



Dredge survey and stock assessment for the Coromandel scallop fishery, 2003

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**Final Research Report for
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Objectives 1 & 2**

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7. **Executive Summary:**

A dredge survey for scallops were carried out in the Coromandel fishery in May 2003. Many strata and parts of strata thought by fishers unlikely to support commercial fishing in 2002 and all areas closed to commercial fishing were excluded. Biomass estimates at the time of the survey and start of the season were made using the area swept method “corrected” using two different analytical approaches. The first method (in use since 1997) applies a constant dredge efficiency scalar (with associated variance) for all scallops likely to recruit to the fishery, and predicts start of season biomass using deterministic, knife-edged “critical sizes”, and deterministic scalars for average survival and average recovery of meatweight from greenweight. The revised method (developed following review of the 2002 stock assessment) applies stochastic size-dependent dredge efficiency scalars and predicts start of season biomass using a stochastic growth transition matrix, and stochastic scalars for average survival and average recovery of meatweight from greenweight. These biomass estimates are considered to be estimates of absolute biomass.

Absolute start-of-season biomass over 100 mm shell length (for comparison with previous surveys) was predicted to be 601 t greenweight (81 t meatweight) with a standard error of about 19% (estimated by simulation). This is a substantial improvement on the 2001 and 2002 survey results and is about average for estimates made since 1995 (though below average for estimates made before 1995). Including all scallops likely to be over the commercial minimum legal size of 90 mm by the start of the season increased this estimate to 1224 t greenweight (165 t meatweight) with a standard error of about 18% of the mean. Yield (as CAY) is estimated for the 2003 season to be 60 t meatweight (using $F_{0.1}$ or $F_{40\%}$), assuming dredge efficiency equal to the highest experimental estimate in the fishery for each substrate, and 13.5% average recovery of meatweight from greenweight.

The revised analytical approach generates slightly higher estimates of start-of-season biomass, largely as a result of the different treatment of dredge efficiency. However, predicted meatweight biomass and yield using the revised approach have wide confidence bounds and the projections are likely to be optimistic in years where conditions for scallop growth and survival are poor.

8. Objectives:

Overall Objectives:

1. To carry out a stock assessment of scallops (*Pecten novaezelandiae*) in the Coromandel fishery, including estimating abundance and sustainable yields.

Specific Objectives:

1. To estimate the absolute abundance and population size frequency of scallops in the main scallop beds around mid-May 2003. The target coefficient of variation (c.v.) of the estimate of absolute recruited abundance is 20%.
2. To estimate yield following the completion of the survey described in Objective 1.

9. Methods:

9.1 General

This report describes dredge surveys for scallops (*Pecten novaezelandiae*) carried out in the Coromandel fishery under contract to the Ministry of Fisheries (project SCA2002/01). Surveys were conducted almost annually between 1978 and 1999, with coverage of the fishery increasing with time. Survey designs incorporating both dive and dredge components were refined over the years using historical survey data, catch-effort information, a review of optimisation procedures, and discussions with managers and fishers. There was no survey in 2000, but dredge-only surveys were conducted in 2001 and 2002.

Between 1992 and 1994, survey results were used to estimate Provisional Yield (PY, after a method by Cryer, 1994) and set catch limits for the Coromandel fishery. The minimum legal size (MLS) for scallops taken commercially in the Coromandel fishery was reduced from 100 to 90 mm at the start of the 1995 season, but remained at 100 mm for amateur fishers. The management plan (for the 1995 to 1997 seasons) adopted an assessment regime whereby the available yield was calculated using Provisional Yield (PY) based on the abundance and biomass of scallops greater than 100 mm shell length, pending research into more appropriate methods. This research was completed in late 1997 when the management plan expired. A more typical "Current Annual Yield" (CAY) yield estimator was adopted in 1998, based on predicted start-of-season recruited biomass and estimates of reference fishing mortality incorporating incidental effects of the dredge method on scallop growth and mortality (Cryer & Morrison 1997).

For poorly understood reasons, biomass and catches from the fishery have been very low since about 1998 (Cryer 2001a). Low biomass has coincided with poor condition, “black gill” syndrome (Diggles et al. 2000), and a rapid increase (since 1996) of the filter-feeding tubeworm *Chaetopterus* sp. on many of the beds. *Chaetopterus* sp. builds large clumps of parchment-like tubes and renders dredging for scallops impossible (because the dredge fills with tubes and therefore cannot catch scallops). There may have been catastrophic mortality of scallops on some beds (Cryer 2001b), but the role played by the expansion of *Chaetopterus* sp. is not known, despite some (not all) anecdotal reports that scallops do not survive where *Chaetopterus* sp. is abundant. The causes of these apparently major changes to the ecology of the Coromandel fishery remain unclear.

The principal aim of the 2003 survey work was to estimate the absolute abundance of scallops by size class on those beds of the Coromandel fishery likely to support successful commercial fishing in the 2003 season. Recruited biomass at the start of the forthcoming season (15 July of each year) can then be predicted in greenweight and meatweight using information on growth, mortality, and likely condition during the season. Estimates of yield are derived using the start-of-season biomass estimates and reference rates of fishing mortality from stochastic yield-per-recruit and egg-per-recruit models (Cryer & Morrison 1997).

9.2 Survey methods

Surveys were conducted in May 2003. The choice of an appropriate time for surveys entails balancing the conflicting pressures of operational ease and uncertainty in the results. Early surveys 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 occurrence. Surveys undertaken later in the year 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 impact 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.

All sampling for the 2003 surveys was undertaken by dredge and no diving to estimate dredge efficiency was done. Single phase stratified random sampling was undertaken in 14 strata: Waiheke Island (one stratum), Colville (two strata), Little Barrier Island (two strata), Mercury Islands (seven strata), and Motiti Island to Papamoa (two strata). After excluding strata thought unlikely to be productive in 2003 and areas closed to commercial fishing, the total sampled area in 2003 was 130 km², compared with 119 km² in 2002, 125 km² in 2001, and 253–341 km² between 1996 and 1999, Figure 2; Appendix 2).

The survey was not formally optimised to minimise the predicted c.v. of the estimate of recruited biomass for two main reasons. First, some strata were redesigned for 2003 surveys in response to major changes in the fishery performance and invasive *Chaetopterus* tubeworms that preclude survey by dredge. Second, time constraints on the surveys 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). Strata that were sufficiently

close together to tackle in a single day (e.g., those at the Mercury Islands) were grouped. Up to about 25 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 qualitative 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.

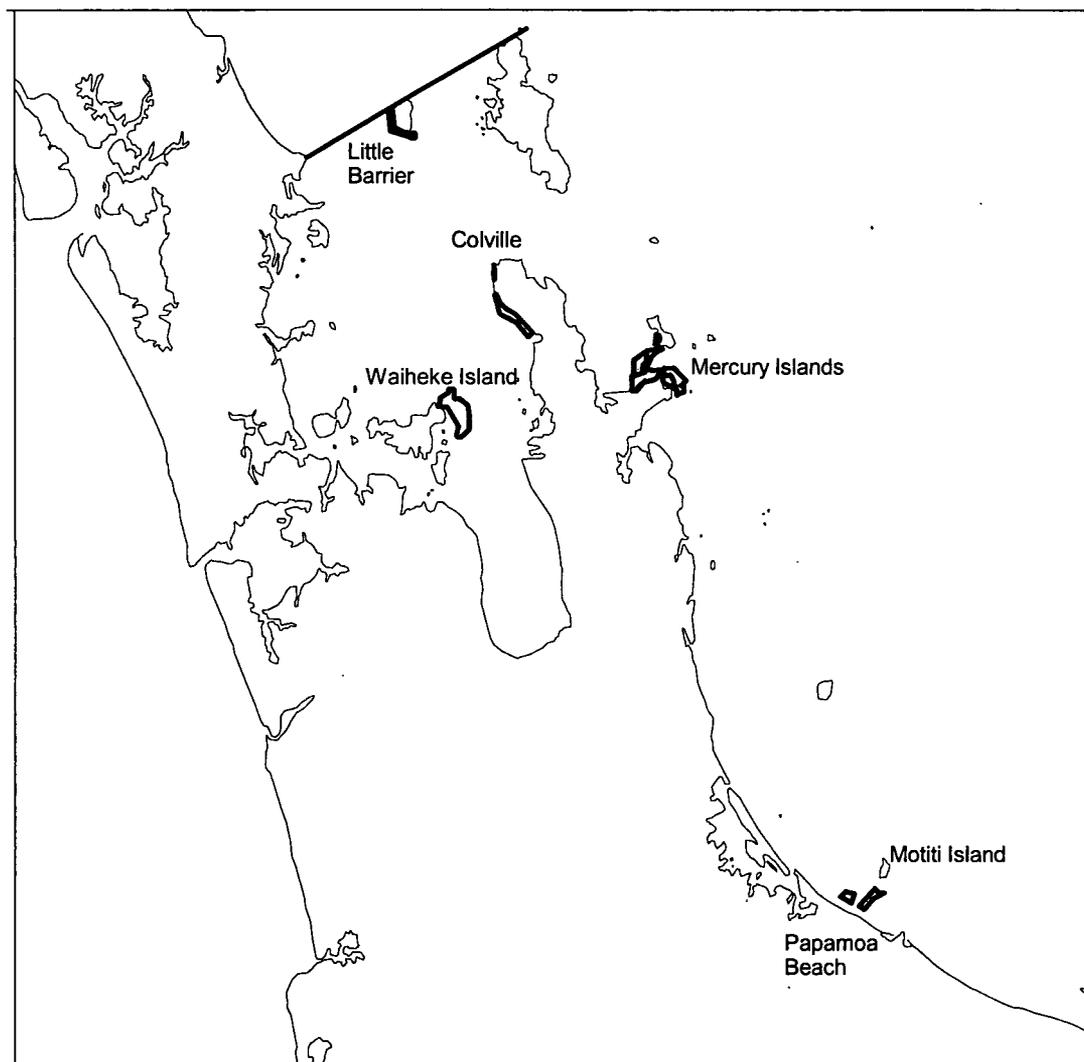


Figure 1: Location of strata for the survey of the Coromandel scallop fishery in 2002. Groups of strata are labelled with geographic descriptions used in the text (see Appendix 1 for details and stratum areas).

Dredging was undertaken from the chartered commercial dredge vessel *Evelyn J.* (whose dredge has a width of 2.34 m for which dredge efficiency has never been estimated). The skipper's brief was 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 detritus or scallops, 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. Occasionally, 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.

