Relative abundance, size and age structure, and stock status of blue cod off South Otago in 2010

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New Zealand Fisheries Assessment Report 2011/42
October 2011

Published by Ministry of Fisheries
Wellington
2011

ISSN 1175-1584 (print)
ISSN 1179-5352 (online)

Beentjes, M.P.; Carbines, G.D. (2011).
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*New Zealand Fisheries Assessment Report 2011/*42

This series continues the informal
New Zealand Fisheries Assessment Research Document series
which ceased at the end of 1999

EXECUTIVE SUMMARY

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***New Zealand Fisheries Assessment Report 2011/*42**

This report describes the 2010 south Otago potting survey, the first in the time series of relative abundance, population length/age structure, and stock status of blue cod for this area. Unlike previous blue cod surveys the design was experimental, comparing random with fixed site sampling, and also directed with systematic pot placement. This survey adheres to the terminology and analysis methods defined in the blue cod potting manual.

Thirty six sites were successfully surveyed from three strata off Otago Peninsula and Taieri Mouth between 21 April and 5 June 2010. In each stratum, six fixed and six random sites were sampled. At each site six pots were set, three using directed pot placement and three using systematic pot placement, resulting in 108 pots from each placement method and 216 overall. There was no phase 2 component to the survey.

A total of 1349 kg (2573 fish) of blue cod was taken on the south Otago survey. Blue cod comprised 97% by weight of the catch of all species on the survey. The overall weighted sex ratio (M:F) was 2.5:1 for all blue cod, and 4.6:1 for fish 30 cm and over.

Both length distribution and catch rates were substantially different between fixed and random sites and were analysed separately. There were no significant differences between pot placement methods, however, and so data from all six pots per site were combined in the analyses.

The blue cod examined were not spawning at the time of the survey.

Otoliths were prepared and read for 324 males and 243 females and these were used to construct a single age-length-key for the survey, applied to both fixed and random sites independently.

Fixed sites

A total of 915 kg of blue cod was taken from fixed sites. The overall weighted sex ratio (M:F) was 2.9:1 for all blue cod. Overall mean catch rates and c.v.s for fixed sites were 9.7 kg/pot (c.v. 17.1%) for all blue cod, and 8.1 kg/pot (c.v. 18.1%) for recruited blue cod (30 cm and over).

Size ranged from 19 to 55 cm for males and 18 to 51 cm for females. The scaled length frequency distributions for males and females were unimodal with mean lengths of 33.6 and 29.4 cm respectively. Overall 67% of blue cod were of minimum legal size (30 cm and over). The estimated population age distributions were generally unimodal with the main peak at about eight years for both sexes. Most males were between 6 and 12 years old and females between 6 and 10 years old. Mean age of males was 9.7 years for males and 8.7 years for females.

The mortality estimates (Z) are between 0.20 and 0.29 (0.23 for age at full recruitment = 6 years).

Based on the default M of 0.14, the $F_{\%SPR}$ was estimated at $F_{50.3\%}$ indicating that the expected contribution to the spawning biomass over the lifetime of an average recruit has been reduced to 50% of the contribution in the absence of fishing.

Random sites

A total of 434 kg was taken from random sites. The overall weighted sex ratio (M:F) was 2:1 for all blue cod. Overall mean catch rates and c.v.s were 4.4 kg/pot (c.v. 17.8%) for all blue cod and 2.9 kg/pot (c.v. 22.5%) for recruited blue cod (30 cm and over).

Size ranged from 16 to 59 cm for males and 11 to 49 cm for females. The scaled length frequency distributions for males and females were unimodal with mean lengths of 29.0 and 23.7 cm respectively. Overall 21% of blue cod were of minimum legal size (30 cm and over). Length frequency distributions for both sexes were also strongly skewed to the right. The estimated population age distributions were generally unimodal with the main peak at about six years for males and four years for females. Most fish (males and females) were between four and eight years old. Mean ages were 7.8 years and 6.0 years for males and females respectively

The mortality estimates (Z) are between 0.26 and 0.28 (0.28 for age at full recruitment = 6 years).

Based on the default M of 0.14, the $F_{\%SPR}$ was estimated at $F_{39.4\%}$ indicating that the expected contribution to the spawning biomass over the lifetime of an average recruit has been reduced to 39% of the contribution in the absence of fishing.

Comparison between fixed and random sites

Blue cod caught from fixed sites were on average larger than those from random sites, and this resulted in lower Z estimates, and higher $F_{\%SPR}$ values in fixed sites. The overall catch rate from fixed sites was more than double that from the random sites. Survey precision for random sites was comparable to those for fixed sites suggesting that for this area, random site surveys are feasible.

1. INTRODUCTION

This report describes the results of a south Otago blue cod potting survey between April and June 2010, the first for this region. This is principally an experimental survey designed to assess different sampling methods and hence has limited value in terms of the time series for this area.

Recreational blue cod (*Parapercis colias*) stock status in the South Island is monitored using potting surveys that provide relative biomass indices. These surveys take place predominantly in areas where recreational fishing is common, but in some areas there is substantial overlap between the commercial and recreational fishing grounds. There are currently eight time series of relative abundance indices located in key recreational fisheries around the South Island, the aim being to repeat each one every four years: Marlborough Sounds (Blackwell, 1997, 1998, 2002, 2005, Willis in prep) Kaikoura (Carbines & Beentjes 2006a, 2009), Motunau (Carbines & Beentjes 2006a, 2009), Banks Peninsula (Beentjes & Carbines 2003, 2006, 2009), north Otago (Carbines & Beentjes 2006b, 2011b), Paterson Inlet (Carbines 2007, in prep), Dusky Sound (Carbines & Beentjes 2003, 2011a), and Foveaux Strait, (Carbines & Beentjes in prep).

The aim of blue cod potting surveys is to provide local abundance indices, and to monitor the size and age structure of geographically separate blue cod populations. The surveys provide a means to evaluate the response of populations to changes in fishing pressure and implementation of management initiatives such as changes to daily bag limit, minimum legal size, and/or area closures. Further, the sex ratio of the populations is of major significance for blue cod, which are protogynous hermaphrodites with some (but not all) females changing into males as they grow. The largest fish in the populations are invariably males (Carbines 2004b). In heavily fished blue cod populations sex ratios skewed towards males are often observed (Beentjes & Carbines 2009). This is thought to result from the removal of the inhibitory effect of large males, and a consequent higher rate (and possibly earlier onset) of sex change by primary females (Beentjes & Carbines 2005).

In addition to catch rates, monitoring age structure provides a further means to evaluate the response of a population to changes in fishing pressure. Otoliths collected during potting surveys have been used to calculate the age structure of blue cod throughout the South Island (Carbines et al. 2008). Estimates of total mortality (*Z*) for each survey are based on catch curve analysis (Chapman & Robson 1960, Dunn et al. 2002) of the age distributions derived specifically for each survey.

An objective for this project is to determine stock status of south Otago blue cod stocks using an MSY-related proxy. B_{MSY} and F_{MSY} are both commonly used as analytical proxies to estimate MSY reference points. For blue cod there is insufficient information to estimate B_{MSY} since recreational catches have not been estimated reliably and are expected to represent a large proportion of the total catch. Hence F_{MSY} is a more appropriate reference point for blue cod and the most widely used proxy for F_{MSY} currently is spawner per recruit analyses ($F_{\%SPR}$). Hence, we are interested in fishing mortality, derived from the catch curve analysis (Z) and estimates of M, in relation to the Ministry of Fisheries Harvest Strategy Standard recommended reference point for blue cod (a medium productivity stock) of $F_{40\%}$ (Ministry of Fisheries 2008).

In the South Island, blue cod (*Parapercis colias*) is the most frequently landed recreational species (James & Unwin 2000, Ministry of Fisheries 2010). Blue cod recreational catches in BCO 3 were estimated at 752 t in 2000 (Boyd & Reilly 2005) and are severalfold greater than BCO commercial catches (5 year average for BCO 3 from 2004–05 to 2008–09 = 174 t) and the TACC (163 t) (Ministry of Fisheries 2010). The bulk of the blue cod commercial catch is taken by potting from statistical area 024; the coastline from Taieri Mouth to Oamaru. Recreational catch is taken by lining from small vessels over areas of biogenic reef. Blue cod is also an important species for Maori customary fishers in all areas, but the catch is unknown.

1.1 Survey design

Before 2010, all blue cod potting surveys were based exclusively on the fixed site design within which predetermined sites (fixed locations within stratum) are used repeatedly on subsequent surveys. The actual fixed sites used in a particular survey are determined by random selection from a larger pool of fixed sites in each stratum. The original design for the south Otago survey was based on a fixed site survey design and included the area from Otago Peninsula south to the Catlins, with the overall objective of providing the first in a series of relative abundance estimates. In late 2009 the Ministry of Fisheries Inshore Working Group considered the notion that the fixed site design may be subject to bias and further that this design is less statistically robust than a purely random site survey design. Hence, rather than providing the first relative abundance indices in the time series in this area, it was agreed to carry out an experimental survey with the aim of comparing catch rates and variances from both random sites and fixed sites in the same strata. Further, the type of pot placement at each site was investigated to determine if placement of the pots in a directed manner by the skipper (historical survey method of placement) or randomly around the site made any difference to catch rates. As a result of these changes to the survey design, the number of strata surveyed was reduced from six to three and the Catlins area was not included. It is envisaged that if a random site survey design proves to be acceptable, future surveys in this area will adopt a totally random site design.

Overall objective

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

2.1 Terminology

In this report we use only the terms defined in the blue cod potting survey manual (Beentjes & Francis 2011), but note that surveys carried out before this manual was written may have used different and inconsistent terminology. The main point of difference between the terms shown below and those used on other South Island surveys (except Marlborough Sounds) before 2010 surveys is that the term station was used to refer to a site.

Site — A geographical location near to which sampling may take place during a survey. A site may be either fixed or random (see below). A site may be specified as a latitude and longitude or a section of coastline (for the latter, use the latitude and longitude at the centre of the section).

Fixed site — A predetermined site within a given stratum, that has a fixed location (single latitude and longitude or the centre point location of a section of coastline) and is available to be used repeatedly on subsequent surveys in that area. Which fixed sites are used in a particular survey is determined by random selection from all available fixed sites in each stratum. Fixed sites are sometimes referred to as index sites or fisher-defined sites.

Random site — A site that can have any location (single latitude and longitude) generated randomly from within a stratum, given the constraints of proximity to other selected sites for a specific survey.

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. Note that random sites do not have site labels.

Set — A group of pots deployed in the vicinity of a selected site in a specific survey. The pots are set in a cluster or linear configuration.

Set number — A number assigned to each set within a survey. Set numbers are defined sequentially in the order fished. Thus, any set within a survey is uniquely defined by a trip code and set number. Note that the set number is not recorded in the *trawl* database in isolation, but is entered as part of attribute *station_no* in table *t_station*.

Station	The position (latitude and longitude) at which a single pot (or other fishing gear) is deployed at a site during a survey, i.e. it is unique for the trip.
Pot number	Pots are numbered sequentially (1 to 6 or 1 to 9) in the order they are placed during a set.
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 number 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.
Pot placement	There are two types of pot placement: **Directed**–the position of each pot is directed by the skipper using local knowledge and the vessel SONAR to locate a suitable area of reef/cobble or biogenic habitat. **Systematic–**the position of each pot is arranged systematically around the site or along the site for a section of coastline. For the former site, the position of the first pot is set 300 m to the north of the site location and remaining pots are set in a hexagon pattern around the site, at about 300 m from the site position.

2.2 Timing

A potting survey off south Otago was carried out between 21 April and 5 June 2010. Initially the survey was scheduled for January-February when weather conditions are generally more settled off the east coast of the South Island. A number of factors resulted in the autumn timing of the survey including changes to the original survey design, a conflict with the Foveaux Strait blue cod potting survey, and bad weather.

2.3 Survey areas

The south Otago 2010 survey area was defined after discussions with local recreational and commercial fishers. Fishers were given charts of the area and asked to mark discrete locations around south Otago where blue cod are commonly caught, ensuring that locations were at least 1 km apart. Based on this the survey area was divided into two inshore and four offshore strata area from the northern side of Otago Peninsula to Taieri Mouth, with each stratum having at least nine discrete locations. A few locations were also obtained from recreational fishing magazines. The outer boundaries of the inshore and offshore strata are defined by approximate 30 m and 50 m depth contours, respectively, except stratum 3 which is between 100 m and 200 m depth and lies at the head of several canyons (Figure 1). The area (km^2) of each stratum was taken as a proxy of available habitat for blue cod. For this experimental survey the Inshore Working Group determined that the survey only include strata 1, 3 and 6.

2.4 Survey design

As mentioned, this survey is an experimental design with the aim of comparing catch rates and variances from both random sites and fixed sites in the same strata. Six random sites and six fixed sites were sampled in each of strata 1, 3 and 6, resulting in a total of 36 sites. Strata 2, 4 and 5 were not sampled. There was no phase 2 component.

2.4.1 Fixed sites

The discrete sites identified by fishers and from magazines are henceforth referred to as fixed sites (see terminology). A total of 75 possible fixed sites was identified within the survey area and following the drawing of stratum boundaries, were allocated as follows: stratum 1 = 12, stratum 2 = 8, stratum 3 = 23, stratum 4 = 12, stratum 5 = 11, and stratum 6 = 9 (Figure 1). From the full list of fixed sites available, six sites per stratum were randomly selected to be surveyed in strata 1, 3, and 6 resulting in 18 fixed sites.

2.4.2 Random sites

In each of strata 1, 3, and 6, 20 random sites were generated using the NIWA program *random_station*, with the constraint that sites were at least two kilometres apart. The first six random sites generated for each stratum were initially selected to be surveyed. Many more sites were generated than required to allow for sites that are unusable because for example they fell on mud, were too deep, or were within one kilometre of a fixed site. If a new random site was required outside the first six selected, the next site on the list was used. A total of 18 random sites were selected for sampling, six in each stratum.

2.5 Vessel and gear

The south Otago survey was conducted from F.V *Triton* (registration number 7515), a Port Chalmers based commercial vessel equipped to set and lift rock lobster and blue cod pots and skippered by the owner Mr Neil McDonald. The vessel specifications are: 11 m length, 4 m breadth, 12 t, wooden monohull, powered by a 120 hp six cylinder Ford diesel engine with propeller propulsion.

Six cod pots were used to conduct the south Otago 2010 survey. Pot specifications correspond to Pot Plan 2 and are provided in Beentjes & Francis (2011). Pots were baited with paua (*Haliotis iris*) guts placed inside “snifter pottles”. Bait was topped up after every lift (or when required) and replaced each day.

A high-performance, 3-axis (3D) acoustic doppler current profiler (SonTek/YSI ADP; Acoustic Doppler Profiler, 500 kHz ADCP) was deployed at each site. The ADCP recorded current flow and direction in 5 m depth bins.

2.6 Sampling methods

For each of the three strata (1, 3 and 6) there were six fixed sites and six random sites, resulting in a total of 36 sites (18 fixed sites and 18 random sites). They were surveyed in order of proximity to each other rather than by type, beginning at stratum 1 and finishing in stratum 3.

At each site (random and fixed), six pots were set sequentially and left to fish (soak) for a target period of one hour, but not longer than one hour 15 minutes, during daylight hours. Soak time was standardised to be consistent with all previous South Island potting surveys. The six pots were set in clusters no further than 0.5 km from the site and separated by at least 100 m to avoid pots competing for fish. Placement of three of the six pots was directed by the skipper using local knowledge and the vessel echo sounder to locate a suitable area of reef/cobble or biogenic habitat (i.e., directed placement). The placement of the other three pots was systematic with pots set in a triangular pattern approximately 300 m from the centre and 400 m from the other two pots. Systematically placed pots were set blind with the first pot placed 300 m north of the site location.

After each site was completed (six pot lifts) the next closest site (either random or fixed) in the stratum was sampled. While it was not logistically possible to standardise for time of day or tides, each stratum was surveyed throughout the day, collectively giving strata roughly equal exposure to all daily tidal and time regimes. The order that strata were surveyed depended on the prevailing weather conditions, as exposed offshore strata (1 and 3) could be surveyed only during calm conditions.

Pots do not have a unique identifiable code and are assumed to have equal catchability. As each pot was placed, a record was made of sequential pot number (1 to 6), latitude and longitude from GPS, depth, time of day, and standard trawl survey physical oceanographic data, including wind direction, wind force, air temperature, air pressure, cloud cover, sea condition, sea colour, swell height, swell direction, bottom type, bottom contour, sea surface temperature, sea bottom temperature, wind speed, and water visibility (secchi depth). Immediately prior to each set of the pots, an acoustic doppler current profiler (ADCP) was deployed at the centre of each site and recovered after the last pot of each set was lifted.

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 10 kg Merel motion compensating scales. The number of individuals of each species per pot was also recorded. Total length down to the nearest centimetre, sex, and gonad maturity were recorded for all blue cod. Sagittal otoliths were removed from a representative size range of males and females (a target of up to five fish of each sex per 1 cm size class over the available length range across all survey strata) and weight of each fish was recorded to the nearest 10 g. Sex and maturity were determined by dissection and macroscopic examination of the gonads (Carbines 1998, Carbines 2004b). Gonads were recorded as one of five stages 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.

2.7 Data analysis

Analysis of catch rates and coefficients of variation (c.v.s), length weight parameters, scaled length and age frequencies and c.v.s, sex ratios, mean length, mean age, use the equations documented in the blue cod potting manual (Beentjes & Francis 2011). For completeness these equations are reproduced below.

2.7.1 Relative abundance

Relative abundance indices was calculated as mean catch rates by set ($\bar{C}_{st}$), stratum ($\bar{C}_t$), and survey ($\bar{C}$) (all with units kg/pot) as per Beentjes & Francis (2011) as follows:

$$\bar{C}_{st} = \sum_p C_{pst} \Big/ m \qquad (1)$$

$$\bar{C}_t = \sum_s \bar{C}_{st} \Big/ n_t \qquad (2)$$

$$\bar{C} = \sum_t A_t \bar{C}_t \Big/ \sum_t A_t \qquad (3)$$

where C_{pst} is the catch weight (kg) of all blue cod (or all recruited blue cod – that is, all those 30 cm and above) in the pth pot in the sth set in stratum t; m is the number of pots per set; n_t is the number of sets in stratum t; and A_t is the area (or coastline length) of that stratum. Note that these indices include no adjustment for soak time.

The precision of the stratum and survey catch rates is set-based and described as a coefficient of variation (c.v.), calculated as per Beentjes & Francis (2011) as follows:

$$\mathrm{c.v.}\left(\bar{C}_t\right) = \left[\frac{\sum_s \left(\bar{C}_{st} - \bar{C}_t\right)^2}{\left(n_t - 1\right) n_t}\right]^{0.5} \Big/ \bar{C}_t \qquad (4)$$

and

$$\mathrm{c.v.}\left(\bar{C}\right) = \left[\sum_t A_t^2\, \mathrm{s.e.}\left(\bar{C}_t\right)^2 \Big/ \left(\sum_t A_t\right)^2\right]^{0.5} \Big/ \bar{C} \qquad (5)$$

Relative abundance and c.v.s were estimated for combinations of site type and pot placement method for all fish, and for fish 30 cm and over.

2.7.2 Length-weight parameters

The length-weight parameters a_k, b_k from this survey are as per Beentjes & Francis (2011) as follows:

$$w_{lk} = a_k l^{b_k} \qquad (6)$$

which calculates the expected weight (kg) 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.

Weights of individual blue cod from the survey that were not weighed, are calculated from the length-weight relationship. Derived individual fish weights are then used to determine catch rates and c.v.s of blue cod for the minimum legal size (30 cm) and over.

2.7.3 Otolith preparation and reading

The thin section technique is used for ageing blue cod otoliths (Carbines 2004a). In this method the whole otolith is embedded in Araldite polymer resin, baked (50° C for at least three hours), and sectioned transversely close to the nucleus with a diamond-tipped cut-off wheel. The sectioned surface of the otolith half is then glued to a glass slide and a second cut is made resulting in a section of about 2 mm thickness. The resultant thin section on the slide is then coated with a slide mountant and sanded with 600-grit sandpaper to about 1 mm thickness before viewing. Sections were observed at x40 and x100 magnification under transmitted light with a compound microscope.

Otolith sections exhibit alternating opaque and translucent zones and age estimates are made by counting the number of annuli (opaque zones) from the core to the distal edge of the section, a technique previously validated and a protocol described for blue cod by Carbines (2004a). Translucent zones are used to define each complete opaque zone, i.e., annuli are counted only if they have a translucent zone on both sides. The readability of each otolith was also graded from 1 (excellent) to 5 (unreadable). Otoliths were read independently by two experienced readers (G. Carbines and D. Kater). Where counts differed, readers consulted to resolve the final age estimate. Otoliths given a grade 5 (unreadable) were removed from the analysis.

2.7.4 Growth parameters

A von Bertalanffy growth model (von Bertalanffy 1938) was fitted to the survey length-age data by sex as follows:.

$$L_t = L_\infty\,(1 - \exp^{-K[t - t0]}) \qquad (7)$$

Where L_t is the length (cm) at age t, L_∞ the asymptotic mean maximum length, K is a constant (growth rate coefficient), t_0 hypothetical age (years) that fish has zero length.

