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Biomass survey and yield calculation for the Coromandel commercial scallop fishery, 2012

New Zealand Fisheries Assessment Report 2013/18

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A dredge survey of scallops was carried out in the Coromandel scallop stock (SCA CS) in April–May 2012, with a total of 168 valid stations (dredge tows) sampled. The survey coverage was the most extensive used to date, and was considered to cover the main commercially fished scallop beds in SCA CS. This included a large area located in relatively deep water (40–50 m) in Hauraki Gulf which has never been surveyed before, part of which supported the majority of scallop fishing in the 2011 season.

Absolute start-of-season recruited biomass (scallops over 90 mm shell length, the commercial minimum legal size in SCA CS) was predicted to be 11 423 t greenweight (median projected value; 95% CI 8374–15 032 t) with a c.v. of 15% or 1380 t meatweight (median projected value; 95% CI 976–1913 t) with a c.v. of 18%. These estimates are sensitive to the predicted dredge efficiency, assumed growth and mortality between survey and season, expected recovery of meatweight from greenweight, exclusion of areas of low scallop density, and relate to the surveyed beds only. Most of the recruited population was held in Hauraki Gulf, in an area that has only recently been exploited by the fishery. Excluding this area, biomasses in the other 'core' areas of the stock (i.e., those usually surveyed and fished) were of similar magnitude to those estimated in 2010.

Current Annual Yield (CAY) was estimated for two scenarios, by applying two different estimates of a reference rate of fishing mortality ($F_{0.1}$) to the estimate of start-of-season recruited meatweight biomass. It must be noted, however, that the estimates of $F_{0.1}$ used to calculate CAY for both scenarios were generated from modelling studies which used a method of correcting for dredge efficiency that is likely to have resulted in an overestimate of the incidental effects of dredging.

Incorporating only the direct incidental effects of fishing (on growth and mortality of adult scallops) and assuming average values for important assumed variables, CAY for the 2012 start-of-season was estimated to be 439 t meatweight. Incorporating direct and indirect incidental effects of fishing reduced the CAY estimate to 300 t meatweight.

For both scenarios, the estimates of CAY would have c.v.s at least as large as those of the estimate of start-of-season recruited biomass (18%), are sensitive to assumptions about dredge efficiency, growth, and expected recovery of meatweight from greenweight, and relate to the surveyed beds only. Further, the second approach to estimating CAY which includes direct and indirect incidental effects of fishing is sensitive to the duration of any habitat-mediated increase in juvenile mortality. There is also additional uncertainty associated with using a point estimate of $F_{0.1}$ (i.e., variance associated with the point estimate of $F_{0.1}$ was not incorporated into the analysis), and the fact that the estimates of $F_{0.1}$ were generated using estimates of dredge efficiency that are different to those used to estimate current biomass; the latter may have resulted in underestimates of yield.

1. INTRODUCTION

1.1 Overview

This report summarises research and fishery information for scallops (*Pecten novaezelandiae*) in the Coromandel scallop stock (SCA CS). The results of a Coromandel scallop biomass survey undertaken in April–May 2012 are summarised and yield estimates for 2012 are derived using methods detailed by the Ministry for Primary Industries (2012).

This work was carried out under Ministry for Primary Industries (formerly MFish) project SCA2010/01B: Stock assessment of Coromandel scallops. The overall objective was to carry out a stock assessment of scallops in the Coromandel fishery, including estimating abundance and sustainable yields. Specific objectives were:

1) to carry out a survey in about May/June 2012 to estimate the absolute abundance and population size frequency of scallops in the main scallop beds. The target coefficient of variation (c.v.) of the estimate of absolute recruited abundance was 20%.

2) to estimate the yield following the completion of the survey described in Objective 1.

1.2 Description of the fishery

Scallops support an important commercial fishery and an intense non-commercial interest in the Coromandel stock area (SCA CS), which lies between Cape Rodney and Town Point (Figure 1). A wide variety of effort controls and daily catch limits have been imposed in the past, and the commercial fishery has been limited by explicit seasonal catch limits specified in meatweight (processed weight, being the adductor muscle with roe attached) since 1992. Some additional controls remain on dredge size, fishing hours, and non-fishing days. Catch and catch rates are variable both within and among years (Table 1), a characteristic of scallop fisheries worldwide (Shumway & Sandifer 1991).

Commercial scallop fishing in SCA CS has previously been conducted within a number of discrete beds around Little Barrier Island, east of Waiheke Island (though not in recent years), at Colville, north of Whitianga (to the west and south of the Mercury Islands), and in the Bay of Plenty (principally off Waihi, and around Motiti and Slipper Islands). In 2011, fishers discovered that a large, relatively deep (40–50 m) area of the Hauraki Gulf contained good densities of predominantly large scallops, which supported a large proportion of the fishing during the 2011 season. This 'new' area of the fishery lies mainly within statistical reporting area 2W and a smaller portion in 2S, and has not been surveyed before. Recreational and Maori customary fishing is undertaken in suitable areas throughout the SCA CS stock area, especially in enclosed bays and harbours, many of which are closed to commercial fishing.

The minimum legal size (MLS) for scallops for commercial and amateur fishers throughout SCA CS was 100 mm shell length until 1995. Starting with the 1995 commercial season in July 1995, the MLS for scallops taken commercially from the Coromandel stock was reduced to 90 mm as part of a package of measures which also included further voluntary closed areas (VCAs) and reduced commercial catch limits. This package was introduced to address concerns expressed by all user groups over the impact of scallop dredging on juvenile scallops. The MLS has remained at 100 mm for all non-commercial fishers. The fishing year applicable to SCA CS is from 1 April to 31 March. The SCA CS commercial scallop fishing season runs from 15 July to 21 December.

The SCA CS stock is managed under the Quota Management System (QMS) using a TACC of 22 t meatweight which can be augmented with additional ACE based on a Current Annual Yield (CAY) calculation using $F_{0.1}$ as a reference point. Pre-season surveys of selected scallop beds in the stock have been conducted on an almost annual basis, as a means of estimating the biomass and yield likely to be available to the fishery in the forthcoming fishing season, and informing potential increases in ACE.

In 2011, however, no survey was conducted. Instead, CAY for the 2011 season was calculated using estimates of projected biomass generated by projecting forward the 2010 survey data to the start of the 2011 fishing season. This projection approach used a length-based growth transition matrix (based on tag return data) to grow the scallops from the time of the survey (May 2010) to the start of the fishing season the following year (July 2011), correcting for dredge efficiency, and allowing for natural mortality and fishing mortality (catch and incidental mortality). Uncertainty was incorporated during the projection process by resampling with replacement (bootstrapping) from the various data sources (Tuck 2011).

1.3 Literature review

General descriptions of the biology of the New Zealand scallop, *Pecten novaezelandiae*, were given by Bull (1988) and Cryer (1994), and little new information on the biology has become available subsequently other than PhD theses by Morrison (1997) and Williams (2005), some papers on reproductive ecology (Williams & Babcock 2004, 2005), and more recent work on scallop growth (Tuck & Williams 2012).

The New Zealand scallop is one of several species of "fan shell" bivalve molluscs found in New Zealand waters. They have a characteristic round shell with a flat upper valve and a deeply concave lower valve. Scallops inhabit waters to about 60 m deep (to 85 m in the Chatham Islands), but are more common in the Coromandel stock in depths of 10 to 30 m (although they are now known to exist at high densities in depths of up to 50 m in the outer Hauraki Gulf) and in the Northland stock in depths of 20 to 50 m.

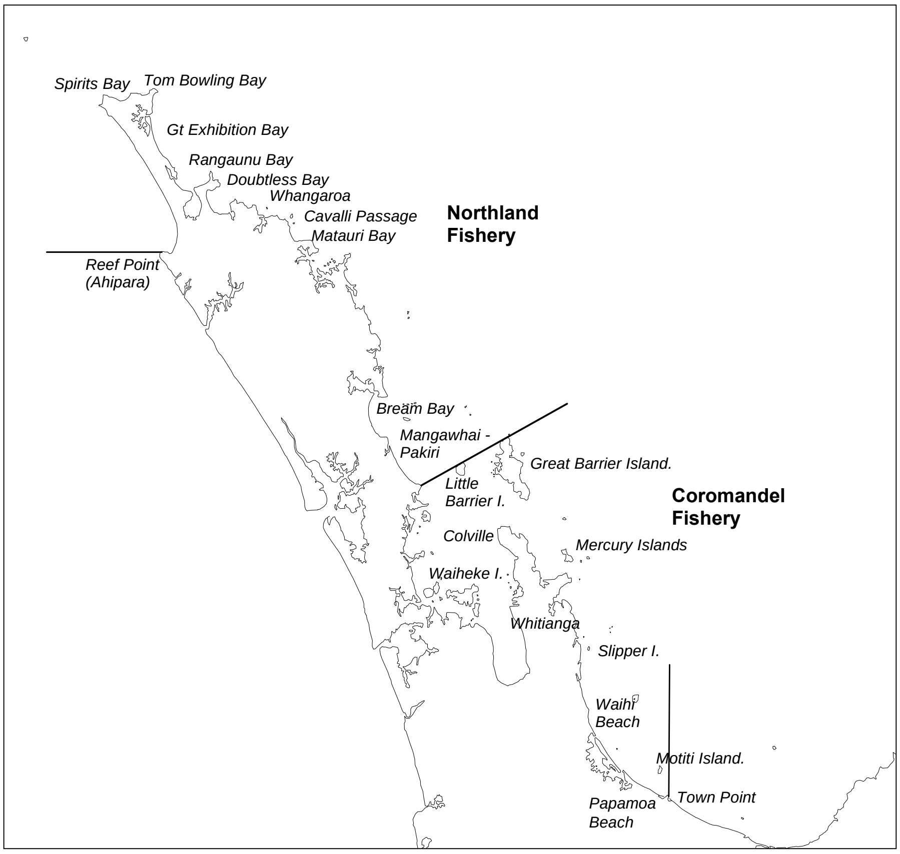

Figure 1: Geographic distribution of the two northern scallop fisheries and the names of locations mentioned in the text. After Cryer & Parkinson (2006).

Growth rates are spatially and temporally variable; growth to 100 mm takes between 1.5 and 3.5 years. In a recent study, historical data on scallop growth were reviewed, new data were collected through the tagging of scallops in 2009–10 and their subsequent recapture during the 2010 and 2011 fishing seasons, and the available tag return data were modelled using an inverse-logistic growth model (Tuck & Williams 2012). The findings of that study showed that the inverse-logistic model described growth increments from tagged scallops well, and its use in stock assessment modelling for scallops was recommended. The seasonal implementation of the growth model consistently fitted the data better (with a lower AIC) than the non-seasonal implementation and maximum shell growth was predicted at the end of October, although the seasonal effect was not dramatic. Estimated growth rates from tag return data in the Whitianga (Mercury) region of SCA CS in the 1980s and 1990s appeared to be markedly faster than in the 2000s, although small sample sizes and the restricted size range of animals available for tagging in some areas limited the comparison. In contrast with the findings of Cryer & Parkinson (1999), there was no clear pattern of growth in relation to depth.

Pecten novaezelandiae is hermaphroditic; each individual carries both male and female gonads at the same time. Most individuals are sexually mature at about 70 mm shell length (see Williams (2005) and Williams & Babcock (2005) for a comprehensive treatment in the Hauraki Gulf), although larger individuals have disproportionately larger gonads. They are extremely fecund and can spawn several times each year (Williams & Babcock 2004), although not all spawning events lead to successful recruitment. Fertilisation is external, and larval development in the plankton lasts for about three weeks. Larvae then settle to the seabed and metamorphose into juvenile scallops (‘spat’). Initially, spat settlement is by byssus thread attachment to some surface free of sediment (shell hashes, hydroids, spat bags, etc.), but later the spat loses the byssus thread and recesses into the surface of the substrate.

Natural mortality appears to be high. Cryer (2001a) reported that studies by Walshe (1984) and Allan & Jorgensen (1984) in the Whitianga bed generated estimates of the instantaneous rate of natural mortality M which averaged about 0.47. It appears that some of the estimates were for scallops in enclosures (i.e., M = 0.42 and 0.46 for seabed and lantern cages, respectively), which could be subject to lower rates of mortality than uncaged scallops, so M = 0.5 is used for yield calculation. Maximum age in unexploited populations is thought to be about six or seven years (Ministry for Primary Industries 2012).

Scallops grow rapidly (albeit with considerable variation), have high natural mortality, and exhibit variable recruitment. Such a life history results in fluctuating biomass, catch, and CPUE in most fisheries for scallops, and reliance on relatively few year-classes (Caddy & Gulland 1983, Orensanz et al. 1991, Shumway & Sandifer 1991). New Zealand stocks are not extreme examples, but Cryer (1994) examined data from 1978 to 1992 and found that recruited biomass in the Coromandel stock could not be predicted from historical biomass estimates, nor even from the biomass in the previous year together with estimates of intervening removals by commercial fishing. However, a more recent study on the utility of scallop surveys in predicting future year’s CAY (Tuck 2011) suggested that future recruited biomass and yield could be predicted a year ahead; and this approach was used to assess the likely stock status and CAY for the 2011–12 fishing season in SCA CS.

Simulation modelling by Cryer et al. (2003) suggested that strategies that vary catch in proportion to biomass (constant-F strategies) should outperform constant catch strategies. This is not surprising, but constant-F strategies provide about 30% more catch at higher catch rates with lower biological risk. “Tuning” the exploitation rate (especially to conservative levels) and setting it to zero at low biomass both decreased biological risk. Conversely, maintaining a “base” TACC (the current management strategy) increased biological risk. Full cost-benefit analysis was not undertaken but, over the long run, the additional model catch available from a constant-F strategy had a much higher value than the cost of the necessary surveys, and there were additional benefits in terms of higher average catch rates and lower biological risk. Rotational fishing provided good levels of catch at relatively low biological risk, but needed high rates of exploitation in the open areas. These high rates of extraction might not be economically sensible (because of low catch rates as biomass declines during a year), or environmentally sustainable (because of reduced habitat structure).

2. REVIEW OF THE COROMANDEL FISHERY

2.1 TACCs, catch, landings, and effort data

Coromandel scallops (SCA CS) were introduced into the Quota Management System (QMS) on 1 April 2002 with a Total Allowable Catch (TAC) of 48 t, comprised of a Total Allowable Commercial Catch (TACC) of 22 t, allowances of 7.5 t for recreational fisheries and 7.5 t for customary fisheries, and an allowance of 11 t for other sources of mortality (values all in meatweight). The fishery is managed using individual transferable quotas (ITQs) that are proportions of the TACC. The fishery has been gazetted on the Second Schedule of the Fisheries Act 1996 which specifies that, for certain "highly variable" stocks, the Annual Catch Entitlement (ACE) can be increased within a fishing season. The TACC is not changed by this process and the ACE reverts to the level of the TACC at the end of each season (15 July to 21 December). Catch rates are variable both within and among seasons, but the relationship between biomass and catch per unit effort (CPUE) at the level of the statistical reporting area is complex and (declines in) CPUE cannot be used to estimate biomass within a season (Cryer 2001b). Recent simulation studies, however, have shown that finer spatial scale CPUE can be used as a basis for some management strategies (Haist & Middleton 2010). For the 2009 commercial scallop season, the fishing industry (Coromandel Scallop Fishermen's Association and SeaFIC) implemented a logbook programme to collect detailed data from the fishery at finer spatial scales than the MPI statistical reporting areas. This logbook programme has been continued to date, and the data have been used by industry as a basis for self-managing their fishing operations using CPUE limits for closing scallop beds. This practise has been conducted in addition to the QMS requirements.

Since 1980, when the fishery was considered to be fully developed, commercial landings have varied more than 30-fold from less than 50 t to over 1500 t greenweight (Table 1). The two lowest recorded landings were in 1999 and 2000. Since 2002 when SCA CS entered the QMS, landings have been close or equal to the catch limit (ACE) set, except for in the recent fishing seasons 2007, 2008, 2009, and 2010 when landings were only 55%, 75%, 33%, and 35% of the agreed catch limit, respectively.

At a Shellfish Fishery Assessment Working Group meeting held on 21–22 January 2010 concerns were raised about the large discrepancy that has been observed over recent years between the CAY estimates for the commercial Coromandel scallop stock and the actual catch taken by the fishers. Fishers that attended the meeting believed that it is not possible to catch the CAY. MFish project SAP2009-10 investigated a number of factors which could affect the difference between CAY and the actual commercial catch, and found that the calculated dredge efficiency was the major factor contributing to the difference (Williams et al. 2011). This result led to the development of a new model of dredge efficiency (Bian et al. 2012) for the box dredges used in northern New Zealand scallop fisheries. The results suggest that the efficiency of these dredges was underestimated previously (2004 to 2010), resulting in an overestimation of biomass and yield.

Table 1: Catch limits and landings (t meatweight or greenweight) from the Coromandel stock since 1974. Data before 1986 are from Fisheries Statistics Unit (FSU) forms. Landed catch figures come from Monthly Harvest Return (MHR) forms, Licensed Fish Receiver Return (LFRR) forms, and from the landed section of Catch Effort and Landing Return (CELR) forms, whereas estimated catch figures come from the effort section of CELRs and are pro-rated to sum to the total CELR greenweight. "Hauraki" = 2X and 2W, "Mercury" = 2L and 2K, "Barrier" = 2R, 2S, and 2Q, "Plenty" = 2A–2I. Seasonal catch limits (since 1992) have been specified as ACE or on permits in meatweight (Green[1] assumes the gazetted meatweight recovery conversion factor of 12.5% and probably overestimates the actual greenweight taken in most years). * 1991 landings include about 400 t from Colville; –, no catch limits set, or no reported catch.

			Landings (t)							
	Catch limits (t)		MHR	LFRR	CELR		Scaled estimated catch (t green)			
Season	Meat	Green[1]	Meat	Meat	Meat	Green	Barrier	Hauraki	Mercury	Plenty
1974	–	–	–	–	–	26	0	0	26	0
1975	–	–	–	–	–	76	0	0	76	0
1976	–	–	–	–	–	112	0	0	98	14
1977	–	–	–	–	–	710	0	0	574	136
1978	–	–	–	–	–	961	3	164	729	65
1979	–	–	–	–	–	790	51	282	362	91
1980	–	–	–	–	–	1 005	23	249	690	77
1981	–	–	–	–	–	1 170	41	332	743	72
1982	–	–	–	–	–	1 050	49	687	385	80
1983	–	–	–	–	–	1 553	120	687	715	31
1984	–	–	–	–	–	1 123	62	524	525	12
1985	–	–	–	–	–	877	82	518	277	0
1986	–	–	–	162	–	1 035	305	135	576	19
1987	–	–	–	384	–	1 431	136	676	556	62
1988	–	–	–	182	–	1 167	234	19	911	3
1989	–	–	–	104	–	360	95	24	253	1
1990	–	–	–	153	–	903	114	98	691	0
1991	–	–	–	203	–	1 392	98	*472	822	0
1992–93	154	1 232	–	147	–	901	68	67	686	76
1993–94	132	1 056	–	62	–	455	60	11	229	149
1994–95	66	528	–	49	–	323	48	17	139	119
1995–96	86	686	–	88	79	574	176	25	323	50
1996–97	88	704	–	81	80	594	193	25	359	18
1997–98	105	840	–	94	89	679	165	26	473	15
1998–99	110	880	–	37	37	204	2	1	199	1
1999–00	31	248	–	6	7	47	17	0	12	18
2000–01	15	123	–	8	10	70	2	0	24	44
2001–02	22	176	–	22	20	161	85	1	63	12
2002–03	35	280	32	32	31	204	12	0	79	112
2003–04	58	464	58	58	56	451	13	63	153	223
2004–05	78	624	78	78	78	624	27	27	333	237
2005–06	118	944	119	119	121	968	75	21	872	0
2006–07	118	944	118	118	117	934	60	28	846	0
2007–08	108	864	59	59	59	471	45	51	373	2
2008–09	95	760	71	71	72	541	12	15	509	5
2009–10	100	800	33	33	33	267	71	12	184	0
2010–11	100	800	35	–	35	281	160	11	110	1
2011–12	50	400	50		50	402	20	220	160	0

2.2 Other information

Incidental mortality caused by commercial scallop dredges was estimated in 1996–97 (Cryer & Morrison 1997). Individual-based modelling and stochastic yield-per-recruit (YPR) analysis suggest that neither the 100 mm MLS previously in force in Coromandel (and still currently in force in Northland) nor the Provisional Yield (PY) method of estimating yield were optimal (for maximising long-term average landings).

2.3 Recreational and Maori customary fisheries

There is a strong non-commercial (recreational and Maori customary) interest in scallops in suitable areas throughout the Coromandel stock, mostly in enclosed bays and harbours. Scallops are usually taken by diving using snorkel or scuba, although considerable amounts are also taken using small dredges. In some areas, especially in harbours, scallops can be taken by hand from the shallow subtidal and even the low intertidal zones (on spring tides), and, in storm events, scallops can be cast onto lee beaches in large numbers. One management tool for northern scallop fisheries is the general spatial separation of commercial and amateur fisheries through the closure of harbours and enclosed waters to commercial dredging. There remain, however, areas of contention and conflict, some of which have been addressed using additional regulated closures. Regulations governing the recreational harvest of scallops from SCA CS include a minimum legal size of 100 mm shell length and a restricted daily harvest (bag limit) of 20 per person. A change to the recreational fishing regulations in 2005 allows divers operating from a vessel to take scallops for up to two nominated safety people on board the vessel, in addition to the catch limits for the divers. Until 2006, the recreational scallop season ran from 15 July to 14 February, but in 2007 the season was changed to run from 1 September to 31 March. There is no overall catch limit for the non-commercial sector.

A pilot study was conducted in 2007–08 to assess the feasibility of estimating the recreational catch in the part of the Coromandel scallop stock from Cape Colville to Hot Water Beach (Holdsworth & Walshe 2009). The study was based on an access point (boat ramp) survey using interviewers to collect catch and effort information from returning fishers, and was conducted from 1 December 2007 to 28 February 2008 (90 days) during the peak of the scallop season. The total estimated harvest during the survey period was 205 400 scallops (c.v. = 8.6%), with an estimated 23.9 t greenweight harvested (about 3 t meatweight).

Currently, there are no reliable stock-wide estimates of non-commercial harvest of scallops from the Coromandel stock. Estimates of catch by recreational fishers have been made on four occasions as part of recreational fishing (telephone and diary) surveys (Table 2). A Marine Recreational Fisheries Technical Working Group reviewed these surveys and recommended “that the telephone-diary estimates be used only with the following qualifications: 1) they may be very inaccurate; 2) the 1996 and earlier surveys contain a methodological error; and 3) the 1999–2000 and 2000–2001 estimates are implausibly high for many important fisheries.”

Table 2: Harvest estimates (number and greenweight) of scallops taken by recreational fishers in the Coromandel scallop stock (SCA CS) from the telephone-diary surveys conducted in 1993–94, 1996, 1999–2000, and 2000–01. The Marine Recreational Fisheries Technical Working Group considered that these estimates may be very inaccurate.

Year	Number of scallops	c.v.	Weight (t green)	Reference
1993–94	626 000	0.14	60.0–70.0	Bradford (1997)
1996	614 000	0.12	62.0	Bradford (1998)
1999–2000	257 000	1.01	30.1	Boyd & Reilly (2002)
2000–01	472 000	0.47	55.3	Boyd et al. (2004)

Given the above concerns about the reliability of stock-wide non-commercial harvest estimates, it is difficult to make comparisons between the levels of commercial and non-commercial scallop harvest. However, in 1993–94 the recreational harvest from the Coromandel scallop stock was an estimated 60–70 t greenweight (Bradford 1997). These estimates may include some Maori customary catch. Commercial landings in the most comparable period (July to December 1994 scallop season) were 323 t, suggesting that, in that year, the recreational catch of scallops was about 16–18% of total removals. It is not known if these estimates were typical of the recreational catch, but the commercial catch was very low and 1993–94 may not have been a typical year. It is likely that the current non-commercial catch is higher than in the 1990s because of an increased human population. The shift in the non-commercial open season (since 2007) has enabled fishers to take scallops later in the summer (mid to late February and March); the typically settled weather and warm sea temperatures at that time of year might encourage more people to harvest scallops.

