Biomass survey and stock assessment for the Coromandel scallop fishery, 2010

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EXECUTIVE SUMMARY

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A dredge survey for scallops was carried out in the Coromandel scallop fishery in May 2010, with a total of 138 valid stations (dredge tows) sampled. Absolute start-of-season recruited biomass (scallops over 90 mm shell length, the commercial minimum legal size in the Coromandel fishery) was predicted to be 4442 t greenweight (median projected value; 95% CI = 3101–6469 t) with a c.v. of 19% or 540 t meatweight (median projected value; 95% CI = 370–825 t) with a c.v. of 22%. These estimates are sensitive to assumptions about dredge efficiency, 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 (62%) was held in the Mercury beds to the north of Whitianga, which collectively form the mainstay of the fishery, with about 21% held in beds at Little Barrier, 9% in the Bay of Plenty, 6% at Colville, and 2% at Waiheke. These results are similar to those of the 2009 survey and assessment, and suggest the downturn in recruited biomass observed since about 2005–06 appears to have stalled.

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. 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 2010 start-of-season was estimated to be 172 t meatweight. Incorporating direct and indirect incidental effects of fishing reduced the CAY estimate to 117 t meatweight. For both scenarios, the estimates of CAY would have c.v.s at least as large as that of the estimate of start-of-season recruited biomass (21%), are sensitive to assumptions about dredge efficiency, growth and mortality, expected recovery of meatweight from greenweight, exclusion of areas of low scallop density, and relate to the surveyed beds only. There is also additional uncertainty associated with using single point estimates of $F_{0.1}$ (i.e., variance associated with each point estimate was not incorporated in the analysis). Further, the second approach to estimating CAY which includes direct and indirect effects of fishing is also sensitive to the duration of any habitat-mediated increase in juvenile mortality. Substantial uncertainty remains in this stock assessment, and future research and management should be aimed at reducing this uncertainty.

1. INTRODUCTION

1.1 Overview

This report summarises research and fishery information for scallops (*Pecten novaezelandiae*) in the Coromandel fishery (SCA CS). The results of a Coromandel scallop biomass survey undertaken in May 2010 are summarised and yield estimates for 2010 are derived using methods detailed by the Ministry of Fisheries (2010).

This work was carried out under the Ministry of Fisheries project SCA2007/01C: 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 2010 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 northern scallop fisheries

Scallops support regionally important commercial fisheries and an intense non-commercial interest off the northeast coast of the North Island. Both the Coromandel (SCA CS) and Northland (SCA 1) commercial fisheries are managed under the Quota Management System (QMS); the two are divided by a line from Cape Rodney to the northernmost tip of Great Barrier Island (Figure 1). A wide variety of effort controls and daily catch limits has been imposed in the past, but both fisheries have been limited by explicit seasonal catch limits specified in meatweight (processed weight, being the adductor muscle with roe attached) since the early to late 1990s. Some additional controls remain on dredge size, fishing hours, and (in the Coromandel fishery) non-fishing days. Catch and catch rates from both fisheries are variable both within and among years (Tables 1 and 2), a characteristic of scallop fisheries worldwide (Shumway & Sandifer 1991).

In the Coromandel fishery, commercial scallop fishing is 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). Fishing in the Northland fishery is within discrete beds in Spirits Bay, Tom Bowling Bay, Great Exhibition Bay, Rangaunu Bay, Doubtless Bay, Stephenson Island, the Cavalli Passage, Bream Bay, the coast between Mangawhai and Pakiri Beach, and to the north of Little Barrier Island. Recreational and Maori customary fishing is undertaken in suitable areas throughout both fisheries, more 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 both fisheries 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 fishery 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 the Northland fishery and for all non-commercial fishers. The fishing year applicable to northern scallop fisheries is from 1 April to 31 March. The commercial scallop fishing season runs from 15 July to 21 December in the Coromandel fishery, and from 15 July to 14 February in the Northland fishery.

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), and some papers on reproductive ecology (Williams & Babcock 2004, 2005). 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 fishery in depths of 10 to 30 m and in the Northland fishery in depths of 20 to 50 m. Growth rates are spatially and temporally variable; growth to 100 mm takes between 1.5 and 3.5 years. The maximum age of scallops in unexploited populations is thought to be about 6 or 7 years.

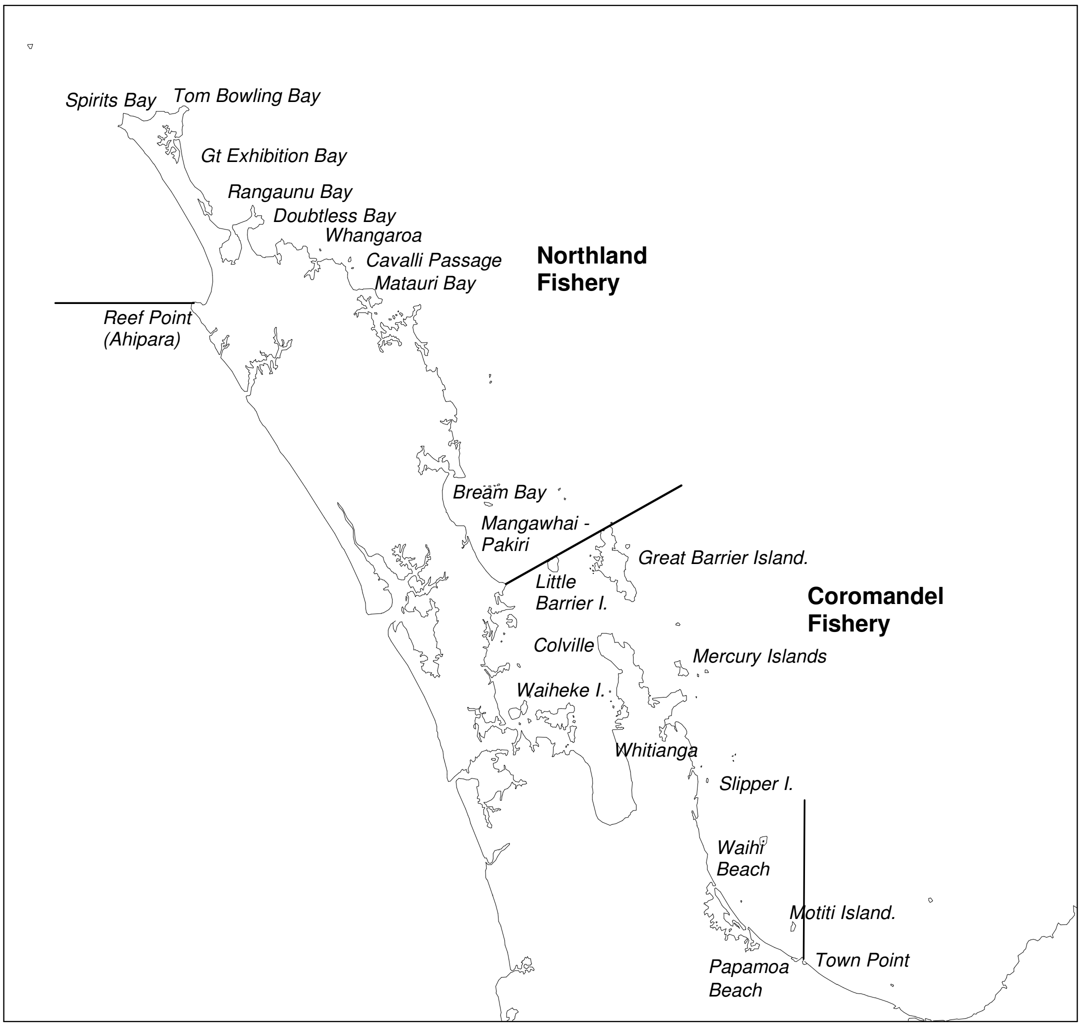

Figure 1: Geographic distribution of the two northern scallop fisheries and the names of locations mentioned in the text. After Cryer & Parkinson (2006).

