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# **Relative abundance, size and age structure, and stock status of blue cod in Foveaux Strait in 2018**

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# Contents

1. INTRODUCTION.....	3
1.1 Foveaux Strait blue cod fishery.....	3
1.2 Foveaux Strait bathymetry and substrate .....	3
1.3 South Island blue cod potting surveys.....	4
1.4 Potting survey design .....	4
1.5 Objectives.....	4
2. METHODS.....	5
2.1 2018 survey timing and area.....	5
2.2 2018 survey design.....	5
2.2.1 Allocation of sites.....	5
2.2.2 Vessels and gear .....	6
2.2.3 Sampling methods .....	6
2.2.4 Data storage.....	7
2.2.5 Age estimates .....	7
2.2.6 Data analyses.....	7
2.3 Analyses of 2010 and 2014 Foveaux Strait surveys.....	10
3. RESULTS.....	11
3.1 2018 random-site survey .....	11
3.1.1 Catch and catch rates .....	11
3.1.2 Biological and length frequency data .....	11
3.1.3 Age and growth .....	11
3.1.4 Spawning activity .....	12
3.1.5 Population length and age composition.....	12
3.1.6 Total mortality estimates (Z) and spawner-per-recruit (SPR) .....	12
3.2 Foveaux Strait random-site survey time series (2010, 2014, 2018) .....	13
4. DISCUSSION .....	13
4.1 General .....	13
4.2 Blue cod habitat and abundance .....	14
4.3 Survey precision .....	14
4.4 Cohort progression and genetic mixing.....	14
4.5 Sex change and sex ratio .....	15
4.6 Reproductive condition .....	16
4.7 Stock status and management implications.....	16
5. ACKNOWLEDGEMENTS .....	17
6. REFERENCES.....	17

7.	TABLES AND FIGURES.....	21
8.	APPENDICES.....	50

## EXECUTIVE SUMMARY

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### 2018 random site survey

This report describes the results of the random-site blue cod (*Parapercis colias*) potting survey carried out in Foveaux Strait in February 2018. Estimates are provided for population abundance, size and age structure, sex ratio, total mortality ( $Z$ ), and spawner biomass-per-recruit ratio. This is the third survey in the Foveaux Strait random-site survey time series, following those in 2010 and 2014.

Thirty-eight random sites (6 pots per site, producing 228 pot lifts) at depths of 14–95 m from eight strata in Foveaux Strait were surveyed in February 2018. Mean catch rates of blue cod (all sizes) by stratum were 4.01–8.41 kg.pot<sup>-1</sup> with the lowest catch in stratum 5 (middle of strait) and highest in stratum 10 (most southern stratum contiguous with Stewart Island). The survey blue cod mean catch rate was 5.66 kg.pot<sup>-1</sup> with a CV of 20%. Catch rates for recruited blue cod (33 cm and over) followed a similar pattern among strata as for all blue cod and overall was 2.45 kg.pot<sup>-1</sup> (CV 18%). Of the 228 random-site pots, 63 (28%) had zero catch of blue cod. The sex ratios were 34–63% male across the eight strata and the overall weighted sex ratio was 51% male. The overall weighted mean length for males was 30.6 cm (range 12–51 cm) and 28.4 cm for females (range 10–42 cm). The scaled length frequency distributions were unimodal and broadly similar among the eight strata for both males and females.

Otolith thin section ages from 199 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 88% agreement, there was minimal bias between readers, and CV and average percent error were 1.1% and 0.8%, respectively. Von Bertalanffy growth parameters ( $L_{\infty}$ ,  $K$ ,  $t_0$ ) in 2018 were 60.8 cm, 0.11 yr<sup>-1</sup>, -1.14 yr for males; and 40.2 cm, 0.17 yr<sup>-1</sup>, and -0.94 yr for females. Sexed based age-length-keys (one each for males and females) were used to estimate the population age composition. Age in 2018 ranged from 1–14 years for males and 1–17 years for females, but most blue cod were 4–8 years old. The estimated population age distributions indicate almost knife-edge selectivity to the potting method at three years with no indications of strong or weak modes for either males or females. Mean age was 5.7 years for males and 6.8 years for females. Von Bertalanffy growth parameters ( $L_{\infty}$ ,  $K$ ,  $t_0$ ) used in the spawner-per-recruit analyses were based on the combined length and age data from the 2010, 2014 and 2018 surveys and were 55.7 cm, 0.14 yr<sup>-1</sup>, -0.82 yr for males ( $n = 495$ ); and 39.9 cm, 0.20 yr<sup>-1</sup>, and -0.52 yr for females ( $n = 429$ ). The traditional catch curve appeared to follow the ideal straight-line descending limb, suggesting that the assumption of constant recruitment has not been violated, and gives confidence in the CR  $Z$  estimates which tend to be less sensitive to age classes with few fish. The steepness of the descending curve, and high  $Z$  value, is a direct result of the lack of recruited older age classes. Total mortality ( $Z$ ) for age-at-full recruitment of eight years was estimated at 0.70 (95% confidence interval 0.47–0.98). Based on the default  $M$  of 0.14, estimated fishing mortality ( $F$ ) was 0.56 and the associated spawner biomass-per-recruit ratio was 22% (95% confidence interval 18–29%).

There were few indications of spawning activity during the survey period with no fish in the running ripe condition and a small percentage in the mature condition, suggesting that the survey took place either before or after the spawning peak.

### Survey time series

The pattern of catch rates among the eight strata were most similar in 2010 and 2014 when the highest catch rates were from strata 1 and 2 and the lowest by far were from stratum 8A. The 2018 catch rates were relatively similar across all strata, and the large confidence intervals indicate that these are not significantly different. There was no trend in abundance across the three surveys.

The scaled length frequency distributions and mean length of all blue cod and recruited blue cod were remarkably similar for all three surveys with no trends.

The sex ratio for all surveys was 47–51% male for all blue cod, and 68–76% male for recruited blue cod, with no clear trends among surveys.

The male age structure is similar among the three surveys except for a weak 5-year-old age class in 2014. Female age structure is also generally similar, except for weak 5-year-old and 8-year-old age classes in 2010. The weak 5-year-old age class appears to have progressed through to 2014 as a weak 9-year-old age class.

The Chapman Robson total mortality estimates ( $Z$ ) increased from 0.52 in both 2010 and 2014, to 0.70 in 2018 with a corresponding decrease in the spawner-per-recruit (SPR) estimates from about 27% to 22%. The slopes of the right-hand limbs of the catch curves can vary considerably depending on the number of recruited age classes which numbered just five for males in 2014 and four in 2018. With so few age classes, the slope can be strongly affected by one older age class and a cautious approach should be taken when interpreting  $Z$  and SPR estimates.

The proportion of pots with zero catch for the three random-site surveys ranged from 25–32% with no clear trends.

## 1. INTRODUCTION

This report describes the random-site potting survey of blue cod (*Parapercis colias*) relative abundance, population length/age structure and stock status in Foveaux Strait in February 2018. This is the third in the time series with previous random-site surveys in 2010 and 2014 (Carbines & Beentjes 2012, Carbines & Haist 2017a).

### 1.1 Foveaux Strait blue cod fishery

In the South Island, blue cod is the finfish species most frequently targeted and landed by recreational fishers (Ministry for Primary Industries 2017) and is caught from small vessels fishing over reef edges on shingle/gravel, biogenic reefs, or sandy bottoms close to rocky outcrops. The Quota Management Area BCO 5 extends from the Slope Point in Southland to Awarua Point in Fiordland (Figure 1). The 2011–2012 panel survey involving face to face interviews with fishers estimated BCO 5 recreational annual take at 51 t (Wynne-Jones et al. 2014), accounting for 15% of the total national recreational blue cod catch, virtually all taken by rod and line. Recreational blue cod catch is spread across BCO 5 with 38% from Slope Point to Te Waewae Bay, 33% from Stewart Island and Foveaux Strait, 19% from Fiordland, and 10% from Paterson Inlet (National Research Bureau unpublished data from 2017–18 panel survey, pers. comm. Bruce Hartill). Within Fiordland, from 2006–2008 recreational fishing was focused on Dusky and Doubtful Sounds, and off Preservation Inlet (Davey & Hartill 2008).

The recreational minimum legal size within BCO 5 is 33 cm, with a combined daily bag limit of 20 fish (or blue cod), except for the internal waters of Fiordland where daily bags limits are 1 to 3 blue cod depending on the fiord, and Paterson Inlet where the daily bag limit is 15 blue cod or 10 inside the mātaitai known as Te Whaka ā Te Wera Mātaitai Reserve; Milford Sound, Doubtful Sound and Ulva Island Marine Reserve (Te Wharawhara Marine Reserve) are closed to all blue cod fishing (Fisheries New Zealand 2018).

The commercial blue cod catch from BCO 5 is the highest by far for any Quota Management Area, with annual catches of 1100–1200 t in the six years up to 2016–17 (Fisheries New Zealand 2018), and is over 20 times higher than the BCO 5 estimated recreational catch in 2011–12 of 51 t. Nearly all commercially landed blue cod in BCO 5 is caught by cod potting, and about half of this is from Statistical Area 025 (Foveaux Strait), and 20% from each of Statistical Areas 030 (west of Stewart Island) and 027 (east of Stewart Island) (Figure 1) (Haist et al. 2013).

### 1.2 Foveaux Strait bathymetry and substrate

Foveaux Strait is a narrow body of water between Stewart Island and the most southern part of the South Island. It is generally around 30 m deep, becoming gradually deeper at the east and west ends over the continental shelf, before steeply dropping away over the shelf edge (Figure 2). The shallow bathymetry and proximity to the mainland tends to accelerate the west to east moving Southland Current through the strait. Tidal velocities within the strait can be high, driven by prevailing westerly winds which frequently result in rough sea conditions.

The survey area includes the entire Foveaux Strait, the eastern Islands such as Ruapuke Island, the north east Stewart Island coastline from Cave Point to Owen Point (excluding Paterson Inlet), and the mainland coastline from New River Estuary to about 25 km east of Bluff (Figure 3). The sediments within Foveaux Strait are predominantly sand and gravel distributed in patches (Figure 4). There is very little mud except for a relatively small area of mud in the north west off the Bluff coast. The carbonate map indicates the level of biological material in the water column or on the seafloor and tends to be most concentrated on the east coast of Stewart Island. Foveaux Strait offers substantial and varied blue cod habitat, both inshore, within the strait, and around the many rugged islands to the east.

### 1.3 South Island blue cod potting surveys

South Island recreational blue cod fisheries are monitored using potting surveys. These surveys take place predominantly in areas where blue cod recreational fishing is common, but in some areas, including Foveaux Strait, 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 Foveaux Strait, 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), south Otago (Beentjes & Carbines 2011, Carbines & Haist 2018c), Paterson Inlet (Carbines 2007, Carbines & Haist 2014, 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 any location (single latitude and longitude) generated randomly from within a stratum (Beentjes & Francis 2011). Following this recommendation, all survey series started to transition to fully random survey designs with interim sampling of both fixed and random sites allowing comparison of catch rates, length and age composition, and sex ratios between the survey designs. Random sites were the only site type used in all the Foveaux Strait surveys, and surveys in south Otago (2013 survey), Kaikoura (2017 survey), and Paterson Inlet (2018 survey) have transitioned to solely random-site surveys. For other areas, the most recent surveys included both fixed and random sites.

### 1.5 Objectives

#### Overall Objective

To estimate relative abundance, maturity state, sex ratio, and age structure of blue cod (*Parapercis colias*) in Foveaux Strait.

#### Specific objectives

1. To undertake a potting survey in Foveaux Strait to estimate relative abundance, 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.



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

## 2. METHODS

### 2.1 2018 survey timing and area

A random-site potting survey of Foveaux Strait was carried out by NIWA from 6–20 February 2018. The survey was consistent with start dates of previous surveys but finished earlier.

The survey area for the 2018 Foveaux Strait random-site survey was identical to the 2014 survey (Figure 3). Strata 7 and 8 were redrawn in 2014 to include mostly foul rugged habitat in stratum 7, and sandy bottom habitat in stratum 8. There are eight strata, six of which are contiguous with the coast and two are in the middle of Foveaux Strait. The inner strata are mostly 10–30 m deep whereas the north (stratum 1) and south strata (strata 10 and 8A) have depths exceeding 50 m (Figure 2). Each stratum was assumed to contain roughly random distributions of blue cod habitat and the total area (km<sup>2</sup>) 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 4).

### 2.2 2018 survey design

#### 2.2.1 Allocation of sites

Simulations to determine the optimal allocation of random sites among the eight strata were carried out using catch rate data from the 2010 and 2014 random-site surveys and NIWA's Optimal Station Allocation Program (*allocate*). The 2010 strata 7 and 8 sites were re-assigned to either strata 7A or 8A. Simulations were constrained to have a minimum of three sites per stratum and a CV (coefficient of variation) of no greater than 12%. The simulations indicated that 38 random sites were required to achieve the target CV of 12%.

The 2018 survey used a two-phase stratified random station design (Francis 1984) with 34 sites allocated to phase 1, and the remaining four available for phase 2, consistent with the proportion of phase 2 sites used in previous surveys (Table 1). Allocation of phase 2 stations was based on the mean pot catch rate (kg.pot<sup>-1</sup>) of all blue cod per stratum and optimised using the “area mean squared” method of Francis (1984). In this way, stations were assigned iteratively to the stratum in which the expected gain is greatest, where expected gain is given by:

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

where for the *i*th stratum *mean<sub>i</sub>* is the mean catch rate of blue cod per pot, *area<sub>i</sub>* is the fishable stratum area, and *n<sub>i</sub>* is the number of sets in phase 1. In the iterative application of this equation, *n<sub>i</sub>* is incremented by 1 each time a phase 2 set is allocated to stratum *i*.

#### Random sites

A random site has a location (single latitude and longitude) generated randomly within a stratum (Beentjes & Francis 2011). 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). Random-site surveys 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.

### 2.2.2 Vessels and gear

The Stewart Island-based vessel F.V. *Provider* (Vessel registration 900807) was used on the 2018 Foveaux Strait survey. The *Provider* is a 17 m fibreglass over plywood monohull, equipped with Cummins diesel engines rated at 1375 kw. The *Provider* was skippered by Brett Hamilton, who has considerable experience in commercial blue cod potting, and was the skipper on the 2014 Foveaux blue cod survey using the F.V. *Francis*.

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 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 initially deployed at each site, but this was discontinued after it was found that the equipment was damaged and was not recording. The ADCP records 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).

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 strata 1, 2 and 4 combined, and strata 5, 6, 7A, 8A and 10 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 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 2018 Foveaux Strait survey trip code was PRO1801. 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). 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.

There were no ADCP data collected on this survey.

## 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 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 and are presented for the 2018 Foveaux Strait 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). 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 ( $\text{kg.pot}^{-1}$ ) estimates were pot-based and the CV estimates were set-based (Beentjes & Francis 2011). Catch rates and 95% confidence intervals ( $\pm 1.96$  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 were all weighed on the survey. The stratum areas ( $\text{km}^2$ ) 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 Foveaux Strait 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  $\log(\text{weight})$  on  $\log(\text{length})$  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 Foveaux Strait 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  $t$ ,  $L_\infty$  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.

Von Bertalanffy growth models (von Bertalanffy 1938) were fitted to the 2010, 2014 and 2018 Foveaux Strait surveys length-age data combined.

### 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 ( $\text{km}^2$ ) shown in Table 1 was taken as the area of the stratum ( $A_t$ ), and the length-weight parameter estimates are from the 2018 Foveaux Strait 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 a single 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, together with CVs for each length and age class, and the mean weighted coefficients of variation (MWCV).

#### **2.2.6.5 Unsexed fish**

All but two very small blue cod (under 10 cm TL) were sexed during the 2018 Foveaux Strait survey. The unsexed fish were not used in ageing or to estimate total mortality ( $Z$ ), but were used to show the total scaled length frequency and corresponding total scaled age compositions.

#### **2.2.6.6 Sex ratios, and mean length and age**

Sex ratios (expressed as percentage male) and mean lengths, for the stratum and survey, were calculated using equations 10 and 11 of Beentjes & Francis (2011) from the stratum or survey scaled LFs. Mean ages were calculated analogously from the scaled age frequencies. Sex ratios were also estimated for recruited blue cod (33 cm and over), and overall survey 95% confidence intervals around sex ratios were generated from the 300 LF bootstraps.

#### **2.2.6.7 Total mortality estimates**

Total mortality ( $Z$ ) was estimated from catch-curve analysis using the Chapman-Robson estimator (CR) (Chapman & Robson 1960). Catch curve analyses measure the sequential decline of cohorts annually. The CR method was shown to be less biased than the simple regression catch curve analysis (Dunn et al. 2002). Catch curve analysis assumes that the right-hand descending part of the curve declines exponentially and that the slope is equivalent to the total mortality  $Z$  (= 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 in situations where there are not many age classes, and so there is potential for strong or weak year classes to introduce bias.

### 2.2.6.8 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%).

Because the lack of older fish often results in unrealistically high  $L_{\infty}$  estimates for fitted growth curves, Fisheries New Zealand Southern Inshore Working Group (SINSWG 2018/41) recommended that the growth curve from the combined surveys (2010, 2014 and 2018) be used to estimate growth parameters for the 2018 spawner-per-recruit analysis.

