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Review of the Southern scallop fishery (SCA 7)

New Zealand Fisheries Assessment Report 2014/07

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EXECUTIVE SUMMARY

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Scallops (*Pecten novaezelandiae*) support regionally important commercial, recreational, and customary fisheries in New Zealand. The Southern scallop fishery (stock SCA 7), also known as the 'Challenger' fishery, comprises three adjoining areas (substocks) at the north of New Zealand's South Island: Golden Bay, Tasman Bay, and the Marlborough Sounds. The commercial fishery in SCA 7 has been in existence for more than 50 years, and during that time has undergone considerable change, in terms of both management and productivity. Substantial declines in the Golden Bay and Tasman Bay scallop substocks over the last decade prompted a desktop review of the SCA 7 fishery to investigate factors affecting its performance. This report describes the findings of that review and introduces new work underway to develop an ecosystem approach to fisheries in this region.

The approach taken focused on reviewing information on both the fishery and the stock in SCA 7. The review of the fishery information comprised a description of the management history, a characterisation of the fishery using commercial catch and effort data, and an examination of the scallop spat enhancement and rotational fishing activities using industry data. Additional analysis of enhancement was also undertaken to supplement this review, by examining the spatial patterns and levels of spat enhancement using linear modelling approaches in relation to fishing patterns and survey catches; this modelling work was reportedly separately (Tuck & Williams 2012a). The review of the stock information comprised an investigation of the scallop population abundance, distribution, and size structure in SCA 7 using data from annual dredge surveys carried out since 1994. Key aspects were re-estimation of the biomass time series for the stock using a revised analytical procedure to better account for uncertainty in the estimates, and comparison of historical landings and estimated exploitation rates with estimates of yield calculated retrospectively.

Commercial dredging for scallops in SCA 7 began in Tasman Bay resulting in the first recorded landings in 1959, and the fishery gradually spread into Golden Bay and the Marlborough Sounds in the 1960s and 1970s as fishing effort and intensity increased. The fishery reached a peak annual catch of almost 10 000 t greenweight in 1975, but landings declined rapidly after that and the fishery was closed for two years after 1980.

The fishery was re-opened in 1983, and scallop stock enhancement techniques from Japan were trialled. Pearl and lantern net culture, and tethering of individual scallops within suspended culture systems were unsuccessful. However, direct enhancement developed from these initial trials, through the collection and release into the wild of large numbers of juvenile scallops, and was apparently successful. Enhanced scallops first formed part of the annual commercial catch in 1986, and large-scale enhancement in Golden Bay and Tasman Bay began in the late 1980s and continued in the 1990s. In addition, harvesting of scallops was to be conducted on a three-year rotational basis in these areas (but not the Marlborough Sounds). The combination of enhancement and rotational fishing were implemented as a means of stabilising fishery production and reducing periods of low abundance. A management strategy evaluation for the fishery examined a range of management approaches, and identified that rotational approaches are highly stabilising, with enhancement further improving safety, catch and biomass, and slightly reducing population variability.

Overall levels of spat enhancement activity increased rapidly during the early 1990s, peaking in 1993. Enhancement activities continued at a significant level until the mid 2000s, but have declined in the most recent years. Primary enhancement (direct release of spat collected from bags) had a significant effect on survey catches, although analysis suggested that increased catches of recruited scallops (90 mm shell length or larger) occurred two years after enhancement in Golden Bay and four years

after enhancement in Tasman Bay. Secondary enhancement (release of spat collected by dredge from under spat collection sites) did not have a detectable effect on survey catches. The fishing history of an area did not appear to affect survey catches, but the rotational nature of enhancement followed by fishing may have confounded the detection of a fishing effect.

The rotational opening and closing of sectors (statistical reporting areas) to fishing was generally carried out in the early 1990s as initially intended in the management plan, but the sector level rotation broke down from about 1996 onwards. Fishing of enhancement plots has been rotated (i.e. these plots were generally not fished on consecutive years), but some other areas appear to have been fished in consecutive years.

Landings from the scallop fishery increased to high levels in the mid 1990s and early 2000s, but have since declined to low levels. Fishing effort for scallops has generally been highest in Golden Bay, and CELR data show that effort was particularly high in Golden Bay in 2001 and 2002. In Golden Bay, the estimated exploitation rate (catch to recruited biomass ratio) on recruited scallops was high (0.54–0.80) in the period 1998–99 (higher than CAY levels calculated retrospectively), followed by a decreasing trend with fluctuation from 2000, and was very low (0.05) in 2011–12. In Tasman Bay, the peak exploitation rate in the time series was 0.25 in 1999, but otherwise has been relatively low; no fishing has occurred in Tasman Bay since 2005. In the Marlborough Sounds, the exploitation rate was high (0.51) in 1998–99 but low (0.05) in 1999–2000, followed by a general increase to reach about 0.31 in 2005–06. Exploitation in the Marlborough Sounds subsequently decreased to only 0.02 in 2007–08, but there has been an increasing trend since then, reaching a high of 0.39 in the most recent fishing year 2012–13 that almost matches the level of the calculated CAY.