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 spat settlement. Larval development lasts for about three weeks, depending on water temperature. Initial spat settlement is by byssus thread attachment to some surface free of sediment (shell hashes, hydroids, spat bags, etc.). The characteristic scallop shell does not develop until a few days after the spat loses the byssus thread and settles to the seabed.

Scallops grow rapidly (albeit with considerable variation), have high natural mortality ($M \sim 0.50\ \mathrm{y}^{-1}$), 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 fishery 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.

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) is complex and (declines in) CPUE cannot be used to estimate biomass within a season (Cryer 2001). Effort data, therefore, are not presented.

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). 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, and 2009 when landings were only 55%, 75%, and 33% of the agreed catch limit, respectively.

At the Shellfish Fishery Assessment Working Group held on 21–22 January 2010, concerns were raised about the large discrepancy that has been observed over recent years between the Current Annual Yield (CAY) estimates for the commercial Coromandel scallop fishery and the actual catch taken by the fishers. Fishers who attended the SFWG meeting believe that it is not possible to catch the CAY. There could be a number of confounding factors that are causing actual catch to be well below the estimated CAY. Currently, MFish project SAP2009-10 (Review of difference between CAY estimates and actual catch for the SCA CS fishery) is determining what factors are most likely to be affecting the difference between estimates of CAY for the commercial Coromandel scallop fishery and the actual commercial catch, and to what degree the different factors may be contributing to the difference.

Table 1: Catch limits and landings (t meatweight or greenweight) from the Coromandel fishery 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

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 fishery, 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 that part of the Coromandel scallop fishery 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 fishery-wide estimates of non-commercial harvest of scallops from the Coromandel fishery. 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 fishery (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 (2005)
2000–01	472 000	0.47	55.3	Boyd et al. (2005)

Given the above concerns about the reliability of fishery-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 fishery 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 fishery. However, scallops encountered by box dredges showed modest reductions in growth rate compared with scallops collected by divers, and their mortality was high (up to about 50% for larger size classes). 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 $F_{0.1}$. More recent field experiments (Talman et al. 2004) and 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.

3. RESEARCH

3.1 Stock structure

Current management assumes the Coromandel fishery is separate from the other New Zealand scallop fisheries (i.e., Northland, the various west coast harbours, Golden Bay, Tasman Bay, Marlborough Sounds, Stewart Island, and Chatham Islands). The stock structure of this fishery 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 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.

The 2010 survey of SCA CS was conducted from 8 to 9 May, 16 to 22 May, and 30 to 31 May 2010. Surveying was not possible in the intervening periods because of bad weather conditions. 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 17 strata which represent the areas that were expected to contain commercial densities of scallops and be amenable to fishing in 2010: Little Barrier Island (2 strata), Colville (1 stratum), Waiheke (2 strata), the west and south of the Mercury Islands (9 strata), and the western Bay of Plenty (3 strata at Motiti Island, Papamoa Beach, and off the Katikati Entrance) (Figure 2; Appendix 1). These strata were the same or very similar to those used in the 2007–09 surveys. The total sampled area in 2010 was 149 km^2 (Appendix 1) compared with 119–175 km^2 between 2001 and 2008, and 253–341 km^2 between 1996 and 1999. The Coromandel fishery was not surveyed in 2000.

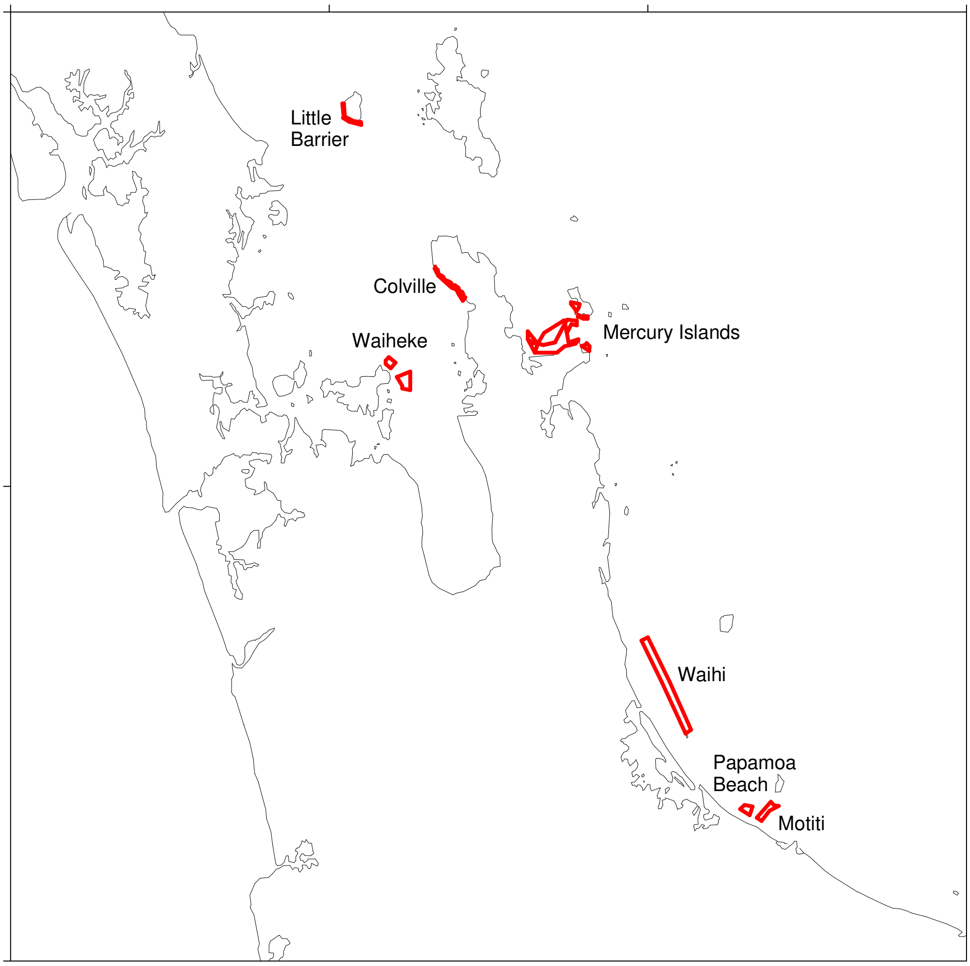

Figure 2: Location of strata for the survey of the Coromandel scallop fishery in 2010. Groups of strata are labelled with geographic descriptions used in the text (see Appendix 1 for stratum details).

The survey was not formally optimised to minimise the predicted c.v. of the estimate of recruited biomass because time constraints on the survey limited the number of ways in which stations could realistically be allocated to strata. These constraints necessitated a more pragmatic approach than was used in the 1990s (e.g., Cryer & Parkinson 1999).

A starting point for station allocation was generated using equation (1):

$$n_i = \frac{NA_iD_i}{\sum A_iD_i} \tag{1}$$

where N is the total number of stations in the sampling phase, n_i is the number of samples allocated to stratum i of area A_i and expected density D_i (after Sukhatme & Sukhatme 1970). The (semi-quantitative) D_i was 3, 2, 1, based on fishers' beliefs that there are very high, high, and medium prospects of finding scallops at commercial densities in the upcoming fishing season. Areas or strata with low prospects of finding scallops were excluded.

The preliminary station 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 fishery 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 stations were allocated to strata within groups according to their relative stratum sizes and a semi-quantitative understanding of historical performance until the total for the group was 20–25. The positions of stations within strata were randomised using the Random Stations package (RAND_STN v 1.7 for PCs; MAF Fisheries (1990)) constrained to keep all stations at least 500 m apart. This package estimates the area of each stratum, and gives the latitude and longitude of each random station.

Dredging in the Coromandel survey was undertaken from the chartered commercial dredge vessel *Kataraina* (whose dredge has a width of 2.0 m for which considerable historical information on dredge efficiency exists). 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 0.3–0.5 nautical miles (556–926 m, assessed using non-differential GPS), depending on the expected average size of the catch. 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 and the actual distance travelled along the ground was estimated using GPS. 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.

Additionally, in 2010 (as in 2009), we categorised the dredge survey bycatch on a station by station basis (Appendix 2). 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.