9.3 Estimating and correcting for dredge efficiency

Work on estimating the efficiency of toothed (or “tined”) scallop dredges started in Europe in the 1950s (Baird 1955, 1959, Baird & Gibson 1956) and in Canada in the 1960s (Caddy 1968, 1971). The efficiency of dredges in common use was found to be very low, leading to the development of more efficient gear such as the “Baird” dredge whose efficiency for scallops close to the minimum legal size (MLS) was found to be 24–33% (Rolfe 1969). Zacharin (1988), however, found the efficiency of Australian variants of the Baird dredge to have an efficiency of less than 10%, and McLoughlin *et al.* (1993) described attempts by the Australian industry and researchers to find more efficient and less damaging alternatives. Chapman *et al.* (1977) studied spring-loaded dredges used in Scottish fisheries and found their efficiency to be about 13% for scallops close to MLS, whereas “standard” dredges with a fixed tooth-bar were about 20% efficient. They found small scallops to be caught with very low efficiency (<5%) by all dredge designs, and efficiency for very large scallops sometimes to be low compared with scallops close to MLS. Chapman *et al.* (*op.cit.*) also reported that dredge efficiency varied with substrate type.

Dredges have been used to survey a wide variety of relatively sessile, soft-sediment invertebrates including oysters (Allen & Cranfield 1979, Chai *et al.* 1992, Doonan *et al.* 1994), crabs (Stagg & Abbe 1996, Voelstad *et al.* 2000), whelks (Stoner *et al.* 1998), and surf clams and other burrowing bivalves (Michael *et al.* 1990, Thorarinsdottir & Einarsson 1996, Gaspar *et al.* 1999), as well as scallops (e.g., Rudders *et al.* 2000, Weinberg *et al.* 2000). Dare *et al.* (1993, 1994) examined the efficiency of research and commercial dredges used in biomass surveys for stock assessments in the English Channel and found the two to be comparable. Average efficiency for scallops close to MLS was about 30%, being lower for very large scallops and much lower for very small scallops. Mason *et al.* (1979) found efficiency in Scottish surveys to be about 20% and attributed the low dredge efficiency to a mound of sediment collecting in the mouth of the dredge during towing. This sediment “block” resulted in further sediment and scallops being pushed out to the side of the dredge. Giguere & Brulotte (1994) found French survey dredges to be 8–19% efficient for scallops close to MLS based on comparisons with parallel video transects. In northern New Zealand, commercial box dredges have been used in stock assessments since the 1980s and estimates of efficiency close to the MLS have varied between ~10% and ~100% (e.g., Allan 1984; Cryer & Morrison 1997; Cryer & Parkinson 1999, 2001).

All strata in the 2003 survey were sampled by dredge and therefore required correction for sampling efficiency. Separate estimates of dredge efficiency have historically been used for sandy and silty or muddy substrates (Cryer & Parkinson 1999), although relatively fewer data have been collected on silty substrates. Unfortunately, all previous estimates of dredge efficiency and selectivity have been made using two very similar vessels (*L’Aries* and *Katarainā*), whereas recent surveys have been conducted using other vessels (e.g., *Betty* in 2002 and *Evelyn J.* in

2003). This introduces considerable un-measurable uncertainty and, in recent years, biomass has therefore been estimated using a range of different assumed rates of dredge efficiency for each substrate. These were 100% efficient, the highest previously recorded efficiency, the upper limit of a 95% confidence distribution of historical average efficiency, and the historical average efficiency (Table 1). Uncertainty about these assumed levels of efficiency was assumed to be zero at 100% efficient, and could be estimated using the *c.v.* of all historical estimates for the historical average efficiency, but could not be easily estimated for the other two approaches. A nominal *c.v.* of 20% was used in these cases. The statistical distribution of all dredge efficiency estimates was truncated at 100% (i.e., no efficiency estimates of >100% were allowed within bootstraps). Clearly, assuming 100% dredge efficiency is the most precautionary approach because observed density estimates are effectively un-scaled for dredge efficiency which is likely to be less than 100%. However, some estimates of dredge efficiency in Northland have been close to 100%. Adopting historical average dredge efficiency is the least precautionary approach because the vessel or dredge used may have been more efficient than those used previously.

Table 1: Scaling factors (“multipliers”) and their *c.v.*s used to correct for dredge efficiency for scallops of a size likely to recruit to the Coromandel fishery by the start of the season in July 2003. Four alternative approaches were used based on 100% efficiency, the highest recorded efficiency, the upper limit of a 95% confidence distribution of historical average efficiency, and the historical average efficiency for all survey vessels.

Assumption	Sandy substrates			Silty substrates		
	Efficiency	Multiplier	<i>c.v.</i>	Efficiency	Multiplier	<i>c.v.</i>
No scaling	100.0	1.000	0.0%	100.0	1.000	0.0%
Highest historical	77.0	1.300	20.0%	70.0	1.431	20.0%
Upper 95% limit	51.6	1.938	20.0%	45.3	2.207	20.0%
Historical average	41.0	2.437	10.2%	32.3	3.096	14.4%

In the past, length frequency distributions by stratum or “bed” have been corrected for dredge efficiency using size-dependent scalars assumed to have no error. These scalars were estimated by averaging the results of several historical dredge efficiency experiments (Table 2)

Table 2: Dredge multipliers applied to survey length frequency distributions between 1999 and 2002 to estimate population length frequency distributions in the Coromandel fishery. These multipliers are not necessarily those used to estimate recruited biomass

Length class (mm)	Sandy substrates	Silty substrates
< 60	6.689	7.955
60–69	5.626	6.690
70–79	4.562	5.425
80–89	3.500	4.162
≥ 90	2.437	3.096

This approach to correcting for dredge efficiency is weak because it assumes constant efficiency for all size classes likely to be part of the recruited biomass and the following analyses suggest that this assumption is not tenable.

Data were collated from 32 experiments where scallop density (by 5 mm size classes) was estimated by dredging and diving. Most of these experiments were conducted as adjuncts to surveys designed to estimate absolute biomass as part of annual stock assessments, but some data collected in 1995 were part of a project to assess the implications of incidental effects of dredging for fishery performance (Cryer & Morrison 1997). Twenty-four experiments were conducted in the Coromandel fishery (19 on sand, 5 on silt or mud), and eight were conducted in the Northland fishery (all on sandy substrates) (Table 3). Dredges were used (159 tows) to sweep a total area of 190 000 m² from which over 22 000 scallops were caught, and divers (227 dives) swept a total area of 30 000 m² catching almost 7 000 scallops. All dive-caught scallops were measured, and 94.6% of dredge-caught scallops (only four of 159 dredge tows were sub-sampled). Shell length was recorded in 5 mm classes for early surveys (e.g., 10–14.9 mm) but to the next whole millimetre below since 1991. Two experiments conducted off Great Mercury Island in 1991 and in Bream Bay in 1996 were excluded because of uncertainty over swept areas.

Table 3: Summary statistics (means with ranges) of dredge efficiency experiments used in this study.

	Northland	Coromandel sand	Coromandel silt
No. of experiments	8	19	5
No. of vessels	4	2	3
Mean depth	20.6 17–23	22.3 12–30	19.2 15–23
Mean number of dredge tows	6.1 3–10	2.9 2–4	11.0 4–20
Mean area swept by dredge	11 424 3 467–21 957	4 048 1 148–7 445	4 322 3 593–5 371
Mean no. scallops caught by dredge	664 146–1 193	415 83–938	1 797 377–4 129
Mean number of dive sites	10.3 7–16	4.8 2–9	10.6 3–16
Mean area swept by divers	1 977 1 128–3 217	602 245–1 731	552 67–1 431
Mean no. scallops caught by divers	218 27–477	180 12–435	335 147–547
Mean density of scallops >85 mm	0.083 0.014–0.183	0.264 0.011–1.162	0.874 0.082–1.543

Each experiment consisted of 2–20 dredge tows (mean 5.0) and 2–16 dive sites (mean 7.1). Basic units for re-sampling were these tows and dive sites, not individual scallops within them. Because area swept was variable for both dredge tows and dive sites within most experiments, and length was recorded with differing precision, all data were first standardised to estimated density per square metre in 5 mm size classes (10–14.9 mm, 15–19.9 mm, etc.). This approach entails an implicit assumption that all samples taken by the same method within an experiment are equivalent. Other approaches could be applied, giving more weight to samples in proportion to area swept or animals caught.

Within an experiment, the mean estimated density was calculated for each size class using each sampling method, and dredge efficiency for that size class in that experiment was estimated by dividing the density estimated by dredge by the density estimated by dive (assumed to be 100% and without error). Size classes where divers caught no scallops were excluded, as were size classes where fewer than a pre-set number of scallops were caught by either dredging or diving (all samples combined) in that experiment. This “minimum acceptable number” of scallops in a size class was varied from 1 (i.e., no filter) through 4 and 9 to 15 to explore the effects of excluding estimates of dredge efficiency that are likely to be highly imprecise (confidence limits for binomial proportions expand markedly at small samples sizes).

Average efficiency for a size class was estimated by calculating the reciprocal of each relevant estimate (resulting in “biomass scalars”), calculating the mean of these reciprocals, and converting back to efficiency (i.e., by averaging the biomass scalars rather than the efficiency estimates). Estimates of zero dredge efficiency for a size class (divers found scallops, but dredges did not) confound this approach because $1/0 = \infty$ and any average biomass scalar containing ∞ must also be ∞ (a dredge efficiency of zero). Biomass scalars for size classes where dredge efficiency was estimated to be zero were therefore set to 100, roughly the lowest estimable dredge efficiency, given our experimental approaches (Figure 2).

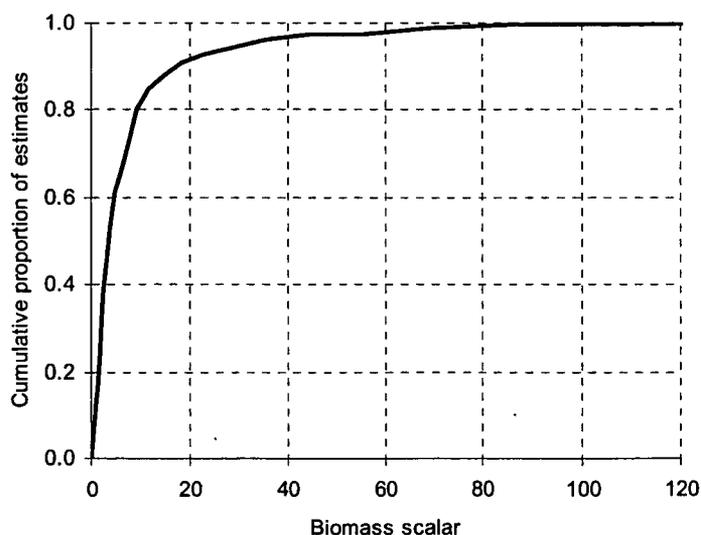


Figure 2: Cumulative frequency distribution of the estimated biomass scalar for the base non-parametric analysis. This distribution was used to establish 100 as the default biomass scalar when estimated dredge efficiency for a size class in an experiment was zero.

