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Manatū Ahu Matua

Survey of scallops in SCA 7, January 2017

New Zealand Fisheries Assessment Report 2017/23

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Williams, J.R.; Parkinson, D.P.; Drury, J.; Roberts, C.L.; Bian, R; Tuck, I.D. (2017). Survey of scallops in SCA 7, January 2017.

***New Zealand Fisheries Assessment Report 2017/23.* 67 p.**

A dredge survey of scallops (*Pecten novaezelandiae*) was conducted from 23 January to 4 February 2017 (the 'January 2017 survey') within the Southern scallop stock, SCA 7 (Golden Bay, Tasman Bay, and Marlborough Sounds). The stock supports highly valued commercial and recreational scallop fisheries but due to sustainability concerns the fisheries in parts of the stock (sectors 7H, 7K, and 7L) were closed for the 2016–17 scallop fishing season (14 July 2016 to February 2017). The aim of the January 2017 survey was to evaluate the status of the SCA 7 scallop stock, to inform fisheries management decisions for the 1 April 2017 sustainability round. This included providing estimates of the current population distribution, size structure, abundance, and biomass, and establishing if changes have occurred in the population since the previous surveys in 2015.

The survey used a stratified random sampling allocation design, with sampling conducted using a chartered commercial fishing vessel and ring-bag scallop dredge. The sample extent was directly comparable with that in the May 2015 survey. A total of 202 valid stations (dredge tows) were sampled within the 50 strata. As expected, the highest catches of recruited scallops (90 mm or larger) were from tows within key strata (primarily in Marlborough Sounds, but also in Croisilles Harbour in Tasman Bay) which represent the banks and bays that support the main scallop beds. Catches were very low in other strata.

Given that a January survey timing is quite different to that of the annual May–June pre-season surveys from 1994–2015, additional analysis was needed to ensure comparability of the survey results. This involved new work to estimate the growth of scallops using length frequency data from recent surveys, and to conduct population projections to predict what the population biomass would be in May 2017 (for comparison with the annual pre-season surveys) and September 2017 (for comparison with previous start of season projected biomass estimates).

Modelling of length frequency data using the Multifan 32 package generated new estimates of scallop growth rates which were consistent with estimates from previous modelling of tag-return and length frequency data. Seasonality in growth was strong, with fastest growth predicted in spring.

The key findings in 2017 were that recruited biomasses in Golden and Tasman Bays (excluding Croisilles Harbour) were at negligible levels, similar to those observed since the large declines in the 2000s, and the declining trend in recruited biomass observed in Marlborough Sounds since 2009 appeared to have discontinued. The size structure of the January 2017 population in Marlborough Sounds provided evidence of successful spat settlement and survival in 2016. In the areas surveyed, population projections predicted the Marlborough Sounds recruited biomass in September 2017 (115 t meatweight, 95% CI = 68 to 194 t) to be comparable with that in September 2015 (102 t, 95% CI = 73 to 148 t) (Williams et al. 2015a). Almost all of the Marlborough Sounds recruited biomass at potentially fishable densities (higher than $0.04 m^{-2}$, or 1 scallop per 25 m^2) was held in only five scallop beds, mostly in the outer Sounds.

1. INTRODUCTION

1.1 Overview

Scallops (*Pecten novaezelandiae*) support important commercial and non-commercial (recreational and customary) fisheries in the Southern, or Challenger, scallop stock 'SCA 7' at the north of New Zealand's South Island. The SCA 7 stock comprises the regions (substocks) of Golden Bay, Tasman Bay, and Marlborough Sounds, subdivided into constituent Scallop Statistical Reporting Areas (sectors) (Figure 1).

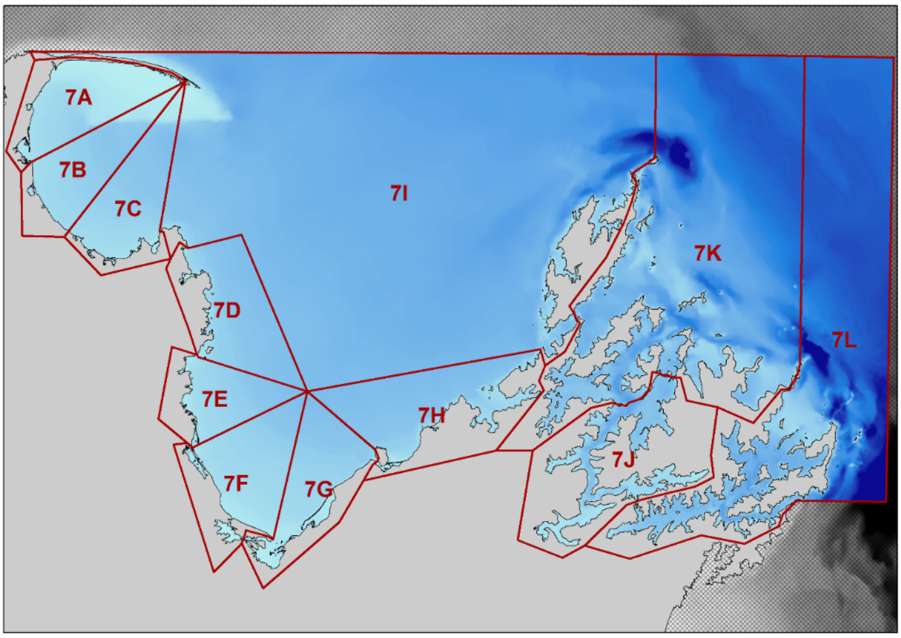


Figure 1: SCA 7 stock area, subdivided into its constituent Statistical Reporting Areas (sectors) 7A–7C (Golden Bay), 7D–7H (Tasman Bay), 7I (outer Golden/Tasman Bays), and 7J–7L (Marlborough Sounds).

SCA 7 is a Group 2 stock in the Draft National Fisheries Plan for Inshore Shellfish (Ministry for Primary Industries 2011), and management objectives for Group 2 stocks in this Plan are 1) "Use Objective – Maximise social, economic and cultural benefits obtained from each stock by enabling annual yield to be maximised"; and 2) "Environment (Stock Sustainability) Objective – Maintain stock size at or above an established minimum reference level". Within Group 2, SCA 7 is listed on the Third Schedule of the Act because of a rotational fishing and enhancement approach to management carried out under a Memorandum of Understanding (MoU) agreement between industry (Challenger Scallop Enhancement Company Ltd) and the Ministry for Primary Industries (MPI, formerly Ministry of Fisheries, MFish) (MFish & CSEC 1998).

Since 1994 annual dredge surveys have been conducted in SCA 7 to assess scallop population status and inform management of the fishery before the start of the commercial fishing season (nominally 1 September). The surveys provide data for estimating scallop population distribution, size structure, abundance, biomass and yield (Williams et al. 2014). Changes in the spatial sampling extent (coverage) of the surveys make it difficult to interpret the pattern of population estimates over the entire period surveyed. However, since 2009 the extent surveyed has not changed significantly meaning that population estimates from 2009 are more directly comparable.

Pre-season surveys conducted before 2015 were all conducted in late autumn (May–June). In 2015 three surveys were conducted: a pre-fishing season survey in May (Williams et al. 2015a), an in-fishing season survey of key scallop beds in October (Williams et al. 2015c) and an extensive post-fishing season stock survey in November (Williams et al. 2015b). There were no surveys in 2016.

Typically, the pre-season survey data are used to estimate biomass at the start of the commercial fishing season. This is done by conducting a population projection from the time of the survey (May–June) to the start of the season (September), accounting for the growth and natural mortality of scallops during the projection period. In this standard projection approach, growth estimates are derived from logarithmic model fits to tag-return data collected in the SCA CS scallop stock (Williams et al. 2015a). Growth increments from tag-returns in the SCA 7 stock are limited, but are similar to those observed in SCA CS (Tuck & Williams 2012).

The surveys have shown that recruited biomass in Golden Bay and Tasman Bay declined substantially during the 2000s and has since remained at very low levels, whereas in Marlborough Sounds recruited biomass generally followed an increasing trend from 1999 to 2009, and a declining trend since 2009 (Williams et al. 2015a). The 2015 pre-season and post-season surveys did indicate the presence of some low density scallop beds in sector 7H of Tasman Bay (Williams et al. 2015b, Williams et al. 2015c). The 2015 surveys showed that recruited biomass in Marlborough Sounds was restricted to a small number of scallop beds located mainly in the outer Sounds (Williams et al. 2015a, Williams et al. 2015b, Williams et al. 2015c).

Information summarising SCA 7 stock status was reviewed by the Fishery Assessment Plenary in May 2016 (Ministry for Primary Industries 2016a). Subsequently, following consultation on an MPI review of sustainability measures for SCA 7, in July 2016 the Minister for Primary Industries decided to close the scallop fishery in the Marlborough Sounds (sectors 7J, 7K and 7L) and the eastern part of Tasman Bay (sector 7H) for the 2016–17 scallop season (15 July 2016 to 14 February 2017); the closures aimed to "rest the beds, allowing mature scallops to spawn uninterrupted and juvenile scallops to grow and help prevent a further decline of this important fishery, while longer-term management options are developed" (Ministry for Primary Industries 2016b).

In December 2016, MPI requested NIWA to carry out a new SCA 7 survey in January 2017, in time to inform fisheries management decisions for the 1st April 2017 Sustainability Round. The April Sustainability Round refers to the annual review of TACs and other sustainability measures that occurs for fisheries with a fishing year commencing on 1 April (primarily rock lobster, scallop and other shellfish fisheries). Under the Fisheries Act 1996 changes to TACs must be in place before the start of the fishing year (1 April to 31 March for scallops). Given that a January survey timing is quite different to that of the past pre-season surveys, additional analysis was required to ensure comparability of the survey results. In particular, the choice of growth model used in the population projections becomes more critical for a 7-month (late January to 1 September) projection compared with the 3-month (late May to 1 September) projection required in previous survey projects. As well as the duration of the growth period, seasonality in growth must also be considered.

1.2 Objectives

The overall research objective for this project SEA2016-07 was "to evaluate the status of specified scallop fishing areas in the SCA 7 scallop stock". The specific research objectives were:

1. To conduct a survey over specified areas within the Marlborough Sounds and Tasman Bay and provide estimates of scallop abundance, length frequency, biomass (in tonnes green weight and meat weight) and density within the specified areas;
2. To compare the estimates from Objective 1 with relevant data from previous surveys to establish if changes have occurred in the scallop population.

1.3 Conceptual framework

The conceptual framework of conducting a dredge survey using stratified random sampling to estimate scallop population abundance is well established. Dredging can provide data for estimating relative abundance because dredges catch only a proportion of scallops within the area of seabed swept by the dredge, but with information on dredge efficiency (a combination of the efficiency and size selectivity of the dredge) relative estimates can also be converted to absolute estimates.

1.4 Previous and current research

This project directly builds on the previous SCA 7 survey series (Williams et al. 2014) with the following recent surveys being of particular relevance to interpreting the results of the present study:

- the November 2015 post-season survey of SCA 7 (Williams et al. 2015b)
- the October 2015 in-season survey of specified areas in M. Sounds (Williams et al. 2015c)
- the May 2015 survey of scallops in SCA 7 (Williams et al. 2015a)
- the in-season survey of Guards Bank (M. Sounds) in September 2014 (Williams 2014)

The project is also relevant to current NIWA research to improve assessment methods for scallops, and can be viewed in the wider context of past and present research on assessing New Zealand scallop resources, including dredge surveys of commercial scallop beds (e.g. Williams et al. 2007, Williams et al. 2013, Williams et al. 2015a), dive surveys of recreational scallop beds (e.g.Williams 2012), and dredge efficiency modelling (Bian et al. 2012).

1.5 Project approach

In this project, a survey of the main scallop beds within SCA 7 was conducted using a commercial scallop fishing vessel and ring-bag dredge. The fieldwork was carried out by four personnel (two NIWA staff, the vessel master and deckhand). All methodology proposed was reviewed by the MPI Shellfish Fisheries Assessment Working Group (Shellfish Working Group) at the initiation of the project in early January 2017, and minor suggestions to further improve methods were addressed before the fieldwork was conducted. A resampling with replacement (bootstrapping) approach to estimating scallop abundance and biomass was used to analyse the survey data collected. The resulting estimates were used to assess the current status (distribution, size structure, abundance, and biomass) of the scallop population in SCA 7, and compare this with the status in 2015 and in previous years to establish if changes have occurred in the population.

The preliminary results of the survey were presented to the Shellfish Working Group on 9 February 2017, days after the completion of the survey. Subsequently, further analytical work was undertaken to aid comparability of the January 2017 survey results with those from past pre-season surveys. This required estimating the growth of scallops using length frequency data from recent surveys, and conducting population projections to predict what the population biomass would be in May 2017 (for comparison with the May annual surveys) and September 2017 (for comparison with the series of September start of season projected estimates). Two projection approaches were used, based on two different sets of growth estimates 1) new estimates of growth derived from length frequency analysis in the present study; 2) existing estimates of growth from logarithmic modelling of tagging data.

2. METHODS

2.1 Survey design

A dredge survey of scallops in SCA 7 was conducted in early 2017 using a stratified random sampling allocation design. Sampling was single phase only due to logistics (steaming time between areas, and the tight timeframe for completing the project). The survey fieldwork started on 23 January and ended on 4 February 2017. The survey is hereinafter referred to as the 'January 2017' survey.

To allow comparisons with previous surveys, the 2017 sample extent (survey coverage; Figure 2 and Figure 3) was virtually identical to that used in the May 2015 survey except for:

- the inclusion of three additional strata that were not sampled in May 2015: stratum 9b adjacent to Farewell Spit, and strata 17 and 18 within Croisilles Harbour (Figure 2)
- the exclusion of a small area of rocky reef ('Luke Rock') from stratum 40 (Figure 4).

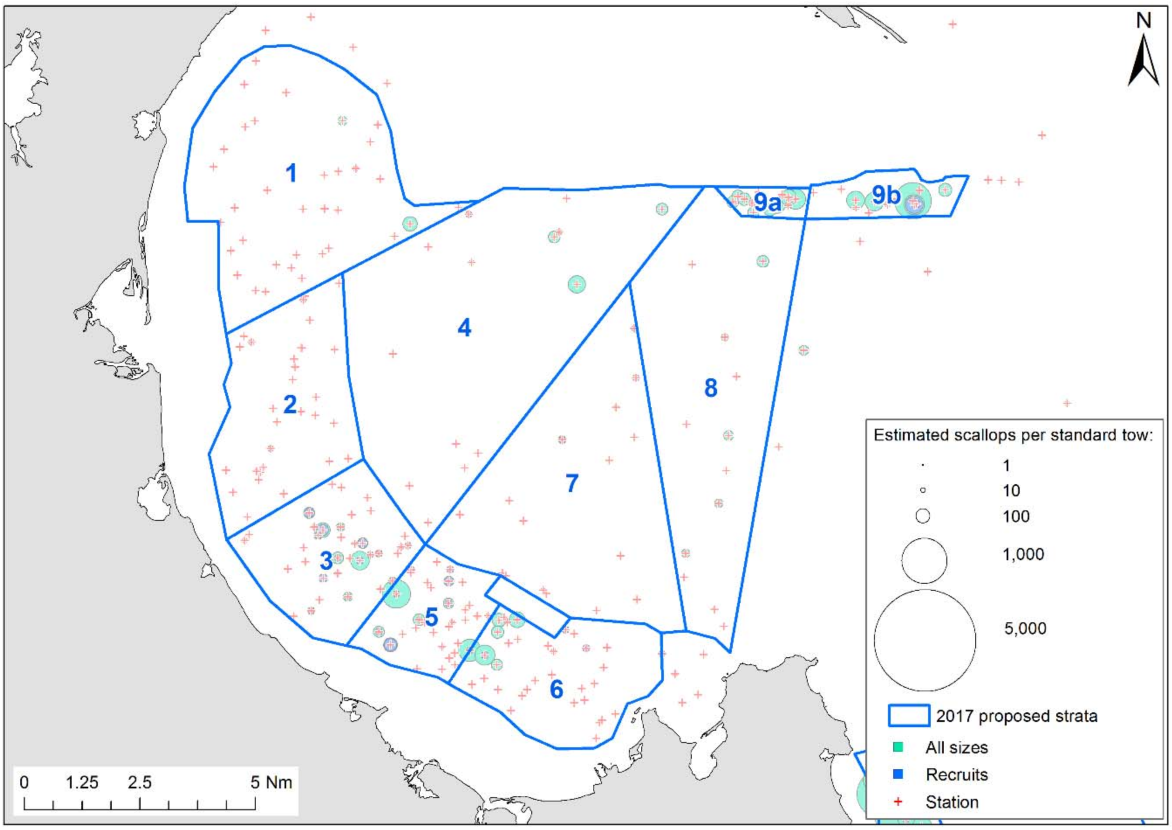
Based on data from previous surveys, in particular the extensive November 2015 survey (Williams et al. 2015b), the extent of the 2017 survey covered the main known scallop beds in the Marlborough Sounds, Tasman Bay and Golden Bay (the latter not stated in Specific Objective One) that have been previously sampled in SCA 7 surveys.

Similarly, to maintain comparability, the 2017 stratification was identical to that used in May 2015 except for the minor revision of some internal stratum boundaries (May 2015 strata 174, 20, 26, 37, 40 and 41(Williams et al. 2015a)) to better partition high and low recruited scallop densities observed in previous surveys.

There were 50 strata in total (10 in Golden Bay, 14 in Tasman Bay, and 26 in Marlborough Sounds), with a combined total area of 1461 km^2 (areas calculated using ArcGIS®) (Table 1). The strata are shown separately by substock for Golden and Tasman Bays (Figure 2) and Marlborough Sounds (Figure 3), overlaid on bubble plots of scallop density from 2011 to 2015 (see Appendix A for similar figures showing density across all survey years 1994–2015, and Appendix B for boxplots of recruited density by stratum). Strata 174 (Figure 2), 20 and 26 (Figure 3), and 37 (Figure 4) from the May 2015 survey were each subdivided into two strata, with suffix 'a' and 'b', representing expected high and low recruited scallop densities, respectively. At Dieffenbach Point (Figure 4), the boundary dividing strata 40 (deep area) and 41 (shallow bank) was modified to follow the depth contour on the marine chart (the main scallop bed is typically on the bank).

Table 1: Stratum details for the SCA 7 survey, January 2017. The combined total area is 1461 km^2.

Substock	Sector	Biotoxin	Stratum	Area (km^2)	Name	Tow length (n.miles)
Golden Bay	7A	A	1	71.9	–	0.4
	7B	B	2	41.7	–	0.4
			3	32.7	–	0.4
			4	106.7	–	0.4
	7C	C	5	19.0	–	0.4
			6	32.2	–	0.4
			7	73.9	–	0.4
			8	77.0	–	0.4
			9a	3.9	Farewell Spit (East)	0.4
	7I	I	9b	9.9	Farewell Spit (West)	0.4
Tasman Bay	7D	D	10	8.6	Awaroa Bay	0.4
			11	246.1	–	0.4
	7E	E	12	47.6	–	0.4
			13	68.7	–	0.4
	7F	F	14	45.5	–	0.4
			15	62.0	–	0.4
	7G	G	16	87.9	–	0.4
	7H	H	171	2.9	T. Bay, Sector H Delaware Bay	0.4
			172	29.1	T. Bay, Sector H 20-30m	0.4
			173	8.3	T. Bay, Sector H Triangle 30m+	0.4
			174a	107.6	T. Bay, Sector H Main 30m+ West	0.4
			174b	82.7	T. Bay, Sector H Main 30m+ East	0.4
			17	5.3	Croisilles Low	0.4
			18	3.6	Croisilles High	0.4
Marlborough Sounds	7K	G100	20a	9.8	Admirality/Penguin Bays High	0.4
			20b	7.0	Admirality/Penguin Bays Low	0.4
			21	5.5	Chetwode Is	0.4
		G43	22	3.4	Waitata Bay	0.2
			23	1.5	Waitata Bank	0.2
			24	2.7	Clara Island	0.2
			25	14.4	Waitata Reach	0.4
		G42	26a	1.0	Horseshoe Bay	0.2
			26b	3.6	Tawhitinui High	0.2
			27	22.1	Tawhitinui Low	0.4
		G43	28	3.6	Richmond Bay	0.2
			29	2.4	Ketu Bay	0.2
		G45	30	2.3	Wynens Bank	0.2
			31	10.9	Forsyth Bay Low	0.4
		G46	32	5.9	Guards Bank Fishing Area	0.4
			321	6.4	Guards Bank Outer	0.4
			33	10.8	Guards Bay Low	0.4
			34	1.2	Guards Anakoha Bank	0.4
		G90	35	37.6	Waitui/Port Gore Low	0.4
			36	6.0	Port Gore Bank	0.4
	7L	G29	37a	6.1	Motuara Is Medium	0.4
			37b	9.9	Motuara Is Low	0.4
			38	4.6	Ship Cove	0.4
			39	4.4	Bay of Many Coves	0.4
			40	1.1	Dieffenbach Low	0.4
			41	1.5	Dieffenbach High	0.4



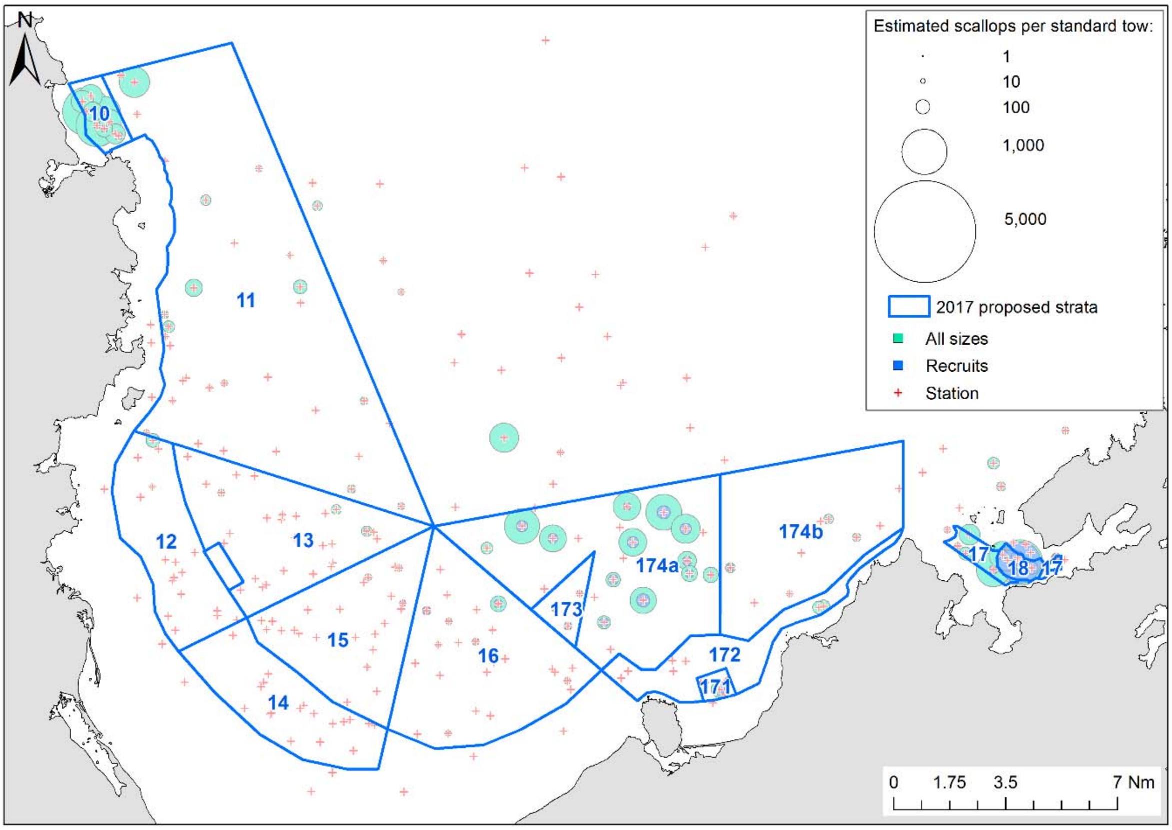


Figure 2: Stratification for the SCA 7 survey, January 2017: Golden Bay (top) and Tasman Bay (bottom) (Marlborough Sounds strata are shown in Figure 3). Circles show the abundance of recruited scallops (90 mm or larger shell length; dark shaded circles) and scallops of any size (light shaded circles) caught in the five years of SCA 7 surveys from 2011 to 2015, crosses denote tow positions. Circle area is proportional to the number of scallops per standard tow (0.4 n.mile in length), uncorrected for dredge efficiency.

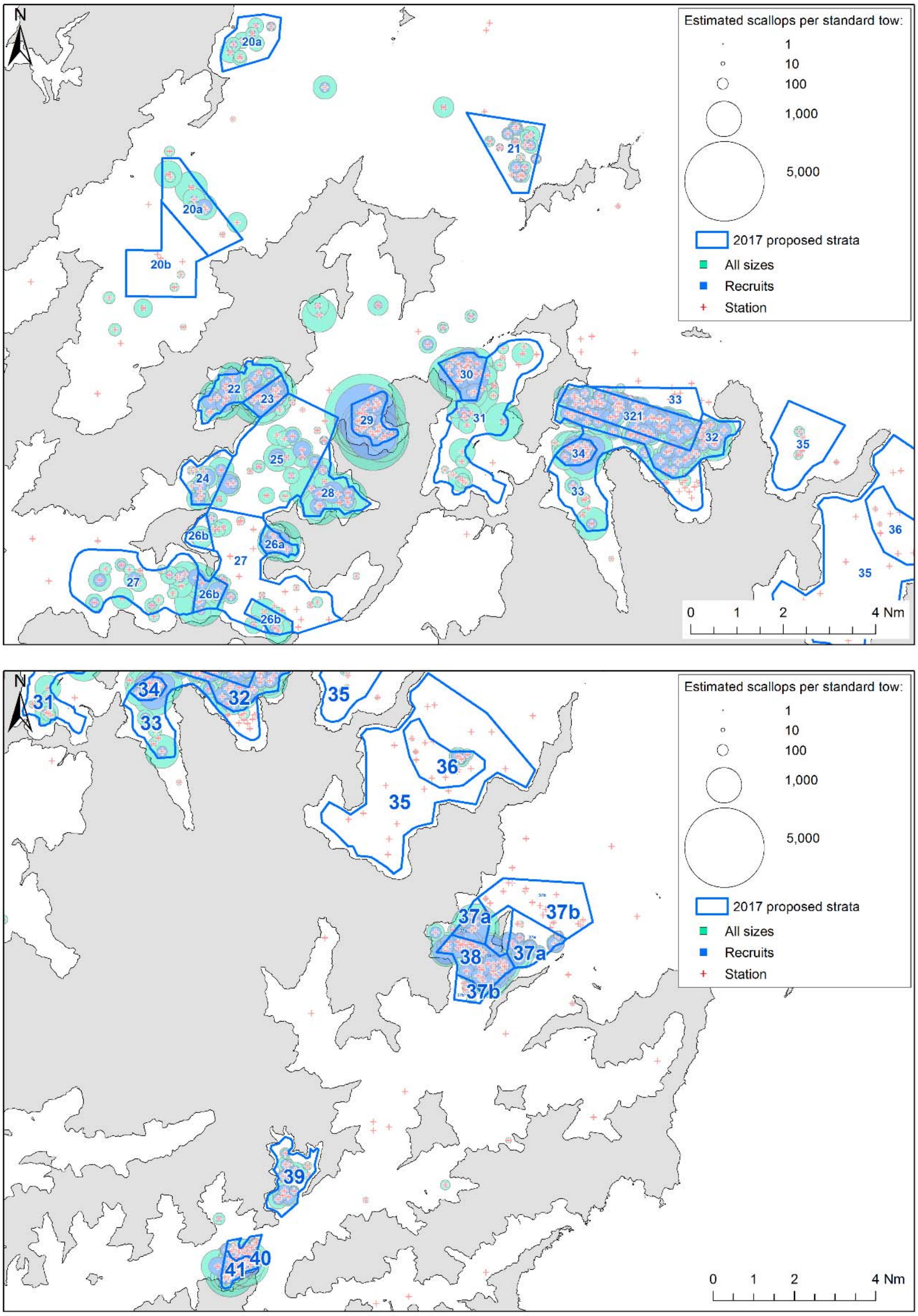
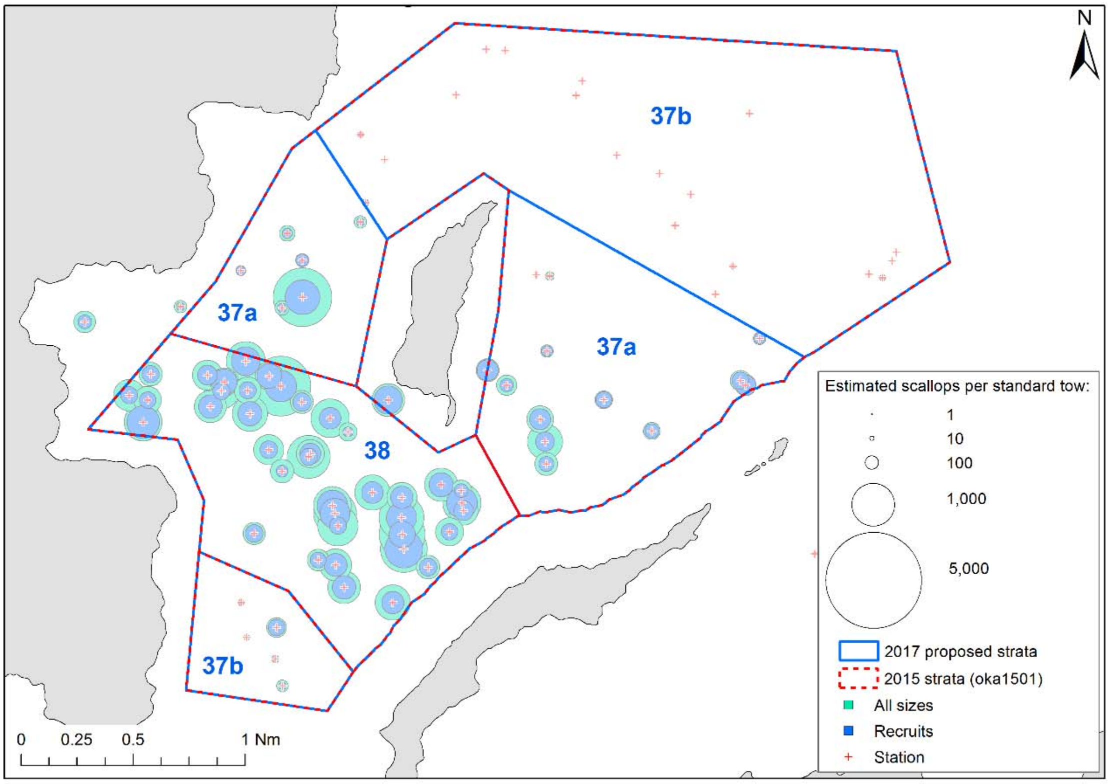


Figure 3: Stratification for the SCA 7 survey, January 2017: Marlborough Sounds sectors 7K Pelorus Sound (top) and 7L Queen Charlotte Sound (bottom) (Golden and Tasman Bay strata are shown in Figure 2). Strata 20, 26, 27, 33, 35, 37a and 37b are multi-part strata (each stratum is made up of geographically separate areas that in combination are treated as a single stratum). Circles show the abundance of recruited scallops (90 mm or larger shell length; dark shaded circles) and scallops of any size (light shaded circles) caught in the five years of SCA 7 surveys from 2011 to 2015, crosses denote tow positions. Circle area is proportional to the number of scallops per standard tow (0.4 n.mile in length), uncorrected for dredge efficiency.