#### Input parameters used in SPR analyses

Growth parameters      von Bertalanffy growth parameters are from the 2010, 2014 and 2018 length and age data combined, and length-weight coefficients are from the 2018 survey:

Parameter	Males	Females
$K (yr^{-1})$	0.137	0.198
$t_0 (yr)$	-0.822	-0.54
$L_{\infty} (cm)$	55.72	39.96
$a$	0.007289	0.008362
$b$	3.2055	3.1696

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 combined 2010, 2014 and 2018 Foveaux Strait surveys von Bertalanffy model. The Foveaux Strait recreational MLS is 33 cm and selectivity was 5.7 years for males and 8.3 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 (8 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 8 years.

## 2.3 Analyses of 2010 and 2014 Foveaux Strait surveys

The 2010 and 2014 Foveaux Strait surveys (trip\_codes THE1010 and FRA1401) 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 sum of the weights of individual fish 33 cm and over, estimated from the respective 2010 and 2014 survey's published length-weight coefficients (Carbines & Beentjes 2012, Carbines & Haist 2017a). The otoliths from these two surveys

were re-aged in 2017 (Fisheries New Zealand project SEA201706), and ages are archived in the *age* database. The same readers aged these and the 2018 survey otoliths in accordance with the ADP, and hence ages are directly comparable among surveys. The new ages from the 2010 and 2014 surveys were analysed in this report and used to estimate population age structure, and mortality ( $M$  and  $Z$ ). The spawner-per-recruit growth parameters inputs were estimated from the combined length and age data of 2010, 2014 and 2018 surveys. Estimates of population age structure, mortality, and SPR given in this report for the 2010 and 2014 Foveaux Strait surveys, supersede those published in previous reports (Carbines & Beentjes 2012, Carbines & Haist 2017a).

### 3. RESULTS

#### 3.1 2018 random-site survey

Thirty-eight random sites (6 pots per site, producing 228 pot lifts) from eight strata in Foveaux Strait were surveyed from 6–20 February 2018 (Table 1, Figure 5). Depths sampled were 14–95 m (mean = 38.5 m). Thirty-four sites were sampled in phase-one and four in phase-two. An example of the systematic pot placement configuration for random sites is shown in Figure 6.

##### 3.1.1 Catch and catch rates

A total of 1384 kg of blue cod (3015 fish) was taken, comprising 75.1% by weight of the catch of all species on the survey (Table 2). Bycatch species included seven teleost fishes, and octopus. The most abundant bycatch species by far was leatherjacket (*Meuschenia scaber*) comprising 23.1% of the catch weight.

Mean catch rates ( $\text{kg.pot}^{-1}$ ) of blue cod (all blue cod, and 33 cm and over) are presented by stratum and overall (Table 3, Figure 7). Mean catch rates of blue cod (all sizes) by stratum were 4.01–8.41  $\text{kg.pot}^{-1}$  with the lowest catch in stratum 5 (middle of strait) and highest in stratum 10 (most southern stratum contiguous with Stewart Island) (Table 3, Figure 7). The all-blue-cod overall survey catch rate was 5.66  $\text{kg.pot}^{-1}$  with a CV of 20.5%. Catch rates for recruited blue cod (33 cm and over) followed a similar pattern among strata as for all blue cod and the overall survey catch rate was 2.45  $\text{kg.pot}^{-1}$  (CV 18.4%) (Table 3, Figure 7). Of the 228 random-site pots, 63 (28%) had zero catch of blue cod.

##### 3.1.2 Biological and length frequency data

Of the 3015 blue cod caught, all were measured for length and weighed, and all but two very small fish were sexed (Table 4). The sex ratios were 34–63% male across the eight strata and the overall weighted sex ratio was 51% male (Table 4). Length was 12–51 cm for males and 10–42 cm for females, although this range varied among strata and the overall weighted mean length was 30.6 cm for males and 28.4 cm for females. The scaled length frequency distributions were generally unimodal and broadly similar among the eight strata for males and females, respectively (Figure 8).

##### 3.1.3 Age and growth

Otolith section ages from 199 males and 159 females collected from the 2018 random-site survey were used to estimate the population age structure from Foveaux Strait in 2018 (Table 5). Similarly, ages from 151 males and 140 females collected from the 2010 random-site survey and 145 males and 130 females collected from the 2014 random-site survey combined were used to estimate the population age structure in those years (Table 5). For each survey, the length-age data are plotted and the von Bertalanffy model fits and growth parameters ( $K$ ,  $t_0$  and  $L_\infty$ ) are shown for males and females separately (Figure 9). 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 10, after which they tend to diverge as older fish become scarce (Figure 10). The von Bertalanffy model fits and growth parameters for the three surveys combined are shown in Figure 11.

Between-reader age comparisons for 2018 are presented in Figure 12. The first counts of the two readers showed 88% agreement, and overall there was no bias between readers with a CV of 1.1% and average percent error (APE) of 0.8%. The 2010 and 2014 surveys between reader comparisons are not shown but indicated good agreement and no bias between the two readers (Fisheries New Zealand, unpublished data).

### **3.1.4 Spawning activity**

Gonad stages of blue cod sampled on the Foveaux Strait survey in February 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 a small percentage in the mature condition, suggesting that the survey took place either before or after the spawning peak.

### **3.1.5 Population length and age composition**

The scaled length frequency and age distributions for the 2018 Foveaux Strait 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 13).

The scaled length frequency distribution for males was unimodal with a broad flat peak centred at about 32 cm and an overall mean length of 30.6 cm. The female distribution was also unimodal with a strong peak at about 30 cm and the overall mean length of 28 cm (Figure 13). The cumulative distribution plots of length frequency are generally similar between sexes, but males are skewed to the right. The mean weighted coefficients of variation (MWCVs) around the length distributions were 22% for both males and females.

The 2018 survey age estimates were 1–14 years for males and 1–17 years for females, but most males and females were 4–8 years old (Figure 13). The estimated population age distributions indicate almost knife-edge selectivity to the potting method at about three years with no indications of strong or weak modes for either males or females. The cumulative distribution plots of age frequency show clearly that females had a higher proportion of older fish than males (Figure 13). The mean age of females was greater than that of males (5.7 for males and 6.8 years for females). The MWCVs around the age distributions were 22% for males and 31% for females, the latter was higher than desired to provide a good representation of the overall population age structure.

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

Chapman-Robson total mortality estimates (Z) and 95% confidence intervals are given for a range of recruitment ages (5–10 y) in Table 7. Age-at-full recruitment (AgeR) is assumed to be eight years, equal to the age at which females reach the MLS of 33 cm. In 2018 the CR Z for AgeR of eight years was 0.70 (95% confidence interval of 0.47–0.98).

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 eight years, is shown for the 2018 survey for diagnostic purposes (Figure 14). The natural log of numbers-at-age appears to follow the ideal straight-line descending limb, suggesting that the assumption of constant recruitment has not been violated, and gives confidence in the CR Z estimates which tends to be less sensitive to age classes with few fish (see



Table 7). The steepness of the descending curve, and hence high  $Z$  value, is a direct result of the lack of recruited older age classes.

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 eight years are shown for the 2018 survey in Table 8. Based on the default  $M$  of 0.14, estimated fishing mortality ( $F$ ) was 0.56 and associated spawner-per-recruit was 21.8% (Figure 15). At the 2018 levels of fishing mortality, the expected contribution to the spawning biomass over the lifetime of an average recruit is reduced to 22% of the contribution in the absence of fishing. The 95% confidence intervals around the 2018 SPR ratios were 18–29% (Table 8).

### 3.2 Foveaux Strait random-site survey time series (2010, 2014, 2018)

Mean catch rates (kg.pot<sup>-1</sup>) for all blue cod and recruited blue cod for the three surveys are presented in Figure 16. The pattern of catch rates among the eight strata are most similar in 2010 and 2014 when the highest catch rates were from strata 1 and 2 and the lowest by far were from stratum 8A (see Figure 3). The 2018 catch rates were similar across all strata, and the large confidence intervals indicate that these are not significantly different. For Foveaux Strait overall, there was no trend in abundance across the three surveys (Figure 16).

The scaled length frequency distributions and mean length of all blue cod were remarkably similar for all three surveys, shown clearly by the cumulative distributions (Figure 17). Similarly, there was no change in the mean length of recruited blue cod (Figure 18).

The sex ratio for all surveys was 47–51% male for all blue cod, and 68–76% male for recruited blue cod, with no clear trends (Figure 19).

The male age structure is similar among the three surveys except for a weak 5-year-old age class in 2014, and it is not clear if this also resulted in a weak 9-year-old age class in 2018 (Figure 20). Female age structure is also generally similar, except for weak 5-year-old and 8-year-old age classes in 2010. The weak 5-year-old age class appears to have progressed through to 2014 as a weak 9-year-old age class (Figure 20).

Despite the general similarities in age compositions, the Chapman Robson total mortality estimates ( $Z$ ) increased from 0.52 in both 2010 and 2014, to 0.70 in 2018 with a corresponding decrease in the SPR estimates from about 27% to 22% (see Table 8 and Figure 15). The slopes of the right-hand limbs of the catch curves can vary considerably depending on the number of recruited age classes, which numbered just five for males in 2018 and four in 2014. With so few age classes, the slope can be strongly affected by one older age class, as in 2010 when there was a 29-year-old male which markedly reduced the slope of the catch curve (see Figure 14). A cautious approach should therefore be taken when interpreting  $Z$  and SPR estimates when so few age classes are included.

The proportion of pots with zero catch for the three random-site surveys ranged from 25–32% with no clear trends (Figure 21).

## 4. DISCUSSION

### 4.1 General

The 2018 Foveaux Strait random-site potting survey was the third Fisheries New Zealand survey in the time series of relative abundance and population structure of blue cod from this area, after previous random-site surveys in 2010 and 2014.

## 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 4) (Bostock et al. 2018). The sediment maps of Foveaux Strait show how sand, mud, and carbonates are distributed within the eight strata and may be useful for re-stratifying future surveys. Foveaux Strait is presently characterised by substrates of predominantly patchy sand and gravel with very little mud, and carbonate is restricted to the east coast of Stewart Island. Foveaux Strait is most famously known for its dredge oyster (*Ostrea chilensis*) fishery which has been in operation since the 1860s when the virgin seafloor was predominantly biogenic reef comprised mainly of oysters and invertebrates including bryozoans, mussels, sponges and tunicates, habitat also known to be favoured by blue cod in Foveaux Strait (Cranfield et al. 1999, Cranfield et al. 2001). The dredge oyster fishery operates on the south west of Foveaux Strait on dense patches or beds which lie within the blue cod survey strata. Where dredging for oysters has occurred, these biogenic reefs have largely been replaced by sandy or gravel bottoms, causing localised depletion of blue cod living on previously undisturbed or recovering biogenic reefs (Cranfield et al. 2001). Further, growth rates of juvenile blue cod were shown to be on average 20% higher on biogenic reefs than from dredged areas (Carbines et al. 2004). Hence, it seems likely that optimal habitat for blue cod is less than in the past and that any enhancement of the biogenic reefs would also benefit blue cod.

Foveaux Strait offers substantial and varied blue cod habitat, both inshore, within the strait, and around the many rugged islands to the east. The relative abundance of blue cod across the eight survey strata does not show any clear pattern in either 2014 and 2018<sup>1</sup>, nor is there a clear association between habitat type and abundance (Figures 22 and 23, see Figure 4). The carbonate sediment map indicates the level of biological material in the water column or on the seafloor and hence can be regarded as a proxy for locations of biogenic reef; there is no clear association between blue cod abundance and concentrations of carbonate. The sediment maps, however, are only approximations based on extrapolations from the nearest sediment sampling stations and most likely do not reflect the dynamic nature of sediment shifts and the ongoing impacts of oyster dredging in Foveaux Strait. 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, dropped underwater video at selected sites during the 2010 potting survey showed some preference by small and large fish for specific habitats (Carbines & Beentjes 2012).

The Foveaux Strait 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 average blue cod density in sampled sites is similar to density in unsampled area within that stratum.

## 4.3 Survey precision

The survey CV around relative abundance (catch rates) was not specified in the project objectives for the 2018 Foveaux Strait survey, but a CV of around 15% is generally targeted. The achieved CV of 20% in 2018 (from 38 sites) was slightly higher than desired and higher than previous random-site surveys (13% for 2010 from 56 sites, and 12% for 2014 from 53 sites). The achieved 2018 CV of 20% indicates that the number of sites used should be increased in future surveys if a lower CV is desired.

## 4.4 Cohort progression and genetic mixing

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 Foveaux Strait (see Figure 11). Blue cod are not fully

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<sup>1</sup> 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.

selected to the potting method until at least 4 to 5 years old, a finding also supported by the age composition in other areas surveyed, most recently Kaikoura and north Otago (Beentjes & Page 2018, Beentjes & Fenwick 2019).

The Foveaux Strait blue cod age structure is reasonably stable showing little in the way of strong or weak year classes, with the exception of a weak 5-year-old age class in 2010 progressing through to 2014 as 9-year olds (see Figure 20). The Foveaux Strait age structure differs 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 weak 2011 year-class. If the age characteristics were broadly similar, a strong 5-year-old and weak 4-year-old age class would be apparent in Foveaux Strait in 2018. 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, but this is not evident in Foveaux Strait. 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 as 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. The age compositions from Foveaux Strait compared to those of the east coast South Island surveys suggest that there may be less mixing and/or different environmental conditions affecting recruitment in these areas.

#### **4.5 Sex change and sex ratio**

The 2018 Foveaux Strait sex ratio is at parity, consistent with the previous surveys in 2010 and 2014. (see Figure 19). 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 possible 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.

However, in Foveaux Strait, offshore Banks Peninsula, and particularly Dusky Sound populations have sex ratios that are more balanced, suggesting that fishing pressure is less intense (Beentjes & Carbines 2009, Carbines & Beentjes 2012, Beentjes & Page 2016). Line caught blue cod around Stewart Island in the mid-1940s were on average much larger than those caught on the last three Foveaux Strait potting surveys (2010, 2014 and 2018), notwithstanding the method selectivity differences which are more likely to affect the catch of small blue cod (Rapson 1956, Beentjes & Carbines 2005). The movement of the length frequency distribution to the left is evidence of the effect of fishing on the Foveaux Strait blue

cod population. Despite having balanced sex ratios, there may be fishing induced sex change operating in these areas, including Foveaux Strait, but the extent of sex change may be in equilibrium with the removal of large males. The processes that drive sex change in blue cod are poorly understood and these may differ regionally.

#### 4.6 Reproductive condition

All Foveaux Strait blue cod surveys commenced in early February with the 2018 survey finishing in mid-February. The 2014 survey was not completed until mid-March and the 2010 survey not until mid-June, so reproductive status is only partially temporally comparable. The first two surveys show indications of spawning activity for both sexes, with variable proportions in the mature and running-ripe condition, whereas there were no running-ripe fish in 2018 (Figure 24).

Blue cod are considered to be 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 can spawn multiple times (Pankhurst & Conroy 1987), and it seems likely they will transition between the ripe and running-ripe conditions during this period. The lack of running-ripe fish in 2018 suggests that peak spawning did not occur during the time of the survey in early to mid-February, or that the survey took place between spawning events.

#### 4.7 Stock status and management implications

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  $F_{45\%SPR}$  (Ministry of Fisheries 2011). Blue cod is categorised as an exploited species with low productivity (on account of complexities of sex change) and the recommended default proxy for  $F_{MSY}$  is  $F_{45\%SPR}$ .

The 2018 Foveaux Strait random-site survey  $Z$  was 0.70,  $F$  was 0.56 and the SPR estimate, ( $M$  value of 0.14, and age at full recruitment of 8 years) was  $F_{21.8\%SPR}$  ( $F_{18\%-29\%}$ , 95% CIs), indicating that the expected contribution to the spawning biomass over the lifetime of an average recruit was reduced to 22% of the contribution in the absence of fishing (see Figure 15). These results suggest that the level of exploitation ( $F$ ) of Foveaux Strait blue cod stocks in 2018 was above the  $F_{MSY}$  target reference point of  $F_{45\%SPR}$  (over-exploited). The SPR estimate declined from 27% in both 2010 and 2014 to 22% in 2018.

Although the level of exploitation rate was well above the  $F_{MSY}$  target reference point, the catch rates in Foveaux Strait are stable and currently the highest of the nine areas surveyed, indicating that this is a productive area. Foveaux Strait (Statistical Area 025) also contributes about half of the annual catch from BCO 5, the largest commercial blue cod fishery in New Zealand.

Displacement of recreational fishing effort from Canterbury to north Otago is likely to have occurred in recent years because of low catch rates around inshore Banks Peninsula combined with lower daily bag limits and larger MLS at Motunau and Kaikoura. It is not known if this displacement of fishing effort extends to Foveaux Strait, but comparisons of the panel surveys in 2011–12 and 2017–18 (National Research Bureau unpublished data from 2011–12 and 2017–18 panel survey, pers. comm. Bruce Hartill) indicate that the number of blue cod harvested recreationally in the Foveaux Strait area increased by 35%, and in BCO 5 by 65% in six years.