3.2.2 Estimating and correcting for dredge efficiency

We used the same methodology as in the 2005–08 scallop stock assessments to estimate and correct for dredge efficiency. This approach was described in detail by Cryer & Parkinson (2006).

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 stock assessments (e.g., Cryer & Parkinson 2004) and documented in detail by Cryer & Parkinson (2006). In brief, the approach contains the following 10 steps.

1. The length frequency distribution for each sample is scaled according to 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 estimated "real" density per unit area of seabed. These are combined to estimate the population length frequency distribution.

4. The (green)weight (per unit area) 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.

8. Mortality between survey and season is incorporated by applying an instantaneous rate of $M = 0.5\ y^{-1}$, bootstrapping (parametrically) from an estimated statistical distribution of M.

9. The absolute recruited biomass at the start of the season is estimated by repeating steps 4–6, again assuming the stratum areas to be without error.

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 (1995 to 2009, excluding 1998 and 2003) suggest that average recovery over a season varies from about 10% to 15% (Appendix 3). Uncertainty in predicting meatweight recovery is incorporated by selecting one of the 13 seasonal averages for each bootstrap estimate of start-of-season recruited biomass (in greenweight).

3.2.4 2010 survey results

3.2.4.1 Coromandel fishery at the time of the survey (May 2010)

During the Coromandel survey, 19 784 of 43 904 scallops caught in 138 valid tows (sweeping an estimated 0.177 km^2) were measured (made up of the entire catch at 93 stations and 45 subsamples). Approximate pooled length frequency distributions corrected for dredge efficiency (by assuming historical average efficiency for each substrate type) and scaled to estimated population size were constructed for the total population of the fishery area surveyed (Figure 3) and the five major fishery regions (Figure 4). Overall, the population at the time of the survey (Figure 3) was dominated by pre-recruit scallops (89 mm or smaller), but still showed a good proportion of recruits (90 mm or more). The shape of the population length frequency distribution was similar to that in 2009 (Williams et al. 2010), except in 2010 there were greater proportions of scallops in the 20 to 50 mm and 60 to 75 mm size ranges. The relatively high abundance of pre-recruit scallops just below the MLS at the time of the survey could suggest good levels of recruitment to the fishery during the 2010 season.

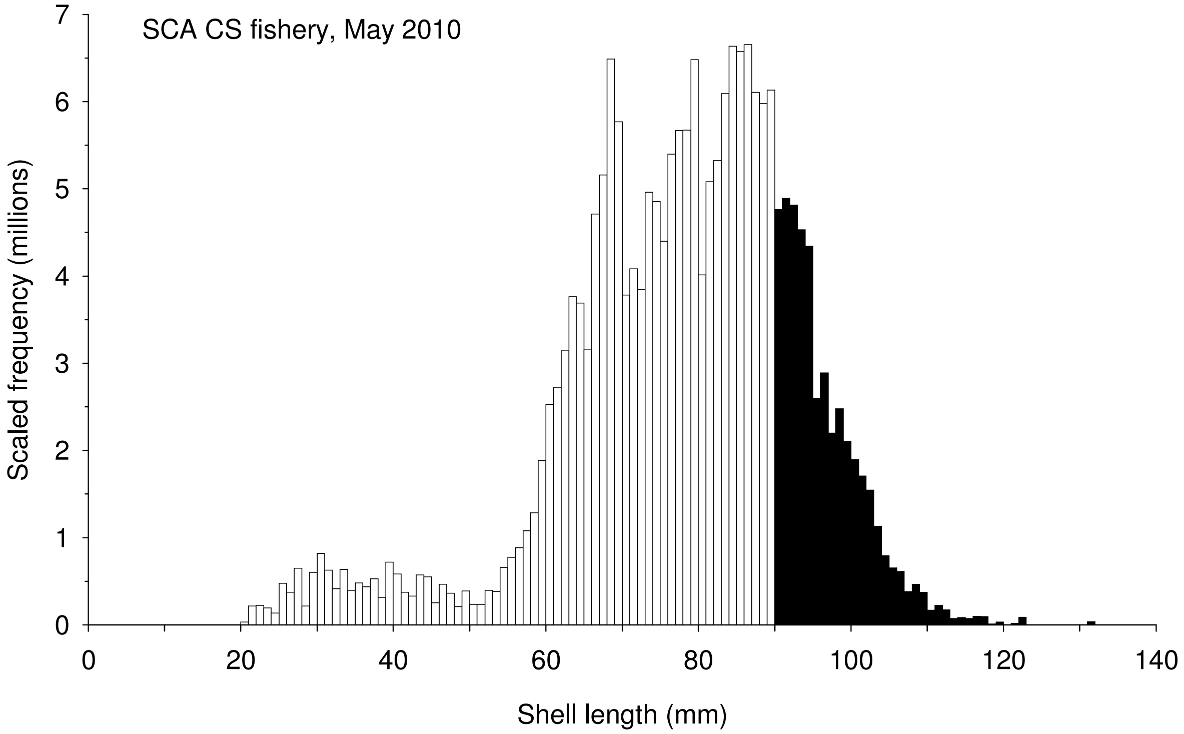

Figure 3: Length frequency distribution for the total population surveyed in the Coromandel fishery (corrected for historical average dredge efficiency), May 2010. Black bars show scallops larger than 90 mm shell length (the MLS for scallops taken commercially from the Coromandel fishery).

Examination of the length frequency distributions for each of the five main regions of the Coromandel fishery (Figure 4) shows the largest population of recruited scallops was found at the Mercury Islands, the recent mainstay of the fishery, which held about 62% of the total recruited population (scallops 90 mm or more shell length). Little Barrier scallop beds held about 21% of the total recruited population, a considerable amount considering their relatively small area, and the other regions held minimal amounts. The beds at Little Barrier, Mercury, and Colville had relatively higher proportions of large scallops than those at Waiheke and the Bay of Plenty which were dominated by very high proportions of pre-recruits, particularly in the 60–89 mm size range. There were good proportions of pre-recruits in all beds, including a notable cohort in the 20–50 mm size range.