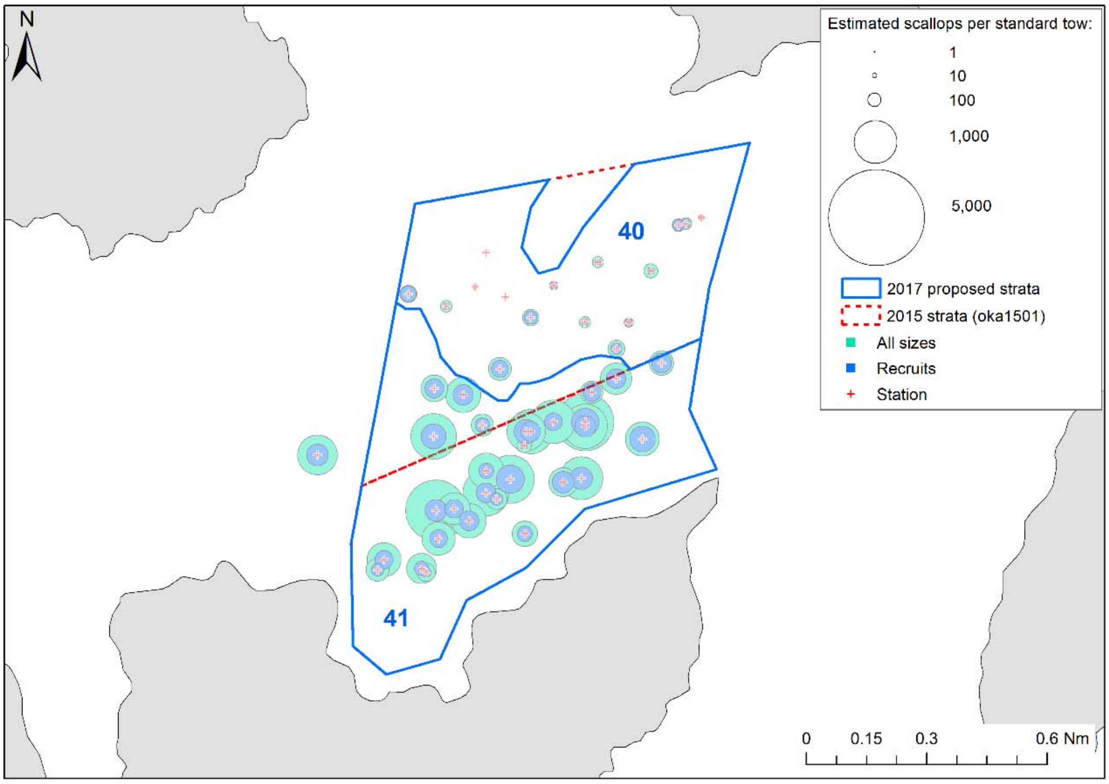


Figure 4: Stratification for the SCA 7 dredge survey, January 2017: revisions to Ship Cove / Motuara Island (top) and Dieffenbach Point (bottom) stratum boundaries in Queen Charlotte Sound. Solid blue polygons denote the boundaries of the proposed strata for the 2017 survey; dashed lines show the boundaries of the May 2015 survey for comparison. Circles show the abundance of recruited scallops (90 mm or larger shell length; dark shaded circles) and scallops of any size (light shaded circles) caught in the five years of SCA 7 surveys from 2011 to 2015, crosses denote tow positions. Circle area is proportional to the number of scallops per standard tow (0.4 n.mile in length), uncorrected for dredge efficiency.

2.2 Station allocation

Station allocation was examined using the R function *allocate* (Francis 2006), which allocates stations to strata so as to achieve a specified coefficient of variation (CV), or to minimise the CV with a fixed number of stations. For the SCA 7 surveys, station allocation is usually to minimise the CV with a fixed number of stations (i.e. which can realistically be sampled within a fixed survey duration). The CV is calculated from historical survey catch data and the estimated areas of the strata. The strata for the January 2017 survey were intersected with station data from the 2011–2015 SCA 7 surveys (five years of survey data) to assign catch densities (number of recruited scallops 90 mm or larger per standard tow of 0.4 nm in length, uncorrected for dredge efficiency) to the specified survey strata. Station positions within strata were randomised using GIS software, constrained to keep stations a minimum distance apart; this software was also used to estimate the area of each stratum.

The May 2015 survey (Williams et al. 2015a) sampled a total of 180 valid stations over 9 days, achieving a CV of 20% (including uncertainty associated with correcting for dredge efficiency) on the time of survey biomass estimate at the SCA 7 stock level, and a CV of 19% at the substock level for Marlborough Sounds. The CVs at the substock level for Golden Bay (28%) and Tasman Bay (26%) were higher, as expected, because abundance in those areas was low and spatially patchy. Before that survey, the Shellfish Working Group agreed that higher CVs for those substocks would be acceptable because a lot of sampling would be required to reduce the CV to 20% or less, and the priority was to achieve CVs of 20% or less for the areas which held the main known scallop beds (i.e. primarily Marlborough Sounds). In 2017, we expected that the distribution of abundance would not have changed markedly since 2015, and again the emphasis was to achieve precise CVs on the abundance estimates for the areas expected to hold the main scallop beds (Marlborough Sounds and Tasman Bay sector 7H). Details of the station allocation process are provided in Appendix C.

2.3 Dredging procedures

Dredging was undertaken from a chartered fishing vessel using the same commercial ring-bag dredge (2.4 m in width) as used in SCA 7 surveys since 1998, and the same vessel master as used since 2011. The fishing vessel *Okarito*, which has been used for SCA 7 surveys since 2009, was not available for the January timing of the survey required by MPI. Instead, we chartered the FV *Rongatea II* which is similar in size and dredging capability to the FV *Okarito*. The FV *Rongatea II* was used previously in the May 2015 survey of SCA 7, to sample stations in Golden Bay and Tasman Bay sector H (Table 13, Appendix D).

A standard protocol for scallop dredge sampling was followed. In this protocol, the vessel is positioned at each random station position allocated with non-differential GPS. A single dredge is deployed (Figure 5) and towed for a standard tow length of 0.4 n.miles, but the tow length is 0.2 n.miles in some strata (22, 23, 24, 26a, 28, 29, and 30) selected *a priori* because of their small size and expected high catches. The actual tow length (distance towed) can be calculated from the logged GPS positions at the start and end of the tow, but a SeaPlot doppler log of the vessel path during the tow is also recorded which potentially provides a more accurate estimate of the distance towed. The tow starts when the winch brakes are set, and ends when hauling with the winch commences. The skipper is instructed to fish the gear (tow towards the next station, maintain constant target speed of 2.8 knots, and maintain consistent warp to depth ratio) so as to maximise the total catch at that station while avoiding crossing stratum boundaries, depth contours, foul ground, and obstructions. At the end of the tow, the dredge is retrieved and the dredge contents are emptied onto a sorting tray at the stern of the vessel.

Figure 5: Stern of FV Okarito showing deployment of ring-bag dredge in Marlborough Sounds. Photo credit: J. Williams.

2.4 Catch sampling

A standard dredge catch sampling procedure was followed. In this procedure, the total volume of the unsorted catch is visually estimated and recorded to the nearest 0.1 of a standard size fish case (bin). All live scallops (*Pecten novaezelandiae*) and dead scallops termed 'cluckers' (articulated scallop shells, shell hinge still intact) are sorted from the entire catch (see Figure 6) and placed into bins by scallop life status category (live or dead). Similarly, all live and dead clucker oysters (*Ostrea chilensis*), and all live green-lipped mussels (*Perna canaliculus*), starfish (*Coscinasterias calamaria*), sea cucumbers (*Australostichopus mollis*) and other taxa that are easily counted (e.g. fish) are sorted from the catch and placed into bins by category. All individuals in each category are counted, and the volume of each category is visually estimated to the nearest 0.1 bin. The remaining unsorted catch is characterised by estimating its total volume (number of bins) and the percentage composition in different taxonomic categories (e.g. algae, sponges, ascidians, bryozoa, echinoderms, crustaceans, bivalves, gastropods, cephalopods, shells).

Size data were also collected for scallops and oysters using the following method. All live and dead clucker scallops are measured for shell length (along the anterior–posterior axis, using digital measuring boards), except for those from large catches (more than 200 live scallops) where a random subsample (of at least 20% of the total catch) may be taken and measured (all unmeasured scallops are counted). For any catches subsampled for scallop length, the random subsample of scallops is taken by progressively halving and mixing the fish cases of scallops sorted from the catch. All live oysters and dead clucker oysters are measured using standard oyster measuring rings (58 mm internal diameter), and the number in each size category (recruits and pre-recruits) is recorded. Recruit size oysters are those that cannot be passed through the measuring ring.

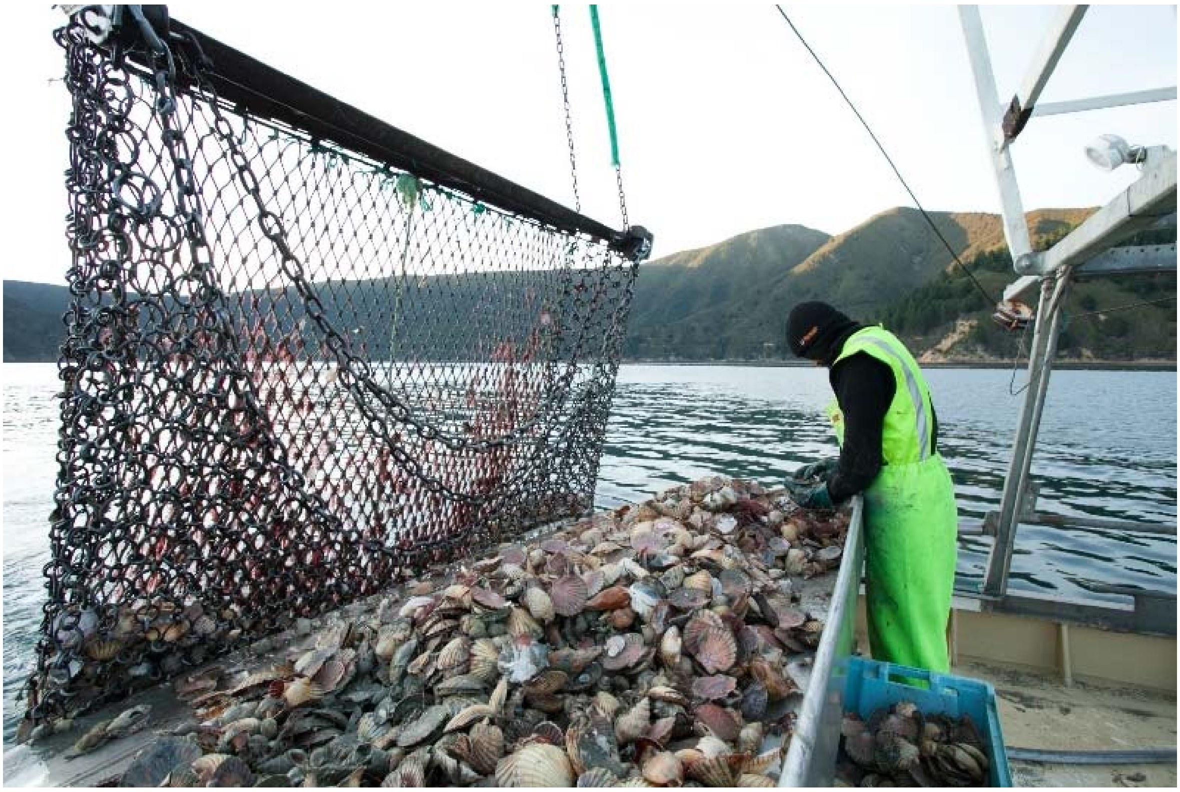


Figure 6: Ring-bag dredge survey catch being sorted at the stern of the vessel. Photo credit: J. Williams.

The station data (date, station number, recorder, tow start and finish times and positions, wind force, water depth, dredge fullness, bottom type) and catch data (species counts, oyster size, catch volumes and percentage compositions by category) were recorded on pre-printed waterproof forms, and the scallop length data were captured electronically. All data were checked and verified, ready for loading to the MPI '*scallop*' database. Raw data forms were scanned.

2.5 Population estimation

The population estimation approach was originally described by Cryer & Parkinson (2006); an updated, and more detailed, description of the method can be found in Williams et al. (2013). The current SCA 7 survey analytical approach has been used since 2008 (Tuck & Brown 2008). Parameters specific to the SCA 7 survey analysis were summarised in Williams et al. (2014), and also detailed in section 2.6 of the May 2015 survey report (Williams et al. 2015a).

The application of the approach for the 2017 survey involved: deriving survey estimates of scallop density, abundance and biomass for each stratum; combining these to produce the population estimates at different spatial scales of interest; and projecting these time of survey estimates both to May and to September, accounting for growth and natural mortality. The method uses a non-parametric resampling with replacement (bootstrapping) approach in the derivation of summary statistics (mean, CV, median and 95% confidence intervals).

Stratum length frequency distributions are calculated at the time of the survey as the mean tow length frequency distribution for that stratum scaled by the stratum area. Substock length frequency distributions are calculated as the sum of the stratum length frequency distributions for the strata within each substock. The stratum areas, used to scale the tow sampling data, are considered to be known without error.

2.6 Growth estimation

A new set of growth estimates were derived from length frequency data collected during SCA 7 surveys since 2014. These data came from three geographically distinct scallop beds (Wynens, Guards, and Ship) in Marlborough Sounds. These beds were selected because the data contain fairly well-defined modal progression (Figure 13). Growth estimates were derived using the analysis package Multifan 32 (Fournier et al. 1990, Otter Research 1992), which attempts to identify and track individual age-cohorts in length frequency time series data using von Bertalanffy (1938) growth curves. Multifan 32 thus can be used to derive estimates of L_∞ (the asymptotic mean length at age, the average length of the old fish) and K (a growth rate coefficient that determines how quickly L_∞ is attained). Seasonal growth can be accounted for in the fitting procedure by adding two extra parameters to the growth model: u, the seasonality amplitude, which describes the magnitude of the seasonal effect ($u = 0$ if growth is constant; $u = 1$ where all growth occurs in part of the year and no growth occurs for the rest of the year); and w, the seasonality phase, which describes the time of year at which growth rates are maximal. The resulting growth curve represents the mean deterministic growth of individuals in the population (variability in individual growth rates cannot be estimated from length frequency analysis). A likelihood ratio test is performed to determine if the inclusion of seasonal growth parameters is warranted, and the best model is identified using the Sigtest function within the Multifan 32 package (Otter Research 1992).

Multifan 32 was configured based on knowledge of *Pecten novaezelandiae* biology (Appendix E). Multifan models time in months, so Month '1' was assigned to May ('sample 1'), the month in which the smallest (presumably youngest age-class of) scallops are first observed in the survey data. The number of possible age classes offered was 3–8, and the range in K offered was 0.2–1.8.

2.7 Comparative analysis

The population estimation work generated estimates of the January 2017 distribution, abundance and size structure of the main scallop beds sampled in the SCA 7 survey series. To enable comparison of the results with those from previous surveys, it was necessary to address spatial and temporal differences among the surveys.

The spatial extent of the January 2017 survey (1461 km^2) was slightly larger than that of the May 2015 survey (1442 km^2), due to the addition of 3 strata (9b, Farewell Spit; 17 and 18, Croisilles Harbour) in 2017 that were not included in the May 2015 survey. For the comparative analysis (including all projection work), the 2017 analysis was re-run excluding strata 9b, 17, and 18, enabling direct comparison of the January 2017 estimates with those from the May 2015 (Williams et al. 2015a) and November 2015 (Williams et al. 2015b) surveys.

Although the above ensured comparisons were spatially valid (i.e. all estimates were produced using the same survey extent), the different timing of the surveys confounds the comparisons. To address this, population projections were conducted to predict what the population would be in May 2017 (enabling comparison with the time series of pre-season survey estimates) and September 2017 (for comparability with previous start of season projected estimates).

Two projection approaches were used to predict the May and September 2017 population estimates:

1. 'Tag-return projection'. This is the standard approach normally used in May to September projections in SCA 7, summarised in Section 2.5, and uses growth estimated from tag-return increment data.

2. 'Multifan projection'. In this new approach, the three sets of von Bertalanffy seasonal growth parameters derived from the Multifan analysis of Wynens, Guards, and Ship length frequency data (Section 2.6) were used to generate the growth-transition matrix in the bootstrapping

estimation procedure (Section 2.5). In each iteration, one of the three sets of Multifan growth parameters were selected at random, and used to predict mean growth increment at length, instead of using tag-return predicted growth. Variability in predicted growth increments was incorporated in the Multifan projection approach by applying CVs on annual increments predicted by Tuck & Williams (2012) from inverse logistic modelling (Table 2).

Table 2: Predicted growth increments (and standard deviations and CVs) from inverse-logistic modelling of *Pecten novaezelandiae* tag recaptures by Tuck & Williams (2012).

Length (mm)	Annualised increment (mm)	Standard deviation	CV
26	48.36	11.15	0.23
36	44.90	10.83	0.24
46	41.05	10.47	0.25
56	36.89	10.05	0.27
66	32.57	9.58	0.29
76	28.22	9.06	0.32
86	24.02	8.52	0.35
96	20.09	7.95	0.40
106	16.54	7.38	0.45
116	13.43	6.81	0.51
126	10.77	6.26	0.58
136	8.55	5.72	0.67

3. RESULTS

3.1 Sampling conducted

The survey was carried out during 10 days at sea from 23 January to 4 February 2017 (no sampling was conducted on 25 or 31 January or 1 February due to unfavourable weather). The survey was conducted in two legs: Leg 1 surveyed Marlborough Sounds and Tasman Bay 7H; Leg 2 surveyed the remainder of Tasman Bay and Golden Bay. The survey was led by NIWA science staff (D. Parkinson, Voyage Leader for the entire survey, assisted by J. Drury on Leg 1) working with the skipper and mate of the chartered vessel.

A total of 202 valid stations (dredge tows) were sampled within the 50 strata (cf. with 220 stations allocated within the 50 strata) (Figure 7). Eighteen fewer stations were sampled than allocated due to unfavourable weather (see Appendix C for stratum-station number allocations as derived from the Francis (2006) allocation process). Overall, a total of 36 161 live scallops were caught, of which 26 083 (72%) were measured and the rest were counted; a total of 1400 dead scallops ('cluckers') were caught, of which 1359 (97%) were measured and the rest were counted.

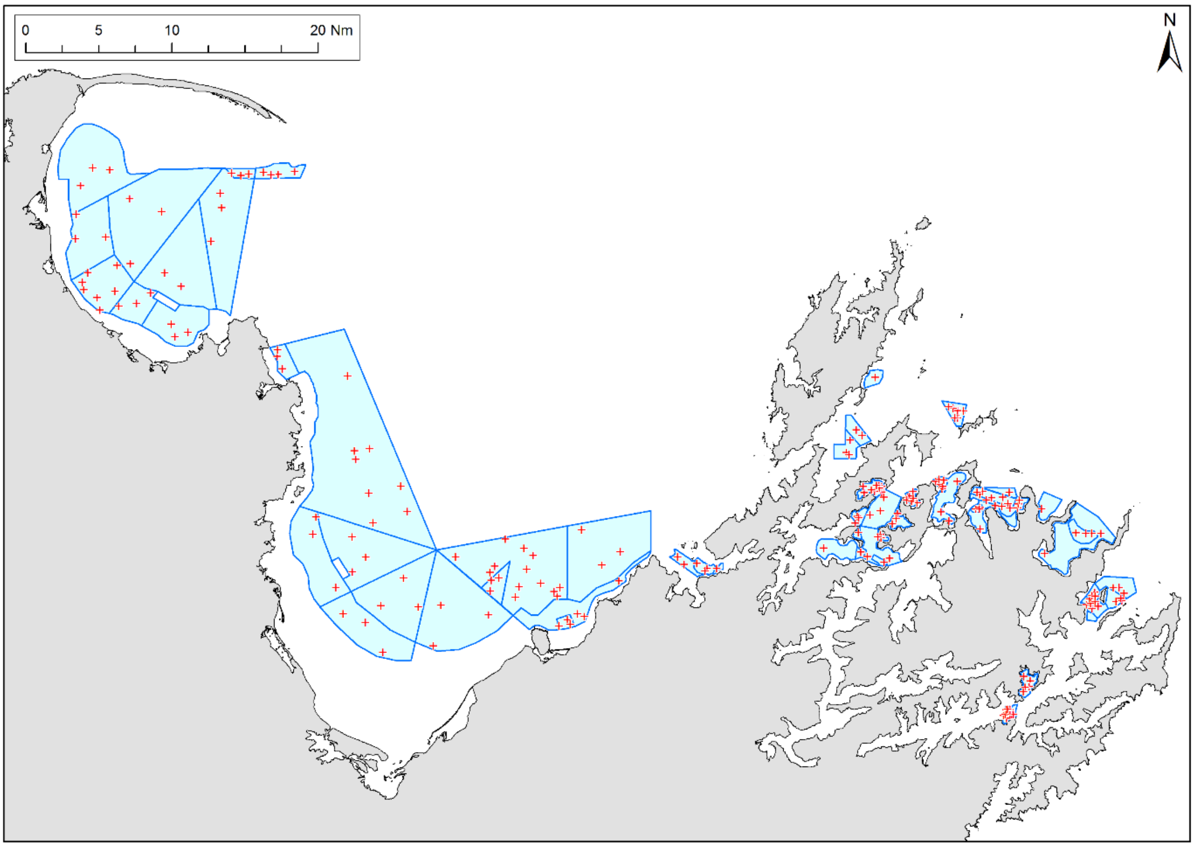


Figure 7: Station positions sampled, SCA 7 survey, January 2017.

Additional to recording the start and finish GPS coordinates of each dredge tow (determined from the vessel's SeaPlot plotter), the path of the vessel during the tow was logged using independent data logger technology (Voyage Tracker software, Lennard Electronics, Wellington). The logged vessel tracks were an additional source of data for error checking and assessing the position of tows in relation to the station positions allocated (see example for Tasman Bay 7H in Figure 8).

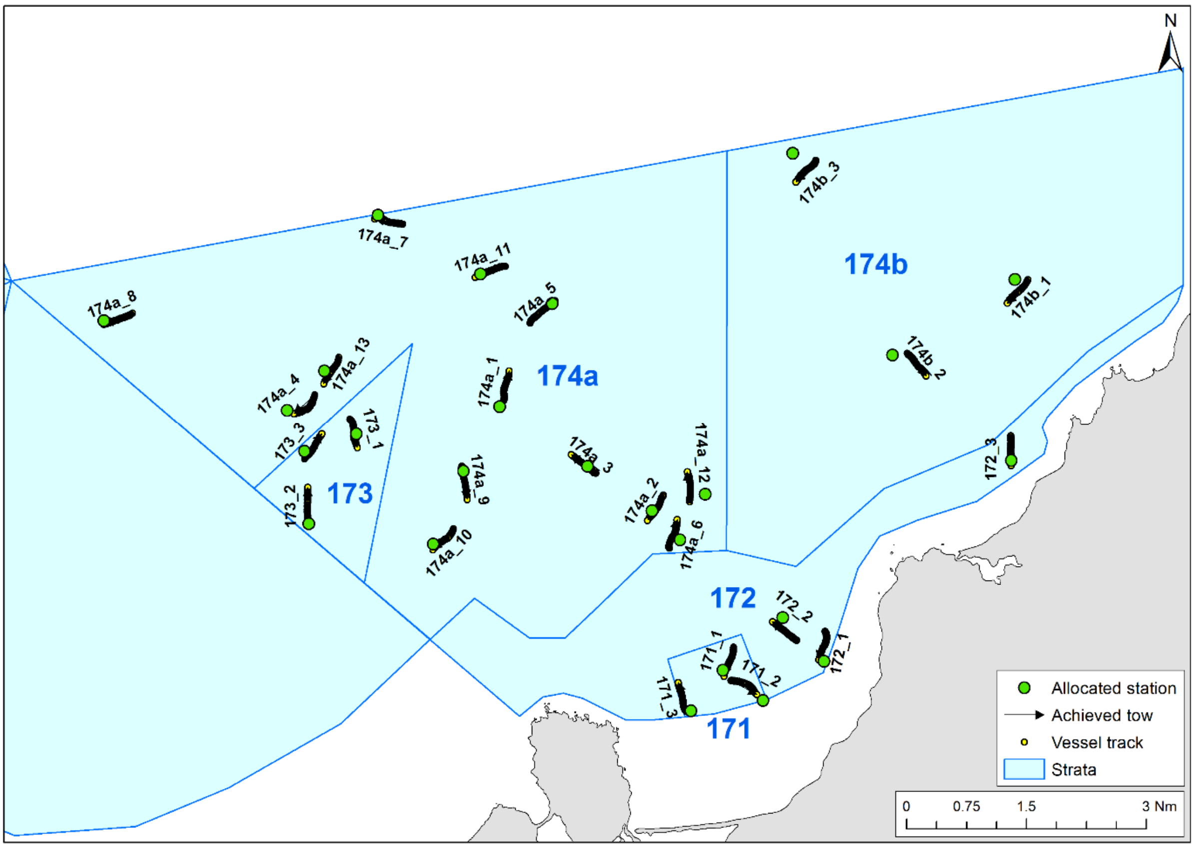


Figure 8: Dredge tow positions conducted compared with station positions allocated, Tasman Bay 7H, January 2017. Green circles denote station positions initially allocated that were subsequently sampled. Arrows denote the approximate position and direction of the dredge tows sampled, calculated from the vessel plotter data. Yellow and black symbols show the vessel track for each tow, recorded using independent vessel tracker technology. Polygons denote survey strata and sector boundaries.

3.2 Achievement of survey CVs

Relative density estimates (i.e. uncorrected for dredge efficiency) and their CVs were calculated from the survey data, enabling comparison of the CVs achieved by the survey with those predicted by *allocate* in the survey design (Table 3). Recruited estimates with high precision (CVs of 20% or lower) were achieved at all of the spatial levels targeted in the design, except for the Ketu Bay (CV = 34.7%) and the Bay of Many Coves (CV = 45.3%) beds where catches varied between the inner and outer parts of each bay, and sector 7H (CV = 25.1%) and the Waitata Bay (CV = 52.6%) bed where abundance was very low compared with that in 2015.

Table 3: Comparison of the coefficient of variation (CV) values predicted in the design ('allocate') with those achieved by the survey ('survey'), SCA 7 survey, January 2017. CVs are on the estimated relative mean density of recruited scallops (uncorrected for dredge efficiency). Relative mean density values are also shown expressed as scallops per metre of seabed swept, or scallops per standard 0.4 n.mile tow.

Level	Code	Tows		CV		Scallops	
		allocate	survey	allocate	survey	m^{-2}	tow^{-2}
Stock	SCA 7	220	202	6.4	6.9	0.004	7
Substock	GB	40	35	20.0	29.2	0.000	1
	TB	60	57	15.1	20.1	0.002	3
	MS	120	110	7.2	7.1	0.023	41
Sector	7H	34	31	16.4	25.1	0.004	7
	7K	84	81	8.5	8.5	0.019	33
	7L	36	29	13.1	12.4	0.047	84
Bed	Croisilles (17, 18)	6	6	16.1	19.8	0.046	81
	Chetwodes (21)	7	7	17.7	19.2	0.063	112
	Waitata Bay (22, 23)	10	10	18.4	52.6	0.005	8
	Ketu Bay (29)	8	7	16.4	34.7	0.065	115
	Wynens Bank (30)	8	6	16.2	20.6	0.236	420
	Guards Bay (32, 321, 33, 34)	18	18	12.5	10.3	0.039	70
	Ship Cove (37a, 37b, 38)	18	15	16.7	14.8	0.046	82
	Bay of Many Coves (39)	8	5	16.8	45.3	0.034	61
	Dieffenbach Point (40, 41)	10	9	16.9	17.6	0.074	131

3.3 Distribution

The distribution of relative density (expressed as the survey catch of scallops per standard 0.4 n.mile tow, uncorrected for dredge efficiency) for the areas surveyed is shown in Figure 9 (and at larger scales in Appendix F). As expected, the highest catches of recruited scallops (90 mm or larger) were from tows within key strata (primarily in the Marlborough Sounds, but also in Croisilles Harbour in Tasman Bay) which represent the banks and bays that support the main scallop beds. Catches were very low in other strata.

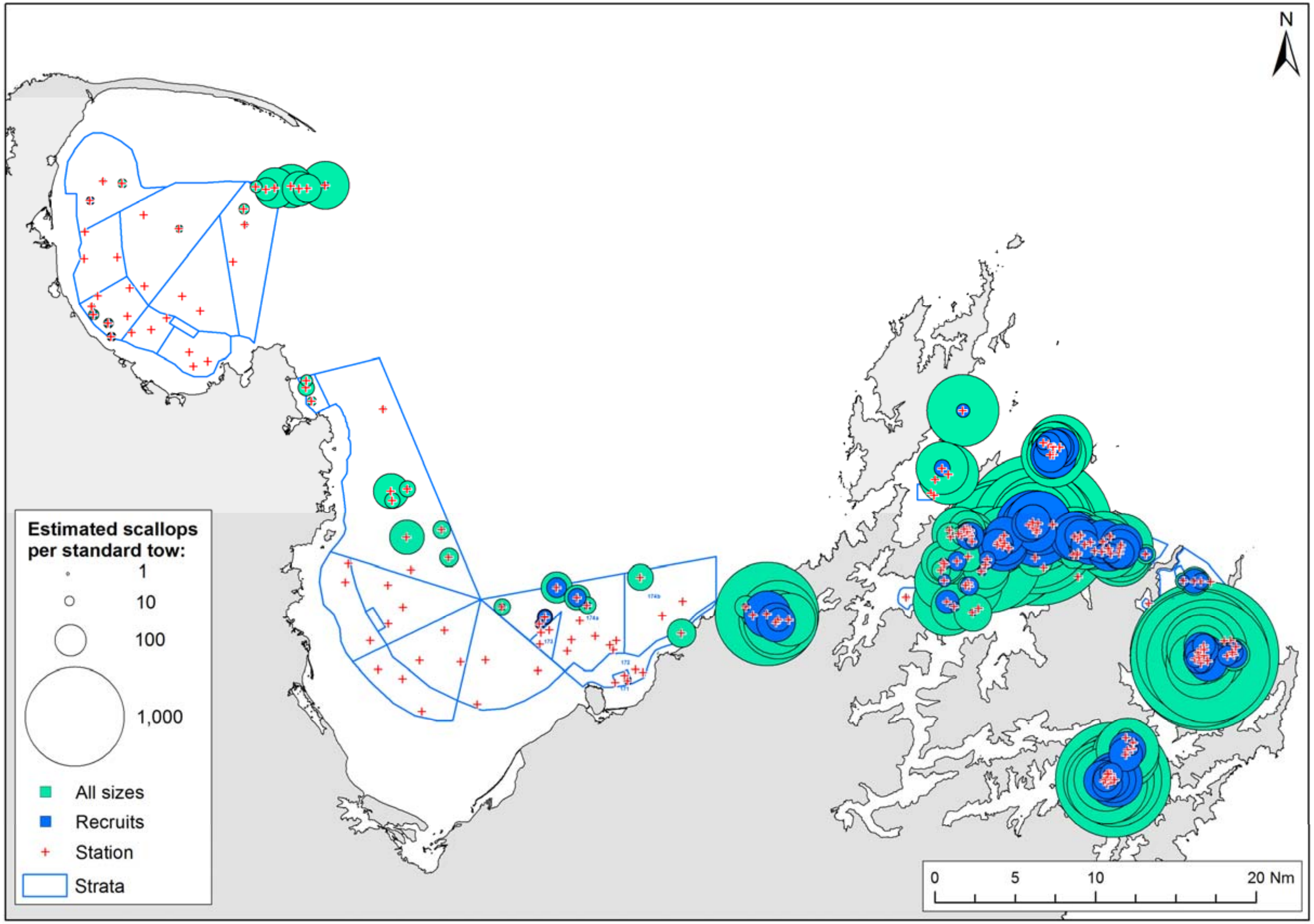


Figure 9: Catch per standard tow, SCA 7 stock survey, January 2017. Circle area is proportional to the number of scallops caught per standard distance towed (0.4 n.miles). Dark blue shaded circles denote scallops of commercial recruited size (90 mm or larger), green shaded circles denote scallops of any size. Values are uncorrected for dredge efficiency. Polygons denote survey strata boundaries.