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## 7. TABLES AND FIGURES

**Table 1: Effort and catch data for the 2018 Foveaux Strait random-site blue cod potting survey.**

Stratum	Area		<i>N</i> sets (sites)		<i>N</i> pots (stations)	Catch (blue cod)		Depth (m)	
	(km <sup>2</sup> )	Site type	Phase 1	Phase 2		<i>N</i>	kg	Mean	Range
1	221.8	Random	5		30	335	163.5	40.0	28–47
2	245.0	Random	5		30	467	203.1	39.6	33–50
4	160.0	Random	4		24	491	201.0	36.6	34–39
5	248.6	Random	5		30	226	120.4	33.9	30–38
6	261.8	Random	3	1	24	255	114.1	30.4	26–36
10	238.8	Random	4	2	36	624	302.6	66.9	41–95
7A	367.6	Random	5		30	347	171.4	25.2	14–36
8A	590.7	Random	3	1	24	270	107.9	35.7	19–54
Total		Random	34	4	228	3015	1384	38.5	14–95

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

Common name	Species	Code	Number	Catch (kg)	% catch
Blue cod	<i>Parapercis colias</i>	BCO	3015	1384.0	75.11
Leatherjacket	<i>Meuschenia scaber</i>	LEA	1600	425.1	23.07
Common octopus	<i>Octopus maorum</i>	OCT	9	16.7	0.91
Tarakihi	<i>Nemadactylus macropterus</i>	NMP	18	7.4	0.40
Wrasse	<i>Labridae</i>	WSE	1	3.9	0.21
Scarlet wrasse	<i>Pseudolabrus miles</i>	SPF	12	4.1	0.22
Banded Wrasse	<i>Notolabrus fucicola</i>	BPF	3	0.7	0.04
Trumpeter	<i>Latris lineata</i>	TRU	1	0.5	0.03
Blue moki	<i>Latridopsis ciliaris</i>	MOK	1	0.2	0.01
Totals			4660	1842.6	100

**Table 3: Mean catch rates for all blue cod and recruited blue cod (33 cm and over) from the 2018 Foveaux Strait 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.**

Stratum	Pot lifts (N)	All blue cod			Recruited blue cod ≥ 33 cm		
		Catch rate (kg.pot <sup>-1</sup> )	s.e.	CV (%)	Catch rate (kg.pot <sup>-1</sup> )	s.e.	CV (%)
1	30	5.45	1.47	26.9	2.60	0.73	28.1
2	30	6.77	3.33	49.2	2.23	1.00	44.9
4	24	8.38	3.11	37.1	4.31	1.33	30.8
5	30	4.01	1.56	38.9	2.31	0.82	35.6
6	24	4.75	2.74	57.7	1.91	0.94	49.0
7A	30	5.71	3.37	58.9	2.87	1.67	58.5
8A	24	4.50	2.58	57.3	1.59	0.92	58.0
10	36	8.41	5.64	67.1	3.55	1.89	53.2
Overall	228	5.66	1.16	20.5	2.45	0.45	18.4

**Table 4: Descriptive statistics for blue cod caught on the 2018 Foveaux Strait random-site blue cod potting survey. Outputs are raw for each stratum, and weighted overall. Sex ratio is also given for recruited blue cod (33 cm and over). m, male; f, female; u, unsexed.**

Stratum	Sex	N	Length (cm)			Random site survey	
			Mean	Minimum	Maximum	Percent male	
						All blue cod	Recruited blue cod $\geq 33$ cm
1	m	169	32.3	18	46.3	50.4	76.7
	f	166	29.5	17.4	40.4		
	u	0					
2	m	158	31.6	21.5	43	33.9	66.3
	f	309	29.3	22	37.7		
	u	0					
4	m	320	30.6	19	44.1	65.3	90.7
	f	170	26.0	18.8	38.3		
	u	1	6.4				
5	m	106	32.9	13.1	41.6	46.8	60.9
	f	120	30.4	15.4	40.5		
	u	0					
6	m	120	30.6	11.8	42.5	46.3	59.4
	f	135	29.8	10.5	40.5		
	u	0					
7A	m	187	32.0	19.6	44.4	53.9	77.7
	f	160	29.1	17.4	42.1		
	u	0					
8A	m	169	29.7	17.5	45.5	62.8	94.0
	f	100	26.8	16.2	36.0		
	u	1	9.2				
10	m	228	32.2	14.8	50.7	36.5	52.6
	f	396	30.2	18	40.4		
	u	0					
Overall	m	1457	30.6	11.8	50.7	50.7	73.4
	f	1556	28.4	10.5	42.1		
	u	2	7.8	6.4	9.2		

**Table 5: Otolith ageing data used in the catch-at-age, Z estimates and SPR analyses for the 2018 Foveaux Strait random-site blue cod potting survey. Age data are also provided for the 2010 and 2014 surveys re-aged in 2017 (Fisheries New Zealand project SEA201706).**

Survey	Sex	No. otoliths	Length of aged fish (cm)		Age (years)	
			Minimum	Maximum	Minimum	Maximum
2018	Total	358				
	Male	199	11	50	1	14
	Female	159	10	42	1	17
2010	Total	291				
	Male	151	12	56	1	29
	Female	140	11	41	1	15
2014	Total	275				
	Male	145	14	46	2	11
	Female	130	9	43	1	18

**Table 6: Gonad stages (%) of blue cod from the 2018 Foveaux Strait random-site blue cod potting survey in February 2018 for all blue cod by sex. 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.**

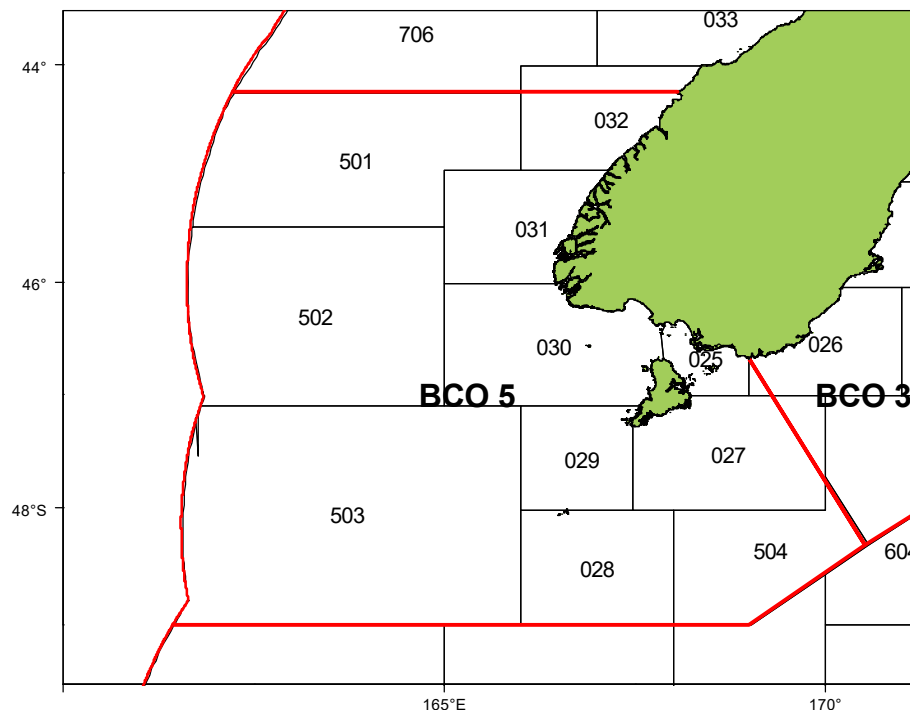
Sex	Gonad stage (%)					N
	1	2	3	4	5	
Males	20.1	78.5	1.4	0.0	0.0	1457
Females	58.4	36.1	5.5	0.0	0.0	1556

**Table 7: Chapman-Robson total mortality estimates ( $Z$ ) and 95% confidence intervals of blue cod for the 2018 Foveaux Strait random-site blue cod potting survey. Estimates are also provided for the surveys in 2010, and 2014. AgeR, age at full recruitment.**

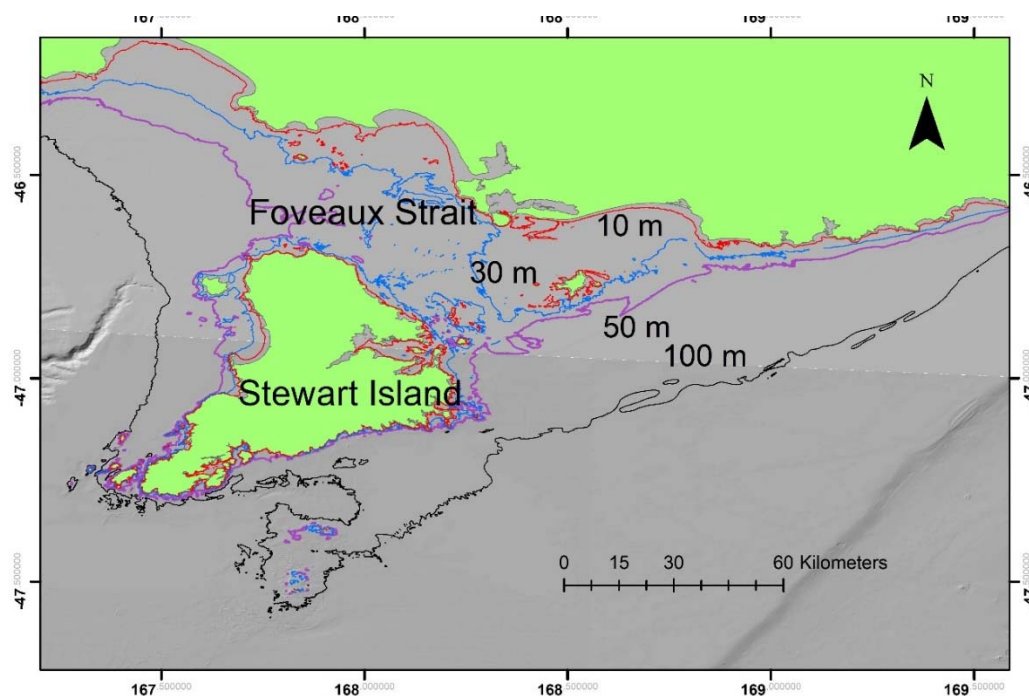
Survey	AgeR	$Z$	95% CIs	
			Lower	Upper
2018	5	0.42	0.29	0.57
	6	0.50	0.34	0.70
	7	0.55	0.39	0.77
	8	0.70	0.47	0.98
	9	0.61	0.38	0.89
	10	0.76	0.44	1.18
2010	5	0.48	0.32	0.67
	6	0.67	0.45	0.94
	7	0.75	0.50	1.10
	8	0.52	0.32	0.77
	9	0.72	0.41	1.13
	10	0.85	0.45	1.34
2014	5	0.39	0.28	0.54
	6	0.53	0.36	0.74
	7	0.50	0.33	0.72
	8	0.52	0.33	0.75
	9	0.48	0.28	0.74
	10	0.64	0.35	1.10

**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 Foveaux Strait 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  $Z$ . Estimates are also given for the 2010 and 2014 surveys. Spawner-per-recruit was estimated for each survey using the same von Bertalanffy parameters, determined from the combined length and age of the three surveys. AgeR, age at recruitment (age at which females reach MLS of 33 cm);  $F$ , fishing mortality;  $M$ , natural mortality;  $Z$ , total mortality; LowerCI, lower 95% confidence interval; UpperCI, Upper 95% confidence interval.**

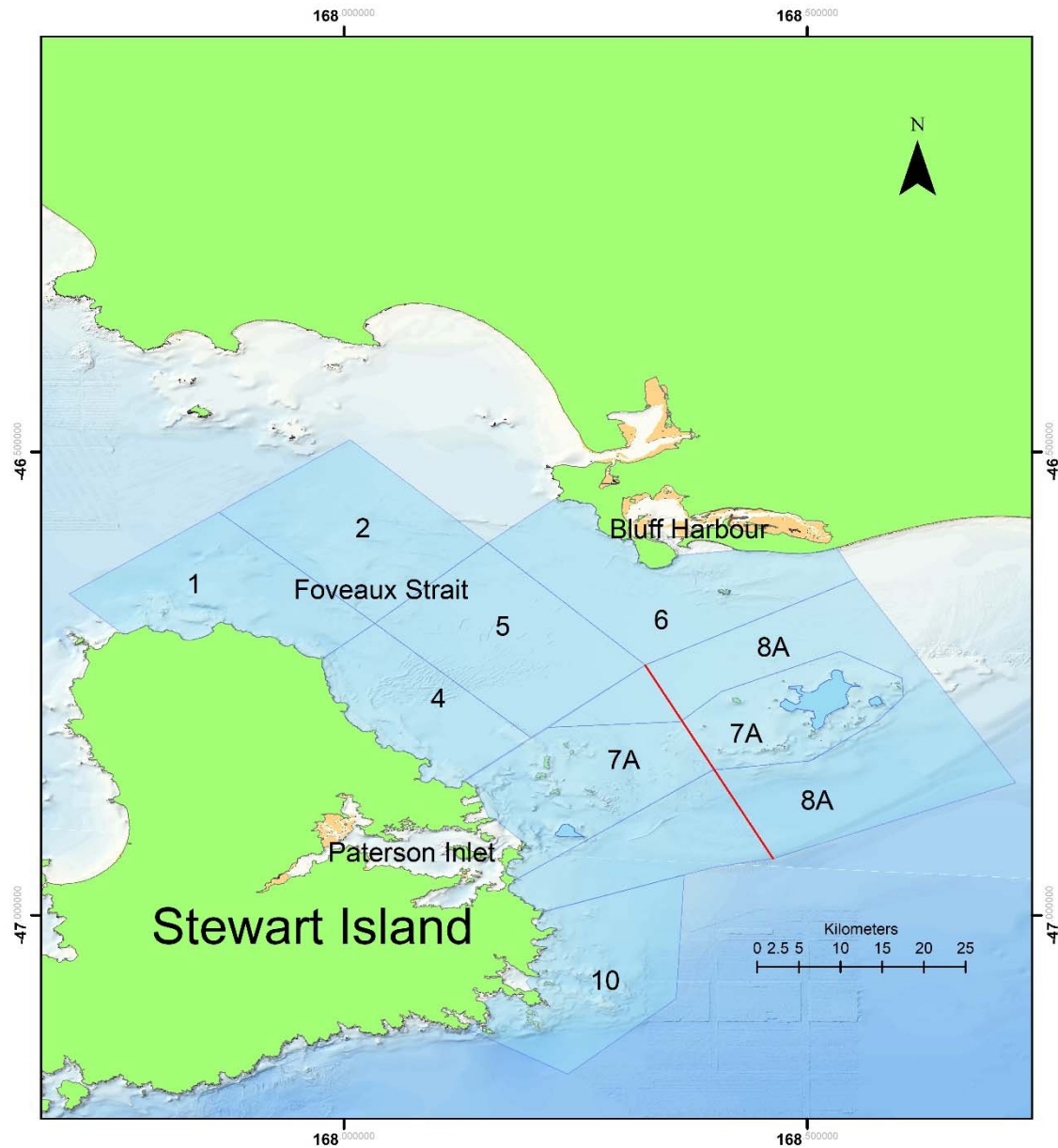
Survey	AgeR	$M$	$Z$	$F$	$F_{\%SPR}$	Estimate
2018	8	0.11	0.70	0.59	F <sub>16.5%</sub>	Point
	8	0.14	0.70	0.56	F <sub>21.8%</sub>	Point
	8	0.17	0.70	0.53	F <sub>27.3%</sub>	Point
	8	0.14	0.47	0.33	F <sub>28.8%</sub>	LowerCI
	8	0.14	0.98	0.84	F <sub>18.3%</sub>	UpperCI
2010	8	0.11	0.52	0.41	F <sub>20.3%</sub>	Point
	8	0.14	0.52	0.38	F <sub>26.9%</sub>	Point
	8	0.17	0.52	0.35	F <sub>33.6%</sub>	Point
	8	0.14	0.32	0.18	F <sub>40.7%</sub>	LowerCI
	8	0.14	0.77	0.63	F <sub>20.8%</sub>	UpperCI
2014	8	0.11	0.52	0.41	F <sub>21.0%</sub>	Point
	8	0.14	0.52	0.38	F <sub>27.6%</sub>	Point
	8	0.17	0.52	0.35	F <sub>34.4%</sub>	Point
	8	0.14	0.33	0.19	F <sub>40.3%</sub>	LowerCI
	8	0.14	0.75	0.61	F <sub>21.9%</sub>	UpperCI



