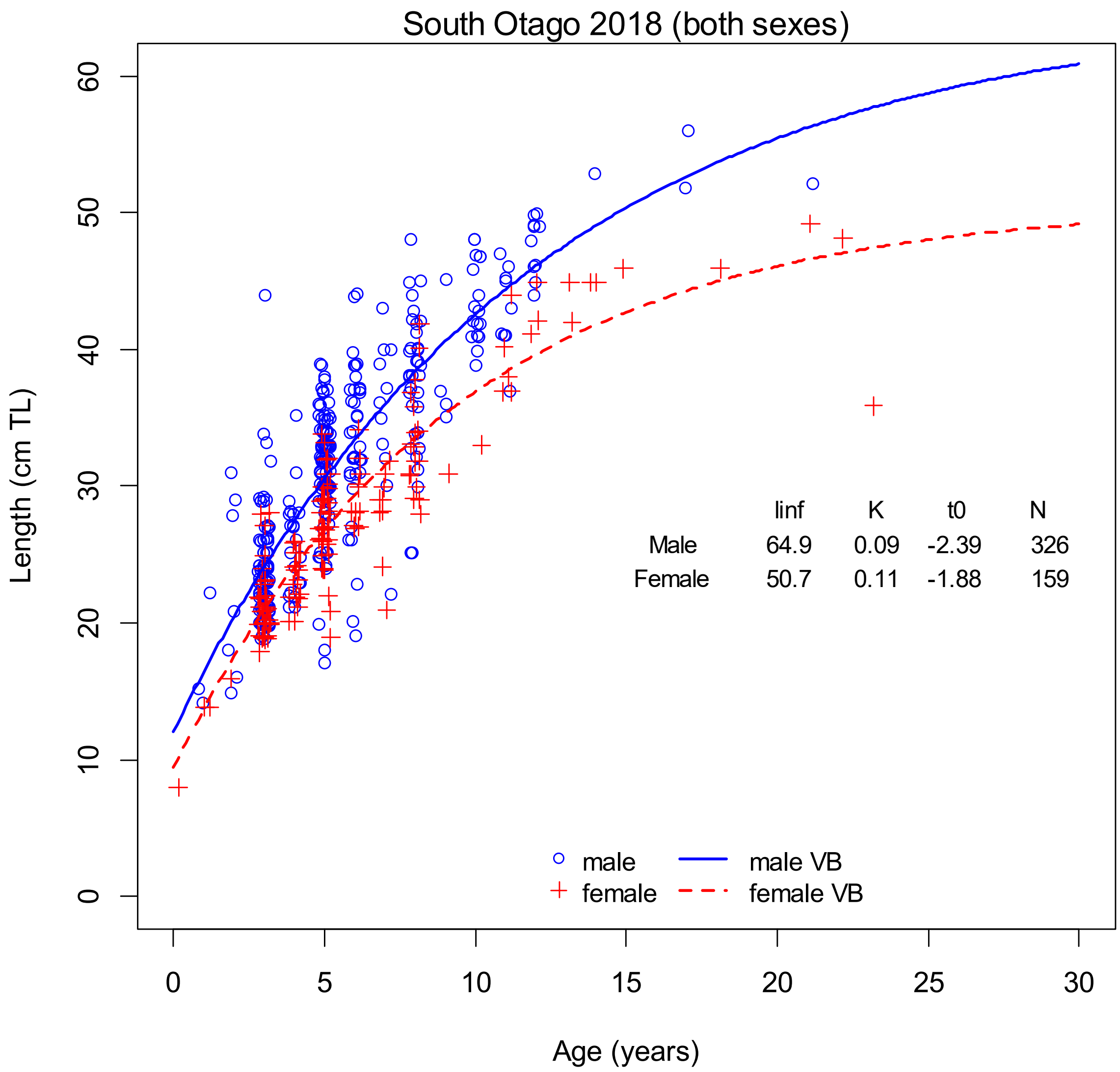

Figure 8: Observed blue cod age and length data by sex for the 2018 south Otago survey with von Bertalanffy (VB) growth models fitted to the data. Linf, average size at the maximum age (cm); K, Brody growth coefficient (yr^{-1}); t0, age when the average size is zero.