The estimated status of the SCA 7 stock in 2013 is the second lowest recorded since extensive (stock-wide) surveys began in 1998 (the lowest was in 2012). In all three substocks of SCA 7, estimated recruited scallop biomass generally increased from the late 1990s to reach peak levels around 2001–02. Since then there has been a substantial biomass decline in both Golden Bay and Tasman Bay, and current biomass in both bays is at historically low levels. In contrast, biomass in the Marlborough Sounds has remained relatively stable over the same period.

The cause of the major declines in the scallop populations of Golden Bay and Tasman Bay is unknown, but our comparison of landings in relation to the CAY at the broad scale of the three substocks within SCA 7 suggest that the downturn is probably associated with factors other than simply the magnitude of direct removals of scallops by fishing. It has been recognised, however, that the estimates of the target fishing mortality $F_{0.1}$ used to calculate CAY may be too high. Nevertheless, declines in stocks of other shellfish (oysters, mussels) have also been observed. In addition to direct fishing mortality, a combination of other anthropogenic (e.g., land-based influences, indirect effects of fishing) and natural (e.g., oceanographic) drivers may have affected productivity of the SCA 7 fishery.

Work is now underway to develop an ecosystems approach to fisheries to potentially restore sustainable fisheries production. As a first step, workshops with stakeholders and iwi were held in 2012, which determined the participants’ shared vision of maintaining healthy, productive, and sustainable fisheries. Information on drivers of shellfish fisheries production is being reviewed, and further engagement with end users is ongoing to develop conceptual models for the shellfish fisheries, which forms part of NIWA’s work on ecosystem modelling.

1 INTRODUCTION

1.1 Overview

Scallops (*Pecten novaezelandiae*) support important commercial, recreational, and customary fisheries in New Zealand (Figure 1). The Southern scallop fishery (fishstock SCA 7), also known as the 'Challenger' or 'Nelson/Marlborough' fishery, comprises three adjoining areas (referred to here as substocks) at the north of New Zealand's South Island: Golden Bay, Tasman Bay, and the Marlborough Sounds. The commercial fishery in SCA 7 has been in existence for more than 50 years, and during that time has undergone considerable change, in terms of both management and productivity. Substantial declines in scallop abundance in the Golden Bay and Tasman Bay substocks over the last decade (illustrated in Figure 2) prompted a desktop review of the fishery to investigate factors affecting its performance. This report describes the findings of that review. The Overall Objective was to review the stock assessment methodology and factors affecting the SCA 7 fishery. The Specific Objective was to review the factors from available sources of information, including fishing plans, which may have affected the performance of the SCA 7 scallop fishery.

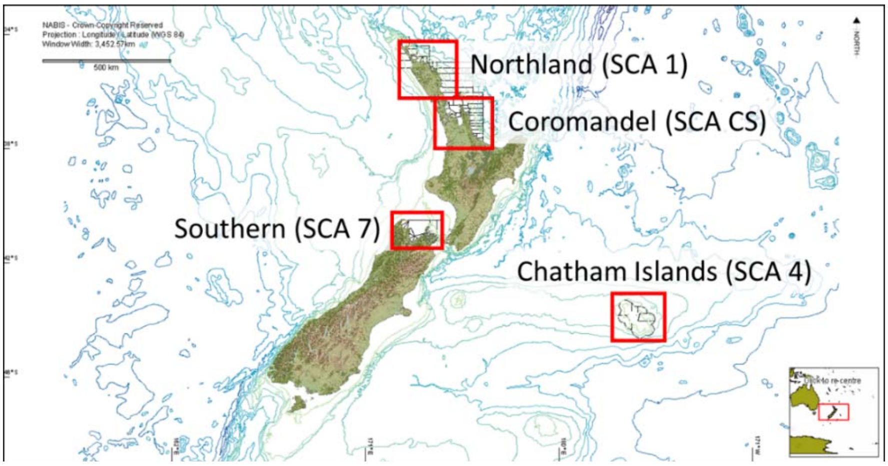


Figure 1: New Zealand scallop (*Pecten novaezelandiae*) stocks that have supported commercial fisheries.

Our approach to this project focused on reviewing the available information on both the scallop fishery and the scallop stock in SCA 7. Review of the fishery information comprised a description of the management history, a characterisation of the fishery using commercial catch and effort data, and an examination of the scallop spat enhancement and rotational fishing activities using industry data. Additional analysis of enhancement was also undertaken to supplement this review, by examining the spatial patterns and levels of spat enhancement using linear modelling approaches in relation to fishing patterns and survey catches; this modelling work was reportedly separately (Tuck & Williams 2012a). Review of the stock information comprised an investigation of the scallop population abundance, distribution, and size structure in SCA 7 using data from annual dredge surveys carried out since 1994. Key aspects were re-estimation of the biomass time series for the stock using a revised analytical procedure to better account for uncertainty in the estimates, and comparison of historical landings and estimated exploitation rates with estimates of yield calculated retrospectively.