Averaging of biomass scalars was done for all data combined, for each fishery, and on different substrates within the Coromandel fishery. Each mean scalar was calculated un-weighted (i.e., assuming each estimate to be equivalent) then using weights to give more credence to estimates that are likely to be more reliable. Weights for a 5 mm size class were proportional to the smaller of the number of scallops caught by dredge and dive sampling (divers usually caught fewer scallops), or by the logarithm of this number plus one. Over the range of counts for the binomial numerator and denominator encountered, the confidence interval (relative to the mean) decreased roughly exponentially with increasing number of animals in the smaller sample so, *a priori*, the log weighting is probably to be preferred.

Because efficiency estimated by 5 mm size classes was found to be poorly estimated for “rare” size classes, average efficiency was estimated for three wider size classes of interest in stock assessment surveys. These were 85–99 mm (immediate pre-recruits and some of the recruited biomass in the Coromandel fishery), 100–114 mm (the bulk of the recruited biomass, especially in the Northland fishery), and ≥ 115 mm (large scallops that preliminary analyses and many anecdotes suggest are caught with low efficiency). Efficiency for each experiment and for each combination of experiments was estimated precisely as for the narrower size classes.

Confidence limits for the size-class-based approach were estimated by non-parametric bootstrapping, re-sampling from experiments and dredge tows and dive sites within experiments. Within an experiment, the dredge tows and dive sites were re-sampled, with replacement, taking the same number of tows and sites as in the original experiment. The mean estimated density was calculated for each size class using each sampling method, and dredge efficiency for that size class in that bootstrap run was estimated by dividing the density estimated by dredge by the density estimated by dive (assumed to be 100% efficient). For each bootstrap sample, average efficiency for a size class was calculated exactly as for the base estimate (weighting according to the log of the number of animals in the smaller sample) for all data combined, for each fishery, and on different substrates within the Coromandel fishery. The bootstrap estimates were stored and their statistical distributions used to estimate confidence intervals around the base estimates.

The results of this analysis were sensitive to the method of averaging the results of individual experiments (averaging efficiencies or their reciprocals), to the weighting procedure, and to constraints on the minimum acceptable number of scallops in a size class. However, the overall trends appear clear; dredge efficiency (relative to divers) increases with increasing scallop size up to about 100 mm, beyond which it declines (Figure 3). This pattern is consistent among the three substrate type examined and is not very sensitive to the weighting procedure (results not shown) or the minimum acceptable number on a size class.

These results suggest that it is probably inappropriate to apply dredge efficiency corrections as a simple scalar for all size classes likely to be part of the recruited biomass. This approach is likely to underestimate the density of large, heavy scallops and, consequently, probably underestimates biomass.

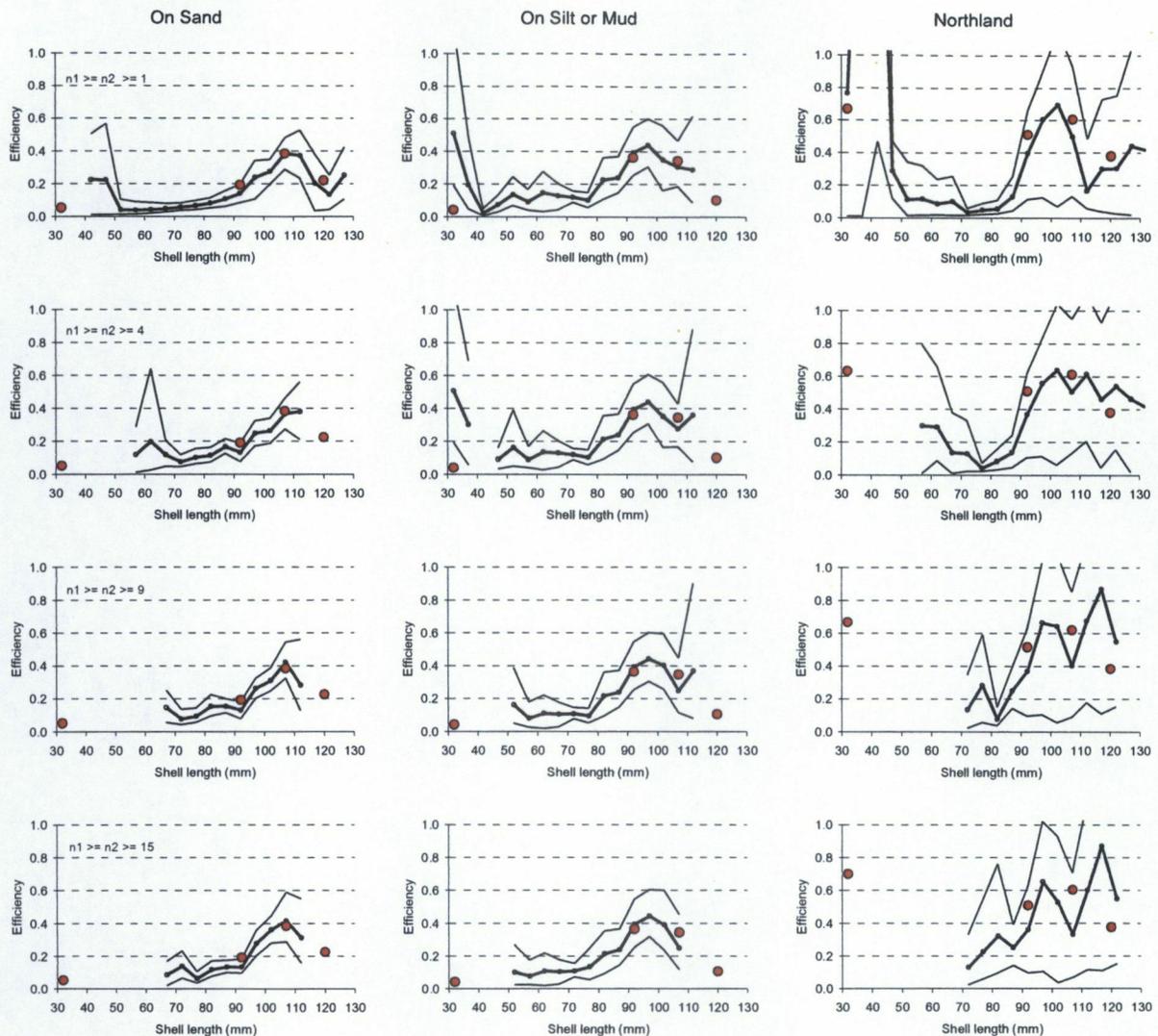


Figure 3: Mean dredge selectivity (efficiency) curves by 5 mm size classes for sandy and silty substrates in the Coromandel fishery (left and middle panels) and for the Northland fishery (right panel) estimated using the log (minimum N) weighting procedure and constraints on the minimum acceptable count by method increasing from 1 to 15 scallops in a size class. In each plot, the middle line is the mean of 1000 bootstraps and the outer lines delimit the 5th and 95th percentiles of the bootstraps. The larger dots are estimates for wider size classes.

9.4 Existing analytical approach

Counts of scallops over the critical size at each site were converted to numbers per square metre of seabed according to the area swept by the dredge and, where appropriate, the sampling fraction. The mean scallop density and its associated variance were calculated for each stratum using standard parametric methods, and the number of scallops calculated by multiplying the density by the area of the stratum.

The total number of scallops in the two groups of strata covered by the two sampling methods (dredge on sand and silt) were then derived by summing the stratum totals within the groups.

Sampling *c.v.s* for the overall estimate of scallop numbers in each group of strata were derived using the formula for strata of unequal sizes (equation (1)) after Snedecor & Cochran (1989).

$$s^2_{(y)} = \sum A_i^2 \cdot S_i^2 \cdot (1 - \phi_i) / n_i \quad (1)$$

where $s^2_{(y)}$ is the variance of the estimated overall number of scallops in the surveyed area, A_i is the relative size of stratum i , and S_i^2 and n_i are the sample variance and the number of samples respectively from that stratum. The finite correction term, $(1 - \phi)$, was set to unity because the sampling fraction was less than 0.01 in all strata. The standard error (SEM) of the overall mean is simply the square root of this variance, and the *c.v.* is the ratio of the standard error to the mean. If the estimates of stratum size are assumed to be without error, then the *c.v.s* of the two population estimates (by substrate) are proportionately the same as those for the estimates of overall mean densities. These two estimates of population abundance and their variances are not corrected for sampling efficiency.

Corrections for dredge efficiency on sand and silt were made by multiplying the estimated abundance of scallops over the critical size by a scalar, either 1.0, the mean of the reciprocals of all historical estimates of dredge efficiency for scallops of 90 mm or greater, or two other precautionary estimates of average dredge efficiency. Dredges were assumed to be similarly efficient for all scallops larger than 85 mm shell length and the same dredge efficiency corrections were made for the two critical sizes of 95 and 85 mm. The overall abundance of scallops over the critical size, N_{total} , in the entire survey area (or any subset of strata), was estimated as the sum of the two estimates by sampling method from equation (2):

$$N_{total} = \sum N_j \cdot E_j \quad (2)$$

where N_j is the estimated abundance within strata sampled using method j (dredge on sand, dredge on silt), and E_j is the scalar (dredge multiplier) for method j . The variance for this estimate was estimated by simulation using equation (3):

$$\hat{N}_{total} = \sum (N_j + \varepsilon_{n,j}) \cdot (E_j + \varepsilon_{e,j}) \quad (3)$$

where the $\varepsilon_{x,j}$ are random normal deviates each with a mean of zero and standard deviations equal to the standard errors associated with estimates of abundance and (reciprocal) efficiency by sampling method. A probability distribution for N_{total} was derived by generating 4000 replicate estimates of \hat{N}_{total} , the standard deviation of which is an estimate of the standard error of N_{total} , from which the *c.v.* can be calculated. This approach was used to estimate the variance structure and *c.v.* of estimates of biomass from the level of single stratum, through clusters of strata considered to represent “beds”, to the total fishery.

This technique for estimating scallop abundance and its variance is identical to that used since 1997, except for the inclusion of alternative dredge multipliers (as in 2001). Before 1997, dredge efficiency was usually incorporated as a selectivity function of size which was assumed to be without variance. Given the variability of dredge efficiency estimates from this and past studies at a range of sites, the assumption of zero variance is clearly untenable, and estimates of confidence limits for biomass estimates by this method were optimistic.

Start-of-season recruited biomass for strata sampled using method j was estimated as the product of N_j (for scallops predicted to grow to MLS by the start of the season), an estimate of average weight at the start of the season, \bar{W}_j , and the expected survival of scallops between the mean survey date and the start of the coming season in mid-July (equation (4)):

$$B_{recruited} = \sum N_j \cdot E_j \cdot \bar{W}_j \cdot e^{-(t \cdot M)} \quad (4)$$

where M is an assumed instantaneous rate of natural mortality ($M = 0.50 \text{ y}^{-1}$, Cryer 2001a) and t is the time lag (years) between the mid-point of the survey and the start of the season. Average weight was estimated for all strata sampled using method j from the pooled length frequency distribution for the strata involved and a length-weight regression from the Coromandel fishery (equation (5)):

$$W = 0.00042 L^{2.662} \quad (5)$$

where W is the greenweight (g) and L the maximum shell length (mm, $n = 861$). The \bar{W}_j for equation (5) were derived incorporating all scallops of shell length greater than the minimum legal size in the fishery within strata sampled using method j at the time of the survey (equation (6)).

$$\bar{W}_j = \frac{\sum W_{l,j} \cdot N_{l,j}}{\sum N_{l,j}} \quad (6)$$

where $N_{l,j}$ and $W_{l,j}$ are respectively the number and predicted weight (from equation 6) of scallops of length l sampled by method j . This estimate was assumed also to be the average weight of individuals likely to be still alive at the start of the forthcoming season (i.e., assuming that, after growth and mortality, the population length frequency distribution would remain the same).