3.4 Population estimates

Our estimation approach used non-parametric re-sampling with replacement (1000 bootstraps) to produce a sample of 1000 estimates of scallop biomass (or other metric of interest). A frequency distribution plot of those estimates (Figure 10) provides the most complete description of the nature of the variation in our sample and can be viewed as an approximation of the uncertainty in our knowledge of the biomass. The CV (standard deviation divided by the mean) is a good measure of the dispersion of that sample. The median (as opposed to the mean) is the best measure of central tendency for our sample, and the 95% confidence interval (CI) is used to express the uncertainty in our estimate.

The estimates of recruited scallops (90 mm or larger) at the time of the 2017 survey are tabulated in Appendix G (at the stock, substock, sector, and bed levels in Table 14; at the stratum level in Table 15 (Golden and Tasman Bays) and Table 16 (Marlborough Sounds)).

At the time of the January 2017 survey, estimates of recruited biomass (t meat weight, median values) in each substock, and for the combined total (SCA 7), were as follows:

- Golden Bay 4 t (95%CI = 2–8 t; mean = 4 t, CV = 0.33)
- Tasman Bay 20 t (95%CI = 12–34 t; mean = 21 t, CV = 0.28)
- M. Sounds 84 t (95%CI = 61–126 t; mean = 86 t, CV = 0.19)

- SCA 7 109 t (95%CI = 78–162 t, mean = 112 t, CV = 0.19).

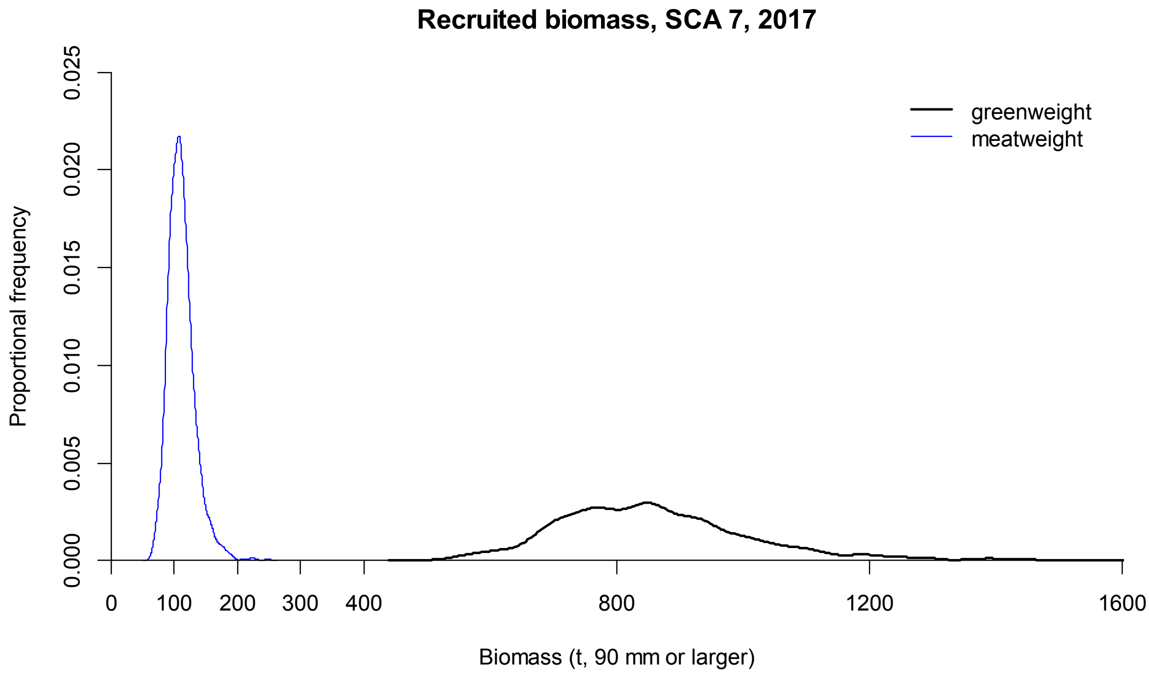


Figure 10: Proportional frequency distribution of the biomass of recruited scallops in SCA 7 at the time of the survey, January 2017. Recruited scallops are those measuring 90 mm or larger. The results of a non-parametric resampling with replacement approach to estimating biomass (1000 bootstraps) are shown in tonnes green weight (solid black line, on the right hand side of the plot) and meat weight (blue line, on the left hand side of the plot).

Within the same area of the SCA 7 stock as that surveyed in May 2015, recruited biomass (t green-weight, median values) was 1514 t in May 2015, 1230 t in November 2015, and 783 t in January 2017 (Table 4). This overall observed decrease in the time of survey estimates is mainly associated with a large decline in Tasman Bay 7H.

Table 4: Population estimates of recruited green weight biomass(scallops 90 mm or larger) at the time of the surveys in May and November 2015 and January 2017, produced using the May 2015 survey extent, assuming historical average dredge efficiency and predicting weight from length. The analysis used a non-parametric resampling with replacement approach to estimation (1000 bootstraps).

Year	Survey	Location	Area (km^2)	*n* tows	Mean	CV	Median	2.5%	97.5%
2015	May	GB	459	39	78	0.28	75	44	128
		TB	797	52	752	0.26	724	449	1185
		MS	186	89	723	0.19	703	512	1046
		SCA 7	1442	180	1553	0.20	1514	1079	2252
2015	Nov	GB	459	35	62	0.29	59	33	98
		TB	797	36	664	0.27	651	357	1049
		MS	186	81	534	0.20	522	368	787
		SCA 7	1442	152	1259	0.21	1230	833	1857
2017	Jan	GB	459	31	26	0.39	24	10	48
		TB	797	51	121	0.34	116	54	215
		MS	186	110	658	0.19	638	470	966
		SCA 7	1442	192	804	0.19	783	572	1185

3.5 Length frequency

To assist in assessing recent changes in population size structure, time series of scallop length frequency distributions from surveys between 2014 and 2017 were plotted for sectors 7H, 7K and 7L (Figure 11) and also for beds of interest in Marlborough Sounds (Figure 12 and Figure 13). In addition, dead scallop 'clucker' data (which have been collected on SCA 7 surveys since May 2015) were analysed and time series of clucker length frequency distributions (Appendix H) were plotted for the same areas as for the live scallop time series, with the aim of providing insight on levels of recent mortality.

In Tasman Bay 7H (Figure 11, excludes Croisilles), low numbers of scallop spat were caught in the May 2015 survey, yet a juvenile cohort with a modal length of 50 mm is apparent in the November 2015 survey. In both May and November 2015, survey catches were dominated by similar numbers of scallops 70 mm or larger. By January 2017 a substantive decline in the abundance of these larger scallops had occurred. Despite this, few cluckers were caught in January 2017 (Appendix H).

In Marlborough Sounds 7K and 7L, there was a notable presence of small scallops (20–60 mm) in May 2015, indicative of fairly widespread spat settlement sometime before the survey, and a strong 50–55 mm mode was observed in November 2015. In January 2017, pre-recruit scallops of about 75–80 mm were abundant, particularly in 7L. In contrast to Tasman Bay 7H, in Marlborough Sounds 7K and 7L there were no obvious signs of any large-scale declines occurring between November 2015 and January 2017. Instead, there was a positive shift in the average size of recruited scallops 90 mm or larger. For example, in 7L there was a larger proportion of recruits in the 100–110 mm size range in January 2017 compared with November 2015.

At the scale of individual scallop beds in Marlborough Sounds, the length frequency time series for some of the main scallop beds show modal progression in 2015, indicative of scallop spat growth during the year: in May 2015 there was widespread occurrence of 20–60 mm scallops, possibly comprising two different size modes (cohorts) of about 30 mm and 50 mm; in October 2015 the modal size was 40–55 mm in the limited beds surveyed (Guards, Ship, Dieffenbach); in November 2015, the modal size was 50–60 mm in most beds. In January 2017, there was a high abundance of pre-recruits (75–78 mm length mode) at several beds (e.g. particularly evident at Ship, but also observed at Ketu, Wynens, and Dieffenbach). The positive shift in the average size of recruits observed at the sector scale between November 2015 and January 2017 was also evident at the scale of individual beds in several areas (e.g. Ketu, Wynens Ship, Dieffenbach), with the exception of Waitata Bank where a large decline in abundance occurred between May 2015 and January 2017.

In summary, the length frequency time series provide evidence of:

- spat settlement, growth and survival in Marlborough Sounds in 2015
- a positive shift in the average size of large scallops in Marlborough Sounds between November 2015 and January 2017
- abundant pre-recruits 75–78 mm in Marlborough Sounds in January 2017
- large-scale declines in abundance between 2015 and 2017 in 7H and at Waitata Bank in 7L
- overall low numbers of cluckers (presumed to be recently dead scallops).

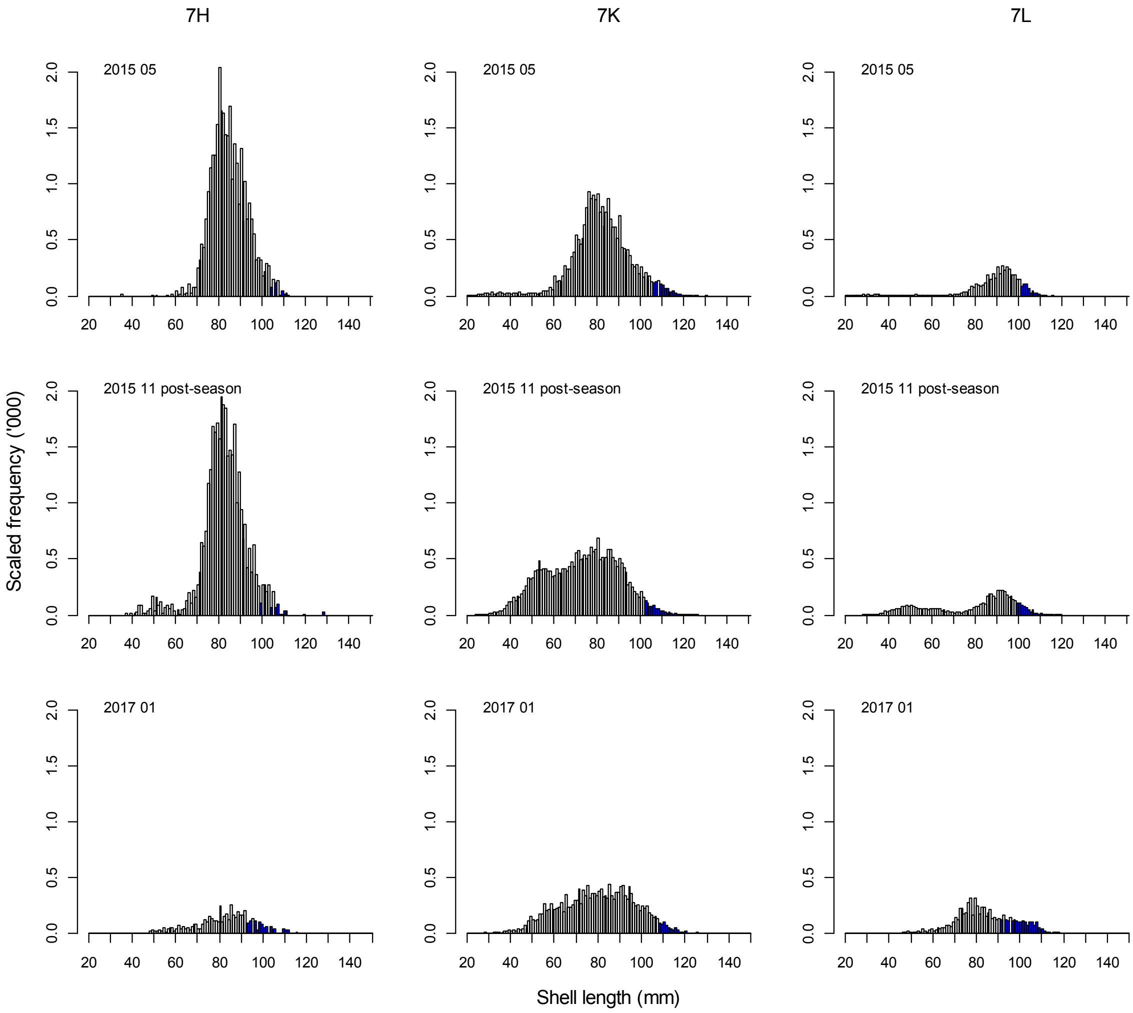


Figure 11: Length frequency distributions for scallops in Tasman Bay sector 7H (strata 171–174 combined; Croisilles Harbour strata 17 and 18 excluded) and Marlborough Sounds sectors 7K (Pelorus Sound) and 7L (Queen Charlotte Sound), SCA 7, May 2015 to January 2017. Data corrected for historical average dredge efficiency. Dark shaded bars show recruited scallops (90 mm shell length or larger).

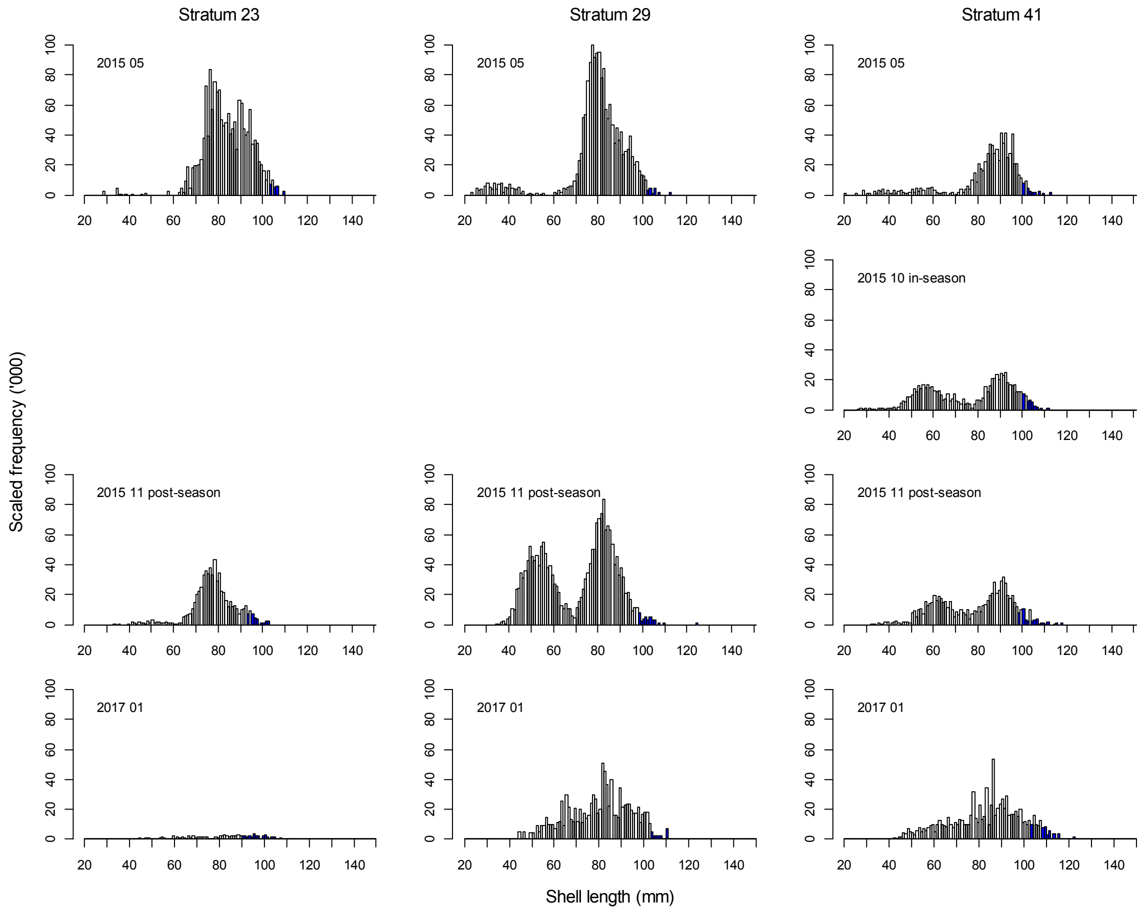


Figure 12: Length frequency distributions for scallops in three beds in Marlborough Sounds, SCA 7, May 2015 to January 2017: stratum 23, Waitata Bank (left); stratum 29, Ketu Bay (centre); stratum 41, Dieffenbach High (right). Data corrected for historical average dredge efficiency. Dark shaded bars show recruited scallops (90 mm shell length or larger).

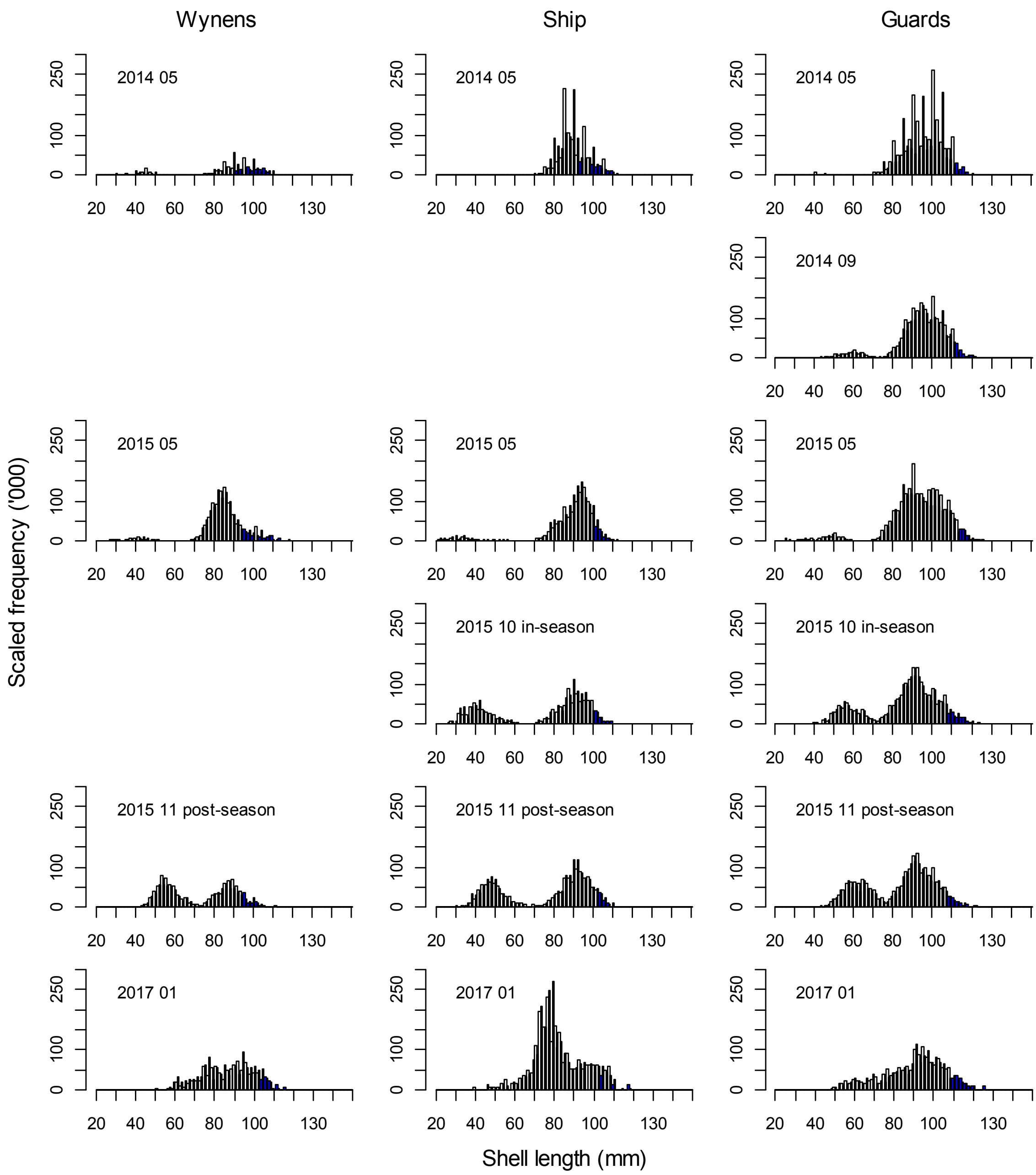


Figure 13:Length frequency distributions for scallops in three beds in Marlborough Sounds, SCA 7, May 2014 to January 2017:stratum 30, Wynens Bank (left); stratum 38, Ship Cove (centre); strata 32 and 321 combined, Guards Bank (right). Data corrected for historical average dredge efficiency. Dark shaded bars show recruited scallops (90 mm shell length or larger).

3.6 Growth estimates

Multifan 32 analysis of length frequency data from the 2014–17 surveys of scallops at Wynens, Guards and Ship generated new estimates of deterministic growth, with the seasonal implementation of the models providing the best fits to the data from each bed (Table 5; see Appendix I for model outputs and diagnostic plots). Although offered, age-dependent standard deviation in length-at-age was never selected for in the models with the best fits. The modelling estimated that there were 5 age classes in the data at Wynens and Ship, and 3 age classes at Guards. Estimates of von Bertalanffy parameters were very similar at Wynens and Guards (K = 0.583 for both beds, L_∞ = 123.7 and 125.1 respectively), suggesting slower growth but to a larger maximum average size than the predicted faster growth and smaller maximum average size at Ship (K = 1.282, L_∞ = 106.2). The Multifan likelihood ratio test indicated that the inclusion of seasonal growth parameters significantly increased the statistical power of the Multifan growth model to account for modal growth progression in the data. For all three beds, seasonality in growth was very strong (u = 0.948–0.960) and fastest growth occurred in spring (w = 0.7–0.9).

Mean growth increments predicted by the Multifan models for Ship, Guards, and Wynens beds were comparable with those predicted by logarithmic modelling of tag-return data (Cryer & Parkinson 2006) and those predicted using von Bertalanffy parameters estimated by Breen (1995) from a subset of length frequency data in Bull (1976).

Table 5: Multifan outputs for best fits to 2014–2017 scallop length frequency datasets from three different scallop beds in Marlborough Sounds, SCA 7. Numbers next to the scallop bed name denote the stratum code(s).

				Scallop bed
Parameter		Wynens 30	Guards 32, 321	Ship 38
K (y^{-1})		0.583	0.583	1.282
L_∞ (mm)		123.700	125.100	106.200
u (seasonal growth amplitude)		0.948	0.950	0.960
w (seasonal growth phase)		0.730	0.852	0.696
Numberof age classes		5	3	5
Age (y) of 1st age class		0.68	0.81	0.15
Mean length (mm) at age in May				
	Age 1	45.92	53.44	28.58
	2	80.25	85.07	84.63
	3	99.41	102.74	100.19
	4	110.12	–	104.51
	5	116.09	–	105.71

3.7 May projected biomass

Absolute estimates of greenweight biomass in 2015 and 2017 in Marlborough Sounds at the time of the surveys and from population projections were tabulated for direct comparison (Table 6). Plotting the projected May 2017 estimates of recruited greenweight biomass together with the time series of May survey estimates (Figure 14) shows that the overall SCA 7 stock was at a very low level in 2017, with no change in the negligible biomass held in Golden Bay, a large biomass decline in Tasman Bay since 2015, and that the Marlborough Sounds biomass in 2017 was comparable with that in 2015.

Table 6: Summary of absolute greenweight recruited biomass estimates (t) in 2015 and 2017. Time of survey estimates are shown, together with estimates projected from the surveys. Two different projection approaches were used 1) using growth estimated from tag-return data (‘Projected tagging’); 2) using growth estimated from multiple length frequency analysis (‘Projected Multifan’).

2015	Month	Location	Bgr_mean	Bgr_cv	Bgr_median	2.5%	97.5%
Time of survey	May	GB	78	0.28	75	44	128
		TB	752	0.26	724	449	1185
		MS	723	0.19	703	512	1046
		SCA 7	1553	0.20	1514	1079	2252
Time of survey	Nov	GB	62	0.29	59	33	98
		TB	664	0.27	651	357	1049
		MS	534	0.20	522	368	787
		SCA 7	1259	0.21	1230	833	1857
2017	Month	Location	Bgr_mean	Bgr_cv	Bgr_median	2.5%	97.5%
Time of survey	Jan	GB	26	0.39	24	10	48
		TB	121	0.34	116	54	215
		MS	658	0.19	638	470	966
		SCA 7	804	0.19	783	572	1185
Projected tagging	May	GB	29	0.38	28	11	55
		TB	121	0.34	116	54	215
		MS	769	0.18	749	559	1084
		SCA 7	919	0.18	900	660	1295
Projected Multifan	May	GB	35	0.41	33	12	66
		TB	121	0.34	115	57	214
		MS	914	0.26	883	547	1464
		SCA 7	1070	0.24	1036	676	1671

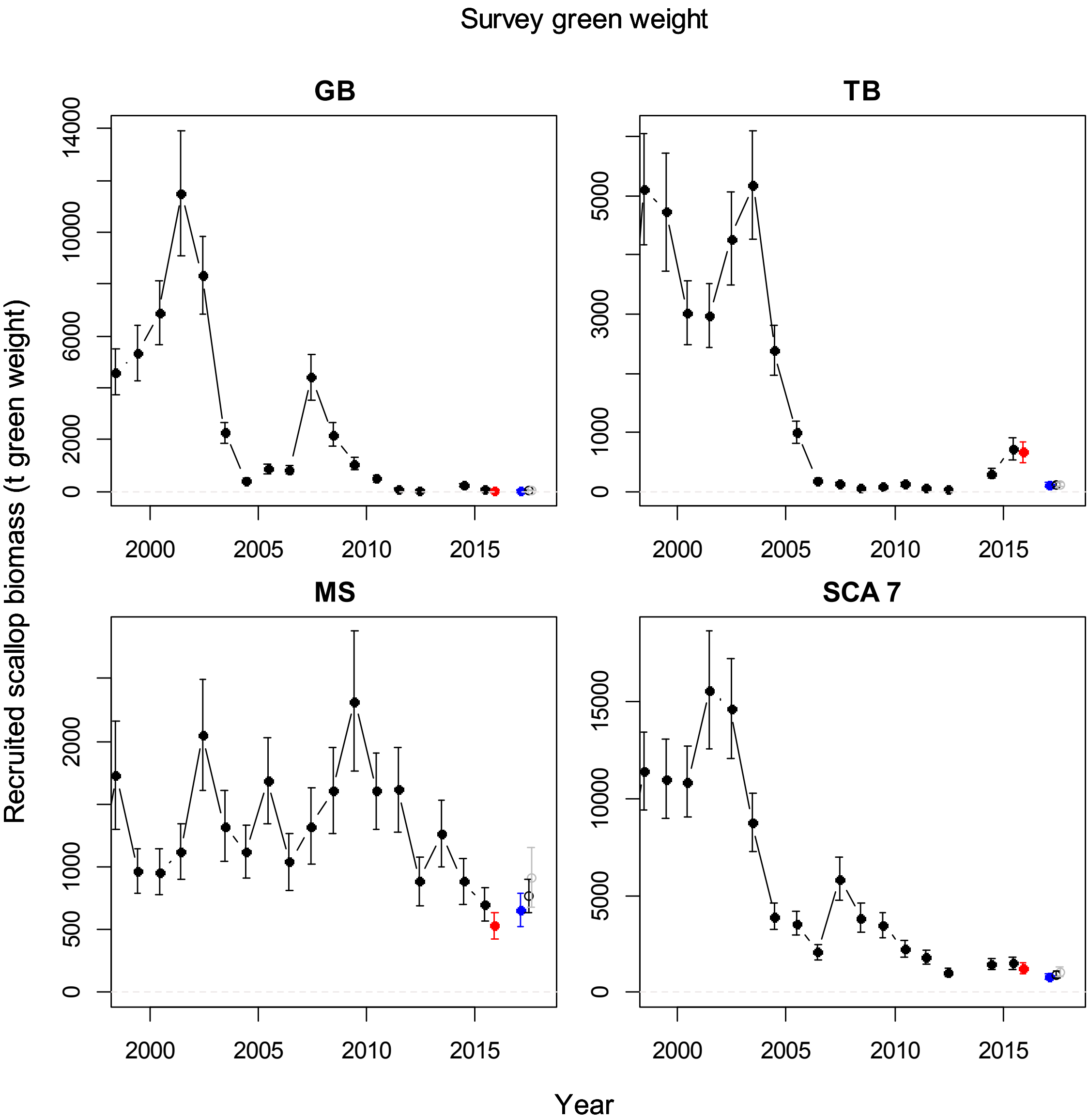


Figure 14: Trends in time of survey (nominally May, black symbols) biomass (t greenweight) of recruited scallops (90 mm or larger) by substock and for the total SCA 7 stock, 1998–2017. Estimates from the November 2015 post-season survey (red symbols) and the January 2017 survey (blue symbols) are also shown. Two projected estimates for 2017 are shown, derived from two different projections: 1) using growth estimated from tag-return data (hollow black symbols); 2) using growth estimated from Multifan analysis of multiple length frequencies (hollow grey symbols, slightly offset for clarity). Values are the estimated mean and CV of the recruited biomass. Note: Golden and Tasman Bays were not surveyed in 2013, and there were no surveys in 2016.

3.8 September projected biomass

Projected estimates of absolute meat weight biomass in September 2015 and 2017 in Marlborough Sounds were also tabulated (Table 7). The two different approaches to estimating growth resulted in very similar estimates of projected biomass in September 2017 (tagging approach = 120 t meat weight; Multifan approach = 115 t meat weight), with higher uncertainty in the estimate from the Multifan approach (CV = 28%) than the tagging approach (CV = 19%). The September 2017 projected biomass was similar to that estimated in September 2015 (102 t, CV = 19%).

Table 7: Summary of absolute recruited meat weight biomass estimates (t) in September 2015 and 2017. Two different projection approaches were used 1) using growth estimated from tag-return data ('Projected tagging'); 2) using growth estimated from multiple length frequency analysis ('Projected Multifan').

2015	Month	Location	Bmt_mean	Bmt_cv	Bmt_median	2.5%	97.5%
Projected tagging	Sep	GB	15	0.30	15	7	25
		TB	88	0.27	84	49	142
		MS	104	0.19	102	73	148
		SCA 7	207	0.19	203	141	304
2017	Month	Location	Bmt_mean	Bmt_cv	Bmt_median	2.5%	97.5%
Projected tagging	Sep	GB	5	0.37	5	2	9
		TB	14	0.35	14	6	25
		MS	123	0.19	120	86	174
		SCA 7	142	0.18	139	100	198
Projected Multifan	Sep	GB	5	0.44	4	2	9
		TB	14	0.35	14	7	25
		MS	119	0.28	115	68	194
		SCA 7	138	0.26	134	82	221

Projected estimates of September recruited biomass were also plotted to assess longer term trends (Figure 15). In Golden Bay, biomass increased from 1999 to reach a major peak in 2001, but rapidly decreased to 2004; biomass increased again to reach a second, smaller peak in 2007, but subsequently decreased and remained at very low levels from 2011 to 2017. In Tasman Bay there was a similar large increase and decrease in biomass that occurred with slightly later timing: biomass increased in Tasman Bay from 2000 to reach a peak in 2002–03, but subsequently decreased and remained at very low levels from 2006 to 2017, with the exception of sector 7H in Tasman Bay which had an abundance of scallops (at generally low density) in 2015 that had not been seen since surveys in the early 2000s. The September 2017 projected biomass in 7H (excluding Croisilles Harbour scallops) was substantially lower than that in 2015. In Marlborough Sounds, biomass generally followed an increasing trend from 1999 to 2009, and a decreasing trend from 2009 to 2015; the results of the January 2017 survey suggested this downturn had abated, with the September 2017 projected biomass predicted to be similar to that in September 2015.