Scallops (*P. novaezelandiae*) are sedentary, suspension feeding, broadcast spawning, bivalve molluscs found patchily distributed subtidally at a range of scales in particular soft sediment benthic habitats. They exhibit variable recruitment, relatively fast growth, and high mortality, but the rates of these processes probably vary in relation to the environmental conditions prevailing and ecological resources available to the scallops. Multiple factors, therefore, have the potential to influence scallop productivity and fishery performance. Such potential drivers of productivity are briefly discussed in this report, but have been reviewed in detail under a separate study (NIWA 2012) as a basis for new work underway to develop an ecosystem approach to fisheries in Golden Bay and Tasman Bay.

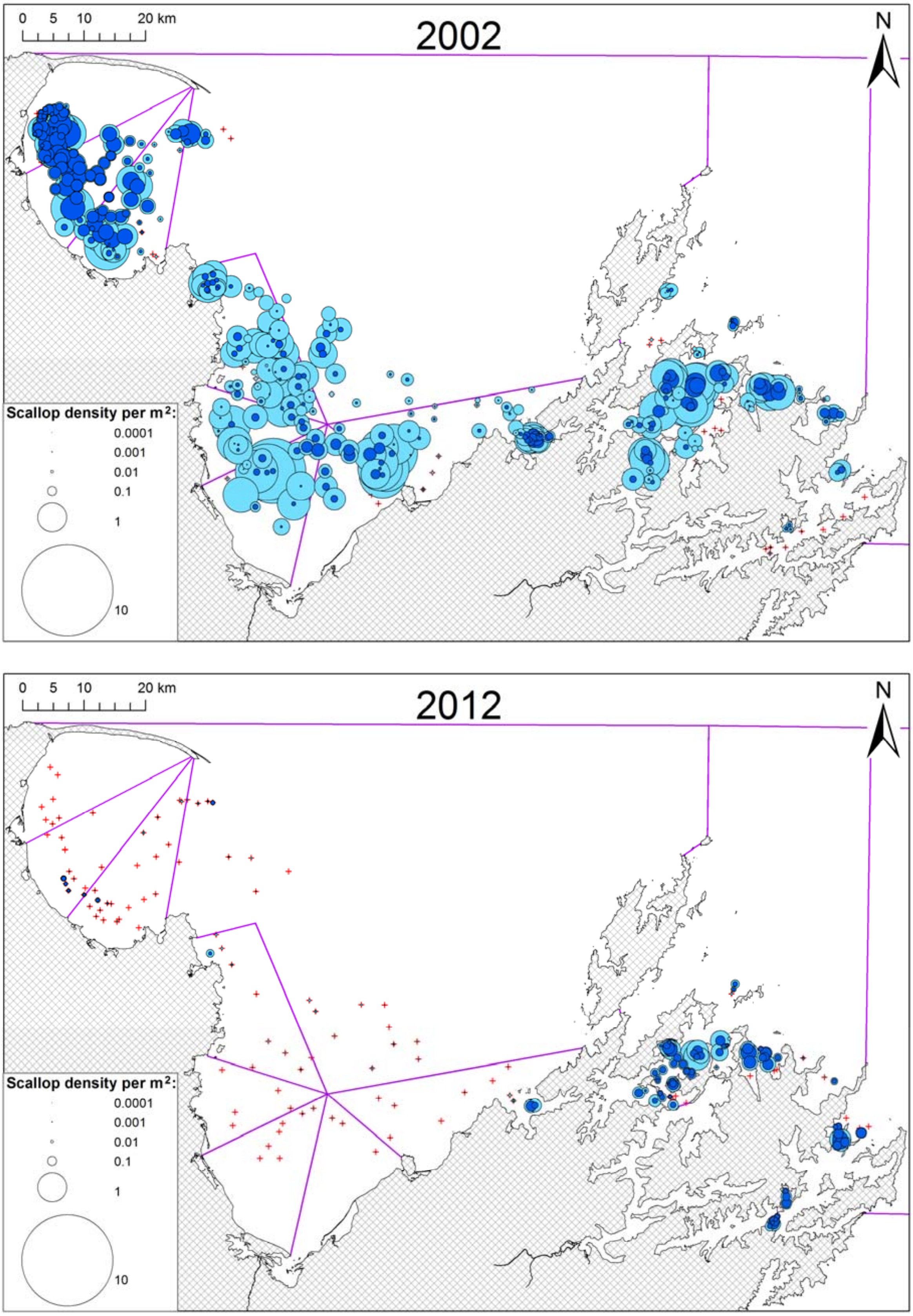


Figure 2: Spatial distribution of scallop density in SCA 7 from CSEC dredge surveys in 2002 and 2012. Circle area proportional to scallop density (m^{-2}), uncorrected for dredge efficiency. Total (light blue circles) and recruited (≥90 mm, dark blue circles) densities, and station positions sampled (red crosses), are shown.