The variance for the estimated start of season recruited biomass was estimated by simulation using equation (7):

$$\hat{B}_{recruited} = \sum (N_j + \varepsilon_{n,j}) \cdot (E_j + \varepsilon_{e,j}) \cdot \bar{W}_j \cdot e^{-(t \cdot M)} \quad (7)$$

where the $\varepsilon_{x,j}$ are random normal deviates each with a mean of zero and standard deviations equal to the standard errors associated with estimates of abundance and (reciprocal) efficiency by sampling method. A probability distribution for $B_{recruited}$ was derived by generating 4000 replicate estimates of $\hat{B}_{recruited}$, the standard deviation of which is an estimate of the standard error of $B_{recruited}$, from which the *c.v.* can be calculated.

The Total Allowable Commercial Catch (TACC) for this fishery is specified in meatweight (the weight of muscle and roe combined), whereas assessments are carried out in numbers of scallops or their aggregate greenweight because these are more tractable. The average ‘‘condition’’ of scallops (meatweight compared with greenweight) varies with location, depth, season, and

between years. Fleet average recovery rates can be as high as 20% in some weeks, but can be less than 10% just after a spawning event (usually in October or November).

Cryer & Parkinson (1999) amalgamated historical data where length, greenweight, and meatweight were available from pre-season and in-season surveys of scallops. Most of this information was collected between 1975 and 1991 during dive and dredge surveys of the Coromandel fishery, but about one third was collected during various experiments and trials conducted during the season. Cryer & Parkinson (1999) also examined the relationship between estimated greenweight and actual meatweight from CELR forms, although the necessary data are frequently not well reported by fishers. They found that, although the overall average recovery of meat from greenweight was very close to 13.5%, there was considerable variation among weeks of the year and among years. The recovery of meatweight from greenweight in a particular year will therefore vary according to whether that year is “good” or “bad” for scallop growth and condition, and when and how the stock is fished.

The prediction of average meatweight recovery for a forthcoming season is complicated by the above factors, but a value of 13.5% is assumed when converting biomass estimates from greenweight to meatweight.

9.4 Revised analytical approach

The new analytical approach contains the following 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 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. 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.

Correction for sampling fraction (if any), swept area, and for average dredge efficiency, and estimating standing biomass using a length-weight regression are identical to the process used in the existing analysis, except that the new analysis uses the new pooled analysis of dredge efficiency and a slightly revised length-weight regression. These analyses are used in the revised approach to estimate mean density and biomass but variances based on these calculations are underestimates unless no scaling for dredge efficiency is applied. From this point on, the revised approach diverges from the existing approach.

Sampling variance can be estimated for the simple case of no dredge efficiency scaling using standard parametric methods (e.g., equation (1) after Snedecor & Cochran 1989) but is estimated for all more complex approaches by re-sampling (with replacement) the individual tows within each stratum. For each iteration, the tows are re-sampled, the average density and standing biomass by size class are estimated, and scaled by stratum size. Variance associated with the revised length-weight regression:

$$W = 0.00037 L^{2.690} \quad (8)$$

is included by (optionally) bootstrapping from the raw length-weight data and generating a new length-weight relationship for each iteration. The absolute recruited biomass at the time of the survey is then estimated by summing all the pertinent stratum estimates (the stratum areas are considered to be without error).

To estimate start-of-season biomass, the corrected population length frequency distribution is projected forward using a growth transition matrix based on tag return data. Growth increments for 129 scallops tagged during pre-season surveys and recaptured in the first half of the following fishing season (after 47–247 days at liberty, mean 113 days) were used to develop a growth model. This growth model was not designed to represent all life stages and seasons, but rather to represent likely growth between survey and season. Linear and logarithmic regressions of expected increment on initial length were tested. The two models fitted the available data similarly well and predicted similar increments for scallops of 70–120 mm, but the logarithmic fit was selected because it predicted the average growth of smaller scallops (not included in the model) much better (Figure 4). Negative expected average growth was disallowed, but negative growth of some animals is possible given some combinations of expected increment and variability. Variability about the expected increment in the growth model was estimated by regressing the standard deviation of observed increments against initial length, including only size classes with three or more observations. The standard deviation of the expected increment in the growth model was constraining to be at least 0.05 mm. Uncertainty about the expected average growth between survey and season is incorporated by re-sampling (with replacement) from the 129 tag returns, refitting the regressions for the expected increment and its standard deviation and generating a new growth model for each iteration (e.g., Figure 5).

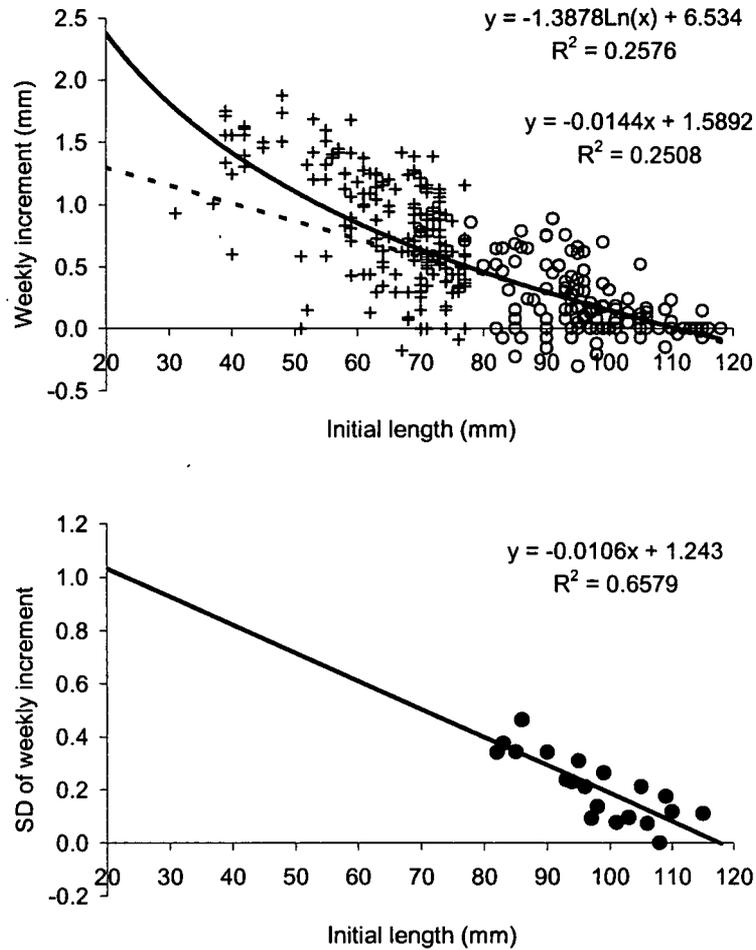


Figure 4: Relationship between initial length and subsequent weekly increment in length for scallops tagged and released during April, May or June (top panel, open circles). The solid and dotted lines are, respectively, linear and logarithmic regressions through these data. Crosses indicate data from scallops with a release length of less than 80 mm. These are shown to only illustrate the choice between growth models; none was tagged during in April, May or June, and they were not used to fit the regression lines. The relationship between initial length and the estimated standard deviation of the weekly increment is show in the bottom panel with a linear least squares regression line (fitted to length classes with 3 or more observations).

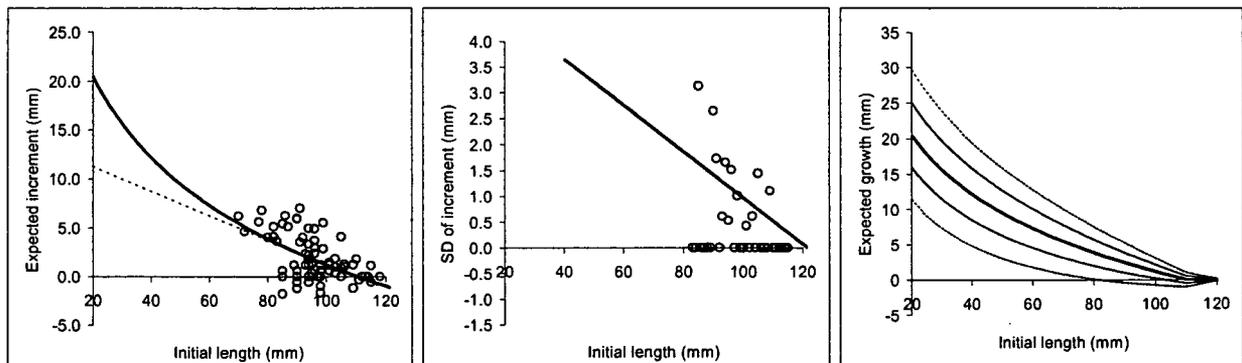


Figure 5: Development of a growth model (right) from regressions predicting mean expected increment (left) and the standard deviation of the mean increment (middle). Data from one bootstrap iteration.

Within each bootstrap iteration, the growth model is applied to each 1 mm size class of the length frequency distribution to generate an expected distribution of sizes at the start of the season. Mortality between survey and season is incorporated at this stage by applying an instantaneous rate of $M = 0.5 \text{ y}^{-1}$ over the time between survey and season, bootstrapping (parametrically) from a normal distribution with a standard deviation of 6.5% of the expected absolute mortality. The growth transition matrix then sums the expected densities by size class to estimate the start of season length frequency distribution which is, in turn, used to estimate recruited biomass (in greenweight). Confidence limits are estimated using the statistical distribution of 1000 or more bootstrap iterations. Correction for average dredge efficiency, and the variances associated with dredge efficiency, the length-weight regression, and the growth transition matrix are all optional.

The final step in the revised analysis is the prediction of meatweight from expected start-of-season greenweight. An updated analysis of recovery suggests that average recovery over a season varies from about 10% to about 15% (Table 4). This is important because the TACC and ACE are allocated in meatweight. Average recovery is typically about 11% when the season opens in July and typically increases to 15% or more through the first 12–16 weeks of the season (to about mid-late October, Figure 6). In some years the recovery rate in the middle of the season is very high, but in others it remains low. Towards the end of the season, the average recovery rate usually declines again.

Table 4: Estimated average recovery for Coromandel scallop seasons 1995–2002, 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).