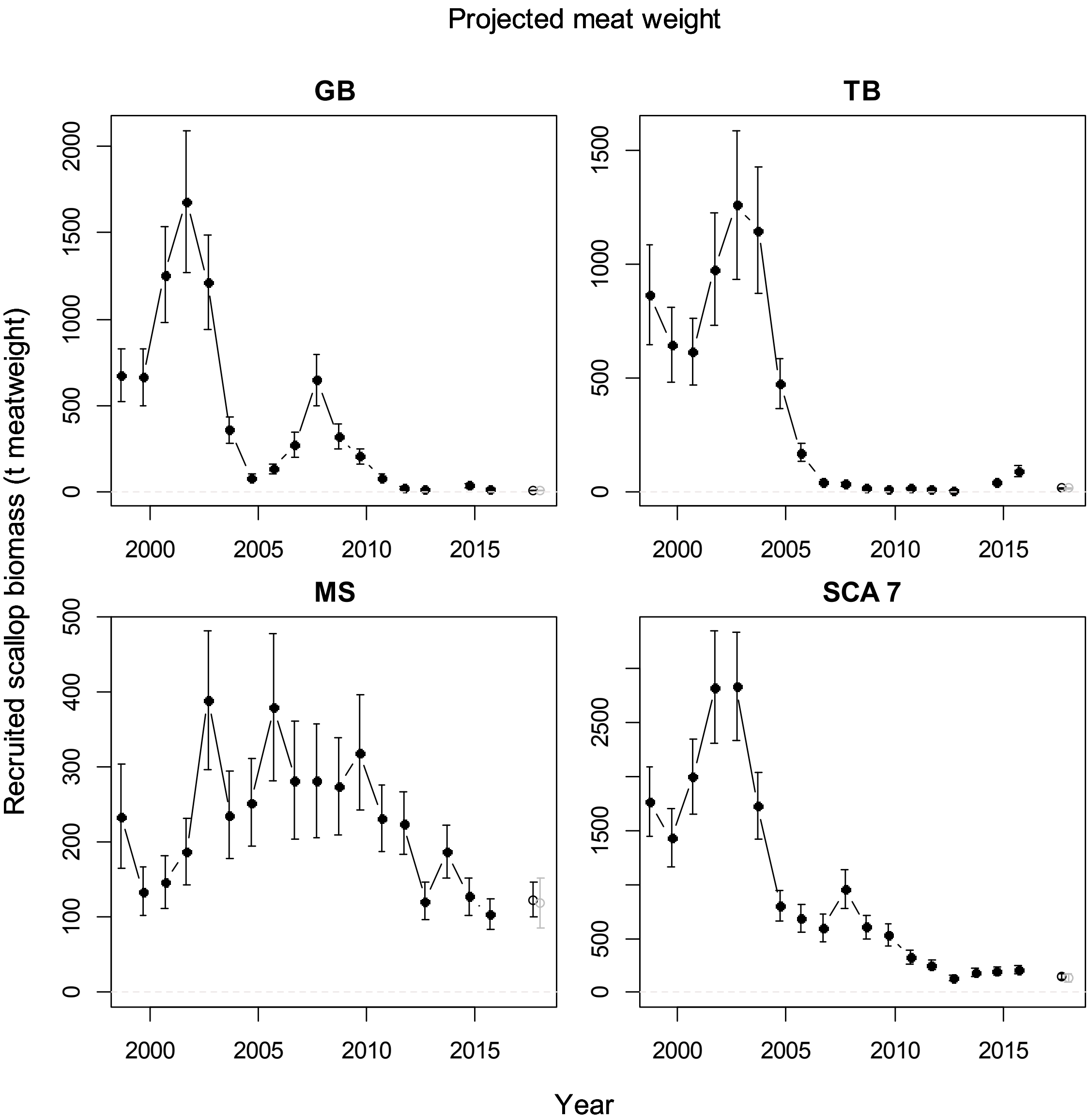


Figure 15: Trends in projected start of season (1 September, black symbols) biomass (t meat weight) of recruited scallops (90 mm or larger) by substock and for the total SCA 7 stock, 1998–2017. Two projected estimates for 2017 are shown slightly offset, derived from two different projections: 1) using growth estimated from tag-return data (hollow black symbols); 2) using growth estimated from Multifan analysis of multiple length frequencies (hollow grey symbols, offset for clarity). Values are the estimated mean and CV of the recruited biomass. Note: Golden and Tasman Bays were not surveyed in 2013, and there were no surveys in 2016.

3.9 Biomass sensitivity to density

Biomass is held at various densities (scallops per unit area) throughout the stock, typically with smaller areas of high density aggregations commonly known as ‘beds’ distributed among larger areas of low densities or no scallops. High density scallop beds are important both for sustainability (i.e. larval production) and for fisheries utilisation.

Estimates of biomass are sensitive to the exclusion of areas of low scallop density, and in the past it has generally been assumed that 0.04 m^{-2} (one recruited scallop for each 25 m^{-2} of seabed) is a reasonable working definition for the lowest limit of economic fishing, although this will vary with market price and costs. A recruited scallop density of 0.04 m^{-2}on the seabed (corrected for historical average dredge efficiency) equates to a catch of about 40 scallops per standard 0.4 n.mile survey tow using a single dredge (Table 8). In the commercial scallop fishery in SCA 7, vessels typically fish two dredges simultaneously for 20–25 mins per tow (a distance of about 1 n.mile). Assuming the same dredge width and efficiency as in the survey, a recruited scallop density of 0.04 m^{-2} on the seabed equates to a catch of about 200 scallops per commercial fishery tow using 2 dredges.

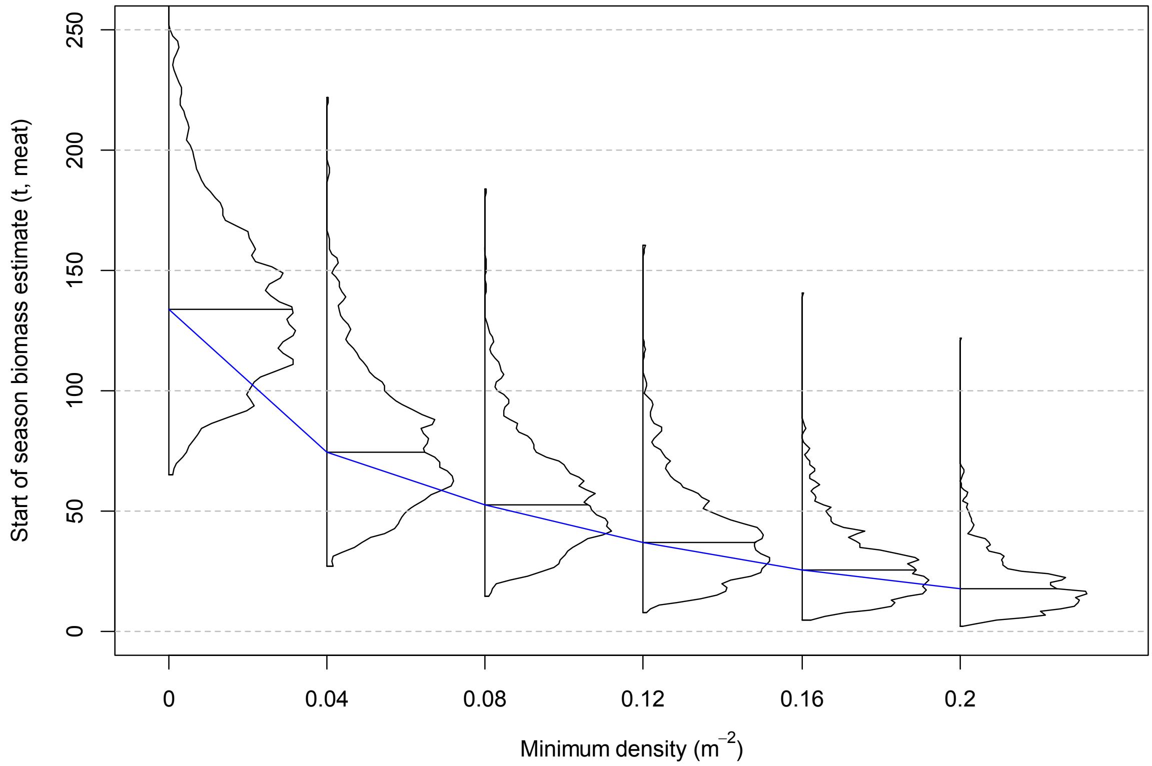
Table 8: Approximation of the relationship between density (scallops.m^{-2} of seabed) and survey catch rate (scallops per standard 0.4 n.mile survey tow using 1 dredge of 2.4 m in width), assuming a dredge efficiency of 0.56 (the ratio of relative to absolute recruited density at the time of the survey in Marlborough Sounds, January 2017).

Density (scallops.m^{-2})	Survey catch rate (scallops.tow)
0.01	10
0.04	40
0.08	80
0.10	100
0.12	119
0.16	159
0.20	199

To assess the amount of biomass held at potentially fishable densities, the survey data were reanalysed assuming that all stations where scallops were scarcer than 0.04 m^{-2} had zero density, and stations where scallops were denser than 0.04 m^{-2} had a density of the actual density minus 0.04 m^{-2}. This was conducted for critical densities in the range 0 to 0.20 scallops m^{-2}. For each critical density level, projected recruited biomass in September 2017 was calculated using the Multifan projection approach.

Projected recruited biomass in SCA 7 in September 2017 was very sensitive to the critical density levels examined (Figure 16, and Table 17 in Appendix J). In Golden Bay (excluding stratum 9b) and Tasman Bay (excluding Croisilles Harbour strata 17 and 18), there was zero recruited biomass held at a critical density of 0.04 m^{-2} or higher. Of the Marlborough Sounds absolute biomass (115 t), 64% (74 t) was held in areas with a critical density of 0.04 m^{-2} or higher, and this reduced to 46% (53 t) at 0.08 m^{-2}, and 32% (37 t) at 0.12 m^{-2}. These are median point estimates, which have increasingly large uncertainty as the critical density threshold increases (Table 17 in Appendix J).

Of the Marlborough Sounds recruited biomass available at the 0.04 m^{-2} density level, 97% was held within 10 strata (Table 17 in Appendix J). Of these 10 strata, the 7 strata that have supported commercial fishing in recent years held 90% of the recruited biomass at densities above 0.04 m^{-2} in September 2017. These 7 strata collectively represent 5 different scallop beds: Chetwodes, Wynens, Guards (2 strata), Ship (2 strata), and Dieffenbach.



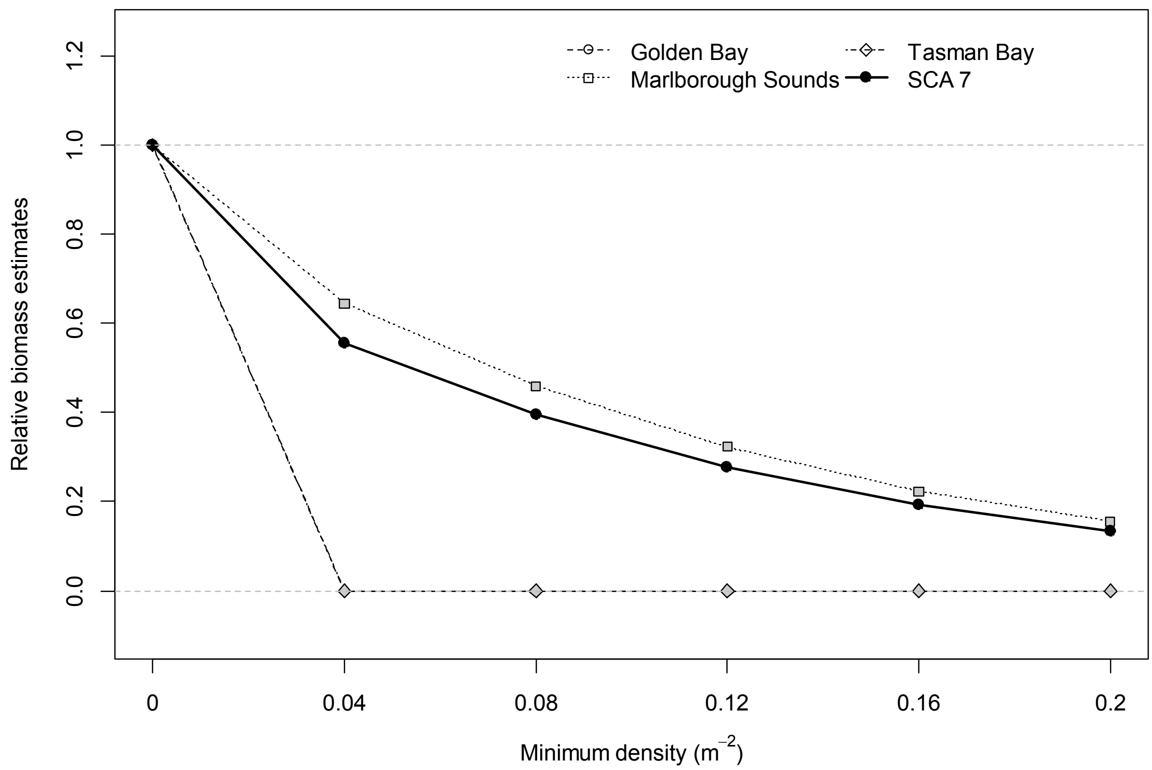


Figure 16: Effect of excluding areas of low scallop density on projected estimates of recruited biomass, SCA 7, September 2017. Estimates were produced using the Multifan projection approach. Critical density corrections were applied after correcting for dredge efficiency. Top plot: for each minimum ('critical') density, the distribution and median (horizontal line) of the recruited biomass in SCA 7 are shown. Bottom plot: Trend in the proportion of the total recruited biomass with increasing critical density, by substock: Golden Bay (circles) symbols are obscured by Tasman Bay (diamonds) symbols; Marlborough Sounds (squares); SCA 7 (black circles joined by solid black line).

4. DISCUSSION

The January 2017 survey provides the most recent information to assess the status of the SCA 7 scallop population. The key findings are that recruited biomasses in Golden and Tasman Bays (excluding Croisilles Harbour) are at negligible levels similar to those observed since the large declines in the 2000s, but that the declining trend in recruited biomass observed in Marlborough Sounds since 2009 appears to have discontinued. The size structure of the January 2017 population in Marlborough Sounds provides evidence of successful spat settlement and survival in 2016. In the area surveyed, population projections predict the Marlborough Sounds recruited biomass in September 2017 (115 t meatweight, 95% CI = 68 to 194 t) to be comparable with that in September 2015 (102 t, 95% CI = 73 to 148 t) (Williams et al. 2015a). Almost all of the Marlborough Sounds recruited biomass at potentially fishable densities (higher than $0.04 m^{-2}$, or 1 scallop per 25 m^2) is held in five scallop beds, mostly in the outer Sounds.

Substantial declines in abundance occurred between 2015 and 2017 in Tasman Bay 7H (excluding Croisilles) and at Waitata Bank in Marlborough Sounds 7L, but the potential causes of these apparent mortalities are unknown. Incursion of disease is a possibility.

Modelling of length frequency data using Multifan 32 generated new scallop growth rate estimates that were consistent with previous estimates derived from tag-return and length frequency data (Breen 1995, Cryer & Parkinson 1999, Tuck & Williams 2012). The modelling suggested that seasonality in growth was strong, with fastest growth predicted in spring, which is biologically meaningful. The possibility that size-dependent fishing mortality may have caused the Multifan analysis to underestimate L_∞ and, consequently, overestimate K (Fournier et al. 1990) cannot be discounted. Other factors that may have biased the Multifan growth estimates were insufficient cohort definition across the larger length frequency classes, and the presence of more than one cohort per year in the data as a result of multiple spawnings (Bull 1976, Williams & Babcock 2004).

Population projections from January to May and January to September 2017 enabled valid comparisons of the 2017 survey results with those of recent previous surveys. Projected estimates and their associated levels of uncertainty must be treated cautiously in the light of inherent uncertainty in estimated growth and natural mortality. However, whereas the May projected biomass estimates from the 2017 January surveys varied depending on the seasonal growth assumptions, there was little difference between the September projected estimates.

5. FUTURE WORK

The January 2017 survey was implemented at short notice, and the design was largely based on that conducted in May 2015. Although fewer stations than planned were sampled due to bad weather, the survey estimates in almost all of the scallop beds achieved acceptably high precision. Further improvements in the precision of estimates could be possible with restratification in some areas, and this, along with agreement over the overall survey coverage, should be conducted before further surveys are undertaken, as recommended previously (Williams et al. 2015b).

Many of the SCA 7 survey strata have held very few or no scallops, particularly so in recent years. Excluding low catch-rate strata from the design of the future survey programme and refocussing sampling effort in 'core areas' which contain the main scallops beds is recommended (Smith et al. 2016). Surveys using the larger historical extent could be conducted periodically to inform whether there has been any recovery in areas that lie outside the core areas.

Scallop populations in almost all parts of Golden and Tasman Bays have remained at extremely low levels for the last 5–10 years, the period producing the lowest recruited biomasses since surveys began in 1994. This is in stark contrast to the former high productivity of these areas, especially in Golden Bay which historically supported the majority of commercial scallop fishing in SCA 7 (Williams et al. 2014). The causes of the declines are unclear but are likely to be a combination of anthropogenic and environmental effects. Workshops with iwi and fisheries stakeholders were held in 2012 and 2013 to initiate a review of potential drivers of shellfish production and to identify critical knowledge gaps (Michael et al. 2015). Potential drivers included: the roles of sediments; climate and weather effects on oceanography and currents; primary production; benthic communities; and the effects of fishing, disease, toxins and pollutants. The review made a number of recommendations for future research to inform rebuilding of shellfish fisheries production. New work is now required to secure sufficient funding to undertake the research recommended.

The Multifan growth analysis was conducted within a limited time frame using the available data for three key scallop beds in Marlborough Sounds. Further exploration of scallop growth using Multifan could be undertaken using existing data, such as the full set of length frequency data from Bull (1976). We also recommend collecting new data for estimating growth, and updating the growth estimates used in assessments accordingly. More frequent sampling of key beds using short-duration surveys (e.g. 2–3 days every 2–3 months) would provide length frequency data for estimating how mean growth varies among areas. The 2015 surveys in May, October, and November illustrate how the timing of sampling is important for detecting the modal progression of smaller scallops as they grow during the year. Conducting regular tagging in the key beds would provide increment data for improving estimates of mean growth and growth variability. Additional study of growth patterns in the shell rings (microstriae) would improve our understanding of scallop growth.

The current target exploitation reference point (U = 22%) for the Marlborough Sounds (Ministry for Primary Industries 2016a) was derived from a previous analysis (Williams et al. 2015a) examining historical commercial fishery exploitation rates over a period of stable or increasing biomass, but over quite large spatial scales. We recommend that new work is needed to develop appropriate target and limit reference points for scallops which explicitly consider the importance of spatial density and differences in productivity among areas at the scale of scallop beds (or at least across similar beds).

6. ACKNOWLEDGEMENTS

This work was funded by the Ministry for Primary Industries (MPI) through project SEA201607. Special thanks to the survey skipper Cris West and crew for their help in conducting the dredge survey aboard the chartered commercial fishing vessel FV *Rongatea II*, and to Grant Roberts (Rongo Marie Ltd) for coordinating the charter arrangements. We are grateful to members of the Shellfish Fisheries Working Group for their appraisal of the survey methods and results, and to Jeremy McKenzie for reviewing an earlier draft of this report.

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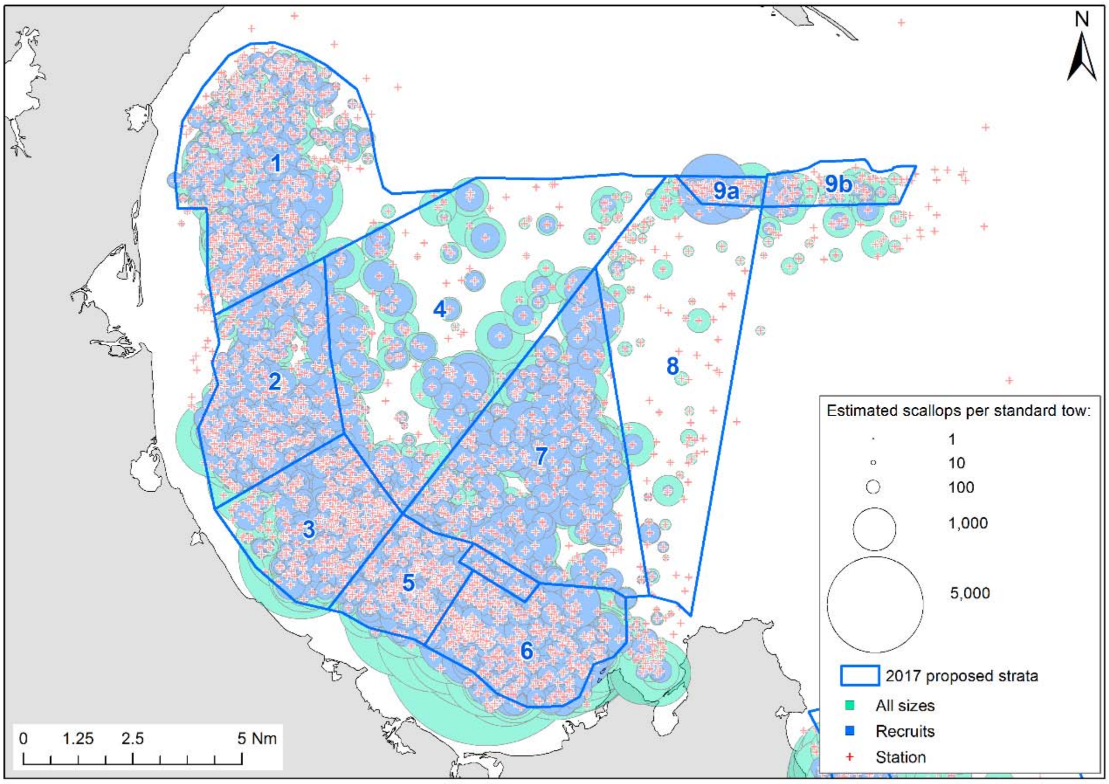
8. APPENDIX A: January 2017 strata vs abundance 1994–2015



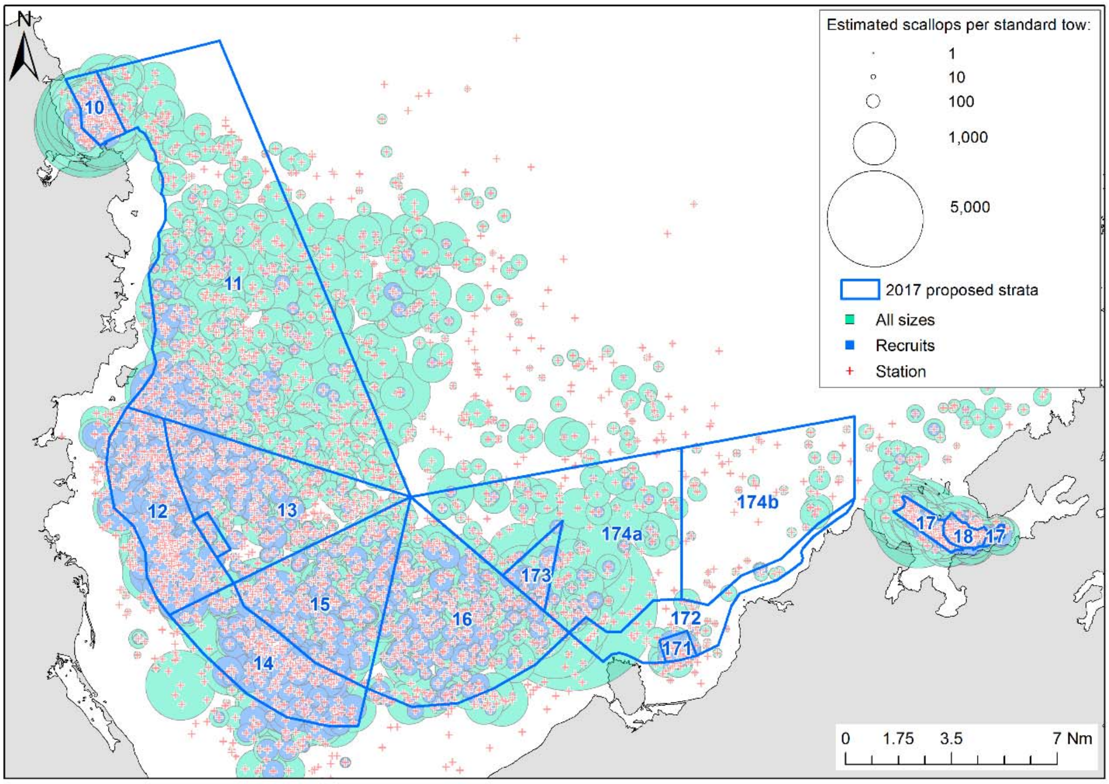
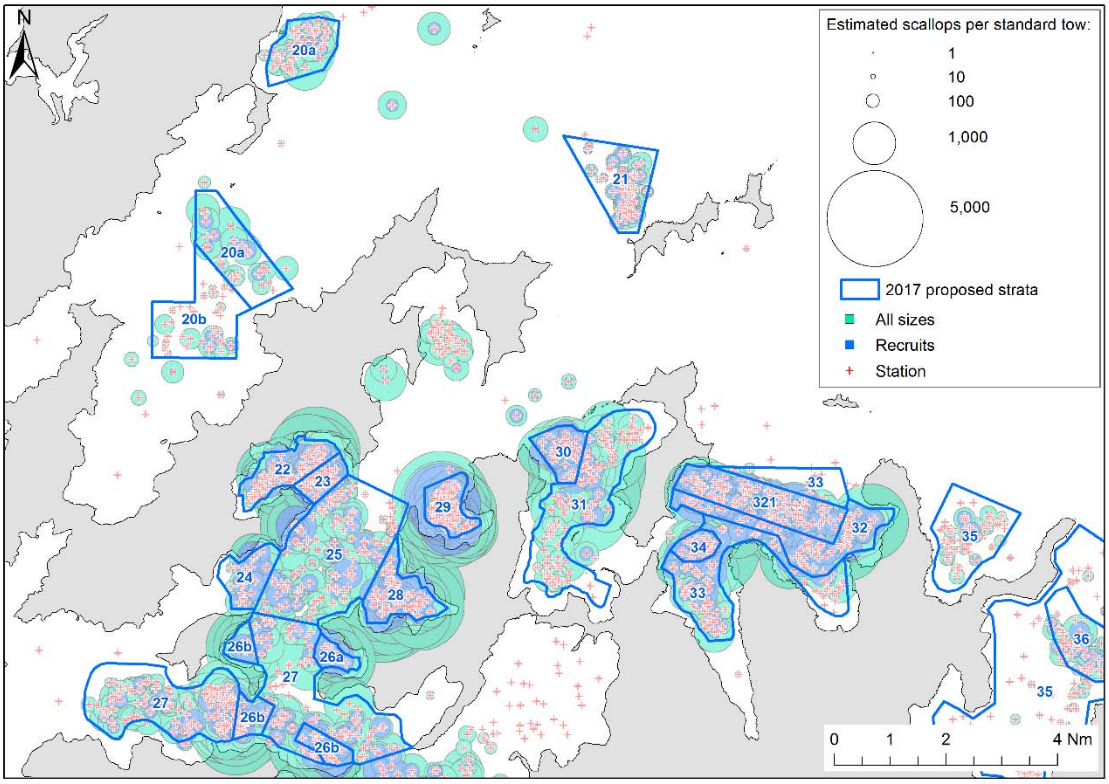


Figure 17: Stratification for the SCA 7 survey, January 2017: Golden Bay (top) and Tasman Bay (bottom) (Marlborough Sounds strata are shown in Figure 3). Circles show the abundance of recruited scallops (90 mm or larger shell length; dark shaded circles) and scallops of any size (light shaded circles) caught in <u>all previous SCA 7 surveys (1994–2015)</u>, crosses denote tow positions. Circle area is proportional to the number of scallops per standard tow (0.4 n.mile in length), uncorrected for dredge efficiency.



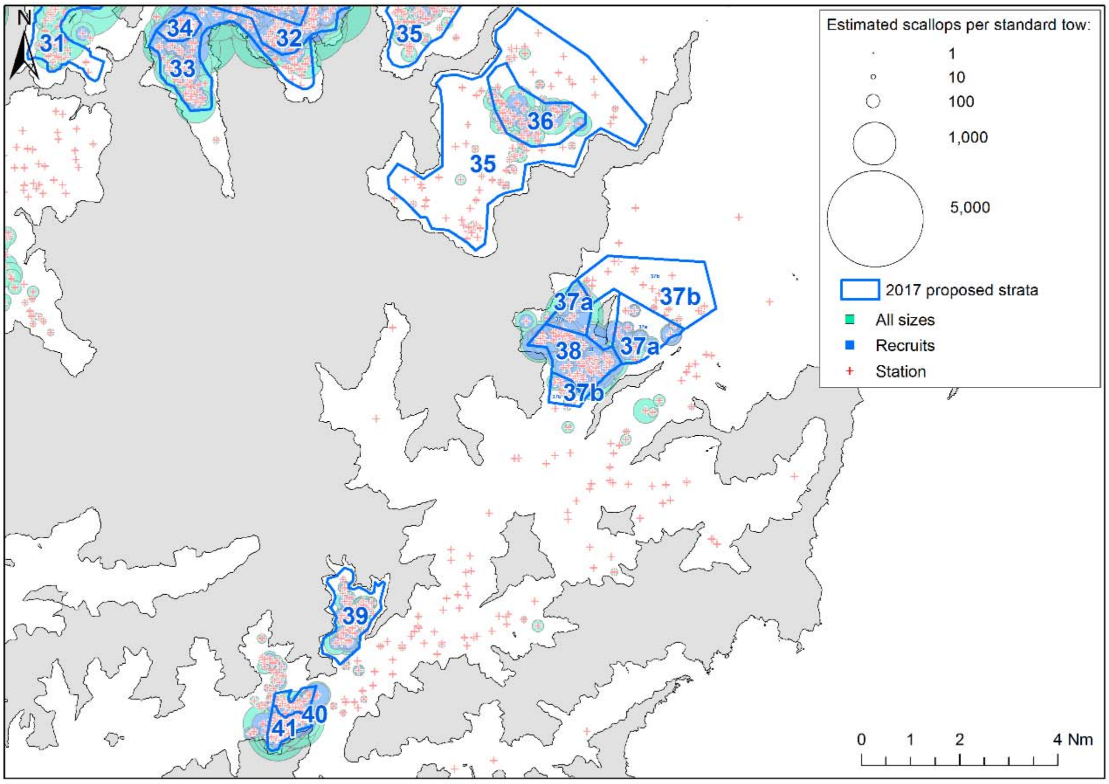
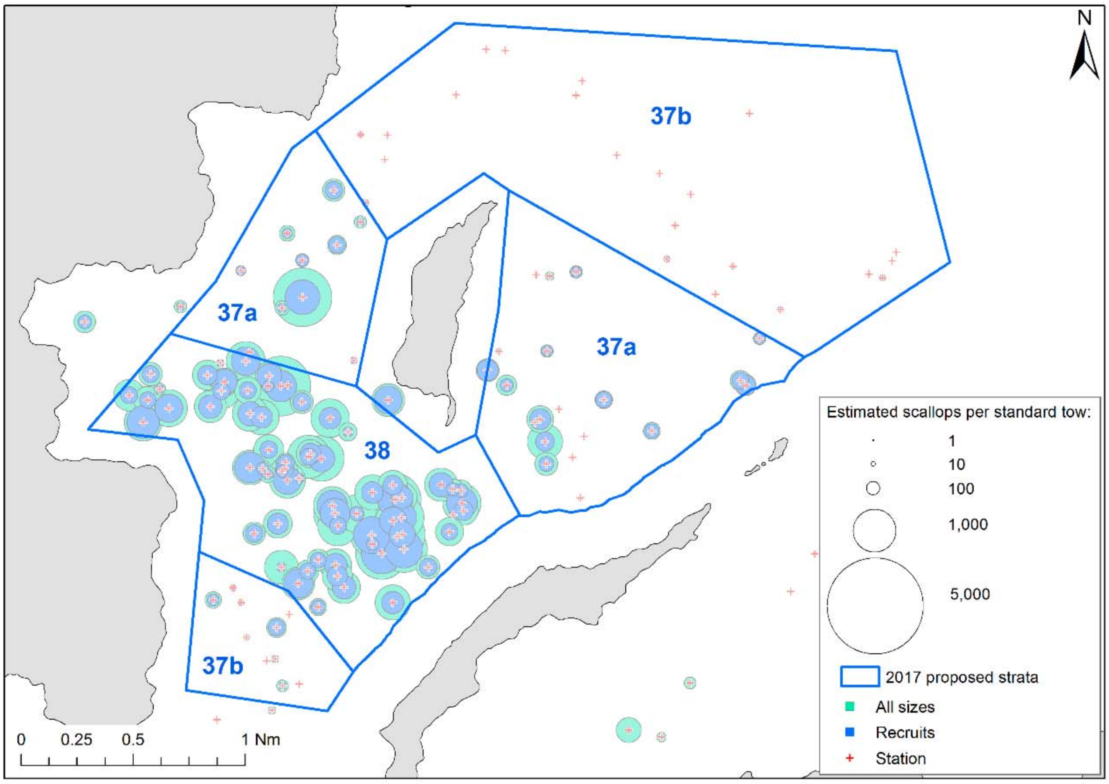


Figure 18: Stratification for the SCA 7 dredge survey, January 2017 in Marlborough Sounds: 7K Pelorus Sound (top) and 7L Queen Charlotte Sound (bottom) (Golden and Tasman Bay strata are shown in Figure 2). Strata 20, 26, 27, 33, 35, 37a and 37b are each made up of geographically separate (non-contiguous) areas that combine to form a single stratum. Circles show the abundance of recruited scallops (90 mm or larger shell length; dark shaded circles) and scallops of any size (light shaded circles) caught in <u>all previous SCA 7 surveys (1994–2015)</u>, crosses denote tow positions. Circle area is proportional to the number of scallops per standard tow (0.4 n.mile in length), uncorrected for dredge efficiency.