2.4 Other sources of fishing mortality

Quantitative information is available on the incidental impacts on scallop growth and mortality of encounters with commercial dredges of several designs (Cryer & Morrison 1997). The box dredges in use in the Coromandel commercial fishery have been found to be considerably more efficient than ring-bag or Keta-Ami dredges in the generally sandy conditions prevalent in the stock. However, scallops encountered by box dredges showed modest reductions in growth rate compared with scallops collected by divers, and their mortality was high. Stochastic modelling suggested that, of the three dredge designs tested, box dredges would generate the greatest yield-per-recruit and catch rates, and that the current MLS of 90 mm was close to optimal (for maximising long term average landings) for the Coromandel fishery (Cryer & Morrison 1997).

Individual-based population modelling and yield-per-recruit analyses strongly suggest that incidental effects, especially on mortality rates, greatly affect yield from scallop dredge fisheries (Cryer & Morrison 1997). The incidental mortality caused by dredging substantially changed the shape of yield-per-recruit curves for Coromandel scallops, causing generally asymptotic curves to become domed, and decreasing estimates of F_{max} and $F_{0.1}$. Field experiments (Talman et al. 2004) and revised modelling (see Cryer & Parkinson 2006) suggest that dredging reduces habitat heterogeneity, increases juvenile mortality, makes yield-per-recruit curves even more domed, and decreases estimates of F_{max} and $F_{0.1}$ even further.

It is important to note that the above work on incidental mortality was done using an older approach to estimating dredge efficiency (see Cryer & Parkinson 2006) which underestimated efficiency, so the incidental effects of dredging reported are likely to be overestimated. More work is required to re-examine the incidental effects of dredging and their effect on the target rate of fishing mortality.

3. RESEARCH

3.1 Stock structure

Current management assumes that the Coromandel stock is separate from the other New Zealand scallop stocks (i.e., Northland, the various west coast harbours, Golden Bay, Tasman Bay, Marlborough Sounds, Stewart Island, and Chatham Islands). The stock structure of SCA CS is assumed to be a single biological stock, although the extent to which the various beds or populations are separate reproductively or functionally is not known.

3.2 Resource surveys

3.2.1 Survey design and field methods

The choice of an appropriate time for surveys entails balancing the conflicting pressures of operational ease and uncertainty in the results. Early surveys (March–April) benefit from long daylight hours and generally more settled weather, but the long lag between survey completion and season opening render biomass estimates sensitive to the assumed values for growth and mortality. In addition, scallops are susceptible to periodic catastrophic declines in abundance, and a longer lag between survey and season increases the probability of such an event occurring undetected. Surveys undertaken later in the year (May–June) can be hampered by short working days and less favourable conditions, and the danger of surveys being seriously delayed by inclement weather increases. However, the effect on biomass estimates of poor assumptions about growth and mortality is smaller, and the chance of catastrophic declines in abundance following the survey is reduced.

Survey coverage (sample extent) has historically varied among years because the aim of the surveys was to assess the status of the main scallop beds likely to be fished in the coming season, rather than for the survey coverage to encompass the main beds of the whole stock to provide an index of abundance representative of the status of the overall population. In reviewing the purpose of these surveys, the Shellfish Working Group agreed that two important aspects of the survey are consistency of survey coverage (sample extent) among years to maintain a standard series and the ability to provide biomass estimates by region. In designing the 2012 survey therefore, special consideration was given to reviewing the available data on scallop distribution from past surveys and information provided by fishers, to ensure that the 2012 survey coverage included the main areas surveyed historically, together with any other areas that are known or expected to be likely to contain substantial scallop beds. Consequently, the 2012 survey coverage was more extensive than previously, with the stratification comprising ‘core’ strata (those surveyed and fished consistently in the past), ‘background’ strata (areas of lower densities outside the core strata that formed part of the survey coverage in the past), and ‘new’ strata (those in Hauraki Gulf that have never been surveyed before).

The 2012 survey of SCA CS was undertaken between 21 April and 5 May, with sampling actually conducted on 21–27 April, 29–30 April, and 1–3 May. All sampling was undertaken by dredge, and no diving to estimate dredge efficiency was conducted. We used the same vessel and skipper as in most recent surveys. To minimise vessel time, the survey design was of only single phase.

Single phase stratified random sampling was undertaken in 29 strata: Little Barrier Island (4 strata), Hauraki Gulf (3 strata), Colville (3 strata), Waiheke (2 strata), the west and south of the Mercury Islands (11 strata), and the western Bay of Plenty (6 strata at Motiti Island, Papamoa Beach, and off the Katikati Entrance) (Figure 2; Appendix 1). Some of these strata were the same or very similar to those used in the 2007–10 surveys, but others were ‘background’ strata which had formed part of the survey extent used in past surveys, or, in the case of the Hauraki Gulf strata, were new and had never been surveyed before. The total sampled area in 2012, therefore, was substantially larger than that surveyed before, at 979 km^2 compared with 119–175 km^2 between 2001 and 2008, and 253–341 km^2 between 1996 and 1999. The Coromandel stock was not surveyed in 2000 or 2011.

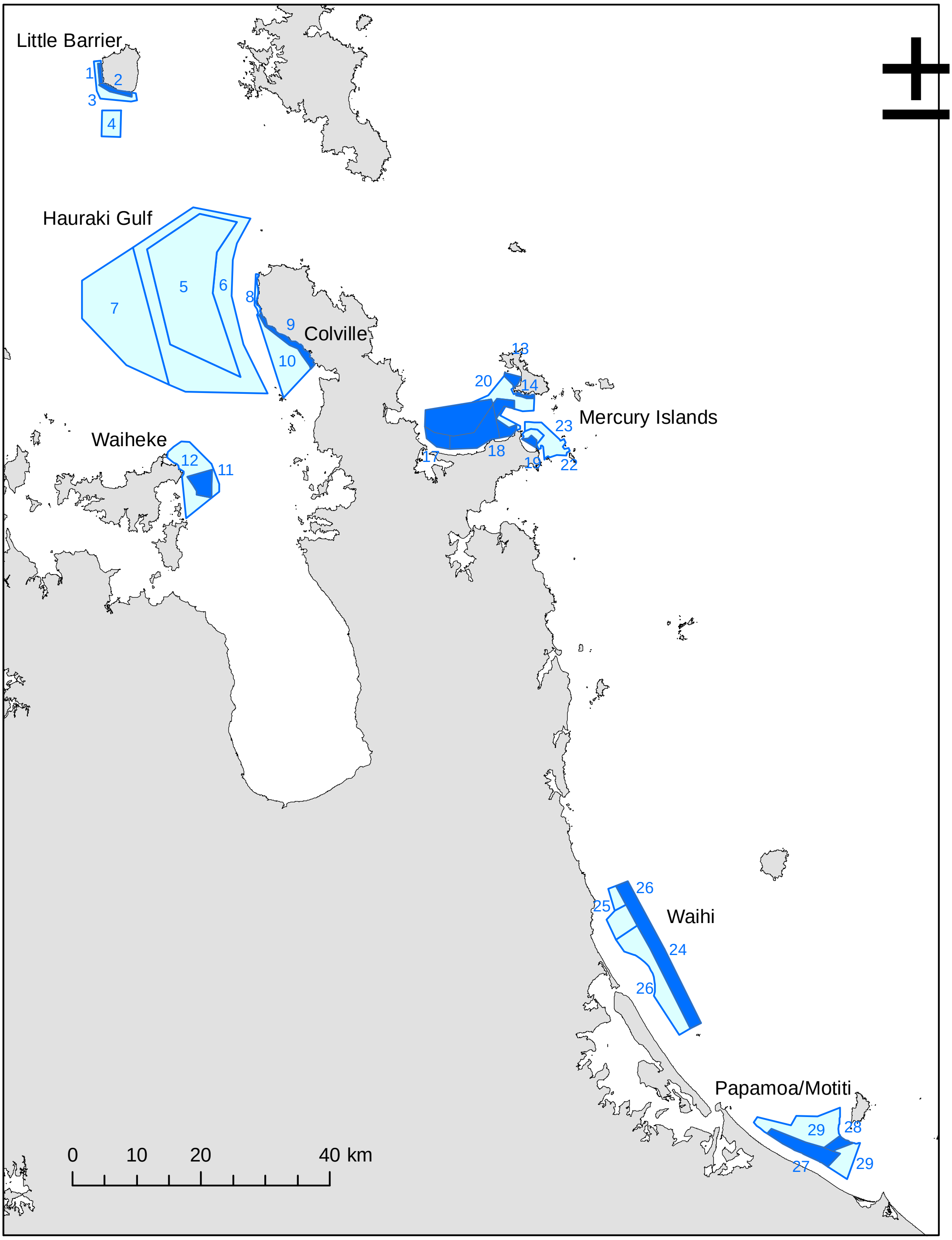

Figure 2: Location of strata for the dredge survey of the Coromandel scallop stock in 2012. Groups of strata are labelled with geographic descriptions used in the text (see Appendix 1 for stratum details). "Core" strata, those areas surveyed and fished consistently in the past, are shown in dark blue shading. Strata 5, 6, and 7 collectively form the "Hauraki Gulf" region of the stock; they are 'new' strata in that they have never been part of the SCA CS survey before; stratum 5 supported fishing for the first time in the 2011 season, strata 6 and 7 have not been fished before.

The 2012 survey was optimised to minimise the predicted c.v. of the estimate of recruited biomass. A theoretical optimum station allocation was generated using the R function *allocate* and the 2010 survey data. This allocation was then modified to produce the final allocation by considering operational and logistical constraints on the survey, including the maximum number of dredge tows possible in a sampling day and the time required to steam between stock regions. Strata that were sufficiently close together to tackle in a single day (e.g., those around the Mercury Islands) were grouped. Up to about 20 shots can be completed in a problem-free day with little steaming, so the number of stations allocated to strata within regions from the optimisation was adjusted according to their relative stratum sizes and a semi-quantitative understanding of historical performance. The positions of stations within strata were randomised using ArcGIS® software by ESRI, constrained to keep all stations at least 200 m apart; this software estimates the area of each stratum, and gives the latitude and longitude of each random station.

Dredging in the 2012 survey was undertaken from the chartered commercial fishing vessel *Kataraina* using the same box dredge (2.0 m wide) used in previous SCA CS surveys. Considerable historical data on dredge efficiency exists for this dredge and vessel (Bian et al. 2012). The vessel was navigated to each station using non-differential GPS, which is sufficiently accurate (to within about 10 m) to estimate the length of even short tows. The skipper was instructed to tune his gear (select course, speed, warp length, etc.) so as to maximise his total catch at that station. Tows were nominally 0.5 nautical miles (926 m, assessed using non-differential GPS), but were shortened whenever necessary depending on the expected size of the catch or for safe navigation. However, the dredge occasionally lost contact with the bottom or “flew” (because of hard or uneven substrates, an increase in depth, a dredge full of scallops or detritus, etc.) and, on these occasions, the tow was terminated (stopped and hauled early). The different dredge efficiency for those ‘terminated’ tows (Bian et al. 2012) is accounted for in the dredge efficiency model. For all tows, the actual distance travelled along the ground was calculated using the positions recorded for the vessel at the start and finish of the tow.

At the end of each tow, the dredge was retrieved and emptied onto the sorting tray on the boat. All live scallops were separated from the detritus and bycatch, and their maximum lengths measured to the nearest millimetre rounded down. Large catches were randomly subsampled for length. All unmeasured scallops were counted. No facilities for weighing the catch at each station were available to estimate the fraction sampled by weight. Survey metadata were captured on a standard trawl survey form (‘Station Record – 1989 Edition’); station details and scallop catch are shown in Appendix 2.

Additionally, in 2012 (as in 2009 and 2010), we categorised the dredge survey bycatch on a station by station basis (Appendix 3). Half of the dredge contents were sorted (from one side of the sorting table to the centre) into broad taxonomic groupings (e.g., red, brown, and green seaweed, finfish and starfish species, live and dead *Tawera spissa*, dog cockles, and horse mussels). Estimates of the relative volume of each taxonomic group in the 50% subsample were recorded for each station, as well a broad descriptor of habitat type (e.g., shell hash, rock, mud, sand, or coralline turf). Bycatch data were collected but not analysed in the present study. Our intention is to routinely collect data on the dredge bycatch during each survey, with a view to conducting bycatch analyses once data from a suitable number of surveys become available.

In previous surveys, only the start position of the vessel at the start of the dredge tow has been recorded. In 2012, both the start and finish positions of the vessel were recorded, and these were plotted in ArcGIS to check the tow positions in relation to the borders of the survey strata. For 15 of the 168 tows, the line between the start and finish position apparently crossed a stratum boundary. To investigate the effect of this, we re-analysed the survey data by excluding those 15 tows which crossed stratum borders. The greenweight biomass of scallops of 90 mm shell length or more at the time of the survey (April–May 2012) was similar when estimated from the data for all tows or from data excluding border tows (Appendix 4). The biomass estimate was not sensitive to this effect, therefore subsequent analyses included data from all 168 valid tows. The allocation of station positions in future surveys should address this issue.

3.2.2 Estimating and correcting for dredge efficiency

We used a new parametric model of dredge efficiency (Bian et al. 2012) that estimates efficiency with respect to scallop length, water depth, substrate type, and tow termination. Other factors may also affect the efficiency of scallop dredges, including the hardness/corrugated nature of the seabed, and the prevailing conditions of the weather, swell, tide, and sea surface. Such factors were not included in the new model (Bian et al. 2012) because data on those factors were not (or could not be) recorded at the time of the historical dredge efficiency sampling. That does not mean, however, that such factors are unimportant in determining dredge efficiency; it is likely that efficiency is affected by a complex interaction of multiple factors, some of which the new model cannot account for. The potential significance of such factors, therefore, must be considered when interpreting estimates of biomass and yield made using any corrections for dredge efficiency. Given that the historical efficiency data used in the modelling were collected at a range of different sites over a number of years, the uncertainty associated with estimating dredge efficiency is assumed to be broadly representative of the variability encountered during the survey.

Although the previous dredge efficiency curve (Cryer & Parkinson 2006) is now considered inappropriate, we also analysed the 2012 data using that same methodology as used in the 2005–10 scallop stock assessments. This allowed for comparisons with the results of past surveys without having to re-analyse all of the survey data, which was outside the scope of this project.

Tows that were considered to be on hard/corrugated seabed, as perceived by the survey skipper from the behaviour of the vessel and gear (e.g., warp tension and action), were noted in the station comments, and their positions were plotted in ArcGIS (Appendix 5a). Fishers consider that the dredge is less efficient at catching scallops in areas where the bottom is hard/corrugated because the dredge teeth do not penetrate into the substrate as far; when the seabed is corrugated (e.g., made up of undulating sand waves), it is thought that the dredge only contacts with the ridges of the corrugations and misses the troughs.

The bottom type, estimated from the contents of the dredge, was recorded for each station (Appendix 5b). This closely matched the categorical substrate type given *a priori* to each stratum and applied in the dredge efficiency corrections in the analytical workup.

3.2.3 Estimating biomass at the time of survey and the start of the season

The analytical approach to estimating start-of-season recruited biomass for scallops was developed during the 2002 and 2003 survey projects (e.g., Cryer & Parkinson 2004) and summarised by Cryer & Parkinson (2006). The approach is described in detail in Appendix 10. In brief, the approach contains the following 10 steps.

1. The length frequency distribution for each sample is scaled by the sampling fraction (if any).

2. The length frequency distribution for each sample is converted to “uncorrected” density per unit area of seabed, i.e., assuming the dredge to be 100% efficient for all size classes.

3. The length frequency distribution for each sample is “corrected” for dredge efficiency to estimate the “real” density per unit area of seabed. These are combined to estimate the population length frequency distribution.

4. The greenweight density of scallops at or above the minimum legal size (or other length of interest) is estimated using a length weight regression ($W = 0.00037\ L^{2.690}$). Variance associated with the regression is included by bootstrapping from the raw length-weight data.

5. The mean recruited biomass (per unit area) for each stratum and for the whole population (or any subset of strata), together with the sampling variance, are estimated using bootstraps from the sampling data.

6. The absolute recruited biomass at the time of the survey is estimated by scaling the estimate of the mean biomass by the combined area of all pertinent strata. The stratum areas are considered to be without error.

7. The corrected population length frequency distribution (from step 3) is projected to the start of the forthcoming season using a growth transition matrix based on tag return data. Uncertainty about the expected average growth between survey and season is incorporated by bootstrapping, generating a new growth model for each iteration by bootstrapping from the original tag return data. The growth data and model used in the 2012 analysis were the same as in previous survey analyses using the method of Cryer & Parkinson (2006); new data and modelling are available from a more recent study of scallop growth (Tuck & Williams 2012), but additional work is required before they can be used in this analytical process.

8. Mortality between survey and season is incorporated by applying an estimate of the instantaneous rate M for each iteration by bootstrapping (parametrically) from an assumed normal distribution of M with a mean of 0.5 and a c.v. of 0.065.

9. The absolute recruited biomass at the start of the season is estimated by repeating steps 4–6.

10. The final step in the analysis is the prediction of meatweight from expected start-of-season greenweight. Analyses of recovery of meatweight from greenweight in the Coromandel fishery in 13 previous fishing seasons suggest that average recovery over a season varies from about 10% to 15% (Williams & Parkinson 2010). Uncertainty in predicting meatweight recovery is incorporated by selecting one of those 13 seasonal averages for each bootstrap estimate of start-of-season recruited biomass (in greenweight).

3.2.4 2012 survey results

3.2.4.1 Population at the time of the survey (April–May 2012)

During the Coromandel survey, 23 362 of 48 574 scallops caught in 168 valid tows (sweeping an estimated 0.251 km^2) were measured (including the entire catch at 127 stations and 41 subsamples). Pooled length frequency distributions corrected for dredge efficiency (Bian et al. 2012) and scaled to estimated population size (i.e., using the stratum areas) were constructed for the total population of the stock area surveyed (Figure 3) and the five major fishery regions (Figure 4a and Figure 4b).

Overall, the population sampled at the time of the survey (Figure 3) contained scallops of a wide range of sizes, with a large proportion of recruited scallops (90 mm or larger), but also contained a good proportion of pre-recruits (smaller than 90mm). The population length frequency distribution was dominated by the large numbers of scallops greater than 90 mm found in the Hauraki Gulf region.

Examination of the length frequency distributions for each of the six regions of the Coromandel fishery (Figure 4a, scaled by area; 4b presented as proportional frequency) shows that the 'new' fishery region in the outer Hauraki Gulf held the largest proportion of recruited scallops. Good proportions of recruits were also found at Colville, and at the Mercury Islands, which, up until the 2011 season, has been the mainstay of the fishery.

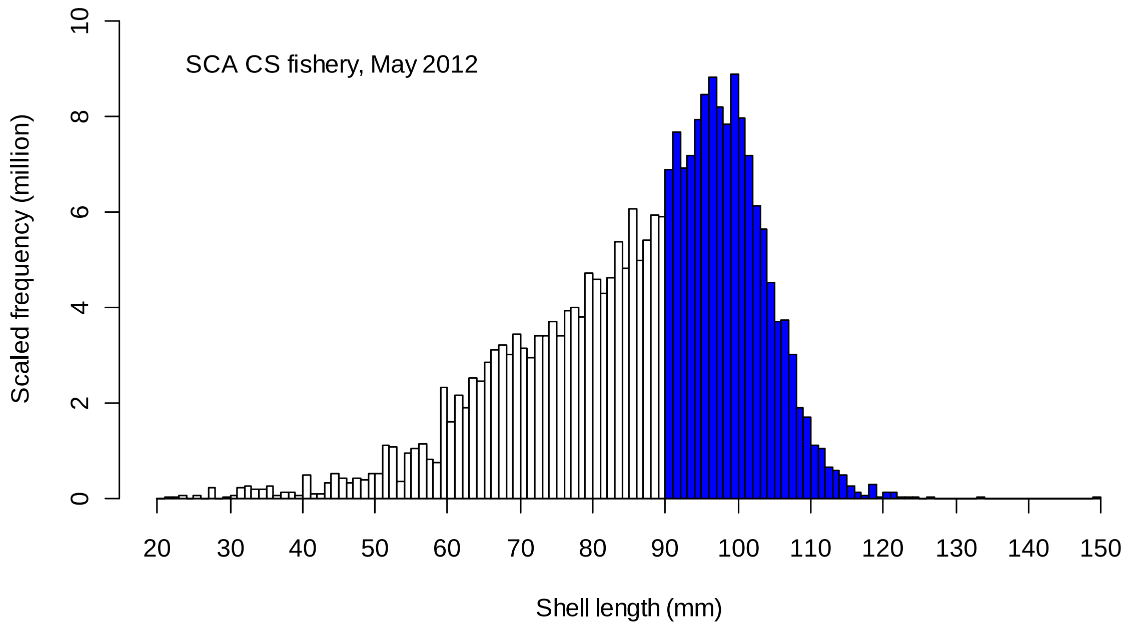

Figure 3: Scaled length frequency distribution for the overall population sampled in the Coromandel stock at the time of the survey (April–May 2012), corrected for dredge efficiency (Bian et al. 2012). Shaded bars show scallops larger than 90 mm shell length (the commercial MLS for SCA CS).

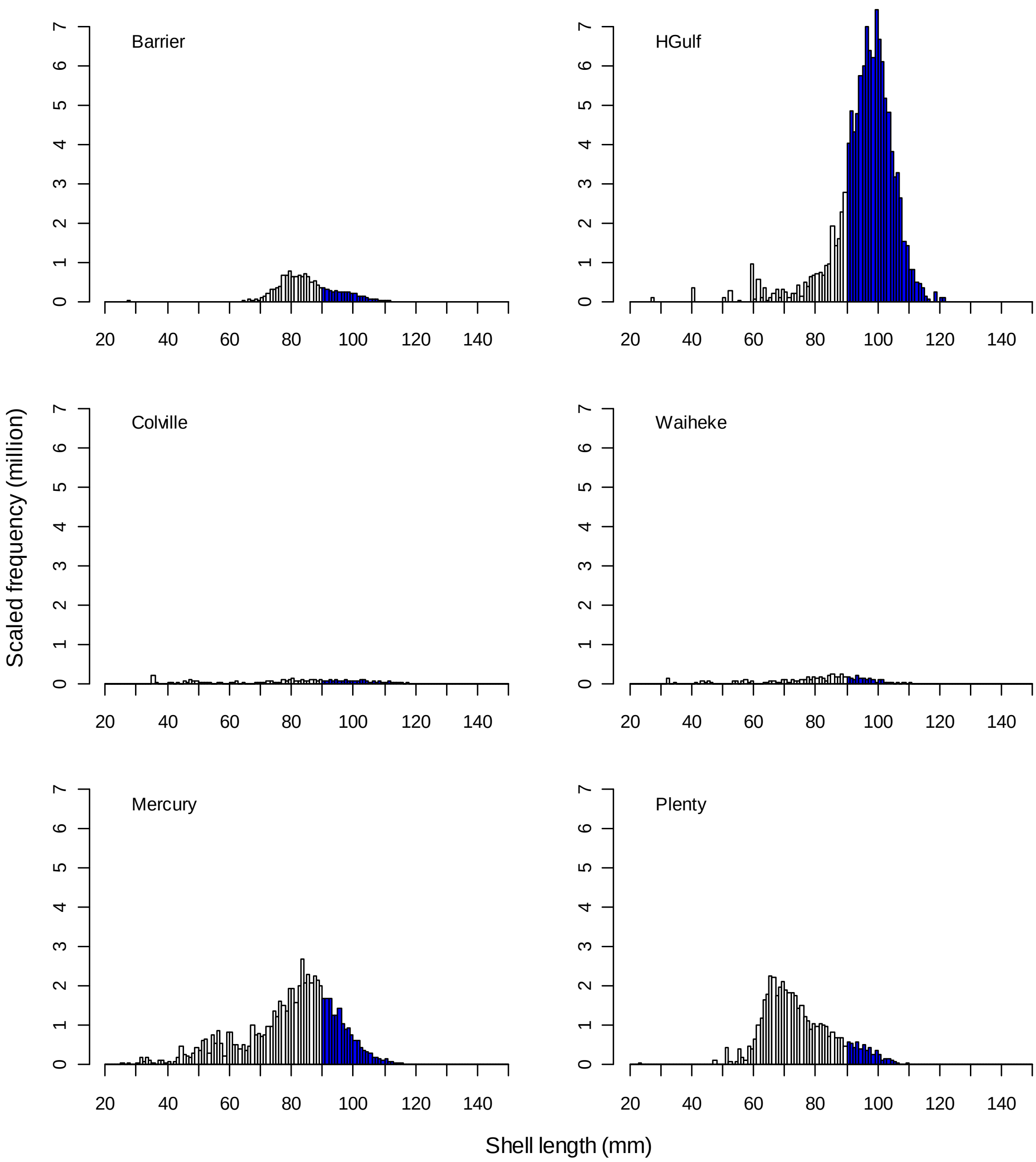

Figure 4a: Scaled length frequency distributions for the six major regions of the Coromandel stock at the time of the survey (April–May 2012), corrected for dredge efficiency (Bian et al. 2012). Shaded bars show scallops larger than 90 mm shell length (the commercial MLS for SCA CS).