The estimated growth parameters K, t_0, and L_∞ were used in the spawner per recruit analyses.

2.7.5 Scaled length and age frequencies

Length and age compositions of south Otago blue cod populations surveyed in 2010 were estimated using the NIWA program Catch-at-age (Bull & Dunn 2002). The program scales the length frequency data by area of the strata, 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 on the survey are measured and if the actual weight of the catch is close to the estimated weight of the catch (which it should be).

The following equations from Beentjes & Francis (2010) describe how length and age frequencies were calculated as numbers of fish. The length and age frequencies are expressed as proportions by dividing by total numbers.

For set s in stratum t, let W_{st} be the weight of blue cod caught, and let f_{lkst} be the number of blue cod of length l and sex k in the length sample from the catch (usually this is the whole catch, but it may be a subsample). Then the sex-specific length frequency (LF) for stratum t, which represents the expected number at length and sex in a set from this stratum, is given by

$$f_{lkt} = 1/n_t \sum\nolimits_s^{\mathrm{LF}} \left[f_{lkst} \left(\frac{W_{st}}{\sum_{l',k'} w_{l'k'} f_{l'k'st}} \right) \left(\frac{\sum_{s'} W_{s't}}{\sum_{s'}^{\mathrm{LF}} W_{s't}} \right) \right] \qquad (8)$$

where $\sum_s^{\mathrm{LF}}$ denotes a summation restricted to those sets for which there is a length sample.

Equation (8) allows for the possibility that not all blue cod caught in the survey were measured. In the 2010 south Otago case all fish were measured from all sets so the second and third terms inside the squares brackets have no effect on the length frequencies generated.

The sex-specific survey LF is given by

$$f_{lk} = \frac{\sum_t A_t f_{lkt}}{\sum_t A_t} \qquad (9)$$

Sex-specific age frequencies (AFs) at the stratum and survey level were calculated by applying the age-length key, K_{lak} (where K_{lak} is the proportion of fish of length l and sex k that are of age a [so $\sum_a K_{lak} = 1$ for each value of k]) in the usual fashion:

$$f_{akt} = \sum_l K_{lak} f_{lkt} \text{ and } f_{ak} = \sum_l K_{lak} f_{lk} \quad (10)$$

LFs (or AFs) for sexes combined, at the stratum and survey level, were calculated by summing the sex-specific LFs (or AFs) across sex.

2.7.6 Sex ratios, and mean length and ages

Sex ratios (expressed as percentage male) and mean lengths, for either the stratum or survey level, were calculated as per Beentjes & Francis (2010) from the stratum or survey LFs. Thus, for example, for stratum *t* the sex ratio was calculated as:

$$100 \sum_l f_{lmt} \Big/ \sum_{l,k} f_{lkt} \quad (10)$$

(where the subscript *m* denotes males) and the mean length for sex *k* as

$$\sum_l l f_{lkt} \Big/ \sum_l f_{lkt} \quad (11)$$

Mean ages were calculated analogously from the AFs. For example, the equation for the mean age for sex *k* in stratum *t* is the same as Equation (11), with *l* replaced by *a*.

2.7.7 C.V.s for LFs and AFs

Bootstrap resampling was used to allow calculation of c.v.s for proportions and numbers at length and age. 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.

LFs and AFs were calculated, as described above, for each simulated data set. For any number (or proportion) at age or length, *f*, a c.v. was calculated as per Beentjes & Francis (2010) as:

$$\text{c.v.}(f) = \sqrt{\frac{\sum_b (f_b - \bar{f})^2}{n_{\text{boot}} - 1}} \Big/ \bar{f} \quad (12)$$

where f_b is the corresponding number (or proportion) calculated from the *b*th of n_{boot} simulated data sets, and $\bar{f}$ is the mean of the f_b. $n_{\text{boot}} = 300$ has been found to be an adequate number of simulated data sets for this calculation for most data sets.

Scaled length frequency and age frequency proportions are presented together with coefficients of variation (cv) for each length and age class, and the mean weighted coefficients of variation (MWCV).

2.7.8 Total mortality (*Z*) estimates

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

As recommended by Beentjes & Francis (2010) we used the method of Dunn et al. (2002) to estimate the variance (95% confidence intervals) associated with Z under three different parameters of recruitment, ageing error, and Z estimate error. We estimated Z and 95% confidence intervals for each age at full recruitment from 5 to 8 years for both sexes combined for all strata combined.

For the south Otago 2010 survey, estimates of total mortality, Z, were calculated for four alternative values of the age at recruitment – a_{rec} = 5, 6, 7, and 8 y – using the maximum-likelihood estimator

$$\hat{Z} = \log_e\left(\frac{1 + \bar{a} - a_{\text{rec}}}{\bar{a} - a_{\text{rec}}}\right) \quad (13)$$

where $\bar{a} = \sum_a^{\text{rec}} af_a \Big/ \sum_a^{\text{rec}} f_a$ is the mean age of recruited fish in the sexes-combined age frequency for the survey, and $\sum_a^{\text{rec}}$ denotes summation across all recruited ages.

The estimation of c.v.s around the Z estimates is described in detail in Appendix 1.

2.7.9 Spawner per recruit analyses

A spawner per recruit analysis was used to estimate the $F_{\%SPR}$. Spawner per recruit calculations were carried out using CASAL (Bull et al. 2005). The calculations involve simulating fishing with constant fishing mortality, F, in a population with deterministic recruitment, and determining the equilibrium spawning biomass per recruit (SPR) associated with that value of F. 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).

The von Bertalanffy growth curve and length-weight parameters (length in centimetres and weight in grams) were estimated from the age-length and length-weight data collected from the survey and are shown below:

Parameter	Males	Females
K	0.065	0.075
t_0	-2.03	-2.29
L_{inf}	63.9	53.5
A	7.89E-03	7.14E-03
B	3.2093	3.2476

The following input parameters were used in this analysis.

Growth parameters	von Bertalanffy growth parameters and length weight coefficients estimated from the current survey
Natural mortality	default assumed to be 0.14. Sensitivities were carried out for M values 20% above and below the default (0.11 and 0.17).

Maturity ogive	the default maturity ogive is as follows: 0, 0, 0, 0.1, 0.4, 0.7, 1 where 10% of fish are mature at age 4, 40% at age 5 etc.
Selectivity	selectivity to the commercial fishery is described as knife-edge equal to age at MLS.
Fishing mortality (F)	fishing mortality is estimated from the catch curve analyses and assumed estimate of M ($F = Z - M$). The Z value is for age at recruitment = 6 years).

Because this is a 'per-recruit' analysis, it doesn't matter what stock-recruit relationship is assumed. However, the calculations are simpler, and the simulated population reaches equilibrium faster, if recruitment is treated as independent of spawning biomass (i.e., a steepness of 1).

3. RESULTS

3.1 Sites surveyed

In each stratum (1, 3 and 6) six fixed site and six random sites were sampled, resulting in 36 sites overall (Table 1, Figure 2). At each site six pots were set, three using directed pot placement and three using systematic pot placement, resulting in 108 pots from each placement method and 216 overall (Table 1, Appendix 2). The survey took fifteen fishable days to complete. Depth ranged from 8 to 134 m for fixed sites and 3 to 124 m for random sites. Environmental data recorded throughout the north Otago survey are presented in Appendix 3. ADCP data are archived at NIWA Greta Point.

3.2 Catch

A total of 1349 kg of blue cod was taken on the south Otago survey, 915 kg from fixed sites and 434 kg from random sites (Table 1). Of this total 678 kg was from stations using directed pot placement, and 671 kg from those using systematic pot placement (Table 2). Catches by the four combinations of site type and pot placement are also shown in Table 2.

The 1349 kg of blue cod comprised 2573 fish (Tables 1 and 2) and accounted for 97% by weight of the catch of all species on the survey. Bycatch included 10 fish, one crustacean, and one octopus species (Table 3). The four most common bycatch species by weight were octopus (*Octopus cordiformis*), banded wrasse (*Notolabus fucicola*), scarlet wrasse (*Pseudolabrus miles*), and girdled wrasse (*Notolabrus cinctus*) (Table 3).

3.3 Catch rates

Mean catch rates (kg/pot) of blue cod (all sizes, and 30 cm and over) are presented by site type (fixed and random) for pot placement method (directed or systematic), and by site type regardless of pot placement method (Tables 4 and 5, Figures 3 and 4).

Only one of the 18 fixed sites had zero catch (5.6%) compared with four random sites (22.2%).

3.3.1 All blue cod sizes

Fixed sites

Mean catch rates (kg/pot) of blue cod (all sizes) for fixed sites ranged from 6.5 to 17.4 kg/pot over the three strata for directed pot placement, and 3.7 to 16.3 kg/pot for systematic pot placement. Overall mean catch rates were 10.1 kg/pot (c.v. 19.0%) for directed pot placement and 9.2 kg/pot (c.v. 17.6%) for systematic pot placement (Table 4–panel A, Figure 3). Overall mean catch rates for fixed sites combining pots regardless of placement method were 9.7 kg/pot (c.v. 17.1%) (Table 4–panel C, Figure 3).

Random sites

Mean catch rates (kg/pot) of blue cod (all sizes) for random sites ranged from 0.8 to 6.2 kg/pot over the three strata for directed pot placement, and 1.6 to 5.9 kg/pot for systematic pot placement. Overall mean catch rates were 4.1 kg/pot (c.v. 22.1%) for directed pot placement and 4.7 kg/pot (c.v. 16.4%) for systematic pot placement (Table 4–panel B, Figure 3). Overall mean catch rates for random sites combining pots regardless of placement method were 4.4 kg/pot (c.v. 17.8%) (Table 4–panel C, Figure 3).

3.3.2 Blue cod 30 cm and over

Fixed sites

Mean catch rates (kg/pot) of blue cod (30 cm and over) for fixed sites ranged from 2.7 to 15.4 kg/pot over the three strata for directed pot placement, and 2.6 to 14.4 kg/pot for systematic pot placement. Overall mean catch rates were 8.4 kg/pot (c.v. 21.5%) for directed pot placement and 7.9 kg/pot (c.v. 17.9%) for systematic pot placement (Table 5, panel A, Figure 4). Overall mean catch rates for fixed sites combining pots regardless of placement method were 8.1 kg/pot (c.v. 18.5%) (Table 5, panel C, Figure 4).

Random sites

Mean catch rates (kg/pot) of blue cod (30 cm and over) for random sites ranged from 0.3 to 5.2 kg/pot over the three strata for directed pot placement, and 1.0 to 4.8 kg/pot for systematic pot placement. Overall mean catch rates were 2.7 kg/pot (c.v. 25.5%) for directed pot placement and 3.1 kg/pot (c.v. 23.2%) for systematic pot placement (Table 5–panel B, Figure 4). Overall mean catch rates for random sites combining pots regardless of placement method were 2.9 kg/pot (c.v. 22.5%_ (Table 5–panel C, Figure 4).

3.4 Biological and length frequency data

3.4.1 All sites combined

Of the 2573 blue cod caught on the south Otago survey (regardless of site type), all were sexed and measured for length, and otoliths were taken from 604 fish across the available size range. The weighted sex ratio (M:F) ranged from 1.8:1 to 3.1:1 across the three strata (Table 6) and the overall weighted sex ratio was 2.5:1 (Table 6).

Size ranged from 16 to 59 cm for males and 11 to 51 cm for females, although this varied among strata. Mean length of males was between 3 to 5 cm greater than females in all three strata and overall weighted mean length was 31.8 cm for males and 26.7 cm for females (Table 6). The largest mean lengths are for blue cod caught in stratum 6.

There were 1252 blue cod of legal size (30 cm and over), corresponding to 49% of all fish caught (by number). The weighted sex ratio (M:F) of fish 30 cm and over ranged from 2.9:1 to 24.6:1 and the overall weighted sex ratio was 4.6:1 (Table 6).

The scaled length frequency distributions for strata 1, 3, and 6 (all sites combined) were unimodal with stratum 6 showing a higher proportion of larger fish (Figure 5).

Of 2573 blue cod examined, nearly all gonads of both sexes were stage 2 (maturing) indicating that sampling had not taken place during the spawning season (Table 7).

The length-weight relationship was estimated using 335 males (range 16–59 cm) and 259 females (range 11–51 cm) from the 2010 south Otago survey. Using the derived model $W = aL^b$, the length-weight parameters are as follows: males – a = 0.00789, b = 3.2093, and $R^2 = 0.99$; females – a = 0.00714, b = 3.2476, and $R^2 = 0.99$.

3.4.2 Fixed and random sites

The scaled length frequency data were plotted by site type (Figure 6) and show a clear difference in the length distributions of both sexes by site type. Fish sampled from fixed sites tend be larger overall than those from random sites. Unscaled length frequency data plotted by pot placement method, however, showed no apparent difference in size of fish caught from the directed or systematic pot placement (Figure 7).

Fixed sites

The weighted sex ratio (M:F) in fixed sites ranged from 2.2:1 to 3.7:1 across the three strata and overall the weighted sex ratio was 2.9:1 (Table 8). Size ranged from 19 to 55 cm for males and 18 to 51 cm for females, although this varied among strata. Mean lengths of males from fixed sites were about 4 cm greater than females in all three strata, and overall weighted mean length was 33.6 cm for males and 29.4 cm for females (Table 8). The smallest mean lengths were from blue cod caught in stratum 1. In fixed sites, 67% of the blue cod were recruited (30 cm and over).

Random sites

The weighted sex ratio (M:F) in random sites ranged from 1.7:1 to 2.5:1 across the three strata and overall the weighted sex ratio was 2.0:1 (Table 9). Size ranged from 16 to 59 cm for males 11 to 49 cm for females, although this varied among strata. Mean lengths of males from random sites were between 2 and 8 cm greater than females across the three strata, and overall weighted mean length was 29.0 cm for males and 23.7 cm for females (Table 9). In random sites, 21% of the blue cod were recruited (30 cm and over).

3.5 Ageing (between reader analyses)

From 604 sectioned otoliths, 37 were rejected as unreadable or damaged, leaving 567 otoliths (324 males, 16–59 cm; 243 females, 11–51 cm) (Table 10). These otoliths were collected across all strata (Appendix 4).

Initial independently derived reader estimates of age class are compared in Appendix 5 and show 48% agreement between the two readers, with reader 2 generally estimating lower age classes than reader 1 for fish over 40 cm. When the differences between age class estimates were resolved by agreement between the readers the more experienced reader 1 was 90% consistent with the agreed age class estimates compared to less experienced reader 2 who was only 49% consistent with the agreed age classes (Appendix 6). The tendency of reader 2 to underestimate the agreed age class was restricted mainly to fish beyond 15 years (Figure 8).

3.6 Growth

The length-age data are plotted and the von Bertalanffy model fits are shown for the 2010 survey for males and females separately (Figure 9). The growth parameters (K, t_0 and L_{inf}) are shown in the methods table of input data for the SPR analysis (section 2.7.9). The growth parameters are similar for males and females except that males achieve a greater L_{inf} than females (i.e., 63.0 cm for males and 53.5 cm for females).

3.7 Population length and age composition

3.7.1 How many age length keys to use?

Catch at age was estimated for all sites combined using a single age-length-key (ALK) as the default analysis. However, because length distributions differed between fixed sites and random sites, catch at age was also estimated independently by site type, initially using one ALK. To determine if more than one ALK should be applied to the fixed and random sites, mean length at age was compared among strata, site type, and pot placement (Figures 10 and 11). Of these, the only ALK split that appeared to be justified was between stratum 3, and strata 1 and 6 combined, since fish in strata 1 and 6 are slower growing than those in stratum 3. Accordingly, a second analysis of catch at age was carried out for the fixed and random sites using two ALKs. Using the approach of Francis (2011), we were interested in knowing what effect using two ALKs would have on the *Z* estimates.

The two ALKs were applied to the fixed site and random site length data in the following manner:

Fixed site length (stratum 3)	ALK stratum 3
Fixed site length (strata 1 and 6)	ALK stratum 1 and 6
Random site length (stratum 3)	ALK stratum 3
Random site length (strata 1 and 6)	ALK stratum 1 and 6

The resulting Z estimates generated from the numbers at length outputs were compared between the one ALK and two ALK methods (see section 3.8). The *Z* estimates were not different enough to warrant using the two ALKs and the catch at age for random and fixed sites are presented only for the single ALK model.

3.7.2 Catch at age

The scaled length frequency and age distributions for all sites are shown as histograms, and as cumulative frequency line plots for males, females, and both sexes combined (Figure 12). The equivalent plots are shown for fixed sites (Figure 13) and random sites (Figure 14). The ALKs by sex are shown in Appendices 7 and 8. Mean-age-at-length is shown in Appendix 9. All fish lengths collected on the survey had at least one valid age reading in the ALK for both males and females for all catch at age analyses.

Cumulative frequency plots comparing length and age composition between fixed and random sites are shown in Figure 15.

All sites

The scaled length frequency distribution for males is unimodal with mean length of 30.4 cm, whereas females show indications of a bimodal distribution with modes at about 23 cm and 30 cm and an overall mean length of 26.7 cm (see Figure 12). Length frequency distributions for both sexes are also skewed to the right with fewer larger fish. The cumulative distribution plots of length frequency show clearly that males have a higher proportion of larger fish than females and also that the largest fish are males. The mean weighted coefficients of variation (MWCVs) around the length distributions are 24% for males and 35% for females, indicating that fish sampled in the survey provide a reasonable representation of the overall population. Fish 30 cm and over comprise 52% of the scaled numbers.

Age of blue cod ranged from 2 to 30 years (Table 10), but most males were between 5 and 12 years old and females between 4 and 10 years old (see Figure 12). The estimated population age distributions are generally unimodal for both sexes with the main peak at about 8 years for males, but less clear for females, although fish of 4 years were the most abundant. The cumulative distribution plots of age frequency show clearly that males have a higher proportion of older fish than females and also that the oldest fish are males. Further, mean age of males is greater than that of females (9.0 years for males and 7.4 years for females). The MWCVs around the age distributions are 26% for males and 33% for females, indicating that fish sampled in the survey for age provide a reasonable representation of the overall population.

Fixed sites

The scaled length frequency distributions for males and females from fixed sites are unimodal with mean lengths of 33.6 cm and 29.4 cm, respectively (see Figure 13). Length frequency distributions for both sexes are also skewed to the right with fewer larger fish. The cumulative distribution plots of length frequency show clearly that males have a higher proportion of larger fish than females and also that the largest fish are males. The mean weighted coefficients of variation (MWCVs) around the length distributions are 27% for males and 37% for females, indicating that fish sampled in the survey provide a reasonable representation of the overall population. Fish 30 cm and over comprise 67% of the scaled numbers.

Most males from fixed sites were between 6 and 12 years old and females between 6 and 10 years old (see Figure 13). The estimated population age distributions are generally unimodal with the main peak at about eight years for both sexes. The cumulative distribution plots of age frequency show clearly that males have a higher proportion of older fish than females and also that the oldest fish are males. Further, mean age of males is greater than that of females (9.7 years for males and 8.7 years for females). The MWCVs around the age distributions are 27% for males and 34% for females, indicating that fish sampled in the survey for age provide a reasonable representation of the overall population.

Random sites

The scaled length frequency distributions for males and females from random sites are unimodal with mean lengths of 29.0 cm and 23.7 cm respectively (see Figure 14). Length frequency distributions for both sexes are also overtly skewed to the right with fewer larger fish. The cumulative distribution plots of length frequency show clearly that males have a higher proportion of larger fish than females and also that the largest fish are males. The mean weighted coefficients of variation (MWCVs) around the length distributions are 31.8% for males and 45.4% for females, indicating that fish sampled in the survey provide a reasonable representation of the overall population. Fish 30 cm and over comprise 21% of the scaled numbers.

Most males and females from random sites were between four and eight years old (see Figure 14). The estimated population age distributions are generally unimodal with the main peak at about six years for males and four years for females. The cumulative distribution plots of age frequency show clearly that males have a higher proportion of older fish than females and also that the oldest fish are males. Further, mean age of males is greater than that of females (7.8 years for males and 6.0 years for females). The MWCVs around the age distributions are 29% for males and 37% for females, indicating that fish sampled in the survey for age provide a reasonable representation of the overall population.

Comparison between fixed and random sites

The scaled length distributions and number at age estimates show clearly that overall blue cod from random sites are smaller and younger than those from fixed sites (Figure 15). The ranges of both length and age are not that dissimilar, but the random sites tend to have more small fish (see Figure 6).

3.8 Total mortality (*Z*) estimates

Total mortality estimates (*Z*) and 95% confidence intervals for the 2010 south Otago survey are given in Table 11. These are presented for estimates that used one ALK for all sites, fixed sites, and random sites. In addition, estimates of *Z* using two ALKs are presented for fixed and random sites (see section 3.7.1). There were negligible differences between *Z* estimates for fixed or random sites using one or two ALKs, and on this basis catch at age is presented only for the one ALK models. The mortality estimates using one ALK were between 0.21 and 0.29 for all sites, 0.20 and 0.29 for fixed sites, and 0.26 and 0.28 for random sites.