2 FISHERY INFORMATION

2.1 Fishery overview

The Southern scallop fishery is dependent on the SCA 7 scallop stock that comprises three adjoining regions, each of which is divided into a number of sectors (statistical reporting areas) (Figure 3): Golden Bay (sectors 7AA to 7CC, and part of 7II), Tasman Bay (7DD to 7HH, and part of 7II), and the Marlborough Sounds (7JJ to 7LL). Scallops are also found to the south of the Marlborough Sounds, in 7MM, but very little if any of the harvest is taken from that sector.

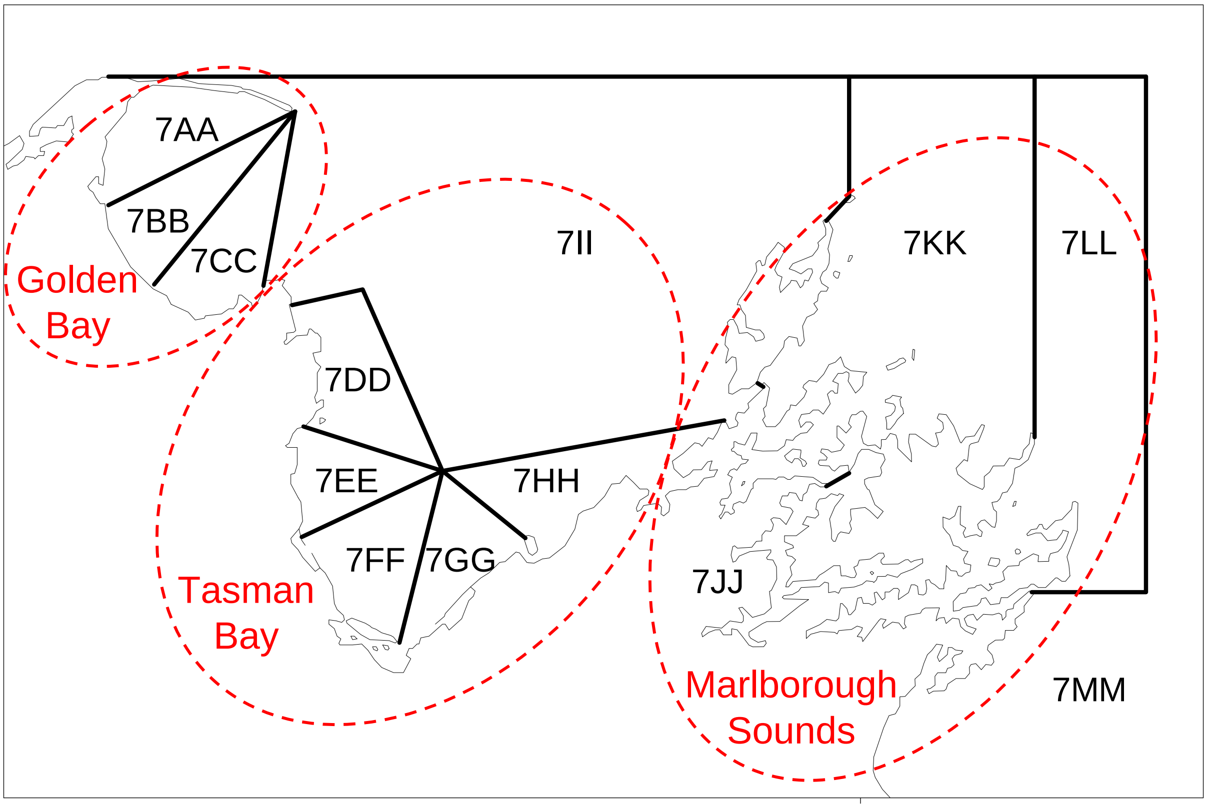


Figure 3: Sectors (statistical reporting areas) within the SCA 7 stock. These spatial definitions were introduced on 1 April 1993, but had been in use as part of the enhancement and rotational fishing plan since 1989.

Licensed commercial fishers use ring bag dredges between 2 and 2.4 metres in width to harvest scallops. Tickler chains are used, rather than the tine bars used in the northern fisheries, to avoid bogging in soft muddy sediments, where the density of scallops is comparatively low.

In the following sections on fishery information we describe: the management history that has driven many of the changes seen in the fishery, the data sources we have used to characterise the changes in catch and effort seen over the more than 50 year history of the fishery, the characterisations themselves, and enhancement and rotational fishing activities.

2.2 Management history

The regimes used to manage the Southern scallop fishery have changed considerably since commercial scallop dredging started in 1959. The history of the fishery and its management from