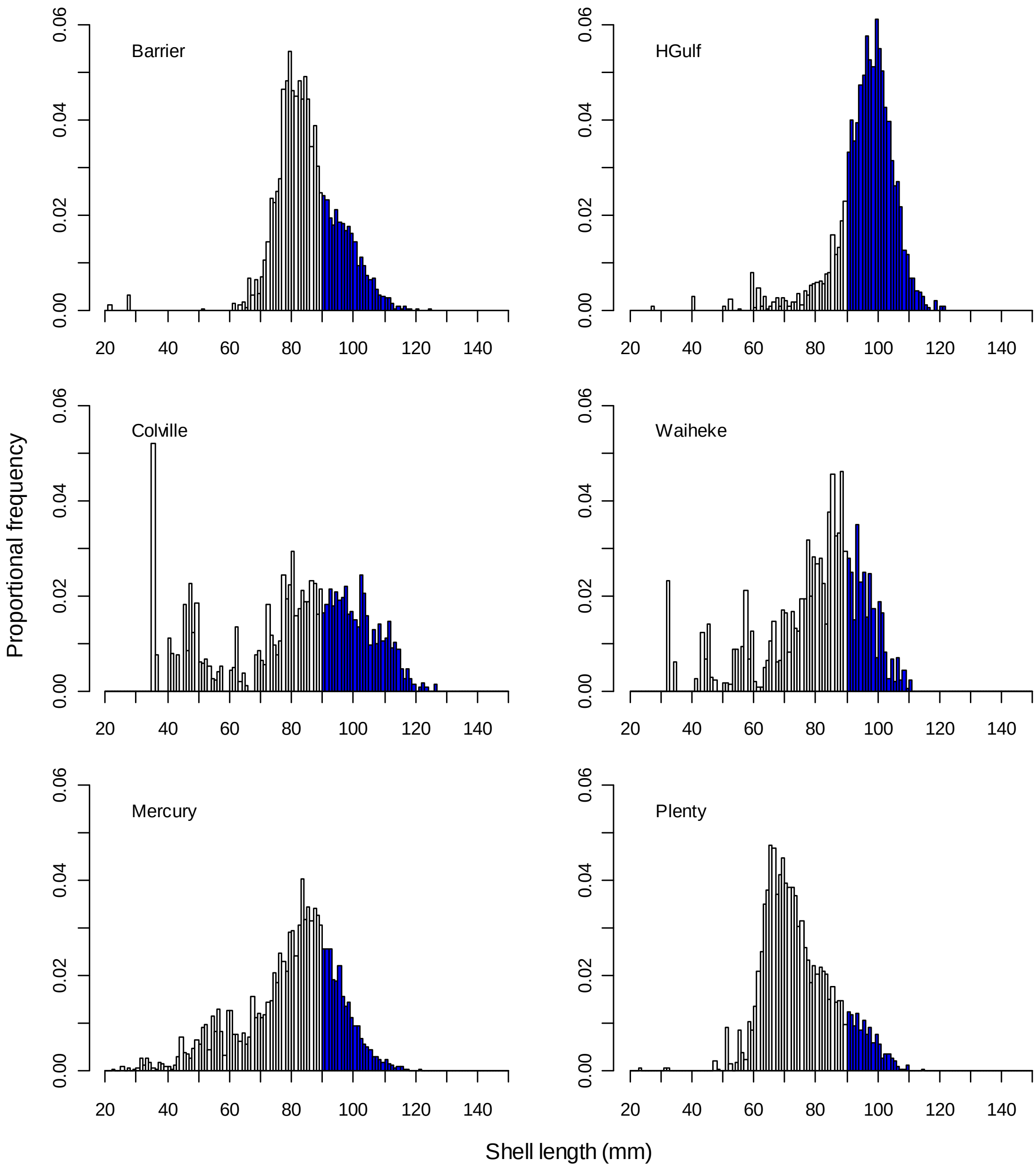

Figure 4b: Proportional length frequency distributions for the six major regions of the Coromandel stock at the time of the survey (April–May 2012), corrected for dredge efficiency (Bian et al. 2012). Shaded bars show scallops larger than 90 mm shell length (the commercial MLS for SCA CS).

Using a standard parametric approach to estimation and no correction for dredge efficiency (i.e., estimating the raw survey results with none of the bootstrapping described in section 3.2.3), the greenweight biomass of scallops of 90 mm shell length or more at the time of the survey was 5 836 t (Appendix 6) with a c.v. of 15%. This biomass estimate is the most conservative interpretation of the survey data possible and might be interpreted as the minimum absolute biomass at the time of the survey; the estimate is reliable, but this simple approach does not incorporate uncertainty other than that of the survey sampling.

A more appropriate approach to estimation is to use 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 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 c.v. (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 most appropriate measure (i.e., best estimate) of central tendency for our sample, and the 95% confidence interval (CI) is used to express the amount of uncertainty in our estimate.

Using the re-sampling with replacement approach to estimation, including variability associated with dredge efficiency (Bian et al. 2012) and the length-weight regression, produced a time of survey recruited biomass estimate of 10 966 t greenweight (median value; 95%CI 8085–14 743 t) with a c.v. of 15%. The frequency distribution of the 1000 bootstrap estimates is shown in Figure 5. The 2012 survey data were also analysed using the previous method of correcting for dredge efficiency (Cryer & Parkinson 2006), which produced a much higher estimated biomass (Appendix 7).

Table 3: Summary statistics for the population of scallops 90 mm shell length or more in the Coromandel stock at the time of the survey (April–May 2012), corrected for dredge efficiency (Bian et al. 2012). The analysis used a non-parametric re-sampling with replacement approach to estimation (1000 bootstraps).

Region	Area	Tows	Density(scallops m^{-2})				Abundance(millions)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI	Mean	c.v.	Median	95%CI
Barrier	26.2	17	0.16	0.18	0.16	0.11–0.23	4.31	0.18	4.25	3.0–6.0
HGulf	537.1	32	0.18	0.19	0.18	0.12–0.26	99.29	0.19	98.17	65.6–139.8
Colville	48.6	15	0.03	0.30	0.03	0.02–0.05	1.66	0.30	1.64	0.8–2.7
Waiheke	49.8	13	0.03	0.55	0.03	0.01–0.08	1.63	0.55	1.56	0.3–3.7
Mercury	127.4	57	0.13	0.19	0.13	0.09–0.19	17.09	0.19	16.89	11.5–24.3
Plenty	190.1	34	0.03	0.24	0.03	0.02–0.04	5.76	0.24	5.74	3.0–8.3
SCA CS	979.2	168	0.13	0.15	0.13	0.10–0.18	129.72	0.15	127.52	95.3–171.7

Region	Area	Tows	Biomass(t green)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI
Barrier	26.2	17	358	0.17	356	255–488
HGulf	537.1	32	8 632	0.19	8 521	5 803–12 198
Colville	48.6	15	155	0.33	151	69–266
Waiheke	49.8	13	131	0.57	126	22–304
Mercury	127.4	57	1 390	0.19	1 374	952–1 964
Plenty	190.1	34	460	0.24	457	235–670
SCA CS	979.2	168	11 126	0.15	10 966	8 085–14 743

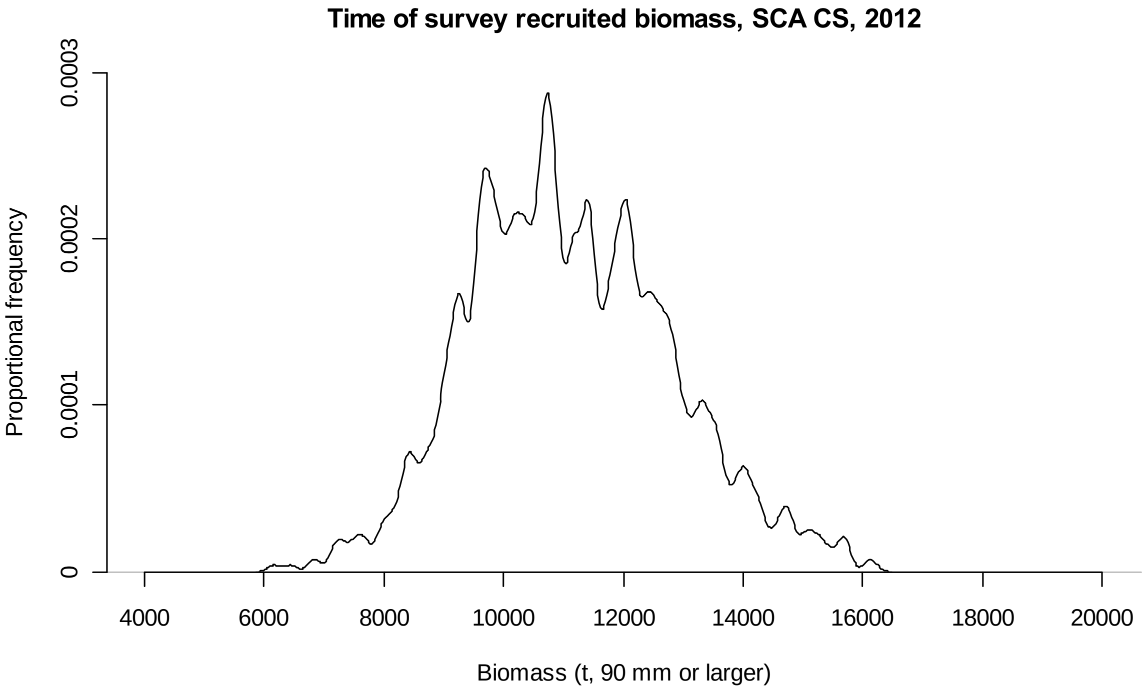

Figure 5: Frequency distribution of the estimated recruited biomass (t greenweight, scallops 90 mm or larger) in the Coromandel stock at the time of the survey (April–May 2012). The distribution shows the results of a non-parametric re-sampling with replacement approach to estimation (1000 bootstraps).

3.2.4.2 Trends in abundance and biomass

Discerning trends in the abundance and biomass of recruited scallops is complicated by changes to survey coverage, the establishment of closed areas, and uncertainty about dredge efficiency in any particular year. However, some changes have been so large as to transcend this combined uncertainty. Time series of abundance and biomass estimates are shown in Figure 4, and scaled length frequency distributions are provided in Figure 6, Figure 7, and Figure 8. It is important to note that these time series were produced by correcting for dredge efficiency using the method of Cryer & Parkinson (2006), so the 2012 values were generated using that same method so that all years are comparable. In future, the data should be re-worked using the new method of Bian. et al (2012). For 2012, the estimates were generated using data from the 'core' strata only (i.e., the 'background' strata, and 'new' strata in the Hauraki Gulf region, were excluded, the latter because there was no survey from the past; it was surveyed for the first time in 2012).

Estimates around the turn of the century (2000) were consistently at or near the lowest on record and it seems reasonable to conclude that the population was, for unknown reasons, at a very low ebb. In contrast, following reasonable increases in 2003 and, especially, 2004, the abundance and biomass in 2005 were the highest on record and probably higher than in the mid 1980s when not all of the beds were surveyed. This remarkable resurgence was strongest in the Mercury region to the north of Whitianga (the mainstay of the fishery), but most beds showed some increase in density. There has been a gradual decline in the overall recruited population since the peak in 2005, but in 2010 this downward trend appeared to have stalled. For the regions usually fished (i.e. for the core strata only, excluding the 'new' area in Hauraki Gulf and the 'background' strata) the status of the recruited population in 2012 appears to be fairly similar to that in 2010 (Appendix 8; estimated using Cryer & Parkinson (2006) dredge efficiency method), and again most of the fishable biomass is held in the Mercury beds, but with high densities of recruits in beds at Little Barrier. For the new Hauraki Gulf region of the fishery (2W/2S), it is unknown whether the large biomass of scallops found in 2012 is a temporally consistent part of the population, or a product of successful recruitment in recent years.

Table 4: Estimated abundance and biomass of scallops 90 mm or more shell length at the time of surveys in the five main regions of the Coromandel fishery since 1998. Excludes the "new", deep fishery region in Hauraki Gulf, which was fished for the first time in 2011, and surveyed for the first time in 2012 (estimated 148.5 million scallops or 13 278 t greenweight biomass). Survey data were analysed using a non-parametric re-sampling with replacement approach to estimation (1000 bootstraps). Note that these estimates were produced by correcting for dredge efficiency using the method of Cryer & Parkinson (2006), which has now been replaced by the method of Bian et al. (2012). Estimates are not necessarily directly comparable between years because of changes to survey coverage. –, no survey in a region or year. The 2001 survey totals include scallops surveyed in 7 km^2 strata at both Kawau (0.5 million, 3 t) and Great Barrier Island (0.8 million, 62 t).

Year	Abundance (millions)						Area surveyed
	Barrier	Waiheke	Colville	Mercury	Plenty	Total	(km^2)
1998	2.0	9.0	0.4	21.3	2.2	36.1	341
1999	0.5	0.5	0.0	7.3	2.7	11.2	341
2000	–	–	–	–	–	–	–
2001	7.4	0.4	–	6.9	2.1	18.1	125
2002	1.8	4.0	–	6.6	2.0	14.7	119
2003	2.5	4.0	4.3	12.3	4.9	28.6	130
2004	4.5	9.8	0.4	58.5	8.2	82.6	149
2005	6.2	3.3	3.0	118.8	12.6	145.3	174
2006	5.6	–	10.3	101.6	6.5	125.3	160
2007	4.2	1.3	4.4	59.9	14.3	84.6	175
2008	2.0	–	1.7	56.3	4.8	65.0	144
2009	10.4	–	3.1	31.8	1.3	46.9	144
2010	9.6	0.8	2.6	28.0	3.9	45.6	149
2011	–	–	–	–	–	–	–
2012	7.7	0.4	2.5	22.8	2.9	36.8	180

Year	Biomass (t green)						Area
	Barrier	Waiheke	Colville	Mercury	Plenty	Total	(km^2)
1998	173	731	30	1 674	205	2 912	341
1999	42	34	1	559	224	873	341
2000	–	–	–	–	–	–	–
2001	554	32	–	525	165	1 362	125
2002	150	289	–	538	163	1 156	119
2003	225	302	387	995	406	2 355	130
2004	348	737	30	4 923	676	6 794	149
2005	544	274	316	10 118	1 058	12 404	174
2006	519	–	1 041	8 731	534	10 902	160
2007	376	96	409	5 498	1 110	7 539	175
2008	166	–	150	4 575	367	5 265	144
2009	823	–	257	2 512	102	3 725	144
2010	764	59	219	2 299	291	3 671	149
2011	–	–	–	–	–	–	–
2012	629	32	250	1 855	225	3 027	180

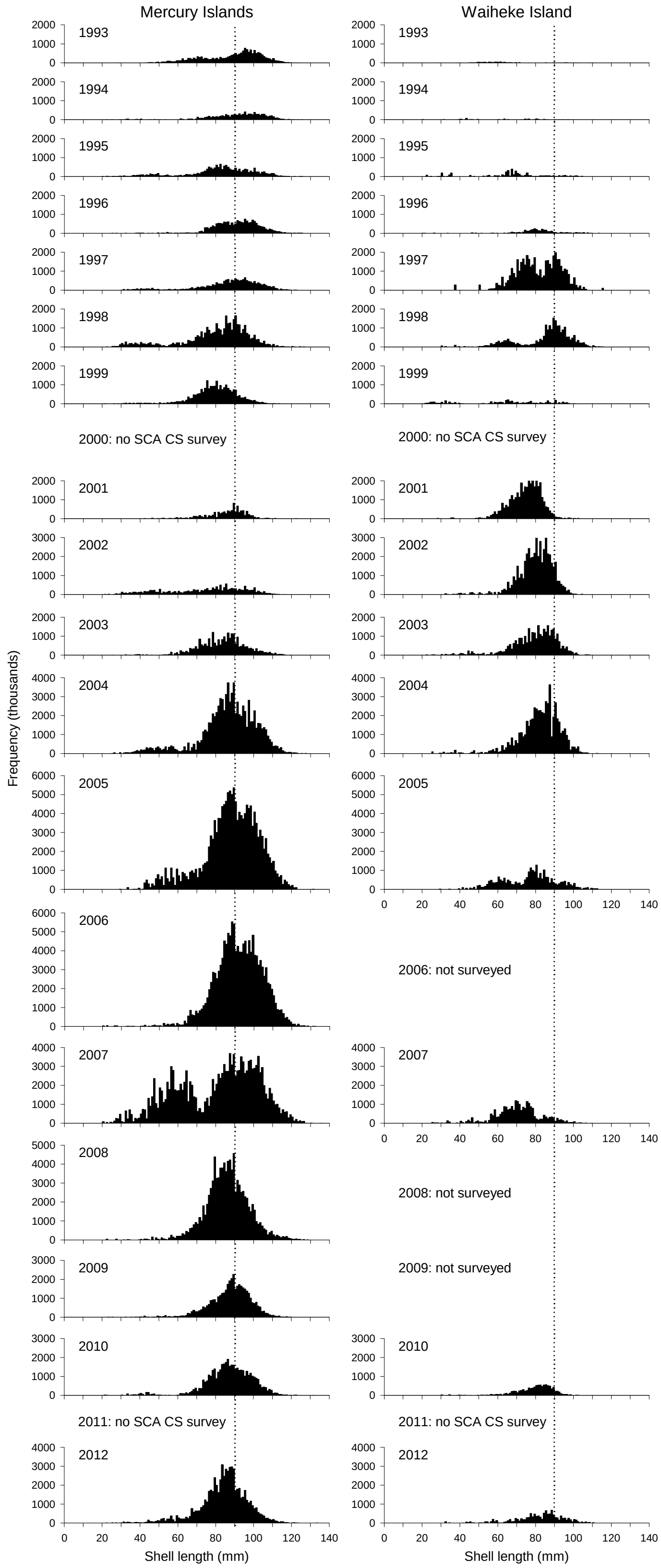

Figure 6: Scaled length frequency distributions at the time of surveys assuming historical average dredge efficiency (applied using the simple scalars reported by Cryer & Parkinson (2002)) for scallops in commercially fished areas of SCA CS at the Mercury Islands (left) and Waiheke Island (right) since 1993. The SCA CS stock was not surveyed in 2000 or 2011, and the Waiheke region was not surveyed in 2006, 2008, and 2009. Vertical dotted lines indicate the minimum legal size of 90 mm shell length.

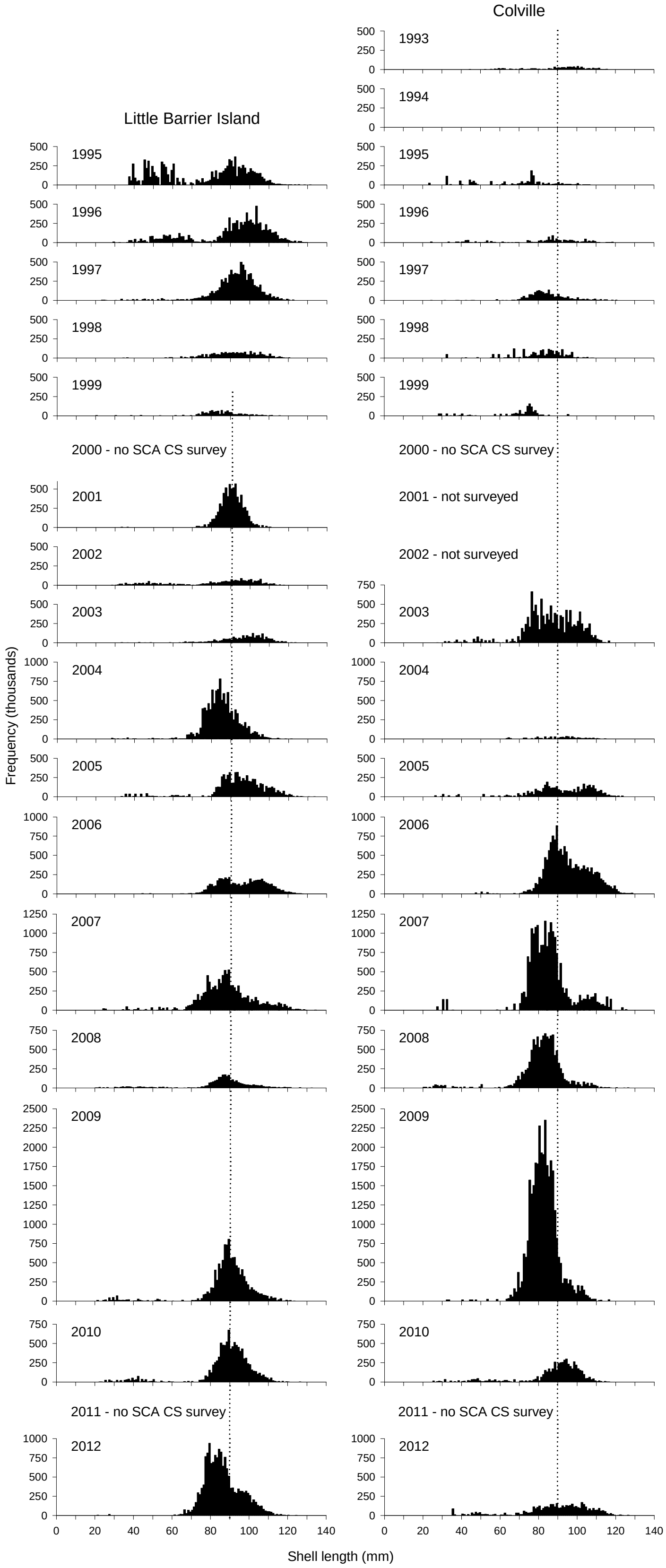

Figure 7: Scaled length frequency distributions at the time of surveys assuming historical average dredge efficiency (applied using the simple scalars reported by Cryer & Parkinson (2002)) for scallops in commercially fished areas of SCA CS at Little Barrier Island (left) since 1995 and Colville (right) since 1993. The SCA CS stock was not surveyed in 2000, and the Colville region was not surveyed in 2001 and 2002. Vertical dotted lines indicate the minimum legal size of 90 mm shell length.