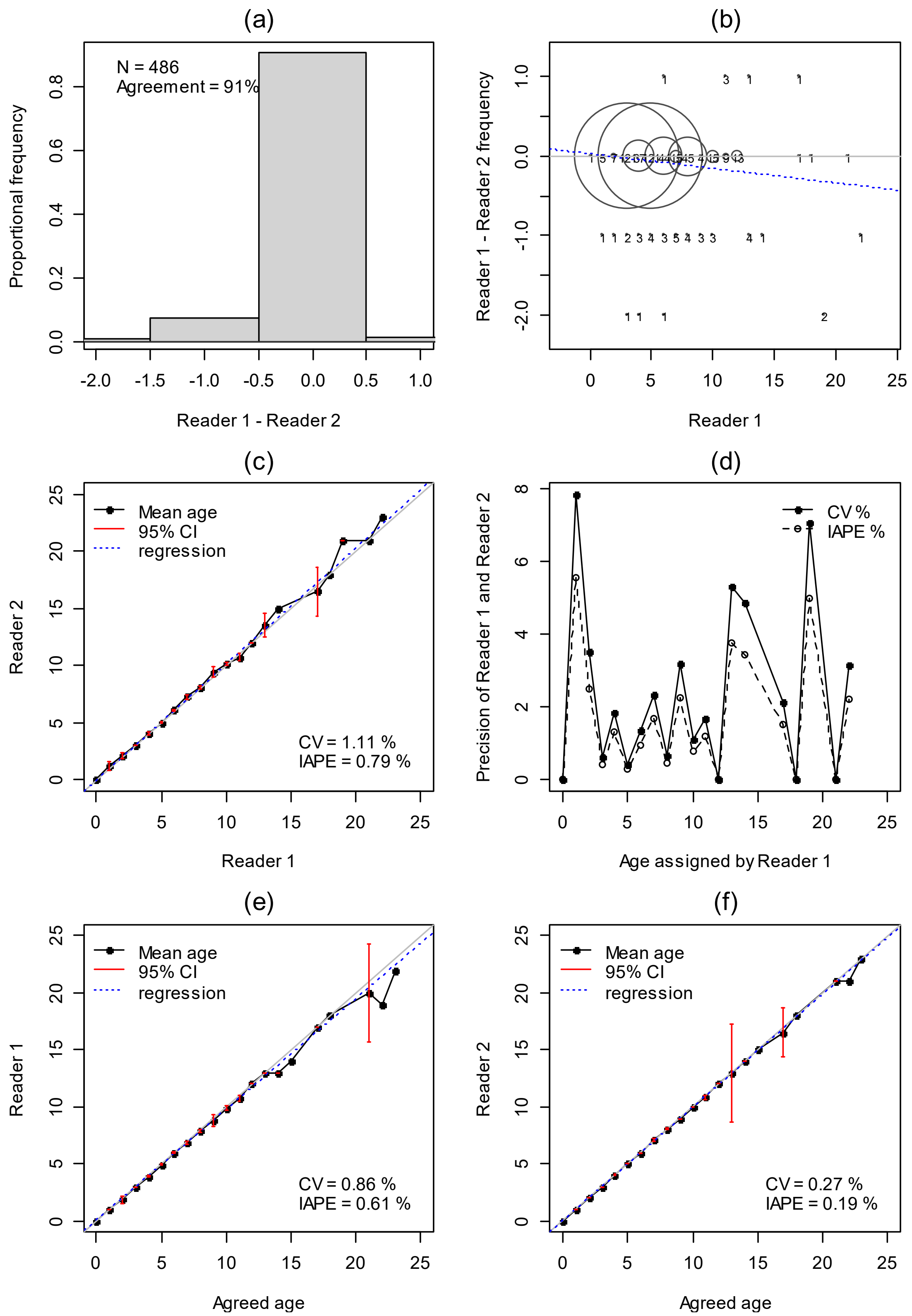

Figure 9: Blue cod age otolith reader comparison plots between reader 1 and reader 2 for the 2018 south Otago survey: (a) histogram of age differences between two readers; (b) difference between reader 1 and reader 2 as a function of the age assigned by reader 1, where the numbers of fish in each age 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.

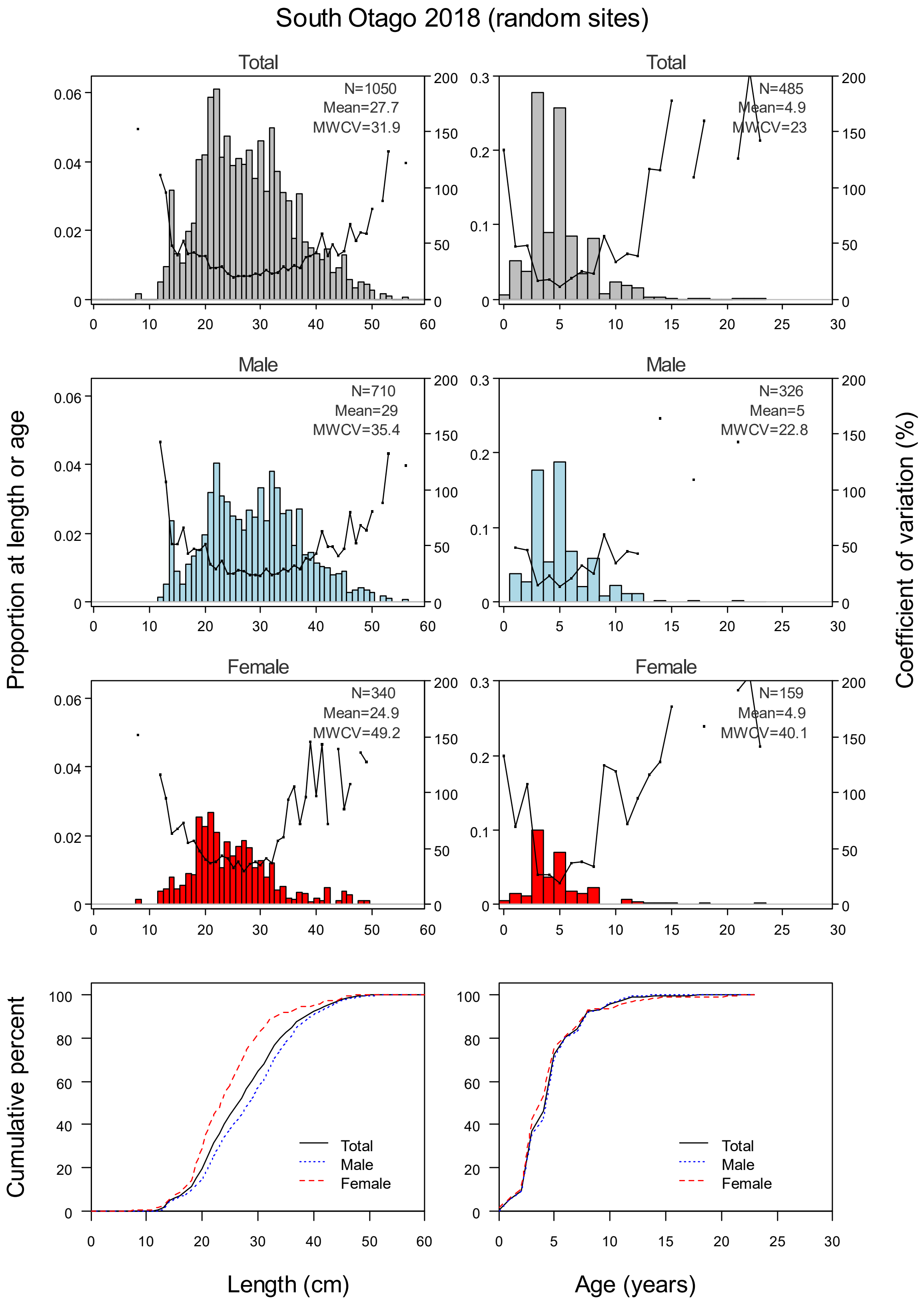

Figure 10: Scaled length frequency, age frequency, and cumulative distributions for total, male, and female blue cod for all strata in the 2018 south Otago random site blue cod potting survey (N, sample size; MWCV, mean weighted coefficient of variation).