Year	Mean recovery (%)
1995	13.65
1996	13.71
1997	12.88
1999	10.37
2000	9.93
2001	12.54
2002	15.61

It is, thus, very difficult to predict the average recovery of meatweight from greenweight for the coming season; the average actually attained will depend on the behaviour of fishers as well as the biological state of the animals. This uncertainty was incorporated in the revised analysis by selecting one of the seasonal averages from Table 4 for each bootstrap estimate of start-of-season recruited biomass (in greenweight). This approach assumes that growth, mortality, and recovery of meatweight from greenweight (essentially “condition”) are independent. In reality, this is unlikely to hold true. Poor conditions for growth between survey and season are likely to result in little or no growth, higher than expected mortality, and poor condition. In a “bad” year, therefore, predictions and confidence limits based on averages are likely to be highly optimistic.

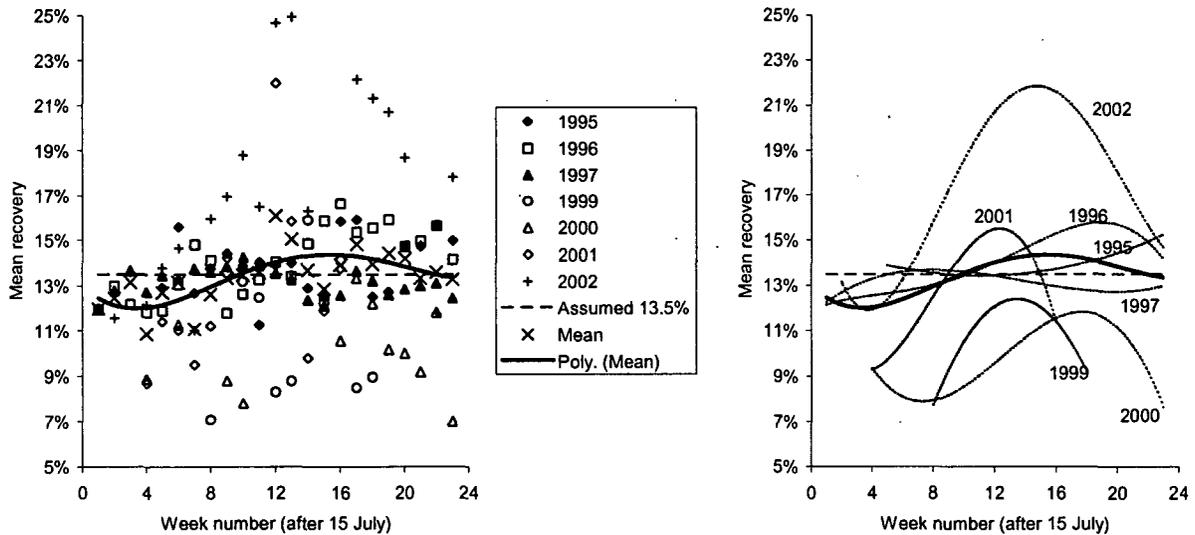


Figure 6: Seasonal progress of weekly average recovery of meatweight from greenweight in the Coromandel fishery based on CELR records. The left panel shows weekly averages and the right panel shows fourth polynomial regressions to simplify trends (indicative only). The bold line shows the average across all these years.

10. Results

10.1 Existing analytical approach

During the survey, 15 409 of 26 866 scallops caught in 107 tows (covering 0.18 km²) were measured. Approximate pooled length frequency distributions corrected for dredge efficiency and scaled to estimated population size (assuming historical average dredge efficiency for each substrate type) are shown for the major areas in Figures 7–9. The promising signs observed in 2002 at the Mercury Island beds (more smaller and more larger animals than in 2001) and at Little Barrier (more smaller animals than in 2001) seem to have translated into higher biomass estimates. Promising sign of recovery at Waiheke Island (e.g., large numbers of relatively large scallops) have not always translated to good fishery performance in the past.

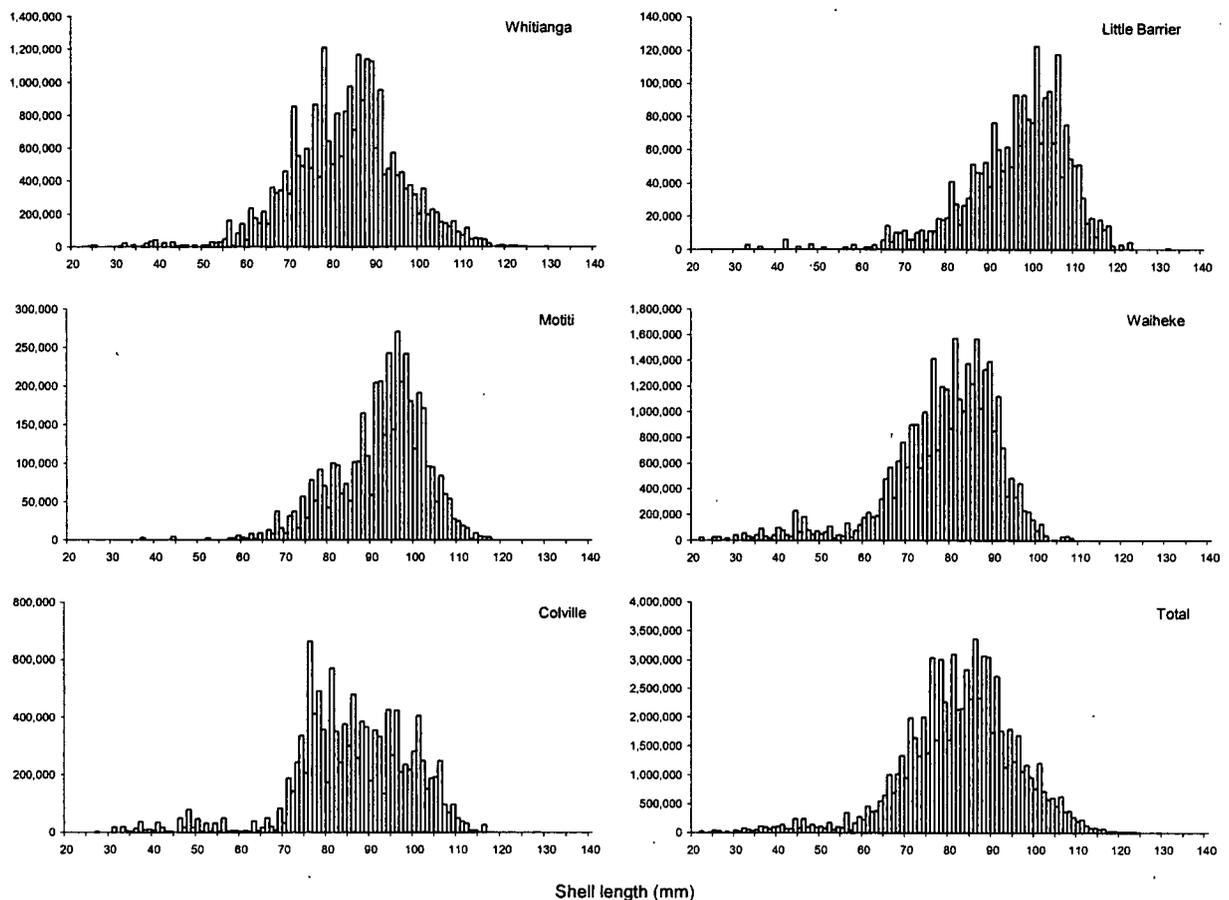


Figure 7: Approximate scaled length frequency distributions for the major areas of the Coromandel scallop fishery, corrected using historical average dredge efficiency by size.

Estimates of mean density, population abundance, and approximate biomass at the time of the survey are given in Tables 5 and 6 (for sizes at recruitment of 90 and 100 mm, respectively), assuming dredge efficiency of 77% on sandy substrates or 70% on silty substrates. Across the fishery, about 16 million scallops (with a *c.v.* of 18%) within the survey area were large enough to grow to the MLS of 90 mm by the start of the season in July or soon afterwards. The average weight of 83 g leads to a biomass estimate of about 1320 t greenweight. The average density was more than 0.1 m⁻² in all areas, considerably above the traditionally accepted threshold for reasonable commercial fishing of about 0.04 m⁻². Of the 16 million scallops, about 6.5 million (over 40%) were large enough to grow to 100 mm by the start of the season. This estimate provides for comparison with historical estimates made when the MLS was 100 mm (1978 to 1995). The major sensitivity was to the assumed value for average dredge efficiency; there was an almost three-fold difference between the estimate un-scaled for dredge efficiency and that scaled at average historical efficiency, whereas the difference in estimates made assuming different critical densities (range 0–0.06 m⁻²) was only 3–8% (Table 7).