3.9 Spawner per recruit analyses

Spawner per recruit analyses were carried out for all sites, fixed sites, and random sites where *Z* was estimated using one ALK. The SPR curve is based on the relationship between %SPR and fishing mortality (Figure 16) and for the random sites analyses the $F_{\%SPR}$ is plotted. Mortality parameters used in the all sites, fixed sites, and random sites analyses, and resulting $F_{\%SPR}$ values are shown in Table 12. Based on the default M of 0.14, for random sites, the fishing mortality estimated was 0.14 which corresponds to $F_{39.4\%}$. This indicates that at the 2010 levels of fishing mortality the expected contribution to the spawning biomass over the lifetime of an average recruit has been reduced to 39% of the contribution in the absence of fishing. Other random sites $F_{\%SPR}$ estimates for M values of 0.11 and 0.17 (20% below and above the default value of 0.14) were $F_{27.6\%}$ and $F_{52.1\%}$ (Table 12).

4. DISCUSSION

The 2010 south Otago potting survey is the first in the time series aimed at estimating relative abundance, population structure, and stock status of blue cod in south Otago. Unlike previous blue cod surveys the design was experimental, comparing random with fixed site sampling, and also directed with systematic pot placement.

Catch rates

This survey has been carried out in accordance with the blue cod potting survey manual (Beentjes & Francis 2011) and all terms used adhere strictly to the manual. There will therefore be differences in terminology between this and earlier survey reports. The most significant is the use of the terms site and station. Here we refer to a site as a geographical location near to which sampling may take place during a survey, and a station as position (latitude and longitude) at which a single pot is deployed at a site (see terminology). The other key difference is that the method for estimating survey precision around catch rates has changed from pot based to set based, although catch rates have remained pot based (Francis 2011). Hence, had we presented the c.v.s using the pot based method, as we have for earlier surveys, the c.v.s would be in the order of 30–40% lower. Because this is the first survey in the time series this is not important because we are not making within survey time series comparisons of survey precision. However, if comparisons are made among surveys then this should be taken into account.

The comparisons of catch rates and c.v.s for directed and systematic pot placement show clearly that pot placement method had no effect on either of these variables (Figures 3 and 4, Tables 4 and 5) for either fixed or random sites. This allowed the data from each site (three directed pots and three systematic pots) to be pooled, regardless of pot placement method. In contrast, site type had a dramatic effect on catch rates. Overall catch rates from random sites were about half that of fixed sites (fixed sites – 9.7 kg/pot, c.v. 17.1%; random sites – 4.4 kg/pot. c.v. 17.8%) (Figures 3 and 4, Tables 4 and 5). The bias was also most evident for inshore stratum 1, whereas there was no real difference in stratum 3, given the overlapping confidence intervals. Catch rates for recruited fish (30 cm and over) displayed the same trends as the all blue cod catch rates.

Size and sex ratio

For all sites combined, the overall sex ratio (M:F) was 2.5:1 for all blue cod and 4.6:1 for recruited blue cod and all strata were biased towards males (Table 6). Males also dominated in both fixed and random sites with similar ratios (Tables 8 and 9). Blue cod are protogynous hermaphrodites with some (but not all) females changing into males as they grow (Carbines 2004b). The finding that males were larger on average than females and that the largest fish were males is consistent with sex structure in protogynous hermaphrodites. However, the skewed sex ratios are contrary to an expected dominance of females resulting from selective removal of the larger terminal sex fish (males). Beentjes & Carbines (2005) suggested 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, and a consequent higher rate (and possibly earlier onset) of sex change by primary females. This hypothesis is supported by the predominance of males in most South Island blue cod fisheries that are known to be heavily fished, in particular, Motunau, inshore Banks Peninsula, and the Marlborough Sounds (Blackwell 1997, 1998, 2002, Beentjes & Carbines 2003, 2006, Blackwell 2006, Carbines & Beentjes 2006a, Blackwell 2008, Beentjes & Carbines 2009, Carbines & Beentjes 2009).

There is a clear difference in the length distributions of both sexes by site type (see Figure 6) with fish sampled from fixed sites larger overall than those from random sites, although the size ranges are not significantly different. Random sites tend to be strongly skewed to the right with higher proportions of smaller fish in the 20 to 30 cm size range for males and 18 to 25 cm for females. There is, however, no apparent difference in size of fish caught from the directed or systematic pot placement (see Figure 7) which allowed size data to be pooled by site type regardless of pot placement.

Population length and age structure

The different length distributions for fixed and random sites required that population length and age distributions be estimated separately by site type. Analysis of mean age at length among a range of variables and the subsequent *Z* estimates based on one or two ALKs indicated that one ALK, comprising all the survey age data, was legitimate for all catch at age analyses, regardless if this was for fixed or random sites (Figures 10 and 11). The advantage of this for the current survey is that MWCVs were lower for each analysis than for two ALKs because there are more ages per length included in the numbers at age estimation. Secondly, the application of a single ALK results in fewer otoliths being collected and hence fewer resources required for processing and reading otoliths for future surveys. The approach used here to examine mean age at length among strata (i.e., area, site type, pot placement etc.), and the effect this has on estimates of Z, is based on the analysis of Francis (2011). It is recommended that this be used as a standard method to assess the number and makeup of ALKs required before the start of future surveys for existing time series. Clearly this is not possible for new surveys in a time series.

The age distributions, and total mortality estimates are based on length data that were weighted (scaled) by stratum area. Scaling by area for fixed sites assumes that the size of each stratum is directly proportional to the amount of blue cod habitat, i.e., area is assumed to be a proxy for habitat; however, this is probably not the case given the discrete nature of areas of foul and biogenic reef habitat. This is a legitimate scaling approach for random sites, however, because the strata boundaries are based less on habitat type and more on distribution of blue cod. Random sites also reduce the potential bias in size and age structure that may exist in sampling only fixed sites which are, in reality, blue cod "hot spots".

For previous fixed site surveys, improving seabed habitat mapping is required to scale catch data to more detailed estimates of the actual areas of suitable blue cod habitat within each stratum – as was recommended by the expert review panel following a workshop on blue cod potting surveys in April 2009 (Stephenson et al. 2009). However, as stratum area (or coastline length) is currently the only available proxy for blue cod habitat, it has been used for scaling all fixed site surveys.

The scaled length and age frequency distributions for all sites combined are a product of those from fixed and random sites. To understand the population structure more fully, catch at age is more appropriately viewed at the site level. Fixed sites have a higher proportion of both larger and older fish than random sites (Figure 15). In fixed sites, 67% of the blue cod were recruited (30 cm and over) compared with only 21% for random sites.

Stock status

Mortality estimates (Z) with age at full recruitment set at 6 years, are lower at fixed than random sites, a reflection of the age structure derived from these sites (fixed sites Z = 0.23; random sites Z = 0.28; Table 11).

The Ministry of Fisheries *Harvest Strategy Standard* (Ministry of Fisheries 2008) specifies that a Fishery Plan should include a fishery target reference point, and this may be expressed in terms of biomass or fishing mortality. The more appropriate target reference point for blue cod is F_{MSY}, which is the amount of fishing mortality that results in the maximum sustainable yield. The recommended proxy for F_{MSY} is the level of spawner per recruit $F_{\%SPR}$. The *Harvest Strategy Standard* (Ministry of Fisheries 2008) includes the following table of recommended default values for F_{MSY} (expressed as $F_{\%SPR}$ levels from spawning biomass per recruit analysis), and also for B_{MSY} (expressed as $\%B_0$).

Productivity level	**$\%B_0$**	**$F_{\%SPR}$**
High productivity	25%	$F_{30\%}$
Medium productivity	35%	$F_{40\%}$
Low productivity	40%	$F_{45\%}$
Very low productivity	≥ 45%	≤ $F_{50\%}$

Based on this and recommendations from the Southern Inshore Working Group, blue cod is categorised as an exploited species with medium productivity and hence the recommended default proxy for F_{MSY} is $F_{40\%}$. Our SPR estimates for all sites, fixed sites, and random sites using the default M value of 0.14 indicated that the expected contribution to the spawning biomass over the lifetime of an average recruit has been reduced to 48%, 50%, and 39% respectively, of the contribution in the absence of fishing (see Table 12). Further, the level of exploitation (F) of south Otago blue cod stocks is less than F_{MSY} target reference point of $F_{40\%}$ for fixed sites and almost equal to F_{MSY} for random sites. The Southern Inshore Working Group recommended using random surveys for this area, and hence the random survey estimate of $F_{\%SPR}$ at M=0.14 ($F_{39.4\%}$) should be used when formulating management advice, noting that for the 2010 survey not all strata were surveyed.

Reproductive condition

Observations of gonad stages in south Otago indicated that nearly all fish sampled were in the resting phase (see Table 7). This indicates that the timing of the survey (April-May) was outside the spawning period which generally occurs from spring to mid-summer (Carbines 2004b).

Differences between fixed and random sites

Blue cod caught from fixed sites were on average larger than those from random sites, and this resulted in lower *Z* estimates and higher $F\%_{SPR}$ values in fixed sites. We can only speculate on the reasons for this finding, but as fixed sites are known hot spots they may have more productive habitat than random sites and hence support larger individuals. The overall catch rate from fixed sites was more than double that from the random sites, a finding that supports this hypothesis. However, the result is counterintuitive since we might have expected the fixed sites, where fishing pressure could be expected to be higher than random sites, to show indications of depletion, the first sign of which is a reduction in size. For example a slightly higher proportion of larger fish was caught in Foveaux Strait in the 2010 random site survey (Carbines & Beentjes in prep) than a 2009 fishing industry survey from fixed sites (Glen Carbines, unpublished data).

The implications of this finding for future surveys of south Otago and other areas are that the time series of abundance indices should be based on either fixed sites, or random sites, but not a combination. If both fixed and random sites types are used in a survey, then they should be treated separately to allow for the potential differences in population size and age composition.

Among survey comparisons

Based on the findings from this survey, it is appropriate to compare only the fixed sites results of the 2010 survey with fixed sites results from other surveys where these have also been used in the design.

The fixed site catch rate of the 2010 south Otago survey was 9.7 kg/pot, and is higher than estimates from any previous survey. Most catch rates indices are around 4 to 5 kg/pot, with the exception of Marlborough Sounds (1.7 kg/pot in 2007 survey), Banks Peninsula (2.6 kg/pot in 2008 survey, inshore and offshore combined), and north Otago (9 kg/pot 2009 survey) (Blackwell, 1997, 1998, 2002, Beentjes & Carbines 2003, Carbines & Beentjes 2003, Blackwell 2005, Beentjes & Carbines 2006, Carbines & Beentjes 2006a, 2006b, Carbines 2007, Beentjes & Carbines 2009, Carbines & Beentjes 2009, 2011b, 2011a, Carbines in prep, Willis in prep).

Overall length and age from south Otago fixed sites are substantially greater than those from the Marlborough Sounds, Kaikoura, Motunau, and inshore Banks Peninsula. They are of similar size to those in Dusky Sound and Paterson Inlet, however, smaller than those from offshore Banks Peninsula.

The fixed sites *Z* estimates for all these earlier surveys (where Z has been estimated) were based on incorrect scaling and combining of the sexes (Francis 2011) and need to be recalculated before strictly valid comparisons can be made. Assuming they will not change substantially, either in magnitude or relative to each other, *Z* estimates from south Otago ($Z = 0.23$) are the lowest of all surveys with the exception of offshore Banks Peninsula where Z was 0.14 in 2008. $F_{\%SPR}$ values have only been estimated hitherto for north Otago, Dusky Sound, and the south Otago survey. Of these, north Otago has higher exploitation ($F_{35.6\%}$) and Dusky Sound slightly lower exploitation ($F_{51\%}$) than south Otago. The *Z* estimates, however, indicate that all other areas, except offshore Banks Peninsula, will have lower values of $F_{\%SPR}$ and hence higher exploitation.

The random sites from the 2010 south Otago survey can validly be compared to those from the 2010 Foveaux Strait survey which was a fully random site survey. Catch rates were similar between these areas and were 4.4 kg/pot and 4.8 kg/pot, respectively. Foveaux Strait had a strong uni-modal size distribution with a peak at about 30 cm, whereas the random sites from south Otago have a smaller modal peak at about 23 cm, but the distribution is strongly skewed to the right (Figure 14). Consequently south Otago has more older fish than Foveaux Strait and a lower Z estimate (south Otago $Z = 0.28$, Foveaux Strait $Z = 0.41$) and higher $F_{\%SPR}$ value (south Otago $F_{39\%}$, Foveaux Strait $F_{35\%}$). Comparisons of *Z* estimates and $F_{\%SPR}$ are valid between the 2010 south Otago and 2010 Foveaux Strait surveys because the *Z* estimates were estimated using the correct scaling and combining of sexes as detailed in the potting manual.

5. ACKNOWLEDGMENTS

This research was carried out by NIWA and Saltwater Research under contract to the Ministry of Fisheries (MFish Project BCO2009/01). We thank Neil McDonald for providing the vessel and crew to undertake the survey. Thanks to NIWA staff Derek Kater for processing and reading otoliths, and Chris Francis (NIWA) for advice on analyses and contributing Figures 10 and 11. Thanks also to Russell Cole (NIWA) and Steve Brouwer (MFish) for reviewing the draft manuscript, and Marianne Vignaux for editorial comments.

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Table 1: South Otago 2010 survey catch summary by site type (see terminology for definitions of site types, Section 2.1).

Stratum	Stratum area	Site type	No. sites	No. pots (= stations)	No. blue cod	Catch (kg)	Depth (m) Mean	Depth (m) Range
1	154.9	fixed	6	36	458	188	19.1	8–52
3	177.9	fixed	6	36	148	119	114.7	106–124
6	251.3	fixed	6	36	876	608	56.0	46–68
Total			**18**	**108**	**1482**	**915**	**63.3**	**8–124**
1	154.9	random	6	36	139	43	30.6	3–53
3	177.9	random	6	36	591	174	101.1	84–117
6	251.3	random	6	36	361	217	66.5	55–77
Total			**18**	**108**	**1091**	**434**	**66.1**	**3–117**
Grand Total			**36**	**216**	**2573**	**1349**	**64.7**	**3–124**

Table 2: South Otago 2010 survey catch summary by site type, and plot placement method (see terminology for definitions of site types and pot placement, Section 2.1).

				Catch (kg)
Pot placement	Stratum	Fixed site	Random site	Combined
Directed	all	482	196	678
Systematic	all	433	238	671
Total		**915**	**434**	**1349**

				Catch (kg)
Pot placement	Stratum	Fixed site	Random site	Combined
Directed	1	116	14	130
Directed	3	52	71	123
Directed	6	314	111	425
Total		**482**	**196**	**678**
Systematic	1	72	29	101
Systematic	3	67	103	171
Systematic	6	294	106	400
Total		**433**	**238**	**671**
Grand Total		**915**	**434**	**1349**

Table 3: Catch weights, numbers of blue cod, bycatch species, and percentage of total weight on the 2010 south Otago survey.

Common name	Scientific name	Catch (kg)	Number	Percent of total catch
Blue cod	*Parapercis colias*	1349.14	2573	97.45
Octopus	*Octopus cordiformis*	19.00	4	1.37
Banded wrasse	*Notolabrus fucicola*	3.64	5	0.26
Scarlet wrasse	*Pseudolabrus miles*	3.34	6	0.24
Girdled wrasse	*Notolabrus cinctus*	3.08	8	0.22
Sea perch	*Helicolenus percoides*	1.73	3	0.12
Ling	*Genypterus blacodes*	1.57	1	0.11
Red cod	*Pseudophycis bachus*	0.70	1	0.05
Leather jacket	*Parika scaber*	0.59	2	0.04
Spotty	*Notolabrus celidotus*	0.48	1	0.03
Trumpeter	*Latris lineata*	0.45	1	0.03
Tarakihi	*Nemadactylus macropterus*	0.38	2	0.03
Paddle crab	*Ovalipes catharus*	0.28	2	0.02
Total		1384.3	2609	100

Table 4: Mean blue cod catch rates for all blue cod caught from the 2010 south Otago survey. Catch rates and statistics are provided by pot placement method at fixed sites (A), pot placement method at random sites (B), and fixed and random sites for all pots (C). Catch rates are pot based, and s.e. and c.v. are set-based. s.e., standard error; c.v. coefficient of variation.

A

	Fixed site (directed pot placement)				Fixed site (systematic pot placement)			
Stratum	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)
1	18	6.5	2.21	34.3	18	4.0	2.29	57.5
3	18	2.9	2.06	71.3	18	3.7	0.95	25.4
6	18	17.4	3.99	22.9	18	16.3	3.43	21.0
Overall	54	10.1	1.92	19.0	54	9.2	1.62	17.6

B

	Random site (directed pot placement)				Random site (systematic pot placement)			
Stratum	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)
1	18	0.8	0.70	90.8	18	1.6	1.55	95.2
3	18	3.9	1.70	43.0	18	5.7	1.21	21.1
6	18	6.2	1.64	26.7	18	5.9	1.26	21.3
Overall	54	4.1	0.89	22.1	54	4.7	0.77	16.4

C

	Fixed site (all pots)				Random site (all pots)			
Stratum	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)
1	36	5.2	2.14	41.1	36	1.2	1.13	93.8
3	36	3.3	1.06	32.1	36	4.8	1.26	26.1
6	36	16.9	3.52	20.9	36	6.0	1.42	23.6
Overall	108	9.7	1.65	17.1	108	4.4	0.78	17.8

Table 5: Mean blue cod catch rates for blue cod 30 cm and over caught from the 2010 south Otago survey. Catch rates and statistics are provided by pot placement method at fixed sites (A), pot placement method at random sites (B), and fixed and random sites for all pots (C). Catch rates are pot based, and s.e. and c.v. are set-based. s.e., standard error; c.v. coefficient of variation.

A

	Fixed site (directed pot placement)				Fixed site (systematic pot placement)			
Stratum	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)
1	18	3.4	1.08	31.3	18	2.6	1.55	59.3
3	18	2.7	2.09	78.3	18	3.4	0.86	25.6
6	18	15.4	3.85	24.9	18	14.4	3.09	21.5
Overall	54	8.4	1.80	21.5	54	7.9	1.42	17.9

B

	Random site (directed pot placement)				Random site (systematic pot placement)			
Stratum	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)
1	18	0.4	0.35	100.0	18	1.0	1.04	100.0
3	18	1.1	0.46	41.3	18	2.5	1.00	40.4
6	18	5.2	1.55	29.5	18	4.8	1.36	28.6
Overall	54	2.7	0.69	25.5	54	3.1	0.71	23.2

C

	Fixed site (all pots)				Random site (all pots)			
Stratum	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)	Pot lifts (N)	Mean (kg/pot)	s.e.	c.v. (%)
1	36	3.0	1.29	42.5	36	0.7	0.70	100.0
3	36	3.0	1.04	34.3	36	1.8	0.52	29.2
6	36	14.9	3.33	22.4	36	5.0	1.40	27.9
Overall	108	8.1	1.51	18.5	108	2.9	0.65	22.5

Table 6: Weighted mean lengths and weighted sex ratio (M:F) for all blue cod by strata in the 2010 south Otago survey (all sites). Weighted sex ratio is also shown for blue cod 30 cm and over.

			Length (cm)			Sex ratio M:F (% male)	
Stratum	Sex	N	Mean	Minimum	Maximum	All blue cod	≥ 30 cm
1	m	455	29.1	17	44	3.1:1 (75.9%)	24.6:1 (96.1%)
	f	144	23.6	11	35		
3	m	476	28.0	18	51	1.8:1 (64.4%)	2.9:1 (74.4%)
	f	263	24.9	16	44		
6	m	903	34.2	16	59	2.7:1 (73.0%)	4.6:1 (82.2%)
	f	334	28.7	14	51		
Overall	m	1834	31.8	16	59	2.5:1 (71.3%)	4.6:1 (82.3%)
	f	739	26.7	11	51		

Table 7: Gonad stages of blue cod in the 2010 south Otago survey (all sites). 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 (%)					
	1	2	3	4	5	N
Males	4.4	94.9	0.4	0.1	0.3	1834
Females	2.0	95.7	2.3	0.0	0.0	739

Table 8: Weighted mean lengths and weighted sex ratio (M:F) for all blue cod by strata in the 2010 south Otago survey (fixed sites).

			Length (cm)			Sex ratio M:F (% male)
Stratum	Sex	N	Mean	Minimum	Maximum	All blue cod
1	m	360	29.4	19	44	3.7:1 (78.6)
	f	98	25.1	18	35	
3	m	102	35.8	24	51	2.2:1 (69.0)
	f	46	31.8	20	42	
6	m	646	34.7	22	55	2.8:1 (73.8)
	f	230	30.2	20	51	
Overall	m	1108	33.6	19	55	2.9:1 (74.5)
	f	374	29.4	18	51	

Table 9: Weighted mean lengths and weighted sex ratio (M:F) for all blue cod by strata in the 2010 south Otago survey (random sites).