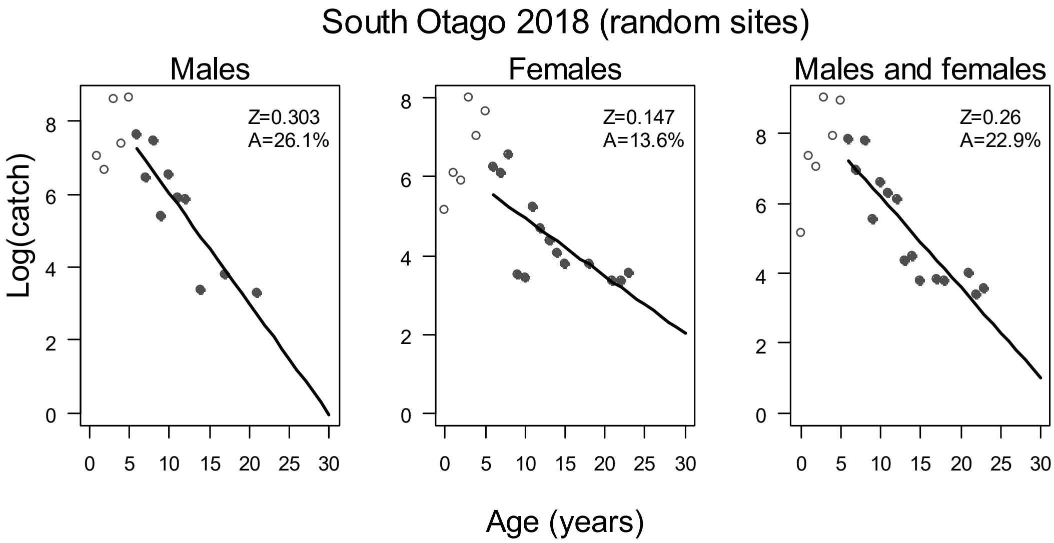

Figure 11: Catch curves (natural log of catch numbers versus age) for the 2018 south Otago random-site survey. The regression line is plotted from age at full recruitment of 6 years (i.e., dark points on the graph). Z, instantaneous total mortality; A, the annual mortality rate or the proportion of the population that suffers mortality in a given year.

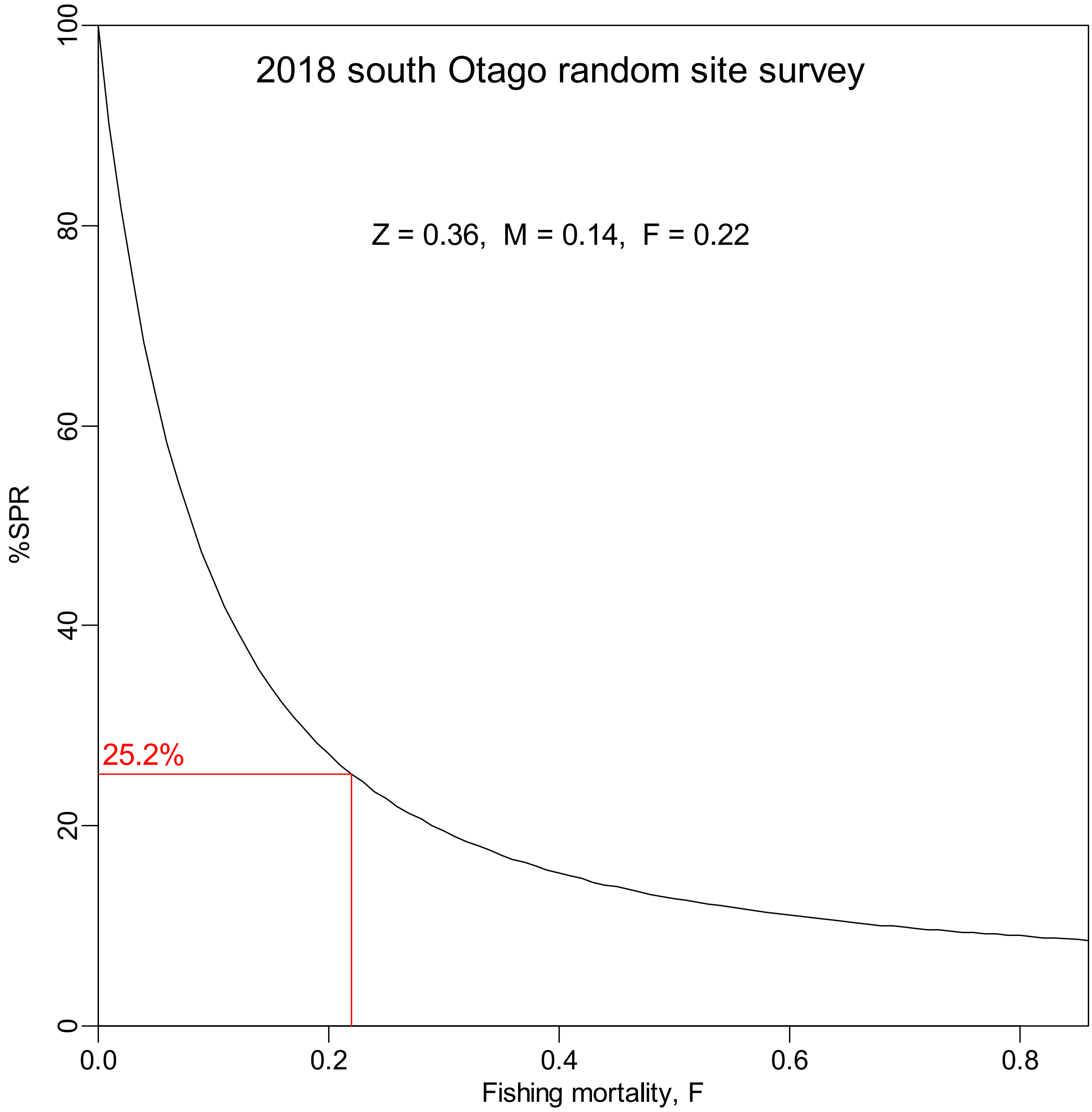

Figure 12: Spawner-per-recruit (SPR) as a function of fishing mortality (*F*) for 2018 south Otago random-site survey. Age at full recruitment is equal to 6 years for females.