1959 to 1988, and the introduction of rotational fishing and enhancement as a new strategy for management, were briefly described by Bull (1990a). Arbuckle & Metzger (2000) and Mincher (2008) provide more details on the entire management history, and particularly the change to industry governance of the fishery. In brief, the Southern scallop fishery gradually developed in the 1960s as an open-access fishery with regulatory controls managed by the government, expanded rapidly in the early 1970s with intensive fishing, and declined sharply in the late 1970s despite the introduction of limited licensing in 1977. The fishery was closed for two years in 1981 and 1982. The fishery reopened in 1983 with more licensing restrictions, and techniques to enhance the stock were trialled through the 1980s. A rotational fishing management regime was initiated in Golden Bay and Tasman Bay in 1989, accompanied by commercial scale enhancement activities, while the management of the Marlborough Sounds region remained unchanged as that of a 'wild' fishery. The Quota Management System (QMS) was introduced to SCA 7 in 1992 with fixed tonnage Individual Transferable Quota (ITQ) allocations, which were later changed to proportional ITQ allocations in 1995. Most of the management responsibilities for the fishery were transferred from government to industry in 1994 when the quota owners established the Challenger Scallop Enhancement Company Ltd. (CSEC) as the formal entity to self-govern the fishery subject to conditions agreed with the government. Key documents associated with CSEC self-governance of the fishery include a Memorandum of Understanding agreement (MFish & CSEC 1998) and fisheries plans (CSEC 1998, 2005). In October 1995, legislation was passed in which the fixed tonnage ITQ allocations were changed to proportional ITQ allocations.

A more detailed overview of the management history of the fishery, including regulatory changes, is provided as follows. Exploratory dredging in Tasman Bay in 1959 led to the development of New Zealand's first commercial scallop fishery, in the early 1960s. The first licence was granted in 1960, and by 1963 there were 12 licensed vessels in the fleet, although landings started to exceed demand, and processors briefly restricted fishers to a landing limit of 20 cases per day. Commercial diving for scallops was prohibited in 1964; the reason for this has not been investigated here. Commercial scallop landings from the fishery started to decline in the late 1960s, despite some fishing further afield in Golden Bay and the Marlborough Sounds. A period of rapid expansion followed in the early 1970s, with landings, from both Tasman and Golden Bay, reaching an all-time peak of 1244 tonnes in 1975, which was taken by a fleet of 245 vessels. At this stage the only management controls in place were restrictions on the number and size of dredges, a five month closed season (February to July), and a 100 mm minimum legal size limit. Catches started to decline rapidly after 1975 and in 1977 the fishery was restricted to 136 non-transferable licences, and closed to new entrants.

A continuing decline led to the closure of the fishery in 1981 and 1982, and only 48 licenses were issued when the fishery was reopened in 1983. A range of management tools were used in this period to restrain the overall harvest from the SCA 7 stock, starting with competitive catch limits in 1979 and 1980, followed by shortened seasons and daily catch limits between 1983 and 1985, and individual seasonal allocations between 1986 and 1991 (Marsden & Bull 2006).

The potential for enhancing wild stocks was also explored in this period, as a way of ensuring sustained catch levels. Spat catching trials conducted by the Ministry of Agriculture and Fisheries (MAF) in the 1970s had indicated that, although a hanging culture industry was technically feasible, it was unlikely to be economic in New Zealand at that time (Cameron 1983). This was partially because of slow growth rates caused by fouling on cage cultures. Seeding of wild stocks (seabed culture) was considered to be a more promising and viable option. Initially small scale seeding trials were conducted in Golden Bay and the Marlborough Sounds, by Talleys Fisheries Ltd and MAF in 1982. This led to a large scale pilot survey in Golden Bay by MAF and the Overseas Fishery Co-operation Foundation of Japan. The aim of this programme was to annually seed 10 million spat between 1984 and 1987.

In 1989 an agreement was made with the licence holders to fund seeding operations, through a levy on the annual harvest. By this stage commercially viable seeding methods enabled rotational fishing in Golden Bay and Tasman Bay. The combined area of these bays was divided up into nine sectors (see Figure 4, 7AA to 7II), which were fished down on a rotational basis, followed by reseeding and closure until the seeded stock had reached harvestable size. Closed sectors prevented the incidental effects of fishing on the growth and mortality of juvenile scallops, and theoretically protected adequate stocks of potential spawners so there was considered little need to conserve the spawning stock in sectors open to fishing.

In 1992 the SCA 7 stock was introduced into the Quota Management System (QMS). The 48 license holders were allocated a fixed annual catch limit of 12 t each, with a further 64 t allocated to Maori (10% of the 640 t base TACC). Provision was also made for further allocations on an annual basis, which could be leased by the crown with preference given to existing license holders. Catch limits were set at a level to achieve a Maximum Economic Yield. In October 1995, legislation was passed in which annual quotas were fixed proportionally rather than as a fixed tonnage, which provided for greater flexibility when setting the TACC. The introduction of the 1996 Fisheries Act led to a shift from achieving the Maximum Economic Yield for the fishery, to a focus on attaining the Maximum Sustainable Yield.

A statutory Enhancement Plan was also introduced, to provide for ongoing enhancement of the fishery. Initially the enhancement was undertaken by the Challenger Scallop Enhancement Company Ltd (CSEC, which was incorporated in 1994) under contract to the Ministry of Fisheries (MFish), but in 1996 the costs of this programme were passed from the government to quota owners, who were levied directly by CSEC. A Memorandum of Understanding (MoU) was drawn up in 1997, constituting an agreement between the Chief Executive of the Ministry of Fisheries and CSEC Ltd. regarding the provision of information necessary to manage the SCA 7 fishery (MFish & CSEC 1998). Conditions for the rotational fishing and enhancement programme were set down by the Minister of Fisheries, and in 1998 an amended Enhancement Plan (CSEC 1998) was approved to better reflect the new arrangements. A revised fisheries plan was drafted in 2005 (CSEC 2005).