			Length (cm)			Sex ratio M:F (% male)
Stratum	Sex	N	Mean	Minimum	Maximum	All blue cod
1	m	95	27.9	17	41	2.0:1 (67.2)
	f	44	20.2	11	28	
3	m	374	25.9	18	45	1.7:1 (63.3)
	f	217	23.5	16	44	
6	m	257	32.7	16	59	2.5:1 (71.1)
	f	104	25.2	14	49	
Overall	m	726	29.0	16	59	2.0:1 (66.9)
	f	365	23.7	11	49	

Table 10: Data used to produce the age length keys for the entire survey (all strata), stratum 3, and strata 1 and 6. These were used for the catch at age, *Z* estimates, and SPR analyses for the 2010 south Otago survey.

		Length of aged fish (cm)			Age (years)		
All strata	No. otoliths	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Total	567	30.7	11	59	9.2	2	30
Male	324	33.1	16	59	10.0	3	30
Female	243	27.6	11	51	8.2	2	28
Stratum 3							
Total	240	29.9	16	51	8.2	3	26
Male	133	32.2	18	51	8.9	3	26
Female	107	27.1	16	44	7.3	3	20
Strata 1 and 6							
Total	327	31.3	11	59	9.9	2	30
Male	191	33.7	16	59	10.7	3	30
Female	136	27.9	11	51	8.8	2	28

Table 11: Total mortality estimates (*Z*) and 95% confidence intervals (CI) of blue cod from all sites, fixed sites, and random sites from the 2010 south Otago potting survey. For fixed and random sites, *Z* was estimated using one ALK (all ages) and two ALKs (stratum 3, strata 1 and 6). ALK, age-length-key.

One ALK			Two ALKs		
		All sites			All sites
AgeR	*Z*	CIs	AgeR	*Z*	CIs
5	0.21	0.16–0.28	–	–	–
6	0.24	0.18–0.32	–	–	–
7	0.27	0.20–0.34	–	–	–
8	0.29	0.22–0.37	–	–	–
		Fixed sites			Fixed sites
AgeR	*Z*	CIs	AgeR	*Z*	CIs
5	0.2	0.15–0.25	5	0.19	0.14–0.24
6	0.23	0.17–0.30	6	0.22	0.16–0.28
7	0.26	0.20–0.34	7	0.25	0.18–0.33
8	0.29	0.22–0.38	8	0.29	0.21–0.37
		Random sites			Random sites
AgeR	*Z*	CIs	AgeR	*Z*	CIs
5	0.26	0.19–0.33	5	0.25	0.18–0.34
6	0.28	0.20–0.37	6	0.27	0.19–0.35
7	0.27	0.2–0.36	7	0.26	0.18–0.34
8	0.27	0.2–0.36	8	0.26	0.18–0.35

Table 12: Mortality parameters (*Z*, *F*, and *M*) and Spawner per recruit ($F_{SPR\%}$) estimates at three values of M for all sites, fixed sites, and random sites for the 2010 south Otago survey. The *Z* value is for age at full recruitment = 6 y, and is based on a single age-length-key (ALK). F, fishing mortality; M, natural mortality; Z, total mortality.

M	Z	F	SPR
			All sites
0.11	0.24	0.13	$F_{33.5\%}$
0.14	0.24	0.10	$F_{47.7\%}$
0.17	0.24	0.07	$F_{63.0\%}$
			Fixed sites
0.11	0.23	0.12	$F_{35.4\%}$
0.14	0.23	0.09	$F_{50.3\%}$
0.17	0.23	0.06	$F_{66.5\%}$
			Random sites
0.11	0.28	0.17	$F_{27.6\%}$
0.14	0.28	0.14	$F_{39.4\%}$
0.17	0.28	0.11	$F_{52.1\%}$

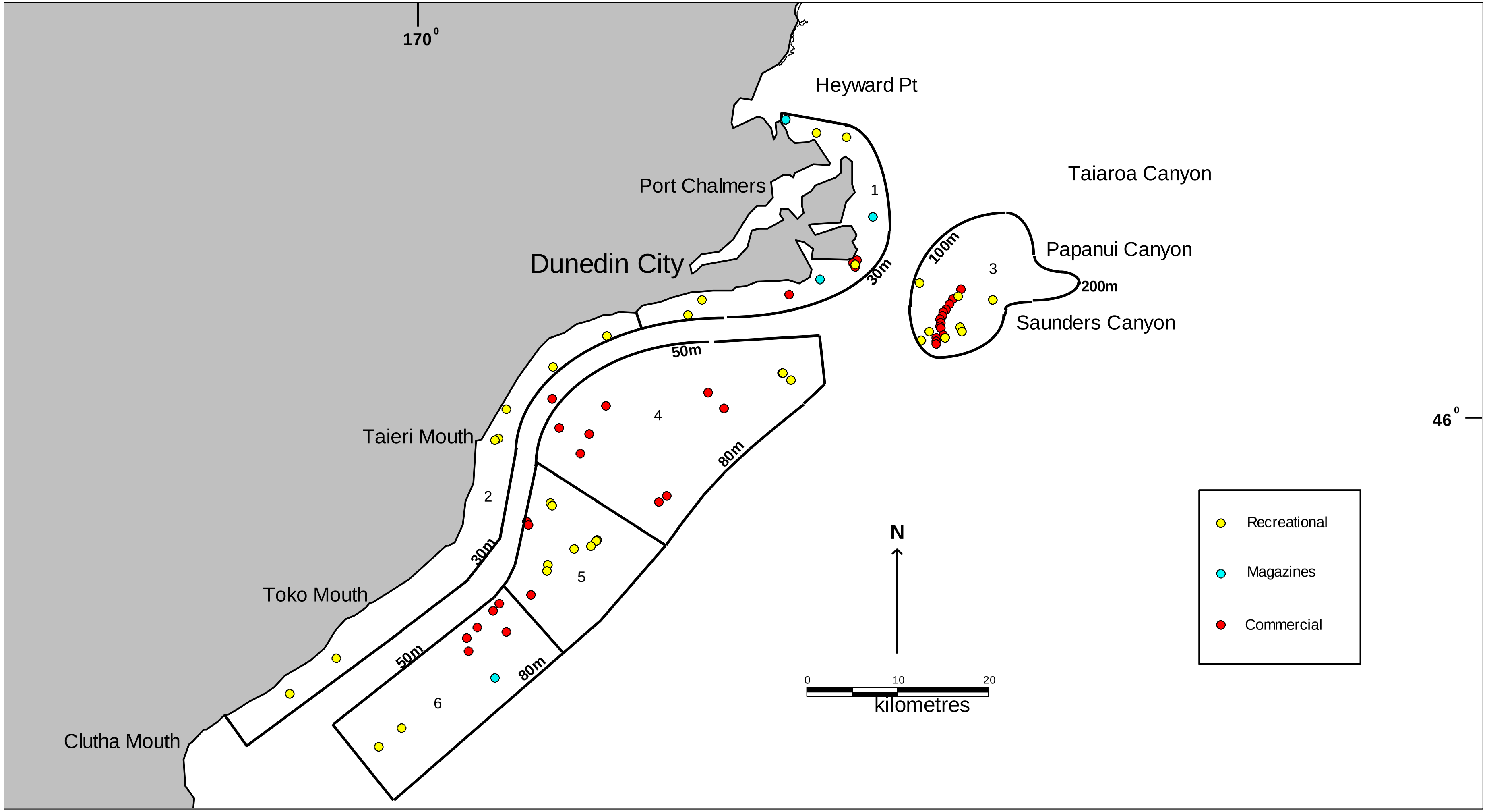


Figure 1: Map of south Otago coast showing strata (1–6) and all possible fixed sites.

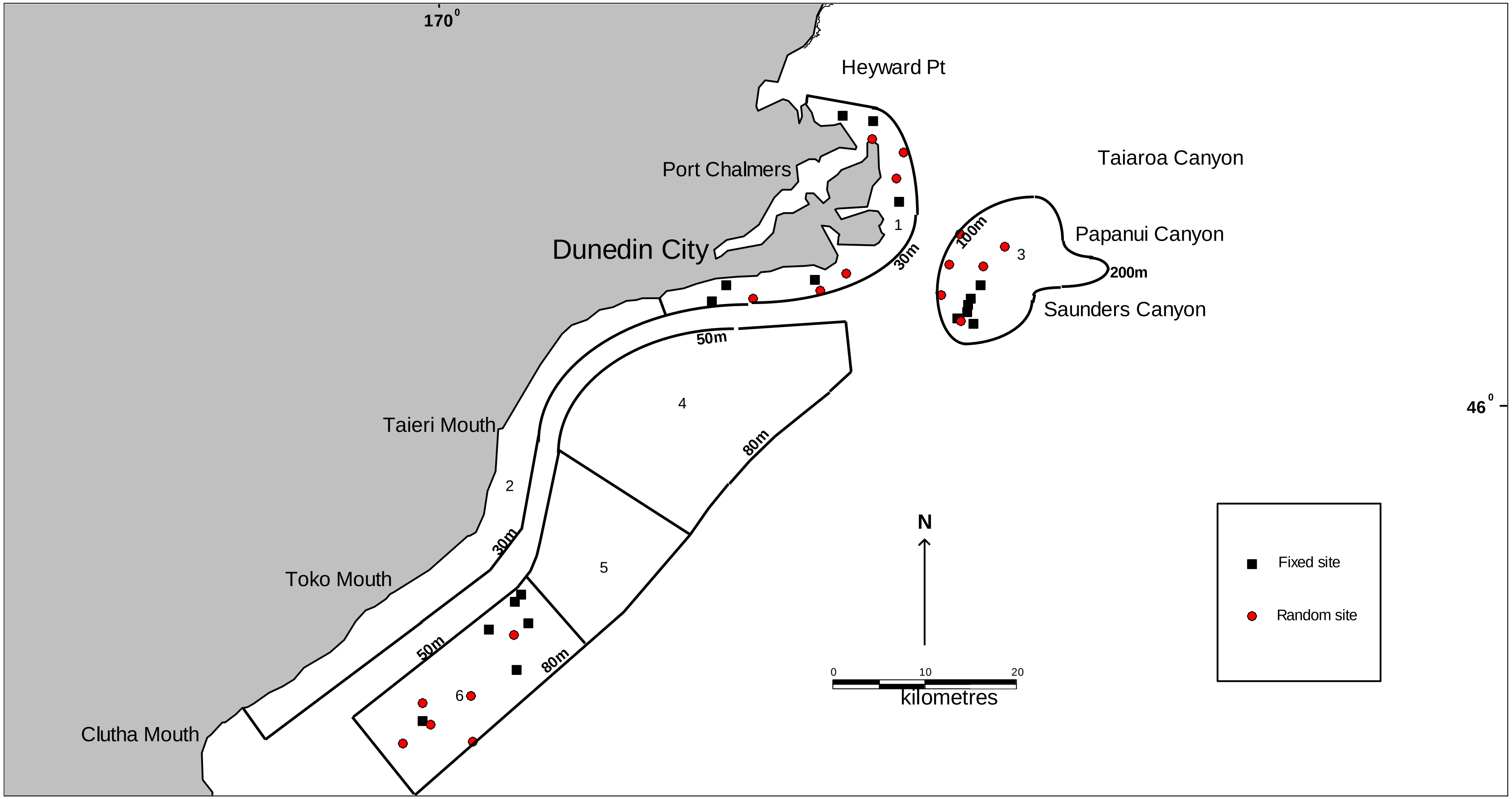


Figure 2: Map of south Otago coast showing strata (1–6) and fixed (n=18) and random sites (n=18) sampled in the 2010 survey.

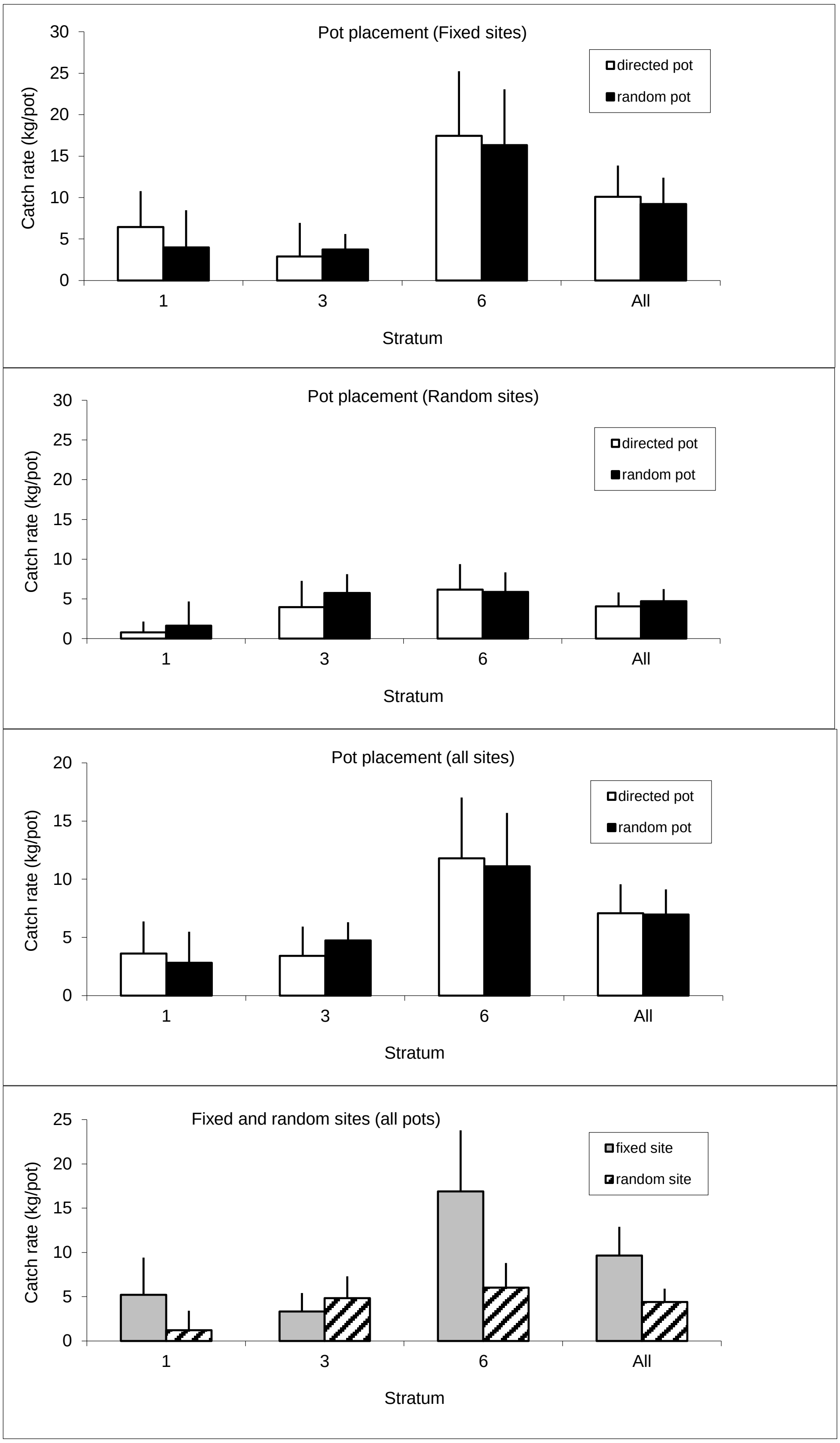


Figure 3. Catch rates for all blue cod from the 2010 south Otago survey by stratum and overall. Top three panels are catch rates using directed or systematic pot placement at fixed sites, random sites, or all sites combined. The bottom panel is catch rates by site type regardless of pot placement. Error bars are 95% confidence intervals.

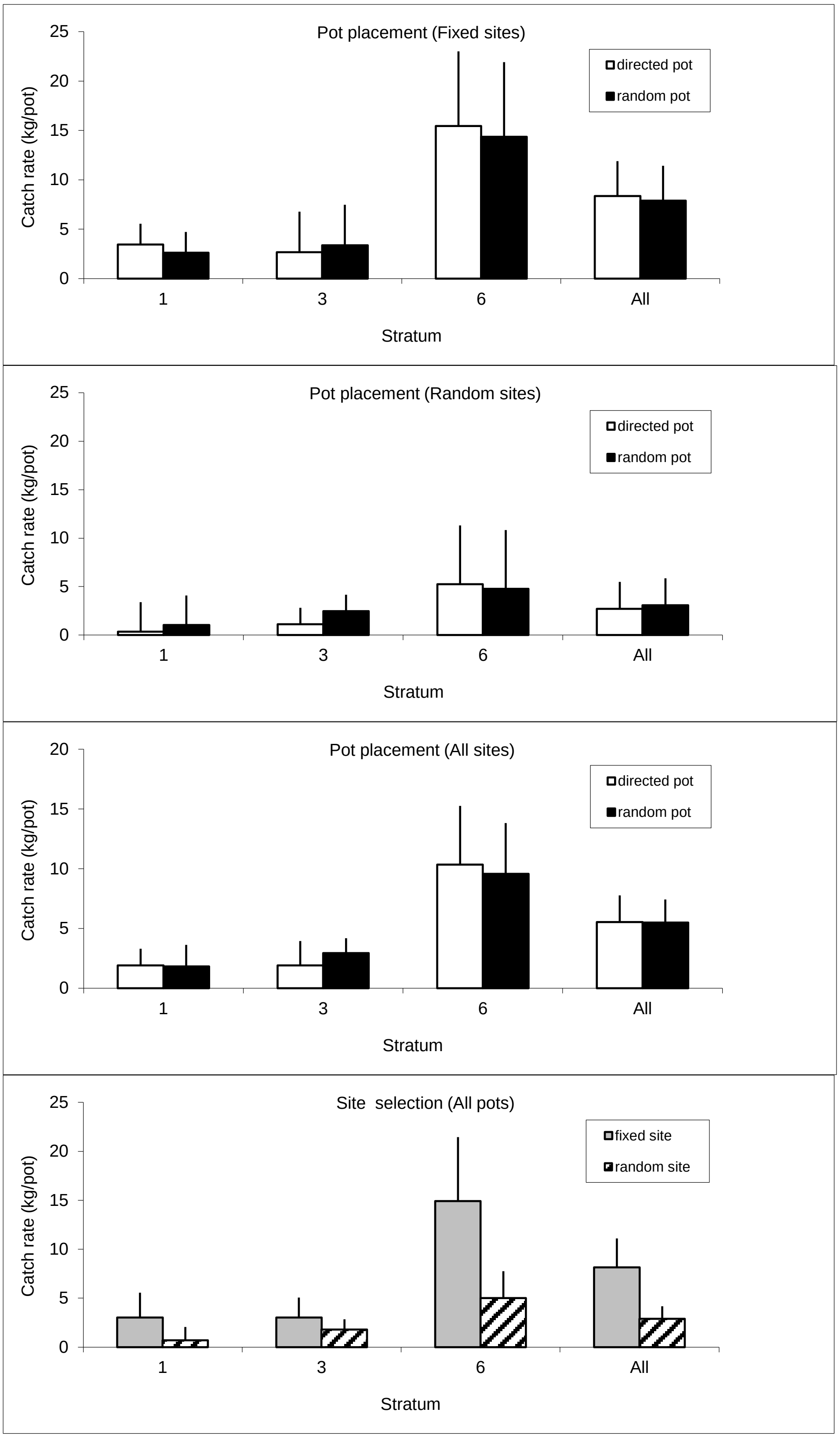


Figure 4. Catch rates for blue cod 30 cm and over from the 2010 south Otago survey by stratum and overall. Top three panels are catch rates using directed or systematic pot placement at fixed sites, random sites, or all sites combined. The bottom panel is catch rates by site type regardless of pot placement. Error bars are 95% confidence intervals.