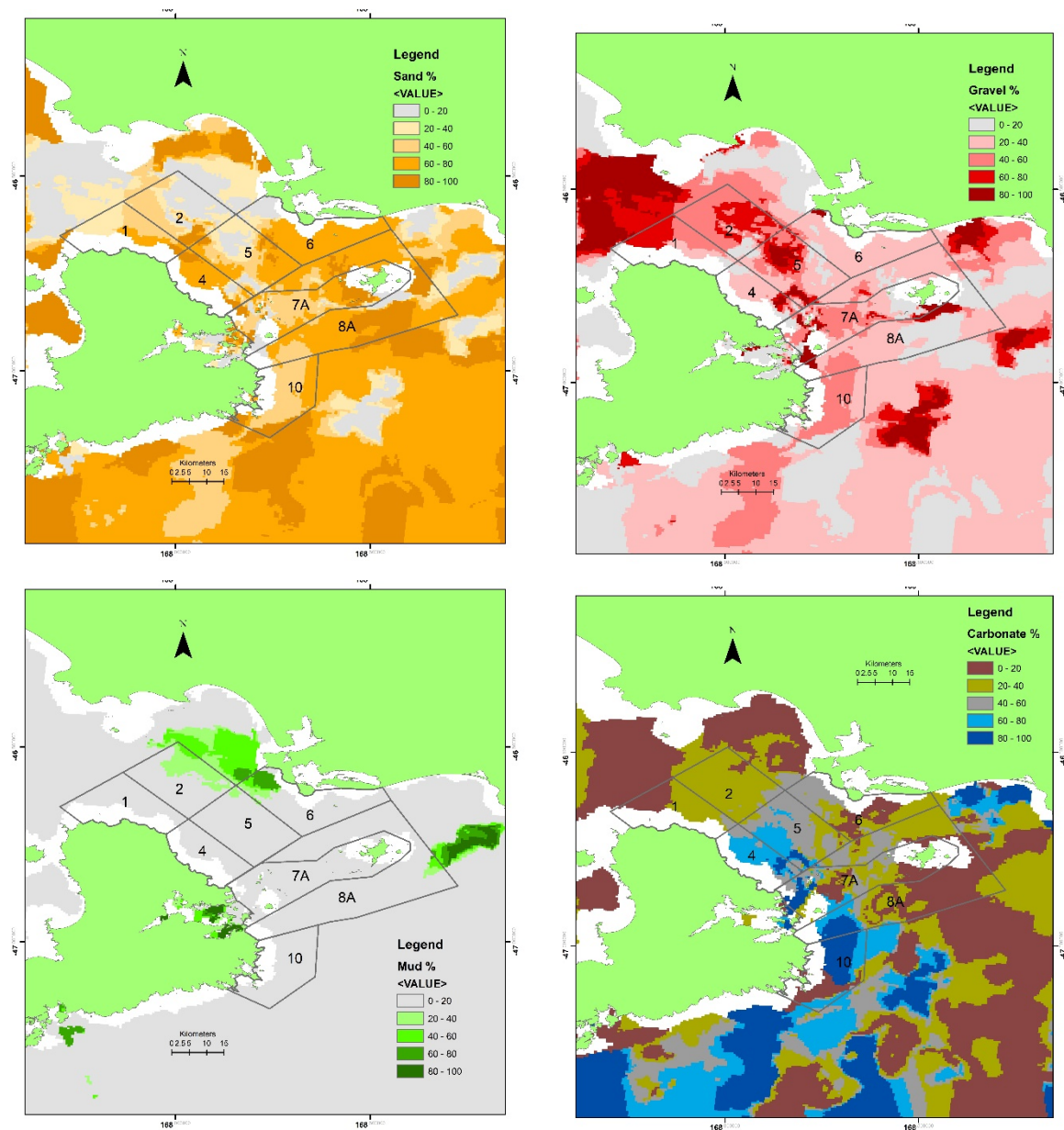
**Figure 1: Blue cod Quota Management Area BCO 5 and statistical areas. The Foveaux Strait blue cod potting survey takes place within Statistical Area 025.**



**Figure 2: Stewart Island and Foveaux Strait 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).**

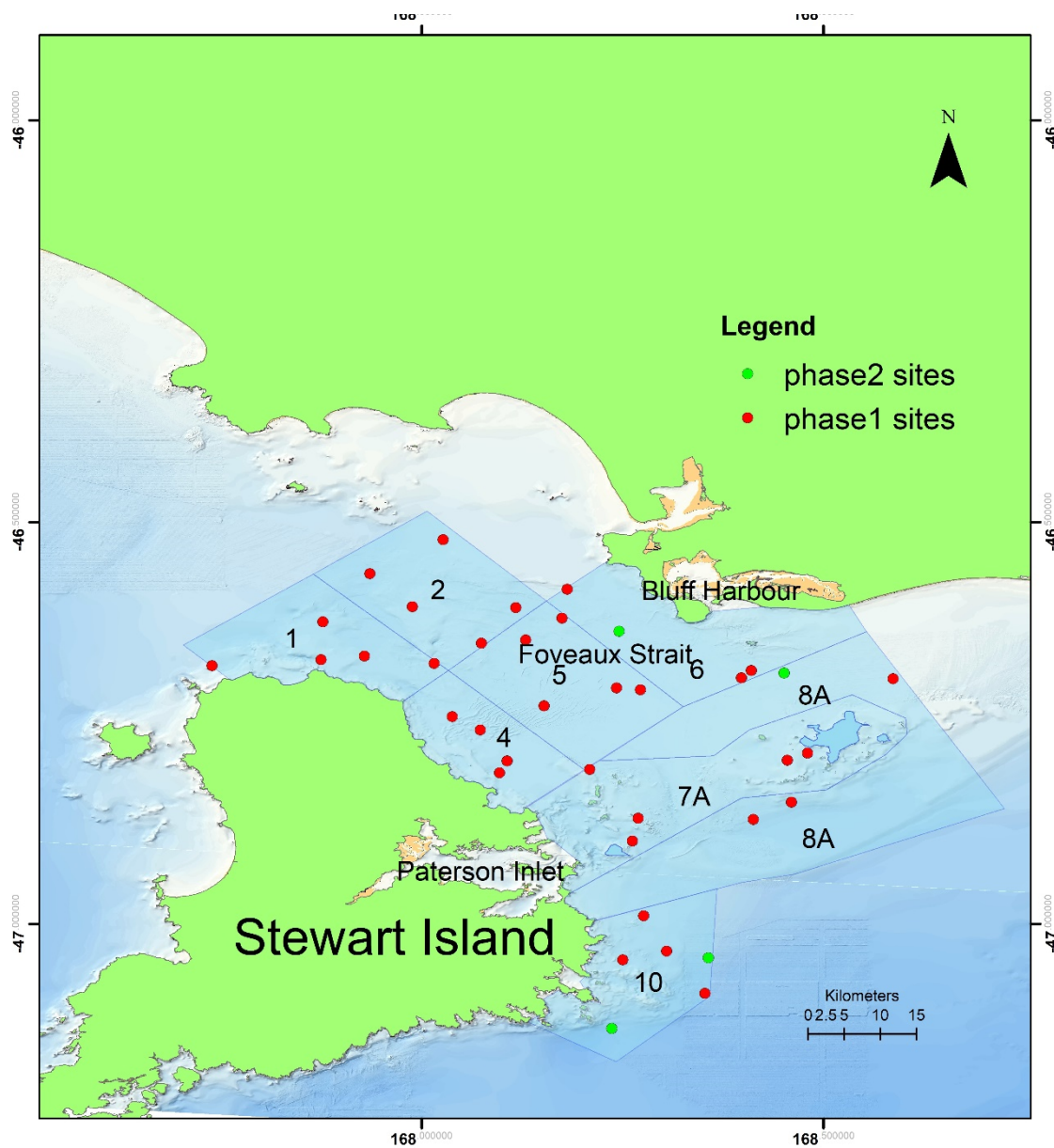


**Figure 3: Foveaux Strait multibeam seafloor map and survey strata used in 2018. The red line indicates the 2010 survey strata boundary between the original stratum 7 (southwest of line) and stratum 8 (northeast of line).**

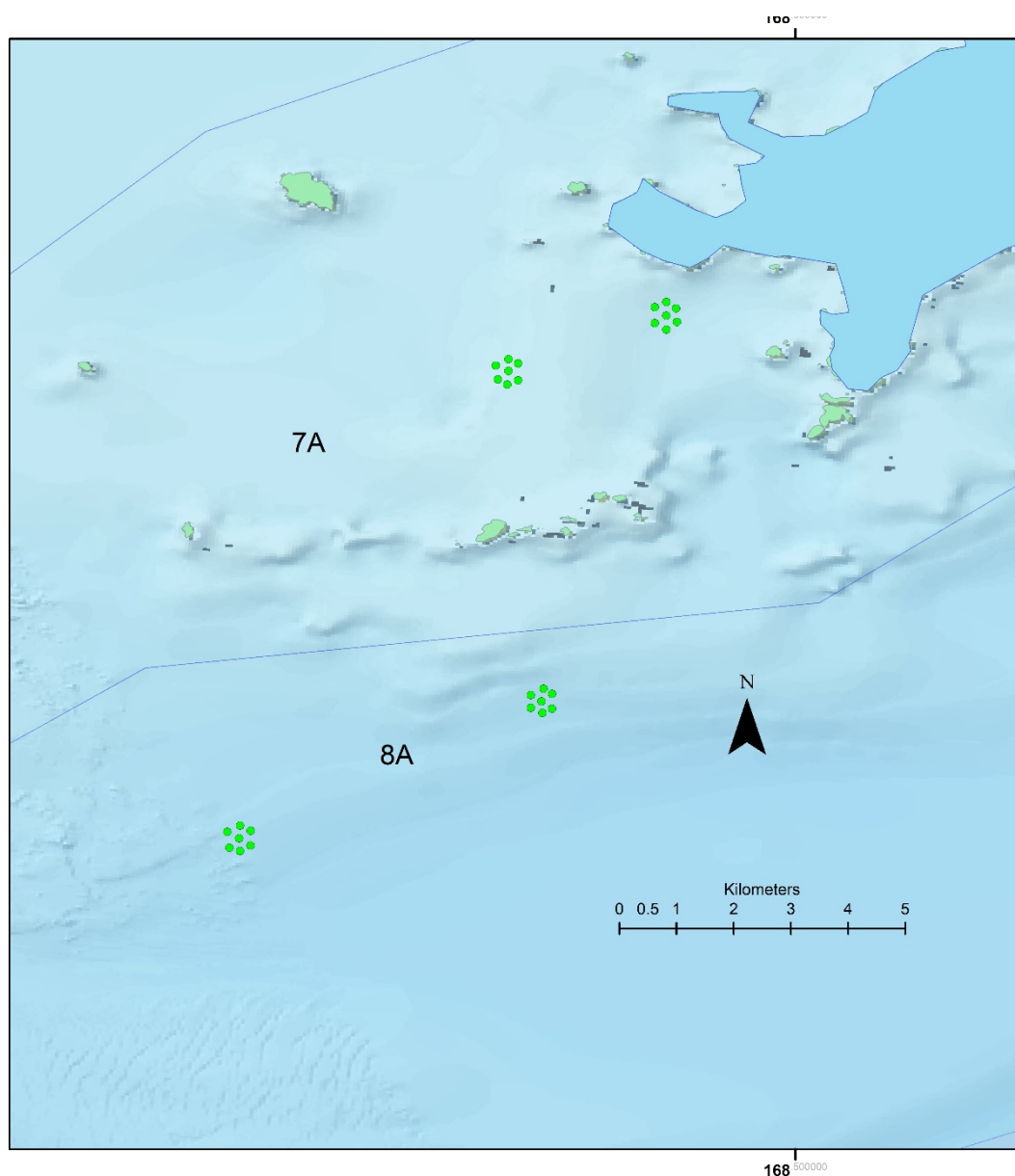


**Figure 4: Foveaux Strait 2018 blue cod survey strata and distribution of mud, sand, gravel and carbonates on the sea floor (sediment data from Bostock et al. 2018). Rock substrates are not included in the sediments database.**

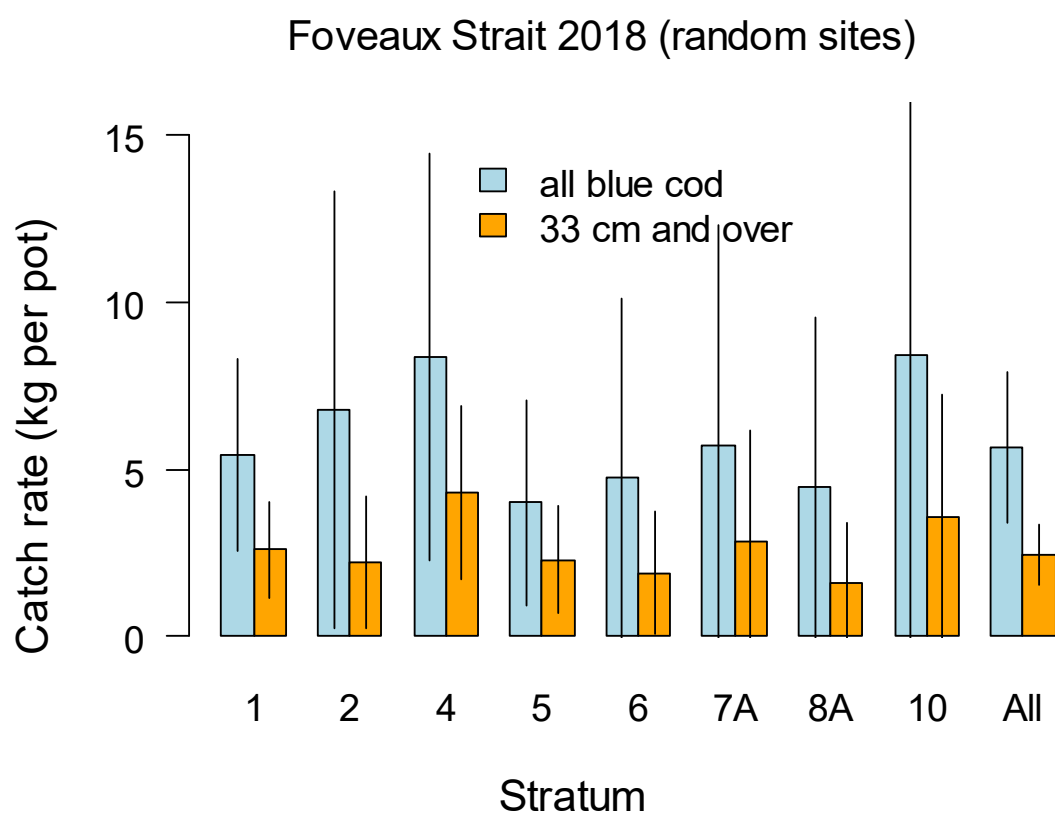




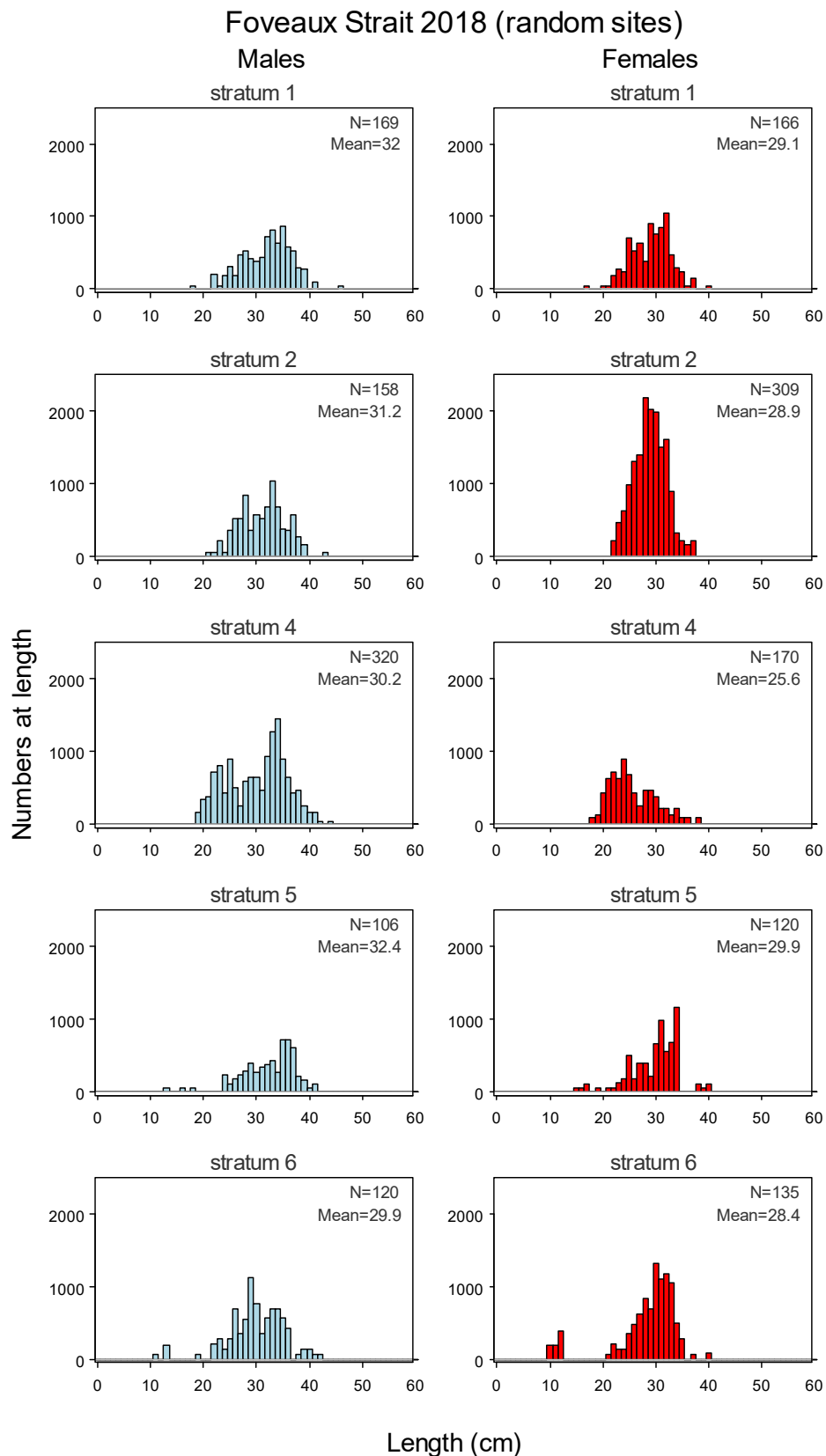
**Figure 5: Strata and site positions for the 2018 Foveaux Strait random-site blue cod potting survey.**