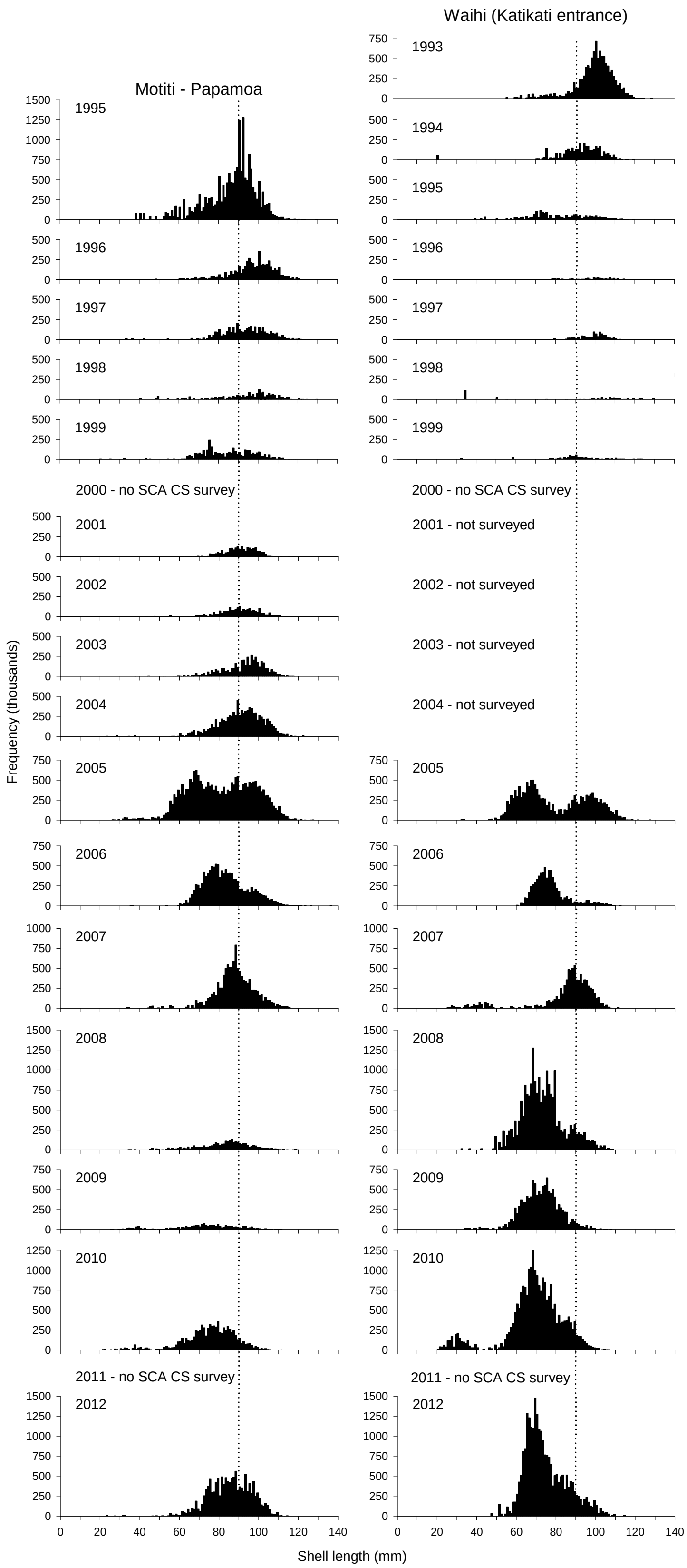

Figure 8: Scaled length frequency distributions at the time of surveys assuming historical average dredge efficiency (applied using the simple scalars reported by Cryer & Parkinson (2002)) for scallops in commercially fished areas of SCA CS in the Bay of Plenty region at Motiti-Papamoa (left) since 1995 and Waihi (right) since 1993. The SCA CS stock was not surveyed in 2000, and the Waihi region was not surveyed between 2000 and 2004. Vertical dotted lines indicate the minimum legal size of 90 mm shell length.

3.2.4.3 Predicted start-of-season biomass (July 2012)

The projected biomass of scallops 90 mm shell length or more at the start of the season (15 July 2012) was 11 423 t greenweight (median projected value; 95% CI 8374–15032) with a c.v. of 15% (Table 5). Further, assuming historical (1998 to 2009) average recovery of meatweight from greenweight led to an estimate of 1380 t meatweight (median projected value; 95% CI 976–1913) with a c.v. of 18% (Table 5). These estimates represent an increase of 4% in the median recruited biomass between survey and season (Figure 9).

Table 5: Summary statistics for the projected population of scallops 90 mm shell length or more in the Coromandel stock at the start of the season (15 July 2012), corrected for dredge efficiency (Bian et al. 2012), assuming average growth, M = 0.5, and average recovery of meatweight from greenweight.

Region	Area	Tows	Density(scallops m^{-2})				Abundance(millions)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI	Mean	c.v.	Median	95%CI
Barrier	26.2	17	0.26	0.22	0.26	0.15–0.37	6.74	0.22	6.70	3.9–9.7
HGulf	537.1	32	0.18	0.20	0.18	0.12–0.25	97.17	0.20	96.62	63.4–136.2
Colville	48.6	15	0.04	0.26	0.04	0.02–0.06	1.83	0.26	1.82	0.9–2.8
Waiheke	49.8	13	0.05	0.45	0.05	0.01–0.09	2.34	0.45	2.25	0.4–4.6
Mercury	127.4	57	0.19	0.23	0.19	0.12–0.29	24.66	0.23	24.23	15.1–36.4
Plenty	190.1	34	0.04	0.22	0.04	0.03–0.06	8.28	0.22	8.25	4.8–12.1
SCA CS	979.2	168	0.14	0.15	0.14	0.11–0.19	141.01	0.15	139.97	103.7–183.4

Region	Area	Tows	Biomass(t green)				Biomass(t meat)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI	Mean	c.v.	Median	95%CI
Barrier	26.2	17	488	0.20	488	304–661	59	0.23	59	34–87
HGulf	537.1	32	8 272	0.20	8 219	5 415–11 561	1 005	0.24	984	610–1 521
Colville	48.6	15	161	0.29	158	81–257	20	0.32	19	10–34
Waiheke	49.8	13	170	0.47	161	29–342	21	0.50	19	3–44
Mercury	127.4	57	1 799	0.21	1 764	1 134–2 598	220	0.24	215	131–339
Plenty	190.1	34	591	0.22	590	340–862	72	0.26	70	40–114
SCA CS	979.2	168	11 480	0.15	11 423	8 374–15 032	1 397	0.18	1380	976–1 913

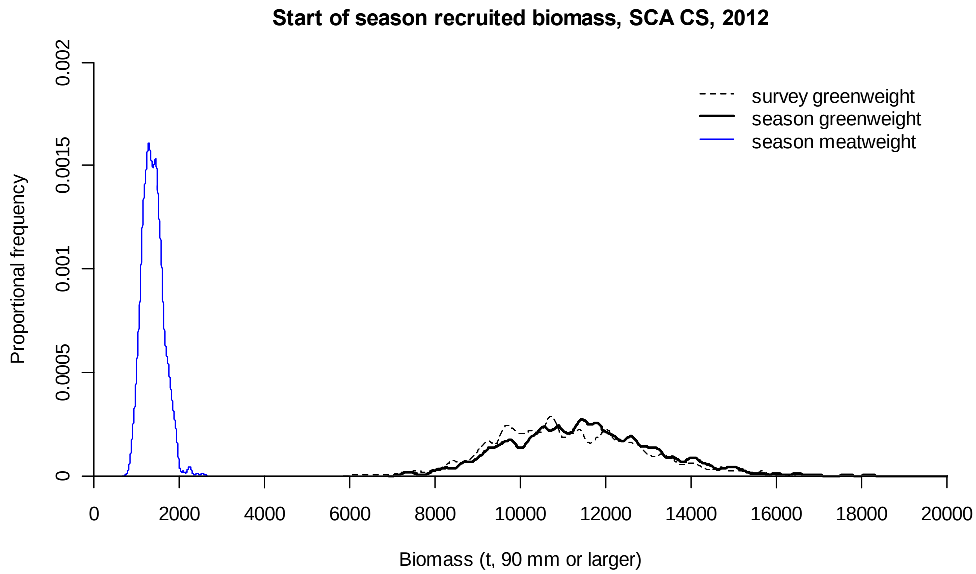

Figure 9: Proportional frequency distributions of estimated recruited biomass (90 mm or larger) in the Coromandel stock at the start of the season (15 July 2012). The results of a non-parametric re-sampling with replacement projection approach are shown in t greenweight (solid bold line) and meatweight (solid blue line). The time of survey distribution in t greenweight (dashed line) is shown for comparison.

3.2.4.4 Sensitivity of projected biomass to exclusion of areas of low scallop density

Estimates of biomass are sensitive to the exclusion of areas of low scallop density, and in the past it has generally been accepted 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 acceptable fishing. Discussions with fishers in 2012 suggested a catch rate of 50 $kg.h^{-1}$ per vessel would be the approximate absolute minimum viable commercial catch rate, below which fishing would become uneconomical. An approximate approach to estimate how 50 $kg.h^{-1}$ equates to an actual "critical density" of scallops on the seabed is as follows. Assuming the mean weight of scallops landed is 100 g, a catch rate of 50 $kg.h^{-1}$ would be 500 scallops per hour. Assuming fishers conducted 4 tows an hour, each being 0.5 n. miles in length with a 2-m wide dredge, the area swept by the dredge would be 7408 m^2. The estimated density of scallops in that area, therefore, would be 0.07 m^{-2}. Obviously this approach provides only a very rough estimate of the actual "critical density" marking the limits of acceptable fishing, but this could be investigated in future work using a more quantitative approach.

Working at a station level, 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}. In previous assessments, these "critical density" corrections were applied before scaling for dredge efficiency, so the estimates were very conservative. In the present study, the critical density corrections were applied after first correcting for efficiency, as we consider this to be more appropriate, representing actual scallop density on the seabed. Subsequently, the time of survey population was projected forward to the start of the season (15 July 2009) using the same projection methodology as used previously (Section 3.2.4.3). This approach was repeated to produce start of season biomass estimates for assumed critical densities in the range 0.00 to 0.20 scallops m^{-2}.

Excluding areas of very low density (below 0.04 m^{-2}) produced a stock-wide estimate of recruited biomass at the start of the season of 1121 t meatweight (c.v. 19%), a reduction of 19% on the absolute estimate of 1380 t (Figure 10). Excluding areas where the density was less than 0.08 m^{-2} reduced the stock-wide biomass estimate to 938 t (a reduction of about 32%), and to 621 t (a reduction of 55%) for a critical density of 0.20 m^{-2}.

Estimates of biomass by region at different critical densities are given in Appendix 9 and plotted in Figure 11. The largest effect of excluding areas of low density from biomass estimates was in the Waiheke and Bay of Plenty beds (Figure 11), where estimates declined by 62% and 65%, respectively, when areas where scallops were less dense than 0.04 m^{-2} were excluded. Thus, most of the biomass in the Waiheke and Bay of Plenty beds appeared to be contained in areas of low density where catch rates are likely to be low. However, the Waiheke and Bay of Plenty beds contained only 7% of the total recruited biomass of the Coromandel stock in 2012.

Where the density of recruited scallops was high (Little Barrier Island, Hauraki Gulf, and Mercury), the estimated biomass was much less affected when areas where scallops were less dense than 0.04 m^{-2} were excluded. At Little Barrier, where the mean density was very high, the biomass estimate declined by only 7%, whereas at Hauraki Gulf and the Mercury Islands, locations with high densities of scallops, the biomass estimate declined by 16 and 18%, respectively, when areas where scallops were less dense than 0.04 m^{-2} were excluded.

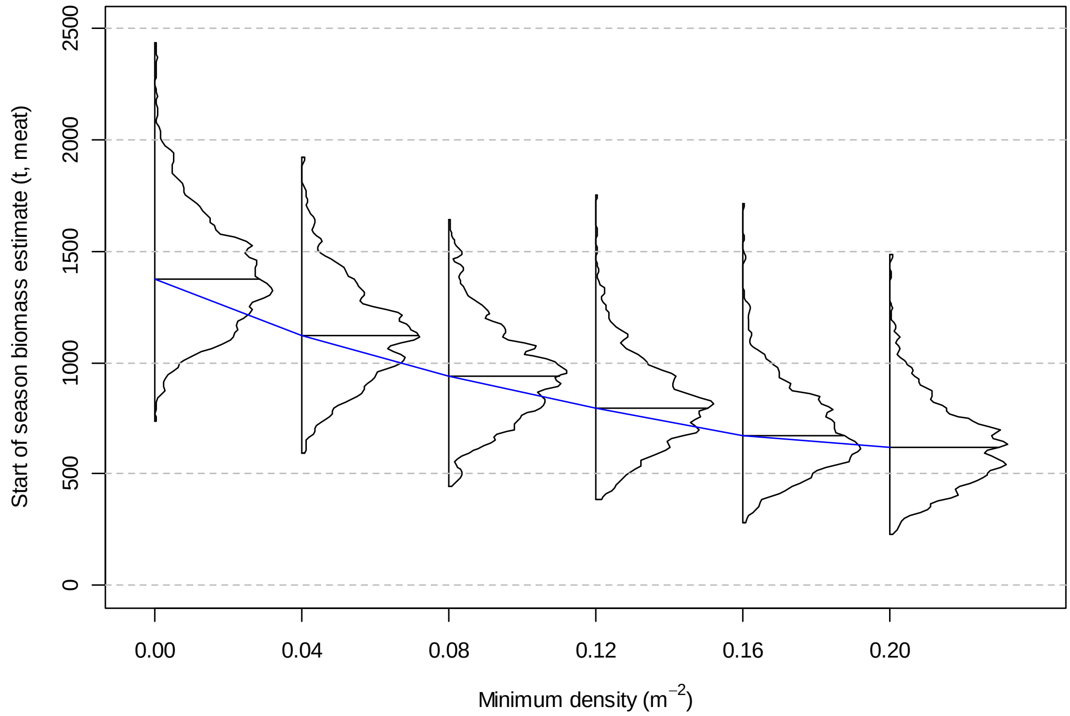

Figure 10: Effect of excluding areas of low scallop density on the stock-wide recruited biomass (t meatweight) in the Coromandel stock at the start of the season (15 July 2012), corrected for dredge efficiency (Bian et al. 2012). For each minimum ("critical") density, the distribution and median (horizontal line) of the estimated biomass are shown. Critical density corrections were applied after correcting for dredge efficiency.

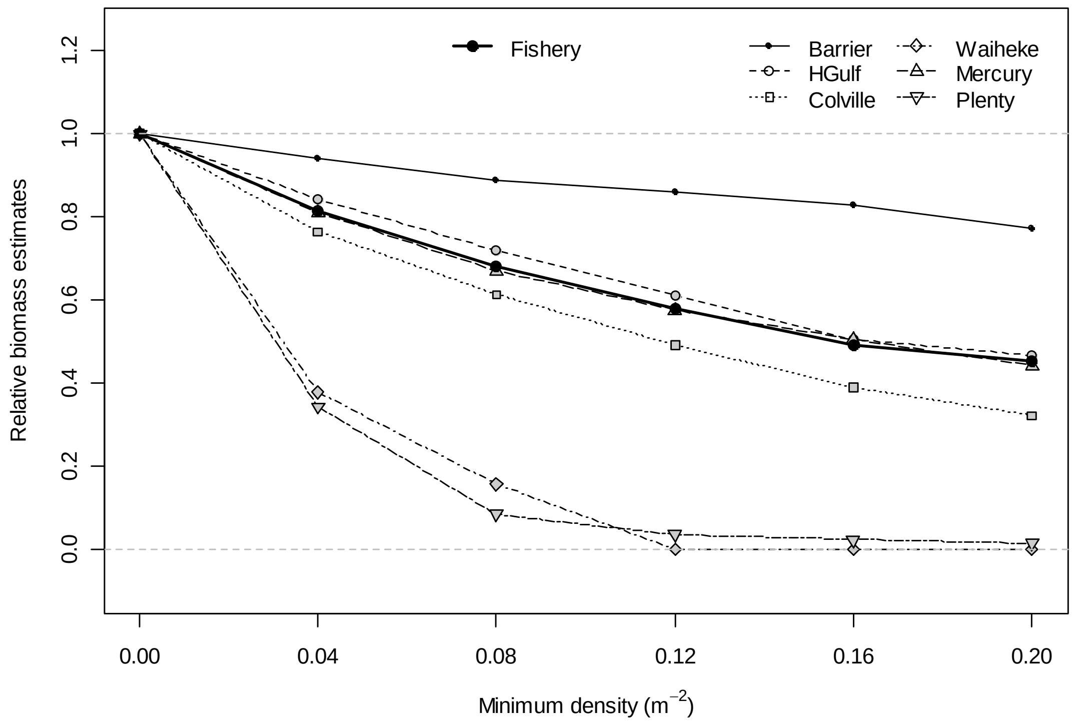

Figure 11: Effect of excluding areas of low scallop density on recruited biomass by region in the Coromandel stock at the start of the season (15 July 2010). Critical density corrections were applied after correcting for dredge efficiency.

3.2.4.5 Sensitivity of projected biomass to dredge efficiency in deep water (≥ 30 m)

The model of dredge efficiency (Bian et al. 2012) applied in the 2012 Coromandel survey analysis is based on historical data from dredge and diver sampling conducted in water depths ranging from 14 to 28 m. In that model, depths are categorised in four depth bins: less than 15, 15–20, 20–25, and greater than or equal to 25 m. The DIC model selection process suggested depth has the most significant effect on dredge efficiency of the covariates examined.

In the 2012 Coromandel scallop survey, 55 of the 168 tows were conducted in water depths between 30 and 50 m (mean of 40.9 m). According to the categorisation of depth in the dredge efficiency model, in the base case estimation of biomass, the survey catch data for those tows were corrected for the dredge efficiency corresponding to the depth bin for depths greater than or equal to 25 m. To evaluate how sensitive the stock biomass estimates are to the (unknown) dredge efficiency applied to the deeper water tow data, we considered an alternative approach.

In this alternative approach, we assumed the six dredge efficiency parameters (Bian, et al. 2012) will continue to follow the apparent trend with depth, so that we can use a linear model to predict the dredge efficiency for the deeper tows. For this alternative, we re-categorised the dredge efficiency data into five depth bins: less than 15, 15–20, 20–25, 25–30 and greater than or equal to 30 m and the weighted means of the depths of the tows within each bin (14.4, 18.0, 22.6, 26.4 and 40.9 m, the latter being the mean depth of tows greater than 30 m depth in the 2012 survey), were used as the depths of the bins. Using the depths for the four depth bins: less than 15, 15–20, 20–25, and 25–30 and the corresponding parameter estimates from the dredge efficiency modelling, we performed a linear regression (least squares) for each of the six parameters.

$$y = \alpha + \beta x$$

$$\hat{\beta} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}, \; \hat{\alpha} = \bar{y} - \hat{\beta}\bar{x}$$

We used the estimated $\hat{\alpha}$ and $\hat{\beta}$ to predict the values of the parameters for the depth of 40.9 m (i.e., the new bin for depth greater than or equal to 30 m). To obtain the uncertainty for the prediction, we repeated the estimation for all 1000 of the MCMC samples of the six parameters and obtained 1000 predictions for each of the parameters for the bin for depth greater than or equal to 30 m (Figure 12). The predicted dredge efficiencies for depths greater than or equal to 30 m were higher, and more uncertain, than for depths less than 30 m (Figure 13), resulting in a lower biomass estimate (with a more skewed distribution) than the base case analysis (Figure 14).

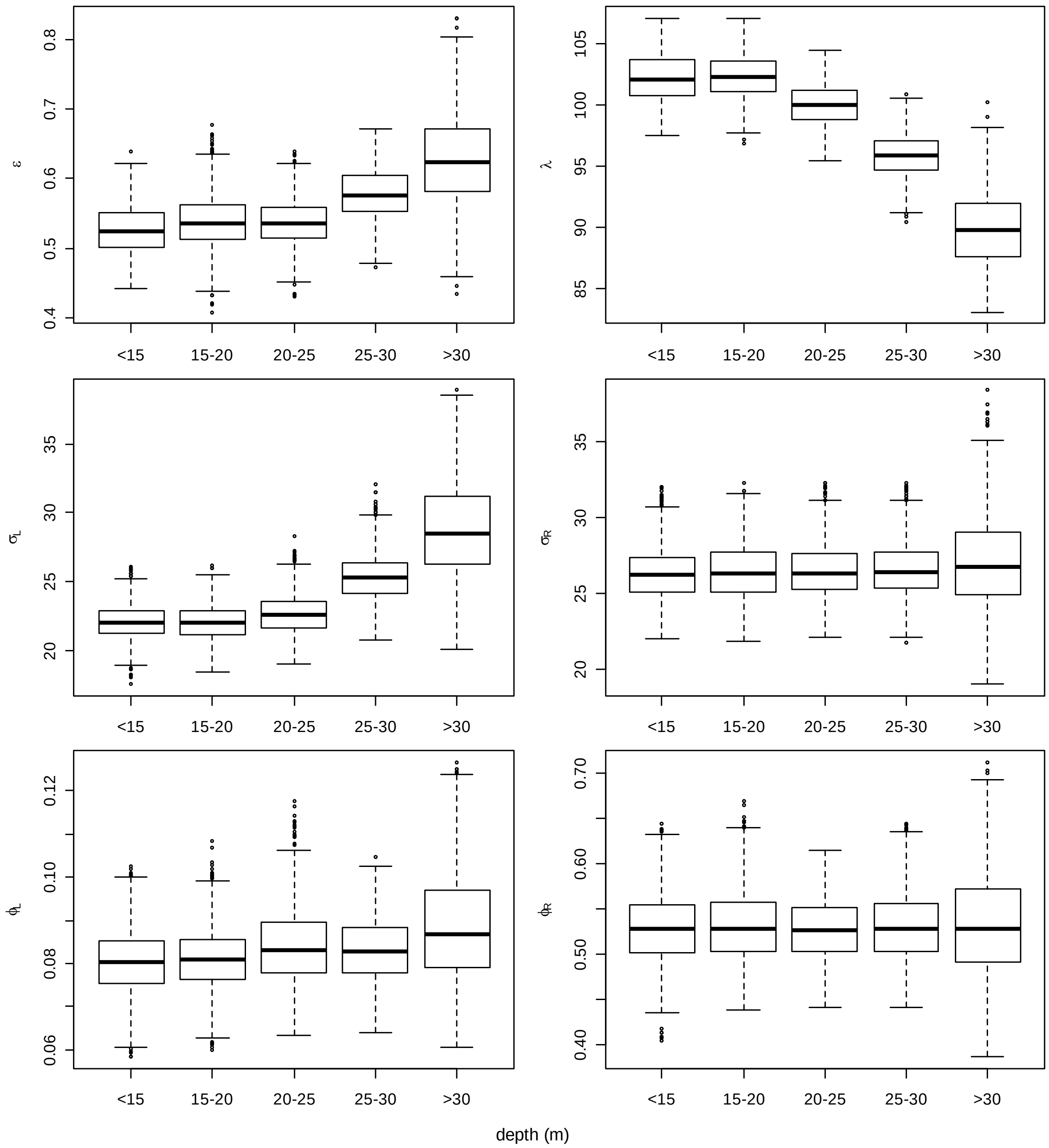

Figure 12: MCMC samples for the dredge efficiency parameters, ε, λ, δL, δR, φL, and φR for depth bins less than 15, 15–20, 20–25, and 25–30 m, and predicted dredge efficiency parameters for depth bin greater than or equal to 30 m.