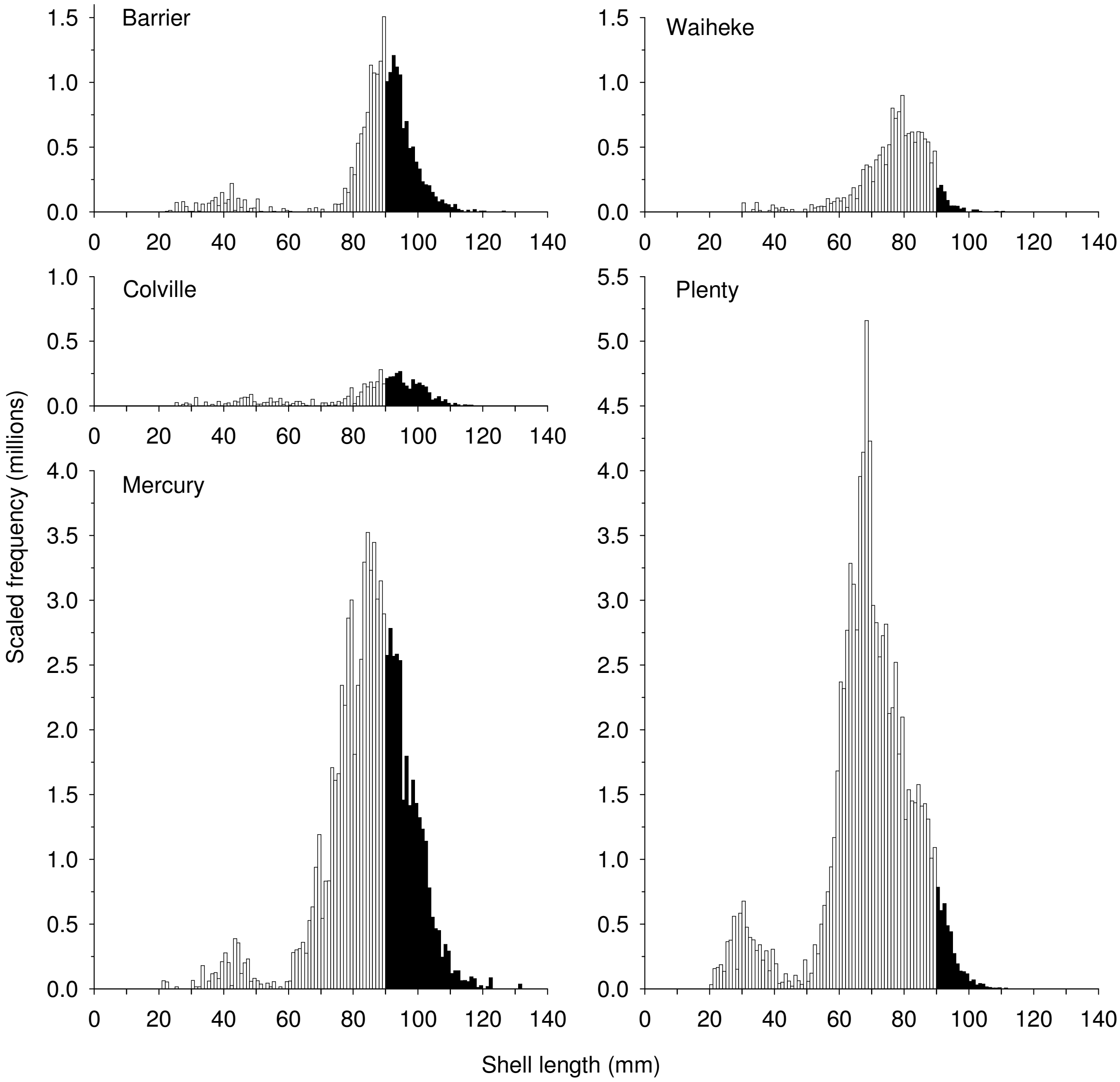

Figure 4: Length frequency distributions for the five major regions of the Coromandel fishery (corrected for historical average dredge efficiency), May 2010. Black bars show scallops larger than 90 mm shell length (the MLS for scallops taken commercially from the Coromandel fishery).

Using a standard parametric approach to estimation (including simple size-dependent scalars to correct for dredge efficiency), the greenweight biomass of scallops of 90 mm shell length or more at the time of the survey was 945 t (no correction for dredge efficiency, Appendix 4) or 3711 t (corrected using historical average efficiency, Appendix 5) with c.v.s of 7% for both estimates. These biomass estimates are reliable, but their uncertainty is grossly underestimated because this simple approach cannot incorporate additional variability associated with dredge efficiency. The biomass estimates in Appendix 4 (i.e., those with no correction for dredge efficiency) are the most conservative interpretation of the survey data possible and might be interpreted as the minimum absolute biomass at the time of the survey.

A more sophisticated 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. 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 the dredge efficiency scalars and length-weight regression, produced density, abundance, and biomass estimates (Table 3) very similar to those from the simple parametric approach (Appendix 5), but with higher c.v.s. For example, the time of survey recruited biomass estimate was 3671 t greenweight (median value; 95%CI = 2559–5228 t) with a c.v. of 19%. The frequency distribution of the 1000 bootstrap estimates (Figure 5) was slightly positively skewed, but not markedly so.

Table 3: Summary statistics for the population of scallops 90 mm shell length or more in the Coromandel fishery at the time of the survey (May 2010), assuming historical average dredge efficiency. 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	4.2	13	2.37	0.26	2.31	1.37–3.76	9.9	0.26	9.6	5.7–15.7
Colville	7.6	12	0.38	0.53	0.34	0.12–0.84	2.9	0.53	2.6	0.9–6.4
Waiheke	14.9	20	0.06	0.46	0.05	0.02–0.11	0.9	0.46	0.8	0.3–1.7
Mercury	63.3	57	0.45	0.20	0.44	0.30–0.64	28.4	0.20	28.0	19.3–40.3
Plenty	59.3	36	0.07	0.34	0.07	0.03–0.12	4.1	0.34	3.9	2.0–7.1
Fishery	149.4	138	0.31	0.19	0.31	0.21–0.44	46.1	0.19	45.6	31.1–65.2

Region	Area	Tows	Biomass (t green)			
	(km^2)	*n*	mean	c.v.	median	95%CI
Barrier	4.2	13	779	0.25	764	456–1207
Colville	7.6	12	241	0.52	219	73–531
Waiheke	14.9	20	63	0.46	59	25–120
Mercury	63.3	57	2334	0.19	2299	1606–3288
Plenty	59.3	36	305	0.34	291	147–533
Fishery	149.4	138	3721	0.19	3671	2559–5228

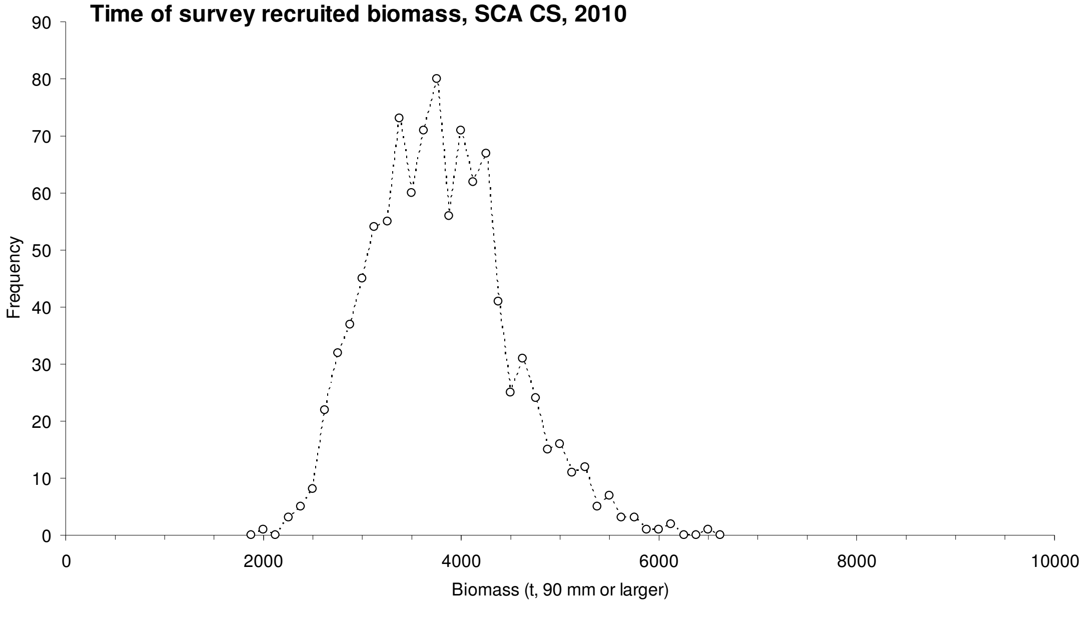

Figure 5: Frequency distribution of the estimated recruited biomass (t greenweight, scallops 90 mm or larger) in the Coromandel fishery at the time of the survey (mid May 2010). The distribution shows the results of a completely non-parametric re-sampling approach to estimating biomass (1000 bootstraps).

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 (Table 4). 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 (Figure 6, Figure 7, and Figure 8). There has been a gradual decline in the overall recruited population since the peak in 2005, but in 2010 this downward trend appears to have stalled. The status of the recruited population in 2010 appears to be similar to that in 2009, and again most of the fishable biomass is held in the Mercury beds, but with high densities of recruits in beds at Little Barrier.