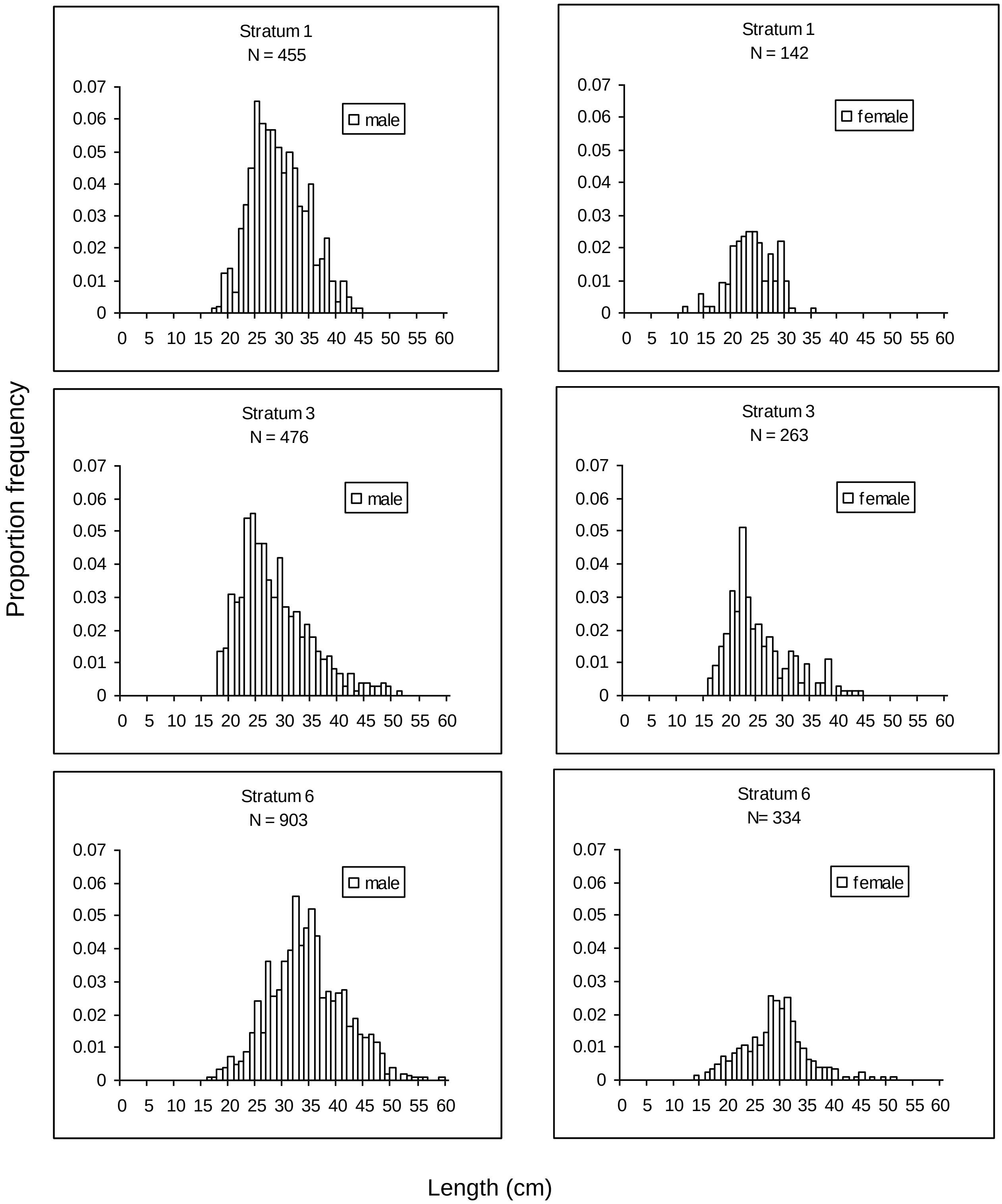


Figure 5: Scaled length frequency distributions of blue cod for each stratum (1–3) (all 36 sites).

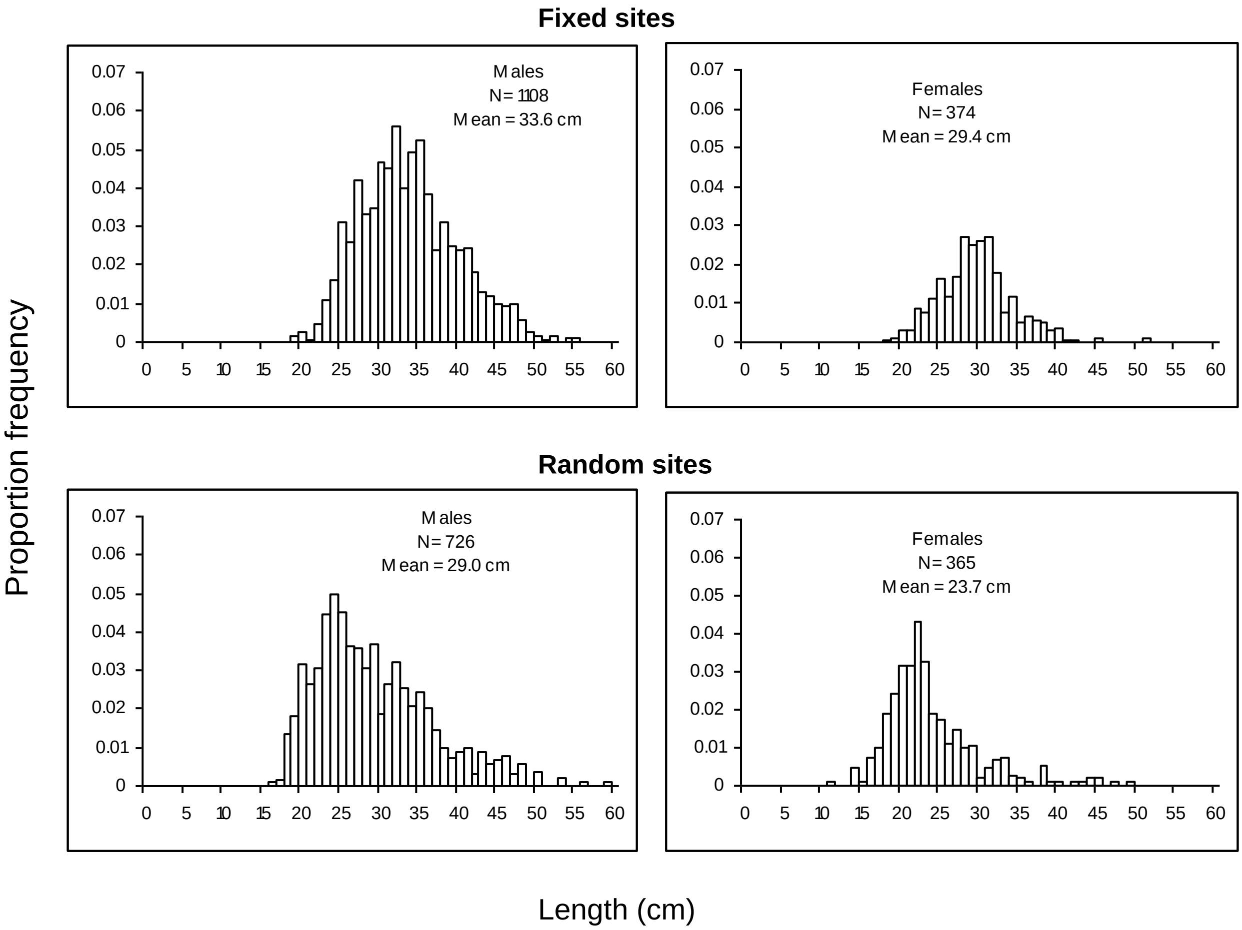
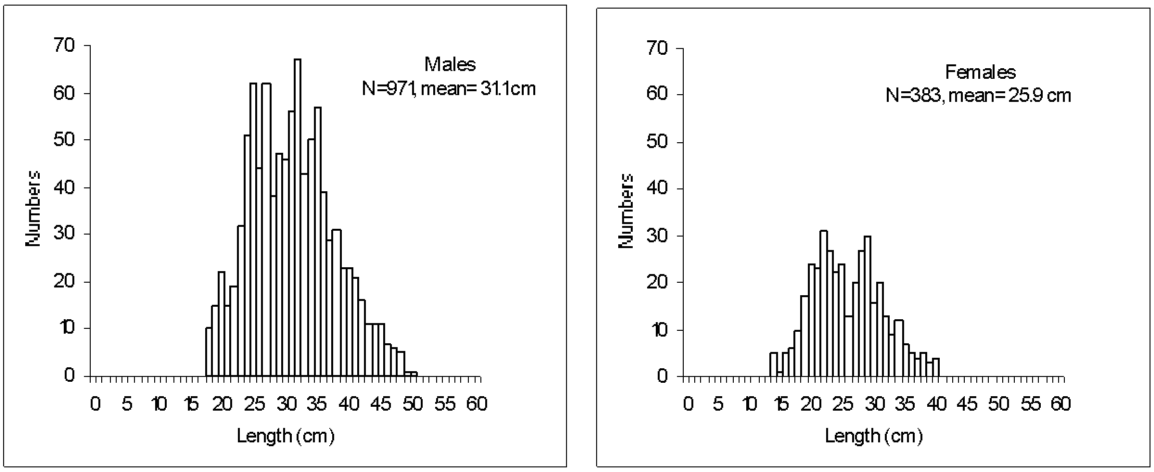


Figure 6: Scaled length frequency distributions of blue cod for all strata combined by sex and by site type (N= 18 fixed sites and 18 random sites).

Directed pot placement



Systematic pot placement

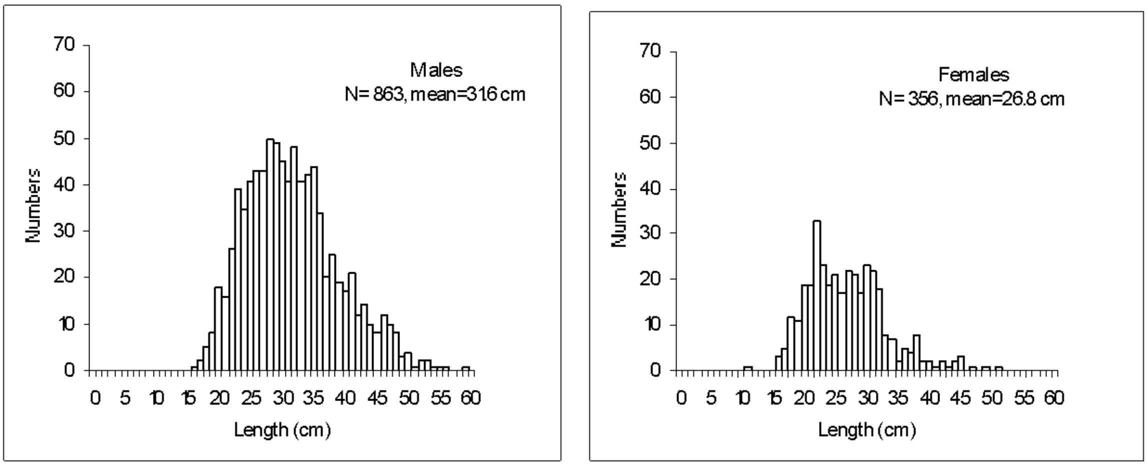


Figure 7: Unscaled length frequency distributions of blue cod for all strata combined by sex and by pot placement type (N= 108 directed pots and 108 systematic pots).

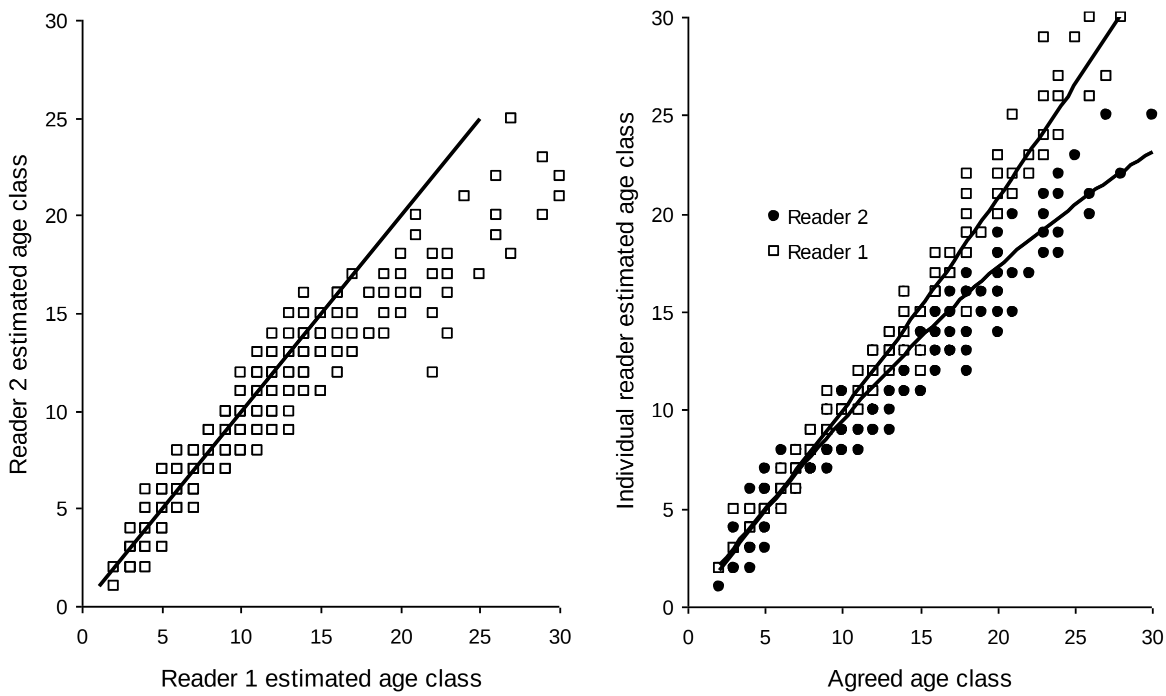


Figure 8: Comparison of individual reader age class estimates from otoliths plotted against each other on the left and against the agreed age class estimates on the right (n = 568). Polynomial trend lines are fitted to the combined reader age class estimates on the right, the fitted line on the left hand panel represents a 1:1 line.

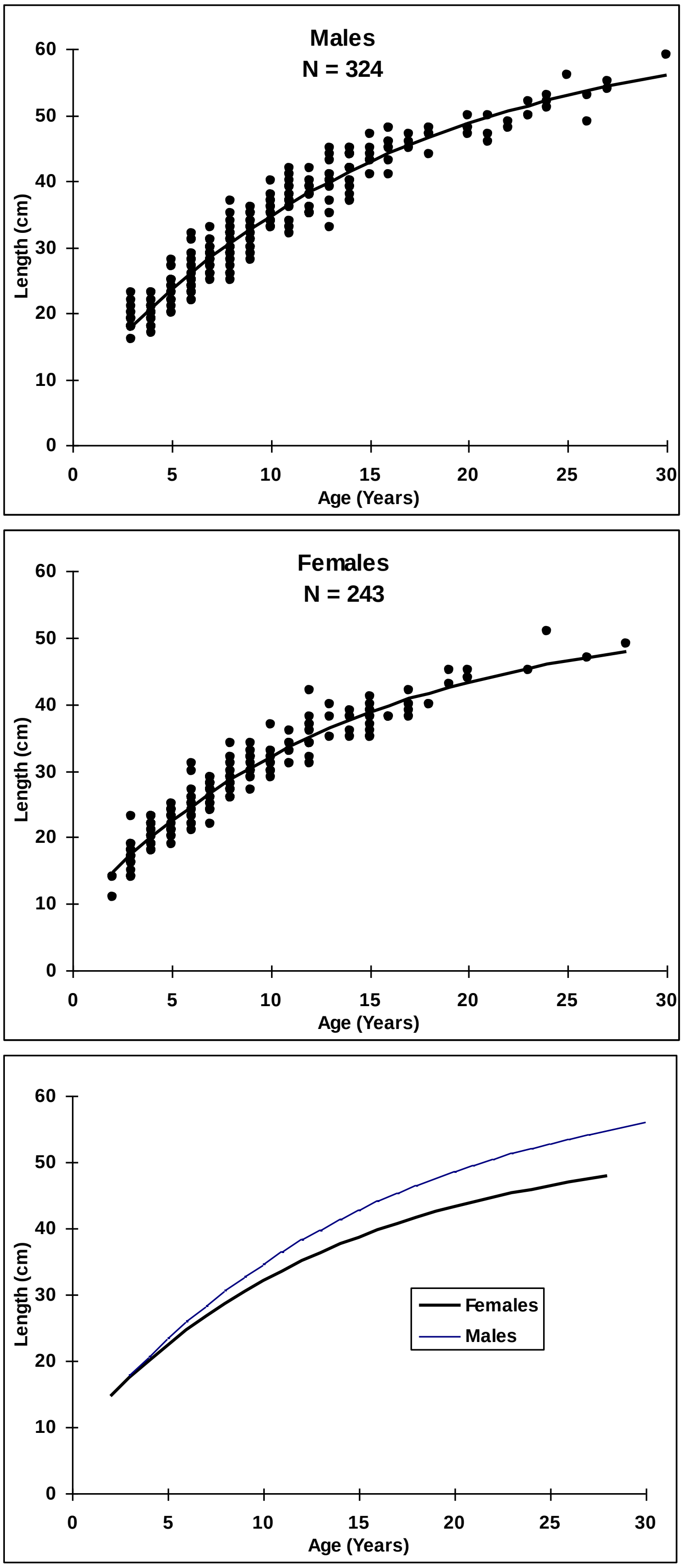


Figure 9: Observed age and length data by sex for the 2010 south Otago survey (all sites) with von Bertalanffy growth models fitted to the data (top 2 panels). Male and female growth models are also shown on the same graph (bottom panel). See Table 10 for description of samples.

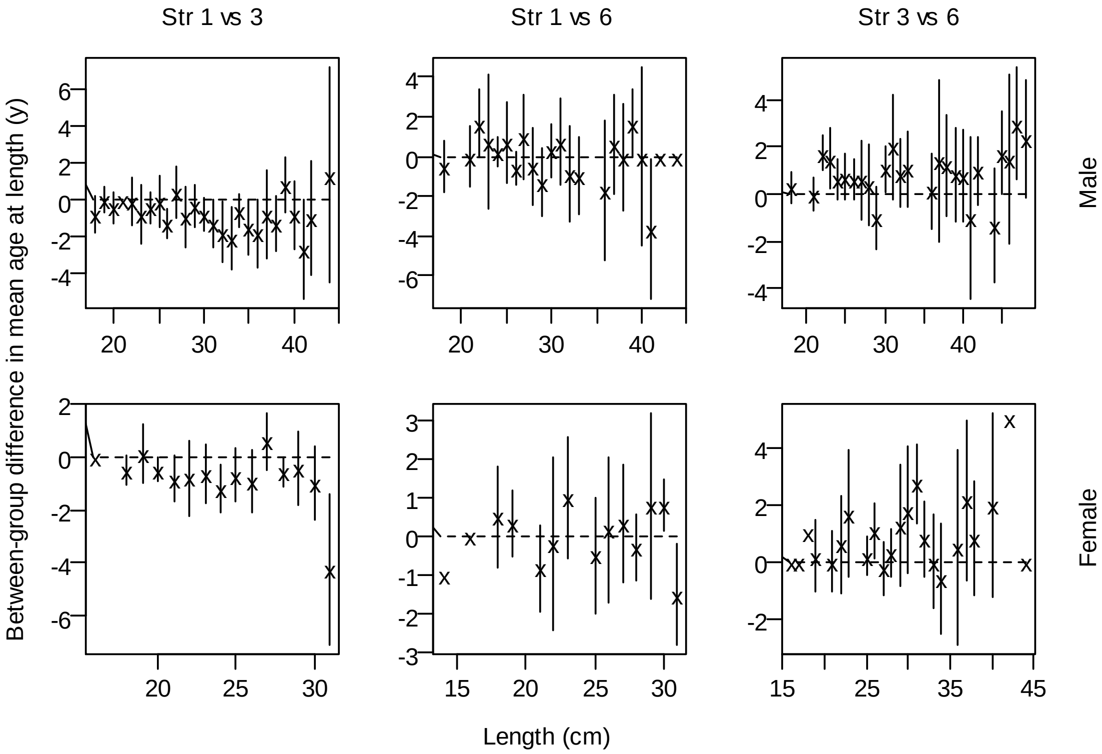


Figure 10: Differences in mean age at length ('x', with vertical lines indicating 95% confidence intervals), by sex, between pairs of strata. Positive differences indicate that mean ages are higher in the second stratum. No confidence interval is plotted when there is no variation in age at length in the samples in both strata.

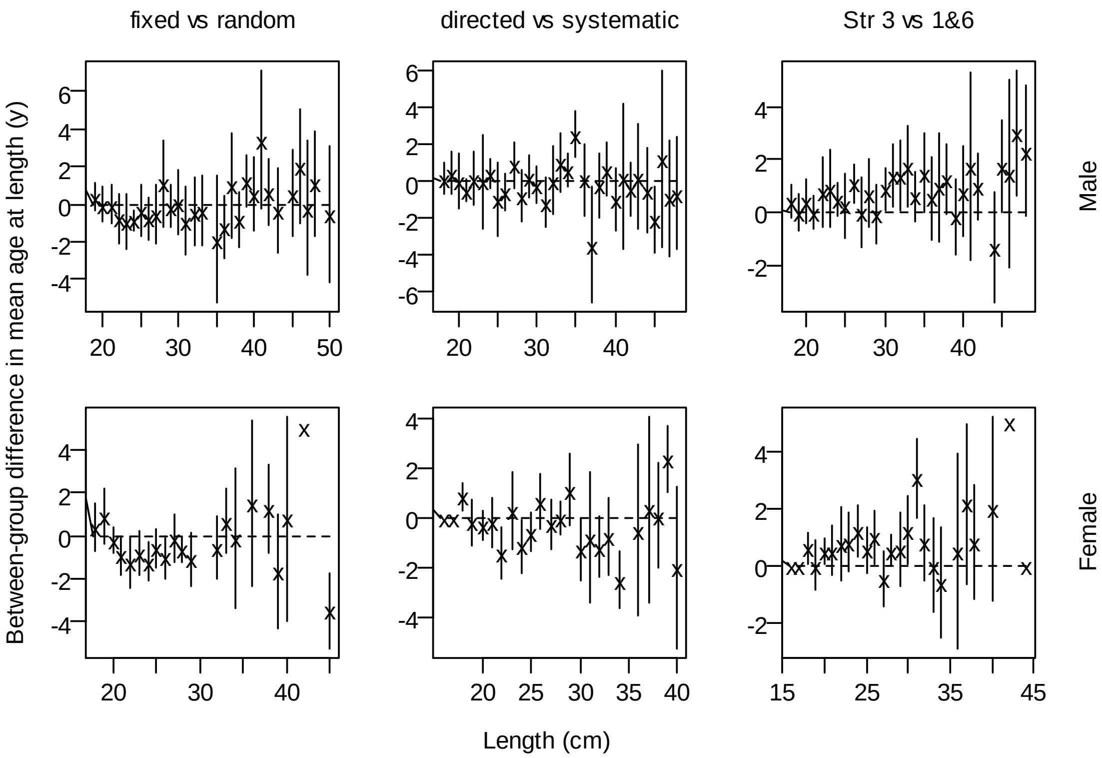


Figure 11: Differences in mean age at length ('x', with vertical lines indicating 95% confidence intervals), by sex between fixed vs random sites (left panels), directed vs systematic pot placement (middle panels), and stratum 3 vs strata 1 & 6 (right panels). Positive differences indicate that mean ages are higher in the second subset. No confidence interval is plotted when there is no variation in age at length in the samples in both strata.