The current management of the SCA 7 fishery is based on annual biomass surveys, which help define biomass levels and population size compositions. The results of these surveys are used to determine which areas of Golden Bay and Tasman Bay should be open to rotational fishing in the coming season, and to set an annual catch limit for the Marlborough Sounds. Initially it was intended that rotationally fished areas were to be at the sector (statistical reporting area) level, and that these would be reseeded at the end of each fished season, as well as those areas with a low abundance of juveniles. Vessels can also be excluded from an area when a biotoxin event is identified. Over time, the size of the areas opened or closed to fishing has changed from the sector level to smaller areas within sectors. Spat reseeding activity has also decreased over time, and spat collection is now carried out cooperatively with the mussel industry, on a more *ad hoc* basis. Catch limits are negotiated annually with the Ministry for Primary Industries, and are contingent on the available sustainable harvest from areas open to fishing in that year, any adverse effects of fishing on the marine environment being avoided, remedied or mitigated, and providing for an allowance for non-commercial fishing.

2.3 Data sources

Several data sources were considered for the characterisation of the SCA 7 commercial fishery. Catch and effort data were available at differing levels of temporal resolution, depending on the data source, but it was possible to summarise all data to the level of month, or fishing year (April to March inclusive).

Catch and effort data were readily available from King & McKoy (1984) for the period 1959–80, in a monthly summary form. This was the only data source for this period and we assumed that it is a reliable summary of scallop landing statistics during the first 20 years of the fishery. The fishery was closed in 1981 and 1982, and we assumed that no scallops were commercially harvested during these years.

Daily catch and effort records were obtained from the Fisheries Statistic Unit (FSU) reporting database for the period 1 April 1983 to 30 March 1989. These data were assumed to be broadly accurate, although some minor errors were identified and corrected. Data from catch and effort tables were linked at the trip level, and landed catch weights were apportioned between reporting areas on the basis of data recorded in effort fields. A comparison of all available data sources suggested that there was insufficient catch and effort data available for the 1989–90 fishing year. The lack of catch effort data for this period is common in many inshore fisheries, as it relates to the faltering transition from the FSU to the CELR (Catch Effort landing Return) reporting systems. Figures provided in this report for that year are, therefore, based on those provided in Marsden & Bull (2006).

Extracts from CELR databases provided by MFish were initially considered for the period 1990–91 to 2008–09. Catch and effort data were linked and groomed on a trip-by-trip basis, by vessel, given a chronological sequencing of events. A considerable number of errors were readily apparent, and these were corrected where possible. Many of the errors identified were inferred from a comparison of the total estimated catch relative to the landed catch total for a trip. Many fishers tended to report landed green weights, rather than meat weights, as should be the case. Monthly landing statistics sourced from the Quota Management Return (QMR) and Monthly Harvest Return (MHR) system databases were used as a benchmark when grooming the CELR data (Figure 4). QMR/MHR statistics are regarded to be broadly reliable given the underlying compliance regime, and are thought to be less prone to confusion surrounding the reporting of meat weights (processed weight of scallop muscle plus attached roe) versus green weights (weight of live scallop in shell). The grooming of the above CELR data led to a considerable reduction in the overall discrepancy between the catch effort and QMR/MHR landing figures, but the CELR totals were still slightly different to the QMR/MHR benchmark in some years.

Investigation revealed a further source of monthly catch and effort records for the period 1996–97 to 2008–09, which provides estimates that are possibly more reliable than, but similar to, estimates derived from the initial groomed CELR data. These records were provided voluntarily by industry (CSEC), who maintain their own catch effort recording systems. The match between the CSEC and QMR/MHR monthly harvest statistic is very close (Figure 4), and the spatial distribution of effort is broadly similar to that reported on the CELR system.

More recent grooming of CELR data extracts for the years 2006–07 to 2012–13 found a close match between the CELR and the MHR totals. It appears that discrepancies between the initial groomed CELR totals and the MHR totals for 2007–08 and 2008–09 were related to the transfer of some catch to a transhipping vessel and misreporting it as destination code ‘L’ (landed) rather than ‘T’ (transhipped); subsequent landing of that catch by the transhipping vessel was reported as destination ‘L’, resulting in ‘double-counting’ of some landed catch.