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. Survey data were analysed using a non-parametric re-sampling with replacement approach to estimation (1000 bootstraps). Figures are not necessarily directly comparable among 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 (km^2)
	Barrier	Waiheke	Colville	Mercury	Plenty	Total	
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

Year	Biomass (t green)						Area (km^2)
	Barrier	Waiheke	Colville	Mercury	Plenty	Total	
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

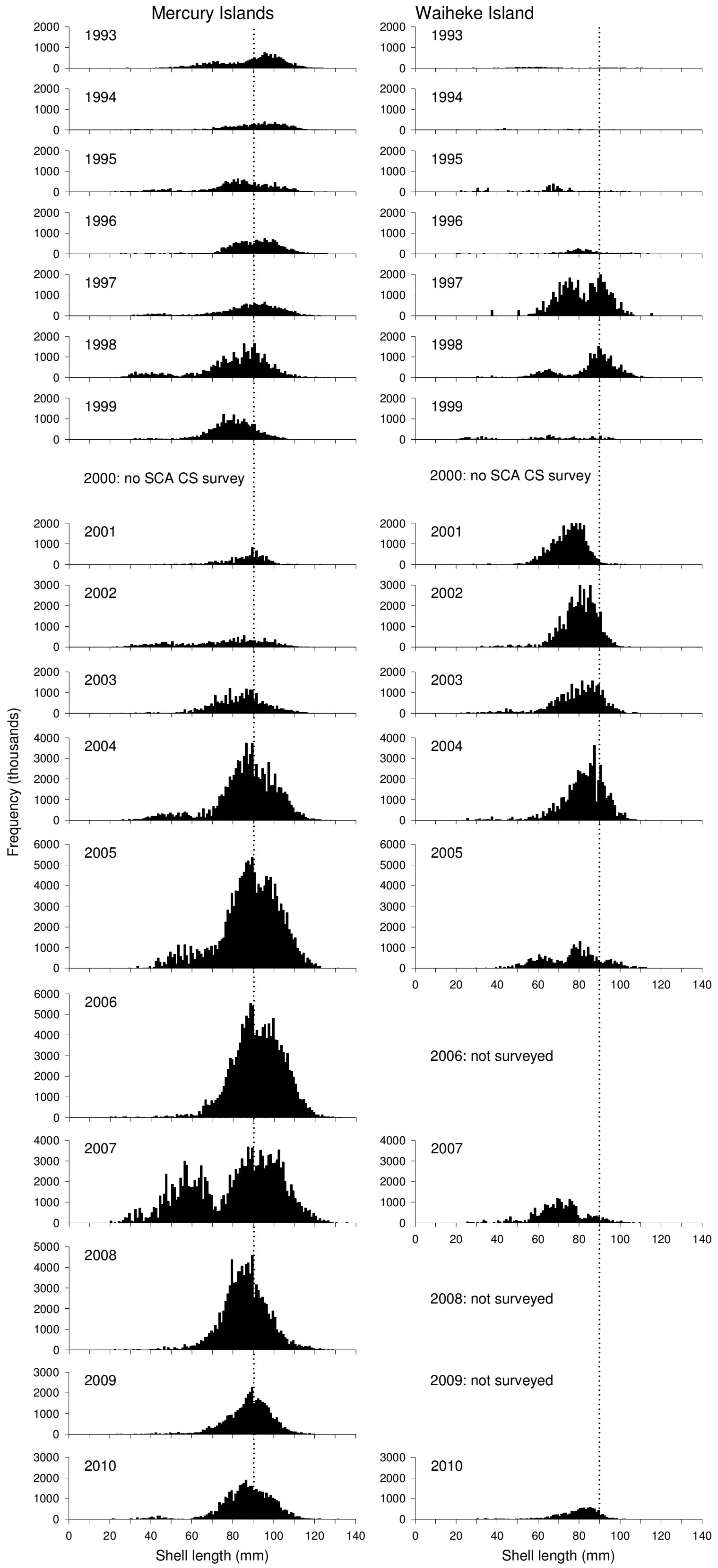

Figure 6: Scaled length frequency distributions at the time of surveys assuming historical average dredge efficiency (applied using the simple scalars reported by Cryer & Parkinson (2002)) for scallops in the Coromandel fishery at the Mercury Islands (left) and Waiheke Island (right) since 1993. The fishery was not surveyed in 2000, 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.

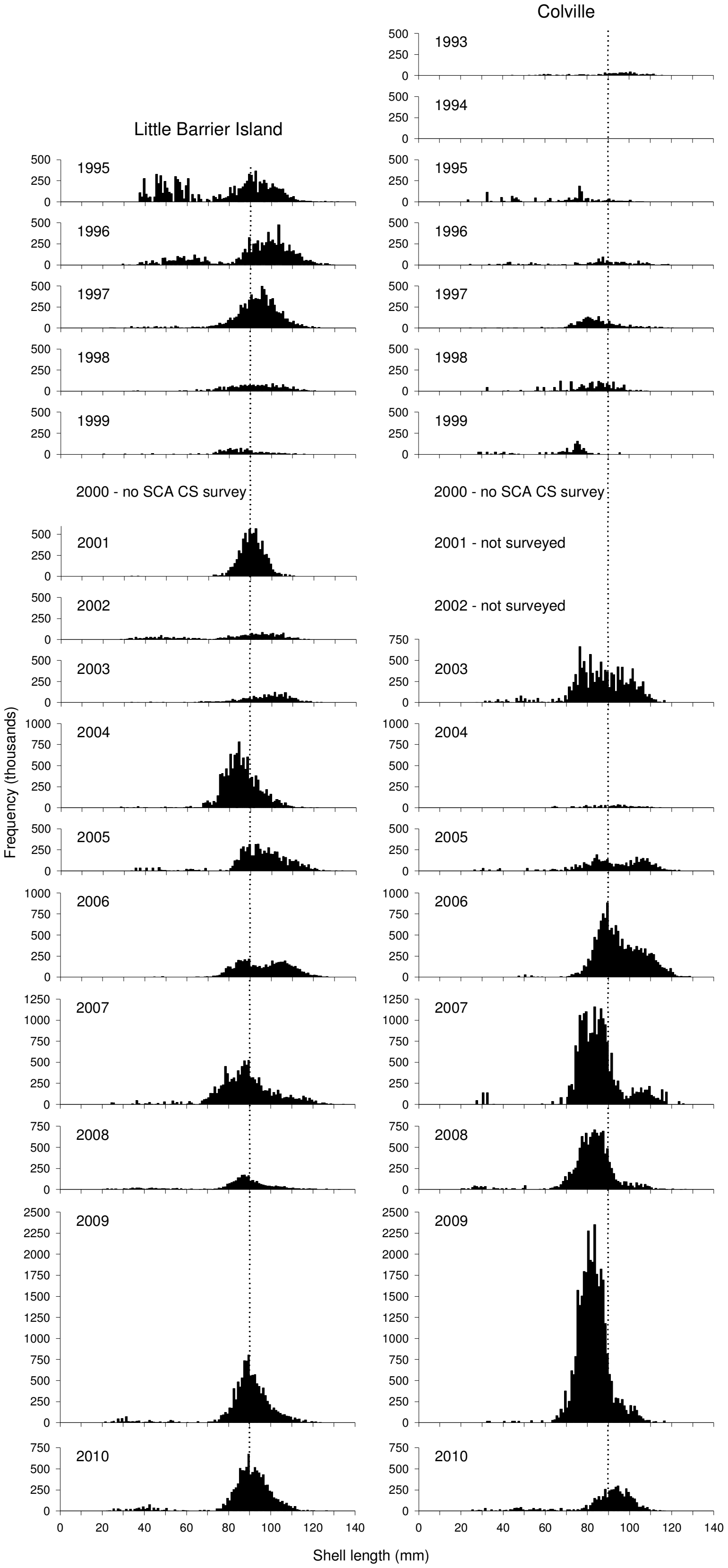

Figure 7: Scaled length frequency distributions at the time of surveys assuming historical average dredge efficiency (applied using the simple scalars reported by Cryer & Parkinson (2002)) for scallops in the Coromandel fishery at Little Barrier Island (left) and Colville (right) since 1993. The fishery 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.