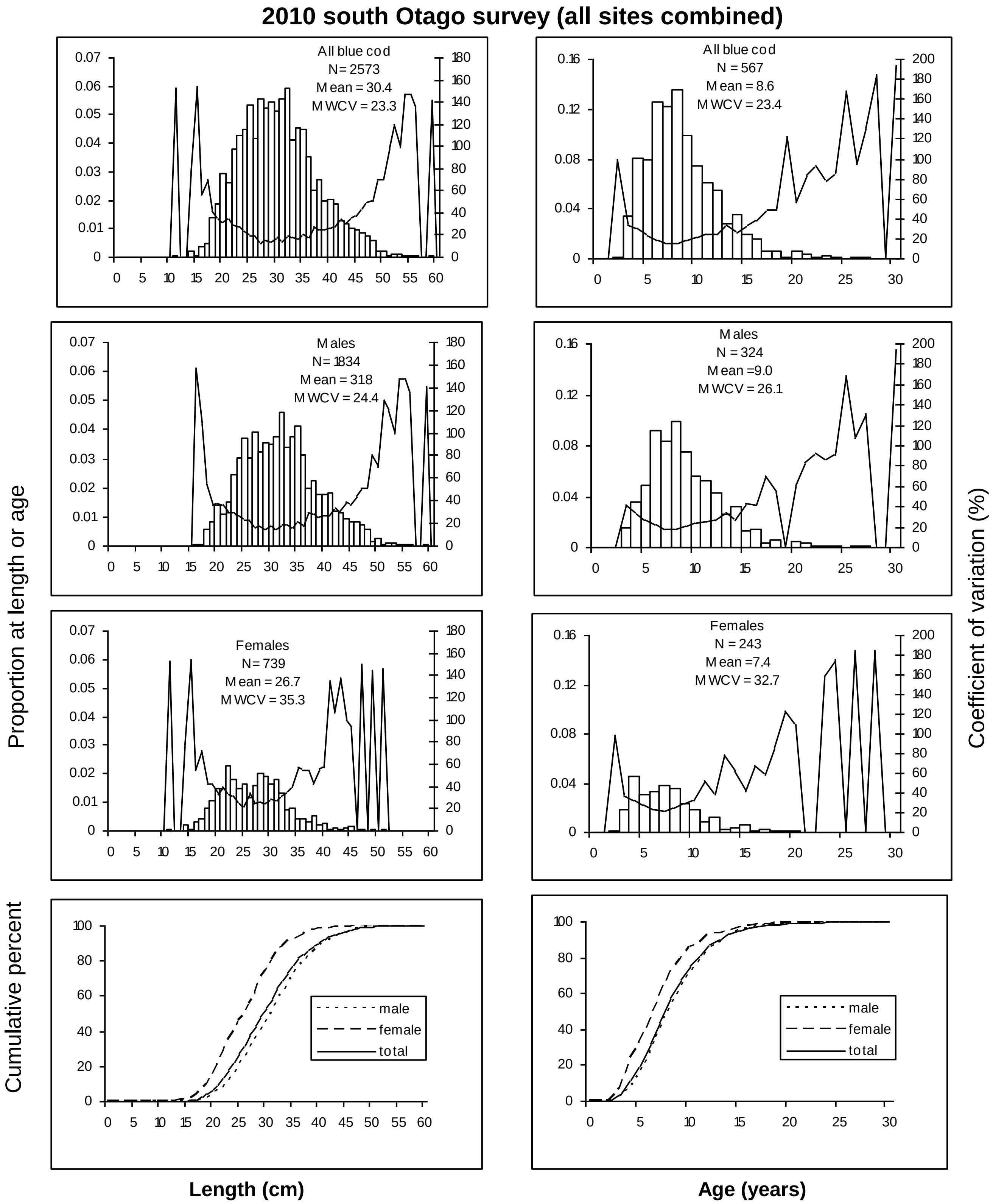


Figure 12: Scaled length frequency, age frequency, and cumulative distributions for total, male, and female blue cod for all strata (1–3) combined, all sites (random and fixed), and a single age-length-key (ALK) for the 2010 south Otago survey. N, sample size; MWCV, mean weighted coefficient of variation.

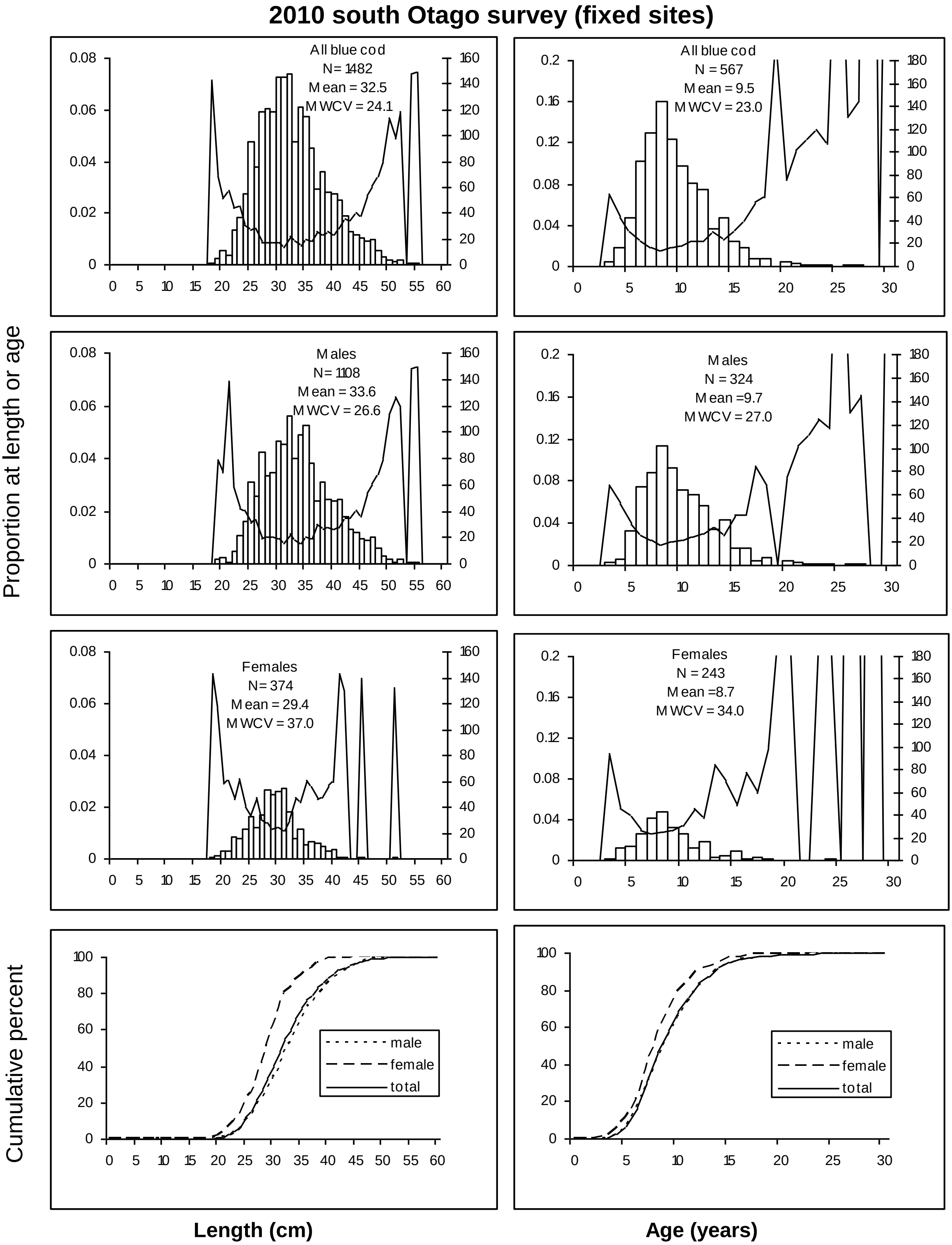


Figure 13: Scaled length frequency, age frequency, and cumulative distributions for total, male, and female blue cod for all strata (1–3) combined, for fixed sites using a single age-length-key (ALK) for the 2010 south Otago survey. N, sample size; MWCV, mean weighted coefficient of variation.

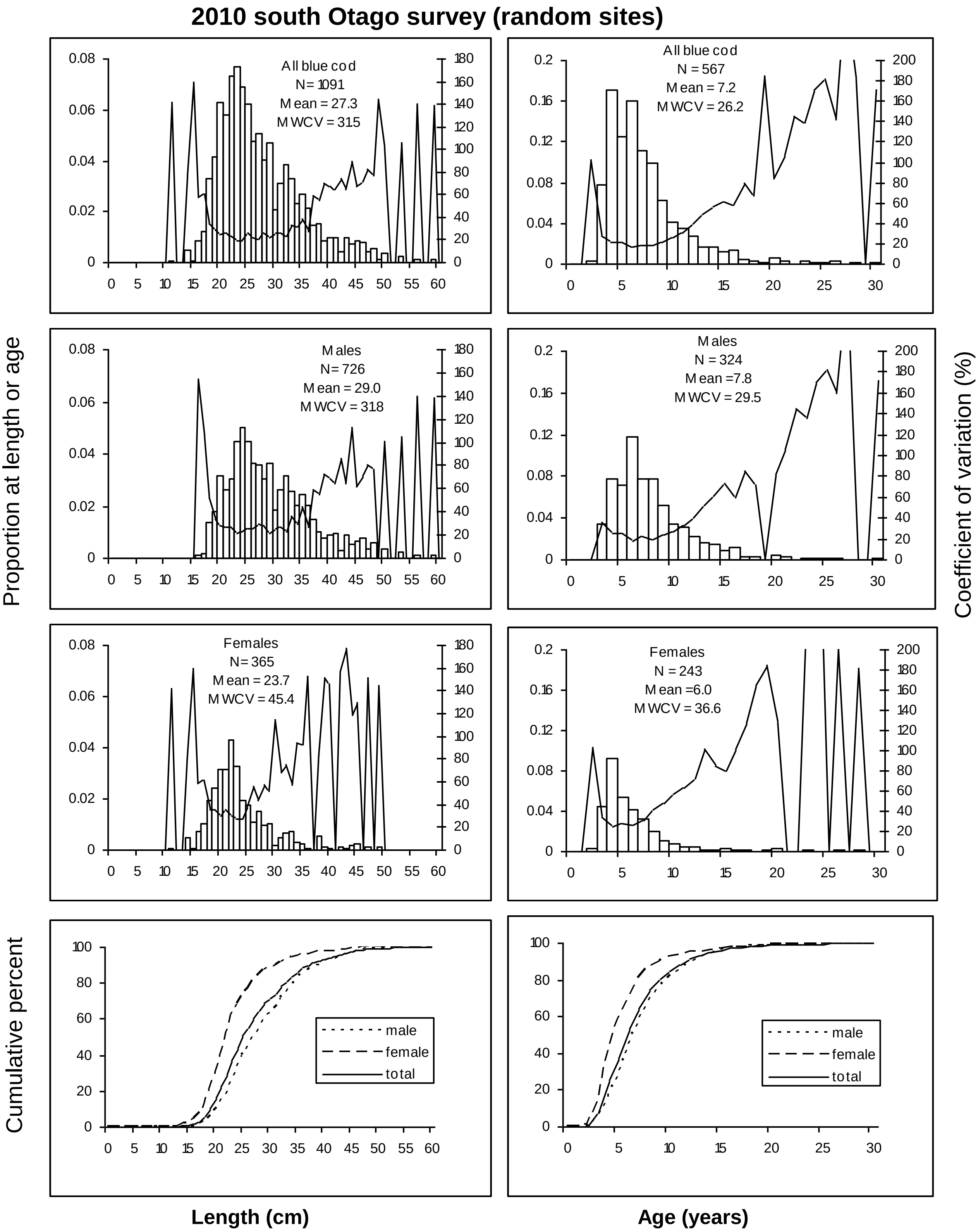


Figure 14: Scaled length frequency, age frequency, and cumulative distributions for total, male, and female blue cod for all strata (1–3) combined, for random sites using a single age-length-key (ALK) for the 2010 south Otago survey. N, sample size; MWCV, mean weighted coefficient of variation.

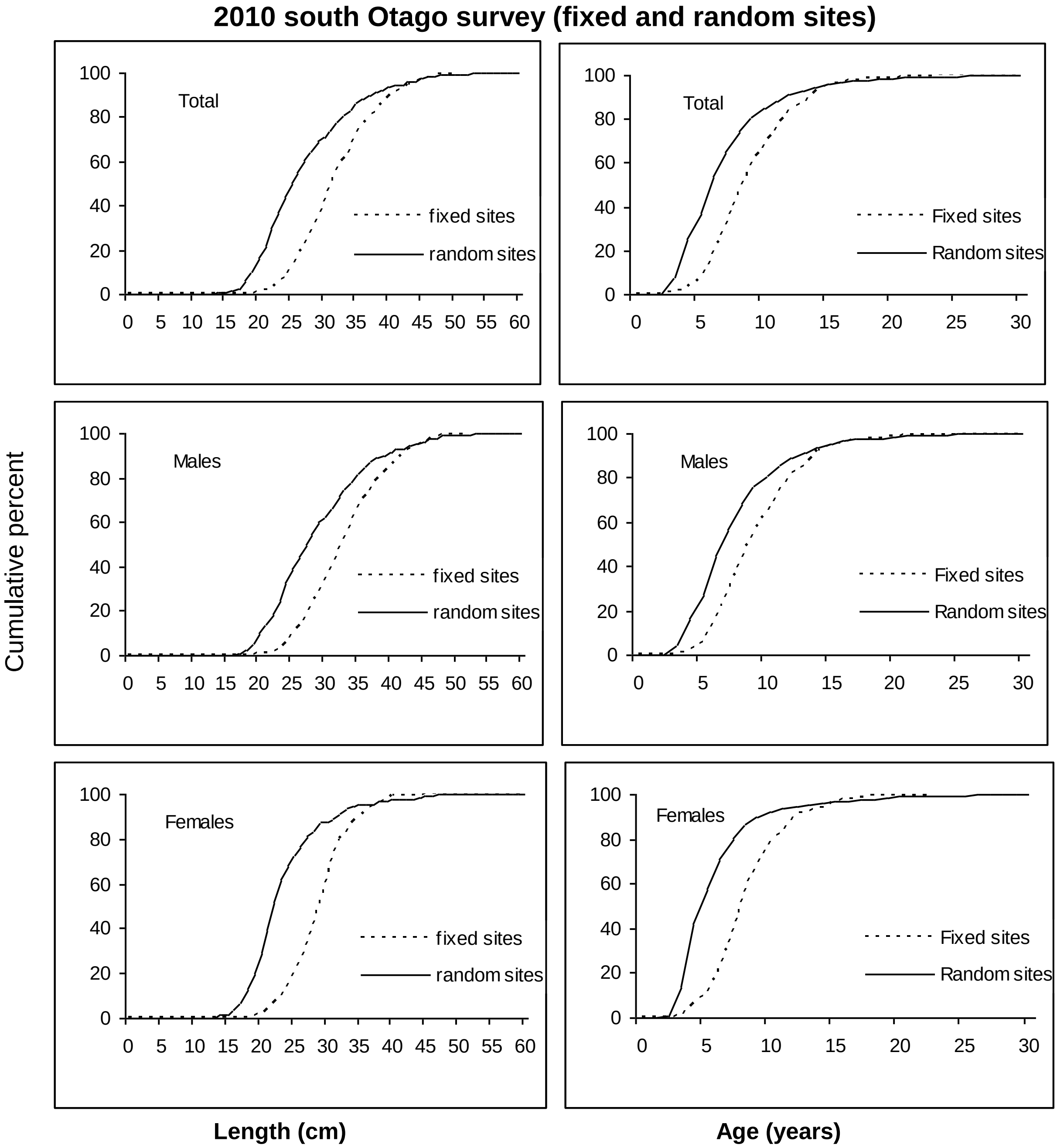


Figure 15: Cumulative distributions of scaled length and age frequencies for total, male, and female blue cod between fixed and random sites, using a single age-length-key (ALK) for the 2010 south Otago survey. These plots are also shown in Figures 13 and 14.

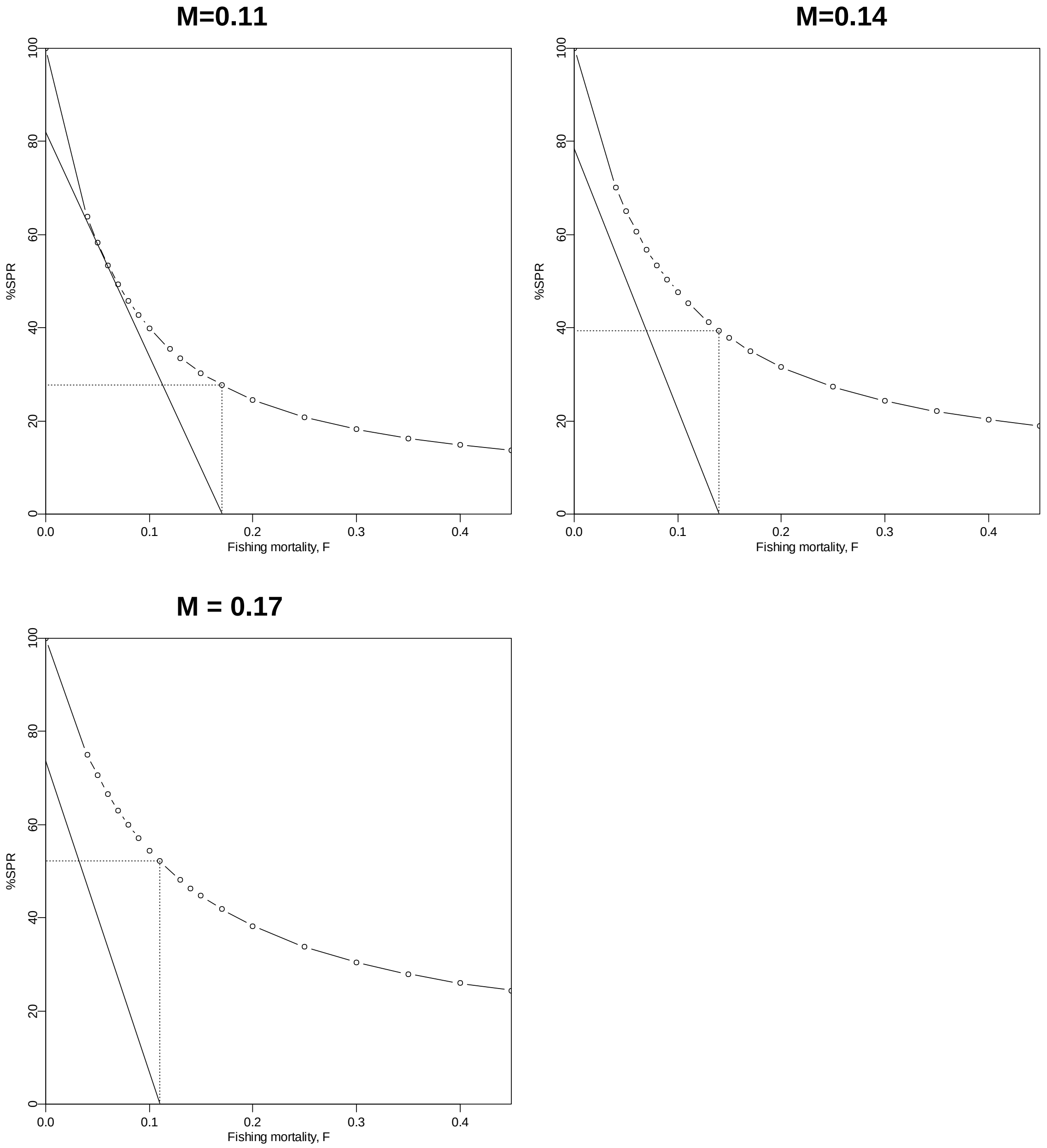


Figure 16: Plot of spawner per recruit (SPR) curves as a function of fishing mortality (F) for the 2010 south Otago random survey at three values of M (0.11, 0.14, and 0.17). The corresponding %SPR is shown on the curves for the random sites estimates of F. See Table 12 for fishing mortalities and $F_{SPR\%}$ values for all sites, fixed sites, and random sites.

Appendix 1: Methodology for estimating c.v.s for total mortality (*Z*) (Beentjes & Francis 2011).