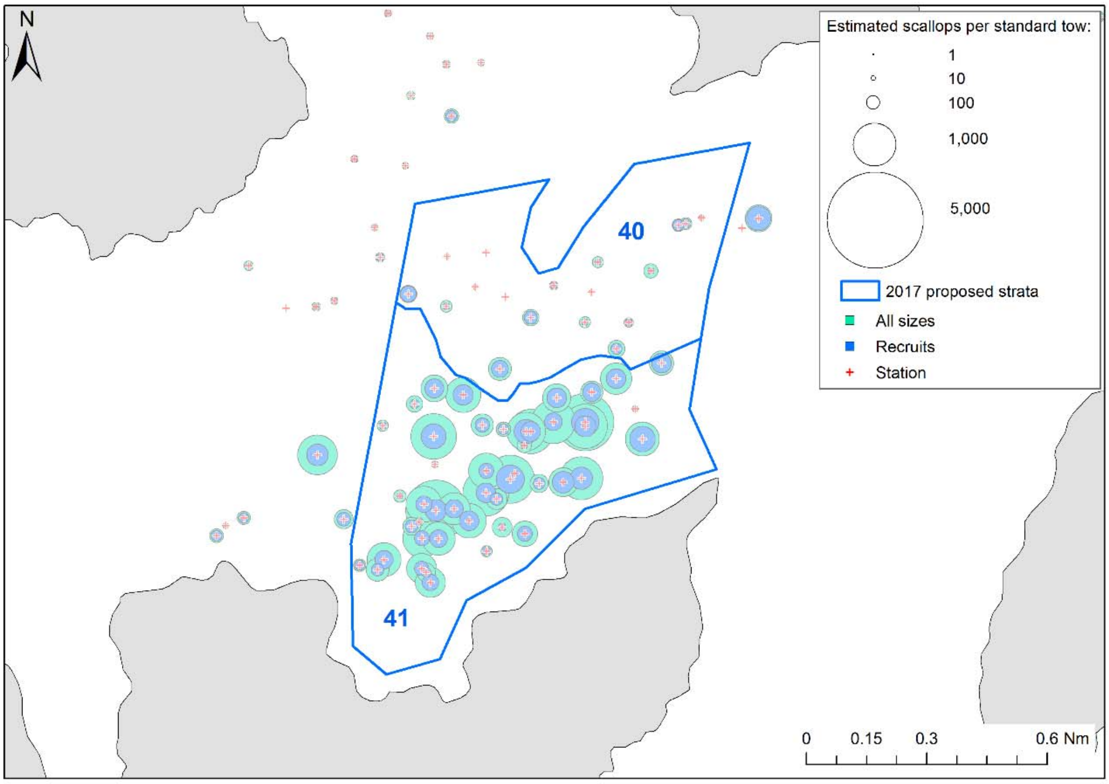


Figure 19: Stratification for the SCA 7 dredge survey, January 2017: Ship Cove / Motuara Island (top) and Dieffenbach Point (bottom) in Queen Charlotte Sound. Solid blue polygons denote the boundaries of the proposed strata for the 2017 survey; dashed lines show the boundaries of the May 2015 survey for comparison. Circles show the abundance of recruited scallops (90 mm or larger shell length; dark shaded circles) and scallops of any size (light shaded circles) caught in <u>all previous SCA 7 surveys (1994–2015)</u>, crosses denote tow positions. Circle area is proportional to the number of scallops per standard tow (0.4 n.mile in length), uncorrected for dredge efficiency.

9. APPENDIX B: Boxplots of scallop density by stratum

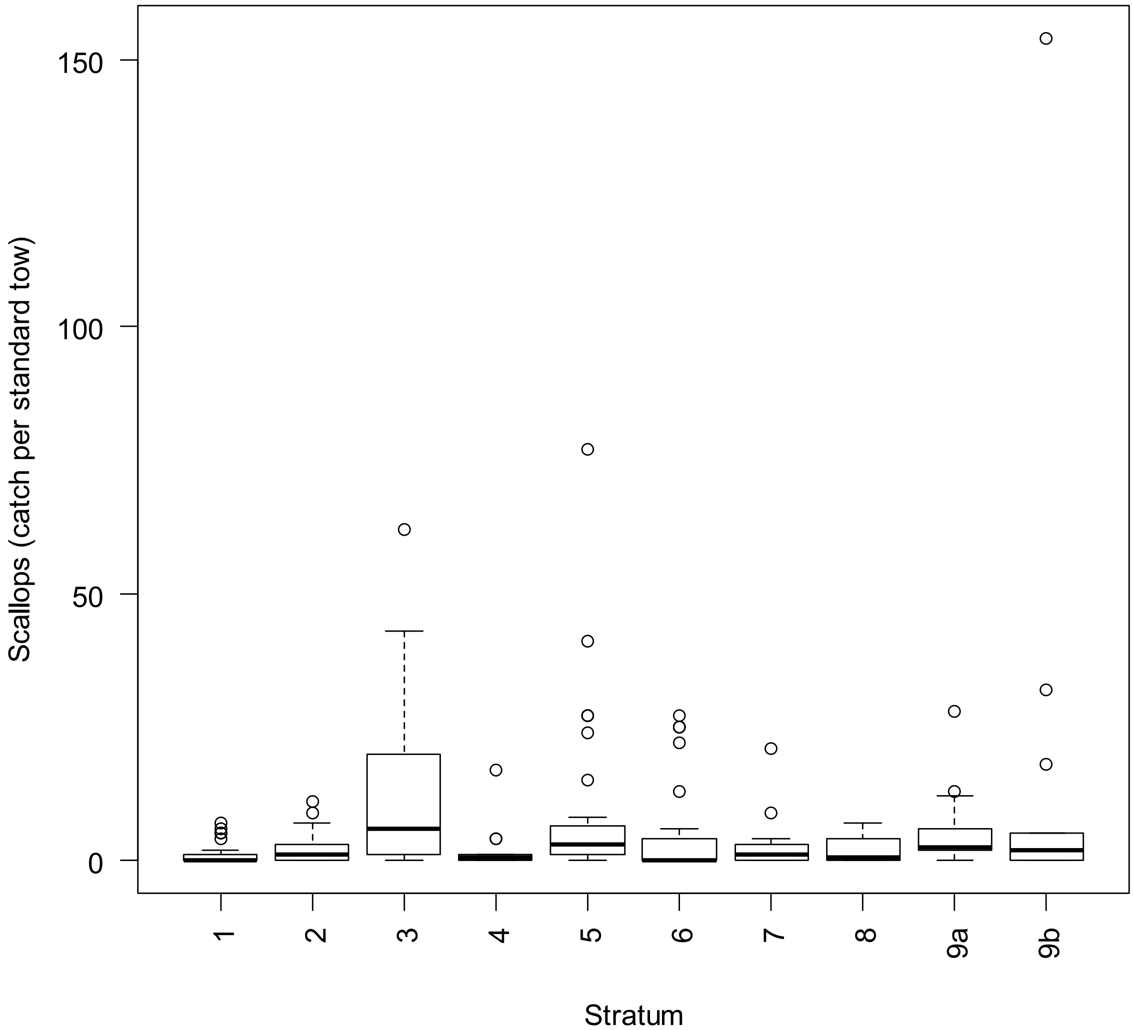


Figure 20: Boxplot of scallop density (recruited scallops per standard 0.4 n.mile tow) in Golden Bay (2011–2015 surveys) by stratum (proposed 2017 stratification).

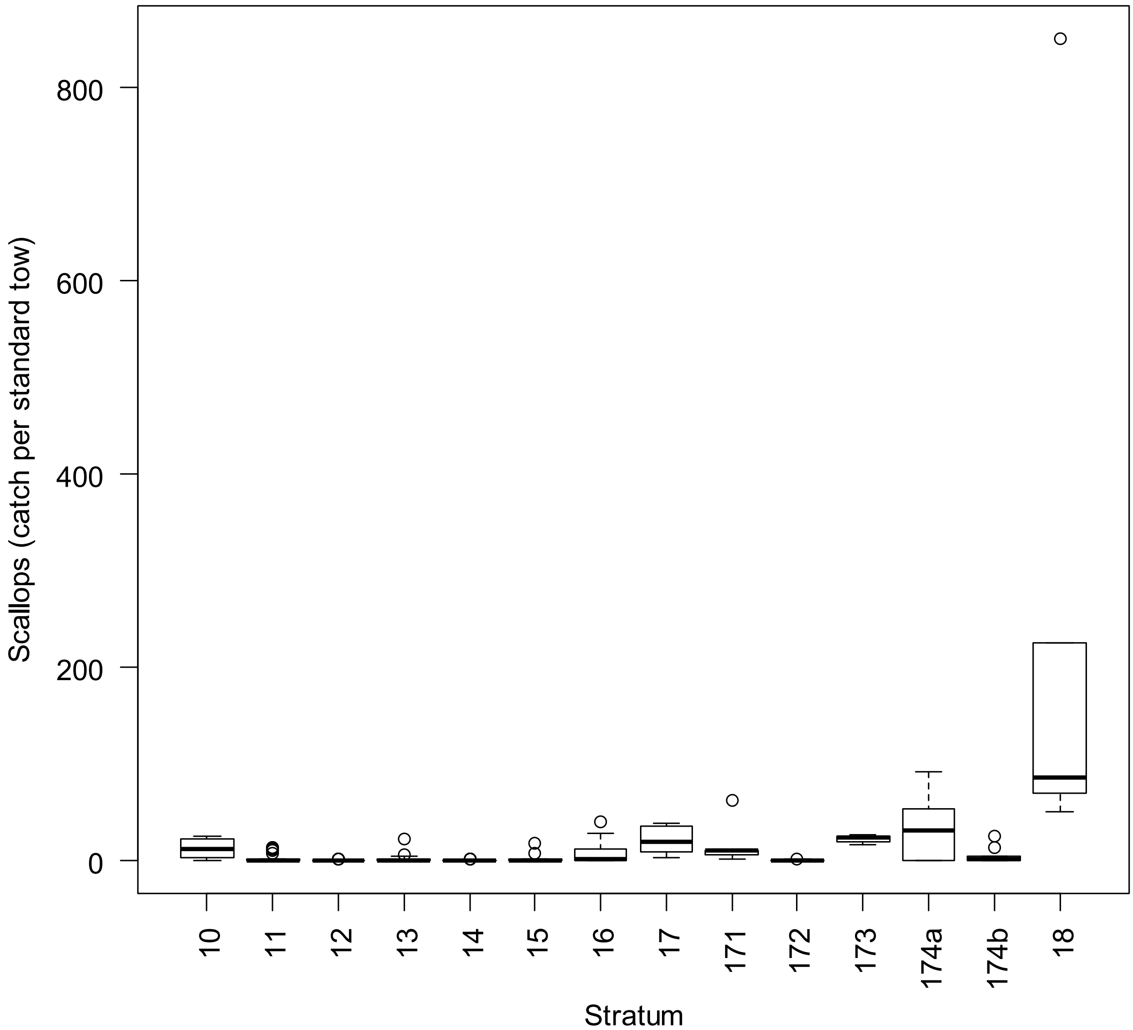


Figure 21: Boxplot of scallop density (recruited scallops per standard 0.4 n.mile tow) in Tasman Bay (2011–2015 surveys) by stratum (2017 stratification).

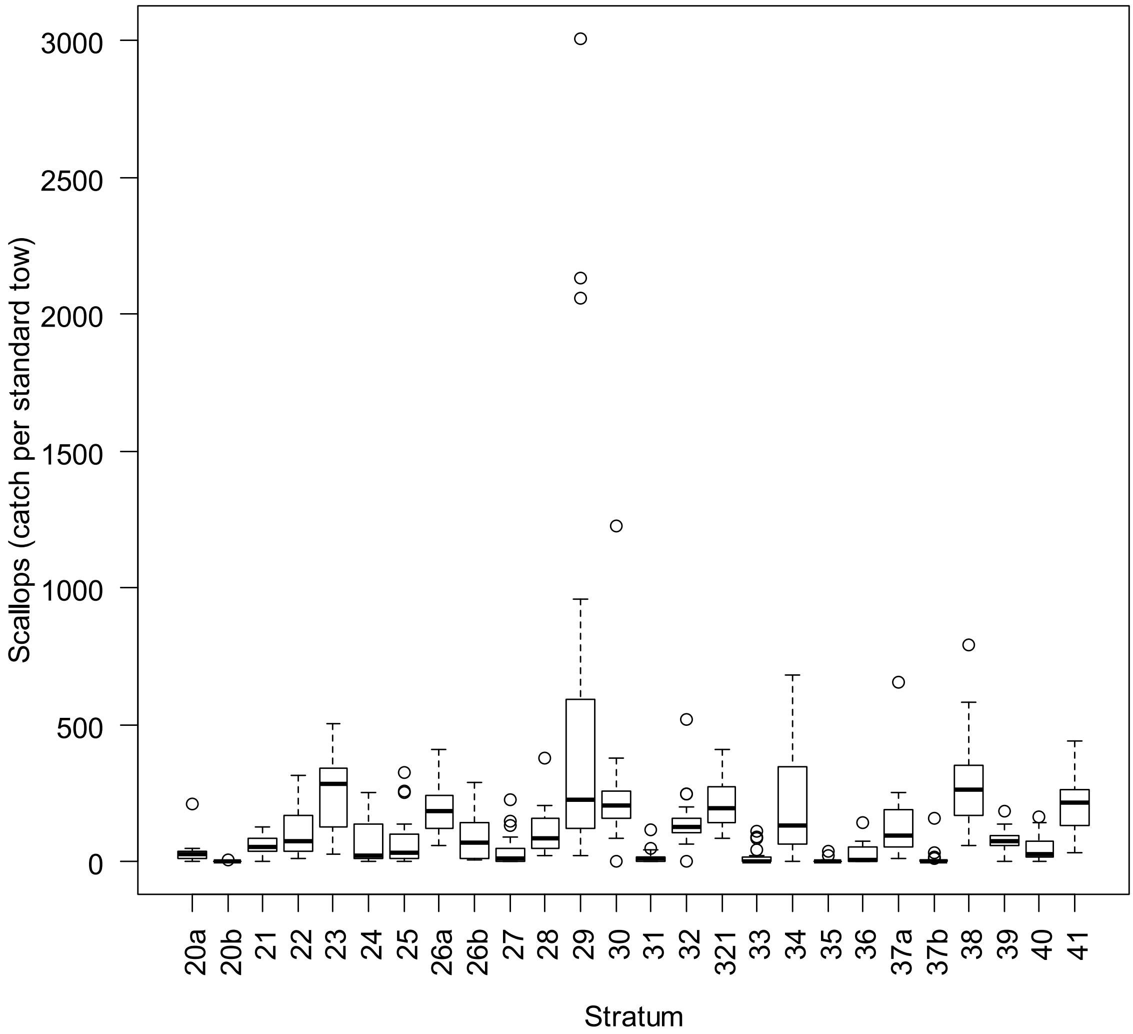


Figure 22: Boxplot of scallop density (recruited scallops per standard 0.4 n.mile tow) in Marlborough Sounds (2011–2015 surveys) by stratum (2017 stratification).

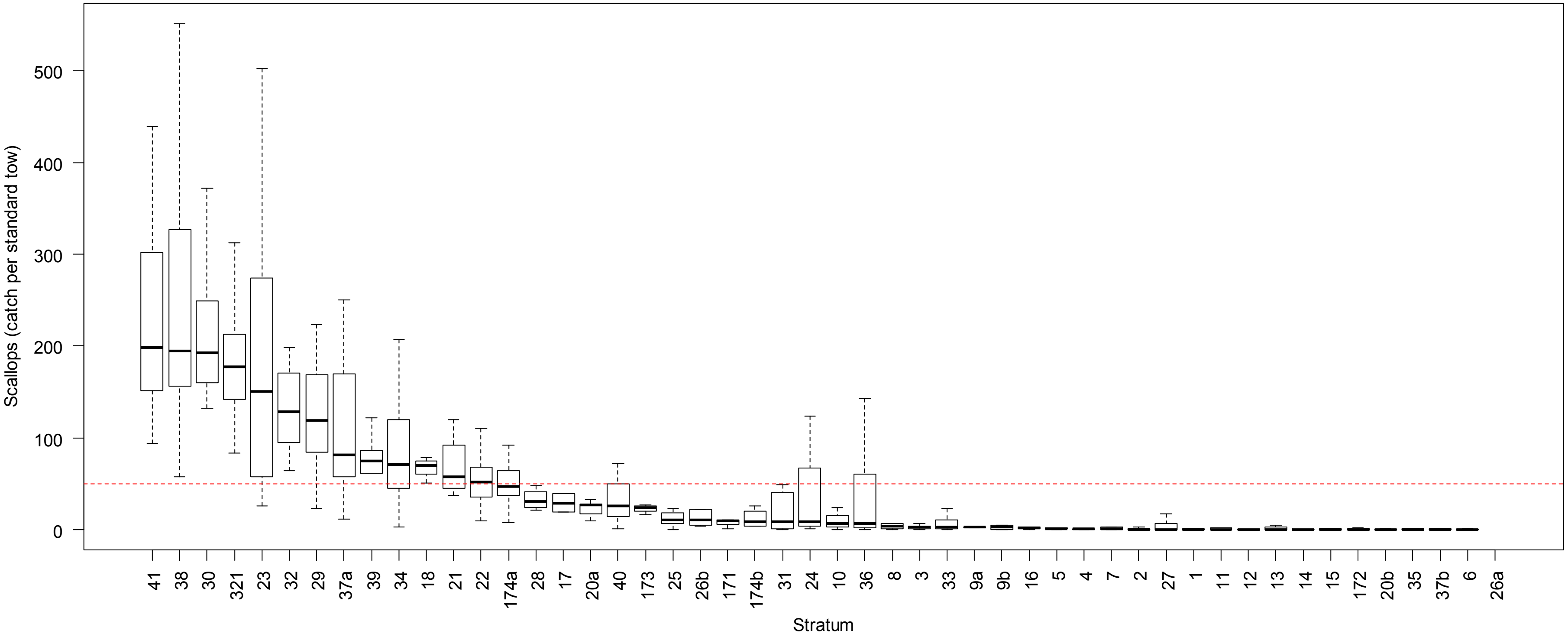


Figure 23: Boxplot of scallop density (recruited scallops per standard 0.4 n.mile tow, 2015 surveys) by stratum (2017 stratification) in decreasing order of median density (x-axis left to right). Outliers have been excluded. Horizontal dashed line denotes a median density of 50 recruited scallops per standard tow. Strata with a median density of 100 or more recruited scallops per tow (median at or above the dashed line) are those of particular interest on the survey.

10. APPENDIX C: Station allocation, January 2017 survey

First, allocations were run using a target CV of 20% (17% specified in *allocate*) for the different spatial area levels (Table 9), including nine scallop beds (strata or groups of strata) of particular interest because they held the highest densities (50 or more recruited scallops per standard tow) in the most recent (2015) surveys (see Figure 23, Appendix B).

Table 9: Number of stations required to achieve a CV of 20% ('CV-limit') at different spatial levels of interest. Analysis conducted with the R function *allocate* (Francis 2006) specifying a CV of 17% and using recruited scallop catch densities from 2011–2015 assigned to the proposed 2017 survey strata.

Level	Code	Name	Stations (n)	CV (%)
Stock	SCA 7	Southern Scallop Stock	150	9.4
Substock	GB	Golden Bay	54	16.9
	TB	Tasman Bay	54	16.7
	MS	Marlborough Sounds	78	8.9
Sector	7H	Golden Bay 7H	33	16.8
	7K	M. Sounds 7K	60	9.9
	7L	M. Sounds 7L	21	16.6
Bed	17, 18	Croisilles	6	16.1
	21	Chetwodes	8	16.5
	22, 23	Waitata Bay	12	16.8
	29	Ketu Bay	8	16.4
	30	Wynens Bank	8	16.2
	32, 321, 33, 34	Guards Bay	12	15.5
	37a, 37b, 38	Ship Cove	18	16.7
	39	Bay of Many Coves	8	16.8
	40, 41	Dieffenbach Point	10	16.9

Second, given that a minimum of about 20 stations can be sampled per day of the survey, allocations were also run by specifying a fixed number of stations for each substock (Table 10). The minimum station limit for each level is three times the number of strata in that level (minimum of n = 3 stations per stratum). To achieve a CV of less than 20% at the SCA 7 stock level, a minimum of 7 days sampling were required; to achieve a CV of 20% or less at each substock level, at least 9 days sampling were required (2 days at Golden Bay, 3 days at Tasman Bay, and 4 days at M. Sounds).

Table 10: Predicted CV with a fixed number of stations ('n-limit') at the stock and substock levels. Analysis conducted with the R function *allocate* (Francis 2006) using recruited scallop catch densities from 2011–2015 assigned to the proposed 2017 survey strata.

Level	Code	Name	n-limit	CV (%)
Stock	SCA 7	Southern Scallop Stock	150	9.4
			160	7.7
			180	6.6
			200	6.1
			220	5.6
Substock	GB	Golden Bay	30	25.0
			40	20.0
			60	16.0
			80	13.8
			100	12.3
	TB	Tasman Bay	42	27.3
			60	15.0
			80	12.1
			100	10.5
	MS	Marlborough Sounds	78	8.9
			80	8.5
			100	6.9
			120	6.1

Given the tight timeframe required by MPI for completion of the survey, a maximum of about 10 days of survey time was available. We proposed to have 2 days in Golden Bay (40 stations), 3 days in Tasman Bay (60 stations), and 5 days in Marlborough Sounds (120 stations should be possible given the short steaming distances in the Sounds). The optimal allocation to minimise the CV by having these fixed numbers of stations by substock (Table 11, 'Base' allocation, n = 220 stations) put a lot of sampling effort (16 stations) in stratum 174a (Tasman Bay sector 7H deep west; Figure 2) which is a large area that held patchily distributed scallops in the period of interest (2011–2015 surveys), while the other strata required 3 to 10 stations per stratum. This base allocation optimised the CV at the level of each overall substock, but in the Marlborough Sounds it did not allocate enough stations to some strata to attain the target CV of 20% at the bed level for some of the beds of interest (Table 11). It also allocated more stations than could realistically be sampled in some strata with small areas.

To address this, the base allocation was re-run using an n-limit of 80 stations in Marlborough Sounds, and sampling effort was increased in key strata within that substock in accordance with the minimum required to meet the 20% CV-limit at the spatial area levels of interest (i.e. those listed in Table 11). This produced the 'bed' allocation (Table 11, 'Bed' allocation), which required 217 stations. The bed allocation was modified slightly to put 1 less station in each of strata 21 (Chetwodes), and 22 and 23 (Waitata), and 3 more stations in each of 32 (Guards Bank) and 321 (Guards Bank Outer) to produce the proposed allocation for the 2017 survey (Table 11, 'Proposed allocation', n = 220 stations). The proposed allocation in theory met the target CV for all of the spatial area levels of interest (Table 12).

Table 11: Allocation of stations to strata for the January 2017 survey of SCA 7.

Substock	Stratum	'Base' allocation n = GB40, TB60, MS120	'Bed' allocation n = GB40, TB60, MS117	Proposed allocation n = GB40, TB60, MS120
Golden Bay	1	3	3	3
	2	3	3	3
	3	7	7	7
	4	4	4	4
	5	4	4	4
	6	4	4	4
	7	4	4	4
	8	3	3	3
	9a	3	3	3
	9b	5	5	5
Tasman Bay	10	3	3	3
	11	8	8	8
	12	3	3	3
	13	3	3	3
	14	3	3	3
	15	3	3	3
	16	3	3	3
	171	3	3	3
	172	3	3	3
	173	3	3	3
	174a	16	16	16
	174b	3	3	3
	17	3	3	3
	18	3	3	3
Marlborough	20a	4	3	3
Sounds	20b	3	3	3
	21	3	8	7
	22	3	6	5
	23	3	6	5
	24	3	3	3
	25	9	3	3
	26a	3	3	3
	26b	5	3	3
	27	8	3	3
	28	3	3	3
	29	10	8	8
	30	4	8	8
	31	3	3	3
	32	5	3	6
	321	7	3	6
	33	5	3	3
	34	3	3	3
	35	3	3	3
	36	3	3	3
	37a	10	8	8
	37b	3	3	3
	38	8	7	7
	39	3	8	8
	40	3	3	3
	41	3	7	7

Table 12: Predicted CVs using the 'Proposed allocation', for the key spatial levels of interest.

Level	Code	Name	Stations (n)	CV (%)
Stock	SCA 7	Southern Scallop Stock	220	6.4
Substock	GB	Golden Bay	40	20.0
	TB	Tasman Bay	60	15.1
	MS	Marlborough Sounds	120	7.2
Sector	7H	Tasman Bay 7H	34	16.4
	7K	M. Sounds 7K	84	8.5
	7L	M. Sounds 7L	36	13.1
Bed	17, 18	Croisilles	6	16.1
	21	Chetwodes	7	17.7
	22, 23	Waitata Bay	10	18.4
	29	Ketu Bay	8	16.4
	30	Wynens Bank	8	16.2
	32, 321, 33, 34	Guards Bay	18	12.5
	37a, 37b, 38	Ship Cove	18	16.7
	39	Bay of Many Coves	8	16.8
	40, 41	Dieffenbach Point	10	16.9

11. APPENDIX D: SCA 7 survey vessels

Table 13: Vessels, masters, and dredge details for SCA 7 surveys since 1994.
–, unknown at time of writing. FV *Rongatea II* is 42 ft (12.8 m) in length and has a 110 horsepower (hp) Gardner engine, and FV *Okarito* is 47 ft (14.37 m) in length and has a 180 hp GM engine; both vessels have similar dredging capability for conducting the survey (and both have been core vessels used in the commercial SCA 7 fishery).

Trip code	Year	Survey type	Vessel	Master	Dredge type and width
hin9401	1994	Pre-season	*Hinewai*	–	MAF ring-bag, 2.45 m
tas9501	1995	Pre-season	*Tasman Challenger*	Paul Botica	MAF ring-bag, 2.45 m
tas9601	1996	Pre-season	*Tasman Challenger*	–	MAF ring-bag, 2.45 m
tas9701	1997	Pre-season	*Tasman Challenger*	–	CSEC ring-bag, 2.40 m
tas9801	1998	Pre-season	*Tasman Challenger*	Paul Botica	CSEC ring-bag, 2.40 m
tas9901	1999	Pre-season	*Tasman Challenger*	–	CSEC ring-bag, 2.40 m
tas0001	2000	Pre-season	*Tasman Challenger*	–	CSEC ring-bag, 2.40 m
tas0101	2001	Pre-season	*Tasman Challenger*	–	CSEC ring-bag, 2.40 m
tas0201	2002	Pre-season	*Tasman Challenger*	Paul Botica	CSEC ring-bag, 2.40 m
tas0301	2003	Pre-season	*Tasman Challenger*	Paul Botica	CSEC ring-bag, 2.40 m
tas0401	2004	Pre-season	*Tasman Challenger*	Paul Botica	CSEC ring-bag, 2.40 m
tas0501	2005	Pre-season	*Tasman Challenger*	Paul Botica	CSEC ring-bag, 2.40 m
tas0601	2006	Pre-season	*Tasman Challenger*	Paul Botica	CSEC ring-bag, 2.40 m
fal0701	2007	Pre-season	*Falcon III*	–	CSEC ring-bag, 2.40 m
cal0801	2008	Pre-season	*Calypso*	Phillip Trewavas	CSEC ring-bag, 2.40 m
oka0901	2009	Pre-season	*Okarito*	Grant Roberts	CSEC ring-bag, 2.40 m
oka1001	2010	Pre-season	*Okarito*	Grant Roberts	CSEC ring-bag, 2.40 m
oka1101	2011	Pre-season	*Okarito*	Cris West	CSEC ring-bag, 2.40 m
oka1201	2012	Pre-season	*Okarito*	Cris West	CSEC ring-bag, 2.40 m
oka1301	2013	Pre-season	*Okarito*	Cris West	CSEC ring-bag, 2.40 m
oka1302	2013	In-season (Ketu)	*Okarito*	Cris West	CSEC ring-bag, 2.40 m
oka1401	2014	Pre-season	*Okarito*	Cris West	CSEC ring-bag, 2.40 m
oka1402	2014	In-season (Guards)	*Okarito*	Cris West	CSEC ring-bag, 2.40 m
oka1501	2015	Pre-season (MS, TB)	*Okarito*	Cris West	CSEC ring-bag, 2.40 m
ron1501	2015	Pre-season (GB, 7H)	*Rongatea II*	Cris West	CSEC ring-bag, 2.40 m
oka1502	2015	In-season (MS areas)	*Okarito*	Cris West	CSEC ring-bag, 2.40 m
oka1503	2015	Post-season	*Okarito*	Cris West	CSEC ring-bag, 2.40 m
ron1701	2017	January	*Rongatea II*	Cris West	CSEC ring-bag, 2.40 m

12. APPENDIX E: Biological considerations

Scallops reproduce by broadcast spawning, with larval development over 3–4 weeks, before settlement and metamorphosis occur. *Pecten novaezelandiae* has an extended spawning period, but major spawnings are typically in spring and summer. The main information on scallop reproduction in SCA 7 comes from a PhD study of *P.novaezelandiae* biology in the Marlborough Sounds (Bull 1976). Bull found that peak spawning at sites in the outer part of Pelorus Sound (North West Bay and Forsyth Bay) occurred in November–December in 1973 and 1974 (although some spawning occurred between August and March), with maximum spat settlement observed in December–January; he predicted a January origin of 0+ year class modes in those years. This information is important because it informs how old scallop spat are likely to be when they are first observed in the SCA 7 survey catches.

Growth of *P.novaezelandiae* is relatively fast but highly variable (Cryer & Parkinson 1999). Variability in growth might be expected both temporally (e.g., among seasons and years) and spatially (e.g., among sites and depths) because of differences in habitat suitability. This is probably determined by the interaction of multiple environmental and biological variables. Of primary importance are those which affect food availability: scallops are sedentary suspension feeders which rely on phytoplankton and suspended benthic microalgae for food (Macdonald et al. 2006).