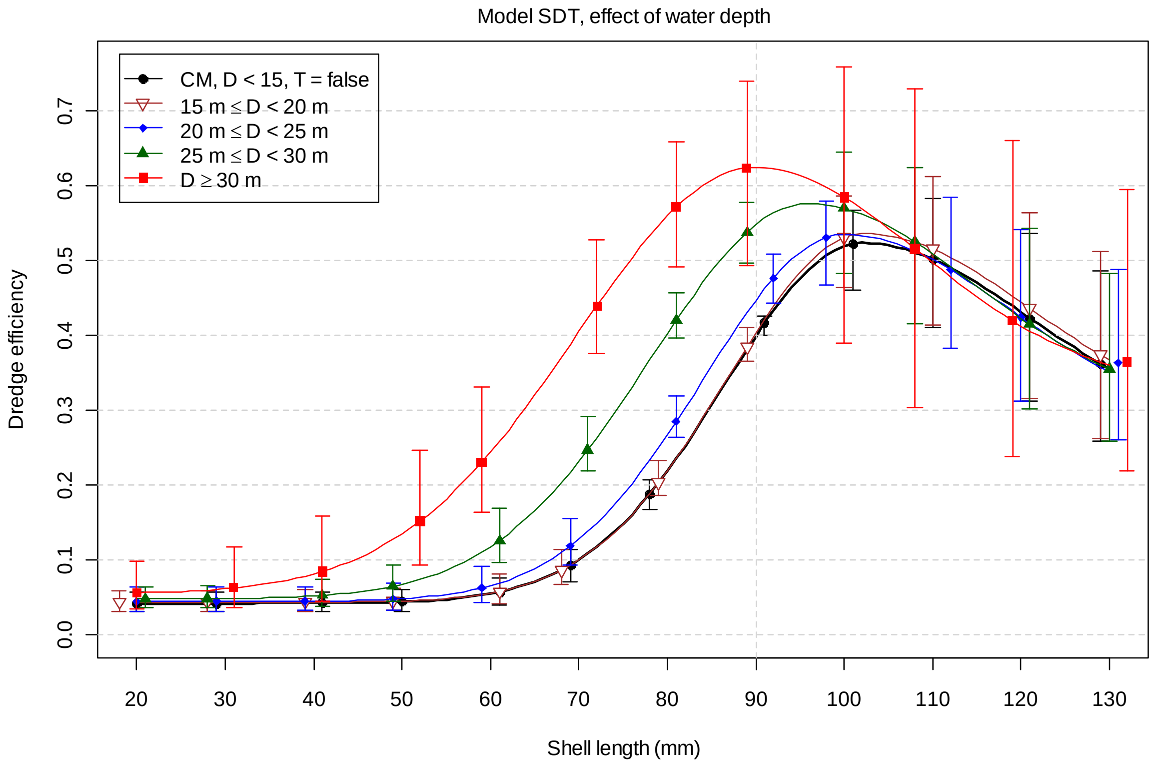

Figure 13: Predicted dredge efficiencies for depths greater than or equal to 30 m, together with modelled dredge efficiencies for depths less than 15, 15–20, 20–25 and 25–30 m for substrates CM (Coromandel mud) and tows-terminated equals false. The vertical lines indicate the 95 % confident interval.

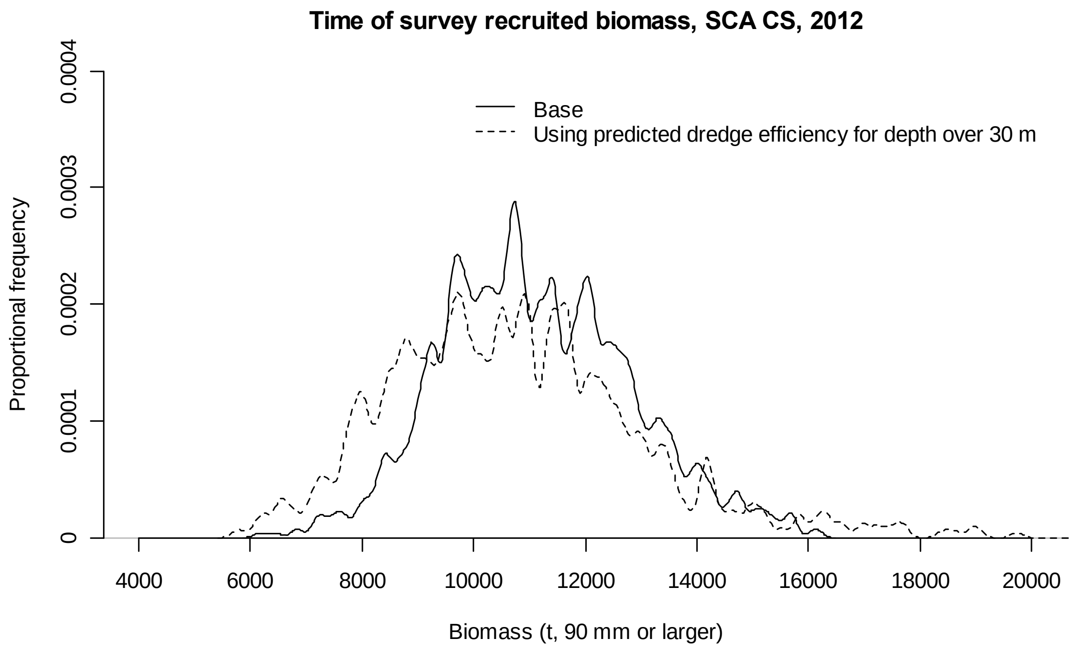

Figure 14: Proportional frequency distribution of the recruited biomass (t, greenweight, scallops 90 mm or larger) in the Coromandel stock at the time of the survey (May 2012) estimated using the dredge efficiencies with four depth bins (solid line) versus the dredge efficiencies with five depth bins (the fifth estimated using predicted dredge efficiencies for depths greater than or equal to 30 m (dashed line).

3.3 Biomass estimates

Estimates of current biomass are described above. In summary, using average values for important assumed variables, the absolute recruited biomass of scallops 90 mm in shell length or greater at the start of the season (15 July 2012) in the Coromandel stock was predicted to be 11 423 t greenweight (95% confidence interval of 8374–15032 t, c.v. of 15%), or 1380 t (95% confidence interval of 976–1 913 t, c.v. of 18%) (median projected values; Table 5). Given the highly variable nature of scallop populations, the concept of virgin biomass is probably not meaningful, but average (recruited) biomass could be estimated from the data presented in the tables.

3.4 Yield estimates

3.4.1 Reference rates of fishing mortality

Yield estimates are generally calculated using reference rates of fishing mortality applied in some way to an estimate of current or reference biomass. Cryer & Parkinson (2006) reviewed reference rates of fishing mortality and summarised modelling studies by Cryer & Morrison (1997) and Cryer et al. (2004). The target rates of fishing mortality currently applied to the SCA CS scallop stock are $F_{0.1}$ including and excluding incidental effects of fishing on scallops, estimated from yield-per-recruit modelling (Cryer et al. 2004). Note that these estimates were generated using dredge efficiency scalars from Cryer & Parkinson (2006), which are now considered to underestimate efficiency (Bian et al. 2012). This should be considered when assessing estimates of yield calculated using the current estimates of $F_{0.1}$, which may overestimate the incidental effects of dredging. The recalculation of $F_{0.1}$ using the Bian et al. (2012) correction for dredge efficiency was beyond the scope of the present study, but this could be done in a future investigation of optimal reference points for scallops.

3.4.2 Estimation of Maximum Constant Yield (MCY)

MCY is not normally estimated for scallops given the highly variable nature of most wild scallop fisheries. Cryer et al. (2003) showed that constant catch strategies for scallops produced lower yield at much higher biological risk than strategies in which catch was varied as biomass varied.

3.4.3 Estimation of Current Annual Yield (CAY)

Management of Coromandel scallops is based on a CAY approach. Since 1998, catch limits have been adjusted in line with estimated start-of-season recruited biomass and an estimate of CAY made using the Baranov catch equation:

$$CAY = \frac{F_{ref}}{F_{ref} + M}\left(1 - e^{-(F_{ref}+M)t}\right) B_{beg}$$

where t = 5/12 years, F_{ref} is a reference fishing mortality ($F_{0.1}$) and B_{beg} is the projected start-of-season (15 July) recruited biomass (scallops of 90 mm or more shell length). Natural mortality is assumed to act in tandem with fishing mortality for the first five months of the fishing season, the length of the current Coromandel commercial scallop season. B_{beg} is estimated by correcting for dredge efficiency (Bian et al. 2012), assuming average growth (from previous tagging studies), M = 0.5 spread evenly through the year, and historical average recovery of meatweight from greenweight. Because of the uncertainty over biomass estimates, growth, and mortality in a given year, and appropriate reference rates of fishing mortality, yield estimates must be treated with caution.

Modelling studies for Coromandel scallops (Cryer & Morrison 1997, Cryer et al. 2004) indicated that $F_{0.1}$ is sensitive not only to the direct incidental effects of fishing (reduced growth and increased mortality on essentially adult scallops), but also to indirect incidental effects such as additional juvenile mortality related to reduced habitat heterogeneity in dredged areas (Talman et al. 2004, Cryer & Parkinson 2006). Consequently, CAY is calculated for two scenarios:

1) CAY including direct effects on adults

By including only the direct incidental effects of fishing on scallops, Cryer et al. (2004) derived an estimate of $F_{0.1}$ = 1.034 (reported by Cryer et al. (2004) as 5/12 * $F_{0.1}$ = 0.431). Using this value and the 2012 start of season meatweight biomass estimate (1380 t, median projected value), CAY for 2012–13 was estimated to be 439 t meatweight.

2) CAY including direct and indirect effects on adults and juveniles

Cryer et al. (2004) modelled the "feedback" effects of habitat modification by the dredge method on juvenile mortality in scallops. They developed estimates of F_{ref} that incorporated such effects, but had to make assumptions about the duration of what they called the "critical phase" of juvenile growth during which scallops were susceptible to increased mortality. To give some guidance on the possible outcome of including "indirect" (as well as direct) effects on yield estimates, Cryer et al.'s (2004) estimate of $F_{0.1}$ = 0.658 (reported as 5/12 * $F_{0.1}$ = 0.274) was applied here. Using this value and the 2012 start of season meatweight biomass estimate (1380 t, median projected value), CAY for 2012–13 was estimated to be 300 t meatweight.

It must be noted that the estimates of $F_{0.1}$ used to calculate CAY for both scenarios were generated from modelling studies which used a method of correcting for dredge efficiency which is likely to have resulted in overestimating the incidental effects of dredging.

For both scenarios, the estimates of CAY would have c.v.s at least as large as those of the estimate of start-of-season recruited biomass (18%), are sensitive to assumptions about dredge efficiency, growth, and expected recovery of meatweight from greenweight, and relate to the surveyed beds only. Sensitivity of CAY in relation to dredge efficiency at depth is tabulated in Table 6. There is also additional uncertainty associated with using a point estimate of $F_{0.1}$ (i.e., variance associated with the point estimate of $F_{0.1}$ was not incorporated in the analysis), and the fact that the estimates of $F_{0.1}$ were generated from modelling studies using estimates of dredge efficiency that are different to those used to estimate current biomass; the latter may have resulted in underestimates of yield. Further, the second approach to estimating CAY which includes direct and indirect incidental effects of fishing is sensitive to the duration of any habitat-mediated increase in juvenile mortality.

Table 6: Sensitivity of CAY to the approach used to correct for dredge efficiency (Bian et al. 2012) at depths greater than or equal to 30 m. B, estimated start of season absolute biomass. Base case assumes dredge efficiency at depths greater than or equal to 30 m is the same as the efficiency at 25–30 m; Predicted is the approach correcting efficiency for depths greater than 30 m based on the predicted efficiency at 40.9 m. CAYa, CAY including direct incidental effects of fishing only; CAYaj, CAY including direct and indirect incidental effects of fishing.

Dredge efficiency	*B* mean	*B* c.v.	*B* median	*B* 95 % CI	CAYa	CAYaj
Base case	1 397.1	0.18	1 374.3	980–1 934	437.5	298.9
Predicted	1 333.7	0.21	1 304.3	883–1 949	415.2	283.7

Regardless of the approach used to estimate CAY, the production of a single 'best estimate' of CAY should be treated with caution; it is better to work with a range of estimates. For the projections to the 2012 start of season, the 1000 combined greenweight estimates were converted to meatweight (resampling from the meatweight greenweight conversion ratio data) (Figure 9). The median of this meatweight distribution was 1380 tonnes. Using the existing target reference $F_{0.1}$ values for Coromandel scallops, this meatweight distribution was converted into a distribution of CAY estimates, and a range of catch limit options were compared with this distribution to provide a decision table (Table 7).

Table 7: Decision table showing probability that a particular catch limit (t meatweight) would exceed reference fishing mortality values, for the Coromandel scallop (SCA CS) 2012–13 fishing year. $F_{0.1}$ (direct effects) represents the probability that the estimate of $F_{0.1}$ = 1.034 incorporating direct incidental mortality effects is exceeded. $F_{0.1}$ (direct and indirect effects) represents the probability that the estimate of $F_{0.1}$ = 0.658 incorporating direct and indirect incidental mortality effects is exceeded. These probabilities were generated from an analysis using estimates of absolute biomass within the surveyed area (i.e., a critical density of 0.00 scallops m^{-2}).

Catch limit (t)	$F_{0.1}$ (direct effects)	$F_{0.1}$ (direct and indirect effects)
150	0.000	0.000
160	0.000	0.000
170	0.000	0.001
180	0.000	0.002
190	0.000	0.005
200	0.000	0.011
210	0.000	0.018
220	0.000	0.036
230	0.000	0.063
240	0.001	0.109
250	0.001	0.162
260	0.002	0.217
270	0.002	0.285
280	0.007	0.351
290	0.010	0.429
300	0.016	0.510
310	0.020	0.577
320	0.033	0.645
330	0.050	0.706
340	0.070	0.772
350	0.104	0.817
360	0.138	0.850
370	0.179	0.886
380	0.213	0.914
390	0.259	0.933
400	0.306	0.950
410	0.353	0.960
420	0.402	0.974
430	0.460	0.985
440	0.513	0.988

4. MANAGEMENT IMPLICATIONS

Scallop abundance can be expected to vary from one year to the next. To get sustainable yield from such a variable stock it is necessary to alter the catch every year. Management of Coromandel scallops (SCA CS) is based on a Current Annual Yield (CAY) approach using $F_{0.1}$ as a target reference point for the stock. With the exception of 2011, annual pre-season research surveys have been required to estimate recruited biomass to calculate CAY. Commercial catch limits have usually been adjusted each survey year following a review of the survey results and yield estimates, and after consultation with fishery stakeholders. Alternative approaches could be considered in future work.

Estimates of current biomass are available from the April–May 2012 dredge survey of SCA CS. Using average values for important assumed variables, the absolute recruited biomass at the start of the season (15 July 2012) was predicted to be 1380 t meatweight (95% confidence interval 976–1913 t; with a c.v. of 18%), although excluding areas of low scallop density (densities in the range 0.04 to 0.20 scallops.m^{-2}) reduced this estimate by 19–55%. Most of the recruited population was found in the Hauraki Gulf, and to a lesser extent in the Mercury and Little Barrier regions of the stock, where scallop densities were highest, with lower numbers of recruits in other regions. For the core regions of the stock usually fished, these results are similar to those of the 2010 biomass survey and assessment. Historical catch levels and biomass estimates suggest that it is likely that fishing mortality has been below the target level for the stock in recent years. Setting the catch limit at or below the level of the estimated CAY for 2012–13 is very likely to maintain fishing mortality at or below the target reference point for the stock; the lower the catch limit set, the greater the level of confidence that the target will not be exceeded.

Uncertainties stemming from assumptions about dredge efficiency during the survey, rates of growth and natural mortality between survey and season, and predicting the average recovery of meatweight from greenweight remain in this analysis of biomass and yield. The use of current estimates of $F_{0.1}$ in this analysis may result in underestimates of yield.

5. ACKNOWLEDGMENTS

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7. APPENDICES

Appendix 1: Stratum details

Appendix 1a: Sampling design, stratum definitions, and final station (tow) allocation used for the 2012 dredge survey of the Coromandel scallop stock. "Core", strata surveyed and fished consistently in the past; 'B'grd", strata encompassing background areas of lower scallop density outside the core strata which formed part of the survey coverage in the past); "New", strata in Hauraki Gulf that have never been surveyed before.

Region	Stratum Code	Stratum Name	Stratum Type	Stratum area (m^2)	Substrate category	Tows sampled	Tows/km^2
Barrier	1	LBW	Core	1 339 565	sand	6	4.48
	2	LBS	Core	2 709 648	sand	5	1.85
	3	LBsh_bg	B'grd	9 984 448	sand	3	0.30
	4	LBdp_bg	B'grd	12 185 880	sand	3	0.25
HGulf	5	HGulf	New	204 604 500	mud	22	0.11
	6	HGulf_bg	New	180 830 100	mud	5	0.03
	7	HGulfW_bg	New	151 657 700	mud	5	0.03
Colville	8	ColvN	B'grd	2 531 560	mud	5	1.98
	9	ColvS	Core	7 876 866	mud	7	0.89
	10	Colv_bg	B'grd	38 170 350	mud	3	0.08
Waiheke	11	Tarahiki	Core	10 639 950	mud	9	0.85
	12	Waiheke_bg	B'grd	39 128 400	mud	4	0.10
Mercury	13	Cove	Core	2 735 926	mud	6	2.19
	14	3MB	Core	4 958 041	sand	7	1.41
	15	Bumper	Core	1 229 187	sand	3	2.44
	16	Kennedy	Core	39 908 950	sand	11	0.28
	17	Wpoua	Core	7 498 420	sand	3	0.40
	18	BJack	Core	22 858 810	sand	10	0.44
	19	Sarahs	Core	4 832 392	sand	4	0.83
	20	Merc_bg	B'grd	20 957 900	sand	4	0.19
	21	Opito_sh	Core	1 878 062	sand	3	1.60
	22	Opito_dp	B'grd	3 911 366	sand	3	0.77
	23	Opito_bg	B'grd	16 646 730	sand	3	0.18
Plenty	24	Wahi_dp	Core	46 956 370	sand	6	0.13
	25	Wahi_sh	B'grd	14 449 150	sand	3	0.21
	26	Wahi_bg	B'grd	49 067 510	sand	5	0.10
	27	Papamoa	Core	19 768 040	sand	13	0.66
	28	Knoll	Core	4 621 197	sand	4	0.87
	29	Tauranga_bg	B'grd	55 282 160	sand	3	0.05

Appendix 2: Station details and catch of scallops.

Appendix 2a: SCA CS dredge survey 2012 (trip code KAT1201) station details and scallop catch. Latitude and longitude are in degrees and minutes. 'Tow term.' distinguishes between tows terminated (0, hauled early because of suspected gear saturation) and other tows (1). 'Recruits' refers to scallops 90 mm or more in shell length; recruit density is the estimated raw number of recruits per unit area of seabed swept by the dredge, uncorrected for dredge efficiency. *station 46 was excluded from the analysis because it was suspected the dredge had turned upside down.

Station number	Stratum	Date	Time (start)	Latitude S (start)	Longitude E (start)	Depth (start)	Tow term.	Distance (n. mile)	Area swept (m)	Total catch	Total measured	Sampled fraction	Recruits measured	Recruit density (m^{-2})
1	21	21-Apr-12	1452	36 42.36	175 47.91	13	0	0.43	1 589	478	231	0.48	150	0.20
2	21	21-Apr-12	1509	36 42.35	175 48.48	19	1	0.44	1 640	725	308	0.42	179	0.26
3	8	22-Apr-12	0700	36 29.39	175 19.37	24	0	0.08	302	32	32	1.00	16	0.05
4	8	22-Apr-12	0707	36 29.54	175 19.46	18	1	0.13	479	68	68	1.00	10	0.02
5	8	22-Apr-12	0731	36 30.36	175 19.54	13	1	0.11	417	63	63	1.00	7	0.02
6	8	22-Apr-12	0740	36 31.04	175 19.39	27	0	0.07	261	0	0	1.00	0	0.00
7	8	22-Apr-12	0755	36 31.96	175 19.84	10	1	0.29	1 088	157	157	1.00	97	0.09
8	9	22-Apr-12	0814	36 32.81	175 20.33	10	1	0.44	1 615	307	170	0.55	110	0.12
9	9	22-Apr-12	0850	36 33.48	175 20.90	10	1	0.29	1 078	243	243	1.00	180	0.17
10	9	22-Apr-12	0908	36 33.80	175 21.28	12	1	0.09	332	0	0	1.00	0	0.00
11	9	22-Apr-12	1122	36 36.39	175 25.49	7	0	0.37	1 368	67	67	1.00	48	0.04
12	9	22-Apr-12	1136	36 35.96	175 25.21	6	0	0.35	1 286	66	66	1.00	39	0.03
13	10	22-Apr-12	1202	36 37.20	175 24.26	14	0	0.20	743	0	0	1.00	0	0.00
14	9	22-Apr-12	1223	36 35.21	175 24.24	8	0	0.25	912	98	98	1.00	55	0.06
15	9	22-Apr-12	1240	36 34.88	175 23.92	5	0	0.42	1 542	448	211	0.47	191	0.26
16	10	22-Apr-12	1313	36 35.23	175 22.40	15	0	0.34	1 260	2	2	1.00	1	0.00
17	10	22-Apr-12	1330	36 35.37	175 21.23	24	0	0.34	1 250	0	0	1.00	0	0.00
18	11	22-Apr-12	1535	36 46.14	175 15.11	31	0	0.31	1 138	2	2	1.00	0	0.00
19	11	22-Apr-12	1547	36 46.57	175 14.61	28	0	0.17	616	30	30	1.00	15	0.02
20	11	22-Apr-12	1559	36 46.68	175 14.98	30	0	0.32	1 198	29	29	1.00	18	0.02
21	11	22-Apr-12	1613	36 46.97	175 14.93	29	0	0.25	911	28	28	1.00	14	0.02
22	12	22-Apr-12	1627	36 47.98	175 14.85	34	0	0.15	556	0	0	1.00	0	0.00
23	12	22-Apr-12	1647	36 48.88	175 13.27	19	0	0.24	903	0	0	1.00	0	0.00
24	11	23-Apr-12	0713	36 47.50	175 13.86	29	0	0.25	938	26	26	1.00	2	0.00
25	11	23-Apr-12	0725	36 47.21	175 13.92	37	0	0.22	798	174	174	1.00	20	0.03
26	11	23-Apr-12	0748	36 47.30	175 14.27	35	0	0.16	593	0	0	1.00	0	0.00
27	11	23-Apr-12	0800	36 47.27	175 14.47	32	0	0.12	445	2	2	1.00	0	0.00