For each age at recruitment, a_{rec}, a 95% confidence interval for the associated total mortality estimate, $\hat{Z}$, was calculated using the following simulation procedure, adapted from that of Dunn et al. (2002). This involves drawing a simple random sample of ages from the recruited part of each of 1000 simulated population in which there is annual variation in *Z* (described by a lognormal distribution with mean $\hat{Z}$ and c.v. c_Z = 0.10) and in recruitment (*R*) (where log recruitment is normally distributed with standard deviation σ_R = 0.7). In such a population, the relative frequency of fish at age a = 1,...,50 is given by

$$f_a = e^{-Z_a + R_a} \tag{14}$$

where Z_a is the cumulative mortality defined by

$$Z_1 = 0, \quad Z_a = \sum_{a'=2}^{a} \hat{Z} d_{a'} \tag{15}$$

the d_a are lognormally distributed with mean 1 and c.v. c_Z, and the R_a are normally distributed with mean 0 and s.d. σ_R.

With ageing errors assumed to be normally distributed with c.v. c_{age} = 0.15, the relative frequency of fish at *apparent* age *a* is given by

$$f'_a = \sum_{a'=1}^{50} f_{a'} E_{a'a} \tag{16}$$

where *E* is an ageing-error matrix, calculated by setting $E_{a'a} = \mathrm{F}(a+0.5, a', c_{\text{age}}) - \mathrm{F}(a-0.5, a', c_{\text{age}})$ [and F(x,μ,c) is the cumulative probability function for the normal distribution with mean μ and c.v. c] and then normalizing the rows of this matrix to sum to 1.

The size, *n*, of the sample of ages from the recruited population was calculated, as follows, to mimic the sampling error in the real data. The mean-weighted c.v. for the recruited part of the real data is calculated as

$$c_{\text{samp}} = \frac{\sum_{a \geq a_{rec}} f_{a,\text{obs}} c_{a,\text{obs}}}{\sum_{a \geq a_{rec}} f_{a,\text{obs}}} \tag{17}$$

where $f_{a,\text{obs}}$ is the age frequency from the real (unsimulated) data, and $c_{a,\text{obs}}$ is its c.v. The mean-weighted c.v. is used to calculate *n* as

$$n = \left(\frac{\sum_{a \geq a_{rec}} \sqrt{f''_a (1 - f''_a)}}{c_{\text{samp}}} \right)^2 \tag{18}$$

where, to maintain consistency in sample sizes across simulated populations, the proportions at age f''_a were calculated as for the f_a above, except that c_Z and σ_R were set to zero; then f''_a was set to 0 for $a < a_{\text{rec}}$, and the f''_a are normalised to sum to 1. Finally, a random sample of size *n* is selected from the AF f''_a; a maximum-likelihood estimate of *Z* and is calculated from this sample; the set of 1000 *Z* estimates is scaled to have mean $\hat{Z}$; and the bounds of the 95% confidence interval for $\hat{Z}$ are set to the

0.025 and 0.975 quantiles of the scaled Z estimates (the scaling is necessary because the maximum-likelihood estimate can be biased, particularly when there is ageing error).

Appendix 2: Summary of site and station data for the 2010 south Otago survey.

				(Pot lift)					Catch of blue cod	
Set	Date	Stratum	Site	Station number	Site type	Pot placement	Depth (m)	Time set	(kg)	Number
1	21-Apr-10	1	1A	11	Fixed	Systematic	8.8	09:10	0.000	0
1	21-Apr-10	1	1A	12	Fixed	Systematic	11.5	09:16	0.000	0
1	21-Apr-10	1	1A	13	Fixed	Systematic	10.1	09:23	0.000	0
1	21-Apr-10	1	1A	14	Fixed	Directed	8.4	09:27	0.000	0
1	21-Apr-10	1	1A	15	Fixed	Directed	11.9	09:38	0.000	0
1	21-Apr-10	1	1A	16	Fixed	Directed	23.6	09:45	0.000	0
2	21-Apr-10	1	1C	26	Fixed	Systematic	12.4	11:10	0.000	0
2	21-Apr-10	1	1C	25	Fixed	Systematic	11.5	11:15	0.000	0
2	21-Apr-10	1	1C	24	Fixed	Systematic	11.0	11:20	0.000	0
2	21-Apr-10	1	1C	23	Fixed	Directed	11.7	11:25	0.000	0
2	21-Apr-10	1	1C	22	Fixed	Directed	11.9	11:30	0.000	0
2	21-Apr-10	1	1C	21	Fixed	Directed	12.1	11:35	11.050	24
3	21-Apr-10	1	1B_R	31	Random	Systematic	5.1	13:05	0.000	0
3	21-Apr-10	1	1B_R	32	Random	Systematic	6.6	13:10	0.000	0
3	21-Apr-10	1	1B_R	33	Random	Systematic	4.4	13:15	0.000	0
3	21-Apr-10	1	1B_R	34	Random	Directed	3.3	13:20	0.000	0
3	21-Apr-10	1	1B_R	35	Random	Directed	5.9	13:25	0.000	0
3	21-Apr-10	1	1B_R	36	Random	Directed	4.9	13:30	0.000	0
4	22-Apr-10	1	1L	46	Fixed	Systematic	25.6	08:34	3.040	12
4	22-Apr-10	1	1L	45	Fixed	Systematic	11.9	08:39	1.920	5
4	22-Apr-10	1	1L	44	Fixed	Systematic	25.3	08:46	1.990	10
4	22-Apr-10	1	1L	43	Fixed	Directed	23.4	08:52	1.500	5
4	22-Apr-10	1	1L	42	Fixed	Directed	22.1	08:58	10.200	33
4	22-Apr-10	1	1L	41	Fixed	Directed	19.4	09:03	20.850	71
5	22-Apr-10	1	1K	51	Fixed	Systematic	19.0	10:20	2.860	5
5	22-Apr-10	1	1K	52	Fixed	Systematic	19.2	10:25	1.170	1
5	22-Apr-10	1	1K	53	Fixed	Systematic	15.9	10:30	20.300	25
5	22-Apr-10	1	1K	54	Fixed	Directed	22.9	10:35	0.000	0
5	22-Apr-10	1	1K	55	Fixed	Directed	15.7	10:40	22.000	33
5	22-Apr-10	1	1K	56	Fixed	Directed	23.2	10:45	0.000	0
6	22-Apr-10	1	1F_R	66	Random	Systematic	44.5	12:15	0.000	0
6	22-Apr-10	1	1F_R	65	Random	Systematic	46.1	12:20	0.830	8
6	22-Apr-10	1	1F_R	64	Random	Systematic	47.9	12:25	0.200	2
6	22-Apr-10	1	1F_R	63	Random	Directed	47.8	12:31	0.400	3
6	22-Apr-10	1	1F_R	62	Random	Directed	47.2	12:37	0.210	2
6	22-Apr-10	1	1F_R	61	Random	Directed	45.9	12:44	0.500	6
7	22-Apr-10	1	1J	71	Fixed	Systematic	8.6	14:12	11.800	39
7	22-Apr-10	1	1J	72	Fixed	Systematic	31.1	14:17	8.750	19
7	22-Apr-10	1	1J	73	Fixed	Systematic	52.2	14:22	19.950	48
7	22-Apr-10	1	1J	74	Fixed	Directed	35.0	14:27	8.570	26
7	22-Apr-10	1	1J	75	Fixed	Directed	34.2	14:32	28.990	74
7	22-Apr-10	1	1J	76	Fixed	Directed	31.5	14:38	5.400	14
8	23-Apr-10	1	1A_R	86	Random	Systematic	52.3	08:02	4.900	19
8	23-Apr-10	1	1A_R	85	Random	Systematic	50.9	08:09	9.100	26
8	23-Apr-10	1	1A_R	84	Random	Systematic	50.1	08:16	14.100	26
8	23-Apr-10	1	1A_R	83	Random	Directed	51.8	08:21	3.400	9
8	23-Apr-10	1	1A_R	82	Random	Directed	52.9	08:27	4.800	18

Set	Date	Stratum	Site	(Pot lift) Station number	Site type	Pot placement	Depth (m)	Time set	Catch of blue cod (kg)	Number
8	23-Apr-10	1	1A_R	81	Random	Directed	53.3	08:32	4.650	19
9	23-Apr-10	1	1D_R	91	Random	Systematic	44.8	09:49	0.150	1
9	23-Apr-10	1	1D_R	92	Random	Systematic	41.5	09:53	0.000	0
9	23-Apr-10	1	1D_R	93	Random	Systematic	40.8	09:58	0.000	0
9	23-Apr-10	1	1D_R	94	Random	Directed	40.8	10:03	0.000	0
9	23-Apr-10	1	1D_R	95	Random	Directed	41.2	10:08	0.000	0
9	23-Apr-10	1	1D_R	96	Random	Directed	44.5	10:13	0.000	0
10	23-Apr-10	1	1F	106	Fixed	Systematic	17.6	11:57	0.000	0
10	23-Apr-10	1	1F	105	Fixed	Systematic	17.4	12:02	0.000	0
10	23-Apr-10	1	1F	104	Fixed	Systematic	18.7	12:10	0.000	0
10	23-Apr-10	1	1F	103	Fixed	Directed	16.7	12:15	3.000	4
10	23-Apr-10	1	1F	102	Fixed	Directed	19.6	12:21	2.200	6
10	23-Apr-10	1	1F	101	Fixed	Directed	18.3	12:27	2.400	4
11	23-Apr-10	1	1E_R	111	Random	Systematic	17.4	14:00	0.000	0
11	23-Apr-10	1	1E_R	112	Random	Systematic	16.3	14:05	0.000	0
11	23-Apr-10	1	1E_R	113	Random	Systematic	15.4	14:10	0.000	0
11	23-Apr-10	1	1E_R	114	Random	Directed	15.4	14:15	0.000	0
11	23-Apr-10	1	1E_R	115	Random	Directed	16.3	14:20	0.000	0
11	23-Apr-10	1	1E_R	116	Random	Directed	17.0	14:25	0.000	0
12	23-Apr-10	1	1C_R	126	Random	Systematic	22.7	15:39	0.000	0
12	23-Apr-10	1	1C_R	125	Random	Systematic	21.6	15:44	0.000	0
12	23-Apr-10	1	1C_R	124	Random	Systematic	21.4	15:49	0.000	0
12	23-Apr-10	1	1C_R	123	Random	Directed	20.9	15:55	0.000	0
12	23-Apr-10	1	1C_R	122	Random	Directed	21.8	16:00	0.000	0
12	23-Apr-10	1	1C_R	121	Random	Directed	21.8	16:05	0.000	0
13	9-May-10	6	6C_R	131	Random	Systematic	60.4	09:50	2.174	1
13	9-May-10	6	6C_R	132	Random	Systematic	58.6	09:55	25.240	13
13	9-May-10	6	6C_R	133	Random	Systematic	62.2	09:58	0.190	1
13	9-May-10	6	6C_R	134	Random	Directed	60.4	10:03	17.760	19
13	9-May-10	6	6C_R	135	Random	Directed	65.9	10:05	7.100	6
13	9-May-10	6	6C_R	136	Random	Directed	64.1	10:10	3.180	5
14	10-May-10	6	6B	146	Fixed	Systematic	47.6	11:00	6.780	13
14	10-May-10	6	6B	145	Fixed	Systematic	47.6	11:05	9.150	12
14	10-May-10	6	6B	144	Fixed	Systematic	49.4	11:08	19.510	39
14	10-May-10	6	6B	143	Fixed	Directed	53.1	11:12	9.340	16
14	10-May-10	6	6B	142	Fixed	Directed	47.6	11:15	10.700	25
14	10-May-10	6	6B	141	Fixed	Directed	47.6	11:19	15.900	29
15	11-May-10	6	6G_R	151	Random	Systematic	69.5	11:50	0.000	0
15	11-May-10	6	6G_R	152	Random	Systematic	69.5	11:55	2.022	9
15	11-May-10	6	6G_R	153	Random	Systematic	71.4	12:00	4.320	4
15	11-May-10	6	6G_R	154	Random	Directed	71.4	12:04	4.870	5
15	11-May-10	6	6G_R	155	Random	Directed	71.4	12:07	0.000	0
15	11-May-10	6	6G_R	156	Random	Directed	71.4	12:13	0.000	0
16	17-May-10	6	6A_R	161	Random	Systematic	54.9	09:31	13.520	18
16	17-May-10	6	6A_R	162	Random	Systematic	59.8	09:37	0.440	2
16	17-May-10	6	6A_R	163	Random	Systematic	59.5	09:42	14.300	13
16	17-May-10	6	6A_R	164	Random	Directed	57.3	09:53	15.990	16
16	17-May-10	6	6A_R	165	Random	Directed	58.6	10:02	5.800	5
16	17-May-10	6	6A_R	166	Random	Directed	59.5	10:07	10.900	15

Set	Date	Stratum	Site	(Pot lift) Station number	Site type	Pot placement	Depth (m)	Time set	Catch of blue cod (kg)	Number
17	18-May-10	6	6D_R	176	Random	Systematic	64.1	11:36	14.400	10
17	18-May-10	6	6D_R	175	Random	Systematic	65.9	11:43	0.000	0
17	18-May-10	6	6D_R	174	Random	Systematic	67.0	11:52	0.850	2
17	18-May-10	6	6D_R	173	Random	Directed	64.1	11:59	0.420	2
17	18-May-10	6	6D_R	172	Random	Directed	64.1	12:06	1.400	2
17	18-May-10	6	6D_R	171	Random	Directed	63.7	12:15	6.100	8
18	18-May-10	6	6B_R	181	Random	Systematic	67.2	13:30	4.700	9
18	18-May-10	6	6B_R	182	Random	Systematic	69.5	13:37	1.920	10
18	18-May-10	6	6B_R	183	Random	Systematic	65.9	13:44	2.260	5
18	18-May-10	6	6B_R	184	Random	Directed	65.9	13:52	4.930	6
18	18-May-10	6	6B_R	185	Random	Directed	67.2	17:57	4.340	4
18	18-May-10	6	6B_R	186	Random	Directed	69.2	18:05	1.065	10
19	19-May-10	6	6H	191	Fixed	Systematic	61.5	10:17	11.800	15
19	19-May-10	6	6H	192	Fixed	Systematic	58.6	10:26	1.660	2
19	19-May-10	6	6H	193	Fixed	Systematic	65.9	10:34	8.960	11
19	19-May-10	6	6H	194	Fixed	Directed	62.2	10:40	12.400	17
19	19-May-10	6	6H	195	Fixed	Directed	61.3	10:50	2.900	4
19	19-May-10	6	6H	196	Fixed	Directed	64.1	10:59	6.550	10
20	19-May-10	6	6F_R	203	Random	Systematic	75.0	12:46	0.000	0
20	19-May-10	6	6F_R	202	Random	Systematic	76.9	12:51	9.850	33
20	19-May-10	6	6F_R	201	Random	Systematic	76.9	12:57	9.720	40
20	19-May-10	6	6F_R	206	Random	Directed	75.0	12:25	13.000	43
20	19-May-10	6	6F_R	205	Random	Directed	75.0	12:35	13.000	37
20	19-May-10	6	6F_R	204	Random	Directed	75.0	12:40	0.960	8
21	20-May-10	6	6A	211	Fixed	Systematic	54.9	08:41	19.200	35
21	20-May-10	6	6A	212	Fixed	Systematic	51.2	08:50	0.000	0
21	20-May-10	6	6A	213	Fixed	Systematic	47.6	09:00	17.400	26
21	20-May-10	6	6A	214	Fixed	Directed	53.1	09:07	13.700	29
21	20-May-10	6	6A	215	Fixed	Directed	51.2	09:15	25.800	45
21	20-May-10	6	6A	216	Fixed	Directed	47.6	09:22	22.000	28
22	20-May-10	6	6C	226	Fixed	Systematic	64.1	11:07	37.400	22
22	20-May-10	6	6C	225	Fixed	Systematic	65.9	11:15	11.200	9
22	20-May-10	6	6C	224	Fixed	Systematic	64.1	11:22	14.200	11
22	20-May-10	6	6C	223	Fixed	Directed	64.1	11:30	33.800	37
22	20-May-10	6	6C	222	Fixed	Directed	65.9	11:38	5.800	6
22	20-May-10	6	6C	221	Fixed	Directed	64.1	11:47	45.700	55
23	20-May-10	6	6G	231	Fixed	Systematic	58.6	13:22	9.400	14
23	20-May-10	6	6G	232	Fixed	Systematic	58.6	13:31	48.300	82
23	20-May-10	6	6G	233	Fixed	Systematic	67.7	13:38	35.100	44
23	20-May-10	6	6G	235	Fixed	Directed	64.1	13:41	24.000	44
23	20-May-10	6	6G	234	Fixed	Directed	54.9	13:45	32.000	50
23	20-May-10	6	6G	236	Fixed	Directed	54.9	13:56	29.500	41
24	23-May-10	6	6E	246	Fixed	Systematic	51.2	09:09	17.700	24
24	23-May-10	6	6E	245	Fixed	Systematic	51.2	09:14	9.100	19
24	23-May-10	6	6E	244	Fixed	Systematic	45.8	09:19	17.000	28
24	23-May-10	6	6E	243	Fixed	Directed	49.4	09:24	12.600	14
24	23-May-10	6	6E	242	Fixed	Directed	49.4	09:29	10.400	19
24	23-May-10	6	6E	241	Fixed	Directed	49.4	09:36	0.710	1
25	2-Jun-10	3	3S	251	Fixed	Systematic	122.6	09:15	4.050	6

Set	Date	Stratum	Site	(Pot lift) Station number	Site type	Pot placement	Depth (m)	Time set	Catch of blue cod (kg)	Number
25	2-Jun-10	3	3S	253	Fixed	Systematic	124.4	09:26	0.000	0
25	2-Jun-10	3	3S	252	Fixed	Systematic	124.4	09:36	6.600	8
25	2-Jun-10	3	3S	254	Fixed	Directed	122.6	09:46	0.000	0
25	2-Jun-10	3	3S	255	Fixed	Directed	122.6	10:01	0.000	0
25	2-Jun-10	3	3S	256	Fixed	Directed	122.6	10:09	0.000	0
26	2-Jun-10	3	3W	266	Fixed	Systematic	111.6	11:38	0.000	0
26	2-Jun-10	3	3W	265	Fixed	Systematic	111.6	11:44	3.600	6
26	2-Jun-10	3	3W	264	Fixed	Systematic	111.6	11:49	14.000	14
26	2-Jun-10	3	3W	262	Fixed	Directed	113.5	11:54	5.900	9
26	2-Jun-10	3	3W	263	Fixed	Directed	115.3	11:59	3.000	6
26	2-Jun-10	3	3W	261	Fixed	Directed	117.1	12:04	0.000	0
27	2-Jun-10	3	3I	271	Fixed	Systematic	115.3	13:35	1.700	2
27	2-Jun-10	3	3I	273	Fixed	Systematic	117.1	13:41	0.900	2
27	2-Jun-10	3	3I	272	Fixed	Systematic	117.1	13:47	5.400	6
27	2-Jun-10	3	3I	274	Fixed	Directed	119.0	13:53	0.000	0
27	2-Jun-10	3	3I	275	Fixed	Directed	117.1	13:57	26.800	29
27	2-Jun-10	3	3I	276	Fixed	Directed	117.1	14:03	12.000	12
28	3-Jun-10	3	3I_R	283	Random	Systematic	115.3	12:10	0.000	0
28	3-Jun-10	3	3I_R	285	Random	Systematic	113.5	12:20	3.930	8
28	3-Jun-10	3	3I_R	284	Random	Systematic	113.5	12:25	19.870	23
28	3-Jun-10	3	3I_R	286	Random	Directed	113.5	12:30	1.000	1
28	3-Jun-10	3	3I_R	281	Random	Directed	113.5	12:35	0.214	1
28	3-Jun-10	3	3I_R	282	Random	Directed	113.5	12:40	0.508	1
29	3-Jun-10	3	3E	292	Fixed	Systematic	108.0	13:57	6.885	10
29	3-Jun-10	3	3E	291	Fixed	Systematic	106.1	14:02	0.000	0
29	3-Jun-10	3	3E	296	Fixed	Systematic	108.0	14:07	0.000	0
29	3-Jun-10	3	3E	294	Fixed	Directed	113.5	14:12	0.000	0
29	3-Jun-10	3	3E	295	Fixed	Directed	111.6	14:18	4.435	11
29	3-Jun-10	3	3E	293	Fixed	Directed	109.8	14:24	0.000	0
30	4-Jun-10	3	3G	303	Fixed	Systematic	113.5	07:59	18.200	20
30	4-Jun-10	3	3G	305	Fixed	Systematic	115.3	08:19	3.148	2
30	4-Jun-10	3	3G	304	Fixed	Systematic	113.5	08:24	0.000	0
30	4-Jun-10	3	3G	306	Fixed	Directed	113.5	08:29	0.000	0
30	4-Jun-10	3	3G	301	Fixed	Directed	111.6	08:34	0.000	0
30	4-Jun-10	3	3G	302	Fixed	Directed	108.0	08:40	0.000	0
31	4-Jun-10	3	3B	312	Fixed	Systematic	113.5	09:53	2.795	5
31	4-Jun-10	3	3B	311	Fixed	Systematic	113.5	09:58	0.000	0
31	4-Jun-10	3	3B	316	Fixed	Systematic	111.6	10:03	0.000	0
31	4-Jun-10	3	3B	314	Fixed	Directed	111.6	10:08	0.000	0
31	4-Jun-10	3	3B	315	Fixed	Directed	111.6	10:13	0.000	0
31	4-Jun-10	3	3B	313	Fixed	Directed	111.6	10:18	0.000	0
32	4-Jun-10	3	3K_R	323	Random	Systematic	109.8	11:30	0.000	0
32	4-Jun-10	3	3K_R	325	Random	Systematic	109.8	11:35	0.000	0
32	4-Jun-10	3	3K_R	324	Random	Systematic	109.8	11:40	0.000	0
32	4-Jun-10	3	3K_R	326	Random	Directed	109.8	11:45	0.000	0
32	4-Jun-10	3	3K_R	321	Random	Directed	111.6	11:50	0.000	0
32	4-Jun-10	3	3K_R	322	Random	Directed	113.5	11:55	0.000	0
33	4-Jun-10	3	3M_R	332	Random	Systematic	117.1	12:54	2.615	7
33	4-Jun-10	3	3M_R	331	Random	Systematic	117.1	12:59	11.025	21