**Figure 6: Foveaux Strait 2018 random-site blue cod potting survey pot placement example for four random sites in strata 8A and 7A, shown to demonstrate how six pots were placed in a hexagon pattern around the central random-site location.**

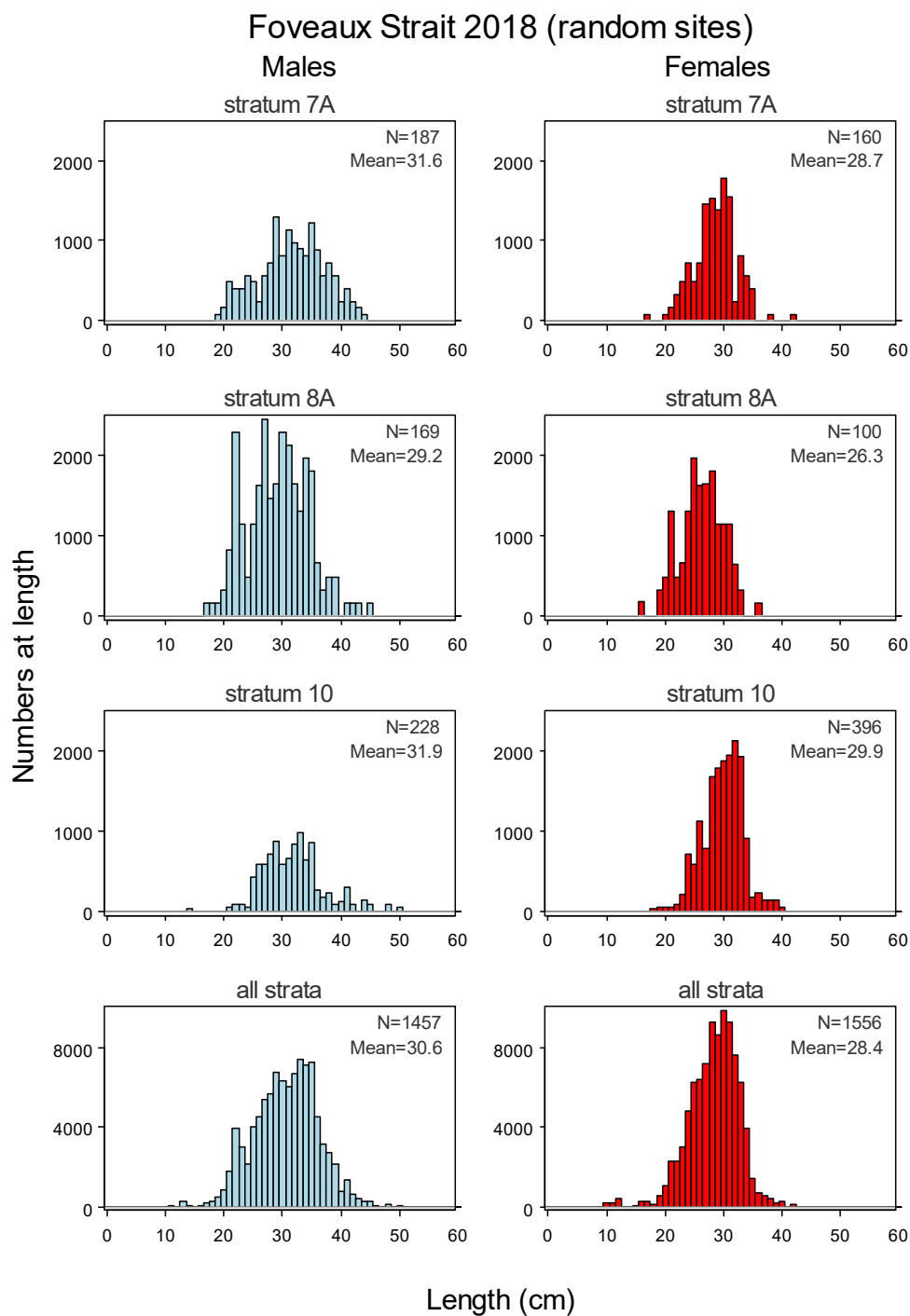


**Figure 7: Catch rates ( $\text{kg.pot}^{-1}$ ) of all blue cod and recruited blue cod (33 cm and over) by strata, and overall for the 2018 Foveaux Strait random site survey. Error bars are 95% confidence intervals.**

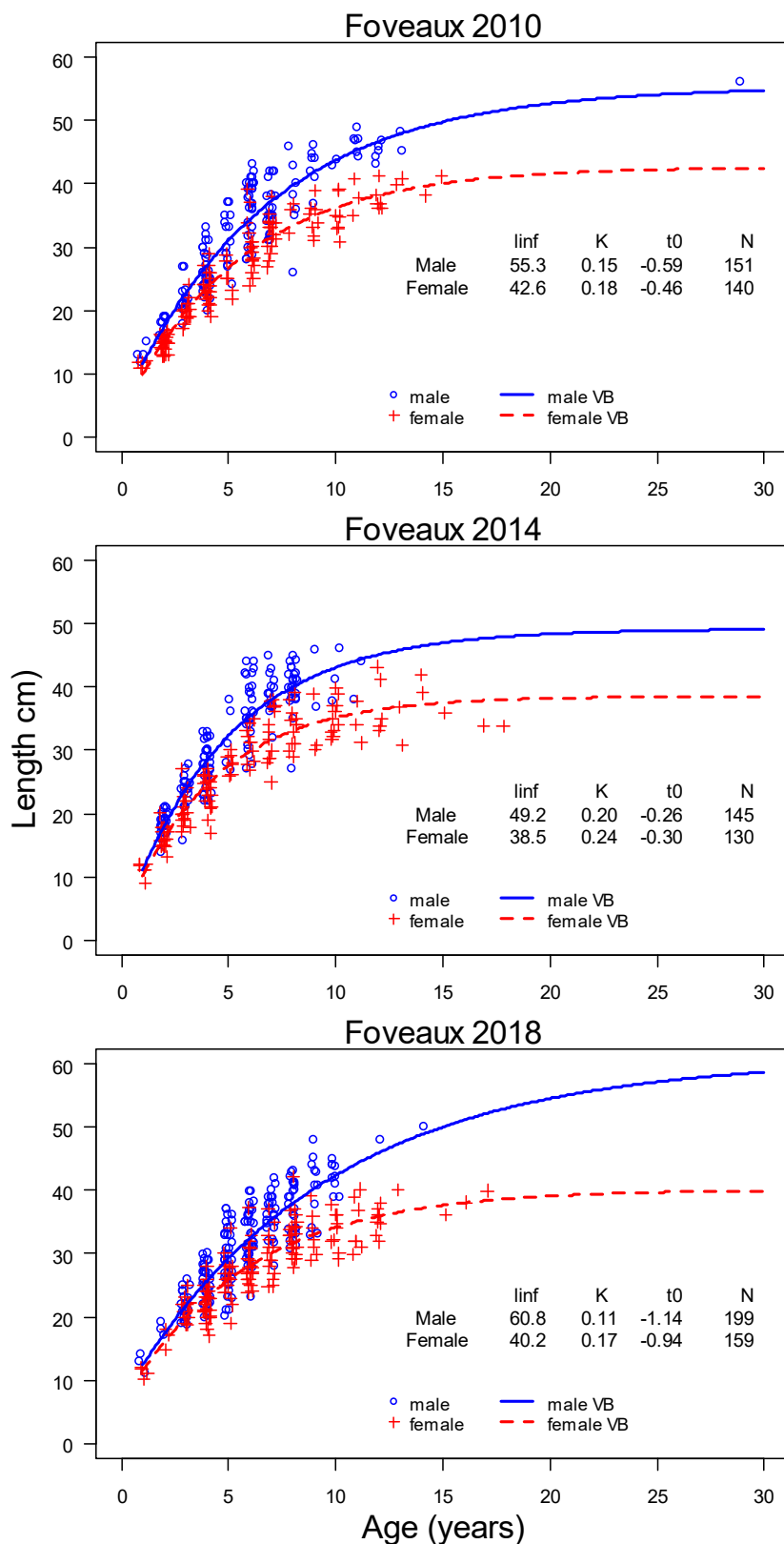


**Figure 8: Scaled length frequency distributions by strata and overall for the 2018 Foveaux Strait random-site potting survey. N, sample numbers; Mean, mean length (cm). Scale differs for the ‘all strata’ panel.**

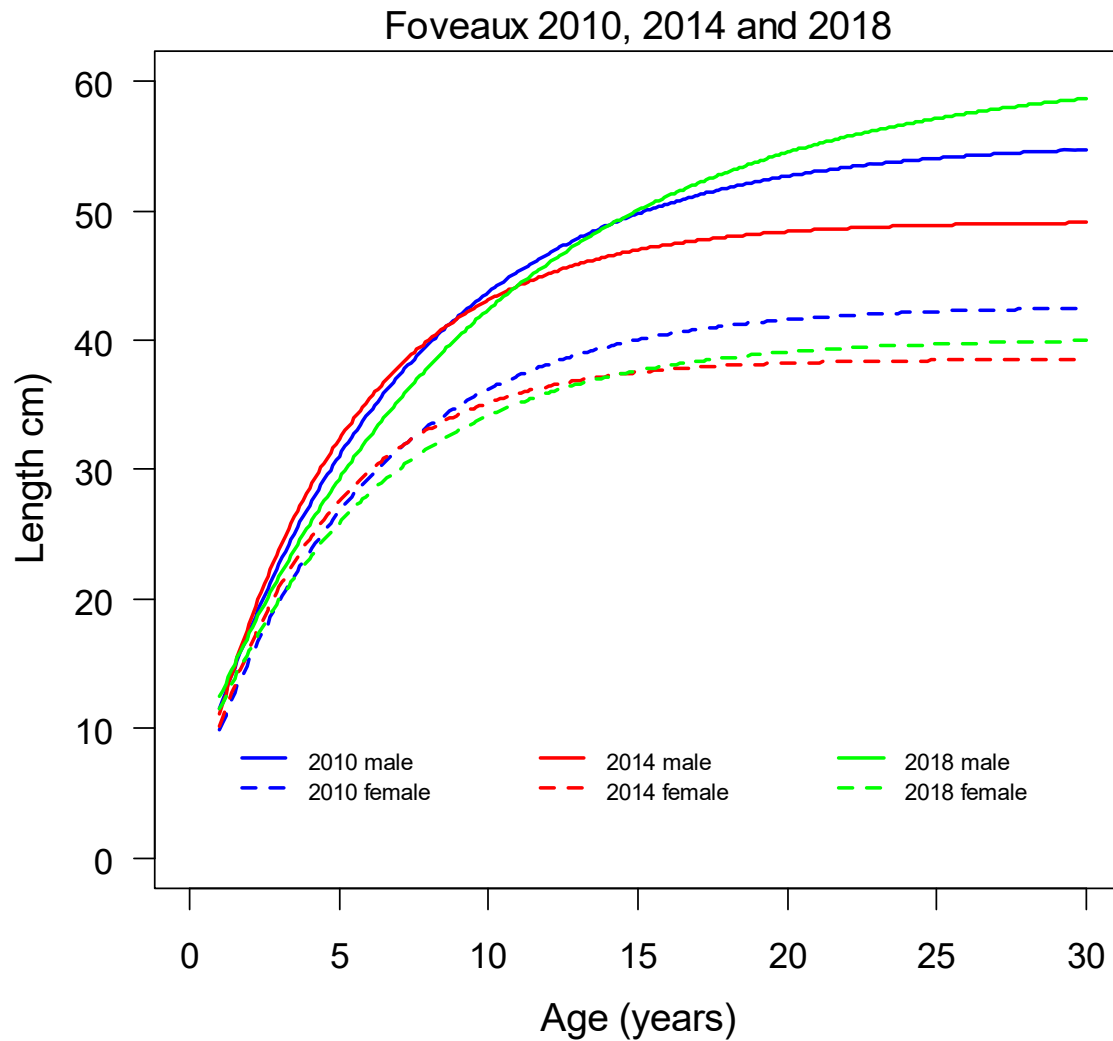
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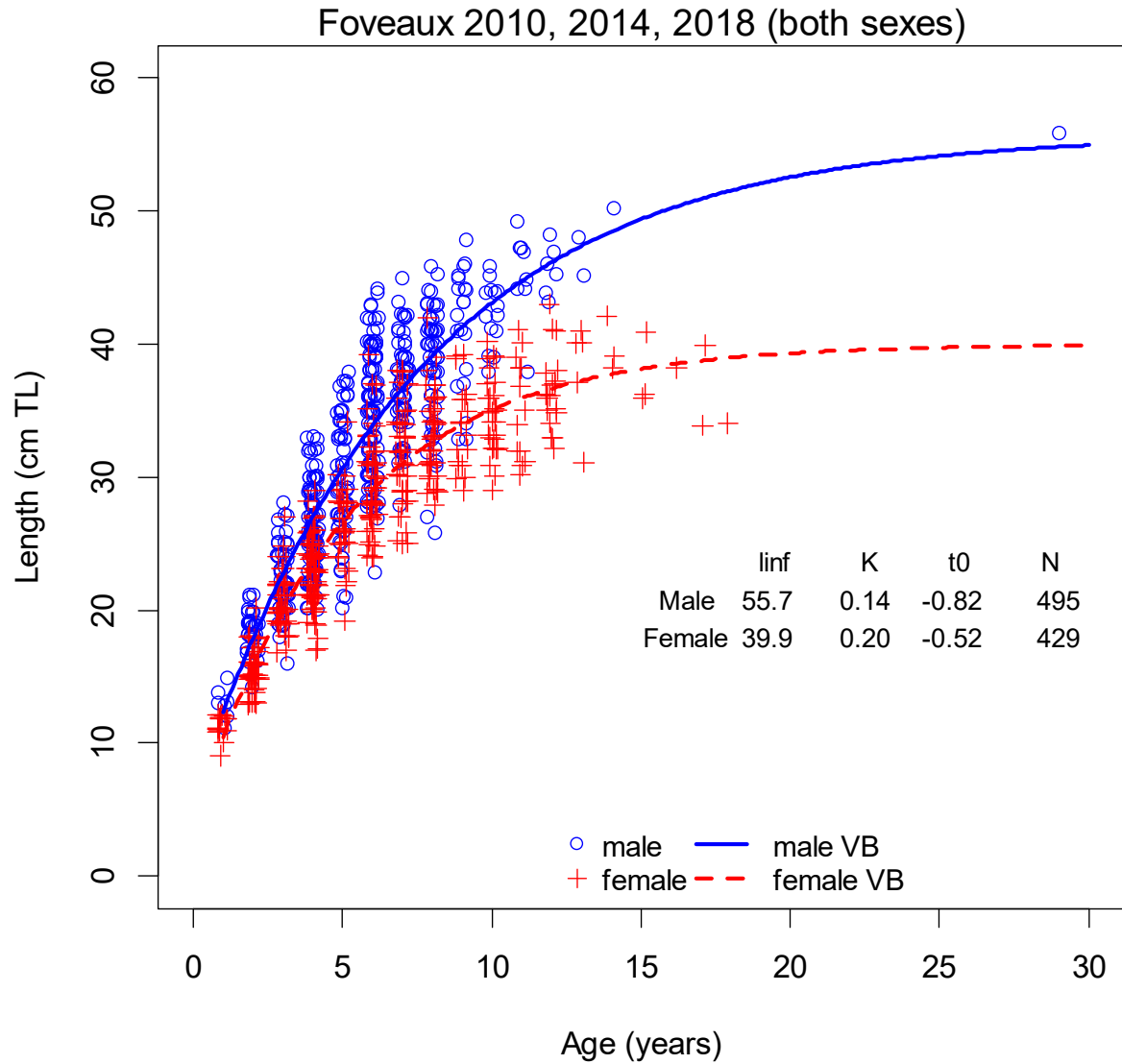
**Figure 8 – continued**



**Figure 9: Observed blue cod age and length data by sex for the 2010, 2014 and 2018 Foveaux Strait survey with von Bertalanffy (VB) growth models fitted to the data. Linf, average size at the maximum age (cm); K, Brody growth coefficient ( $\text{yr}^{-1}$ ); t0, age when the average size is zero.**