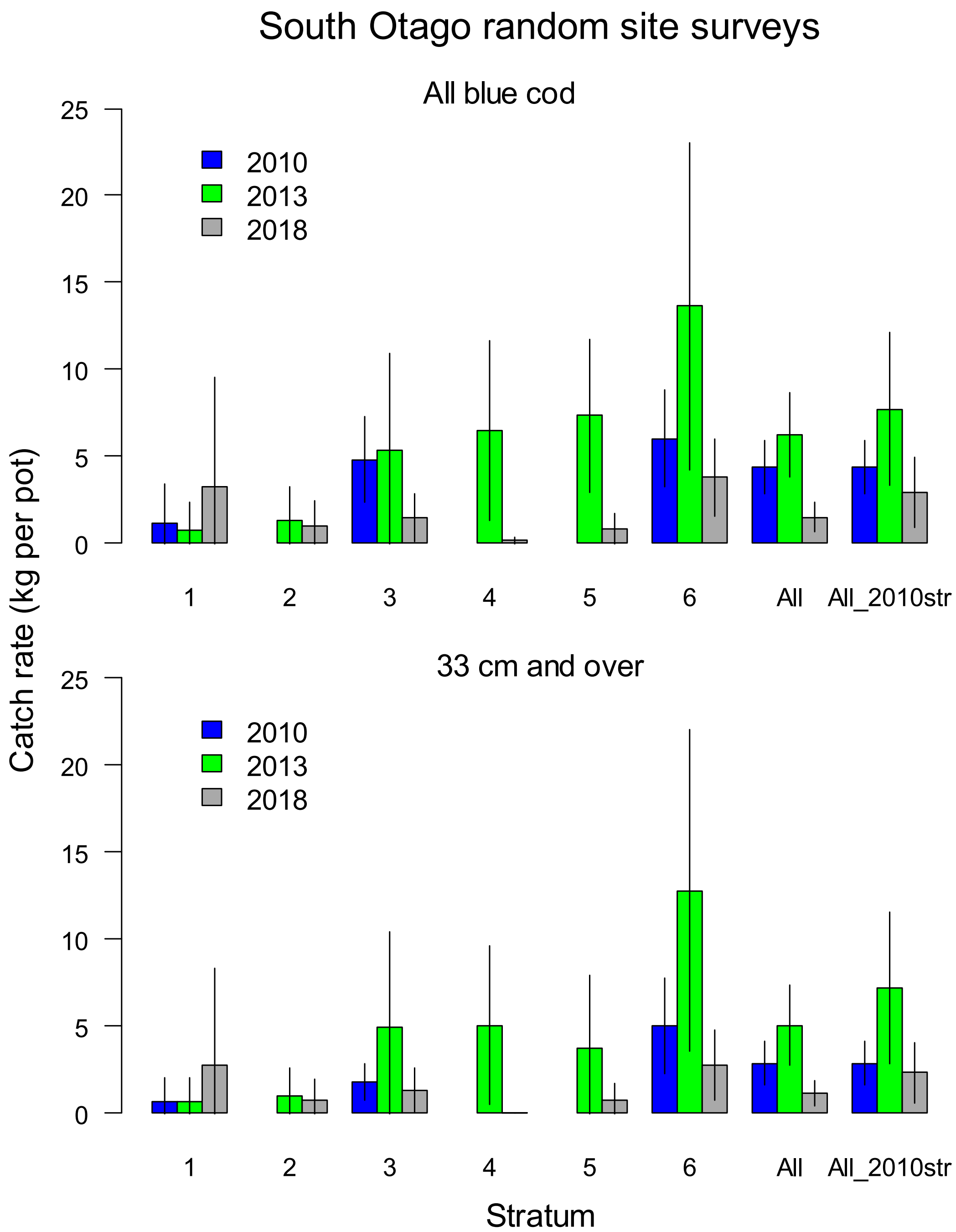

Figure 13: Catch rates (kg.pot^{-1}) of all blue cod and for recruited blue cod (30 cm and over) for the south Otago random-site potting surveys in 2010, 2013 and 2018. Catch rates are shown by strata, for all strata combined (All), and for strata 1, 3, and 6 combined (All_2010str) to compare with 2010 when only these three strata were surveyed. Error bars are 95% confidence intervals.

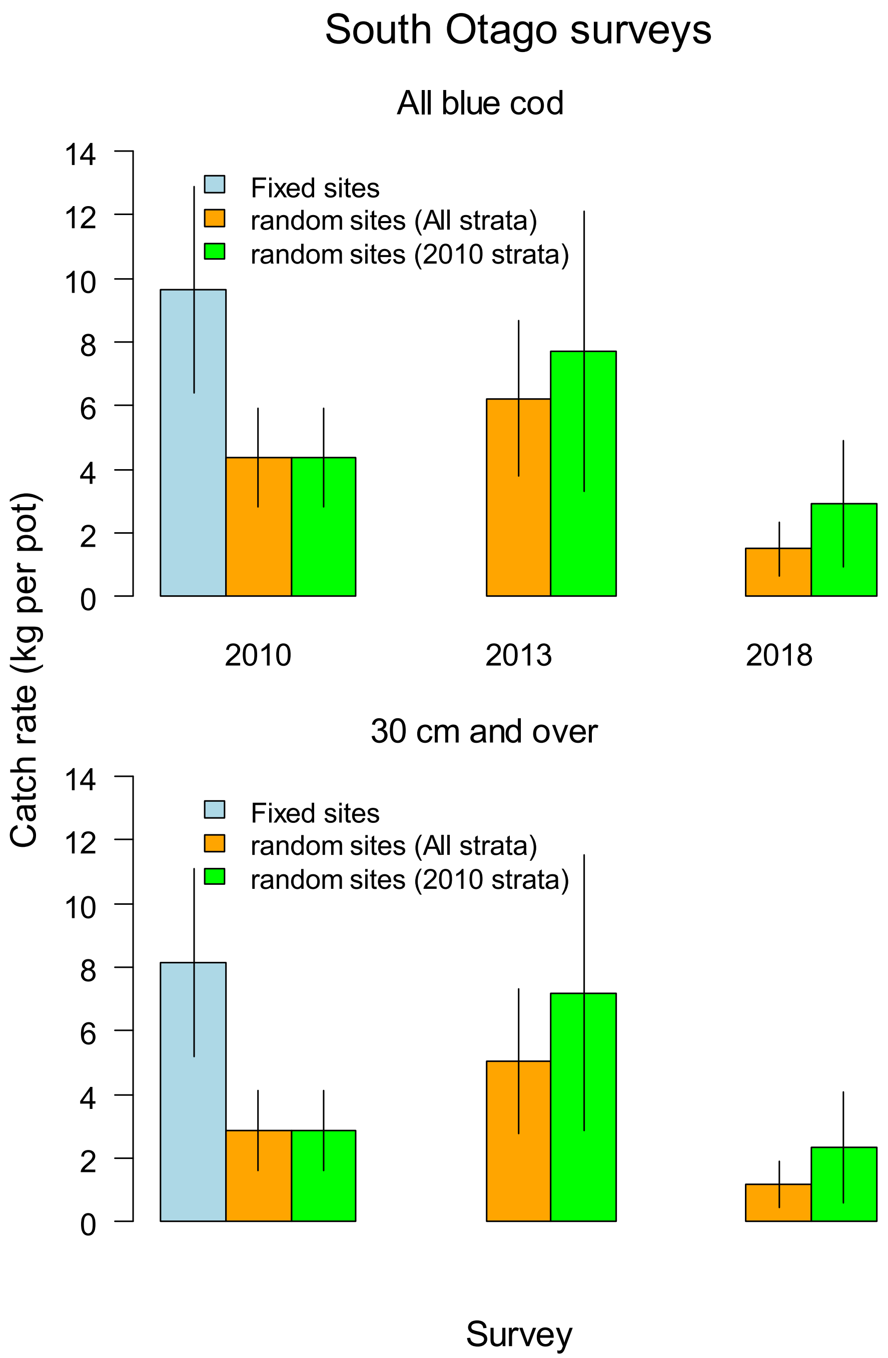

Figure 14: Catch rates (kg.pot^{-1}) of all blue cod and for recruited blue cod (30 cm and over) for the south Otago fixed-site potting survey in 2010, and random-site potting surveys in 2010, 2013 and 2018. Random-site survey catch rates are shown for all strata combined (All), and for strata 1, 3, and 6 combined (2010 strata) to compare with 2010 when only these three of the six strata were surveyed for both the fixed and random site surveys. Error bars are 95% confidence intervals.