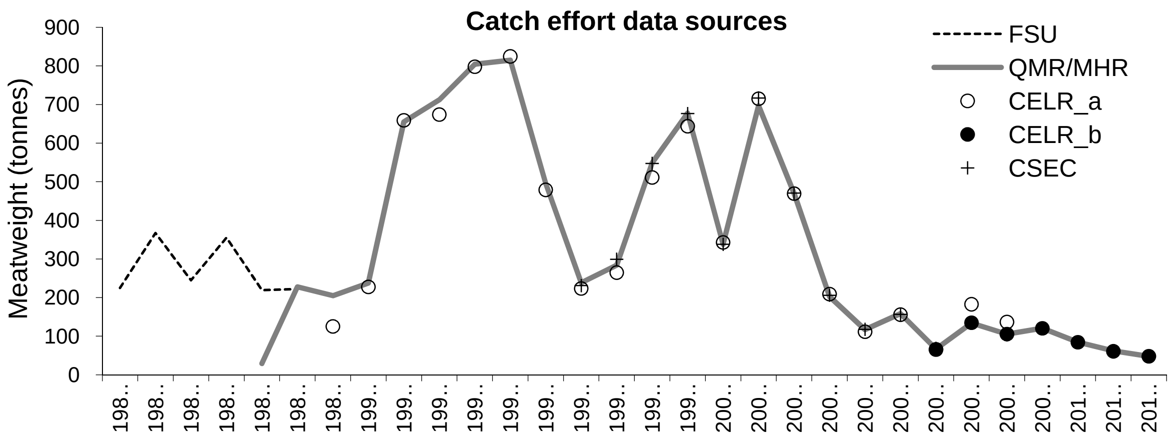


Figure 4. Catch effort data source selection based on a QMR/MHR (Quota Management Return / Monthly Harvest Return) benchmark for the fishing years 1983–84 to 2012–13. The FSU (Fisheries Statistics Unit) database is the most reliable source of catch effort data for most of the 1980s. CELR (Catch Effort Landing Return) database extracts for the years 1989–90 to 2008–09 were groomed initially (CELR_a), and subsequent CELR extracts for the years 2006–07 to 2012–13 were groomed more recently (CELR_b). CELR data were used for the periods 1989–90 to 1995–96 and 2009–10 to 2012–13, and CSEC (Challenger Scallop Enhancement Company) data were used for the intervening period 1996–97 to 2008–09. These combined data sources were used to characterise spatial and temporal catch and effort patterns in SCA 7.

2.4 Spatial reporting definitions

Both the spatial and temporal resolution of the information available is largely determined by the reporting regime in place at any given time. Fishers have been required to provide catch and effort data since the inception of the fishery in 1959, although there have been marked changes in the reporting systems used through time.

Between 1959 and 1973, scallop fishers were required to provide monthly returns on the number of landings, the quantity of scallops landed, areas fished, and the port of landing. The fishery was divided into two reporting areas, Tasman Bay/Golden Bay and the Marlborough Sounds (Figure 5). From 1965 onwards fishers were also required to report the number of days fished and the number of landings made by each vessel in each month.