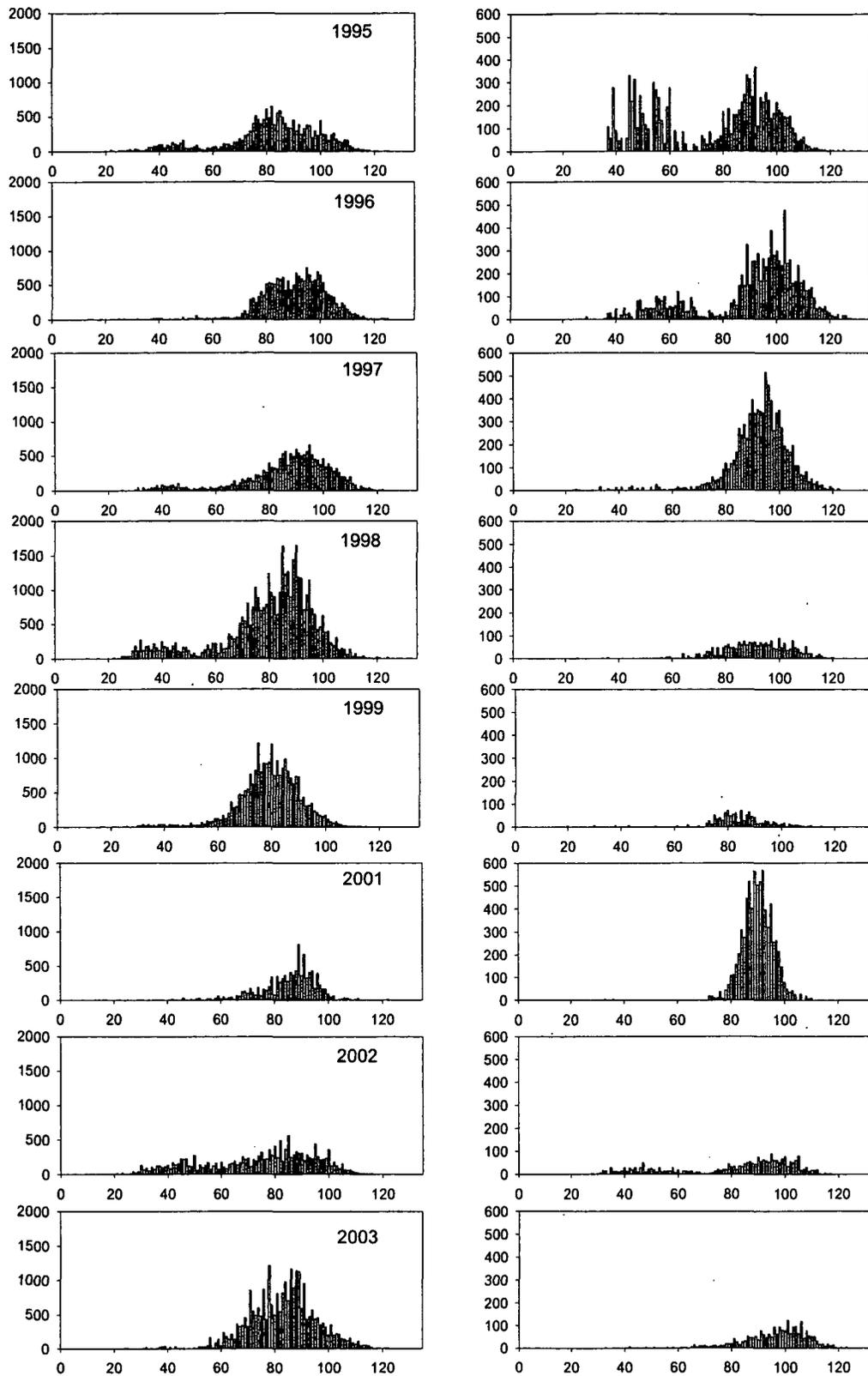


Figure 8: Approximate scaled length frequency distributions (thousands of animals) for the Coromandel scallop fishery since the inception of the 90 mm MLS in 1995, corrected using historical average dredge efficiency by size. Left panel, Mercury Islands; right panel, Little Barrier Island.

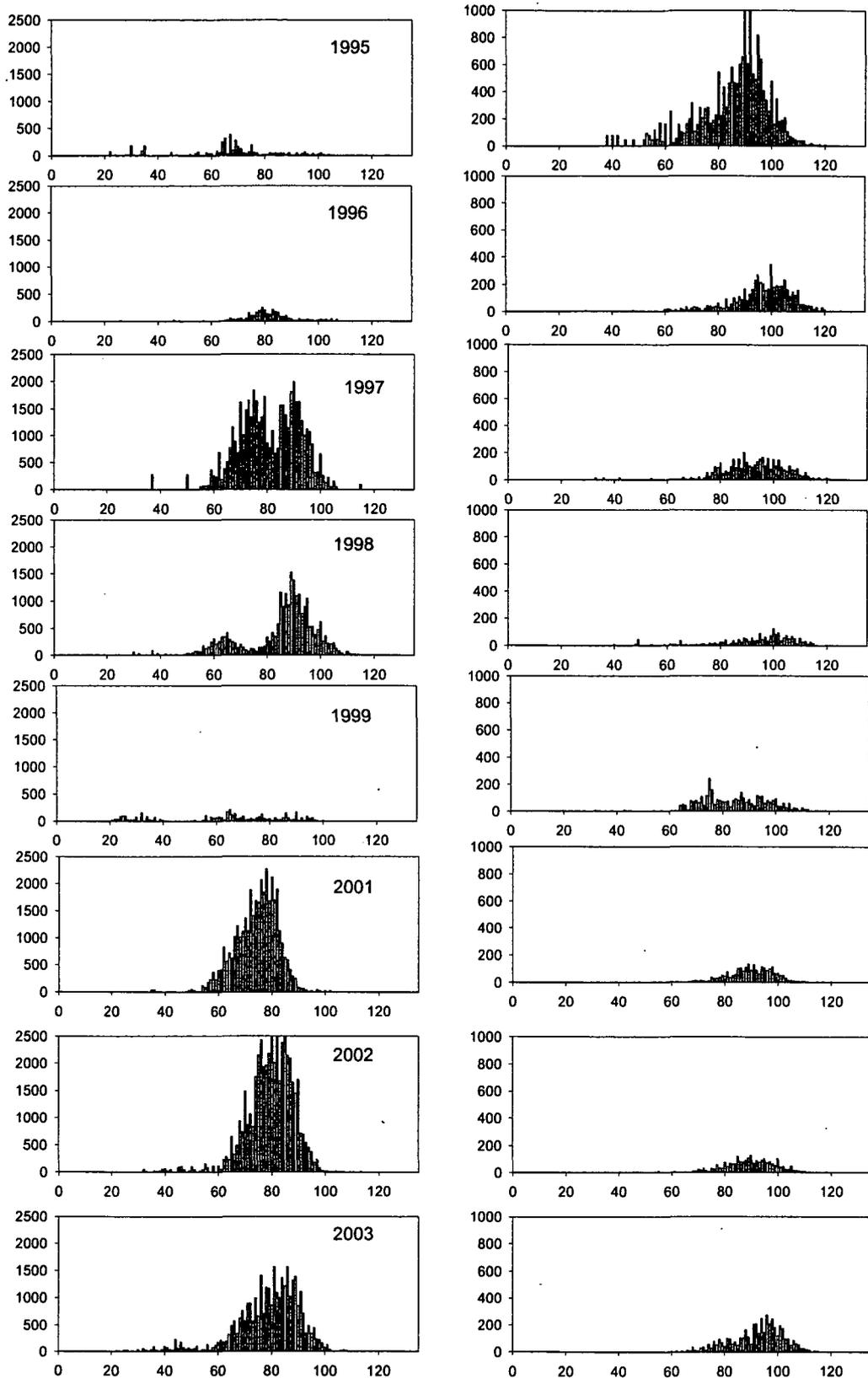


Figure 9: Approximate scaled length frequency distributions (thousands of animals) for the Coromandel scallop fishery since the inception of the 90 mm MLS in 1995, corrected using historical average dredge efficiency by size. Left panel, Waiheke Island; right panel, Motiti and Papamoa Beach.

Table 5: Abundance of scallops likely to recruit (corrected using dredge efficiency of 77% on sandy substrates and 70% on silty substrates, both with an assumed c.v. of 20% truncated at 100% efficiency) in major areas of the Coromandel fishery surveyed during 2003 based on a size at recruitment of 90 mm. The recruited population size is the estimated number of scallops 85 mm or greater shell length at the time of the survey, it being assumed that all such scallops will grow to 90 mm by the start of the season in July. Mean weight of recruits is estimated as the mean weight of all individuals of 90 mm shell length or greater at the time of the survey.

Bed	Population > 85 mm (millions)	Recruited density (m ⁻²)	c.v. of recruited density	Mean Weight of recruits (g)	Approx. biomass (t)
Mercury	5.69	0.1016	0.26	83.4	477
Motiti / Papamoa	1.75	0.1413	0.22	84.7	150
L. Barrier	0.99	0.1155	0.36	93.7	93
Waiheke	4.65	0.1311	0.30	74.4	345
Colville	2.88	0.1675	0.41	85.8	247
Fishery	15.95	0.1231	0.18	82.7	1 320

Table 6: Abundance of scallops likely to reach 100 mm shell length recruit (corrected using dredge efficiency of 77% on sandy substrates and 70% on silty substrates, both with and assumed c.v. of 20% truncated at 100% efficiency) in major areas of the Coromandel fishery surveyed during 2003. The recruited population size is the estimated number of scallops 95 mm or greater shell length at the time of the survey, it being assumed that all such scallops will grow to 100 mm by the start of the season in July. Mean weight of recruits is estimated as the mean weight of all individuals of 100 mm shell length or greater at the time of the survey.

Bed	Population > 95 mm (millions)	Recruited density (m ⁻²)	c.v. of recruited density	Mean Weight of recruits (g)	Approx. biomass (t)
Mercury	2.22	0.0396	0.24	102.2	227
Motiti / Papamoa	1.10	0.0890	0.22	98.3	108
L. Barrier	0.75	0.0880	0.38	104.1	78
Waiheke	0.78	0.0220	0.31	94.1	73
Colville	1.61	0.0934	0.44	98.5	158
Fishery	6.46	0.0498	0.19	100.3	648

Table 7: Sensitivity of estimates of recruited biomass (B, scallops ≥ 85 mm) at the time of surveying to different assumptions about dredge efficiency and the critical density of scallops for harvesting. In all cases, statistical distributions of dredge efficiency multipliers within bootstraps are truncated at 100%, i.e., dredge efficiency of >100% is disallowed. The assumptions made in presenting the distribution of recruited biomass in Tables 3 and 4 are shown in bold.

Assumptions	Critical density (m ⁻²)							
	0.00		0.02		0.04		0.06	
	B (t)	c.v.	B (t)	c.v.	B (t)	c.v.	B (t)	c.v.
No scaling	971	0.12	953	0.12	921	0.13	895	0.13
Highest historical	1 320	0.18	1 298	0.18	1 277	0.18	1 248	0.19
Upper 95% limit	2 000	0.18	1 987	0.19	1 964	0.19	1 935	0.19
Historical average	2 656	0.15	2 648	0.15	2 613	0.15	2 594	0.16

To predict start-of-season recruited biomass in the Coromandel fishery, assumptions about growth and mortality between the time of survey and the start of the season must be made. The mid-point of the survey was 20 May, 56 days before the start of the 2003 season (nominally 15 July). It has hitherto been assumed that most scallops of 85 mm or more in shell length would grow to 90 mm by the opening of the season or shortly afterward, although “average” growth may be sensitive to the depth distribution of scallops close to the minimum legal size (Cryer 2001a), and to the (unpredictable) growth conditions in 2003. Assuming a natural mortality rate of $M = 0.50$ spread evenly over the year leads to mortality of about 7.3% between survey and season.

Recruited biomass, from equation (4), is essentially the product of the abundance of scallops of 85 mm or more shell length at the time of the survey (assuming dredge efficiency of 77 or 70%), their expected average weight at the start of the season, and their expected survival rate of 92.7%. For the surveyed beds in 2003, this equates to

$$15.951 \text{ million} * 82.75 * 0.927 = 1224 \text{ t (greenweight), or}$$

$$\text{assuming 13.5\% recovery, } 1224 * 0.135 = 165 \text{ t (meatweight)}$$

These estimates both have a *c.v.* of 18% which includes variance associated with estimated or assumed dredge efficiency, but not associated with estimates of growth rate, mortality rate, mean weight, or expected recovery fraction. They are sensitive to assumptions about dredge efficiency in 2003 (see Table 7), and to the assumed growth between survey and season (estimates assuming no growth between survey and season are about 68% of those assuming growth of 5 mm, Table 8).

Table 8: Sensitivity of estimates of start-of-season recruited biomass (B) to different assumptions about dredge efficiency and growth between survey and season. In all cases, statistical distributions of dredge efficiency multipliers within bootstraps are truncated at 100%, i.e., dredge efficiency of >100% is disallowed. The assumptions made in presenting the distribution of recruited biomass at the time of surveys in Tables 3 and 4 are shown in bold.