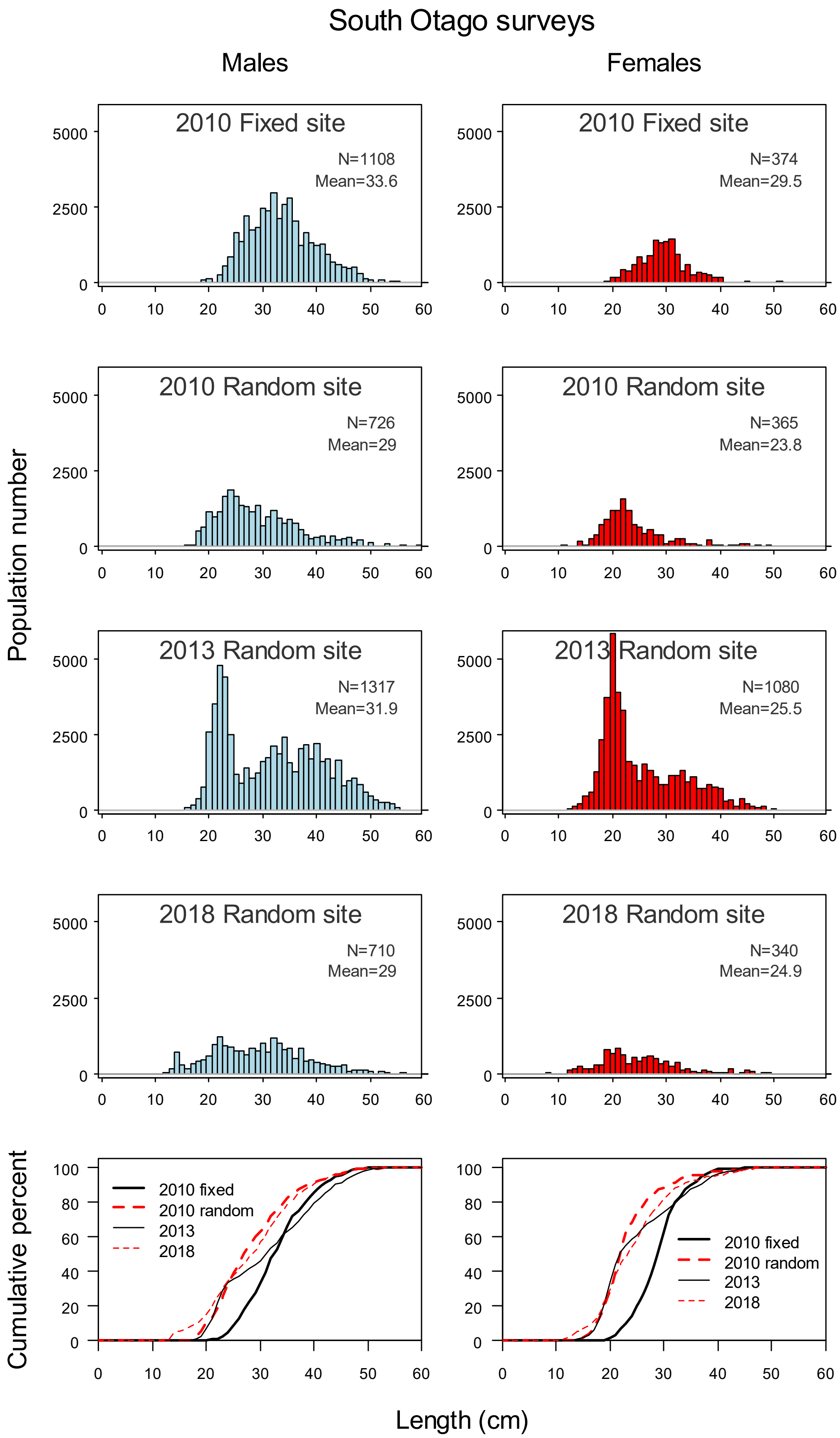

Figure 15: Scaled length frequency and cumulative distributions for male and female blue cod from the south Otago fixed-site potting survey in 2010, and random-site potting surveys in 2010, 2013, and 2018. The 2010 surveys included only three of the six strata (1, 3, and 6). N, sample numbers; no, population number; Mean, mean length (cm); MWCV, mean weighted coefficient of variation.

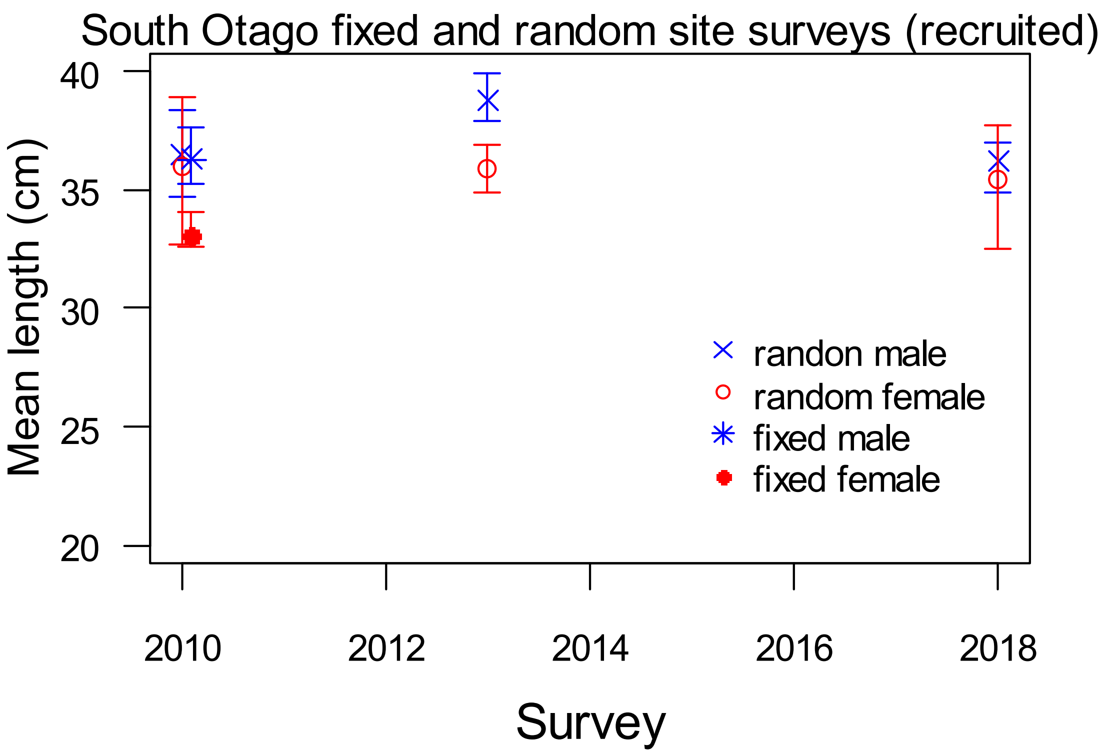

Figure 16: Mean length and 95% confidence intervals for male and female recruited blue cod (30 cm and over) from the south Otago fixed-site survey in 2010 and the random-site surveys in 2010, 2013 and 2018. The 2010 surveys included only three of the six strata (1, 3, and 6).