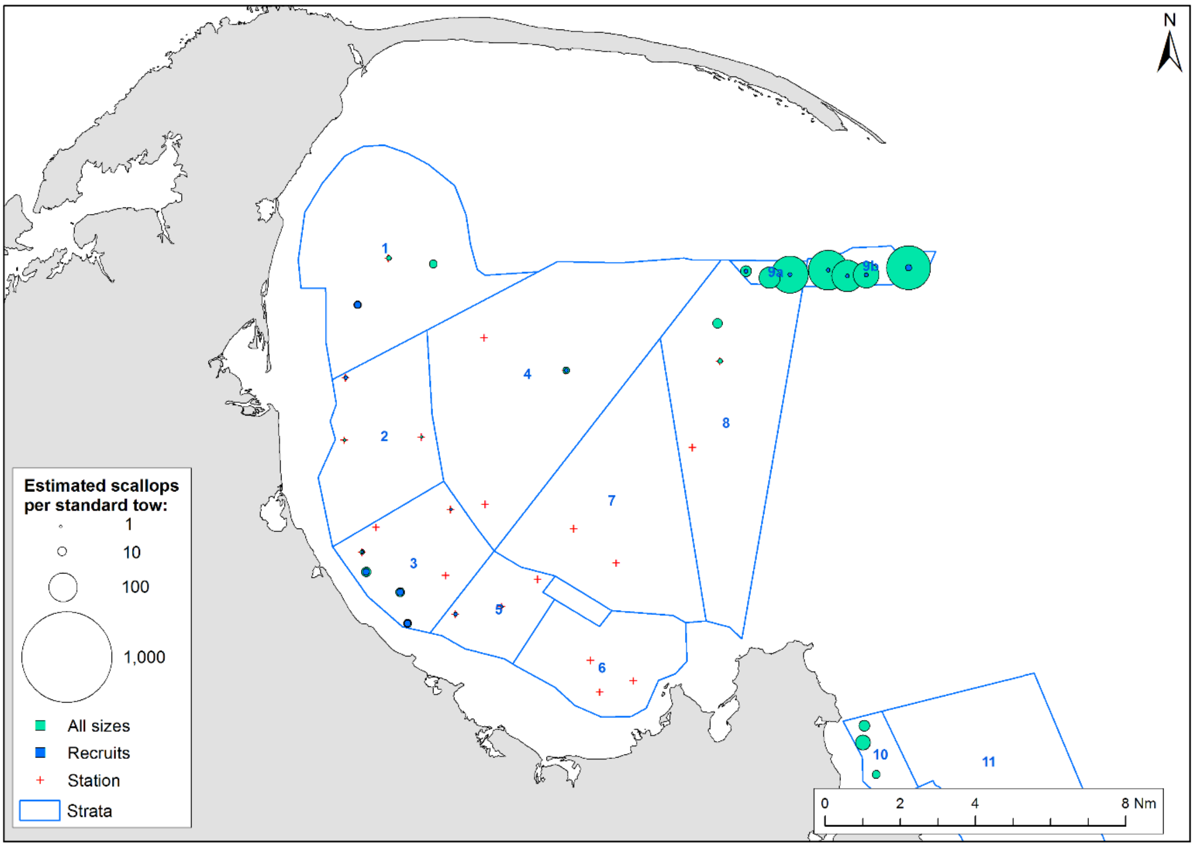
Growth has been estimated from data collected by a variety of tagging and length frequency studies. Tuck & Williams (2012) analysed the available tag-return length increment data using an inverse-logistic growth model (Haddon et al. 2008). The seasonal implementation of the model consistently fitted the data better, with maximum shell growth predicted at the end of October. Variability in predicted growth increment was high, but initial growth was very fast: the mean annual growth increment for a 40 mm scallop was predicted to be 51 mm from model fits to 2000s tag-return data (or 72 mm predicted from model fits to 1980s tag-return data, which suggested growth in the 1980s may have been faster than in the 2000s). Data on the predicted mean annual growth increment at length from the inverse-logistic model were used in the present study to inform how much growth could be expected in the periods between the 2014–2017 surveys in SCA 7. For example, applying 51 mm of expected growth to the 40 mm mode cohort observed at Ship Cove in Marlborough Sounds in October 2015 (Figure 13) suggests that the modal size in October 2016 would have been 91 mm, and larger again by January 2017.

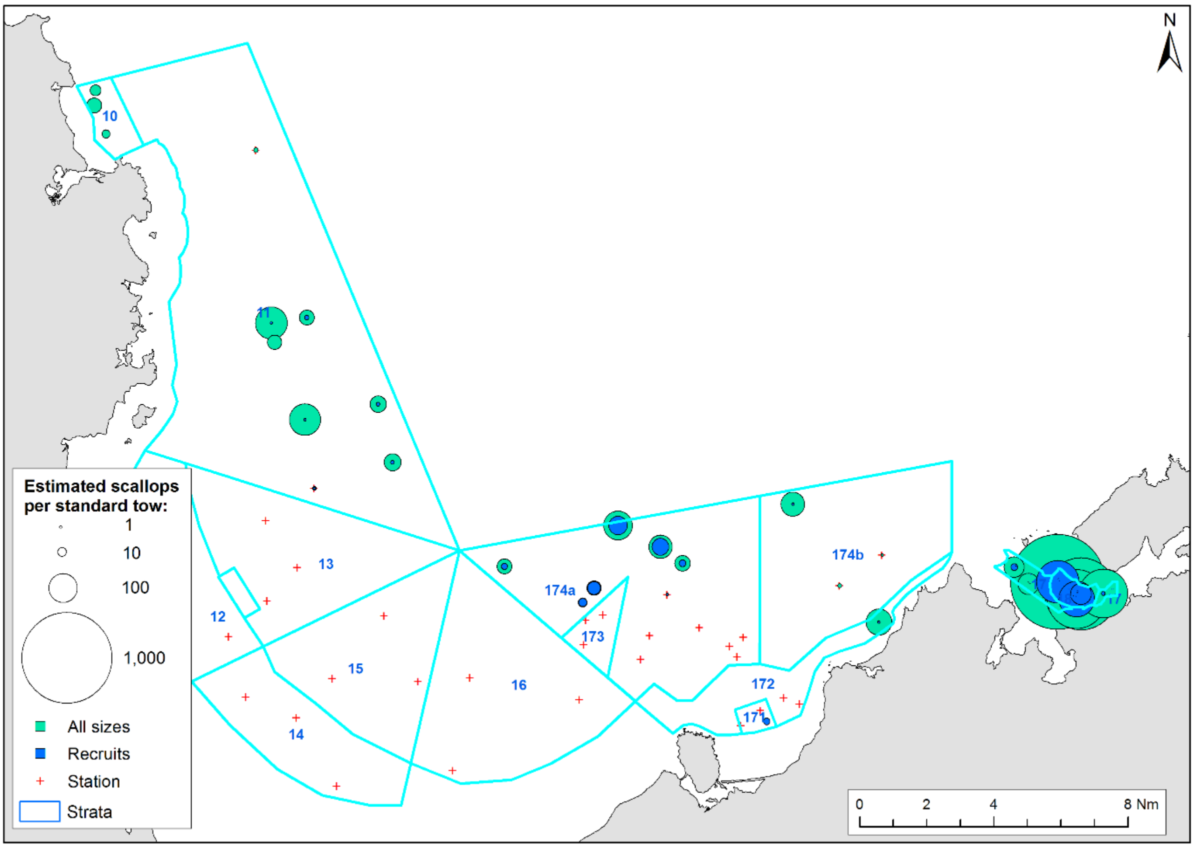
Few tag-recapture growth increments (n = 59 from the 2000s) are available from within SCA 7, but modelling these SCA 7 data together with SCA CS data revealed no consistent patterns in the residuals between the SCA 7 and SCA CS areas, suggesting that the estimated model parameters appropriately describe scallop growth in each of the areas (Tuck & Williams 2012).

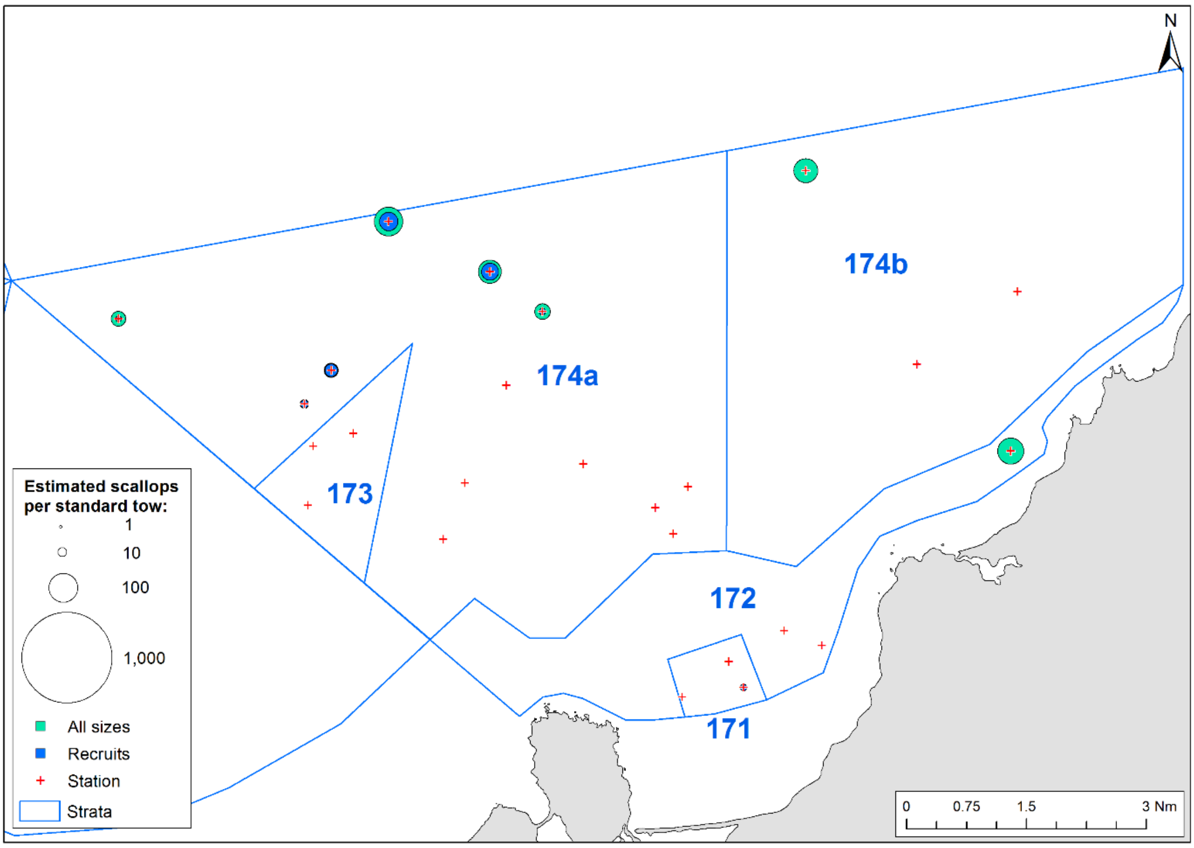
Length frequency data from Bull (1976) have been analysed previously to estimate growth. Breen (1995) used a subset of length frequency data (Bull's figure 5.6) to provide a rough first approximation of von Bertalanffy growth for scallops in North West Bay, Pelorus Sound (K = 0.4, L_∞= 144). Breen assumed L_∞ was equal to the maximum size observed by Bull, thus L_∞ = 144 may be an overestimate.

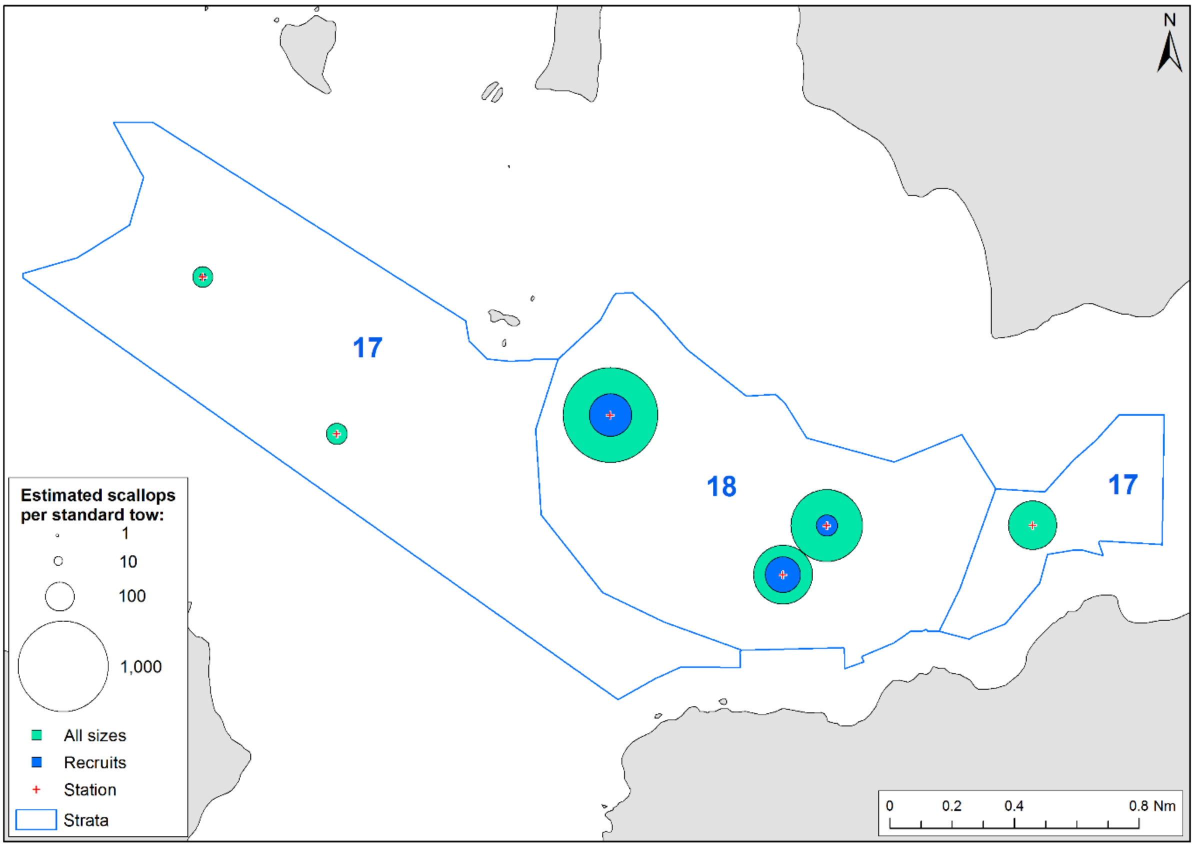
The full length frequency data series from Bull (1976) for scallops at North West Bay and Forsyth Bay in the period 1973–75 (Bull's figures 5.3–5.5) show clear modal progression; brief informal analysis in the present study (estimating the modal length of each of the cohorts in Forsyth Bay, Bull's figure 5.5) gave expected mean annual increments similar to those predicted by Tuck & Williams (2012) from tagging data. Bull's data suggest scallops 80 mm in length would have been about 14 months old. In the present study, assuming the 78 mm mode observed at Ship Cove in January 2017 (Figure 13) was 14 months old suggests that this cohort would have originated from spat settlement in December 2015. There were no surveys in 2016, so the early growth of this putative 2016 'year-class' was not observed in 2016, and it first appears as the 78 mm mode in the January 2017 survey data. The 2015 year class (25 mm mode in May, 40–50 mm in Oct–Nov) is predicted (from tag-return estimates) to grow well into the recruited size by January 2017 (i.e. larger than the 78 mm mode observed).

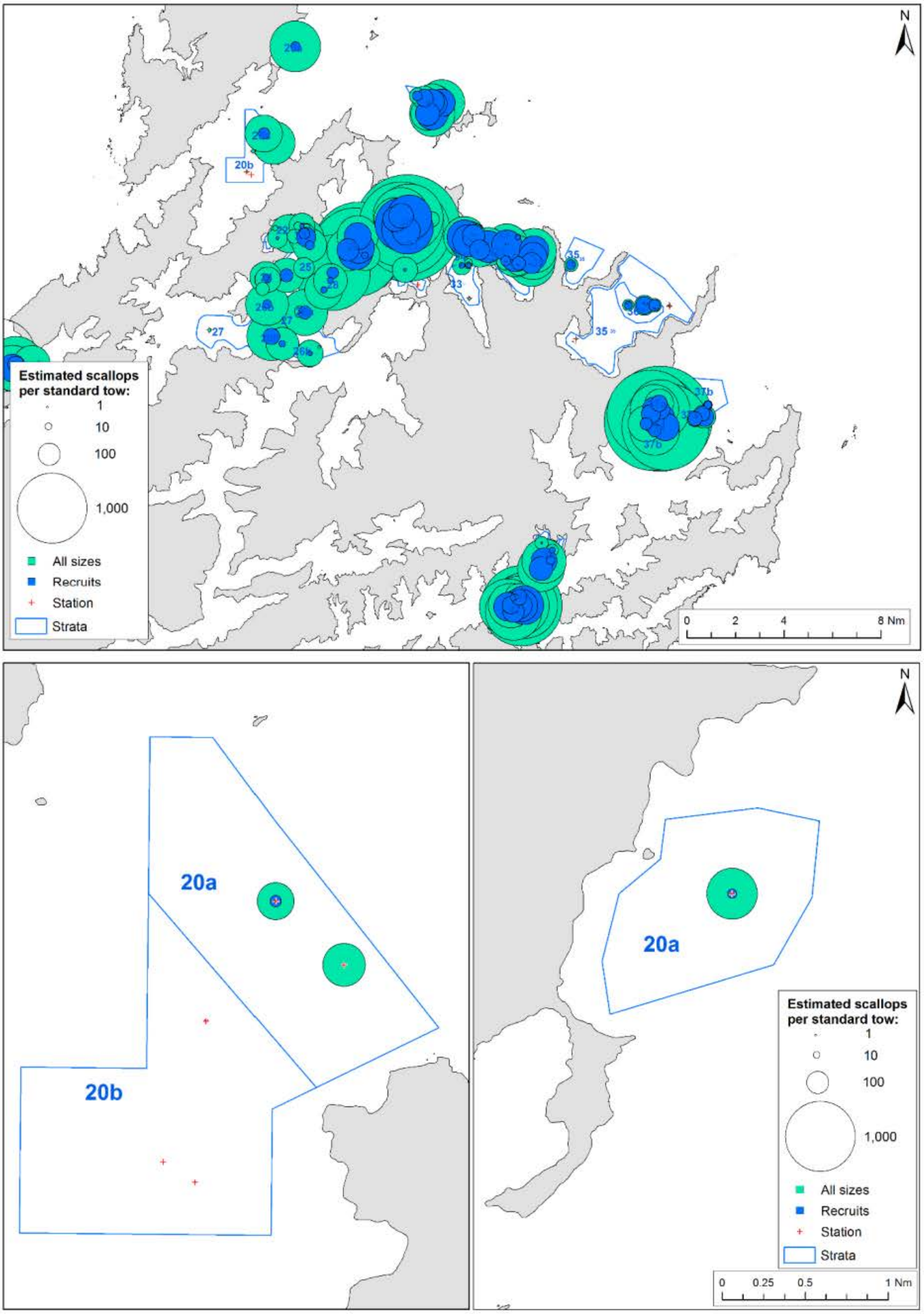
13. APPENDIX F: Catch per standard 0.4 n.mile tow maps, January 2017

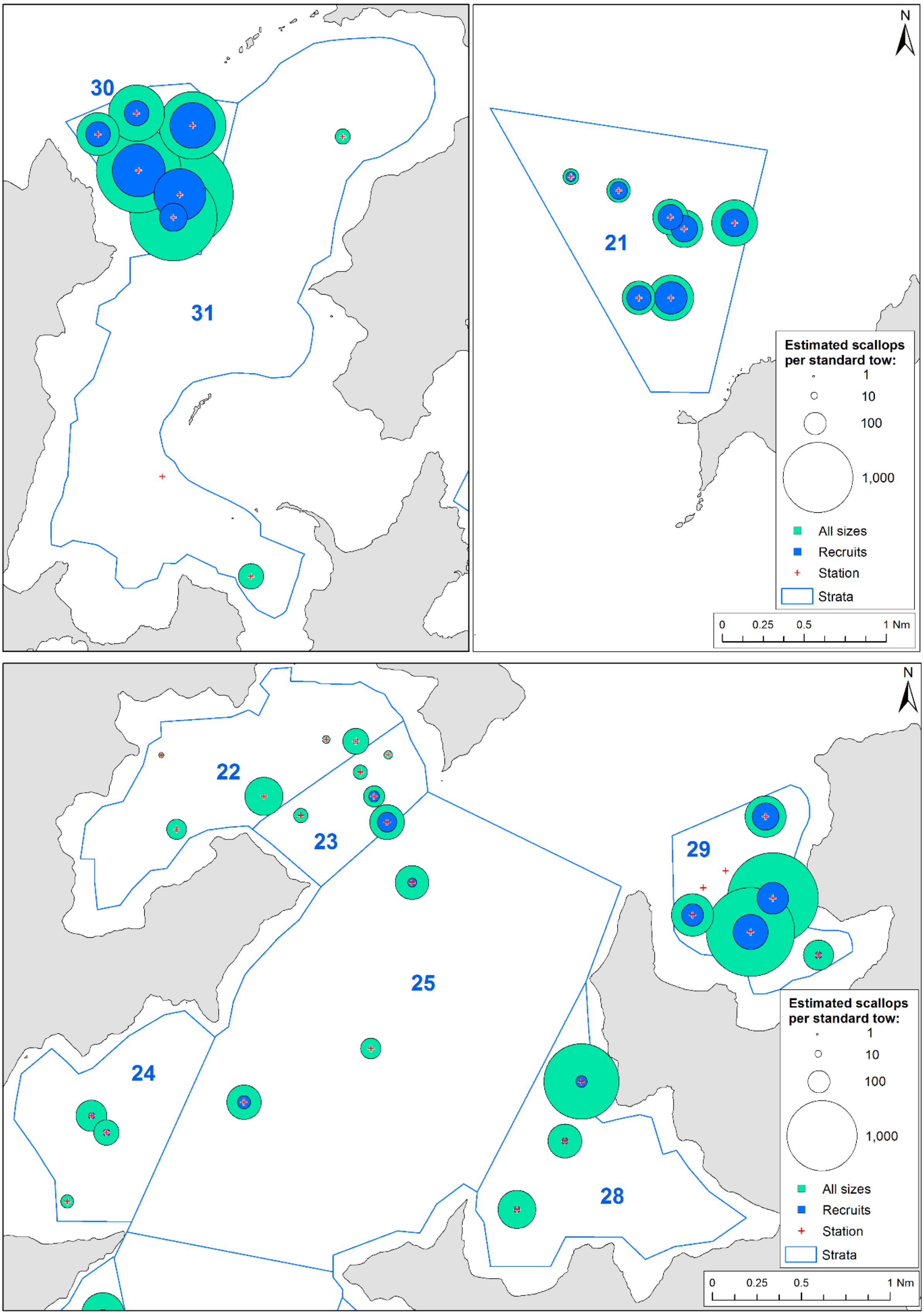


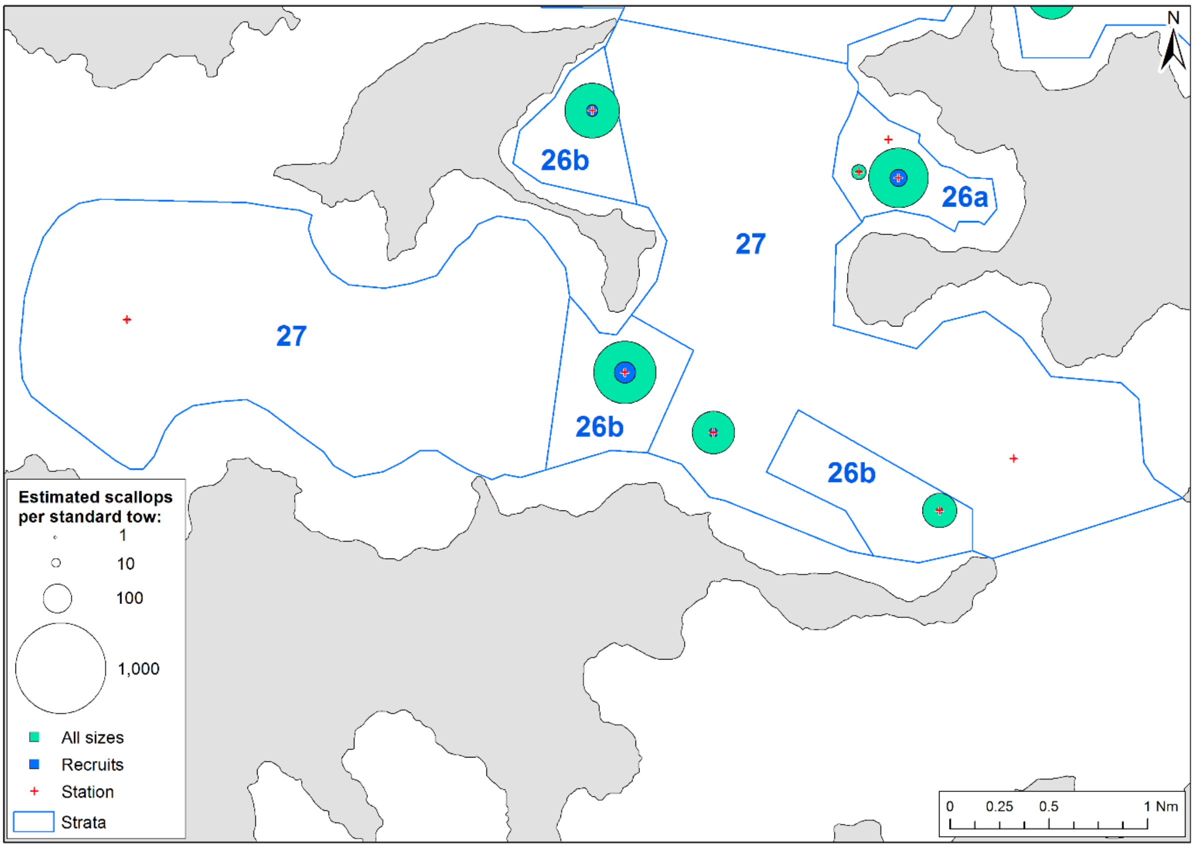


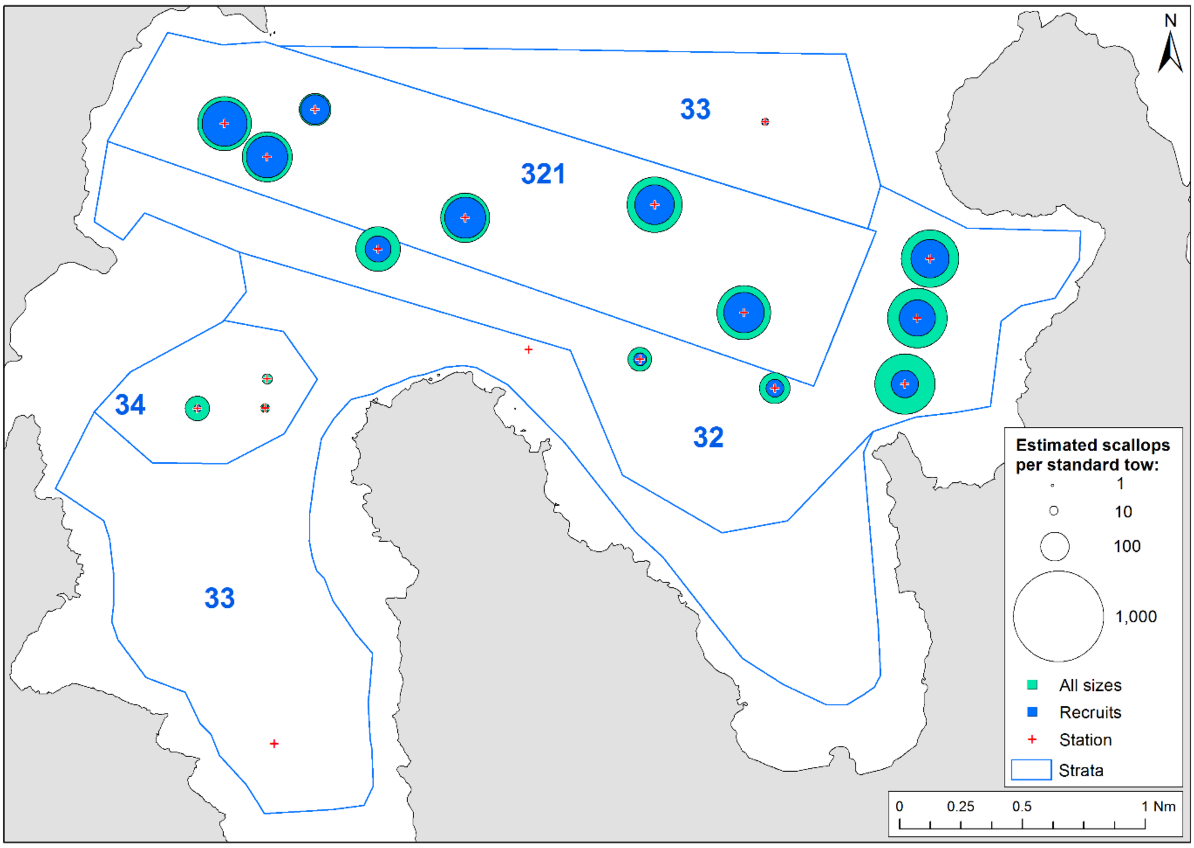

N
174b
174a
173
172
171
Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
0 0.75 1.5 3 Nm

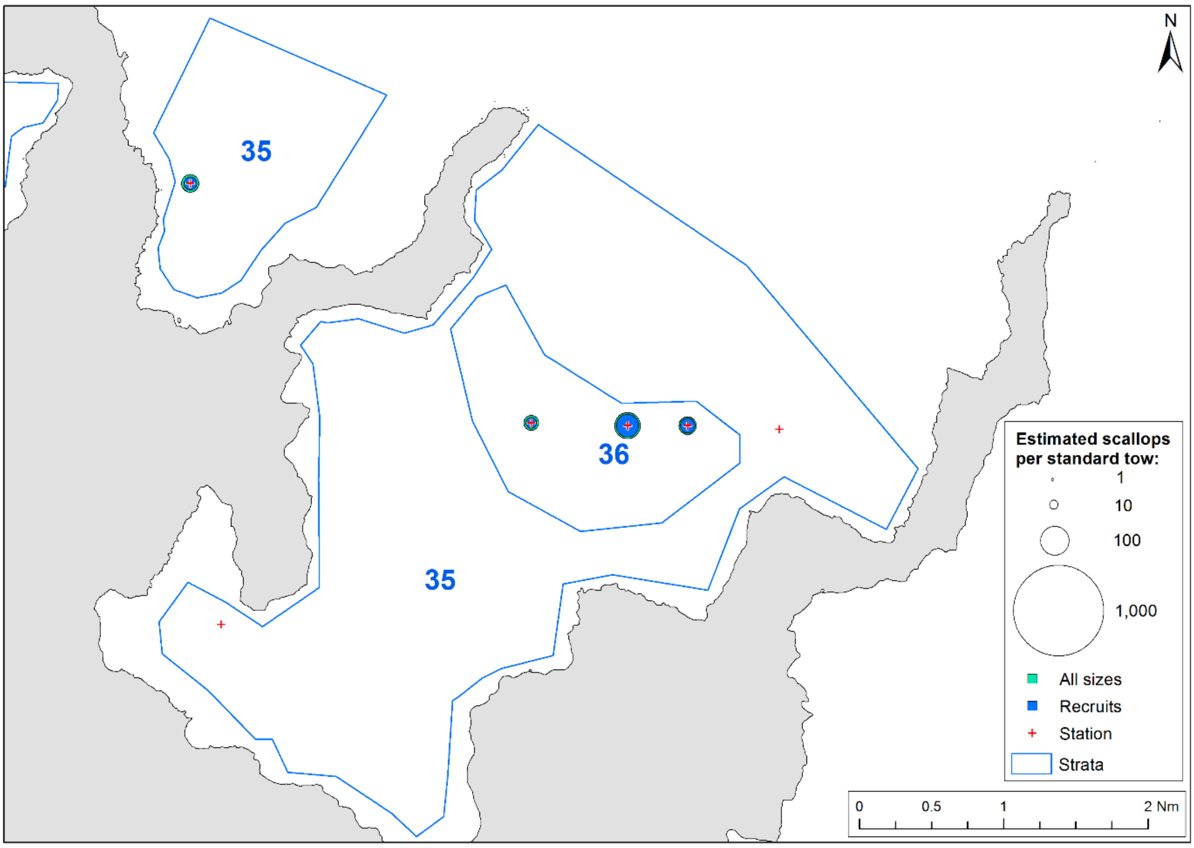

N
17
18
17
Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
0 0.2 0.4 0.8 Nm