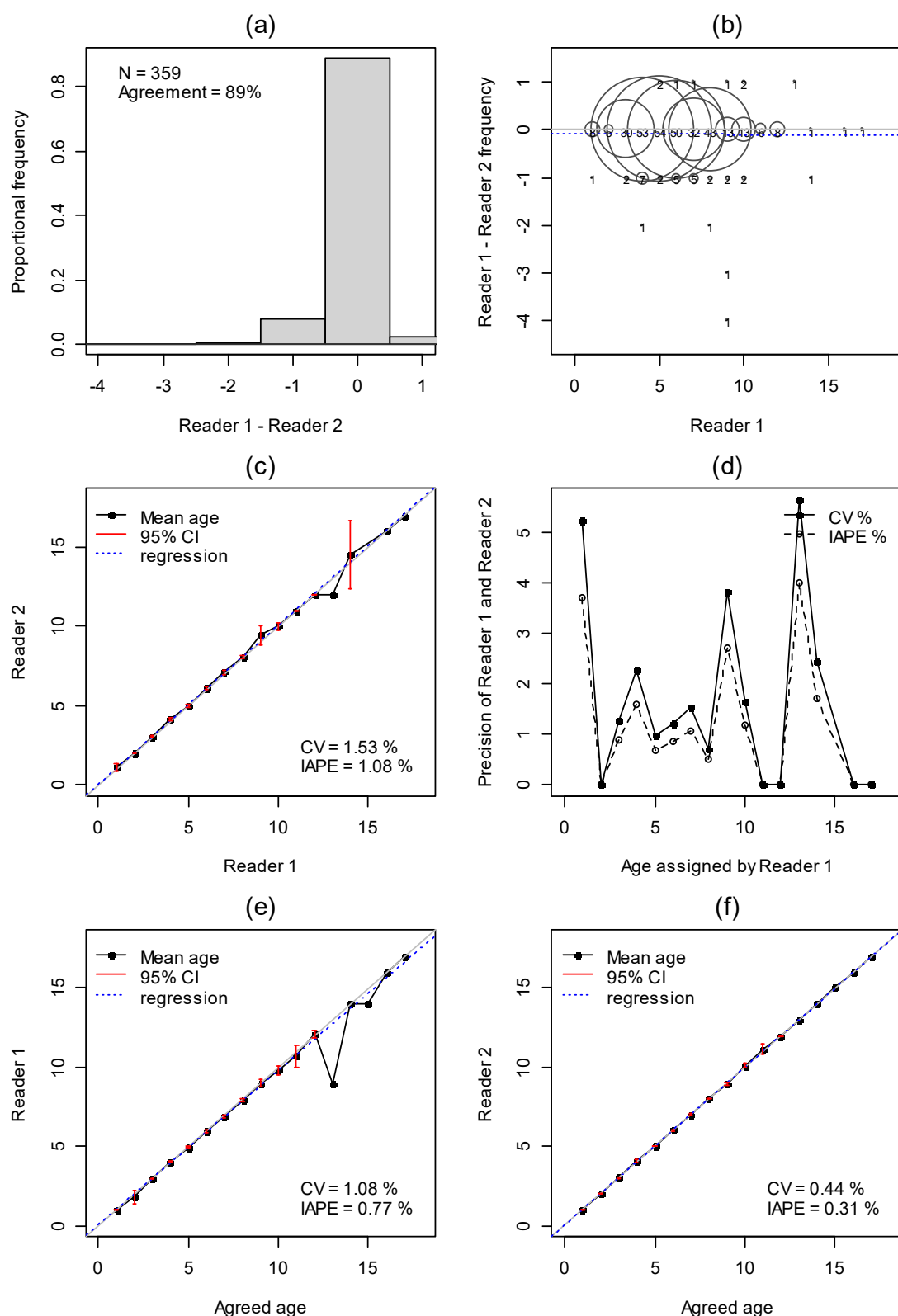


**Figure 10: von Bertalanffy growth models fitted to the Foveaux Strait 2010, 2014 and 2018 blue cod surveys age and length data. All curves are fitted to age 30 years to capture the 29-year-old fish in 2010. Max ages in 2014 were 18 years and in 2018 were 17 years.**

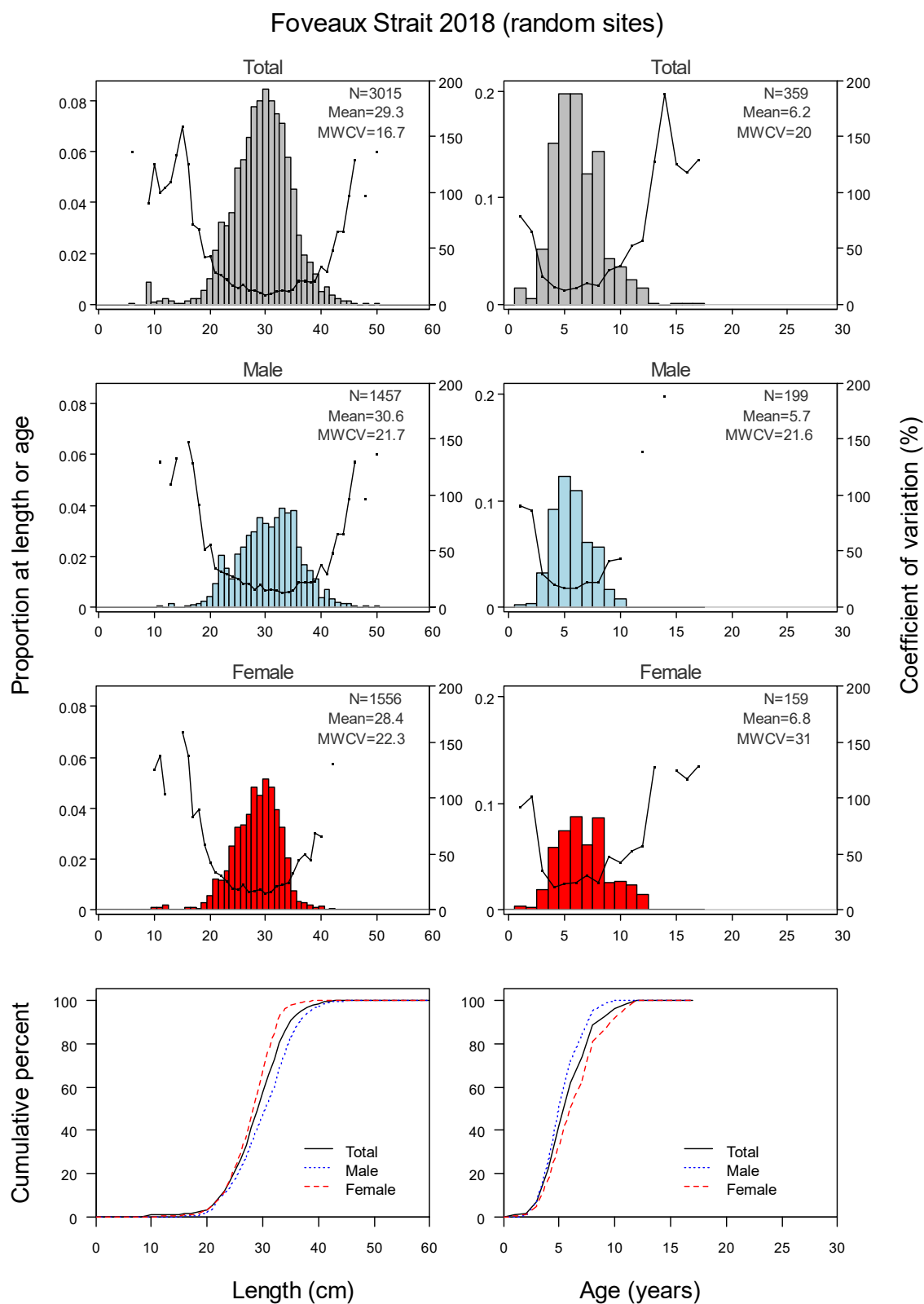


**Figure 11: Observed blue cod age and length data by sex for the 2010, 2014 and 2018 Foveaux Strait surveys combined, with von Bertalanffy (VB) growth models fitted. Linf, average size at the maximum age (cm); K, Brody growth coefficient ( $\text{yr}^{-1}$ ); t0, age when the average size is zero.**

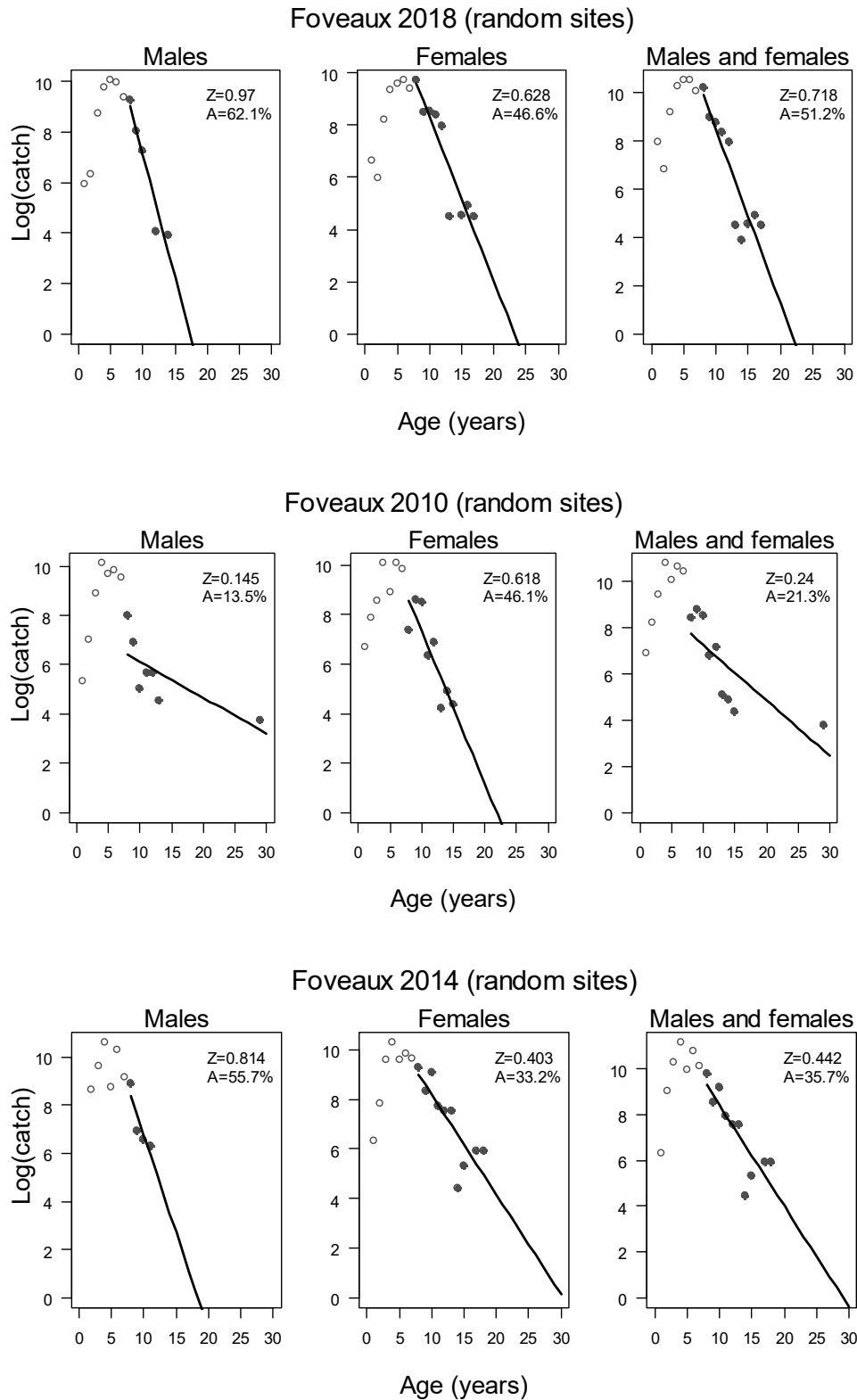




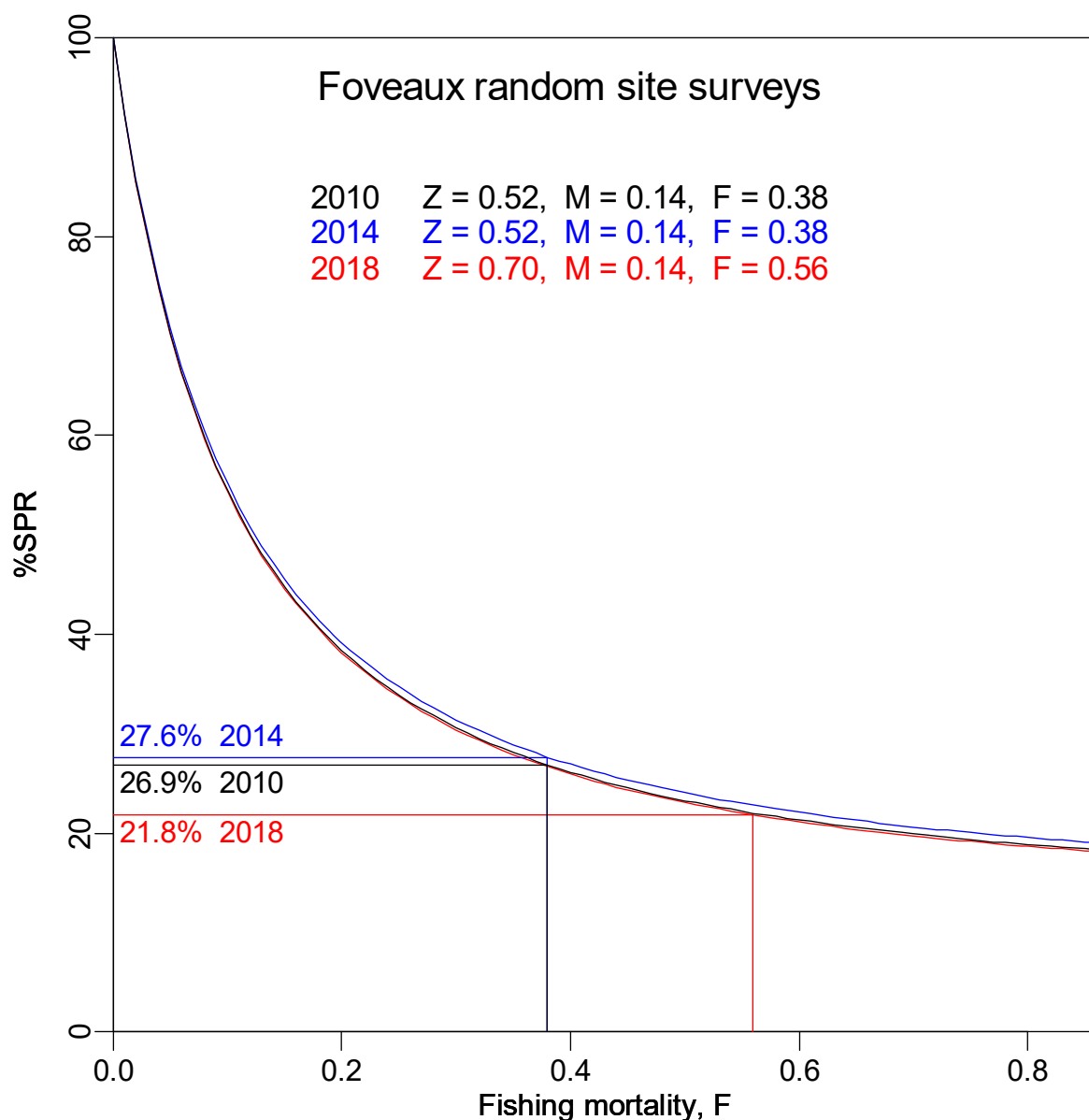
**Figure 12: Blue cod age otolith reader comparison plots between reader 1 and reader 2 for the 2018 Foveaux Strait survey: (a) histogram of age differences between two readers; (b) difference between reader 1 and reader 2 as a function of the age assigned by reader 1, where the numbers of fish in each 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, c, e and f, solid grey lines show perfect agreement, dashed blue lines show the trend of a linear regression of the actual data.**



**Figure 13: Scaled length frequency, age frequency, and cumulative distributions for total, male, and female blue cod for all strata in the 2018 Foveaux Strait random-site blue cod potting survey (N, sample size; MWCV, mean weighted coefficient of variation, %).**