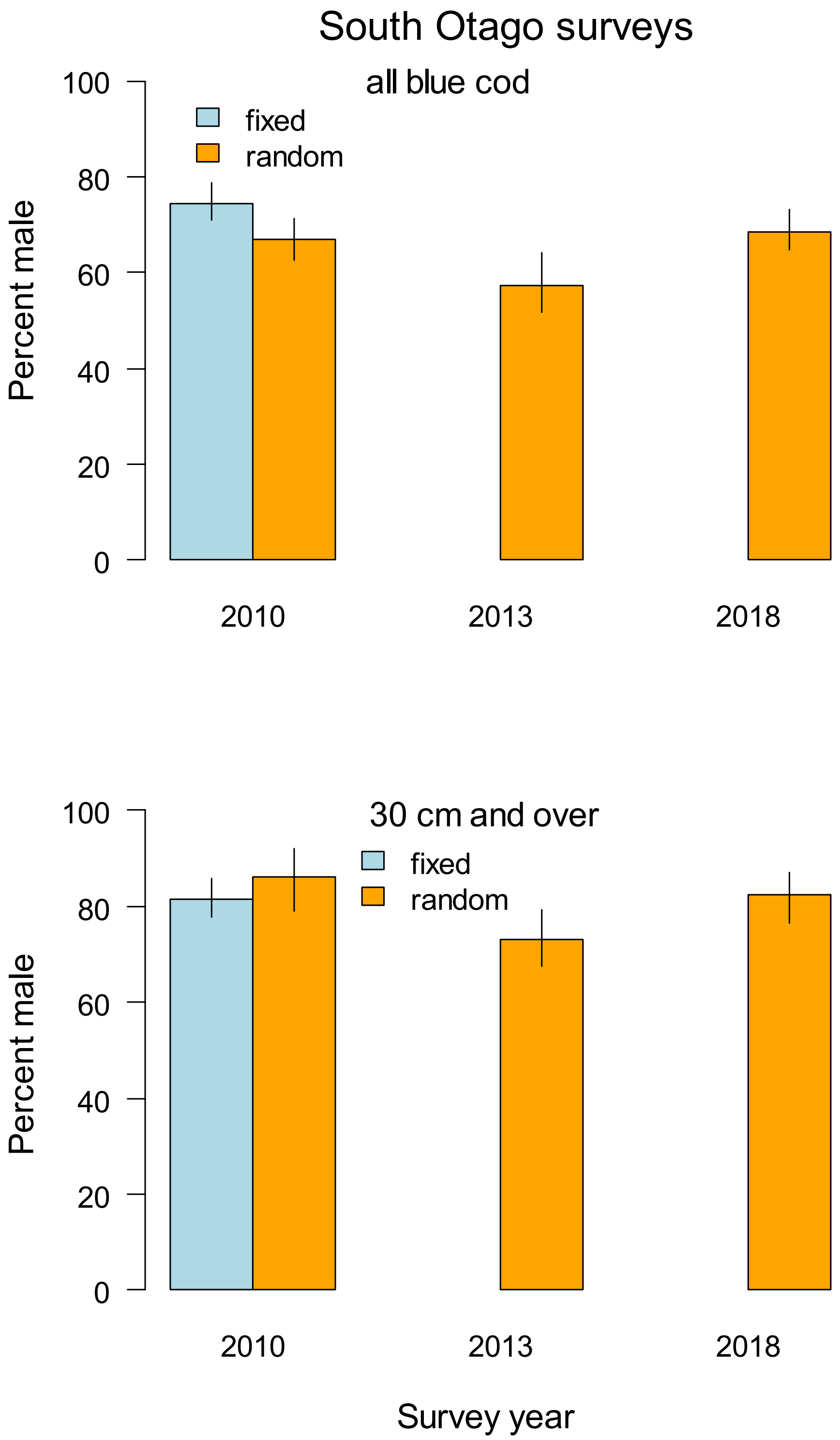

Figure 17: Proportion of males in the south Otago fixed-site potting survey in 2010, and random-site potting surveys in 2010, 2013, and 2018. The 2010 surveys included only three of the six strata (1, 3, and 6).

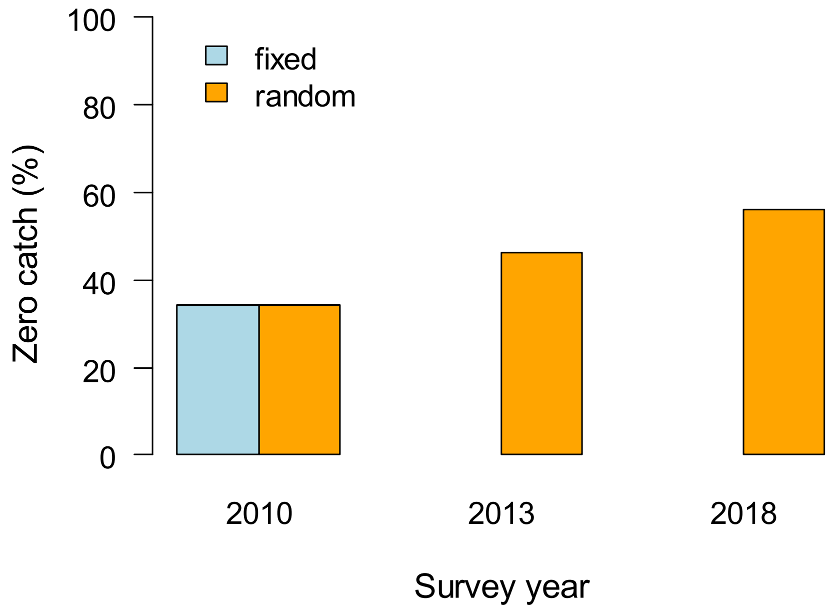

Figure 18: Proportion of pots with zero blue cod catch for the south Otago fixed-site potting survey in 2010, and random-site potting surveys in 2010, 2013, and 2018. The 2010 surveys included only three of the six strata (1, 3, and 6).