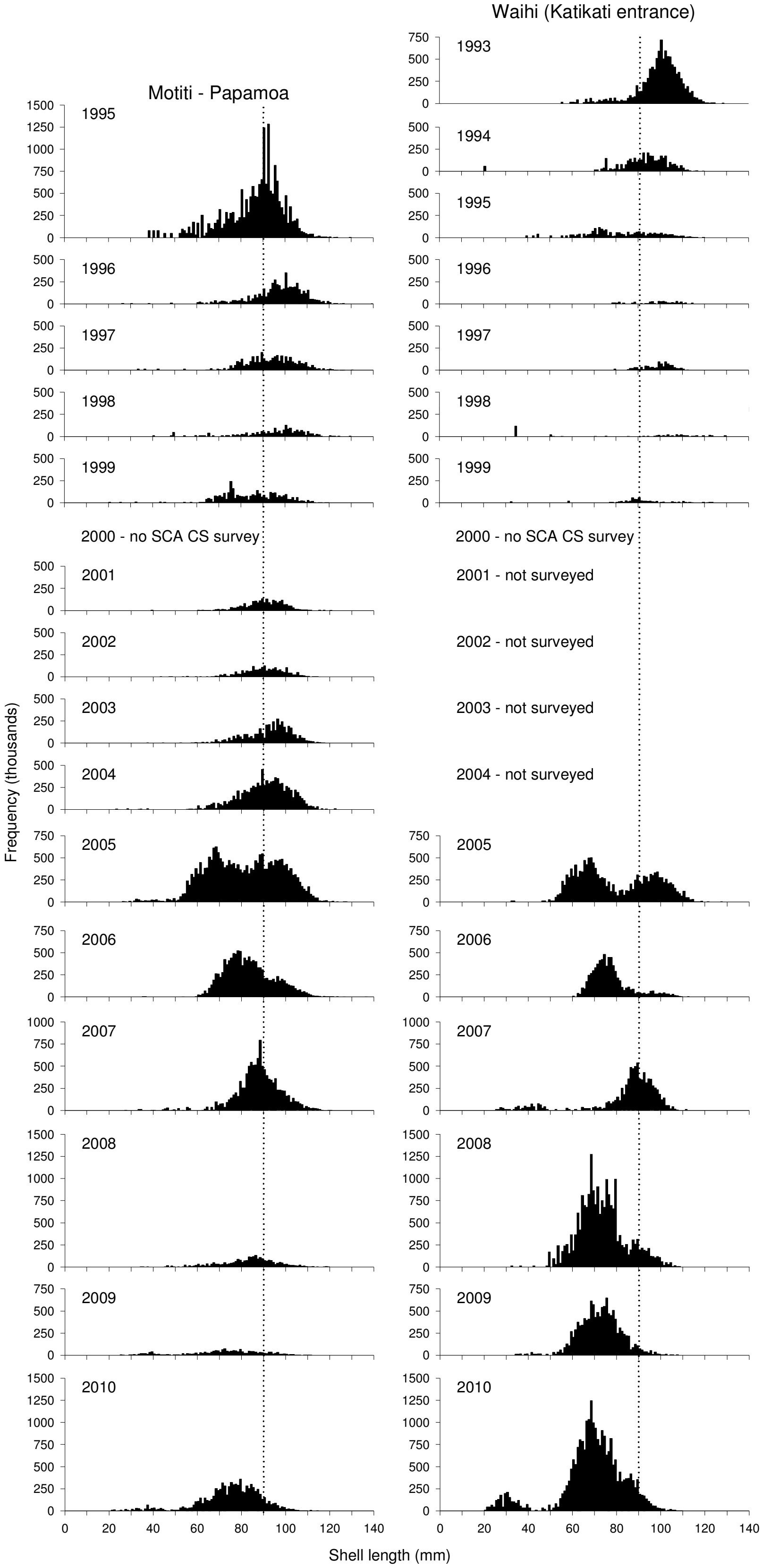

Figure 8: Scaled length frequency distributions at the time of surveys assuming historical average dredge efficiency (applied using the simple scalars reported by Cryer & Parkinson (2002)) for scallops in the Bay of Plenty region of the Coromandel fishery at Motiti-Papamoa (left) and Waihi (right) since 1993. The SCA CS fishery 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 100 mm shell length.

3.2.4.3 Predicting start-of-season biomass in the Coromandel fishery

The projected biomass of scallops 90 mm shell length or more at the start of the season (15 July 2010) was estimated using resampling with replacement, assuming historical average dredge efficiency at length, average growth (from previous tagging studies), and $M = 0.5$ spread evenly through the year. This approach produced an estimated start of season biomass of 4442 t greenweight (median projected value; 95% CI = 3101–6469) with a c.v. of 19% (Table 5). Further, assuming historical (1998 to 2009) average recovery of meatweight from greenweight led to an estimate of 540 t meatweight (median projected value; 95% CI = 370–825) with a c.v. of 22% (Table 5). These estimates represent an increase of about 21% in recruited biomass between survey and season (Figure 9). The average weight of a recruited scallop in Coromandel in 2010 was projected to decline from about 80 g at the time of the survey to 75 g by the start of the season. Together, these results could be explained by the predicted growth and survival of about 13 million pre-recruit scallops (just smaller than 90 mm) from the time of the survey to recruit into the fishable biomass by the start of the season. Further growth of pre-recruit scallops during the 2010 season could see additional recruitment to the fishable biomass.

Table 5: 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, average growth, $M = 0.5$, 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	4.2	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
Waiheke	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
Fishery	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	535–1398	112	0.28	107	61–185
Colville	7.6	12	264	0.51	234	92–577	33	0.56	29	11–73
Waiheke	14.9	20	145	0.51	130	48–330	18	0.52	16	6–41
Mercury	63.3	57	2690	0.19	2655	1830–3789	331	0.23	321	210–508
Plenty	59.3	36	486	0.31	469	246–833	60	0.34	57	28–104
Fishery	149.4	138	4504	0.19	4442	3101–6469	553	0.21	540	370–825