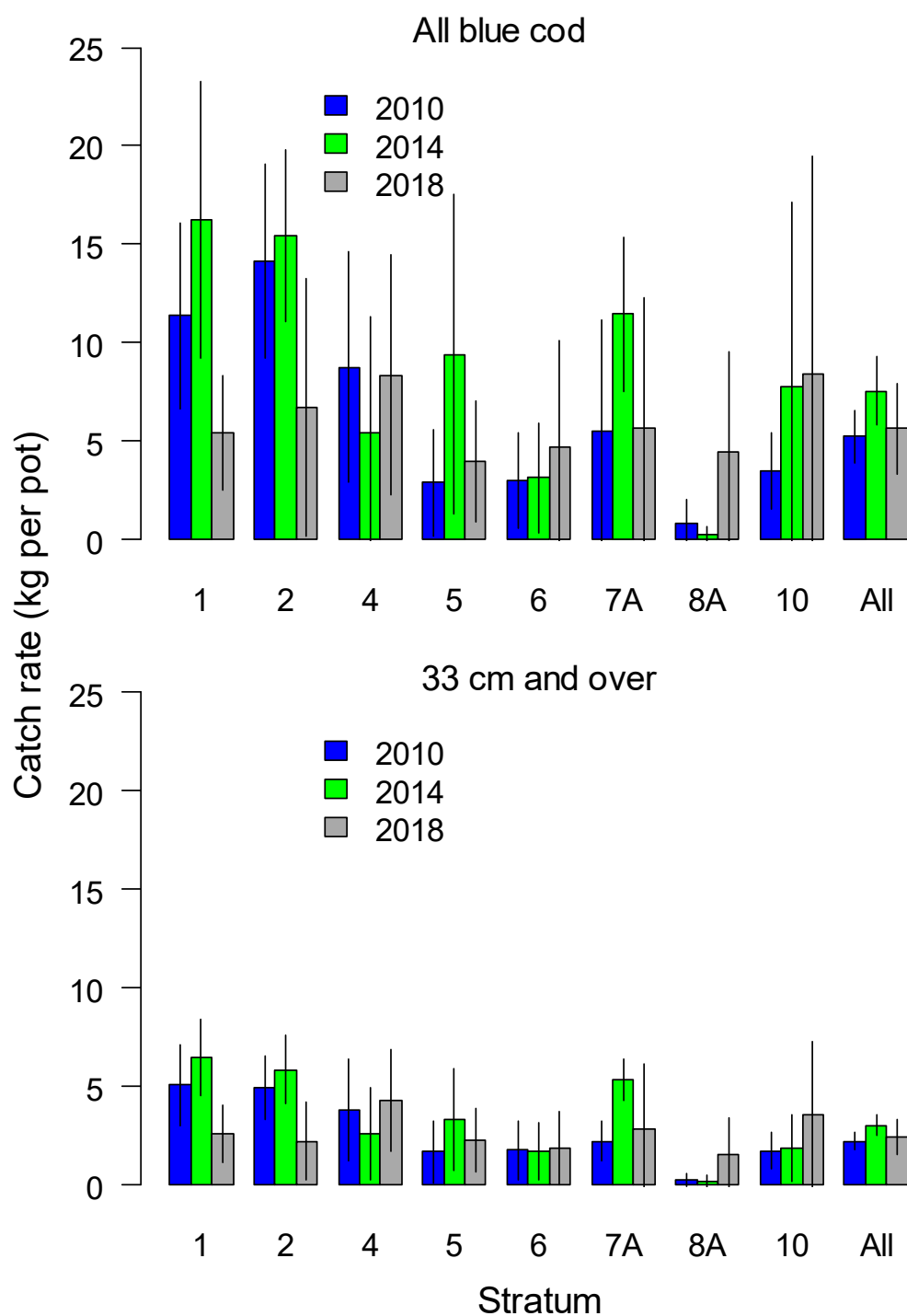


**Figure 14: Catch curves (natural log of catch numbers versus age) for Foveaux Strait 2018 random-site survey. Catch curves are also shown for the 2010 and 2014 surveys. The regression line is plotted from age at full recruitment of 8 years (i.e., dark points on the graph). Z, instantaneous total mortality; A, the annual mortality rate or the proportion of the population that suffers mortality in a given year.**

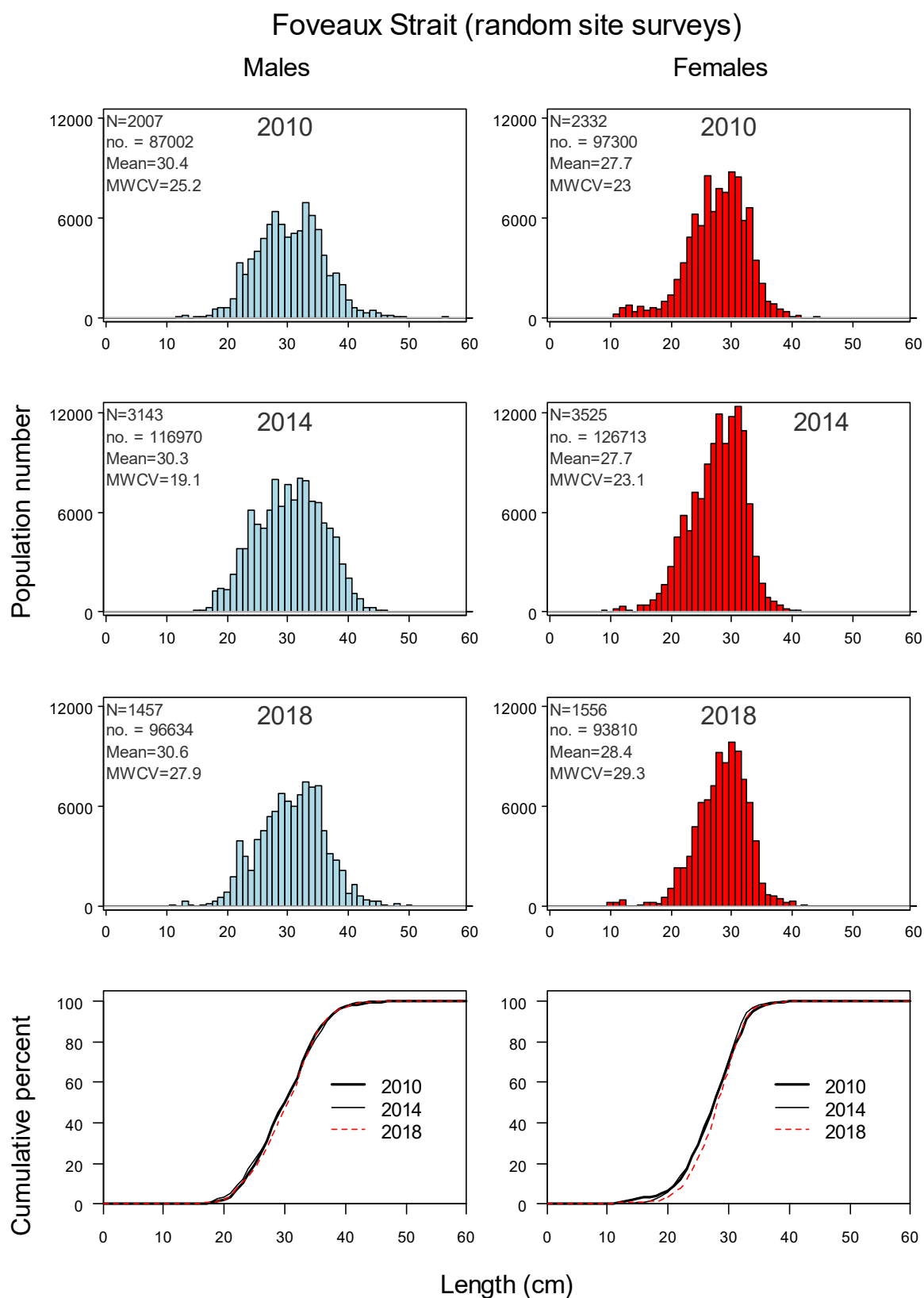


**Figure 15: Spawner-per-recruit (SPR) as a function of fishing mortality ( $F$ ) for the 2018 Foveaux Strait random-site survey. Results are also shown for the 2010 and 2014 surveys. SPR was estimated for each survey using the same von Bertalanffy parameters, determined from the combined length and age of the three surveys. In this plot  $M = 0.14$ , and the  $F$  value is for age of full recruitment equal to 8 years for females.**

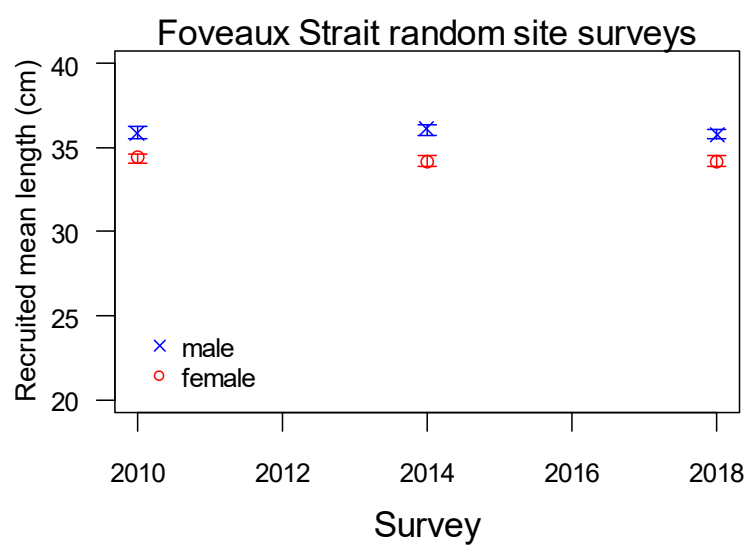
## Foveaux Strait random site surveys



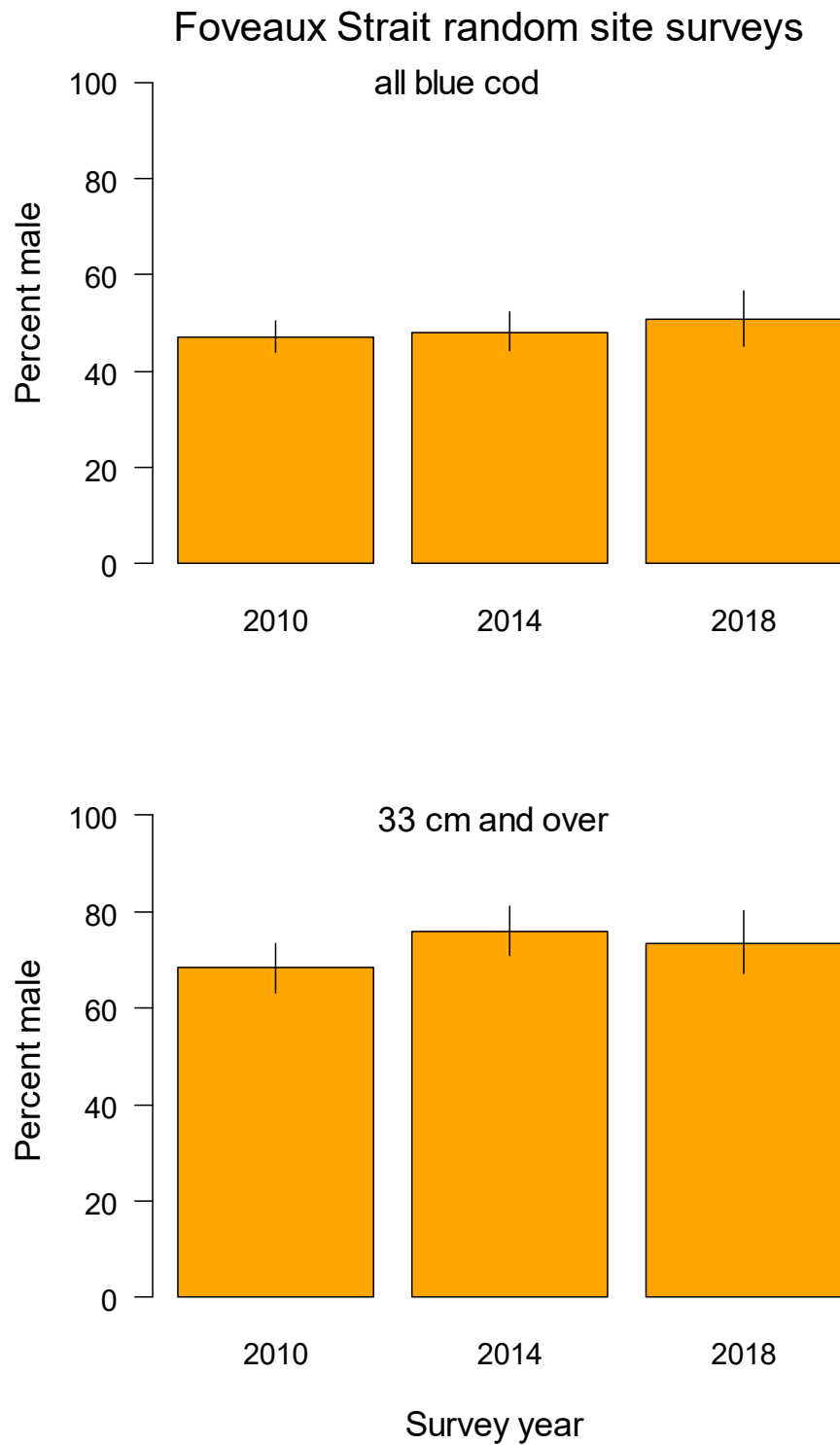
**Figure 16:** Catch rates ( $\text{kg.pot}^{-1}$ ) of all blue cod and for recruited blue cod (33 cm and over) for the Foveaux Strait random-site potting surveys in 2010, 2014 and 2018. Error bars are 95% confidence intervals. Sites in 2010 strata 7 and 8 were reassigned to strata 7A and 8A in these catch rate analyses (see Figure 3).



**Figure 17: Scaled length frequency and cumulative distributions for male and female blue cod from Foveaux Strait random-site blue cod potting surveys in 2010, 2014, and 2018. N, sample numbers; no, population number; Mean, mean length (cm); MWCV, mean weighted coefficient of variation %.**



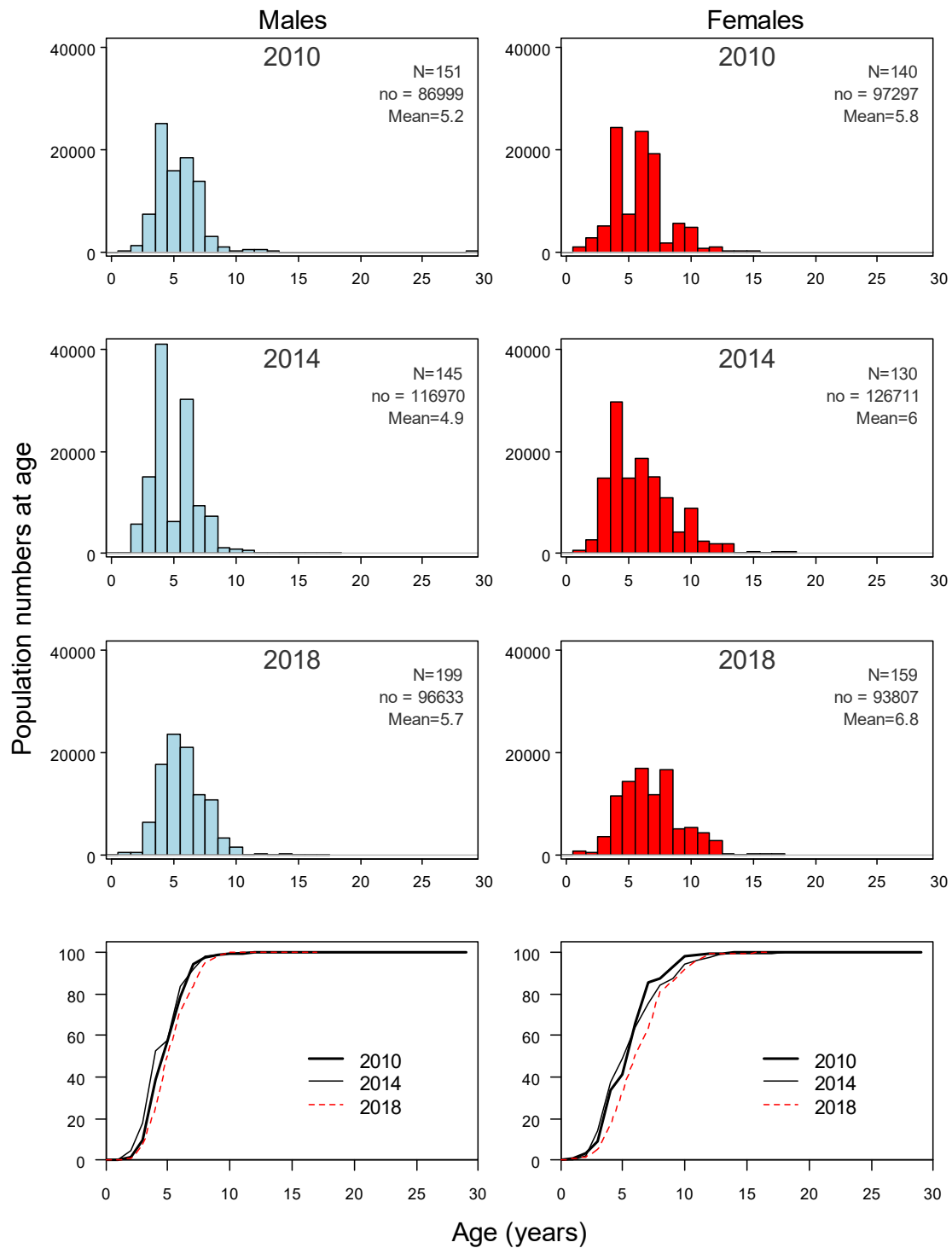
**Figure 18: Mean length of recruited blue cod (33 cm and over) for males and females from Foveaux Strait random-site blue cod potting surveys in 2010, 2014, and 2018. Error bars are 95% confidence intervals around the mean.**