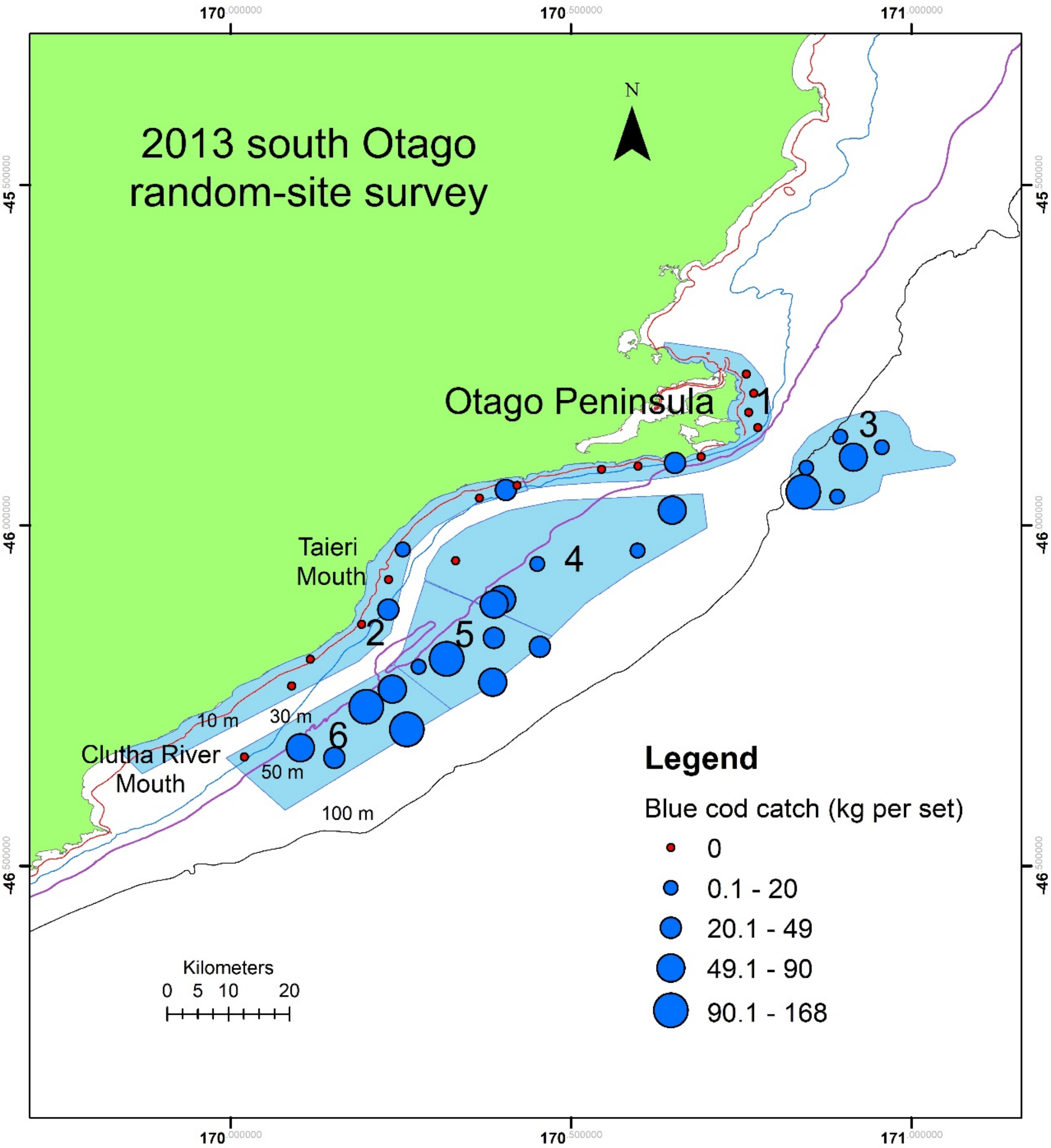

Figure 19: Blue cod catch rates (kg.set^{-1}) for the 2013 south Otago random-site blue cod potting survey (TRI1302) plotted at each random site. Catch is summed for the six pots in each set. N = 40 sites.