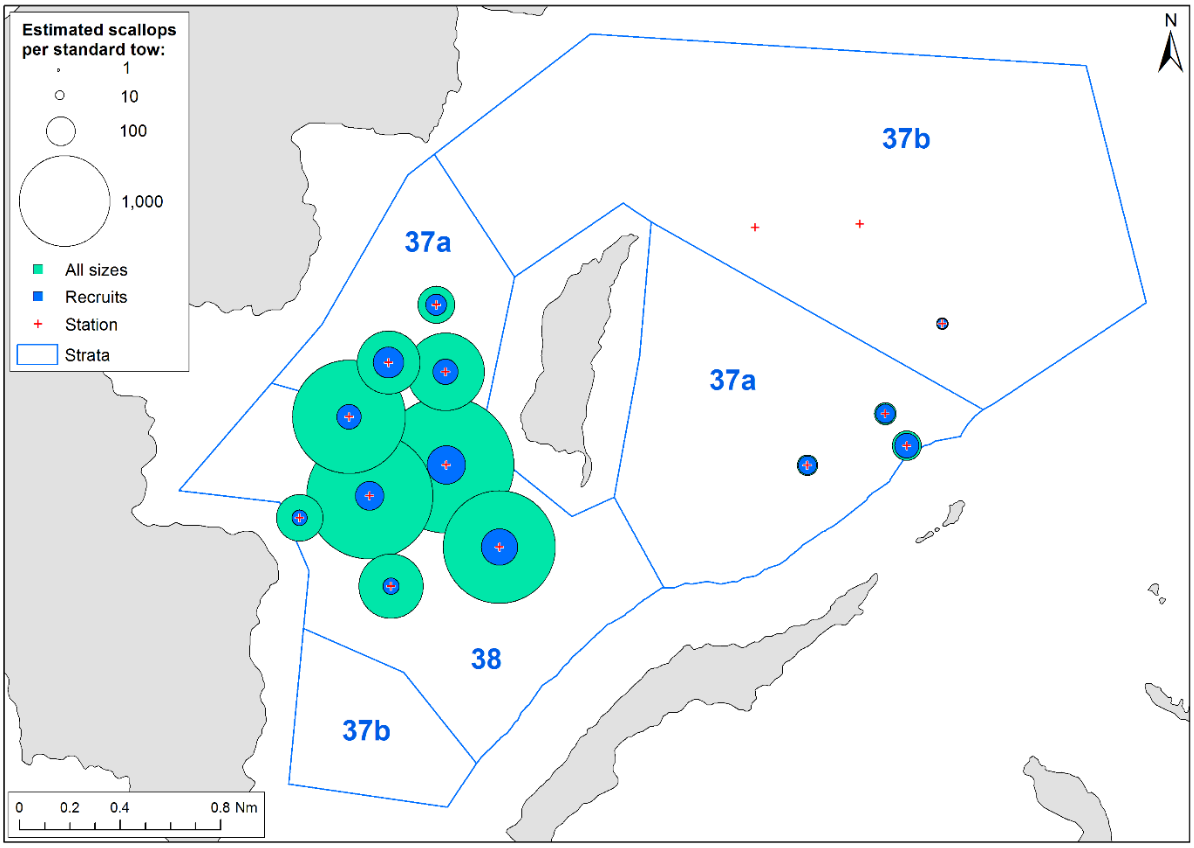

N
20b
27
25
28
33
35
37b
Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
0 2 4 8 Nm
20a
20b
N
20a
Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
0 0.25 0.5 1 Nm

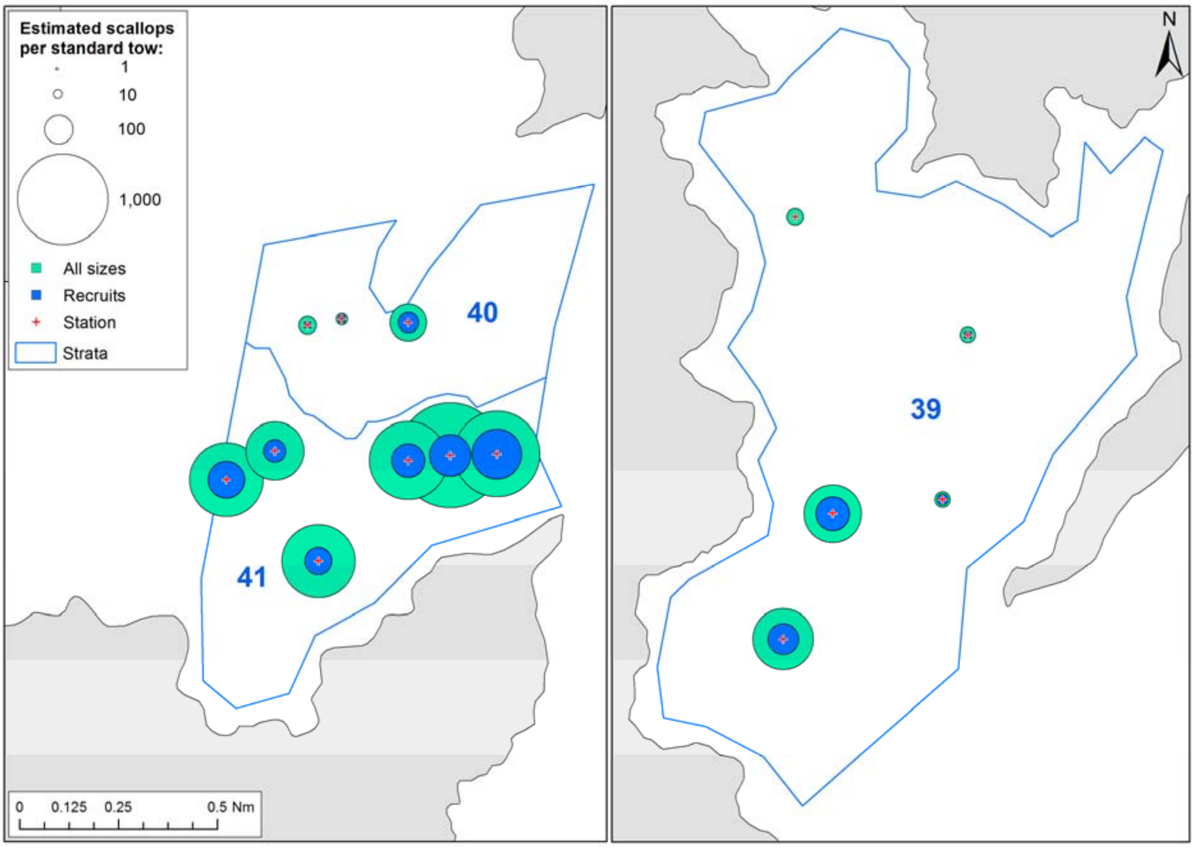

30
31
21
N
Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
0 0.25 0.5 1 Nm
22
23
25
24
29
28
N
Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
0 0.25 0.5 1 Nm


N
26b
26a
27
27
26b
26b
Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
0 0.25 0.5 1 Nm


N
33
321
34
32
33
Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
0 0.25 0.5 1 Nm


N
35
35
36
Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
0
0.5
1
2 Nm


Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
N
37b
37a
37a
38
37b
0
0.2
0.4
0.8 Nm



Estimated scallops per standard tow:
1
10
100
1,000
All sizes
Recruits
Station
Strata
40
41
39
N
0 0.125 0.25 0.5 Nm

14. APPENDIX G: Tabulated population estimates of recruited scallops, January 2017

Table 14: Population estimates of scallops in SCA 7, January 2017 (full survey extent) at different spatial scales (stock, substock, sector, bed). Estimates were produced for recruited scallops (90 mm or larger), assuming historical average dredge efficiency and predicting weight from length. The analysis used a non-parametric resampling with replacement approach to estimation (1000 bootstraps). N.B. Bed estimates are shown for only nine beds (strata or groups of strata) of particular interest because they held the highest densities (50 or more recruited scallops per standard tow) in the most recent (2015) surveys.

Grouping	Location	Area	Tows	Density (scallops.m^{-2})				Abundance (millions)				Scallop weight (g)		Biomass (t green)				Biomass (t meat)			
		(km^2)	n	Mean	CV	Median	95%CI	Mean	CV	Median	95%CI	Mean	Median	Mean	CV	Median	95%CI	Mean	CV	Median	95%CI
RECRUITED																					
Bed	Wynens Bank	2	6	0.417	0.26	0.412	0.229–0.644	0.955	0.26	0.944	0.524–1.476	84.6	84.7	80.8	0.27	80.0	44–127.9	10.7	0.27	10.5	5.6–17
	Dieffenbach	3	9	0.131	0.24	0.128	0.08–0.203	0.342	0.24	0.336	0.21–0.533	85.9	85.9	29.4	0.25	28.9	17.4–47	3.9	0.25	3.8	2.3–6.1
	Chetwodes	6	7	0.113	0.26	0.110	0.067–0.182	0.625	0.26	0.609	0.37–1.003	97.3	97.2	60.8	0.27	59.1	35.7–99.1	8.0	0.29	7.7	4.6–13.4
	Ketu Bay	2	7	0.109	0.41	0.104	0.036–0.208	0.257	0.41	0.248	0.085–0.495	80.4	80.6	20.8	0.41	20.0	6.7–40.4	2.7	0.42	2.6	0.9–5.3
	Ship	21	15	0.083	0.23	0.081	0.051–0.125	1.704	0.23	1.664	1.06–2.578	88.0	87.6	149.8	0.24	145.7	91.9–231.8	19.7	0.25	19.1	12.2–30.7
	Guards	24	18	0.071	0.20	0.069	0.048–0.105	1.719	0.20	1.674	1.168–2.556	89.8	89.6	154.4	0.21	150.0	105.1–232.2	20.4	0.22	19.8	13.6–30.8
	BayofManyCoves	4	5	0.061	0.51	0.059	0.008–0.131	0.271	0.51	0.261	0.034–0.576	85.5	85.4	23.1	0.51	22.3	2.8–49.2	3.1	0.51	3.0	0.4–6.5
	Croisilles	9	6	0.079	0.26	0.077	0.047–0.125	0.697	0.26	0.679	0.418–1.111	82.9	82.4	57.8	0.25	56.0	35.3–91.6	6.8	0.26	6.6	4–11.1
	Waitata	5	10	0.008	0.57	0.007	0.001–0.018	0.039	0.57	0.036	0.004–0.09	86.0	85.6	3.3	0.56	3.1	0.3–7.6	0.4	0.56	0.4	0–1
Sector	7A	72	3	0.001	0.82	0.001	0–0.004	0.106	0.82	0.100	0–0.302	76.8	76.7	8.2	0.82	7.7	0–23.2	1.1	0.83	1.1	0–3.3
	7B	181	13	0.001	0.41	0.001	0–0.002	0.176	0.41	0.172	0.055–0.347	87.9	88.1	15.4	0.41	15.2	4.9–30.2	2.1	0.41	2.1	0.6–4.2
	7C	206	15	0	0.40	0	0–0	0.029	0.40	0.028	0.009–0.053	79.3	79.4	2.3	0.42	2.2	0.7–4.4	0.3	0.42	0.3	0.1–0.6
	7I	10	4	0.007	0.36	0.007	0.003–0.013	0.072	0.36	0.069	0.03–0.13	73.7	74.1	5.3	0.36	5.1	2.2–9.5	0.7	0.37	0.7	0.3–1.3
	7D	255	11	0.002	0.30	0.002	0.001–0.003	0.484	0.30	0.477	0.228–0.792	75.2	74.9	36.4	0.31	35.7	16.5–59.7	4.3	0.32	4.2	2–7.3
	7E	116	6	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	7F	108	6	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	7G	88	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	7H	240	31	0.007	0.31	0.007	0.004–0.012	1.726	0.31	1.655	0.893–2.947	81.5	81.6	140.8	0.31	135.1	73.2–236.1	16.5	0.31	15.8	8.5–28.1
	7K	158	81	0.033	0.19	0.032	0.023–0.048	5.216	0.19	5.097	3.615–7.557	86.8	86.5	452.8	0.20	440.7	313.1–658.7	59.8	0.20	58.2	40.8–87.4
	7L	28	29	0.084	0.22	0.082	0.055–0.121	2.317	0.22	2.256	1.515–3.359	87.4	87.3	202.4	0.22	196.9	133.8–300.3	26.7	0.23	25.8	17.5–40.4
Substock	GB	469	35	0.001	0.33	0.001	0–0.001	0.383	0.33	0.371	0.173–0.66	81.5	81.5	31.2	0.33	30.3	14.3–53.8	4.3	0.33	4.2	2–7.6
	TB	806	57	0.003	0.27	0.003	0.002–0.004	2.210	0.27	2.136	1.28–3.544	80.2	80.1	177.2	0.27	171.1	102.4–284.5	20.8	0.28	20.1	11.9–33.7
	MS	186	110	0.041	0.19	0.040	0.029–0.058	7.533	0.19	7.354	5.349–10.78	87.0	86.7	655.2	0.19	637.3	463.6–948.1	86.5	0.19	84.5	61–126.3
Stock	SCA 7	1461	202	0.007	0.18	0.007	0.005–0.01	10.126	0.18	9.927	7.106–14.506	85.3	85.1	863.6	0.19	845.2	604.7–1255.1	111.6	0.19	108.7	78.3–161.8

Table 15: Population estimates of scallops by stratum in Golden and Tasman Bays, SCA 7 survey, January 2017 (full survey extent). Estimates were produced for recruited scallops (90 mm or larger), assuming historical average dredge efficiency and predicting weight from length. The analysis used a non-parametric resampling with replacement approach to estimation (1000 bootstraps).

Grouping	Location	Area	Tows	Density (scallops.m^{-2})				Abundance (millions)				Scallop weight (g)		Biomass (t green)				Biomass (t meat)			
		(km^2)	*n*	Mean	CV	Median	95%CI	Mean	CV	Median	95%CI	Mean	Median	Mean	CV	Median	95%CI	Mean	CV	Median	95%CI
RECRUITED																					
Stratum	1	72	3	0.001	0.82	0.001	0–0.004	0.106	0.82	0.100	0–0.302	76.8	76.7	8.2	0.82	7.7	0–23.2	1.1	0.83	1.1	0–3.3
	2	42	3	0.001	0.86	0.001	0–0.002	0.030	0.86	0.028	0–0.088	94.5	94.4	2.9	0.86	2.7	0–8.3	0.4	0.87	0.4	0–1.2
	3	33	7	0.003	0.39	0.002	0.001–0.005	0.083	0.39	0.080	0.028–0.152	88.5	87.8	7.4	0.40	7.0	2.4–13.7	1.0	0.41	1.0	0.3–1.9
	4	107	3	0.001	0.88	0.001	0–0.002	0.062	0.88	0.061	0–0.185	83.8	83.8	5.2	0.88	5.1	0–15.5	0.7	0.88	0.7	0–2.1
	5	19	3	0.001	0.52	0.001	0–0.002	0.018	0.52	0.017	0–0.037	84.0	82.7	1.5	0.55	1.4	0–3.3	0.2	0.55	0.2	0–0.5
	6	32	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	7	74	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	8	77	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	9a	4	3	0.003	0.55	0.003	0–0.006	0.011	0.55	0.011	0–0.024	71.9	71.7	0.8	0.55	0.8	0–1.7	0.1	0.56	0.1	0–0.2
	9b	10	4	0.007	0.36	0.007	0.003–0.013	0.072	0.36	0.069	0.03–0.13	73.7	74.1	5.3	0.36	5.1	2.2–9.5	0.7	0.37	0.7	0.3–1.3
	10	9	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	11	246	8	0.002	0.30	0.002	0.001–0.003	0.484	0.30	0.477	0.228–0.792	75.2	74.9	36.4	0.31	35.7	16.5–59.7	4.3	0.32	4.2	2–7.3
	12	48	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	13	69	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	14	46	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	15	62	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	16	88	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	171	3	3	0.001	0.87	0.001	0–0.004	0.004	0.87	0.004	0–0.013	109.0	107.5	0.5	0.87	0.4	0–1.4	0.1	0.88	0.1	0–0.2
	172	29	3	0.001	0.89	0.001	0–0.002	0.021	0.89	0.021	0–0.063	68.6	68.6	1.4	0.89	1.4	0–4.3	0.2	0.89	0.2	0–0.5
	173	8	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	174a	108	13	0.009	0.47	0.008	0.002–0.018	0.934	0.47	0.884	0.236–1.901	81.8	82.2	76.4	0.47	72.6	19.5–152.3	9.0	0.48	8.5	2.3–18.5
	174b	83	3	0.001	0.83	0.001	0–0.002	0.070	0.83	0.068	0–0.198	66.6	66.6	4.6	0.83	4.5	0–13.2	0.5	0.84	0.5	0–1.6
	17	5	3	0.005	0.46	0.005	0–0.01	0.029	0.46	0.028	0–0.054	70.7	70.8	2.0	0.46	2.0	0–3.8	0.2	0.46	0.2	0–0.5
	18	4	3	0.187	0.26	0.182	0.112–0.301	0.669	0.26	0.650	0.4–1.074	83.4	83.3	55.8	0.26	54.1	34–89	6.6	0.27	6.3	3.8–10.8

Table 16: Population estimates of scallops by stratum in Marlborough Sounds, SCA 7 survey, January 2017 (full survey extent). Estimates were produced for recruited scallops (90 mm or larger), assuming historical average dredge efficiency and predicting weight from length. The analysis used a non-parametric resampling with replacement approach to estimation (1000 bootstraps).

Grouping	Location	Area	Tows	Density (scallops.m^{-2})				Abundance (millions)				Scallop weight (g)		Biomass (t green)				Biomass (t meat)			
		(km^2)	*n*	Mean	CV	Median	95%CI	Mean	CV	Median	95%CI	Mean	Median	Mean	CV	Median	95%CI	Mean	CV	Median	95%CI
RECRUITED																					
Stratum	20a	10	3	0.031	0.47	0.031	0–0.059	0.304	0.47	0.307	0–0.579	78.7	78.4	24.0	0.47	24.0	0–46.1	3.2	0.48	3.2	0–6.1
	20b	7	3	0	–	0	0–0	0	–	0	0–0	–	–	0	–	0	0–0	0	–	0	0–0
	21	6	7	0.113	0.26	0.110	0.067–0.182	0.625	0.26	0.609	0.37–1.003	97.3	97.2	60.8	0.27	59.1	35.7–99.1	8.0	0.29	7.7	4.6–13.4
	22	3	5	0.002	0.71	0.002	0–0.005	0.007	0.71	0.006	0–0.018	109.0	109.5	0.7	0.79	0.7	0–2.2	0.1	0.79	0.1	0–0.3
	23	1	5	0.022	0.66	0.020	0–0.056	0.032	0.66	0.029	0–0.082	81.2	80.8	2.6	0.66	2.3	0–6.5	0.3	0.67	0.3	0–0.9
	24	3	3	0.010	0.44	0.010	0–0.019	0.028	0.44	0.028	0–0.053	73.6	73.8	2.1	0.44	2.1	0–3.9	0.3	0.44	0.3	0–0.5
	25	14	3	0.025	0.46	0.025	0–0.046	0.360	0.46	0.357	0–0.656	78.4	78.8	28.3	0.47	28.1	0–53.4	3.7	0.48	3.7	0–7.1
	26a	1	3	0.023	0.78	0.022	0–0.063	0.024	0.78	0.023	0–0.065	78.6	78.5	1.9	0.79	1.8	0–5.1	0.2	0.79	0.2	0–0.7
	26b	4	3	0.036	0.51	0.035	0.009–0.077	0.132	0.51	0.128	0.032–0.281	74.8	74.9	9.9	0.53	9.6	2.2–21.6	1.3	0.54	1.3	0.3–2.9
	27	22	3	0.006	0.83	0.006	0–0.017	0.129	0.83	0.126	0–0.365	75.8	75.7	9.8	0.83	9.5	0–27.5	1.3	0.84	1.3	0–3.7
	28	4	3	0.043	0.54	0.041	0.013–0.094	0.153	0.54	0.147	0.046–0.334	75.1	75.0	11.5	0.56	11.0	3.2–25.7	1.5	0.56	1.5	0.4–3.4
	29	2	7	0.109	0.41	0.104	0.035–0.208	0.259	0.41	0.248	0.085–0.495	80.4	80.6	20.8	0.41	20.0	6.7–40.4	2.7	0.42	2.6	0.9–5.3
	30	2	6	0.417	0.26	0.412	0.229–0.644	0.955	0.26	0.944	0.524–1.476	84.6	84.7	80.8	0.27	80.0	44–127.9	10.7	0.27	10.5	5.6–17
	31	11	3	0.002	0.84	0.002	0–0.005	0.019	0.84	0.019	0–0.054	67.6	67.6	1.3	0.84	1.3	0–3.6	0.2	0.83	0.2	0–0.5
	32	6	6	0.104	0.28	0.102	0.055–0.166	0.615	0.28	0.601	0.326–0.977	85.8	85.8	52.8	0.28	51.6	28–85.1	7.0	0.29	6.7	3.6–11.4
	321	6	6	0.169	0.21	0.164	0.114–0.25	1.082	0.21	1.051	0.734–1.603	92.4	92.0	99.9	0.21	96.7	67.4–151.2	13.2	0.22	12.8	8.7–19.8
	33	11	3	0.002	0.86	0.002	0–0.005	0.017	0.86	0.017	0–0.049	78.1	77.9	1.3	0.86	1.3	0–3.8	0.2	0.86	0.2	0–0.5
	34	1	3	0.004	0.42	0.004	0.001–0.008	0.005	0.42	0.005	0.001–0.01	73.3	73.6	0.4	0.42	0.4	0.1–0.7	0.1	0.42	0.0	0–0.1
	35	38	3	0.007	0.90	0.007	0–0.021	0.270	0.90	0.258	0–0.806	95.2	95.2	25.7	0.91	24.6	0–76.8	3.4	0.91	3.2	0–10.2
	36	6	3	0.033	0.35	0.032	0.016–0.06	0.198	0.35	0.188	0.098–0.356	92.1	92.2	18.2	0.34	17.4	9.2–32.9	2.4	0.35	2.3	1.2–4.5
	37a	6	6	0.086	0.31	0.083	0.045–0.144	0.521	0.31	0.505	0.27–0.87	89.0	88.4	46.4	0.31	44.6	24–79.1	6.1	0.32	5.9	3.1–10.5
	37b	10	3	0.005	0.85	0.004	0–0.013	0.045	0.85	0.042	0–0.131	92.5	91.8	4.2	0.85	3.9	0–12	0.6	0.86	0.5	0–1.6
	38	5	6	0.245	0.26	0.238	0.138–0.386	1.137	0.26	1.107	0.643–1.792	87.3	87.0	99.2	0.27	96.3	55.4–158	13.1	0.28	12.6	7.1–21.3
	39	4	5	0.061	0.51	0.059	0.008–0.131	0.271	0.51	0.261	0.034–0.576	85.5	85.4	23.1	0.51	22.3	2.8–49.2	3.1	0.51	3.0	0.4–6.5
	40	1	3	0.023	0.55	0.023	0.007–0.05	0.027	0.55	0.026	0.008–0.057	86.1	85.3	2.3	0.58	2.2	0.6–5.1	0.3	0.58	0.3	0.1–0.7
	41	1	6	0.213	0.24	0.208	0.131–0.329	0.316	0.24	0.309	0.195–0.489	85.9	86.1	27.1	0.25	26.6	16.2–42.6	3.6	0.26	3.5	2.1–5.6

15. APPENDIX H: Dead 'clucker' scallop length frequency distributions, 2015–2017

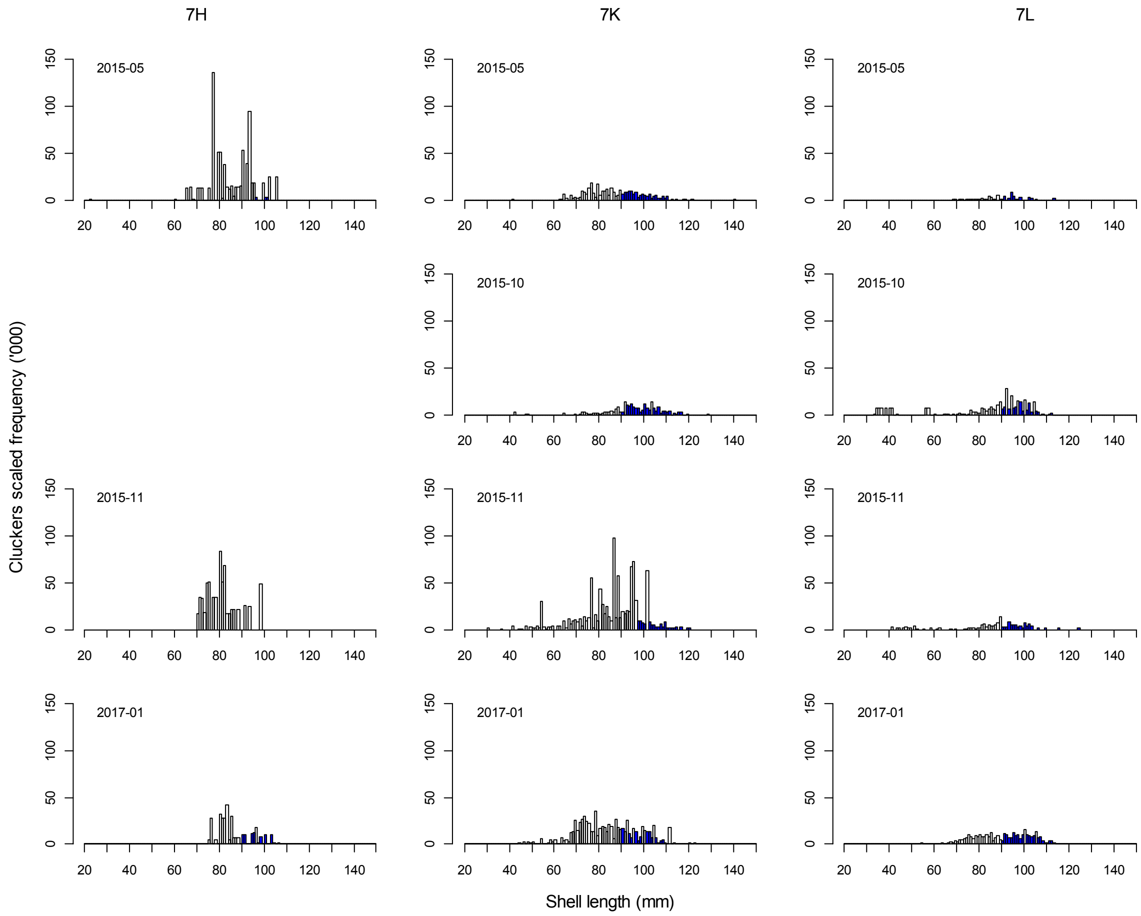


Figure 24: Length frequency distributions for dead scallops termed 'cluckers' (articulated scallop shells, shell hinge still intact)in Tasman Bay sector 7H (strata 171–174 combined; Croisilles Harbour strata 17 and 18 excluded) and Marlborough Sounds sectors 7K (Pelorus Sound) and 7L (Queen Charlotte Sound), SCA 7, May 2015 to January 2017. Data corrected for historical average dredge efficiency. Dark shaded bars denote shells of recruited size (90 mm shell length or larger).

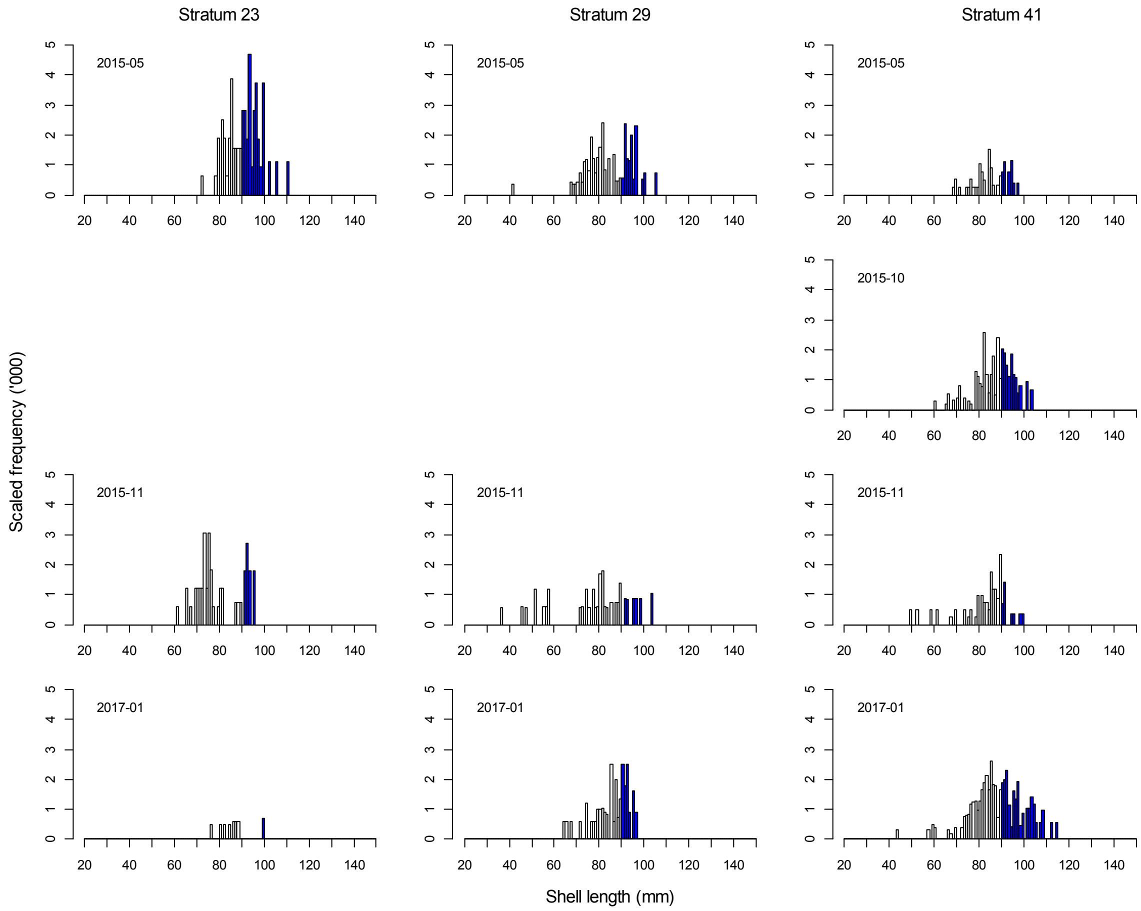


Figure 25: Time series of length frequency distributions for dead scallops termed 'cluckers' (articulated scallop shells, shell hinge still intact) in three beds in Marlborough Sounds, SCA 7, May 2015 to January 2017: stratum 23, Waitata Bank (left); stratum 29, Ketu Bay (centre); stratum 41, Dieffenbach High (right). Data corrected for historical average dredge efficiency. Dark shaded bars denote shells of recruited size (90 mm shell length or larger).