Station number	Stratum	Date	Time (start)	Latitude S (start)	Longitude E (start)	Depth (start)	Tow term.	Distance (n. mile)	Area swept (m)	Total catch	Total measured	Sampled fraction	Recruits measured	Recruit density (m^{-2})
28	12	23-Apr-12	0823	36 46.37	175 12.73	37	0	0.31	1 162	163	163	1.00	20	0.02
29	11	23-Apr-12	0900	36 46.31	175 12.95	35	0	0.14	504	72	72	1.00	34	0.07
30	12	23-Apr-12	0931	36 43.94	175 13.45	36	0	0.40	1 489	133	133	1.00	96	0.06
31	6	23-Apr-12	1045	36 37.49	175 14.62	41	0	0.32	1 187	79	79	1.00	67	0.06
32	6	23-Apr-12	1113	36 36.88	175 14.81	41	1	0.42	1 559	142	142	1.00	133	0.09
33	5	23-Apr-12	1135	36 36.64	175 16.01	42	0	0.46	1 699	22	22	1.00	20	0.01
34	5	23-Apr-12	1215	36 33.11	175 15.08	45	0	0.40	1 477	106	106	1.00	89	0.06
35	5	23-Apr-12	1234	36 33.32	175 15.59	42	0	0.27	995	341	206	0.60	165	0.27
36	6	23-Apr-12	1320	36 34.30	175 16.91	41	1	0.43	1 597	7	7	1.00	2	0.00
37	5	23-Apr-12	1356	36 35.99	175 15.17	40	1	0.42	1 565	152	152	1.00	146	0.09
38	5	23-Apr-12	1415	36 35.96	175 13.99	40	0	0.53	1 946	435	213	0.49	192	0.20
39	5	23-Apr-12	1438	36 35.61	175 13.64	42	0	0.35	1 311	536	245	0.46	223	0.37
40	5	23-Apr-12	1507	36 35.55	175 12.74	39	1	0.34	1 250	289	151	0.52	146	0.22
41	5	24-Apr-12	0804	36 27.41	175 13.24	48	0	0.27	1 007	662	287	0.43	277	0.63
42	5	24-Apr-12	0857	36 24.23	175 13.30	47	0	0.40	1 463	498	251	0.50	125	0.17
43	6	24-Apr-12	0944	36 24.97	175 10.33	50	0	0.43	1 603	11	11	1.00	0	0.00
44	5	24-Apr-12	1030	36 25.80	175 14.06	48	1	0.47	1 746	1 557	415	0.27	394	0.85
45	5	24-Apr-12	1100	36 25.63	175 15.75	48	1	0.44	1 626	1 188	323	0.27	286	0.65
*46	5	24-Apr-12	1150	36 28.36	175 12.98	47	0	0.42	1 560	0	0	0.00	0	0.00
47	5	24-Apr-12	1218	36 29.94	175 12.28	46	1	0.46	1 703	277	165	0.60	156	0.15
48	5	24-Apr-12	1257	36 30.20	175 14.61	44	0	0.50	1 852	312	150	0.48	138	0.15
49	5	24-Apr-12	1329	36 31.34	175 14.18	46	1	0.52	1 926	240	240	1.00	220	0.11
50	5	24-Apr-12	1358	36 31.24	175 12.76	45	1	0.49	1 803	218	218	1.00	210	0.12
51	5	24-Apr-12	1428	36 32.55	175 11.41	45	1	0.28	1 050	49	49	1.00	43	0.04
52	5	24-Apr-12	1450	36 33.15	175 10.66	43	1	0.47	1 758	111	111	1.00	98	0.06
53	5	25-Apr-12	0701	36 34.52	175 13.88	40	1	0.52	1 934	670	249	0.37	233	0.32
54	5	25-Apr-12	0750	36 34.67	175 11.11	42	1	0.48	1 792	123	123	1.00	114	0.06
55	7	25-Apr-12	0824	36 34.14	175 08.47	47	1	0.50	1 859	32	32	1.00	25	0.01
56	7	25-Apr-12	0905	36 33.08	175 04.24	45	0	0.52	1 920	39	39	1.00	35	0.02
57	7	25-Apr-12	0937	36 31.60	175 03.89	46	0	0.21	778	10	10	1.00	9	0.01
58	7	25-Apr-12	1004	36 29.68	175 03.19	48	1	0.53	1 948	73	73	1.00	34	0.02
59	6	25-Apr-12	1058	36 31.47	175 08.50	44	1	0.50	1 866	177	177	1.00	159	0.09
60	5	25-Apr-12	1130	36 29.92	175 09.18	47	0	0.38	1 424	25	25	1.00	10	0.01

Station number	Stratum	Date	Time (start)	Latitude S (start)	Longitude E (start)	Depth (start)	Tow term.	Distance (n. mile)	Area swept (m)	Total catch	Total measured	Sampled fraction	Recruits measured	Recruit density (m^{-2})
61	5	25-Apr-12	1150	36 29.21	175 09.84	47	1	0.52	1 911	148	148	1.00	94	0.05
62	5	25-Apr-12	1216	36 28.37	175 09.19	47	1	0.50	1 836	235	235	1.00	140	0.08
63	7	25-Apr-12	1257	36 28.02	175 06.07	46	1	0.50	1 856	17	17	1.00	6	0.00
64	4	25-Apr-12	1444	36 17.29	175 04.55	44	0	0.47	1 730	41	41	1.00	1	0.00
65	4	25-Apr-12	1507	36 15.75	175 04.34	43	1	0.50	1 867	11	11	1.00	1	0.00
66	4	25-Apr-12	1534	36 15.57	175 04.16	43	1	0.50	1 843	7	7	1.00	0	0.00
67	3	25-Apr-12	1600	36 14.34	175 02.87	45	1	0.51	1 894	42	42	1.00	5	0.00
68	1	26-Apr-12	0704	36 13.21	175 02.75	13	1	0.50	1 867	243	243	1.00	203	0.11
69	1	26-Apr-12	0725	36 13.10	175 02.88	11	1	0.52	1 923	162	162	1.00	152	0.08
70	1	26-Apr-12	0751	36 12.77	175 02.69	21	1	0.51	1 901	212	212	1.00	201	0.11
71	3	26-Apr-12	0813	36 11.66	175 02.22	44	1	0.50	1 839	36	36	1.00	11	0.01
72	3	26-Apr-12	0832	36 12.07	175 02.21	42	1	0.52	1 912	65	65	1.00	38	0.02
73	1	26-Apr-12	0857	36 12.11	175 02.72	17	1	0.49	1 798	182	182	1.00	173	0.10
74	1	26-Apr-12	0910	36 12.42	175 02.79	13	1	0.50	1 856	230	166	0.72	161	0.12
75	1	26-Apr-12	0926	36 12.24	175 02.66	16	1	0.50	1 852	297	199	0.67	184	0.15
76	2	26-Apr-12	0958	36 13.52	175 03.01	16	1	0.39	1 431	561	268	0.48	201	0.29
77	2	26-Apr-12	1016	36 14.05	175 04.79	18	0	0.41	1 524	4 538	961	0.21	166	0.51
78	2	26-Apr-12	1127	36 14.01	175 05.01	12	0	0.52	1 943	3 475	799	0.23	356	0.80
79	2	26-Apr-12	1146	36 14.02	175 05.24	16	0	0.38	1 392	3 196	786	0.25	353	1.03
80	2	26-Apr-12	1227	36 13.71	175 03.69	12	1	0.50	1 866	1 341	501	0.37	372	0.53
81	13	27-Apr-12	0700	36 36.88	175 46.60	22	0	0.28	1 028	251	251	1.00	119	0.12
82	13	27-Apr-12	0725	36 37.26	175 46.42	27	0	0.35	1 313	140	140	1.00	43	0.03
83	13	27-Apr-12	0751	36 36.83	175 45.86	23	0	0.27	1 016	319	257	0.81	160	0.20
84	13	27-Apr-12	0813	36 37.33	175 46.11	30	0	0.46	1 716	91	91	1.00	20	0.01
85	13	27-Apr-12	0840	36 37.66	175 46.72	18	0	0.26	979	270	217	0.80	149	0.19
86	13	27-Apr-12	0908	36 37.06	175 46.91	14	0	0.32	1 203	281	228	0.81	173	0.18
87	21	29-Apr-12	0744	36 42.23	175 48.69	25	1	0.46	1 686	1 594	332	0.21	118	0.34
88	20	29-Apr-12	0826	36 39.79	175 47.45	20	0	0.15	551	4	4	1.00	0	0.00
89	14	29-Apr-12	0842	36 39.19	175 46.60	19	0	0.46	1 698	1 360	310	0.23	214	0.55
90	14	29-Apr-12	0930	36 39.12	175 45.39	15	1	0.51	1 896	77	77	1.00	35	0.02
91	14	29-Apr-12	0952	36 39.09	175 44.85	23	1	0.50	1 850	33	33	1.00	4	0.00
92	20	29-Apr-12	1015	36 38.53	175 44.41	31	1	0.51	1 890	85	85	1.00	8	0.00
93	20	29-Apr-12	1050	36 38.42	175 44.79	31	0	0.38	1 421	99	99	1.00	9	0.01

Station number	Stratum	Date	Time (start)	Latitude S (start)	Longitude E (start)	Depth (start)	Tow term.	Distance (n. mile)	Area swept (m)	Total catch	Total measured	Sampled fraction	Recruits measured	Recruit density (m^{-2})
94	20	29-Apr-12	1121	36 38.63	175 45.40	24	0	0.38	1 396	1 350	302	0.22	108	0.35
95	14	29-Apr-12	1206	36 39.52	175 44.91	22	0	0.50	1 837	1 337	328	0.25	91	0.20
96	18	29-Apr-12	1303	36 39.98	175 44.54	24	1	0.50	1 854	470	273	0.58	86	0.08
97	18	29-Apr-12	1345	36 39.71	175 44.34	20	1	0.50	1 869	658	251	0.38	115	0.16
98	14	29-Apr-12	1407	36 39.47	175 44.77	20	0	0.20	746	1 451	267	0.18	61	0.44
99	15	30-Apr-12	0722	36 38.62	175 48.40	15	1	0.39	1 450	510	231	0.45	159	0.24
100	15	30-Apr-12	0748	36 38.74	175 48.21	16	0	0.39	1 427	879	273	0.31	182	0.41
101	15	30-Apr-12	0807	36 38.71	175 47.98	18	0	0.27	1 017	689	223	0.32	142	0.43
102	19	30-Apr-12	0852	36 41.16	175 46.82	17	1	0.51	1 896	114	114	1.00	91	0.05
103	19	30-Apr-12	0915	36 41.45	175 46.59	11	1	0.53	1 966	40	40	1.00	27	0.01
104	19	30-Apr-12	0935	36 41.97	175 45.97	12	1	0.51	1 881	161	161	1.00	118	0.06
105	19	30-Apr-12	1001	36 42.03	175 45.83	12	1	0.50	1 859	298	298	1.00	185	0.10
106	18	30-Apr-12	1039	36 42.45	175 42.69	18	1	0.51	1 905	181	181	1.00	137	0.07
107	18	30-Apr-12	1101	36 42.57	175 41.99	17	1	0.51	1 877	319	209	0.66	179	0.15
108	18	30-Apr-12	1155	36 42.96	175 42.27	15	1	0.49	1 825	73	73	1.00	69	0.04
109	18	30-Apr-12	1212	36 42.93	175 42.08	16	1	0.51	1 890	178	178	1.00	146	0.08
110	18	30-Apr-12	1238	36 42.94	175 41.63	16	1	0.47	1 723	271	271	1.00	234	0.14
111	18	30-Apr-12	1258	36 42.24	175 41.31	20	1	0.53	1 949	64	64	1.00	31	0.02
112	17	30-Apr-12	1321	36 43.08	175 40.15	14	1	0.51	1 876	7	7	1.00	7	0.00
113	17	30-Apr-12	1344	36 43.06	175 39.08	12	1	0.54	2 017	2	2	1.00	1	0.00
114	17	30-Apr-12	1407	36 42.48	175 38.32	19	1	0.53	1 970	87	87	1.00	36	0.02
115	16	1-May-12	0657	36 41.07	175 38.05	24	1	0.51	1 875	45	45	1.00	12	0.01
116	16	1-May-12	0717	36 40.61	175 39.49	30	0	0.23	839	0	0	1.00	0	0.00
117	16	1-May-12	0734	36 39.75	175 39.57	36	0	0.16	584	7	7	1.00	0	0.00
118	16	1-May-12	0749	36 39.66	175 41.02	35	0	0.22	802	2	2	1.00	0	0.00
119	16	1-May-12	0805	36 40.45	175 41.13	29	1	0.51	1 872	29	29	1.00	11	0.01
120	16	1-May-12	0826	36 40.34	175 40.79	31	1	0.51	1 884	31	31	1.00	11	0.01
121	16	1-May-12	0847	36 40.91	175 40.40	26	1	0.50	1 836	146	146	1.00	67	0.04
122	16	1-May-12	0910	36 41.20	175 40.68	24	1	0.51	1 890	194	194	1.00	113	0.06
123	16	1-May-12	0938	36 41.53	175 39.32	22	1	0.50	1 857	71	71	1.00	43	0.02
124	16	1-May-12	1000	36 41.85	175 40.87	20	1	0.53	1 948	61	61	1.00	53	0.03
125	16	1-May-12	1023	36 41.08	175 42.63	22	1	0.53	1 951	67	67	1.00	57	0.03
126	18	1-May-12	1044	36 41.06	175 43.56	18	1	0.51	1 889	96	96	1.00	81	0.04

Station number	Stratum	Date	Time (start)	Latitude S (start)	Longitude E (start)	Depth (start)	Tow term.	Distance (n. mile)	Area swept (m)	Total catch	Total measured	Sampled fraction	Recruits measured	Recruit density (m^{-2})
127	18	1-May-12	1103	36 40.42	175 43.78	16	1	0.50	1 856	478	256	0.54	150	0.15
128	14	1-May-12	1138	36 39.62	175 44.93	20	1	0.51	1 903	1 398	328	0.23	116	0.26
129	14	1-May-12	1236	36 40.06	175 45.00	19	0	0.33	1 209	135	135	1.00	70	0.06
130	22	1-May-12	1332	36 41.50	175 48.65	28	0	0.23	849	147	147	1.00	1	0.00
131	23	1-May-12	1353	36 41.30	175 48.95	30	0	0.20	743	84	84	1.00	1	0.00
132	22	1-May-12	1406	36 41.83	175 48.78	28	0	0.37	1 361	1 016	336	0.33	49	0.11
133	22	1-May-12	1545	36 42.07	175 49.65	27	0	0.31	1 148	93	93	1.00	0	0.00
134	23	1-May-12	1610	36 42.21	175 51.24	29	0	0.17	647	33	33	1.00	6	0.01
135	23	1-May-12	1628	36 42.57	175 51.62	28	0	0.28	1 039	112	112	1.00	47	0.05
136	24	2-May-12	1126	37 20.47	175 59.74	29	1	0.53	1 952	6	6	1.00	1	0.00
137	26	2-May-12	1148	37 20.71	175 59.06	26	1	0.52	1 908	42	42	1.00	5	0.00
138	25	2-May-12	1215	37 21.96	175 59.83	27	1	0.53	1 958	60	60	1.00	15	0.01
139	25	2-May-12	1237	37 22.36	175 59.36	24	1	0.47	1 729	126	126	1.00	19	0.01
140	25	2-May-12	1254	37 22.25	175 58.52	25	1	0.47	1 757	35	35	1.00	6	0.00
141	26	2-May-12	1337	37 24.85	176 01.21	26	0	0.45	1 668	224	224	1.00	88	0.05
142	26	2-May-12	1359	37 25.33	176 02.95	29	1	0.53	1 958	86	86	1.00	0	0.00
143	24	2-May-12	1423	37 25.75	176 04.60	33	1	0.52	1 912	74	74	1.00	0	0.00
144	24	2-May-12	1442	37 26.45	176 05.05	32	1	0.51	1 895	231	231	1.00	0	0.00
145	24	2-May-12	1507	37 28.36	176 05.85	30	1	0.51	1 878	0	0	1.00	0	0.00
146	24	2-May-12	1525	37 29.36	176 06.25	30	1	0.50	1 853	65	65	1.00	0	0.00
147	26	2-May-12	1550	37 29.63	176 04.87	26	1	0.26	948	39	39	1.00	16	0.02
148	24	2-May-12	1607	37 30.06	176 06.56	29	1	0.51	1 894	157	157	1.00	1	0.00
149	26	2-May-12	1625	37 30.64	176 06.77	28	1	0.50	1 849	110	110	1.00	30	0.02
150	27	3-May-12	0632	37 39.78	176 15.84	23	1	0.51	1 886	37	37	1.00	15	0.01
151	27	3-May-12	0653	37 40.12	176 16.78	21	0	0.15	558	5	5	1.00	2	0.00
152	27	3-May-12	0705	37 40.22	176 17.93	27	0	0.33	1 206	15	15	1.00	7	0.01
153	29	3-May-12	0735	37 39.14	176 18.76	26	1	0.50	1 855	106	106	1.00	70	0.04
154	29	3-May-12	0802	37 38.66	176 19.05	27	1	0.50	1 837	84	84	1.00	53	0.03
155	27	3-May-12	0831	37 40.39	176 18.68	19	1	0.51	1 890	320	175	0.55	107	0.10
156	27	3-May-12	0854	37 40.8	176 18.21	16	0	0.49	1 813	218	218	1.00	77	0.04
157	27	3-May-12	0917	37 41.36	176 20.02	20	1	0.50	1 852	64	64	1.00	12	0.01
158	27	3-May-12	0943	37 40.89	176 20.30	22	0	0.33	1 210	3	3	1.00	0	0.00
159	29	3-May-12	0958	37 40.04	176 20.97	20	0	0.35	1 297	1	1	1.00	0	0.00

Station number	Stratum	Date	Time (start)	Latitude S (start)	Longitude E (start)	Depth (start)	Tow term.	Distance (n. mile)	Area swept (m)	Total catch	Total measured	Sampled fraction	Recruits measured	Recruit density (m^{-2})
160	27	3-May-12	1011	37 40.91	176 20.87	24	1	0.34	1 264	90	90	1.00	34	0.03
161	27	3-May-12	1039	37 41.78	176 20.68	17	1	0.35	1 287	183	183	1.00	36	0.03
162	27	3-May-12	1116	37 41.17	176 21.64	21	1	0.19	719	148	148	1.00	6	0.01
163	27	3-May-12	1135	37 41.53	176 22.30	24	1	0.51	1 896	187	187	1.00	28	0.01
164	27	3-May-12	1203	37 41.44	176 23.12	25	1	0.56	2 090	397	194	0.49	18	0.02
165	28	3-May-12	1238	37 40.24	176 24.18	24	1	0.52	1 936	135	135	1.00	116	0.06
166	28	3-May-12	1302	37 40.28	176 23.42	20	1	0.51	1 872	173	173	1.00	125	0.07
167	28	3-May-12	1331	37 40.66	176 22.94	25	1	0.54	1 988	243	243	1.00	115	0.06
168	28	3-May-12	1357	37 40.66	176 22.08	20	1	0.21	762	1	1	1.00	0	0.00
169	27	3-May-12	1414	37 40.95	176 21.86	22	1	0.51	1 880	88	88	1.00	26	0.01

Appendix 3: Bycatch

Introduction

Data on bycatch during the 2012 survey were collected to provide a means of identifying and mapping the distribution of benthic habitats (and particularly those thought to be sensitive to scallop dredging) in relation to the spatial distribution of the scallop fishery. This approach to collecting information about benthic habitats has not been routinely applied to New Zealand dredge fisheries in the past, but was undertaken as a pilot study during the 2009 survey of SCA CS (Williams et al. 2010), with three separate tasks of

1. Characterising the bycatch of the survey
2. Describing the benthic habitat from the bycatch
3. Identifying appropriate approaches to employ for future sampling of bycatch.

The bycatch sampling methodology developed in 2009 was used again in 2010 (Williams & Parkinson 2010) and 2012 (present study).

Methods

The catch from all stations was physically examined, with the total volume of the catch estimated, and the percentage volume by main species or group quantified. The species and groups used to categorise the dredge catches are listed below. Data are available on the total catch volume and percentage volume by main species or group for all valid survey tows.

Appendix 3a. Species and groups used to categorise dredge catches.

Type	Species or group
Habitat formers	Sponge, tubeworm, coralline turf
Starfish	*Astropecten*, *Coscinasterias*, cushion star, carpet star
Main bivalves	Dog cockles, horse mussels, scallops, *Tawera*; all split into live or dead
Other benthic invertebrates	Anemone, crabs, snails, polychaetes, octopus, rock lobster
Fish	Gobie, gurnard, john dory, lemon sole, pufferfish, red cod, sand eel, snake eel, stargazer, yellowbelly flounder
Seaweed	Brown seaweed and *Ecklonia*, green seaweed, red seaweed
Shell	Other dead shell, shell hash
Substrate	Mud, sand (different categories), rock
Other	Rubbish

As described above (Section 3.2.1), the survey tows were allocated randomly within predefined survey strata (see Figure 2). The survey strata were defined using historical data on scallop density from past surveys, in conjunction with information and input provided by the SCA CS commercial fishers, with the aim that they represented the main scallop beds of the stock. However, since fishing effort undertaken by the fishery is highly likely to be concentrated in areas of high scallop catch rate and low bycatch, the overall survey bycatch (and incidence of species within it) may not necessarily reflect the overall commercial bycatch.

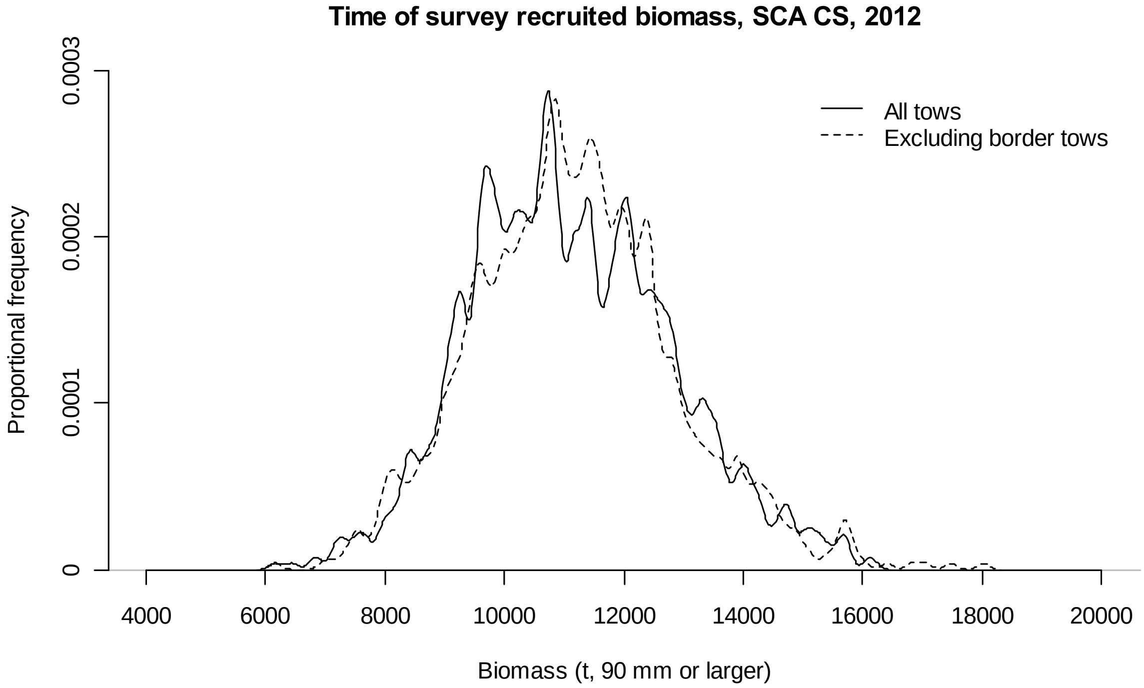
Data storage

Bycatch data collected during the 2012 survey of SCA CS were loaded to the MPI database *scallop*, but were not analysed as part of the present study. We suggest bycatch data should be routinely collected during each dredge survey, with a view to conducting bycatch analyses once data from a suitable number of surveys become available.