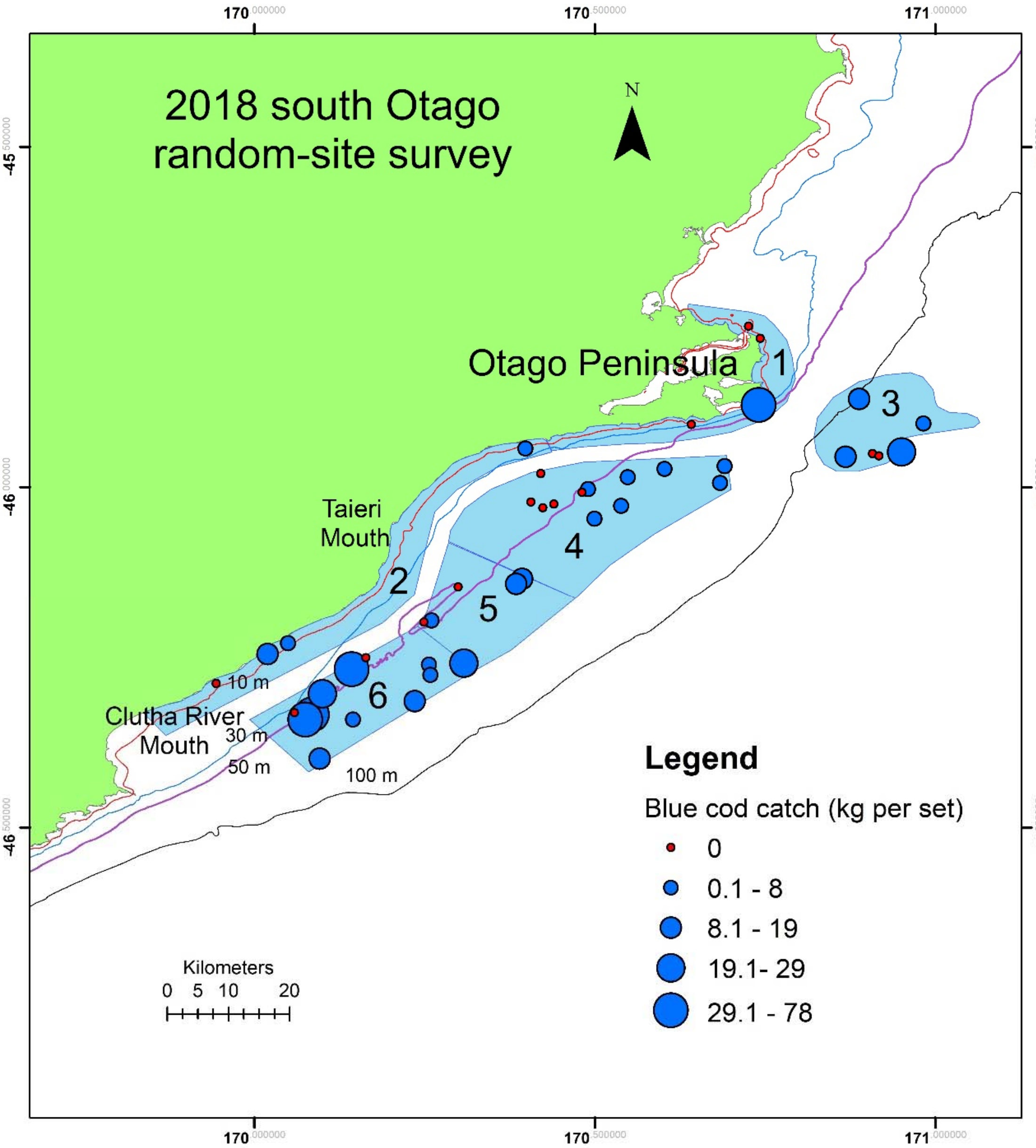

Figure 20: Blue cod catch rates (kg.set^{-1}) for the 2018 south Otago random-site blue cod potting survey (TRI1802_CHV1801) plotted at each random site. Catch is summed for the six pots in each set. N = 43 sites.

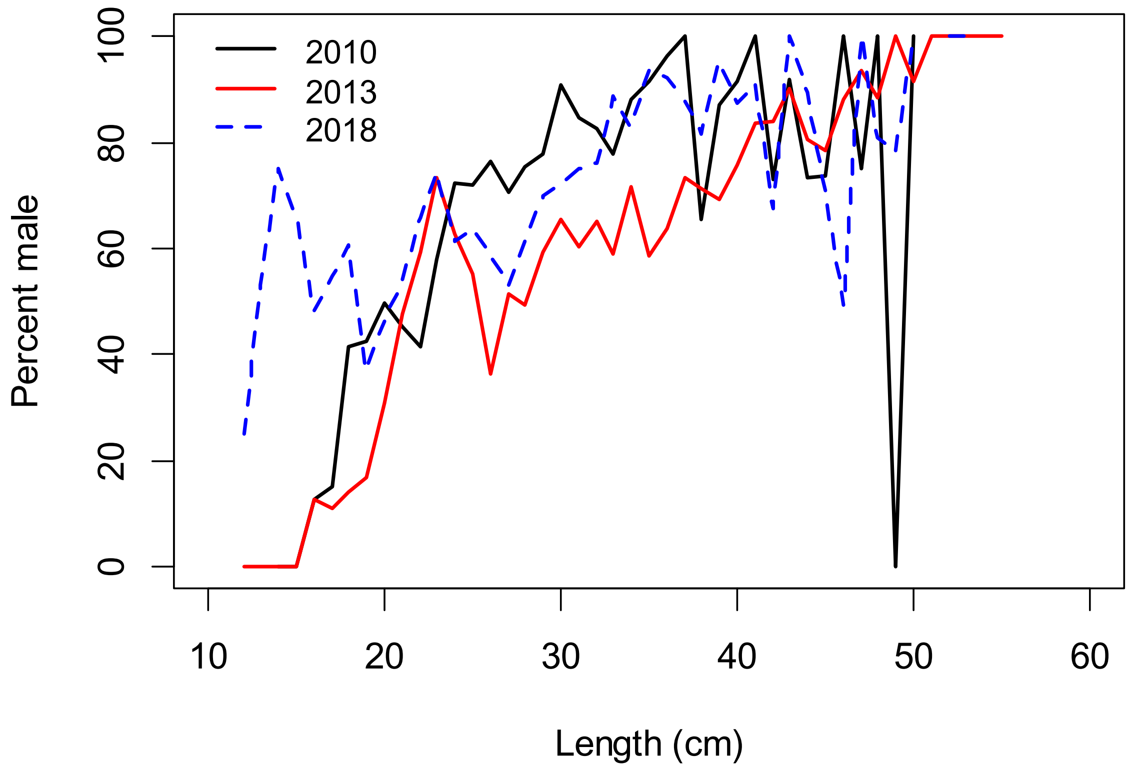

Figure 21: Blue cod percent male by length for the 2010, 2013 and 2018 south Otago random-site blue cod potting surveys. The 2010 surveys included only three of the six strata (1, 3, and 6).

8. APPENDICES

Appendix 1: 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 south 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 2. Numbers of otoliths collected during the 2018 south Otago survey for males and females, by strata and length class. Lgth, length.

	Males							Females						
	Strata							Strata						
Lgth (cm)	1	2	3	4	5	6	Male totals	1	2	3	4	5	6	Female totals
8											1			1
9														
10														
11														
12														
13														
14						1	1				2			2
15				2			2							
16						1	1						1	1
17						1	1							
18				1		1	2				1			1
19				3		1	4			1	4		4	9
20		1		8		5	14			1	6		4	11
21		1	1	6		5	13		2		4		4	10
22		1	1	5	3	4	14		2	1	2		5	10
23		1	1	6	1	5	14	2					5	7
24	1	2	1	4	2	5	15		2	1	1		5	9
25	2	3	1	2	1	5	14			1	1		4	6
26	4	1				4	9		4		1		4	9
27	3		3	1		4	11	2	1	1		2	5	11
28	2	1	1		1	3	8	2	2	2			5	11
29	2	2	2		1	4	11	3	1	1			4	9
30	4	1	4		2	4	15	2		1			5	8
31	3	1	3		1	4	12	2		1			4	7
32	4	3	5		1	5	18	3					4	7
33	4	3	6			5	18	1					3	4
34	3	2	1		4	5	15					2	2	4
35	4	1	4			3	12							
36	2	2	1		1	4	10						2	2
37	3	3	3		2	4	15			1		1	1	3
38	2		1			4	7					2		2
39	3	1			1	5	10							
40	3		1			4	8			1			1	2
41		3				5	8					1		1
42	2					4	6			1		1	1	3
43	1					4	5							
44	2					4	6			1				1
45	2	1				3	6			4				4
46						4	4			2				2
47						4	4							
48					1	3	4			1				1
49						3	3			1				1
50						2	2							
51														
52			1			1	2							
53			1				1							
54														
55														
56						1	1							
Total	56	34	42	38	22	13	326	17	14	23	23	9	73	159