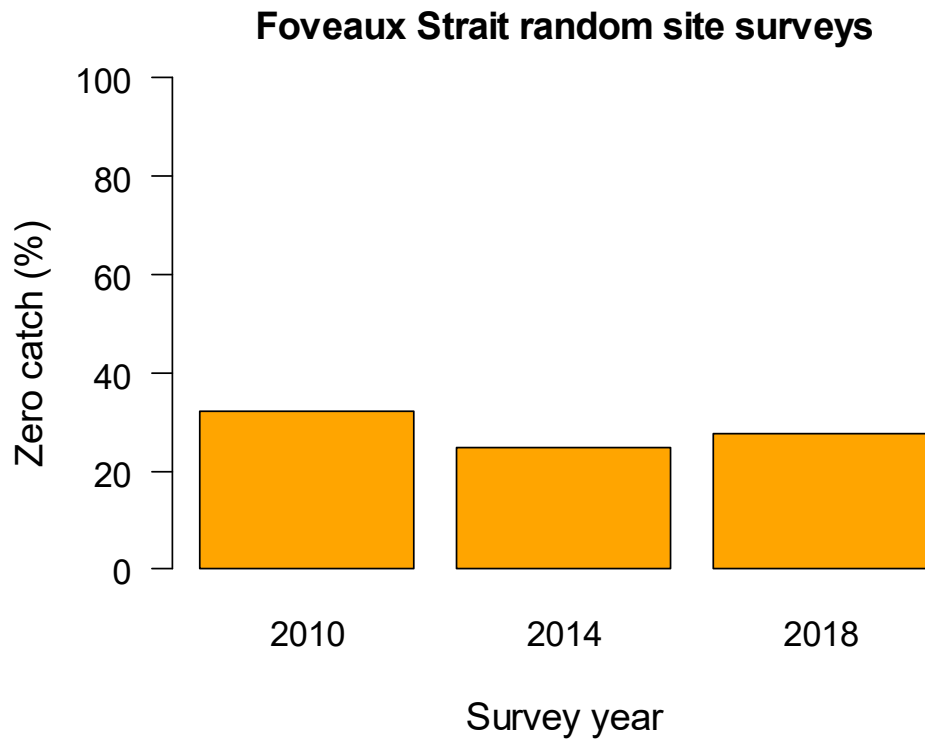
**Figure 19: Proportion of males for all blue cod and recruited blue cod from Foveaux Strait random-site potting surveys in 2010, 2014 and 2018. 95% confidence intervals are shown.**



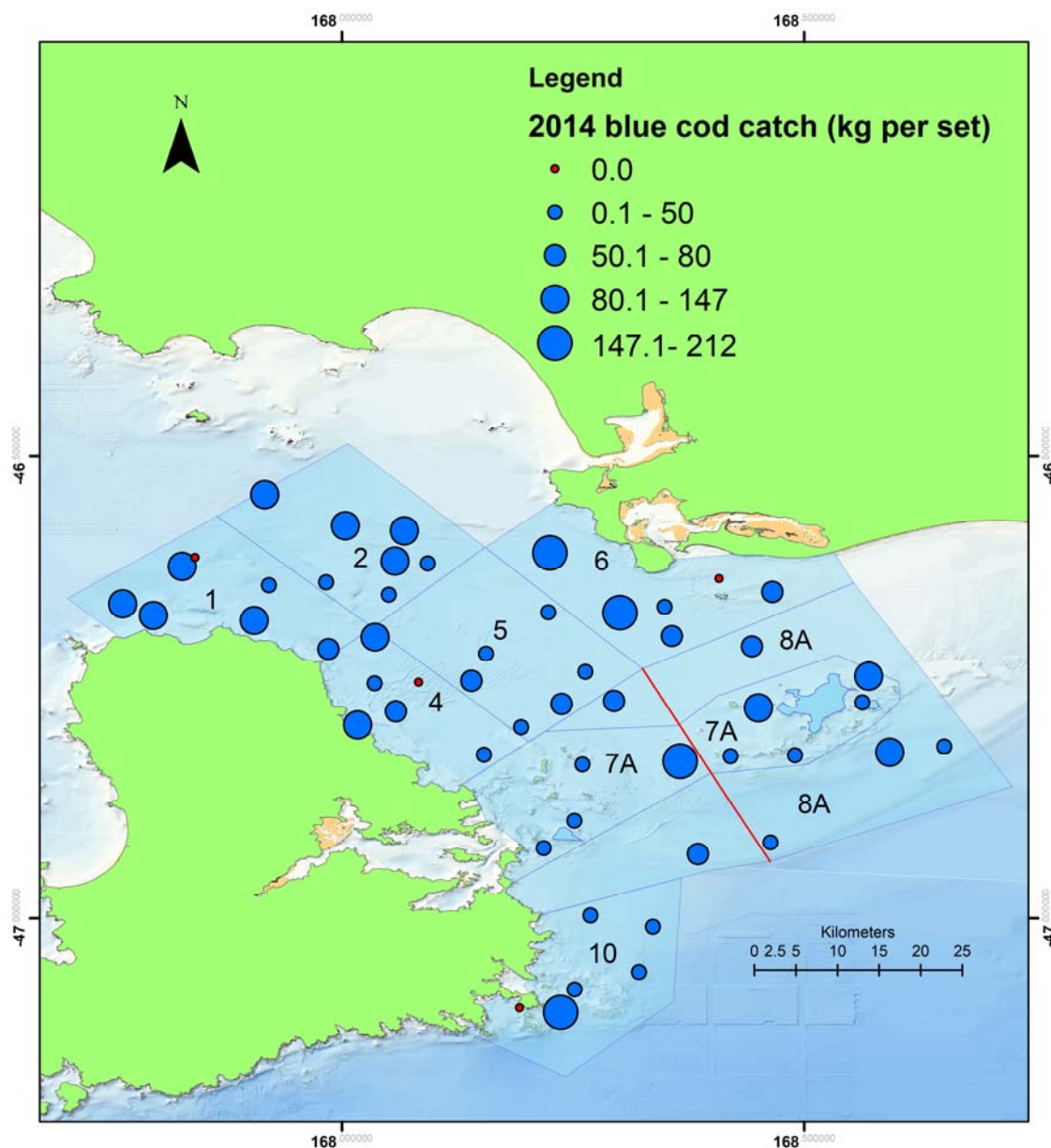
## Foveaux Strait random site surveys



**Figure 20: Scaled age frequency distributions for male and female blue cod for all strata in the 2010, 2014 and 2018 Foveaux Strait random-site blue cod potting surveys. N, sample size; no, population number; Mean, mean length (cm).**



**Figure 21: Proportion of pots with zero blue cod catch for the Foveaux Strait random-site potting surveys in 2010, 2014 and 2018. N= 336, 318, and 228 pots for each survey, respectively.**



**Figure 22: Blue cod catch rates (kg.set<sup>-1</sup>) for the 2014 Foveaux Strait random-site blue cod potting survey (FRA1401) plotted at each random site. Catch is summed for the six pots in each set. The red line indicates the 2010 survey boundary between strata 7 and 8. N= 53 sites.**

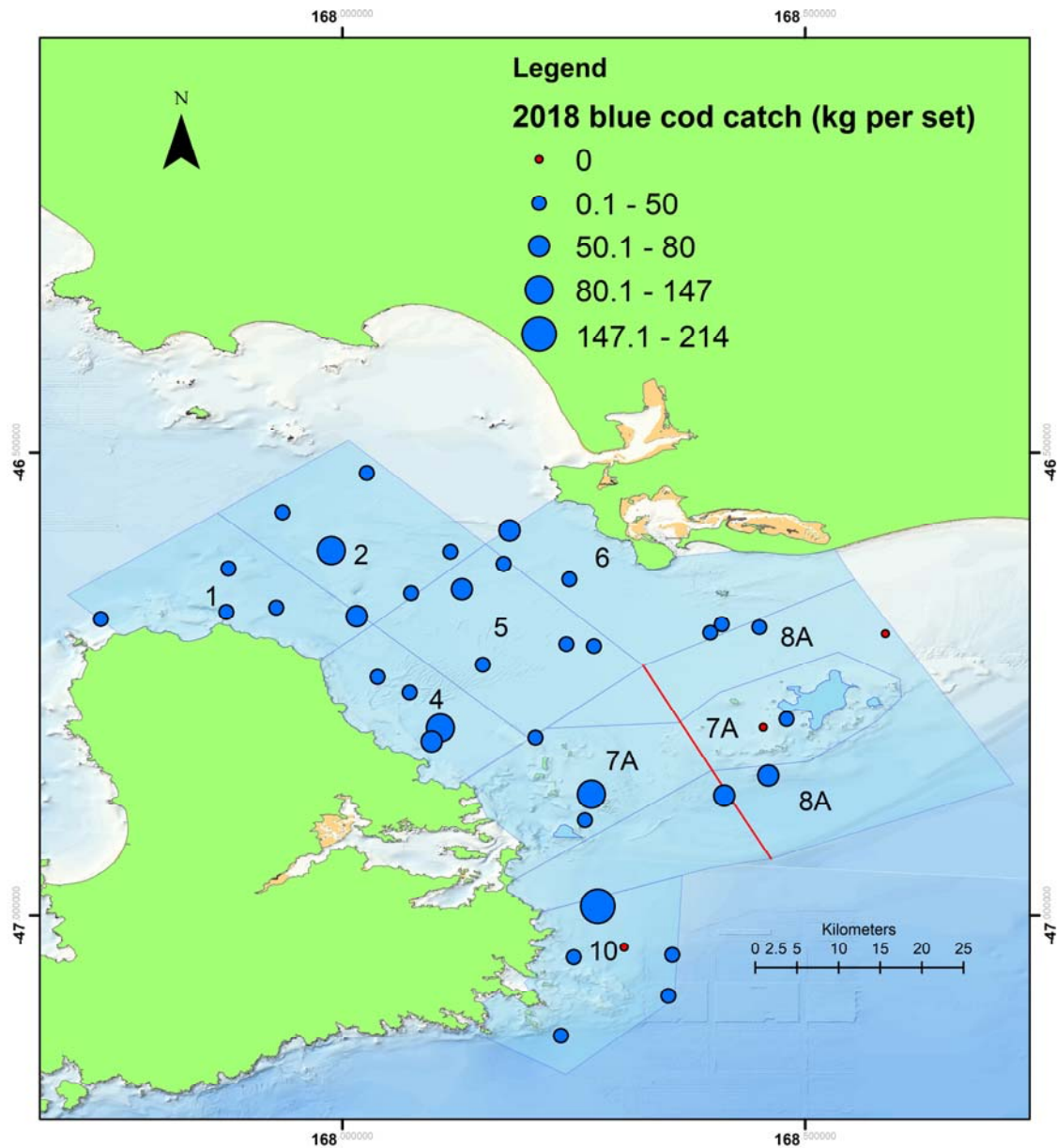
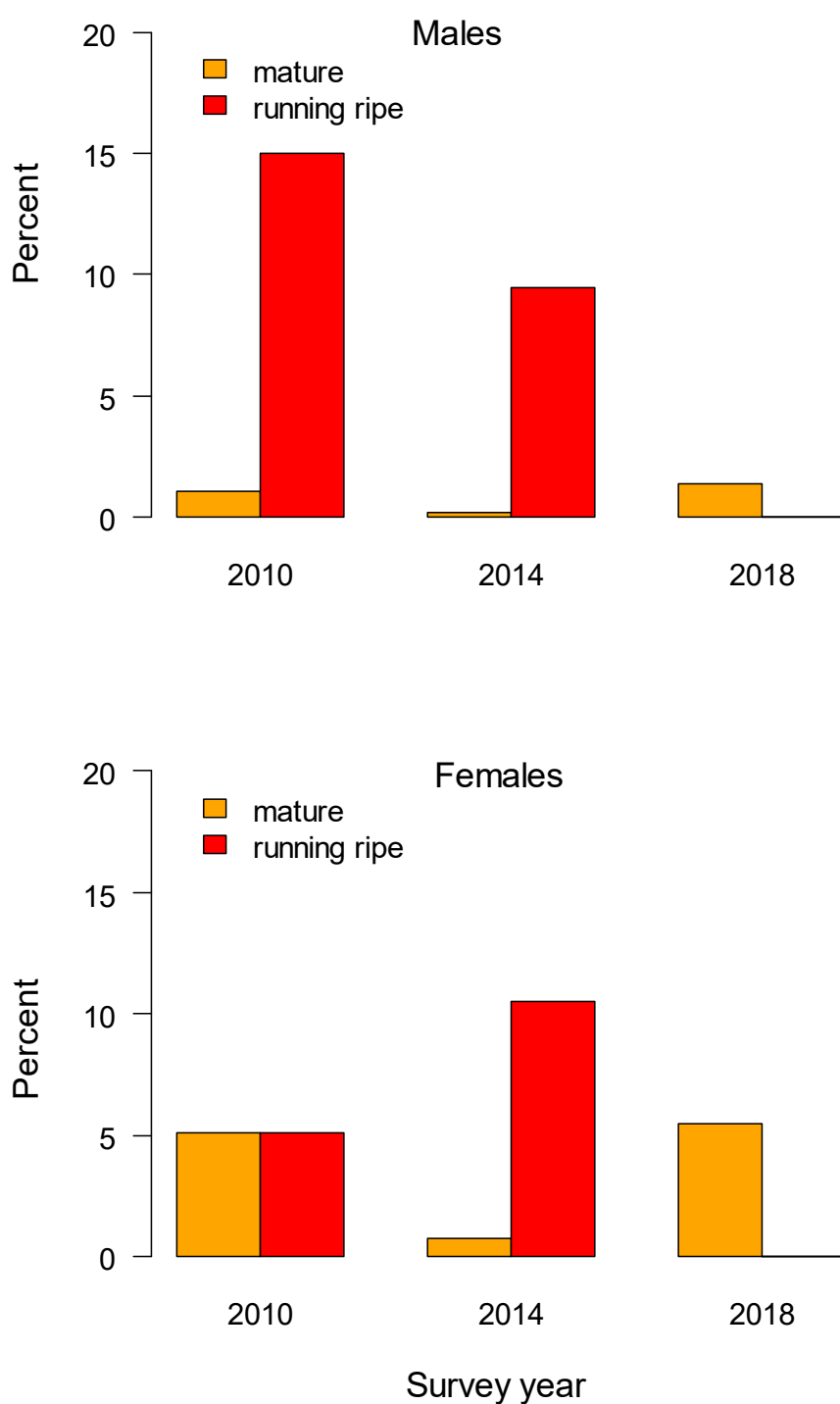


Figure 23: Blue cod catch rates ( $\text{kg.set}^{-1}$ ) for the 2018 Foveaux Strait random-site blue cod potting survey (PRO1801) plotted at each random site. Catch is summed for the six pots in each set. The red line indicates the 2010 survey boundary between strata 7 and 8.  $N=38$  sites.



**Figure 24: Percent of blue cod with gonads in the mature or running ripe reproductive condition from Foveaux Strait random-site blue cod potting surveys in 2010, 2014 and 2018. The percentage of the three other gonads stages is not shown, i.e., resting/immature, maturing, and spent.**

## 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.

<b>Fixed site</b>	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)
<b>Pot number</b>	Pots are numbered sequentially (1–6 or 1–9) in the order they are placed during a set. In the Foveaux Strait survey six pots were used.
<b>Pot placement</b>	There are two types of pot placement: <b>Directed</b> —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. <b>Systematic</b> —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.
<b>Random site</b>	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.
<b>Site</b>	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).
<b>Site label</b>	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).
<b>Station</b>	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.
<b>Station number</b>	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 <i>station_no</i> 234. This convention is important in enabling users of the <i>trawl</i> 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 <i>trawl</i> database.

**Appendix 2. Numbers of otoliths collected during the 2018 Foveaux Strait survey for males and females, by strata and length class. Lgth, length.**

Lgth (cm)	Males								
	Strata								Totals
	1	2	4	5	6	7A	8A	10	
11					1				1
12									
13					1				1
14						1			1
15									
16									
17								1	1
18	1								1
19			3		1		1		5
20			2				2	1	5
21		1	2				3	1	7
22	1		2		1		2		6
23		1	3		1		2		7
24	1		1	1			3		6
25	1	1	3	1			2		8
26		2	2	1			2		7
27	3	1	1	1		1	2		9
28	1	1	3				3		8
29		2	3	1			3		9
30	2		3				2		7
31	2	1	1	1			4		9
32		1	3			1	3		8
33	3	2	3			1	3		12
34	2	1	3	1			2		9
35	1	2	3	1			3		10
36	1	1	3	2		1	2		10
37	1		3	1			3		8
38	1	1	1	1			3		7
39	2		1				4		7
40			3		1		1		5
41	1		2			2	3		8
42			1		1		2		4
43		1					2	1	4
44			1			2	1		4
45						1		1	2
46									
47									
48						2			2
49									
50						1			1
Totals	24	19	56	12	7	13	63	5	199

	Females								
Lgth (cm)	Strata								
	1	2	4	5	6	7A	8A	10	Totals
10					1				1
11					1				1
12					2				2
13									
14									
15				1					1
16									
17	1						1		2
18			1			1			2
19			2					2	4
20	1		2					3	6
21			3	1	1	1	1	2	9
22	1		2	1	2		1		7
23	1		2	1	1		2		7
24	1	3	2	2			1		9
25	1	2	2	2			2		9
26	1	2	1	2			2		8
27	2		1				3	1	7
28	2	2	2	1	1		2		10
29	1	2	1			1	4		9
30	1	2	1				3		7
31	2	1	1			1	4		9
32	4	1		3		1			9
33	1	1	1				3		6
34	1	1	1	1		1	2		7
35	2				1	1	1		5
36	1		2			4			7
37	1	2			1	2			6
38				2		1			3
39				1		1			2
40	1			2					3
41									
42							1		1
Totals	26	19	27	20	11	15	33	8	159