Set	Date	Stratum	Site	(Pot lift) Station number	Site type	Pot placement	Depth (m)	Time set	Catch of blue cod (kg)	Number
33	4-Jun-10	3	3M_R	336	Random	Systematic	115.3	13:06	2.480	8
33	4-Jun-10	3	3M_R	334	Random	Directed	115.3	13:12	1.490	3
33	4-Jun-10	3	3M_R	335	Random	Directed	117.1	13:19	2.630	8
33	4-Jun-10	3	3M_R	333	Random	Directed	111.6	13:24	0.000	0
34	4-Jun-10	3	3L_R	344	Random	Systematic	95.2	12:16	1.250	5
34	4-Jun-10	3	3L_R	343	Random	Systematic	93.3	15:07	2.136	8
34	4-Jun-10	3	3L_R	345	Random	Systematic	93.3	15:12	17.315	65
34	4-Jun-10	3	3L_R	346	Random	Directed	93.3	12:20	1.026	6
34	4-Jun-10	3	3L_R	341	Random	Directed	93.3	15:24	3.100	21
34	4-Jun-10	3	3L_R	342	Random	Directed	93.3	15:28	6.625	30
35	5-Jun-10	3	3D_R	352	Random	Systematic	85.1	07:47	6.790	23
35	5-Jun-10	3	3D_R	351	Random	Systematic	86.0	07:52	6.645	25
35	5-Jun-10	3	3D_R	356	Random	Systematic	86.0	07:58	5.800	20
35	5-Jun-10	3	3D_R	354	Random	Directed	84.2	08:02	7.815	24
35	5-Jun-10	3	3D_R	355	Random	Directed	84.2	08:07	4.125	13
35	5-Jun-10	3	3D_R	353	Random	Directed	84.2	08:12	14.036	42
36	5-Jun-10	3	3G_R	363	Random	Systematic	87.8	09:54	12.035	52
36	5-Jun-10	3	3G_R	365	Random	Systematic	87.8	09:59	3.725	22
36	5-Jun-10	3	3G_R	364	Random	Systematic	86.0	10:05	7.615	29
36	5-Jun-10	3	3G_R	366	Random	Directed	87.8	10:10	5.945	35
36	5-Jun-10	3	3G_R	361	Random	Directed	89.7	10:15	10.855	46
36	5-Jun-10	3	3G_R	362	Random	Directed	89.7	10:20	11.568	44

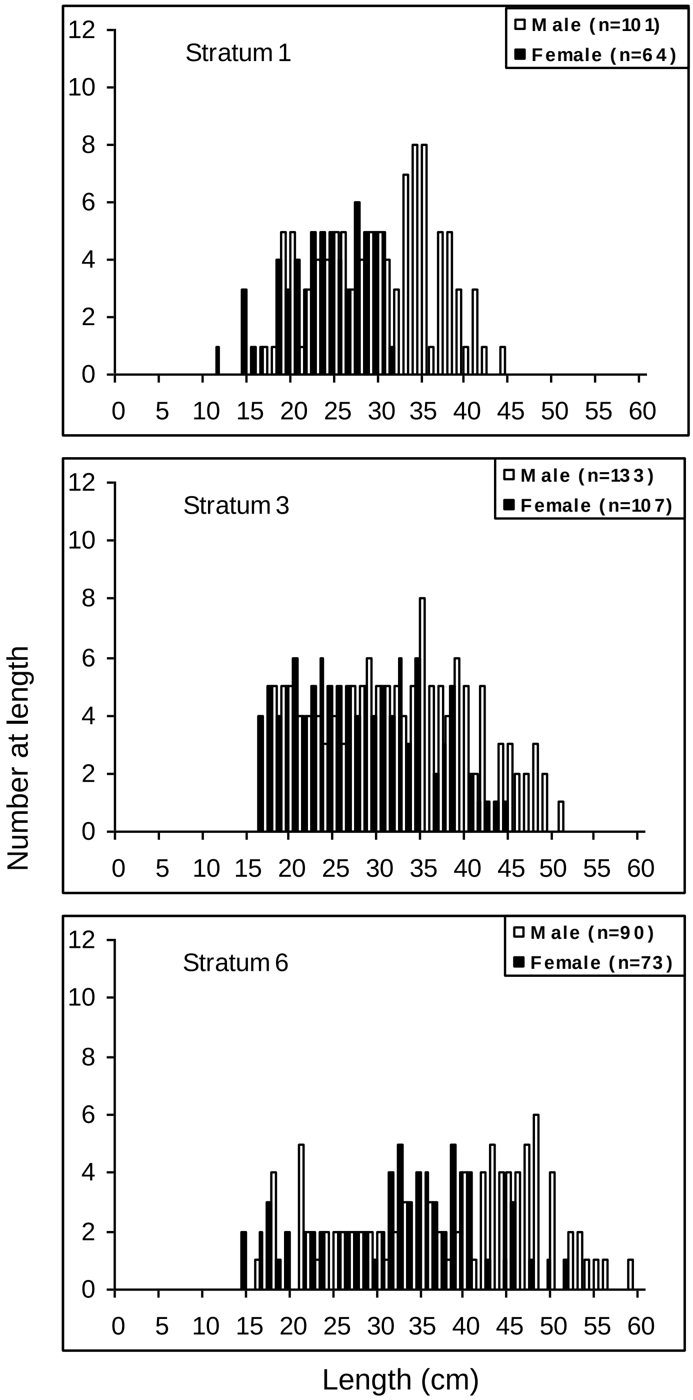
Appendix 3: Summary of the Otago 2010 survey oceanographic environmental station data. Depths are measured in meters, wind direction in compass degrees (999 = nil), wind force in the Beaufort scale, temperatures in degrees centigrade, air pressure in millibars, cloud cover in oktas, sea condition in the Douglas scale, sea colour in a categorical scale from 1 (deep blue) to 8 (yellow green), swell height in the Douglas classification 1 (low) to 3 (heavy), bottom type in a categorical scale from 1 (mud or ooze) to 12 (sponge beds), bottom contour in a categorical scale from 1 (smooth/flat) to 5 (very rugged), and wind speed in metres per second.

Set	Average Depth	Wind Direction	Wind Force	Air Temp	Air Pressure	Cloud Cover	Sea Condition	Sea Colour	Swell Height	Swell Direction	Bottom Type	Bottom Contour	Surface Temp	Bottom Temp	Wind Speed	Secchi Depth
1	12	999	0	17.0	1020	3	1	7	0.5	135	3	2	12.8	12.7	0.0	4.5
2	12	999	0	18.0	1021	5	1	7	0.5	135	3	1	12.8	12.7	0.0	4.6
3	5	999	0	18.1	1013	5	1	7	0.5	090	3	3	13.0	13.1	0.0	4.8
4	21	270	2	15.8	1011	6	4	8	3.0	135	7	3	12.9	12.9	10.0	3.6
5	19	225	1	14.9	1011	7	3	8	2.0	090	4	2	12.9	12.9	6.4	2.5
6	47	180	3	15.8	1012	8	3	8	2.0	135	3	1	12.8	12.7	18.2	4.5
7	32	180	1	14.7	1012	8	3	8	3.0	135	12	4	12.8	12.7	2.8	2.8
8	52	270	1	13.4	1007	6	3	7	2.0	090	4	1	12.9	12.8	4.7	4.5
9	42	999	0	16.0	1005	5	3	7	1.5	090	4	1	12.9	12.8	0.0	4.8
10	18	180	4	15.3	1007	3	3	7	0.5	090	3	4	12.9	12.8	28.7	4.8
11	16	225	4	15.9	1005	6	3	6	0.5	090	3	1	12.9	12.8	28.1	4.0
12	22	225	4	15.0	1005	8	4	6	0.5	090	3	1	12.9	12.8	29.0	4.9
13	62	315	1	13.3	1013	4	3	2	1.0	135	6	2	12.1	12.0	7.0	5.3
14	49	270	2	13.6	1016	6	1	8	0.5	045	6	2	12.1	12.0	7.4	5.9
15	71	135	2	13.6	1019	1	3	8	2.0	045	4	1	12.1	12.0	9.4	5.0
16	58	180	2	13.0	1011	3	1	5	0.5	180	6	2	12.1	12.0	8.4	8.0
17	65	180	2	13.1	1010	3	1	5	0.5	180	4	1	12.1	12.1	8.9	8.1
18	67	180	1	14.0	1010	4	1	5	0.8	180	3	1	12.1	12.1	6.9	7.9
19	62	225	3	12.0	1017	4	3	7	1.5	180	7	3	12.1	12.1	16.8	8.0
20	76	225	3	13.0	1017	4	3	7	1.5	180	7	3	12.1	12.1	15.2	8.0
21	51	270	2	12.0	1019	2	1	2	0.8	135	12	2	12.1	12.1	11.2	6.6
22	65	270	3	14.1	1018	2	1	2	0.8	135	12	2	12.1	12.1	16.4	6.5
23	60	270	3	14.8	1017	3	1	2	0.8	135	7	4	12.1	12.1	16.4	6.8
24	49	248	3	10.7	1018	6	3	5	0.5	180	7	3	12.8	13.0	15.7	8.4
25	123	045	4	12.5	1016	4	3	6	1.5	090	6	1	12.0	12.0	28.5	7.5

Appendix 3– *continued*.

Set	Average Depth	Wind Direction	Wind Force	Air Temp	Air Pressure	Cloud Cover	Sea Condition	Sea Colour	Swell Height	Swell Direction	Bottom Type	Bottom Contour	Surface Temp	Bottom Temp	Wind Speed	Secchi Depth
26	113	045	3	11.3	1017	1	3	6	1.5	090	6	1	12.0	12.0	17.6	7.5
27	117	090	3	12.6	1016	2	3	6	1.5	090	6	1	12.0	12.0	16.1	7.3
28	114	270	1	12.0	1022	2	4	6	1.0	225	4	1	12.0	12.0	7.1	8.0
29	109	270	1	12.5	1021	2	3	6	1.0	225	6	1	12.0	12.0	7.0	7.9
30	112	225	0	8.6	1024	5	4	6	2.0	225	6	2	12.0	12.0	0.2	7.8
31	112	225	2	10.2	1023	6	4	6	2.5	225	6	1	12.1	12.0	12.0	7.8
32	111	225	3	10.9	1023	1	4	6	3.0	225	6	1	12.0	12.0	21.3	7.9
33	116	225	2	11.4	1023	1	4	6	2.0	225	6	1	12.0	12.0	10.3	8.3
34	94	225	1	12.0	1022	1	4	6	3.0	225	6	1	12.0	12.0	2.7	15.3
35	85	000	2	7.3	1018	5	3	7	1.5	225	6	2	12.0	12.0	9.6	3.5
36	88	225	3	8.8	1017	6	3	7	1.5	225	6	1	11.9	11.5	18.1	9.5

Appendix 4: Unscaled length frequency distributions of blue cod for each stratum from which otoliths were used in the age length key. N= 324 males 244 females.



Appendix 5: Between-reader comparisons (using first independent readings only) for age estimate from otoliths collected in south Otago 2010.

Reader two difference	Age class (reader one) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	>19	Total
-10																				1	1
-9																				4	4
-8																				2	2
-7																				5	5
-6																				5	5
-5																			1	5	6
-4													1		2	2	4	2	1	3	15
-3											2	3	1	2		1	1		1	3	14
-2				2	2		2		4	7	3	8	5	5	8	1	2	2	1	4	56
-1		1	14	19	6	5	9	16	8	11	5	10	3	8	5	2				1	123
0		2	28	35	23	39	34	31	23	16	10	9	5	8	3	6	1				273
1			2	2	8	4	7	6	7	3	7	4	1	2							53
2				1	3	2				1	1	1	1	1							11
Total		3	44	59	42	50	52	53	42	38	28	35	17	26	18	12	8	4	4	33	568
% agreement		67	64	59	55	78	65	58	55	42	36	26	29	31	17	50	13	0	0	0	48

Appendix 6: Independent reader comparisons with agreed age from age estimate from otoliths collected in south Otago 2010.

Reader one difference	Agreed age class 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	>19	Total
-3															1			1			2
-2															1						1
-1						1	1				2	2	1	1							8
0		3	44	59	38	49	50	52	40	35	25	30	13	24	15	11	7	2	2	11	510
1				2		2	1	2	1		3	2	2	2		1	1	2		5	26
2			1						1					1		1		1		5	10
3																		1		5	6
4																		1		3	4
5																					0
6																				1	1
Total		3	45	61	38	52	52	54	42	35	30	34	16	28	17	13	8	8	2	30	568
% agreement		100	98	97	100	94	96	96	95	100	83	88	81	86	88	85	88	25	100	37	90

Reader two difference	Agreed age class 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	>19	Total
-6																		1		6	7
-5																		1		7	8
-4													1		4	1	3	2	1	4	16
-3											2	3	1	2		2	1		1	4	16
-2				2	1				2	5	3	8	2	4	6	2	2	3		7	47
-1		1	14	20	4	7	9	17	10	11	5	9	5	9	4	2	1	1		2	131
0		2	28	36	23	39	35	31	23	16	12	9	5	9	3	6	1				278
1			3	2	8	5	8	6	7	3	8	5	2	3							60
2				1	2	1								1							5
Total		3	45	61	38	52	52	54	42	35	30	34	16	28	17	13	8	8	2	30	568
% agreement		67	62	59	61	75	67	57	55	46	40	26	31	32	18	46	13	0	0	0	49

Appendix 7: Estimates of proportion of length at age for male blue cod sampled from the south Otago 2010 survey (age length key, ALK).

	Age																												Total
Lgth (cm)	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	
16	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
18	0.6	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
19	0.4	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
20	0.2	0.6	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
21	0.1	0.8	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
22	0.11	0.33	0.33	0.22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
23	0.11	0.22	0.22	0.44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
24	0	0	0.33	0.67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
25	0	0	0.36	0.45	0.09	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
26	0	0	0	0.2	0.5	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
27	0	0	0.2	0.3	0.4	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
28	0	0	0.09	0.18	0.45	0.18	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
29	0	0	0	0.15	0.38	0.31	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
30	0	0	0	0	0.33	0.42	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
31	0	0	0	0.2	0.2	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
32	0	0	0	0.1	0	0.6	0.2	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
33	0	0	0	0	0.07	0.14	0.36	0.21	0.14	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
34	0	0	0	0	0	0.08	0.23	0.54	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
35	0	0	0	0	0	0.06	0.25	0.19	0	0.38	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16
36	0	0	0	0	0	0	0.22	0.33	0.22	0.22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
37	0	0	0	0	0	0.08	0	0.25	0.42	0	0.08	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
38	0	0	0	0	0	0	0	0.2	0.3	0.4	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
39	0	0	0	0	0	0	0	0	0.36	0.36	0.09	0.18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
40	0	0	0	0	0	0	0	0.1	0.1	0.2	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
41	0	0	0	0	0	0	0	0	0.33	0	0.33	0	0.17	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
42	0	0	0	0	0	0	0	0	0.1	0.1	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
43	0	0	0	0	0	0	0	0	0	0	0.2	0	0.6	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
44	0	0	0	0	0	0	0	0	0	0	0.12	0.62	0.12	0	0	0.12	0	0	0	0	0	0	0	0	0	0	0	0	8
45	0	0	0	0	0	0	0	0	0	0	0.14	0.29	0.14	0.29	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	7
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0.67	0.17	0	0	0	0.17	0	0	0	0	0	0	0	0	0	6
47	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0	0.14	0.43	0	0.14	0.14	0	0	0	0	0	0	0	0	0	7
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0.22	0	0.22	0	0.44	0	0.11	0	0	0	0	0	0	0	0	9
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0.5	0	0	0	0	2
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.25	0	0.5	0	0	0	0	0	0	0	4
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	2
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0.5	0	0	0	0	2
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Total	16	30	18	29	27	30	25	22	23	19	13	23	7	10	3	6	0	6	3	2	3	3	1	2	2	0	0	1	324

Appendix 8: Estimates of proportion of length at age for female blue cod sampled from the south Otago 2010 survey (age length key, ALK).

	Age																											
Lgth (cm)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Total
11	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0.4	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
15	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
16	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
18	0	0.67	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
19	0	0.3	0.6	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
20	0	0	0.8	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
21	0	0	0.33	0.56	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
22	0	0	0.58	0.08	0.25	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
23	0	0.08	0.33	0.33	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
24	0	0	0	0.5	0.2	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
25	0	0	0	0.18	0.55	0.27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
26	0	0	0	0	0.4	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
27	0	0	0	0	0.08	0.5	0.33	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
28	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
29	0	0	0	0	0	0.3	0.4	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
30	0	0	0	0	0.08	0	0.17	0.42	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
31	0	0	0	0	0.11	0	0.22	0.11	0.22	0.22	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
32	0	0	0	0	0	0	0.18	0.45	0.27	0	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
33	0	0	0	0	0	0	0	0.33	0.33	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
34	0	0	0	0	0	0	0.1	0.1	0	0.2	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
35	0	0	0	0	0	0	0	0	0	0	0	0.25	0.25	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	4
36	0	0	0	0	0	0	0	0	0	0.2	0.4	0	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	5
37	0	0	0	0	0	0	0	0	0.2	0	0.6	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	5
38	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.2	0.2	0.3	0.1	0	0	0	0	0	0	0	0	0	0	0	10
39	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.5	0	0.25	0	0	0	0	0	0	0	0	0	0	0	4
40	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0.17	0	0.33	0.33	0	0	0	0	0	0	0	0	0	0	6
41	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
42	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	2
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33	0	0	0.33	0	0	0	0	0	3
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Total	3	29	31	20	22	25	24	17	13	7	15	3	5	10	3	5	2	2	3	0	0	1	1	0	1	0	1	243

Appendix 9: Mean-age-at-length for the 2010 south Otago survey.

Length (cm)	All fish		Males		Females	
	N	Mean age (y)	N	Mean age (y)	N	Mean age (y)
11	1	2.0			1	2.0
14	5	2.6			5	2.6
15	1	3.0			1	3.0
16	8	3.0	1	3.0	7	3.0
17	9	3.1	1	4.0	8	3.0
18	19	3.4	10	3.4	9	3.3
19	20	3.7	10	3.6	10	3.8
20	20	4.1	10	4.0	10	4.2
21	19	4.4	10	4.0	9	4.8
22	21	4.8	9	4.7	12	4.8
23	21	4.9	9	5.0	12	4.8
24	19	5.7	9	5.7	10	5.8
25	22	6.0	11	5.9	11	6.1
26	20	7.0	10	7.1	10	6.9
27	22	7.0	10	6.4	12	7.4
28	23	7.3	11	7.0	12	7.5
29	23	7.7	13	7.5	10	8.1
30	24	8.4	12	7.9	12	8.9
31	19	8.5	10	7.7	9	9.4
32	21	8.9	10	8.3	11	9.4
33	20	9.7	14	9.5	6	10.0
34	23	10.3	13	9.8	10	11.1
35	20	11.5	16	10.8	4	14.3
36	14	11.3	9	10.4	5	12.8
37	17	11.5	12	11.2	5	12.2
38	20	13.2	10	11.5	10	14.8
39	15	12.9	11	12.1	4	15.3
40	16	14.0	10	12.6	6	16.3
41	7	13.4	6	13.2	1	15.0
42	12	13.7	10	13.5	2	14.5
43	6	15.5	5	14.8	1	19.0
44	10	15.6	8	14.5	2	20.0
45	10	16.7	7	15.0	3	20.7
46	6	17.0	6	17.0		
47	8	19.1	7	18.1	1	26.0
48	9	18.9	9	18.9		
49	3	25.3	2	24.0	1	28.0
50	4	21.8	4	21.8		
51	2	24.0	1	24.0	1	24.0
52	2	23.5	2	23.5		
53	2	25.0	2	25.0		
54	1	27.0	1	27.0		
55	1	27.0	1	27.0		
56	1	25.0	1	25.0		
59	1	30.0	1	30.0		
Total	567	9.2	324	10.0	243	8.2