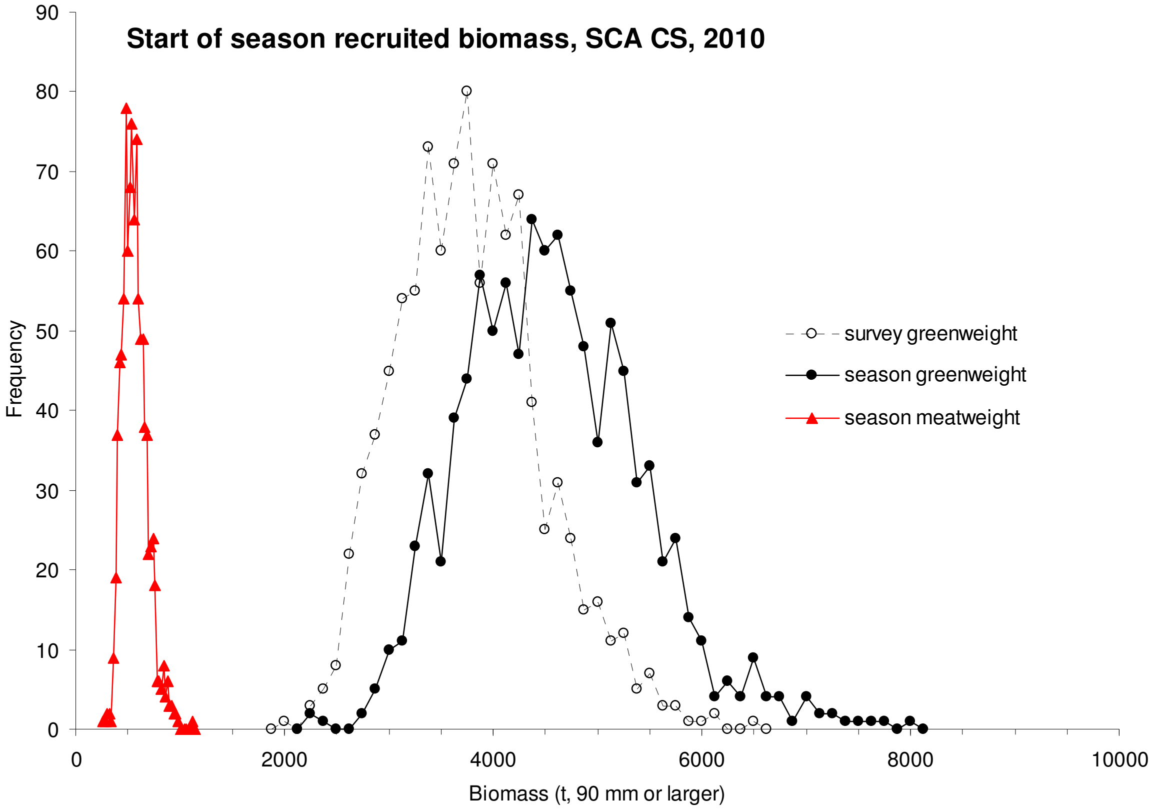

Figure 9: Frequency distributions of estimated recruited biomass (90 mm or larger) in the Coromandel fishery at the start of the season (mid July 2010). The results of a completely non-parametric re-sampling and projection approach are shown for the start of the season in t greenweight (closed circles, solid line) and meatweight (closed triangles, solid line). The results of the time of survey analysis in t greenweight (open circles, dashed line) are also 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 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 limit of acceptable fishing. Working at a station level, therefore, 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}. These “critical density” corrections were applied before any scaling for dredge efficiency, so they are conservative. 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 fishery-wide estimate of recruited biomass at the start of the season of 373 t meatweight (c.v. = 22%), a reduction of 31% on the absolute estimate (Figure 10). Excluding areas where the density was less than 0.08 m^{-2} reduced the fishery-wide biomass estimate by about 48%, and by 72% for a critical density of 0.20 m^{-2}.

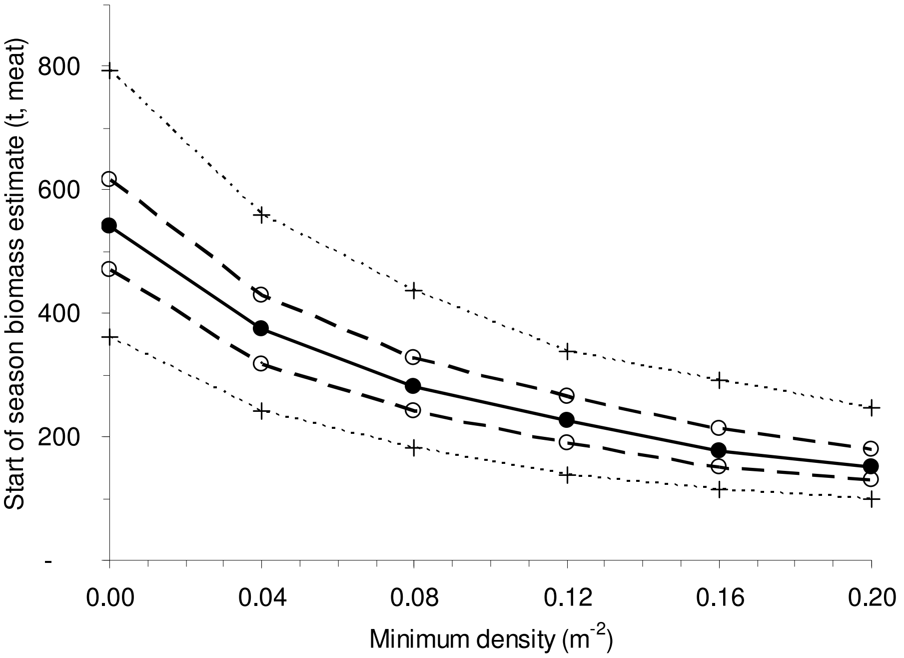

Figure 10: Effect of excluding areas of low scallop density on the fishery-wide estimate of recruited biomass (t meatweight) in the Coromandel fishery at the start of the season (15 July 2010). For increasing minimum acceptable densities (unscaled for dredge efficiency) the median biomass estimates (solid line, closed circles) corrected for average historical dredge efficiency are given together with their quartiles (dashed lines) and 95% confidence range (dotted lines).

The effect of excluding areas of low density from biomass estimates was dramatic in the Waiheke and Bay of Plenty beds (Figure 11), where estimates declined by 78% and 86%, respectively, when areas where scallops were less dense than 0.04 m^{-2} were excluded. Thus, virtually all of the biomass in the Waiheke and Bay of Plenty beds appeared to be contained in areas of low density where catch rates may not be very good. However, the Waiheke and Bay of Plenty beds contained only 10% of the total biomass of the Coromandel fishery in 2010.

Where the mean density of recruited scallops was high (Little Barrier Island, Colville, and Mercury), the biomass estimates were 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 exceptionally high, the biomass estimate declined by only 6%, whereas at Colville and the Mercury Islands, locations with reasonably high densities of scallops, the biomass estimate declined by 20 and 28%, respectively, when areas where scallops were less dense than 0.04 m^{-2} were excluded.

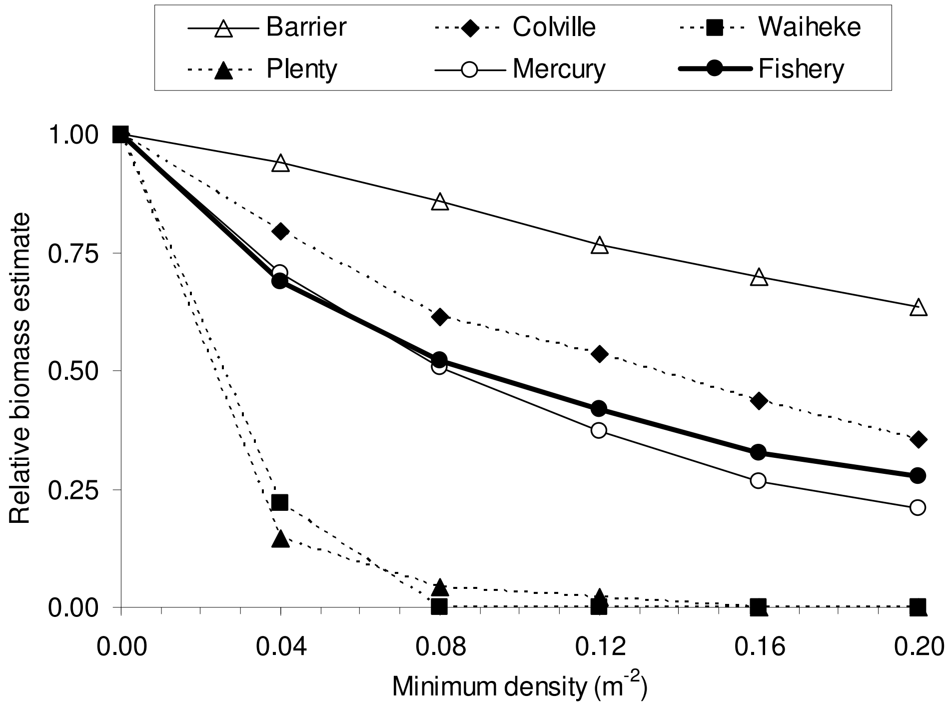

Figure 11: Effect of excluding areas of low scallop density on estimated recruited biomass by bed in the Coromandel fishery at the start of the season (15 July 2010). For increasing minimum acceptable densities (unscaled for dredge efficiency) the median biomass estimates (corrected for historical average dredge efficiency) for each area surveyed are given.

3.3 Biomass estimates

Estimates of current biomass are described above. In summary, using average values for important assumed variables, the recruited biomass of scallops 90 mm in shell length or greater at the start of the season (15 July 2010) in the Coromandel fishery was predicted to be 4442 t greenweight (95% confidence interval of 3101–6469 t, c.v. of 19%), or 540 t meatweight (95% confidence interval of 370–825 t, c.v. of 21%) (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 Ministry of Fisheries Shellfish Working Group recommend $F_{0.1}$ as the most appropriate reference rate (target) of fishing mortality for scallops.