Appendix 4: Effect of tows crossing a stratum border

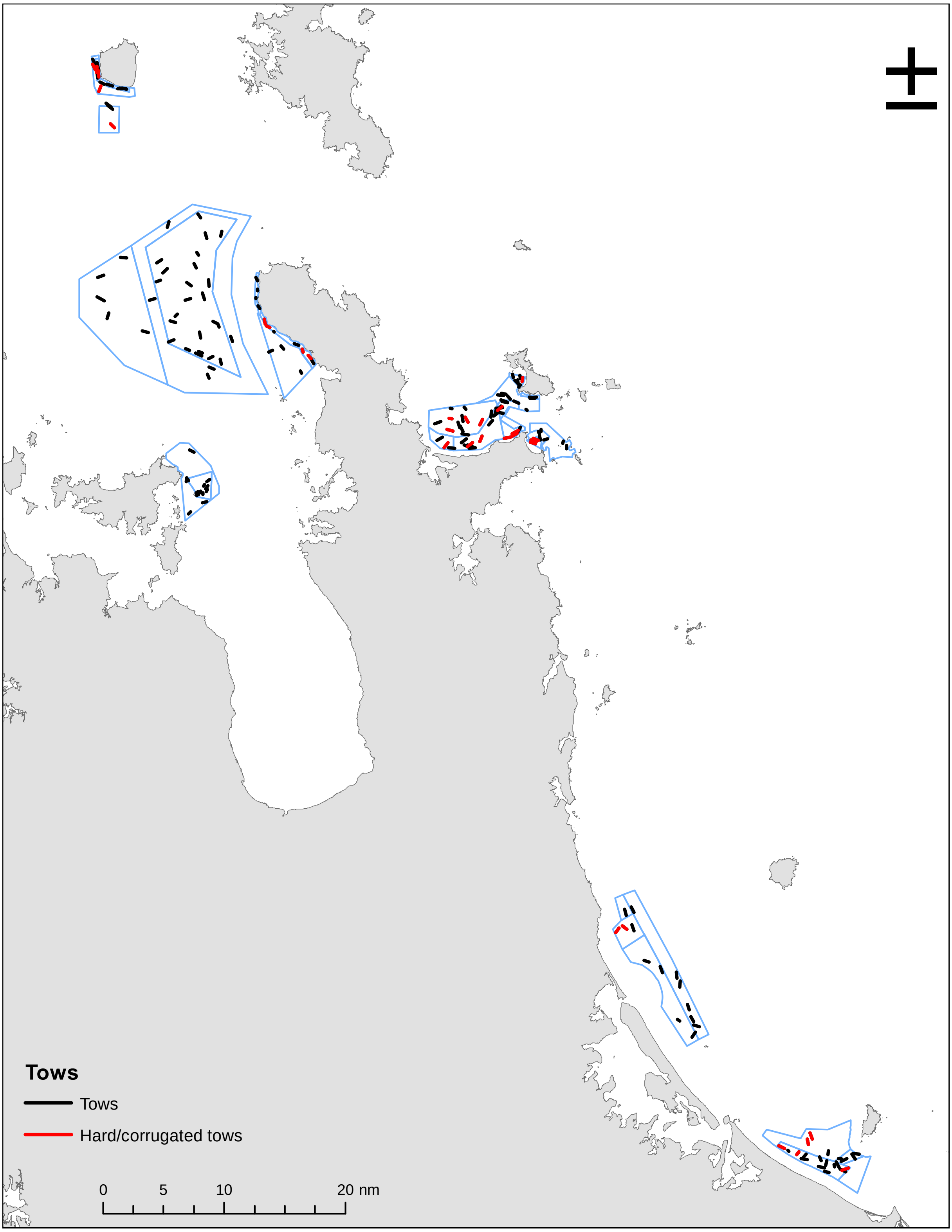
Appendix 4a: Comparison of biomass estimates in the Coromandel stock at the time of the survey (May 2012) using all tows (columns All) and excluding tows crossing stratum borders (Excl.).

									Biomass (t green)	
Region	Tows *n*		Mean		c.v.		Median		95%CI	
	All	Excl.	All	Excl.	All	Excl.	All	Excl.	All	Excl.
Barrier	17	16	358	359	0.17	0.16	356	357	255–488	253–475
HGulf	32	32	8 632	8 662	0.19	0.19	8 521	8 610	5 803–12 198	5 637–12 039
Colville	15	14	155	163	0.33	0.32	151	157	69–266	73–276
Waiheke	13	13	131	130	0.57	0.59	126	124	22–304	19–293
Mercury	57	47	1 390	1 378	0.19	0.20	1 374	1 350	952–1 964	909–1 987
Plenty	34	31	460	508	0.24	0.26	457	502	235–670	271–770
SCA CS	168	153	11 126	11 199	0.15	0.15	10 966	11 121	8 085–14 743	8 058–14 796

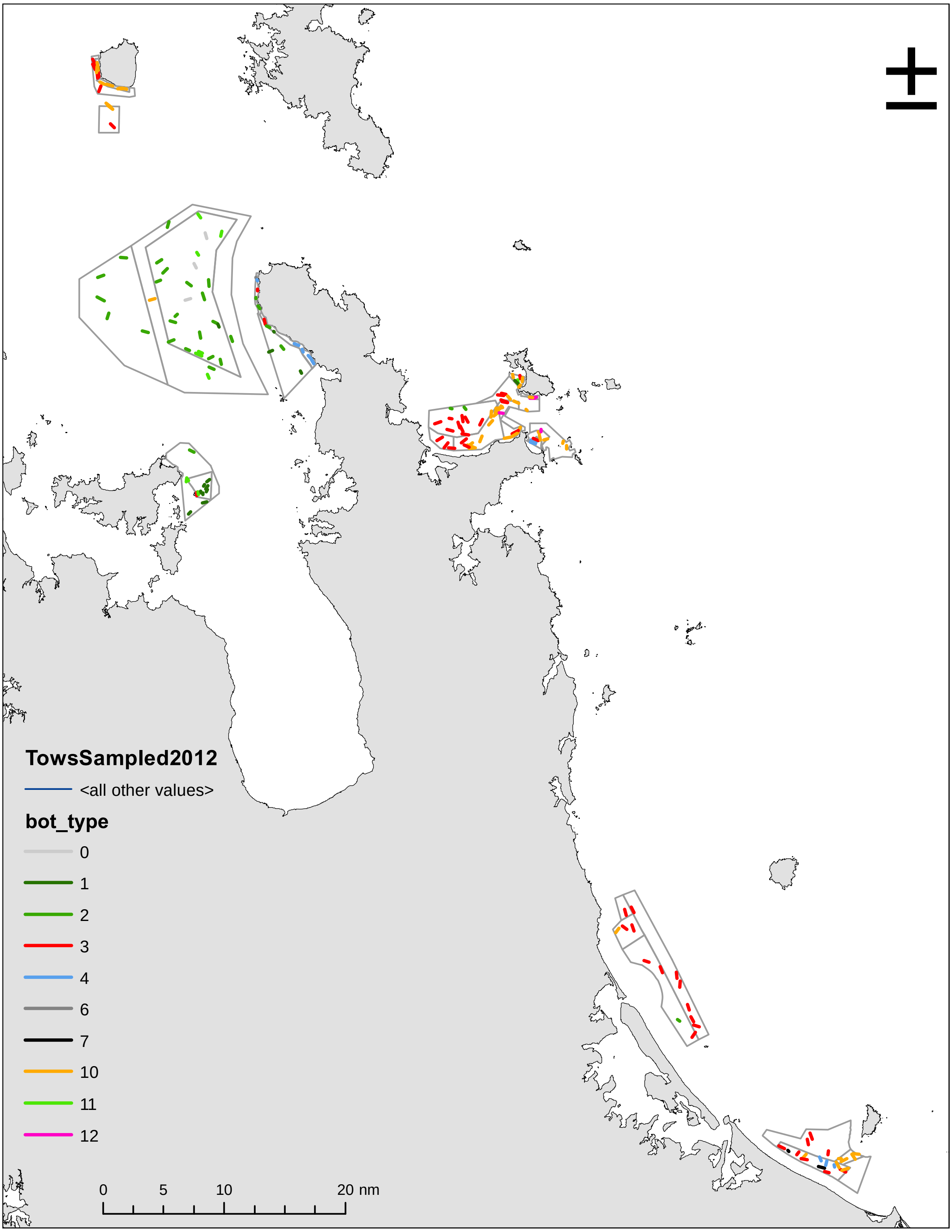


Appendix 4b: Frequency distribution of the estimated recruited biomass (t greenweight, scallops 90 mm or larger) in the Coromandel stock at the time of the survey (April–May 2012); solid line, including all valid tows; dashed line, excluding stations where the tow crossed a stratum border (as judged by the finish position of the vessel at the end of the tow). The distribution shows the results of a non-parametric re-sampling with replacement approach to estimation (1000 bootstraps).

Appendix 5: Hard/corrugated tows, and bottom type



Appendix 5a: Distribution of normal tows (coloured in black) and hard/corrugated tows (coloured in red), the latter as perceived by the survey skipper by the action of the dredge gear.



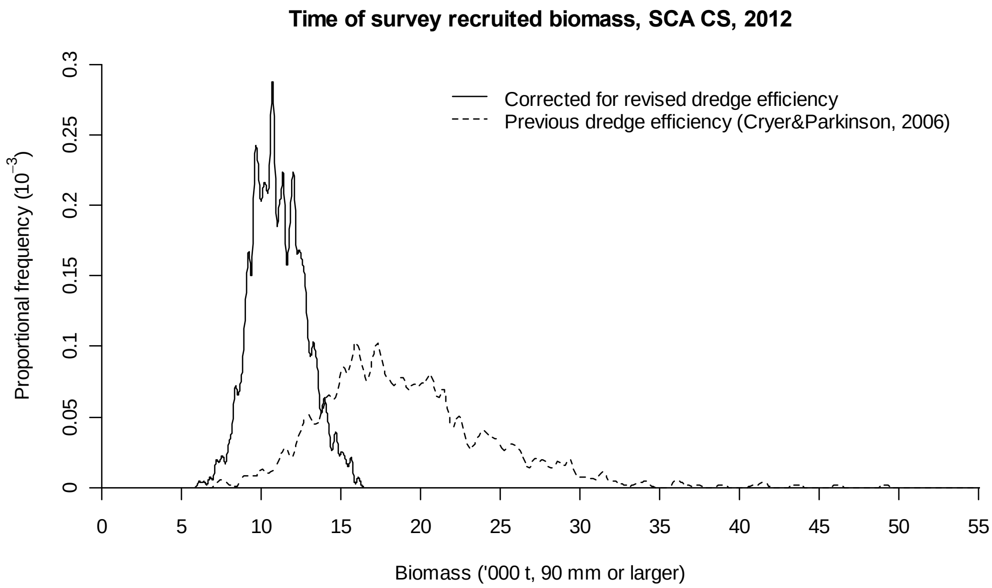
Appendix 5b: Distribution of bottom type (seabed substrate), estimated from the contents of the dredge catch at each station. Bottom type codes: 0, unknown; 1, mud or ooze; 2, mud with some sand; 3, sand; 4, sand/gravel and shells; 5 , shells; 6, gravel; 7, rock; 8, coral; 9, stone; 10, sand/shell hash; 11,mud/shell hash; 12, sand/coralline turf/shell hash.

Appendix 6: Parametric estimates of biomass

Appendix 6a: Standard parametric estimates of density and biomass of scallops 90 mm shell length or more at the time of the 2012 Coromandel survey, assuming 100% dredge efficiency.

Region	Area (km^2)	*n*	Density (m^{-2})	SEM	c.v.	Abundance (millions)	Biomass (g/m^{-2})	SEM	c.v.	Scallop wt(g)	Biomass (t green)
Barrier	26.22	17	0.07	0.01	0.18	1.96	6.28	1.04	0.17	83.84	165
HGulf	537.09	32	0.10	0.02	0.19	53.82	8.65	1.67	0.19	86.36	4 648
Colville	48.58	15	0.02	0.01	0.32	0.86	1.66	0.58	0.35	93.14	81
Waiheke	49.77	13	0.02	0.01	0.62	0.98	1.56	0.99	0.63	79.47	78
Mercury	127.42	57	0.06	0.02	0.25	7.81	5.01	1.17	0.23	81.70	638
Plenty	190.14	34	0.01	0.00	0.28	2.85	1.20	0.34	0.28	79.96	228
SCA CS	979.22	168	0.07	0.01	0.16	68.29	5.96	0.93	0.16	85.47	5 836

Appendix 7: Biomass using previous dredge efficiency (Cryer & Parkinson 2006)



Appendix 7a: Proportional frequency distribution of the recruited biomass (t, greenweight, scallops 90 mm or larger) in the Coromandel stock at the time of the survey (May 2012) corrected using revised dredge efficiency (Bian et al. 2012) (solid line) versus previous dredge efficiency (Cryer & Parkinson 2006) (dashed line).

Appendix 7b. Summary statistics for the projected population of scallops 90 mm shell length or more at the start of the season (15 July 2012) in the Coromandel fishery (all strata included), corrected for dredge efficiency using the method of Cryer & Parkinson (2006), assuming average growth, an M of 0.5, and average recovery of meatweight from greenweight.

Region	Area	Tows	Density(scallops m^{-2})				Abundance(millions)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI	Mean	c.v.	Median	95%CI
Barrier	26.22	17	0.54	0.32	0.51	0.28-0.93	14.11	0.32	13.46	7.3–24.4
HGulf	537.09	32	0.30	0.42	0.27	0.15-0.54	159.51	0.42	145.45	79.0–287.8
Colville	48.58	15	0.07	0.44	0.06	0.03-0.14	3.30	0.44	3.04	1.2–6.7
Waiheke	49.77	13	0.09	0.57	0.09	0.01-0.20	4.56	0.57	4.28	0.7–10.0
Mercury	127.42	57	0.45	0.36	0.42	0.22-0.81	57.15	0.36	53.72	28.2–103.4
Plenty	190.14	34	0.11	0.31	0.10	0.05-0.17	20.05	0.31	19.42	9.9–33.2
Fishery	979.22	168	0.26	0.29	0.25	0.16-0.42	258.69	0.29	247.89	158.5–409.3

Region	Area	Tows	Biomass(t green)				Biomass(t meat)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI	Mean	c.v.	Median	95%CI
Barrier	26.22	17	1 001	0.30	958	549–1 695	121.95	0.32	115.95	65–220
HGulf	537.09	32	13 840	0.42	12 594	6 771–24 800	1 678.83	0.43	1 524.08	759–3 100
Colville	48.58	15	309	0.49	280	112–673	38.04	0.52	33.83	13-89
Waiheke	49.77	13	321	0.59	301	47–706	39.46	0.64	35.62	6–90
Mercury	127.42	57	4 029	0.34	3809	2 058–7 146	492.63	0.36	470.53	238–896
Plenty	190.14	34	1 405	0.31	1359	688–2 343	171.88	0.33	164.36	79–298
Fishery	979.22	168	20 907	0.30	19 961	12 833–33 212	2 542.8	0.30	2 401.24	1 533–4147

Appendix 8: Comparison of 2010 and 2012 biomass in core strata using previous dredge efficiency (Cryer & Parkinson 2006)

Appendix 8a: Core strata 2010. Summary statistics for the projected population of scallops 90 mm shell length or more in the Coromandel fishery at the start of the season (15 July 2010), assuming historical average dredge efficiency (Cryer & Parkinson 2006), average growth, an *M* of 0.5, and historical average recovery of meatweight from greenweight. From Williams & Parkinson (2010).

Region	Area	Tows	Density (scallops m^{-2})				Abundance (millions)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI	Mean	c.v.	Median	95%CI
Barrier	4.2	13	2.96	0.26	2.86	1.69–4.57	12.3	0.26	11.9	7.0–19.0
Colville	7.6	12	0.44	0.52	0.39	0.14–0.99	3.3	0.52	2.9	1.1–7.6
Waihek	14.9	20	0.15	0.52	0.13	0.05–0.33	2.2	0.52	2.0	0.7–5.0
Mercury	63.3	57	0.55	0.20	0.54	0.37–0.79	34.9	0.20	34.3	23.4–49.9
Plenty	59.3	36	0.12	0.32	0.12	0.06–0.21	7.1	0.32	6.9	3.5–12.3
SCA CS	149.4	138	0.40	0.20	0.39	0.27–0.59	59.9	0.20	58.8	40.1–87.5

Region	Area	Tows	Biomass (t green)				Biomass (t meat)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI	Mean	c.v.	Median	95%CI
Barrier	4.2	13	919	0.25	892	535–1 398	112	0.28	107	61–185
Colville	7.6	12	264	0.51	234	92–577	33	0.56	29	11–73
Waihek	14.9	20	145	0.51	130	48–330	18	0.52	16	6–41
Mercury	63.3	57	2 690	0.19	2 655	1 830–3789	331	0.23	321	210–508
Plenty	59.3	36	486	0.31	469	246–833	60	0.34	57	28–104
SCA CS	149.4	138	4 504	0.19	4 442	3 101–6469	553	0.21	540	370–825

Appendix 8b: Core strata 2012. Summary statistics for the projected population of scallops 90 mm shell length or more in the <u>core strata</u> of the Coromandel fishery at the start of the season (15 July 2012), assuming historical average dredge efficiency (Cryer & Parkinson 2006), average growth, an *M* of 0.5, and historical average recovery of meatweight from greenweight.

Region	Area	Tows	Density (scallops m^{-2})				Abundance (millions)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI	Mean	c.v.	Median	95%CI
Barrier	4.05	11	3.15	0.33	3.05	1.49–5.56	12.76	0.33	12.33	6.0–22.5
Colville	7.88	7	0.36	0.47	0.33	0.12–0.75	2.86	0.47	2.59	1.0–5.9
Waiheke	10.64	9	0.10	0.80	0.08	0.02–0.23	1.02	0.80	0.87	0.2–2.5
Mercury	85.90	47	0.39	0.27	0.37	0.22–0.61	33.13	0.27	31.94	19.0–52.5
Plenty	71.35	23	0.08	0.31	0.07	0.04–0.13	5.44	0.31	5.23	2.7–9.3
SCA CS	179.81	97	0.31	0.24	0.30	0.19–0.47	55.22	0.24	53.70	33.6–84.0

Region	Area	Tows	Biomass (t green)				Biomass (t meat)			
	(km^2)	*n*	Mean	c.v.	Median	95%CI	Mean	c.v.	Median	95%CI
Barrier	4.05	11	910.77	0.30	882.84	465–1533	111.22	0.325	108.01	56–195
Colville	7.88	7	277.34	0.50	248.14	93–607	33.87	0.521	30.06	11–81
Waiheke	10.64	9	68.33	0.79	59.03	16–162	8.35	0.763	7.27	2–21
Mercury	85.90	47	2 428.79	0.25	2 360.88	1 461–3705	296.09	0.282	283.21	163–488
Plenty	71.35	23	365.80	0.30	350.94	188–616	44.55	0.327	42.70	22–77
SCA CS	179.81	97	4 051.03	0.22	3 960.94	2 585–6011	494.08	0.241	477.07	297–780

Appendix 8c: Start of season biomass by region for the 2010 and 2012 surveys including only core strata.

		2010		2012	Diff.
Region	c.v.	Median	c.v.	Median	prop.
Barrier	0.28	107	0.33	108	0.01
Colville	0.56	29	0.52	30	0.04
Waiheke	0.52	16	0.76	7	-0.55
Mercury	0.23	321	0.28	283	-0.12
Plenty	0.34	57	0.33	43	-0.25
SCA CS	0.21	540	0.24	477	-0.12

Appendix 9: Biomass at different critical densities

Appendix 9: Estimated median recruited biomass at the start of the 2012 season by fishery region at different commercial density thresholds ('critical densities') in the range of zero to 0.20 scallops m^{-2}.

Region	Critical density (scallops.m^{-2})	Biomass (t meat)	c.v.
Barrier	0.00	59	0.23
HGulf	0.00	984	0.24
Colville	0.00	19	0.32
Waiheke	0.00	19	0.50
Mercury	0.00	215	0.24
Plenty	0.00	70	0.26
SCA CS	0.00	1 380	0.18
Barrier	0.04	55	0.24
HGulf	0.04	830	0.24
Colville	0.04	14	0.40
Waiheke	0.04	7	0.80
Mercury	0.04	176	0.28
Plenty	0.04	24	0.36
SCA CS	0.04	1 121	0.19
Barrier	0.08	52	0.24
HGulf	0.08	710	0.28
Colville	0.08	12	0.47
Waiheke	0.08	3	0.81
Mercury	0.08	146	0.32
Plenty	0.08	6	0.51
SCA CS	0.08	938	0.22
Barrier	0.12	50	0.25
HGulf	0.12	603	0.31
Colville	0.12	9	0.55
Waiheke	0.12	0	–
Mercury	0.12	125	0.33
Plenty	0.12	3	0.82
SCA CS	0.12	798	0.24
Barrier	0.16	48	0.26
HGulf	0.16	498	0.34
Colville	0.16	7	0.57
Waiheke	0.16	0	–
Mercury	0.16	110	0.36
Plenty	0.16	2	1.01
SCA CS	0.16	675	0.27
Barrier	0.20	45	0.26
HGulf	0.20	461	0.38
Colville	0.20	6	0.60
Waiheke	0.20	0	–
Mercury	0.20	96	0.34
Plenty	0.20	1	1.00
SCA CS	0.20	621	0.29

Appendix 10: Analytical method used in scallop survey analysis software

Scallop Survey Analyses (SSA) is a software tool developed by NIWA in C++ for scallop survey analyses. SSA has been specifically developed to analyse pre-season dredge and dive surveys of the Northland (SCA 1), Coromandel (SCA CS) and Southern (SCA 7) scallop fishstocks. SSA implements the survey workup procedures documented in Cryer & Parkinson (2006), with modifications to incorporate recent advances in modelling dredge efficiency for the northern (box-dredge) fisheries (Bian et al., 2012). It uses individual tow or dive data to estimate scallop density, abundance and biomass, and their uncertainties, in the surveyed region at the time of survey and at the start of the forthcoming fishing season. The following is a description of the mathematical process used for SSA's survey data analyses. See *Scallop Survey Analysis User's manual* for the operational usage of SSA.

1. The number of scallops at length for each sample is scaled by the sampling fraction

The original scallop counts at length from a survey station are scaled by the station's sampling fraction (p), which is the number of the scallops that have been measured for shell length divided by the total number of scallops caught at that station, $0 \leq p \leq 1$. The number of measured scallops in length class l (l =19, 20, …, 130 mm), $\tilde{n}_l$, is scaled by fraction p and the number of scallops in length class l, n_l, is obtained.

i.e., $n_l = \begin{cases} 0, & if\ p = 0 \\ \frac{\tilde{n}_l}{p}, & if\ 0 < p \leq 1 \end{cases}$.

2. The number of scallops at length for each sample is converted to an observed density (number of scallops caught per unit area of seabed swept by the sampling method)

The scaled number of scallops in length class l, n_l, is converted to observed density ($\tilde{d}_l$), which is the number of scallops caught per unit area of seabed swept. The observed density is defined as $\tilde{d}_l = \frac{n_l}{a}$, where a is the area swept in a dredge tow. No correction for dredge efficiency is applied at this stage.

3. The observed density at length is corrected for dredge efficiency to estimate the actual density (number of scallops per unit area of seabed) for dredge surveys

Assuming divers are 100% efficient, the density at length observed by a diver will be considered as a sample of the actual density, i.e., $d_l = \tilde{d}_l$ for dive surveys.

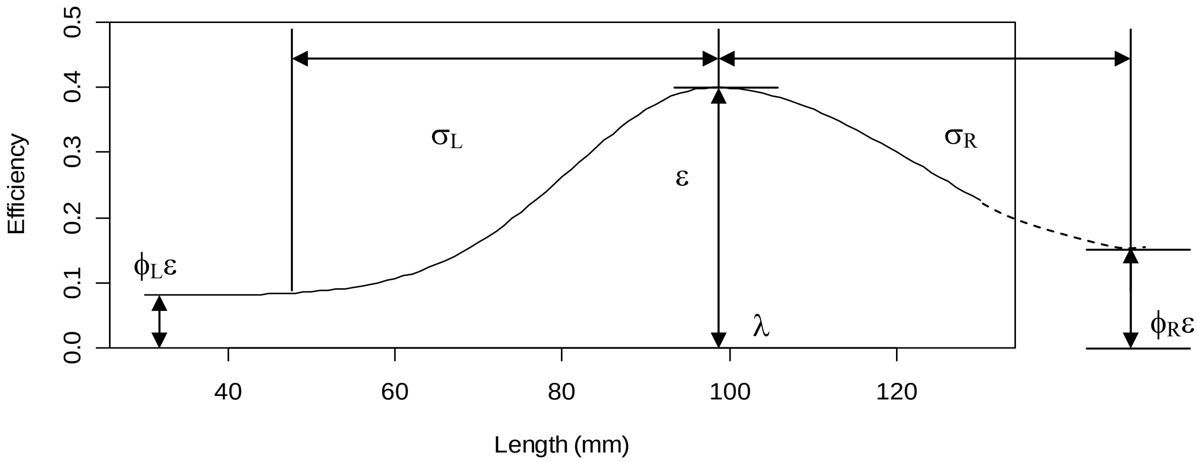
The density at length observed by a dredge $\tilde{d}_l$ is corrected for dredge efficiency for dredge surveys. Dredge efficiency is pre-determined and the efficiency scalars (the inverse of dredge efficiency) or the parameters to be used to calculate the efficiencies are saved in a file and SSA reads in the dredge efficiency information and uses the information to correct observed density at length for dredge efficiency.