Assumptions	85 mm critical size		No growth	
	B (t)	<i>c.v.</i>	B (t)	<i>c.v.</i>
No scaling	971	0.12	670	0.12
Highest historical	1 224	0.18	908	0.18
Upper 95% limit	2 000	0.18	1 374	0.19
Historical average	2 656	0.15	1 816	0.15

For comparison with survey results between 1978 and 1995, and for estimation of Provisional Yield (PY, Cryer 1994), it is here assumed that all scallops of 95 mm or greater length will grow to 100 mm between the survey and the start of the season.

Recruited biomass at 100 mm, using equation (4), is essentially the product of the abundance of scallops longer than 95 mm in shell length at the time of the survey, their expected average weight at the start of the season, and their expected survival rate of 92.7%. For the surveyed beds in the Coromandel fishery in 2003, this equates to

$$6.458 \text{ million} * 100.33 * 0.927 = 601 \text{ t (greenweight), or}$$

$$\text{assuming 13.5\% recovery, } 601 * 0.135 = 81 \text{ t (meatweight)}$$

These estimates both have a *c.v.* of 19% which includes variance associated with estimated or assumed dredge efficiency, but not associated with estimates of growth rate, mortality rate, mean weight, or expected recovery fraction. They are also sensitive to assumptions about dredge efficiency in 2003 and to the assumed growth between survey and season (estimates assuming no growth between survey and season average 53% of those assuming growth of 5 mm, but no detailed results are presented because the estimated start-of-season biomass at 100 mm is not used to estimate CAY).

10.2 Revised analytical approach

The revised analytical approach is still being fine-tuned and only broad results can be presented at this stage. The results are broadly similar to those from the existing approach (e.g., the form of length frequency distributions are almost identical) but variability in estimates of start-of-season biomass (especially for meatweight) tends to be higher using the revised approach. This is predictable because the revised approach incorporates uncertainty from sources that have been ignored or in the past.

The revised analytical approach suggested a standing biomass (greenweight) of 669 t at the time of the survey if no scaling for dredge efficiency was made and if only scallops currently at or above the MLS of 90 mm are included (Table 9). This can be regarded as close to a minimum estimate for the start-of-season biomass estimate because it assumes no growth, and 100% dredge efficiency (although it does not provide for any mortality between survey and season). Applying the revised analysis of all historical dredge efficiency experiments, increases the estimated recruited biomass at the time of the survey to 2393 t greenweight with a *c.v.* of 23%, more than three times as big as the estimate based on 100% efficiency. Projections made using a growth transition matrix suggest that the recruited biomass should increase by the start of the season to 779 t with a *c.v.* of 11% (unscaled) or 3115 t with a *c.v.* of 22% (scaled for average dredge efficiency). Converting these estimates to projected meatweight by incorporating the variability among years as well as the overall average recovery rate of 12.7% since 1995 suggests a start-of-season meatweight biomass of 99 t with a *c.v.* of 19% (unscaled) or 393 t with a *c.v.* of 27% (scaled for average dredge efficiency).

Table 9: Sensitivity of estimates (made using the revised analytical approach) of start-of-season recruited biomass (B, MLS = 90 mm) to different assumptions about dredge efficiency and changes between survey and season.

Dredge efficiency	Time of survey		Start of season	
	B (t)	c.v.	B (t)	c.v.
No scaling (100%)	669	0.11	779	0.11
Historical average	2 393	0.22	3 115	0.22

10.3 Relationships among biomass estimates and analytical approaches

Despite their many differences, the existing and revised analytical approaches give similar results where the estimated start of season biomass is not corrected for dredge efficiency or when historical average dredge efficiency is applied (Figure 10). If no scaling is applied, the start of season recruited meatweight biomass is predicted to be about 100–120 t. If historical average dredge efficiency is applied this increases to 350–400 t, but with considerable uncertainty. Even this uncertainty may be conservative, however, because the analysis does not incorporate correlation among growth, mortality, and the “condition” of scallops (which affects meatweight recovery).

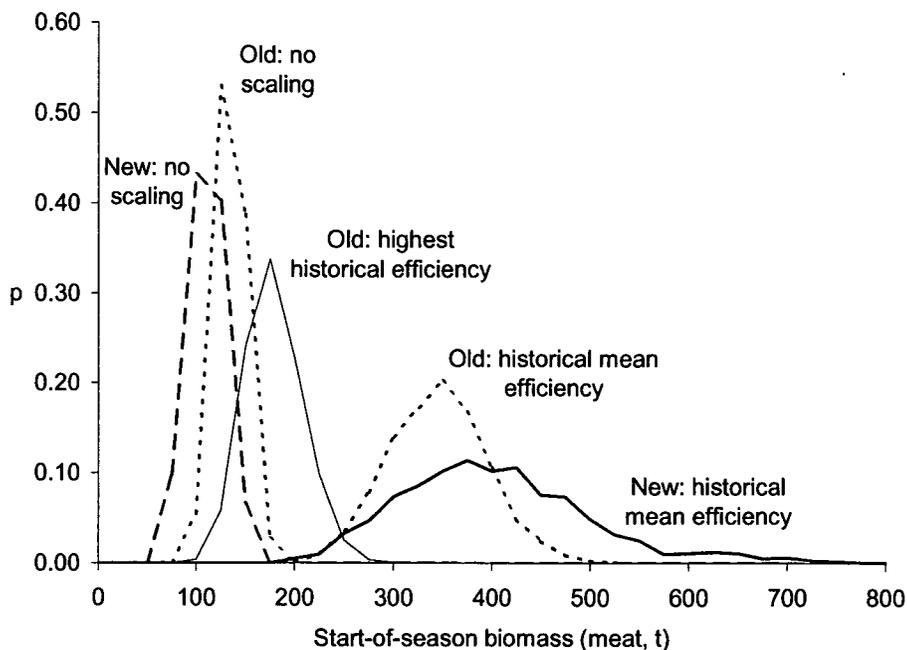


Figure 10: Frequency distributions of the predicted start-of-season recruited (meatweight) biomass using the existing (old) analytical approach assuming a critical size of 85 mm and assumed dredge efficiency of 100% (i.e., no scaling), equal to the highest historical estimate on sand and silt substrates, and equal to the average of all historical estimates. The results from the new analytical approach incorporating a growth transition matrix and average historical dredge efficiency are shown for comparison.

10.4 Yield estimates

10.4.1 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.

10.4.2 Estimation of Current Annual Yield (CAY)

Yield is estimated here biomass estimates based on the existing analytical approach incorporating dredge efficiency as the highest historical estimate of dredge efficiency by substrate. Different biomass estimates could be used but the Ministry's Shellfish Fishery Assessment Working Group has not considered or approved such a change.

CAY is estimated for a constant-F fishing strategy using a reference rate of fishing mortality applied to an estimate of current biomass, but the choice among reference rates is not simple. It is probably useful to use Caddy's (1998) notation of target reference points (TRP) and limit reference points (LRP) where reference points can be measures of fishing mortality (F) or biomass (B). F_{max} (the zenith of a yield-per-recruit curve) was the classical TRP (Caddy 1998), but may be too high as a target (Annala et al. 2000) and has more recently been generally regarded as an LRP (a "threshold" beyond which fishing mortality should not be increased) and $F_{0.1}$ has been substituted as a "target" (Caddy 1998). Mace (1994) recommended $F_{40\%}$ as a "default" TRP in the "common situation where there is adequate information to place bounds on all relevant life history parameters except those characterising the stock-recruit relationship" (although Collie & Gislason, 2001, list $F_{40\%}$ as a LRP). Mace's (1994) simulations showed that, in her model, $F_{40\%}$ was similar to $F_{0.1}$ when recruitment and maturity schedules coincided, and approximated F_{MSY} for fisheries of average to high resilience to fishing. She also affirmed Mace & Sissenwine's (1993) proposition that the default overfishing threshold should be 20% B_0 for stocks of at least average resilience to fishing. However, Myers et al. (1994) considered this threshold (20% of virgin stock size) the least desirable and the least precautionary of those they examined. The available information and models for Coromandel scallops allow the estimation of F_{max} as a LRP, and $F_{0.1}$ and $F_{40\%}$ as TRPs in 2001.

Cryer & Morrison's (1997) estimates of $F_{40\%}$ (0.514 y^{-1}), $F_{0.1}$ (0.508 y^{-1}), and F_{max} (0.650 y^{-1}) (all assuming $M = 0.50 \text{ y}^{-1}$) were used to estimate yield as CAY. Yield estimates based on $F_{40\%}$ and $F_{0.1}$ should probably be preferred as targets over that based on F_{max} (which might be considered a limit). Because of the derivation of these estimates, they should be applied to the modified version of the Baranov equation given by Cryer & Morrison (equation 8)

$$CAY = \frac{F_{ref}}{F_{ref} + \frac{5M}{12}} * \left[1 - e^{-(F_{ref} + 5M/12)} \right] * B_{jul} \quad (8)$$

where B_{jul} is the estimate of recruited biomass in July. In this formulation of the Baranov equation, natural mortality is assumed to act in tandem with fishing mortality for the first 5 months of the year, the length of the current Coromandel commercial scallop season.

The recruited biomass of scallops 90 mm in shell length or greater in the Coromandel fishery was predicted using the existing analytical approach to be 1224 t (greenweight) in 2003. CAY was calculated using this biomass and each of the reference fishing mortality rates $F_{0.1}$, F_{max} , and $F_{40\%}$ as follows (the conversion rate from greenweight to meat was assumed to be 13.5% (Cryer & Parkinson 1999a)):

For $F_{40\%}$, $CAY = 0.7116 * 0.5144 * 1224 = 445 \text{ t (green) or } 60 \text{ t (meat)}$

For $F_{0.1}$, $CAY = 0.7092 * 0.5115 * 1224 = 444 \text{ t (green) or } 60 \text{ t (meat)}$

For F_{max} , $CAY = 0.7573 * 0.5761 * 1224 = 534 \text{ t (green) or } 72 \text{ t (meat)}$

These estimates of CAY would have a c.v. at least as large as that 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. The level of risk to the putative Coromandel scallop stock of fishing at the estimated CAY level cannot be determined.

10.4.3 Estimation of Provisional Yield

Provisional Yield (PY) (Cryer 1994) is estimated as the lower limit of a 95% confidence distribution for the estimate of start-of-season recruited biomass, plus an amount to account for beds not surveyed before the season. The amount added for un-surveyed beds is estimated as the product of the variability factor (Annala et al. 2002; $M > 0.35$, $c = 0.6$ for scallops) and the historical average landings from the unsurveyed beds. PY is estimated only for comparison with historical estimates of yield.

For Coromandel scallops in 2003, start-of-season recruited biomass (100 mm or greater) was estimated at 601 t (greenweight) with a c.v. of 19%, giving a lower tail to the 95% confidence distribution of 373 t. Beds not included in the surveys were excluded specifically because they were thought unlikely to support commercial fishing in 2003, so no addition for un-surveyed beds was made:

$$PY = 373 \text{ t} + 0.6 * 0 \text{ t} = 373 \text{ t (greenweight) or } 50 \text{ t (meat)}$$

This estimates of PY would have a c.v. at least as large as that of the estimate of start-of-season recruited biomass (19%), and is sensitive to assumptions about dredge efficiency and growth. The level of risk to the putative Coromandel scallop stock of fishing at the estimated PY level cannot be determined.