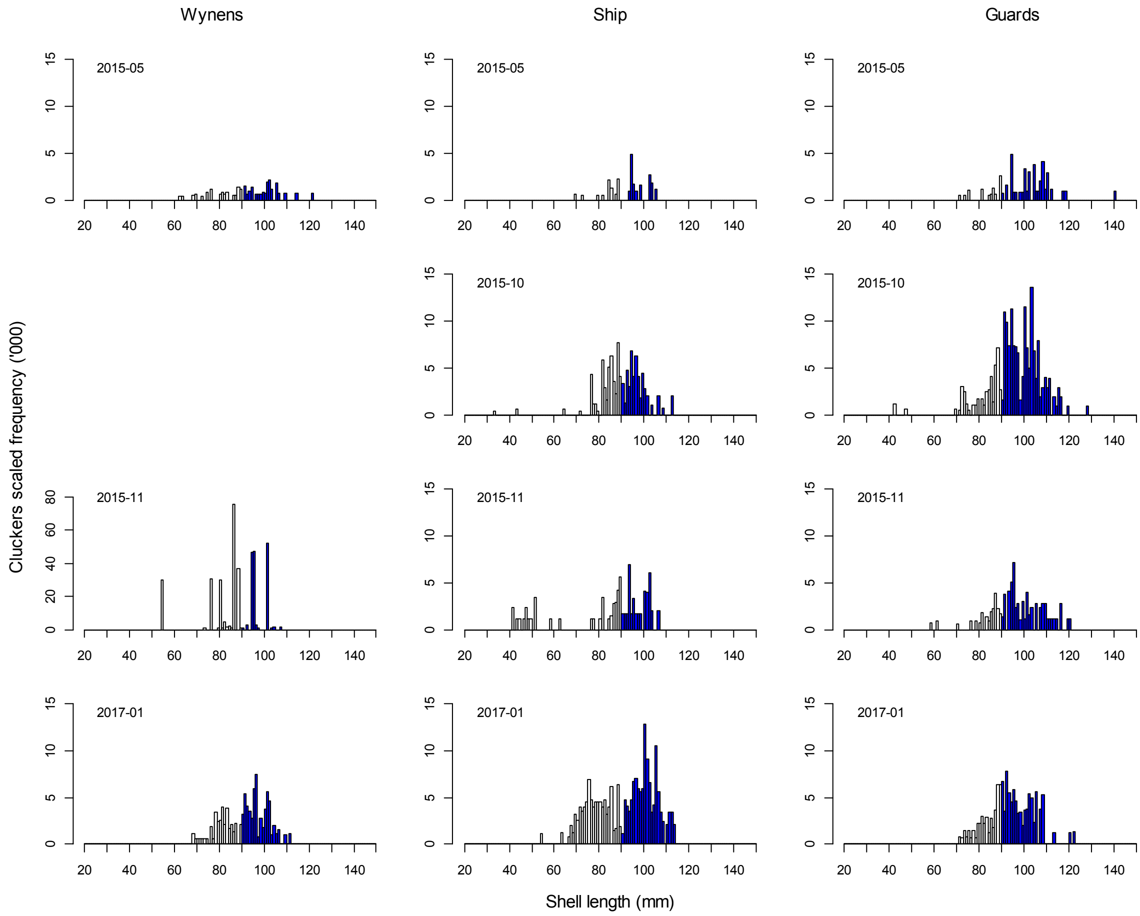


Figure 26: Time series of length frequency distributions for dead scallops termed 'cluckers' (articulated scallop shells, shell hinge still intact) in three beds in Marlborough Sounds, SCA 7, May 2014 to January 2017: stratum 30, Wynens Bank (left); stratum 38, Ship Cove (centre); strata 32 and 321 combined, Guards Bank (right). Data corrected for historical average dredge efficiency. Dark shaded bars denote shells of recruited size (90 mm shell length or larger).

16. APPENDIX I: Multifan model outputs

Ship Cove (stratum 38)

```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
File: s38: scallop LF stratum 38                                          Page 1

Fit: A6
Objective function value = 2426.00000; total penalty = 2.43216
Maximum gradient component = 0.00070
Number of non-empty length intervals: 119; Number of estimated parameters: 22
Approximate number of degrees of freedom: 97

Number of age classes: 5
Parameter Estimates:
   von Bertalanffy K = 1.282 (1/year); L infinity = 106.2
   First Length = 18.017; Last Length = 105.643; Brody rho  =   0.278 (1/year).
   Estimated age of the first age class =  0.15 years.
   Mean length at age in month 1:
     28.58  84.63 100.19 104.51 105.71
   Standard Deviations of length at age in month 1:
      5.96   5.96   5.96   5.96   5.96
   Average Standard Deviation >=  5.960; ratio of first to last S.D.=  1.000
   Seasonal Growth Amplitude =   0.960; Seasonal Growth Phase =   0.696
```

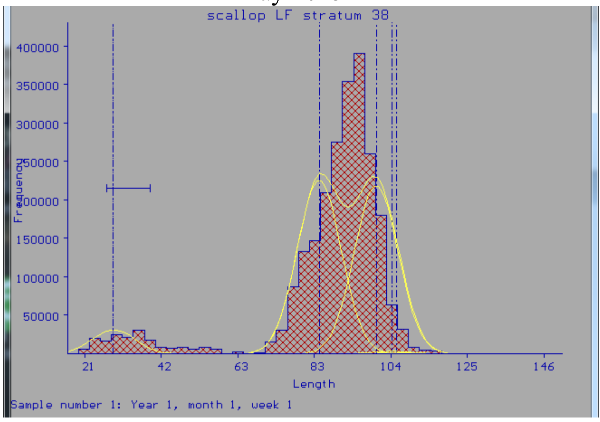
```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
Proportions at Age:                                                       Page 2
              Sample
 Age    1    2    3    4
   1  0.07 0.33 0.34 0.67
   2  0.47 0.55 0.57 0.26
   3  0.45 0.12 0.07 0.05
   4  0.01 0.00 0.01 0.01
   5  0.00 0.00 0.00 0.00
```

```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
Numbers at Age:                                                           Page 3
                        Sample
 Age          1          2          3          4
   1     156844     766390     968092    2965159
   2    1125154    1280758    1613925    1148619
   3    1088852     275725     204430     219632
   4      18158      11104      15740      60087
   5       8703       8770      12134      21286

   n    2397711    2342747    2814321    4414783
```

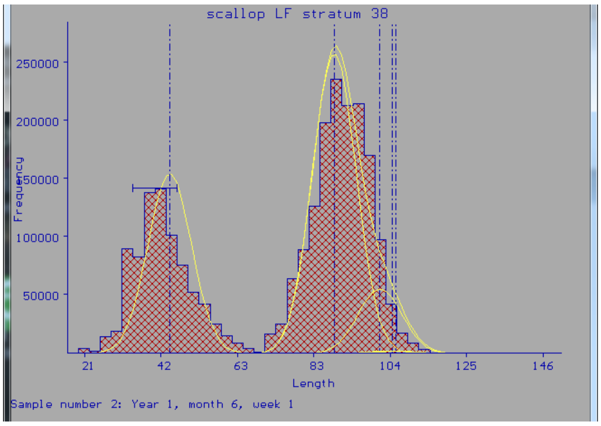
```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
Standard Deviations of Parameter Estimates:                               Page 5

    L[1]    L[2]     Rho  S_Ampl  S_Phas  Ave SD   Age 1   L_inf       K
 0.40955 0.20496 0.00071 0.00449 0.00588 0.10688 0.00351 0.35691 0.00255

        Correlation Coefficients between Parameter Estimates:
            L[1]     L[2]     Rho  S_Ampl  S_Phas  Ave SD   Age 1   L_inf
    L[2]   0.503
     Rho   0.070    0.378
  S_Ampl   0.254   -0.469   0.001
  S_Phas   0.937    0.709  -0.012  -0.028
  Ave SD   0.019   -0.003   0.001  -0.006   0.011
   Age 1   0.996    0.462   0.119   0.304   0.906   0.020
   L_inf  -0.863    0.003   0.153  -0.563  -0.672  -0.024  -0.881
       K  -0.070   -0.378  -1.000  -0.001   0.012  -0.001  -0.119  -0.153
```

Ship Cove (stratum 38): plots

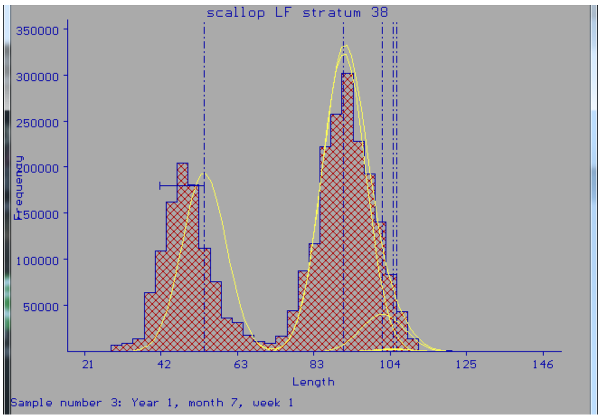
May 2015



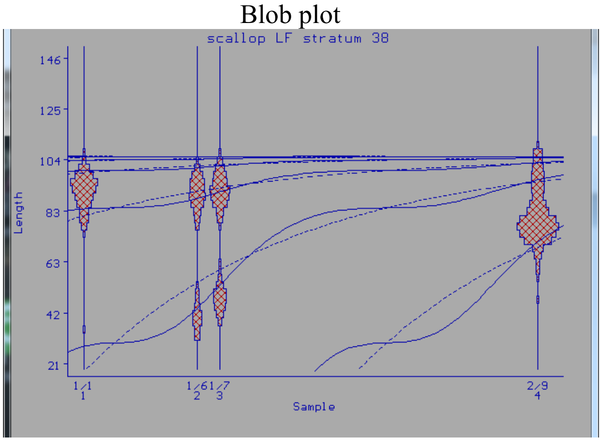
Oct 2015



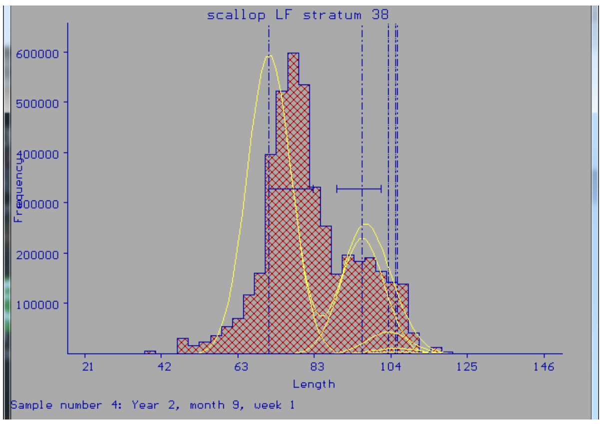
Nov 2015



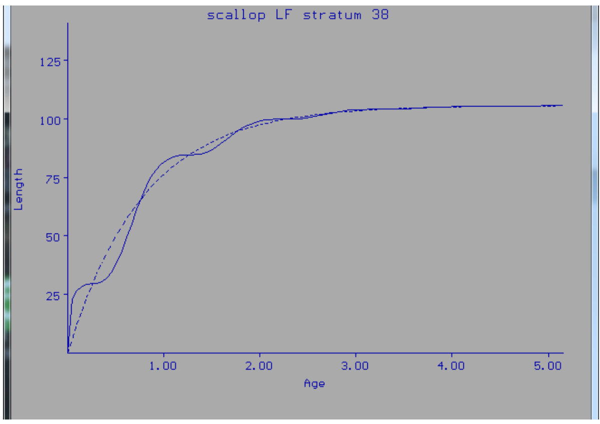
Blob plot



Jan 2017



Growth curve



Guards Bank (strata 32 and 321)

```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
File: guards: scallop LF guards                                           Page 1

Fit: 48
Objective function value = 3901.00000; total penalty = 2.12243
Maximum gradient component = 0.00012
Number of non-empty length intervals: 191; Number of estimated parameters: 18
Approximate number of degrees of freedom: 173

Number of age classes: 3
Parameter Estimates:
   von Bertalanffy K = 0.583 (1/year); L infinity = 125.1
   First Length = 46.886; Last Length = 100.693; Brody rho  =   0.558 (1/year).
   Estimated age of the first age class =  0.81 years.
   Mean length at age in month 1:
     53.44  85.07 102.74
   Standard Deviations of length at age in month 1:
      5.97   5.97   5.97
   Average Standard Deviation >=  5.967; ratio of first to last S.D.=  1.000
   Seasonal Growth Amplitude =   0.950; Seasonal Growth Phase =   0.852
```

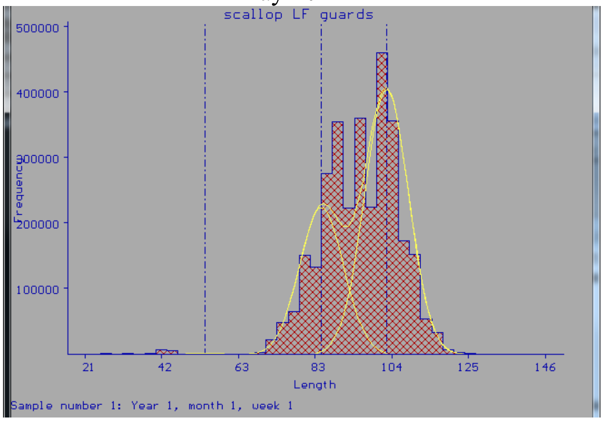
```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
Proportions at Age:                                                       Page 2
                   Sample
 Age    1    2    3    4    5    6
   1  0.00 0.08 0.05 0.23 0.33 0.20
   2  0.36 0.43 0.42 0.52 0.47 0.56
   3  0.64 0.49 0.54 0.26 0.21 0.25
```

```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
Numbers at Age:                                                           Page 3
                                  Sample
 Age         1         2         3         4         5         6
   1     10168    258129    193713    826209   1171426    582863
   2   1120963   1364516   1653178   1866384   1679893   1648009
   3   2020386   1574245   2128414    925933    743790    734023

   n   3151517   3196890   3975305   3618526   3595109   2964895
```

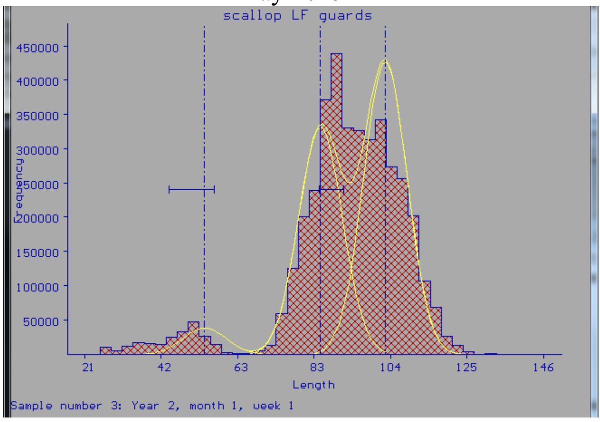
```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
Standard Deviations of Parameter Estimates:                               Page 5

    L[1]    L[2]     Rho  S_Ampl  S_Phas  Ave SD   Age 1   L_inf       K
 0.14208 0.10745 0.00115 0.00786 0.01001 0.08061 0.00469 0.31145 0.00206

        Correlation Coefficients between Parameter Estimates:
            L[1]    L[2]     Rho  S_Ampl  S_Phas  Ave SD   Age 1   L_inf
    L[2]  -0.265
     Rho   0.162   0.029
  S_Ampl  -0.231   0.155  -0.047
  S_Phas   0.102  -0.438  -0.007   0.143
  Ave SD   0.090   0.021  -0.008   0.000  -0.032
   Age 1   0.907  -0.470   0.470  -0.239   0.197   0.062
   L_inf  -0.720   0.691   0.377   0.209  -0.290  -0.053  -0.617
       K  -0.162  -0.029  -1.000   0.047   0.007   0.008  -0.470  -0.377
```

Guards Bank (strata 32 and 321): plots

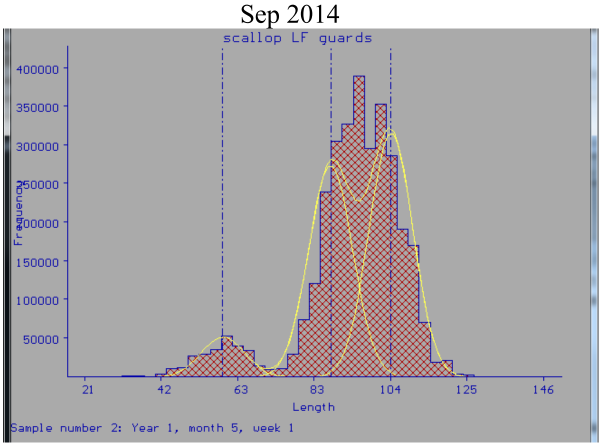
May 2014



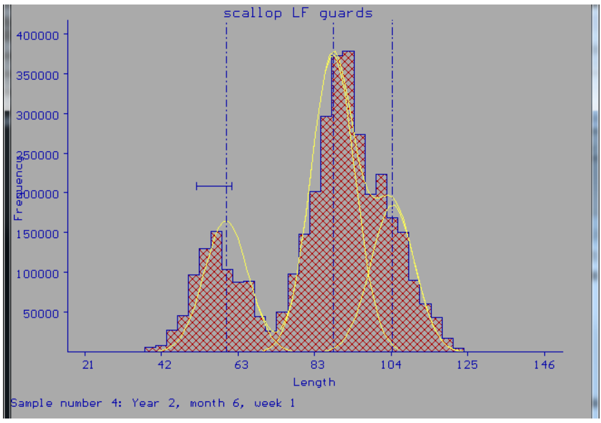
May 2015



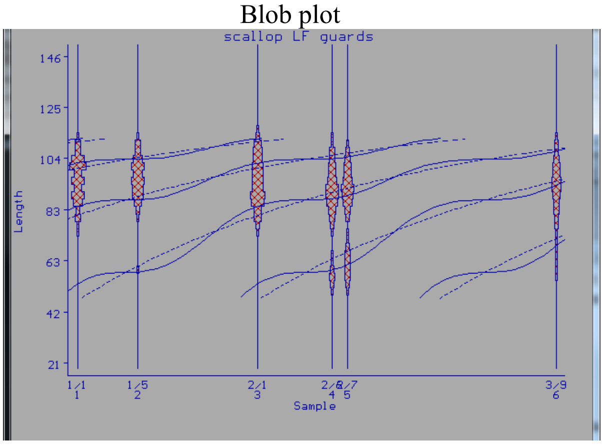
Sep 2014



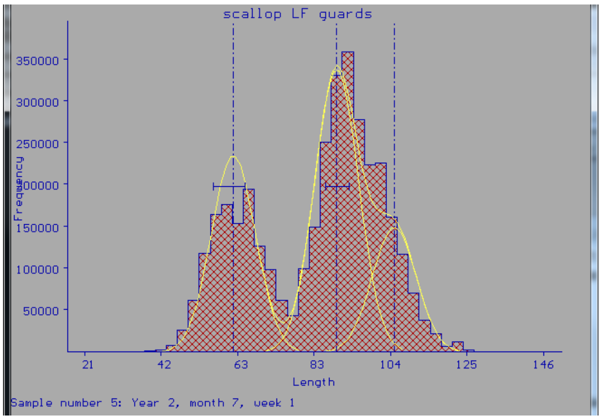
Oct 2015



Blob plot

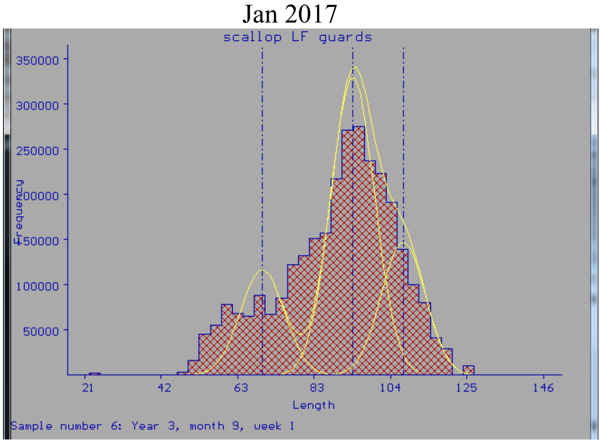


Nov 2015



Growth curve

Jan 2017



Wynens Bank (stratum 30)

```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
File: s30: scallop LF stratum 30                                          Page 1

Fit: 54
Objective function value = 2487.00000; total penalty = 2.36250
Maximum gradient component = 0.00032
Number of non-empty length intervals: 115; Number of estimated parameters: 22
Approximate number of degrees of freedom: 93

Number of age classes: 5
Parameter Estimates:
   von Bertalanffy K = 0.583 (1/year); L infinity = 123.7
   First Length = 40.290; Last Length = 115.547; Brody rho  =   0.558 (1/year).
   Estimated age of the first age class =  0.68 years.
   Mean length at age in month 1:
     45.92  80.25  99.41 110.12 116.09
   Standard Deviations of length at age in month 1:
      5.96   5.96   5.96   5.96   5.96
   Average Standard Deviation >=  5.959; ratio of first to last S.D.=  1.000
   Seasonal Growth Amplitude =   0.948; Seasonal Growth Phase =   0.730
```

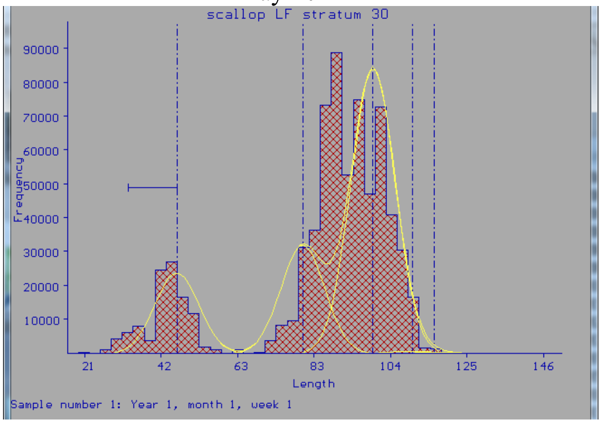
```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
Proportions at Age:                                                       Page 2
              Sample
 Age    1    2    3    4
   1  0.17 0.05 0.48 0.26
   2  0.23 0.75 0.46 0.60
   3  0.60 0.19 0.05 0.14
   4  0.01 0.01 0.00 0.00
   5  0.00 0.00 0.00 0.00
```

```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
Numbers at Age:                                                           Page 3
                        Sample
 Age         1         2         3         4
   1    118611     96831    905052    548133
   2    159241   1595587    862828   1282632
   3    419207    409543     96923    297943
   4      3940     24762      5524      8137
   5      2131      8461      4946      6238

   n    703129   2135184   1875272   2143083
```

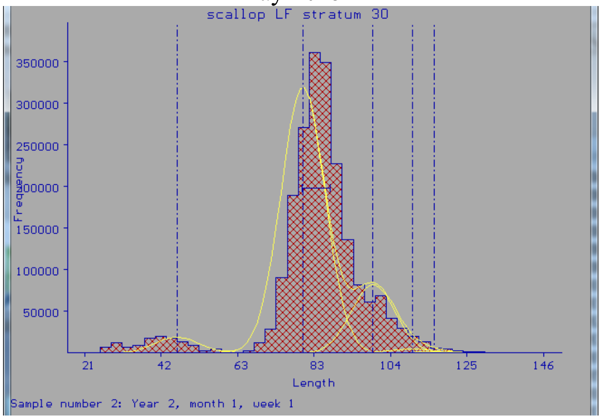
```
 MultiFan  32 (f)  Length-Frequency Analyzer  Copyright 1992 Otter Research Ltd.
Standard Deviations of Parameter Estimates:                               Page 5

    L[1]    L[2]     Rho  S_Ampl  S_Phas  Ave SD   Age 1   L_inf       K
 0.22635 0.38692 0.00122 0.00904 0.00741 0.11957 0.00747 0.64575 0.00219

        Correlation Coefficients between Parameter Estimates:
            L[1]    L[2]     Rho  S_Ampl  S_Phas  Ave SD   Age 1   L_inf
    L[2]  -0.726
     Rho   0.110   0.184
  S_Ampl  -0.019  -0.085  -0.000
  S_Phas  -0.956   0.677  -0.068  -0.235
  Ave SD  -0.020   0.099   0.000   0.005   0.005
   Age 1   0.955  -0.805   0.270   0.020  -0.897  -0.051
   L_inf  -0.857   0.968   0.202  -0.049   0.812   0.073  -0.872
       K  -0.110  -0.184  -1.000   0.000   0.068  -0.000  -0.270  -0.202
```

Wynens Bank (stratum 30): plots

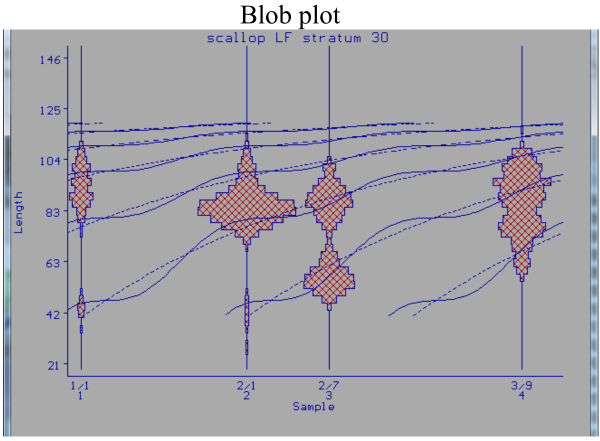
May 2014



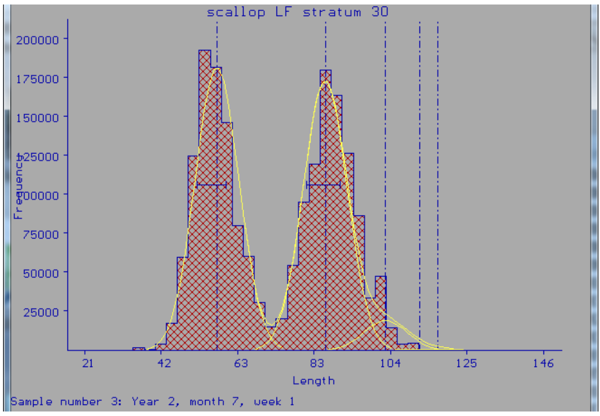
May 2015



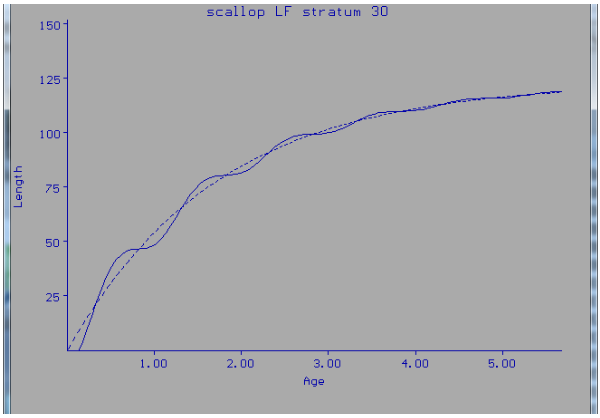
Blob plot



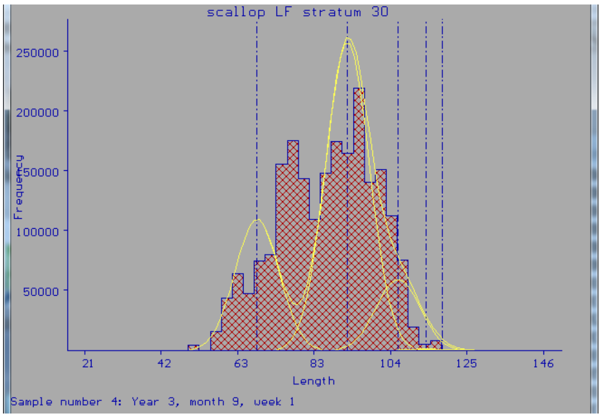
Nov 2015



Growth curve



Jan 2017



17. APPENDIX J: Sensitivity of September 2017 projected biomass to critical density

Table 17: Sensitivity of the SCA 7 September 2017 projected estimates of recruited scallop biomass (t meat weight) to the exclusion of areas of low scallop density. Estimates were produced using the Multifan projection approach. Critical density thresholds in the range 0.04–0.20 scallops m^{-2} were examined. The estimates were produced using a non-parametric resampling with replacement approach (1000 bootstraps) to estimation. Critical density corrections were applied after correcting for dredge efficiency.

Grouping	Location	Critical density (scallops.m^{-2}) 0			0.04			0.08			0.12			0.16			0.20		
RECRUITED		mean	CV	median	mean	CV	median	mean	CV	median	mean	CV	median	mean	CV	median	mean	CV	median
Stratum	30 (Wynens Bank)	16	0.37	15	14	0.39	13	13	0.42	12	11	0.46	10	10	0.48	9	9	0.51	8
	38 (Ship Cove)	27	0.47	24	23	0.50	20	18	0.55	16	15	0.58	13	12	0.61	10	9	0.69	7
	41 (Dieffenbach High)	6	0.34	6	5	0.37	4	4	0.44	3	3	0.52	2	2	0.63	2	1	0.77	1
	321 (Guards Bank Outer)	14	0.27	14	11	0.33	10	8	0.43	7	5	0.60	4	2	1.04	2	1	2.13	0
	37a (Motuara Is Medium)	10	0.44	10	6	0.61	5	4	0.77	3	2	1.07	1	1	1.71	0	0	3.43	0
	32 (Guards Bank Fishing Area)	10	0.37	9	6	0.49	6	4	0.63	3	2	0.95	1	0	2.23	0	0	5.84	0
	21 (Chetwode Is)	8	0.30	8	6	0.42	5	3	0.61	3	2	1.07	1	1	1.90	0	0	3.79	0
	29 (Ketu Bay)	3	0.41	3	2	0.46	2	2	0.54	2	1	0.66	1	1	0.85	1	0	1.18	0
	39 (Bay of Many Coves)	4	0.56	4	3	0.68	3	2	0.78	1	1	1.43	0	0	4.20	0	0	11.23	0
	28 (Richmond Bay)	2	0.56	1	1	0.91	1	0	1.46	0	0	6.50	0	0	31.03	0	0	NA	0
Sector	7A	1	0.82	1	0	–	0	0	–	0	0	–	0	0	–	0	0	NA	0
	7B	2	0.48	2	0	–	0	0	–	0	0	–	0	0	–	0	0	NA	0
	7C	1	0.80	1	0	–	0	0	–	0	0	–	0	0	–	0	0	NA	0
	7D	4	0.33	4	0	–	0	0	–	0	0	–	0	0	–	0	0	NA	0
	7E	0	NA	0	0	–	0	0	–	0	0	–	0	0	–	0	0	NA	0
	7F	0	NA	0	0	–	0	0	–	0	0	–	0	0	–	0	0	NA	0
	7G	0	NA	0	0	–	0	0	–	0	0	–	0	0	–	0	0	NA	0
	7H	10	0.44	9	0	2.88	0	0	31.62	0	0	–	0	0	–	0	0	NA	0
	7K	71	0.24	69	41	0.31	39	29	0.38	27	20	0.47	19	14	0.57	12	10	0.61	9
	7L	49	0.38	46	36	0.43	34	27	0.48	25	20	0.54	18	14	0.60	13	10	0.68	9
Substock	GB	5	0.44	4	0	NA	0	0	–	0	0	–	0	0	–	0	0	NA	0
	TB	14	0.35	14	0	2.88	0	0	31.62	0	0	–	0	0	–	0	0	NA	0
	MS	119	0.28	115	78	0.34	74	56	0.40	53	40	0.47	37	28	0.54	26	20	0.59	18
Stock	SCA 7	138	0.26	134	78	0.34	74	56	0.40	53	40	0.47	37	28	0.54	26	20	0.59	18