For the Southern scallop stock (SCA 7), dredge efficiency E and associated variance was determined from experiments where concurrent dredge and diver estimates of scallop density were available (Tuck & Brown, 2008) and dredge efficiency scalars for length class l (l = 15–19, 20–24, 25–29,…, 130–134 mm), $\frac{1}{E(l)}$, are saved in file *sand efficiency Nelson.txt*. SSA multiplies the dredge efficiency scalar with the observed density to obtain corrected density, i.e., $d_l = \tilde{d}_l \cdot \frac{1}{E(l)}$.

For the northern scallop stocks (SCA 1 and SCA CS), a parametric dredge efficiency model was developed (Bian et al. 2012) that is composed of six parameters, $\boldsymbol{\alpha}$ = {ln(ε), ln(λ), ln(δ_L), ln(δ_R),

$\ln(\phi_L)$, $\ln(\phi_R)$}. See the equation and figure below for the relationship between dredge efficiency and these parameters.

$$
\mathrm{E}(l, \exp(\boldsymbol{\alpha})) = \begin{cases} \varepsilon\left(\phi_L + (1-\phi_L)\exp\left(-\left(\frac{l-\lambda}{\sigma_L}\right)^2\right)\right), & l < \lambda, \\ \varepsilon\left(\phi_R + (1-\phi_R)\exp\left(-\left(\frac{l-\lambda}{\sigma_R}\right)^2\right)\right), & l \geq \lambda. \end{cases} \tag{A.1}
$$



This study showed that dredge efficiency was significantly affected by substrate, water depth, and whether a dredge tow was terminated (hauled early). Within the model, substrate is categorised as either Coromandel Mud (CM), Coromandel Sand (CS) or Northland Sand (NS); depth is categorised into levels < 15m, 15m – 20m, 20m – 25m, ≥ 25m; and tow termination is either true or false. The six dredge efficiency parameters estimated for the base case (substrate = CM, depth < 15m and tow termination = false) are denoted as α_0 and the effects of other combinations of substrate, depth and tow termination, denoted as $\alpha_1, \alpha_2, \ldots, \alpha_6$, are

- α_1, substrate = CS
- α_2, substrate = NS
- α_3, $15 \leq \text{depth} < 20$
- α_4, $20 \leq \text{depth} < 25$
- α_5, $\text{depth} \geq 25$
- α_6, tow termination = true

There are six parameters for the base case and each of the six effects, so there are 42 parameters estimated by the dredge efficiency model.

To reflect the uncertainty in the estimates of those dredge efficiency parameters, a Bayesian approach has been used, and 1000 MCMC samples of the posteriors of those 42 parameters, $\ln(\varepsilon)$, $\ln(\lambda)$, $\ln(\delta_L)$, $\ln(\delta_R)$, $\ln(\phi_L)$, and $\ln(\phi_R)$ in each of $\alpha_0, \alpha_1, \ldots, \alpha_6$, have been stored in a file for use within SSA. SSA loads this file and calculates the median of each parameter, calculates appropriate dredge efficiencies for each station, and corrects observed densities for dredge efficiency.

In a dredge survey, the substrate, water depth and tow distance are recorded for each dredge tow.
The process of finding the parameters for a specific tow is

- Effects for substrate, $\boldsymbol{\alpha}_s = \begin{cases} 0, & if \text{ substrate } = \text{ CM} \\ \boldsymbol{\alpha}_1, & if \text{ substrate } = \text{ CS} \\ \boldsymbol{\alpha}_2, & if \text{ substrate } = \text{ NS} \end{cases}$
- Effects for depth, $\boldsymbol{\alpha}_d = \begin{cases} 0, & if \text{ depth} < 15 \\ \boldsymbol{\alpha}_3, & if\ 15 \leq \text{depth} < 20 \\ \boldsymbol{\alpha}_4, & if\ 20 \leq \text{depth} < 25 \\ \boldsymbol{\alpha}_5, & if \text{ depth} \geq 25 \end{cases}$
- Effects for tow termination, $\boldsymbol{\alpha}_t = \begin{cases} 0, & if \text{ tow termination } = \text{ false} \\ \boldsymbol{\alpha}_6, & if \text{ tow termination } = \text{ true} \end{cases}$

The parameters to be used for a dredge tow are $\boldsymbol{\alpha} = \boldsymbol{\alpha}_0 + \boldsymbol{\alpha}_s + \boldsymbol{\alpha}_d + \boldsymbol{\alpha}_t$, and the dredge efficiency for scallops of length *l* is calculated with equation (A.1). The dredge efficiency corrected density at length *l* , d_l, is $d_l = \tilde{d}_l \cdot \frac{1}{\mathrm{E}(l, \exp(\boldsymbol{\alpha}))}$.

4. Scallop greenweight density at length is estimated from scallop density using a length-weight relationship

Scallop greenweight density (greenweight of scallops per unit area) at length *l* , ρ_l, is calculated from the dredge-efficiency-corrected scallop density at length *l*, d_l, using the length weight relationship (i.e., $\rho_l = a \cdot l^b \cdot d_l$) for scallops reported by Cryer & Parkinson (2006); for the basic analytical calculation (no resampling or projection conducted), $a = 0.00037$ and $b = 2.690$.

5. The expected scallop density (number and greenweight) and raised abundance and biomass at or above the minimum legal size (or other length of interest) for each stratum, specified grouping of strata, and the whole population, are estimated, and the variances associated with the expected quantities are calculated.

Absolute estimates, and estimates above specific critical (threshold) densities are calculated. Critical density is used to account for the fact that fishing low density scallop beds may not be economically viable, and applying a critical density excludes low density components of the population. In effect, a critical density correction rate is calculated from a specified critical density and the estimated density of scallops above the minimum legal size (or other length of interest) for each station with Equation A.2 and the rate is then used in the calculation of stratum densities (Equation A.3). The effective economic critical density has not been accurately determined (and will vary with a number of factors including fuel price), so normally several critical densities (0, 0.04, 0.08, 0.12, 0.16 and 0.20) are considered in a survey analysis.

Assuming $d_{t,l}$ is the dredge-efficiency-corrected density for tow *t* at length *l* and l_{min} is the minimum legal size, for a given critical density *c*, the critical density correction rate for tow *t*, r_t, is calculated by

$$r_t = \begin{cases} 0, & if\ \sum_{l \geq l_{min}} d_{t,l} < c \\ \frac{(\sum_{l \geq l_{min}} d_{t,l}) - c}{\sum_{l \geq l_{min}} d_{t,l}}, & if\ \sum_{l \geq l_{min}} d_{t,l} \geq c \end{cases} \tag{A.2}$$

Note: in previous implementations, the critical density correction is conducted before the correction for dredge efficiency and in the June 2012 version, densities are corrected for critical density after the dredge efficiency correction.

Given $d_{t,l}$ and $\rho_{t,l}$, the scallop densities in number and greenweight respectively in tow t at length l, and l_{min}, the minimum legal size, the scallop densities in number and greenweight in stratum s, d_s and ρ_s, are calculated by

$$d_s = \frac{1}{N_{t\in s}} \cdot \sum_{t\in s}\left(\sum_{l\geq l_{min}} d_{t,l} \cdot r_t\right) \text{ and } \rho_s = \frac{1}{N_{t\in s}} \cdot \sum_{t\in s}\left(\sum_{l\geq l_{min}} \rho_{t,l} \cdot r_t\right) \qquad \text{(A.3)}$$

Standard deviation of the densities in number and greenweight in stratum s, $\hat{\sigma}(d_s)$ and $\hat{\sigma}(\rho_s)$ (here $\hat{\sigma}$ is used for standard deviation of sample instead of s because s is already used to represent stratum)

$$\hat{\sigma}(d_s) = \sqrt{\frac{(\sum_{t\in s}[(\sum_{l\geq l_{min}} d_{t,l}) - d_s])^2}{(N_{t\in s}-1)}} \text{ and } \hat{\sigma}(\rho_s) = \sqrt{\frac{(\sum_{t\in s}[(\sum_{l\geq l_{min}} \rho_{t,l}) - \rho_s])^2}{(N_{t\in s}-1)}}$$

Standard errors of the mean for densities in number and greenweight in stratum s, $SEM(d_s)$ and $SEM(\rho_s)$, are calculated by

$$SEM(d_s) = \frac{\hat{\sigma}(d_s)}{\sqrt{N_{t\in s}}} \text{ and } SEM(\rho_s) = \frac{\hat{\sigma}(\rho_s)}{\sqrt{N_{t\in s}}}$$

Coefficient of variation (c.v.) for the densities in number and greenweight in stratum s are

$$\text{c.v.}(d_s) = \frac{SEM(d_s)}{d_s} \text{ and } \text{c.v.}(\rho_s) = \frac{SEM(\rho_s)}{\rho_s}$$

Assuming A_s is the area of stratum s, expected scallop densities in number and greenweight of the whole population or specified grouping of the survey strata are calculated by

$$d = \frac{1}{\sum_s A_s}\sum_s(d_s \cdot A_s) \text{ and } \rho = \frac{1}{\sum_s A_s}\sum_s(\rho_s \cdot A_s)$$

SEMs for densities in number and greenweight of the whole population or any strata grouping are

$$SEM(d) = \frac{1}{\sum_s A_s}\sqrt{\sum_s[{A_s}^2 \cdot \hat{\sigma}^2(d_s)/N_{t\in s}]} \text{ and } SEM(\rho) = \frac{1}{\sum_s A_s}\sqrt{\sum_s[{A_s}^2 \cdot \hat{\sigma}^2(\rho_s)/N_{t\in s}]}$$

Coefficients of variation for the densities in number and greenweight of the whole population or any specified grouping of the strata are

$$\text{c.v.}(d) = \frac{SEM(d)}{d}, \text{ where } d = \frac{1}{\sum_s A_s}\sum_s A_s \cdot d_s$$

$$\text{c.v.}(\rho) = \frac{SEM(\rho)}{\rho}, \text{ where } \rho = \frac{1}{\sum_s A_s}\sum_s A_s \cdot \rho_s$$

where $N_{t\in s}$ is the number of tows in stratum s in the survey.

Given stratum area A_s, the abundance and biomass for stratum s, are $P_s = d_s \cdot A_s$ and $B_s = \rho_s \cdot A_s$. The abundance and biomass for the whole population or any specified grouping of the strata are

$$P = \sum_s P_s \text{ and } B = \sum_s B_s$$

Note: $l \geq l_{min}$ in all equations will be replaced by $l_{low} \leq l < l_{min}$, if a user chooses the lengths of interest $l_{low} < 19\ mm$.

6. The scallop density, greenweight density, abundance and biomass at the time of survey at or above the minimum legal size (or other length of interest) for each stratum, any specified grouping of the strata and the whole population are estimated and the associated variance is estimated using bootstraps (resampling with replacement) of the original survey data.

Bootstraps are conducted in each stratum – resampling stations with replacement within each stratum – for n times (user specified and n = 1000 recommended). Corresponding to each bootstrap of the survey data, for dredge surveys, dredge efficiency scalars (for SCA 7 fishery) or dredge efficiency parameters (for Northland and Coromandel fisheries) and length weight relationship parameters are also resampled from 4000 sets of dredge efficiency scalars or 1000 sets of dredge efficiency parameters and 2000 length weight relationship parameters, which are loaded from files.

For bootstrap i, (i = 1, 2, …, n), density at length l from station t of the resampled stations in stratum s, ${\tilde{d}_{t,l}}^{(i)}$, is corrected for dredge efficiency if it is a dredge survey, ${d_{t,l}}^{(i)} = {\tilde{d}_{t,l}}^{(i)} \cdot \frac{1}{E^{(i)}(l)}$ for SCA 7 fishery and ${d_{t,l}}^{(i)} = {\tilde{d}_{t,l}}^{(i)} \cdot \frac{1}{E(l, \exp(\boldsymbol{\alpha}^{(i)}))}$ for Northland and Coromandel fisheries. Greenweight density at length ${\rho_{t,l}}^{(i)}$ is calculated from density at length ${d_{t,l}}^{(i)}$ using resampled length weight relationship parameters a_i and b_i, i.e., ${\rho_{t,l}}^{(i)} = a_i \cdot l^{b_i} \cdot {d_{t,l}}^{(i)}$. The densities in number and greenweight for stratum s, ${d_s}^{(i)}$ and ${\rho_s}^{(i)}$ are calculated by

$${d_s}^{(i)} = \frac{1}{N_{t\in s}} \cdot \sum_{t\in s}\left(\sum_{l\geq l_{min}} {d_{t,l}}^{(i)} \cdot r_t\right)$$

$${\rho_s}^{(i)} = \frac{1}{N_{t\in s}} \cdot \sum_{t\in s}\left(\sum_{l\geq l_{min}} {\rho_{t,l}}^{(i)} \cdot r_t\right)$$

where r_t is critical density correction rate for tow t and $N_{t\in s}$ is the number of stations in stratum s. The densities in number and greenweight for the whole population or any specified grouping of the strata are

$d^{(i)} = \frac{1}{\sum_s A_s} \sum_s \left({d_s}^{(i)} \cdot A_s\right)$ and $\rho^{(i)} = \frac{1}{\sum_s A_s} \sum_s \left({\rho_s}^{(i)} \cdot A_s\right)$.

The abundance and biomass for stratum s for bootstrap i are ${P_s}^{(i)} = {d_s}^{(i)} \cdot A_s$ and ${B_s}^{(i)} = {\rho_s}^{(i)} \cdot A_s$. The abundance and biomass for the whole population or any specified grouping of the strata are $P^{(i)} = \sum_s {P_s}^{(i)}$ and $B^{(i)} = \sum_s {B_s}^{(i)}$.

The mean density of stratum s from n bootstraps is $\bar{d}_s = \frac{1}{n}\sum_{i=1}^{n} {d_s}^{(i)}$ and c.v. of the density of stratum s is $c.v.(d_s) = \frac{1}{\bar{d}_s}\sqrt{\frac{\sum_{i=1}^{n}({d_s}^{(i)} - \bar{d}_s)^2}{n}}$. Median and 95% confidence intervals for density d_s are determined from ${d_s}^{(1)}$, ${d_s}^{(2)}$, …, ${d_s}^{(n)}$. The means, c.v.s, medians and 95% confidence intervals for greenweight density, abundance and biomass for each survey stratum, the whole population or any specified grouping of the strata are obtained using the same method as for stratum density.

7. Estimating scallop density, greenweight density, abundance and biomass at the start of the forthcoming fishing season by projecting the corrected density at length using a growth transition matrix based on tag return data. Uncertainty about the expected average growth between survey and season is incorporated by bootstrapping the original tag return data.

To estimate the scallop population at the start of the forthcoming fishing season from survey data, the corrected density at length at time of survey d_{l_0} is projected forward in time to become the density at length at the start of the season d_l, before it is used in the calculation of greenweight density, abundance and biomass. SSA predicts the scallop population at the start of the season from the estimated scallop population at the time of survey (from step 6) by simulating the process of growth and natural mortality.

Assuming $\boldsymbol{l}_0$ and $\boldsymbol{l}$ are the scallop lengths (19, 20, …, 130 mm) at the time of survey and the start of the fishing season respectively, a growth matrix is generated and the proportion for scallops of length $l_0(j)$ at the time of survey to grow to length $l(k)$ at the start of the season is

$$G_{l_0(j),l(k)} = \frac{1}{\sqrt{2\pi}\cdot\sigma(j)} e^{\frac{-[l(k)-(l_0(j)+\mu(j))]^2}{2\sigma^2(j)}}, j = 1, 2, \dots, 111, k = 1, 2, \dots, 111$$

where $\mu(j)$ is the expected length increase during the period between the time of survey and the start of the season for $l_0(j)$ and $\sigma(j)$ is the standard deviation of the expected length increase in the period and $\boldsymbol{\mu}$ and $\boldsymbol{\sigma}$ are determined by $\mu(j) = \alpha_\mu + \beta_\mu \cdot \ln[l_0(j)]$ and $\sigma(j) = \alpha_\sigma + \beta_\sigma \cdot l_0(j)$, $j = 1, 2, \dots, 111$.

α_μ and β_μ are the parameters of the linear model for expected length increase $\boldsymbol{\mu}$ and α_σ and β_σ are the parameters of the linear model for standard deviation $\boldsymbol{\sigma}$, and they are estimated from $n_{tag} = 129$ scallop tagging recaptures using least square regression. α_μ and β_μ are estimated by

$$\beta_\mu = \frac{\sum_{g=1}^{n_{tag}}(x_g - \bar{x})(y_g - \bar{y})}{\sum_{g=1}^{n_{tag}}(x_g - \bar{x})^2}$$

$$\alpha_\mu = \bar{y} - \beta_\mu \bar{x}$$

where x_g and y_g (g = 1, 2, …, n_{tag}) are respectively the logarithm of the initial length of the gth tagged scallop and the calculated length increase of the scallop with that initial length in the time between the time of survey and the start of the season, $y_g = \frac{\Delta T}{\Delta t_g}\tilde{y}_g$, where ΔT is the number of weeks between the time of survey and the start of the season, Δt_g is the number of weeks of liberty for the gth tagged scallop and $\tilde{y}_g$ is the weekly length increase during the liberty time for the gth tagged scallop.

α_σ and β_σ are estimated by

$$\beta_\sigma = \frac{\sum_{j=j_{min}}^{j_{max}}(x_j - \bar{x})(y_j - \bar{y})}{\sum_{j=j_{min}}^{j_{max}}(x_j - \bar{x})^2}$$

$$\alpha_\sigma = \bar{y} - \beta_\sigma \bar{x}$$

where j_{min} and j_{max} are the indices for the minimum initial length and maximum initial length of the tagged scallops in the tagging data, x_j is the jth initial length of the tagged scallops and y_j is the standard deviation of the length increases of those tagged scallops with that initial length. $\bar{x}$ and $\bar{y}$ are the means of x_j and y_j for $j = j_{min}, j_{min}+1, \dots, j_{max}-1, j_{max}$.

Given natural mortality m (assumed to be constant through the year) and its c.v., weekly scallop survival is $\bar{v} = e^{-m\cdot\Delta T/52}$. SSA assumes the probability of scallop survival is normal distributed with mean of $\mu = e^{-m\cdot\Delta T/52}$ and standard deviation $\sigma = c.v.\cdot e^{-m\cdot\Delta T/52}$. SSA users can specify m and its c.v. (see SSA's user manual for details), and by default natural mortality is $m = 0.5$ and its c.v. is $c.v. = 0.065$.

For scallops with densities at length at the time of survey $\boldsymbol{d}_{l_0} = [d_{l_0(1)}, d_{l_0(2)}, \dots, d_{l_0(111)}]^T$, given growth matrix $\boldsymbol{G}_{l_0,l} = \begin{bmatrix} G_{l_0(1),l(1)}, & G_{l_0(2),l(1)}, \cdots, & G_{l_0(111),l(1)} \\ G_{l_0(1),l(2)}, & G_{l_0(2),l(2)}, \cdots, & G_{l_0(111),l(2)} \\ & \cdots & \\ G_{l_0(1),l(111)}, & G_{l_0(2),l(111)}, \cdots, & G_{l_0(111),l(111)} \end{bmatrix}$ and survival rate v, the predicted densities at length at the start of fishing season $\boldsymbol{d}_l = [d_{l(1)}, d_{l(2)}, \dots, d_{l(111)}]^T$ are calculated by
$\boldsymbol{d}_l = v \cdot \boldsymbol{G}_{l_0,l} \cdot \boldsymbol{d}_{l_0}$

For bootstrap i, (i = 1, 2, …, n), density at length l_0 ($l_0 = 19, 20, \dots, 130$ mm) from station t of the resampled stations in stratum s, $\tilde{d}_{t,l_0}{}^{(i)}$, is corrected for dredge efficiency and critical density if it is a dredge survey and $d_{t,l_0}{}^{(i)}$ is obtained. For given natural mortality $m = 0.5$ and its c.v. 0.065, SSA randomly samples normal distribution $N(\mu = e^{-0.5\frac{\Delta T}{52}}, \sigma^2 = (0.065e^{-0.5\frac{\Delta T}{52}})^2)$ and obtains the survival rate $v^{(i)}$, where ΔT is the number of weeks between the time of survey and the start of the season. To reflect the variance in growth, the tagging data are resampled with replacement for each iteration i and the growth matrix $\boldsymbol{G}_{l_0,l}{}^{(i)}$ is calculated from the bootstrapped tagging data.

The growth data and model used in the 2012 analysis were the same as in previous survey analyses using the method of Cryer & Parkinson (2006); new data and modelling are available from a more recent study of scallop growth (Tuck & Williams 2012), but additional work is required before these data and a revised growth model can be used in this analytical process.

8. Predicting meatweight from expected start-of-season biomass in greenweight using recovery rates of meatweight from greenweight of the previous years in the surveyed fisheries. Uncertainty in predicting meatweight recovery is incorporated by randomly sampling one of those historical recovery rates for each bootstrap estimate.

Meatweight recovery rates are obtained from the previous years' total meatweight and total catch in fisheries. The predicted meatweight w_{meat} available for the forthcoming fishing season is calculated from the historical recovery rates r_{meat} and estimated biomass in greenweight B from the survey, i.e., $w_{meat} = r_{meat}B$.

To reflect the variance in meat recovery, for bootstrap i (i = 1, 2, …, n), the meat recovery rate r_{meat} is randomly sampled from the historical recovery rates.

There are currently 13 years of recovery rate data for Coromandel fishery and 7 years of recovery rate data for Northland fishery. For SCA 7 fishery, meatweight recovery rates were recorded separately for areas Golden Bay (13 years), Tasman Bay (10 years) and Marlborough Sounds (13 years).

9. Calculating CAY from the predicted meatweight biomass

Current Annual Yield (CAY) is calculated from the predicted start of season meatweight biomass. $F_{0.1}$, the fishing mortality rate at which the slope of the yield-per-recruit curve is only one-tenth the slope of the curve at its origin, is used in the calculation of CAY and $F_{0.1}$ will have different values when we assume only direct effects of fishing on adult scallops ($F_{0.1}$) or direct and indirect effects of fishing on adult and juvenile scallops ($F_{0.1}^{(AJ)}$). Corresponding to $F_{0.1}$ and $F_{0.1}^{(AJ)}$, CAY and $\text{CAY}^{(AJ)}$ are calculated accordingly for a particular scallop stock or region within a stock.

- Northland (SCA 1)

Given the fishery target reference point $F_{0.1}$, natural mortality m, meatweight w_{meat} and time period in proportion of a year τ, CAY is calculated as

$$CAY = \frac{F_{0.1}}{F_{0.1}+m}\left(1 - e^{-(F_{0.1}+m)\tau}\right) \cdot w_{meat} \quad \text{(A.4)}$$

where $F_{0.1} = 0.943$, $m = 0.5$ by default, $\tau = \frac{7}{12}$ (seven month fishing season) and w_{meat} can be the meatweight predicted for the whole fishstock or any specific region within the fishstock. No estimate of $F_{0.1}^{(AJ)}$ is available for SCA 1.

- Coromandel (SCA CS)

The CAY calculation for Coromandel follows an identical process to the calculation for Northland (A.4), but with different values for $F_{0.1}$ and τ, $F_{0.1} = 1.034$ (because of the different minimum legal size), $\tau = \frac{5}{12}$ (five month fishing season) and w_{meat} as the predicted meatweight for the whole fishery or any specific area in Coromandel fishery.

$$CAY^{(AJ)} = \frac{F_{0.1}^{(AJ)}}{F_{0.1}^{(AJ)}+m}\left(1 - e^{-(F_{0.1}^{(AJ)}+m)\tau}\right) \cdot w_{meat}$$

where $F_{0.1}^{(AJ)} = 0.658$.

- Southern (SCA 7)

CAY and $CAY^{(AJ)}$ are calculated for SCA 7 fishery by

$$CAY = \left(1 - e^{-F_{0.1}}\right) \cdot w_{meat} \text{ and } CAY^{(AJ)} = \left(1 - e^{-F_{0.1}^{(AJ)}}\right) \cdot w_{meat}$$

where $F_{0.1} = 0.631$ or $F_{0.1} = 0.553$, derived using an assumed natural mortality of $M = 0.5$ or $M = 0.4$. No estimate of $F_{0.1}^{(AJ)}$ is available for SCA 7.