10.4 Fishery trends

Discerning trends in the 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, and there seems to have been significant improvement since 2002 (Table 10, although this table may be slightly misleading because it is based on a size at recruitment of 95 mm). The “mainstay” of the fishery at the Mercury Islands has recovered significantly from the lowest ever recorded abundance of scallops in 2001 (4.2 vs. 1.5 million scallops 95 mm or longer). *Chaetopterus* tubeworms were still abundant in places, but were only an occasional hindrance to surveying (filling the dredge and causing it to “fly”). The bed at Little Barrier Island has returned to a similar biomass to 2001 (1.4 vs. 1.6 million scallops), and *Chaetopterus* tubeworms were a hindrance in only a few of the shots conducted in 2003. A much smaller area than in previous years was surveyed at Motiti–Papamoa in 2001–03, but the biomass in 2003 was much increased (2.1 vs. 0.7 million scallops 95 mm or longer). Scallops were again very numerous at Waiheke Island, and the scallops were significantly larger in 2003 than they have been in the recent past. It appears that there should be a reasonable fishery in 2003. The 2003 survey at Colville gave the highest estimated biomass since surveys began there in 1993. Beds at Waihi, Great Barrier, Otama, and at Shoe and Slipper Islands were not surveyed because they were not expected to contain many scallops. Overall, the survey gives a considerably higher estimate of total biomass of scallops (95 mm or greater length) than in 2001 and 2003 from a slightly larger area, and the improvement is across most beds.

Table 10: Number of scallops at the time of survey in constituent areas of the Coromandel fishery since 1990 (millions 95 mm or greater shell length assuming historical average dredge efficiency for all years, including 2001 and 2002 when different vessels were used). Totals include data from all surveyed beds and are not directly comparable among years. Dashes (–) indicate no survey

	Mercury	Waihi	Motiti, Papamoa	Little Barrier	Colville	Waiheke	Total
1990	7.4	–	–	–	–	6.4	13.8
1991	11.1	–	–	–	–	2.8	13.9
1992	10.7	–	–	–	–	0.7	11.4
1993	6.6	7.1	–	–	0.3	0.4	14.4
1994	4.8	1.5	–	–	–	0.0	6.3
1995	4.4	0.6	4.5	2.5	0.1	0.3	12.5
1996	6.1	0.2	2.2	3.3	0.1	0.3	12.6
1997	6.1	0.7	1.9	4.0	0.3	5.4	18.4
1998	6.4	0.1	1.2	1.0	0.2	5.3	14.2
1999	1.8	0.2	0.9	0.2	0.0	0.2	3.3
2000	–	–	–	–	–	–	–
2001	1.5	–	0.7	1.6	–	0.2	4.2
2002	2.7	–	0.7	0.8	–	1.0	5.3
2003	4.2	–	2.1	1.4	3.5	1.7	12.9

11. Conclusions:

1. A survey of 107 valid dredge stations in the Coromandel scallop fishery was completed in late May 2003.
2. Absolute start-of-season biomass over 100 mm shell length (for comparison with previous surveys) was predicted to be 601 t greenweight (81 t meatweight) with a standard error of about 19% of the mean. This estimate is sensitive to assumptions about dredge efficiency and growth between survey and season.

3. Absolute start-of-season biomass over 90 mm shell length (the commercial minimum legal size) was predicted to be 1224 t greenweight (165 t meatweight) with a standard error of about 18% of the mean. This estimate is sensitive to assumptions about dredge efficiency and growth between survey and season.
4. These results suggest a substantial improvement on the 2001 and 2002 biomass estimates in most beds.
5. Estimated recruited biomass at the time of the survey and its standard error are both sensitive to the (assumed) dredge efficiency multiplier, but not to the exclusion of areas of low scallop density.
6. Estimated start-of-season biomass is sensitive to factors affecting the estimate of survey biomass, but is also very sensitive to assumptions about growth between survey and season.
7. Yield (as CAY) is estimated for the 2003 season to be 60 t meatweight (using $F_{0.1}$ or $F_{40\%}$ as target reference points), assuming dredge efficiency equal to the highest experimental estimate in each substrate, growth of about 5 mm between survey and season, and 13.5% average recovery of meatweight from greenweight. These estimates are sensitive to assumptions about dredge efficiency and growth, but not to exclusion of areas of low scallop density.

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12. Publications:

There are no other publications except a voyage programme and a voyage report for the fieldwork, and a substantial research progress report that was used as the basis for an electronic “virtual review” of the work.

13. Data Storage:

Data have been transferred to the appropriate Empress database, *scallop*. Various analytical files in MS-Excel are held on a secure, backed-up server at NIWA Auckland and copied to the Ministry’s data manager.

Appendix 1: Stratum definitions and station allocations, Coromandel scallop survey 2003

Stratum	Location / description	Area (m ²)	Method	2003 Shots
1.1	Mercury (Blackjack)	9 313 599	Dredge (sand)	5
1.2	Mercury (Sarah’s Gully)	7 748 230	Dredge (sand)	4
2	Mercury (Three Mile Bank)	10 784 668	Dredge (sand)	7
3	Mercury (Opito Bay)	5 393 677	Dredge (sand)	5
3.5	Mercury (Opito Bay deeps)	13 923 828	Dredge (sand)	4
4	Mercury (Mercury Cove)	1 713 959	Dredge (silt)	4
7	Mercury (Bumper Cove)	7 125 244	Dredge (sand)	9
13	Motiti South	7 808 594	Dredge (sand)	13
14	Papamoa Beach	4 572 998	Dredge (sand)	6
18	Little Barrier West	3 771 729	Dredge (sand)	8
19	Little Barrier South	4 795 044	Dredge (sand)	12
20	Waiheke Island	35 452 759	Dredge (silt)	23
31	Colville South (shallow)	15 770 264	Dredge (silt)	4
34	Colville North	1 409 119	Dredge (sand)	3
Total	–	129 583 712	–	107

Appendix I: Summary of dredge efficiency experiments used in the historical analysis and revised analytical approach.

Code	Year	Vessel	Site	Fishery	Substrate	Dredge width (m)	Depth (m)	Dredge			Dive			Density >=85 mm
								Tows	Area	Scallops	Sites	Area	Scallops	
1984CP	1984	L'Aries	Pakatoa	Coro	Silt/mud	1.55	23	11	3 950	1 037	3	150	238	0.6867
1985CT	1985	L'Aries	Tarahiki	Coro	Silt/mud	1.90	15	16	4 607	2 615	7	67	147	1.5528
1986CT	1986	Elco	Tarahiki	Coro	Silt/mud	1.30	15	20	4 090	4 129	12	108	238	1.3609
1992C3	1992	L'Aries	3 Mile Bank	Coro	Sand/shell	2.00	17	4	7 445	938	15	628	350	0.4711
1993CA	1993	L'Aries	Opito A	Coro	Sand/shell	2.00	16	4	2 963	90	16	314	80	0.1560
1993CB	1993	L'Aries	Opito B	Coro	Sand/shell	2.00	27	4	3 148	920	8	314	435	1.1618
1993CC	1993	L'Aries	Opito C	Coro	Sand/shell	2.00	30	2	1 148	224	4	314	206	0.4806
1994CA	1994	L'Aries	Opito A	Coro	Sand/shell	2.00	16	2	3 704	193	4	314	47	0.1273
1994CB	1994	L'Aries	Opito B	Coro	Sand/shell	2.00	27	2	3 704	125	4	314	12	0.0222
1994CC	1994	L'Aries	Opito C	Coro	Sand/shell	2.00	30	2	1 926	208	4	314	97	0.1432
1995CC	1995	Kataraina	Opito C	Coro	Sand/shell	2.00	27	2	5 556	446	4	647	127	0.0971
1995CA	1995	Kataraina	Opito A	Coro	Sand/shell	2.00	17	2	5 556	217	4	647	210	0.2702
1995CB	1995	Kataraina	Opito B	Coro	Sand/shell	2.00	26	3	3 395	423	4	245	154	0.1959
1995C3	1995	Kataraina	3 Mile Bank	Coro	Sand/shell	2.00	17	3	3 297	83	4	1 181	206	0.1019
1995CN	1995	Kataraina	Opito N	Coro	Sand/shell	2.00	20	3	2 963	189	2	1 329	304	0.1398
1995CS	1995	Kataraina	Opito S	Coro	Sand/shell	2.00	17	3	2 926	93	9	1 731	286	0.1251
1996CB	1996	Kataraina	Opito B	Coro	Sand/shell	2.00	25	3	4 889	870	8	481	193	0.2609
1996CA	1996	Kataraina	Opito A	Coro	Sand/shell	2.00	12	3	5 556	499	9	569	232	0.4010
1996CC	1996	Kataraina	Opito C	Coro	Sand/shell	2.00	28	3	2 290	610	4	358	170	0.3763
1997CB	1997	Kataraina	Opito B	Coro	Sand/shell	2.00	27	3	6 116	752	4	525	120	0.1960
1997CA	1997	Kataraina	Opito A	Coro	Sand/shell	2.00	15	3	7 408	186	4	804	12	0.0112
1997CC	1997	Kataraina	Opito C	Coro	Sand/shell	2.00	29	4	2 929	822	4	402	175	0.2857
1998CH	1998	Kataraina	Hooks Bay	Coro	Silt/mud	2.00	20	4	3 593	825	4	1 002	506	0.6888
1999CT	1999	Kataraina	Tarahiki	Coro	Silt/mud	2.00	23	4	5 371	377	4	1 431	547	0.0820
1992NB	1992	Avalon	Bream Bay	North	Sand/shell	2.40	17	4	8 190	938	8	1 608	349	0.1834
1994NB	1994	Wyzanne	Bream Bay	North	Sand/shell	2.10	22	6	9 450	505	9	1 810	477	0.1149
1995NR	1995	BenGunn	Rangaunu	North	Sand/shell	2.40	18	7	10 326	711	16	3 217	233	0.0619
1995NB	1995	BenGunn	Bream Bay	North	Sand/shell	2.40	21	6	11 779	429	10	2 011	119	0.0522
1996NR	1996	BenGunn	Rangaunu	North	Sand/shell	2.40	22	3	3 467	146	7	1 128	59	0.0549
1997NW	1997	BenGunn	Whangaroa	North	Sand/shell	2.40	23	5	9 512	643	14	2 579	400	0.1389
1998NW	1998	Marewa	Whangaroa	North	Sand/shell	2.40	22	10	21 957	1 193	10	1 854	81	0.0423
1998NM	1998	Marewa	Matauri Bay	North	Sand/shell	2.40	20	8	16 712	747	8	1 608	27	0.0143