3.4.2 Estimation of Maximum Constant Yield (MCY)

MCY is not normally estimated for scallops and, given the highly variable nature of most wild scallop fisheries, is likely to be close to zero. Cryer et al. (2003) showed that constant catch strategies for scallops produced lower yield at much higher biological risk than strategies wherein 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:

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

where $t = 5/12$ years, F_{ref} is a reference fishing mortality ($F_{0.1}$) and B_{jul} is the estimated 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 5 months of the fishing season, the length of the current Coromandel commercial scallop season. B_{jul} is estimated assuming historical average dredge efficiency at length, 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). 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 2010 start of season meatweight biomass estimate (540 t, median projected value), CAY for 2010–11 was estimated to be 172 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 2010 start of season meatweight biomass estimate (540 t, median projected value), CAY for 2010–11 was estimated to be 117 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 (21%), are sensitive to assumptions about dredge efficiency, growth, and expected recovery of meatweight from greenweight, and relate to the surveyed beds only. These yield estimates are also sensitive to excluding areas of low density; excluding stations with scallop density less than 0.04 m^{-2} and 0.2 m^{-2} reduced the fishery-wide start of season biomass estimate by about 31% and 72%, respectively, so the calculated CAY would be reduced by the same amounts. 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). 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.

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 (e.g., using a confidence interval). One way to do this is to decide how confident one wishes to be that a particular CAY will not cause fishing mortality to exceed $F_{0.1}$. For example, a range of one-sided confidence intervals can be formed for CAY at different levels of confidence; the lower limit of each interval is the potential catch limit which gives the specified level of confidence that $F_{0.1}$ will not be exceeded (Table 6).

Table 6: Decision table to evaluate the confidence of not exceeding $F_{0.1}$ given a variety of alternative catch limits for the 2010–11 Coromandel fishing season. $F_{0.1}$ was estimated using two approaches: 1) including direct incidental effects of fishing only, and 2) including direct and indirect incidental effects of fishing.

Potential catch limit	Confidence (%) that fishing mortality is less than $F_{0.1}$	
(t meatweight)	$F_{0.1}$ direct effects	$F_{0.1}$ direct and indirect effects
50	100.0	100.0
60	100.0	99.8
70	100.0	99.4
80	99.9	97.6
90	99.8	90.0
100	99.4	78.1
110	99.1	62.4
120	97.0	45.2
130	91.3	31.5
140	83.6	20.3
150	73.8	12.0
160	63.4	6.9
170	52.7	4.0

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. Annual pre-season research surveys are required to estimate recruited biomass to calculate CAY. Commercial catch limits can be adjusted each survey year following a review of the survey results and stock assessment, and after consultation with fishery stakeholders.

Estimates of current biomass are available from the May 2010 dredge survey of SCA CS. Using average values for important assumed variables, the absolute recruited biomass at the start of the season (15 July 2010) was predicted to be 540 t meatweight (95% confidence interval = 370–825 t; c.v. = 21%), although excluding areas of low scallop density reduced this estimate by 31–72%. Most of the recruited population was found in the Mercury and Little Barrier regions of the fishery where scallop densities were highest, with minimal numbers of recruits in other regions. These results are similar to those of the 2009 biomass survey and assessment, and suggest the decline in recruited biomass observed since about 2005–06 appears to have stalled. Historical catch levels and biomass estimates suggest 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 2010–11 is 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.

Substantial 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 stock assessment. The findings of current research projects on modelling scallop dredge efficiency and investigating factors influencing scallop growth should help to reduce these uncertainties.

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Appendix 1: Sampling design, stratum definitions, and station (tow) allocations used for the 2010 dredge survey of the Coromandel scallop fishery. After detailed consultation with fishers, only areas expected to contain commercial densities of scallops and be amenable to fishing were included. Areas closed to commercial fishing were excluded.

Region	Stratum name	Code	Area (m^2)	Substrate	# stations	Stns/km^2
Little Barrier	Little Barrier West	18	1 361 542	sand	5	3.67
	Little Barrier South	19	2 802 673	sand	8	2.85
Colville	Colville South (shallow)	31	7 634 644	mud/silt	12	1.57
Waiheke	Hooks	20	4 201 172	mud/silt	8	1.90
	Tarahiki	21	10 708 618	mud/silt	12	1.12
Mercury Islands	Mercury Cove	4	2 863 844	mud/silt	3	1.05
	Three Mile Bank	2	4 924 946	sand	6	1.22
	Bumper Cove	43	1 210 602	sand	3	2.48
	Kennedy	41	19 199 951	sand	14	0.73
	Kennedy West	41.1	3 035 889	sand	3	0.99
	Blackjack	1	25 421 875	sand	19	0.75
	Blackjack West	1.1	2 843 018	sand	3	1.06
	Sarah's Gully	42	1 906 738	sand	3	1.57
	Opito Bay	3	1 896 500	sand	3	1.58
Bay of Plenty	Waihi(Katikati entrance)	11	47 210 938	sand	16	0.34
	Papamoa Beach	14	4 505 615	sand	8	1.78
	Motiti (The Knoll)	13	7 580 078	sand	12	1.58
Total	17 strata	–	149 308 643	–	138	1.57

Appendix 2: Bycatch

Data on bycatch during the 2010 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

Methods

The bycatch sampling methodology developed in 2009 (Williams et al. 2010) was used again in 2010. 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.

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 & *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 randomly allocated within predefined survey strata (see Figure 2). The survey strata were agreed with commercial Coromandel scallop fishers prior to the survey, to represent the area likely to be fished in the following season. Therefore, the areas fished can be considered to be generally representative of the scallop grounds in the region, but 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 2010 survey of SCA CS were loaded to the MFish 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 3: Estimated average recovery (%) of meatweight from greenweight for Coromandel scallop seasons 1995–2009. Values for 1995–2002 were estimated by Cryer & Parkinson (2006), based on the ratio of actual measured meatweight (reported on the bottom half of CELRs) to estimated greenweight (often reported on the top half of CELRs), screened to remove extreme outliers (recovery <5% or >30%). Values for 2004–2009 were estimated in the present study, based on the ratio of measured meatweight to measured greenweight, using data supplied by the Coromandel fishery's principal processor of scallops (Whangamata Seafoods Ltd.). –, no estimate.

Year	Recovery (%)
1995	13.7
1996	13.7
1997	12.9
1998	–
1999	10.4
2000	9.9
2001	12.5
2002	15.6
2003	–
2004	12.4
2005	12.4
2006	12.1
2007	10.3
2008	11.4
2009	11.6

Appendix 4: Standard parametric estimates of density and biomass of scallops 90 mm shell length or more at the time of the 2010 Coromandel survey, assuming 100% dredge efficiency.

Region	Area (km^2)	*n*	Density (m^{-2})	SEM	c.v.	Abundance (millions)	Scallop weight (g)	Biomass (g m^{-2})	SEM	c.v.	Biomass (t green)
Barrier	4.16	13	0.53	0.08	0.14	2.19	81.10	42.66	6.09	0.14	178
Colville	7.63	12	0.14	0.05	0.38	1.06	81.17	11.28	4.18	0.37	86
Waiheke	14.91	20	0.02	0.01	0.25	0.32	72.67	1.56	0.40	0.26	23
Mercury	63.35	57	0.11	0.01	0.08	7.14	83.45	9.41	0.75	0.08	596
Plenty	59.30	36	0.01	0.00	0.24	0.83	75.69	1.06	0.26	0.24	63
SCA CS	149.35	138	0.08	0.01	0.07	11.54	81.94	6.33	0.43	0.07	945

Appendix 5: Standard parametric estimates of density and biomass of scallops 90 mm shell length or more at the time of the 2010 Coromandel survey, assuming historical average dredge efficiency (but not including variance associated with dredge efficiency).

Region	Area (km^2)	*n*	Density (m^{-2})	SEM	c.v.	Abundance (millions)	Scallop weight (g)	Biomass (g m^{-2})	SEM	c.v.	Biomass (t green)
Barrier	4.16	13	2.37	0.35	0.15	9.89	78.35	186.04	26.98	0.15	775
Colville	7.63	12	0.39	0.14	0.37	2.96	82.31	31.89	11.57	0.36	243
Waiheke	14.91	20	0.06	0.01	0.25	0.87	72.73	4.24	1.08	0.25	63
Mercury	63.35	57	0.45	0.04	0.08	28.51	81.52	36.69	3.06	0.08	2 324
Plenty	59.30	36	0.07	0.02	0.23	4.12	74.09	5.15	1.21	0.24	305
SCA CS	149.35	138	0.31	0.02	0.07	46.34	80.07	24.84	1.69	0.07	3 711