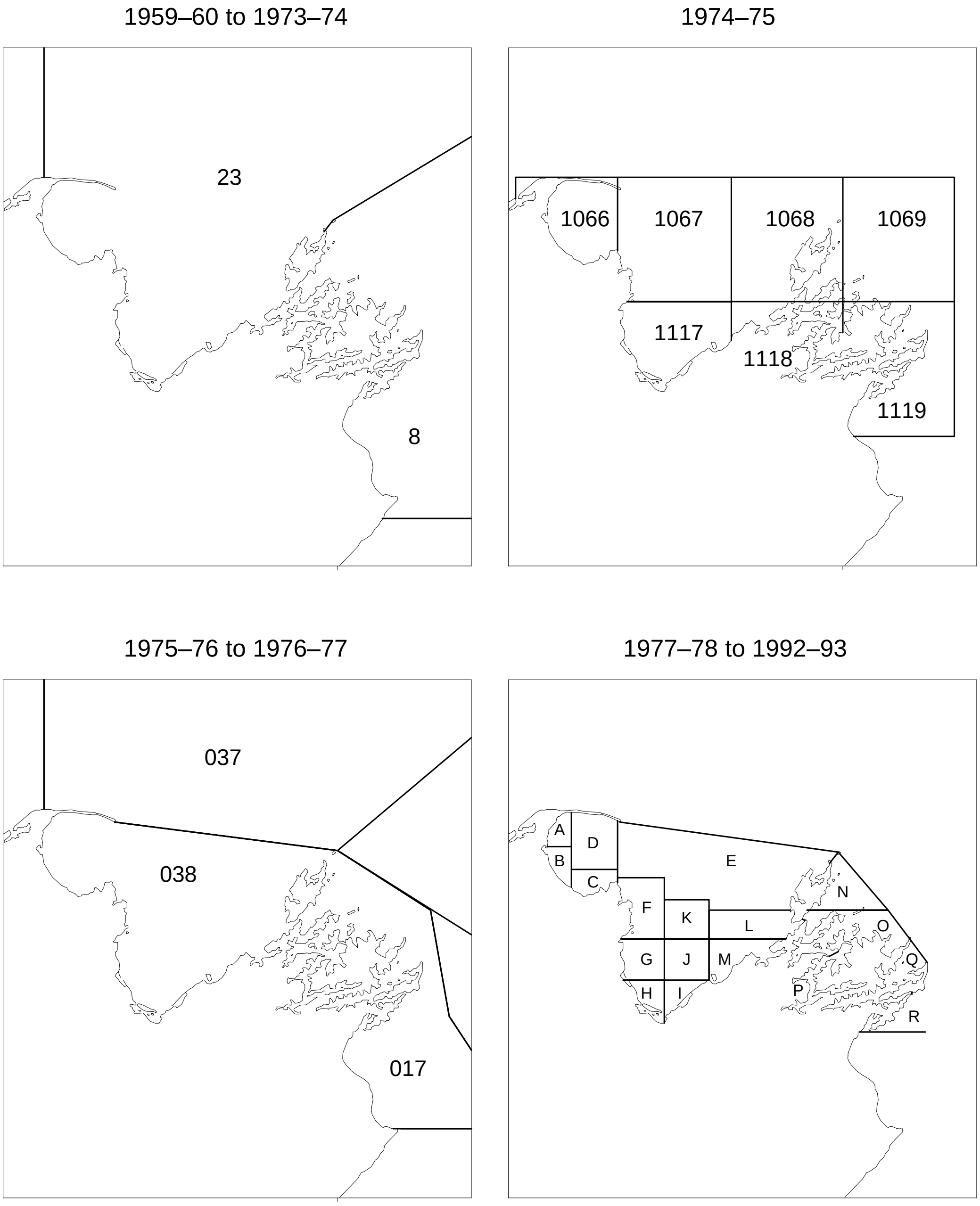


Figure 5: Statistical reporting areas used by commercial scallop fishers between 1959 and March 1993.

New reporting systems were introduced in early 1974, which provided greater detail. Fishers were required to submit records of daily landed catch and effort, in addition to the monthly returns they were already submitting. The fishery was also divided up into seven statistical reporting areas based on half degree squares of latitude and longitude (Figure 5). In 1975, fishers were asked to adopt the statistical reporting areas used for other forms of fishing, which were far coarser in their resolution. A fine scale reporting regime was introduced in 1977, which remained in place until the current statistical reporting areas were introduced on 1 April 1993 (see Figure 3).

At times, the frequent change in reporting regimes has clearly caused some confusion, as some fishers have continued to report catches from reporting areas which were no longer in use, often over many years. Fortunately it is clear where a fisher fished during the period 1959 and 1993 regardless of the area definitions used by a fisher, as there is sufficient difference in the area codes available to avoid confusion. For example, fishers fishing in Golden Bay would have either used the codes: 23 before 1974, or 1066 in 1974–75, or 038 between 1975–76 and 1976–77, or A to D between 1977–78 and 1992–93. These coding systems are, therefore, distinct in their nature, although boundary definitions vary greatly from reporting system to reporting system.

There was clearly some confusion when the catch reporting area definitions in use between 1977–78 and 1992–93 (Figure 5) were replaced by the current definitions (Figure 3). This is because the area codes 7A to 7R were replaced by the similar codes 7AA to 7MM, which have different spatial definitions. We inferred the area fished from a close and chronological examination of the data reported by each vessel, and made some minor corrections where necessary.

There is little spatial consistency in the reporting areas defined as part of the five different management regimes in use since 1959. A coarser and more consistent level of spatial definition was therefore used when characterising long term trends in catch and effort. For the first 14 years of the fishery, from 1959–60 to 1976–77, two regional definitions were used; Golden/Tasman (both bays combined, and the Marlborough Sounds. From 1977–78 onwards, three regional definitions were considered: Golden Bay (areas 7A to 7D, and 7AA to 7CC), Tasman Bay (7E to 7M and 7DD to 7II) and the Marlborough Sounds (7N to 7Q and 7JJ to 7LL) (see Figure 3).

2.5 Commercial fishery characterisation

Commercial scallop fishing effort in SCA 7 has undergone large changes over the fishery history: these changes are shown in Figure 6 in terms of the number of commercial dredge vessels operating and the total number of vessel days fished each year. In the first 20 years of the fishery, between 1959 and 1980, effort was largely unconstrained, and a period of exploration in the 1960s led to a rapid expansion of the fishery in the early to mid 1970s. Effort peaked in the mid 1970s, coincident with maximum landings from the fishery, but declined in the late 1970s before the fishery was closed in 1981 and 1982. After the fishery re-opened in 1983, the restricted number of licences permitted in the fishery meant that the number of vessels operating was much lower than in the 1970s. The number of vessels increased slightly in the 1990s but gradually decreased since about 2002. In the 2012–13 fishing year, only 11 vessels were operating (M. Campbell, CSEC, pers. comm.). From 1983 to 2002, the number of vessel days fished each year fluctuated between about 500 and 3500 days, but was subsequently followed by a declining trend and is currently at about 300 days.

Examination of the same effort data by substock from 1989 to 2012 (Figure 7) shows that fishing effort was mainly focused in Golden Bay until 2002, with particularly high levels of effort in 2001 and 2002. Effort in Tasman Bay was lower than in Golden Bay except for substantial peaks in 1993 and 2003. In the Marlborough Sounds, effort has fluctuated at generally lower levels than in the other two areas, but since 2009 fishing has occurred almost entirely in the Marlborough Sounds.

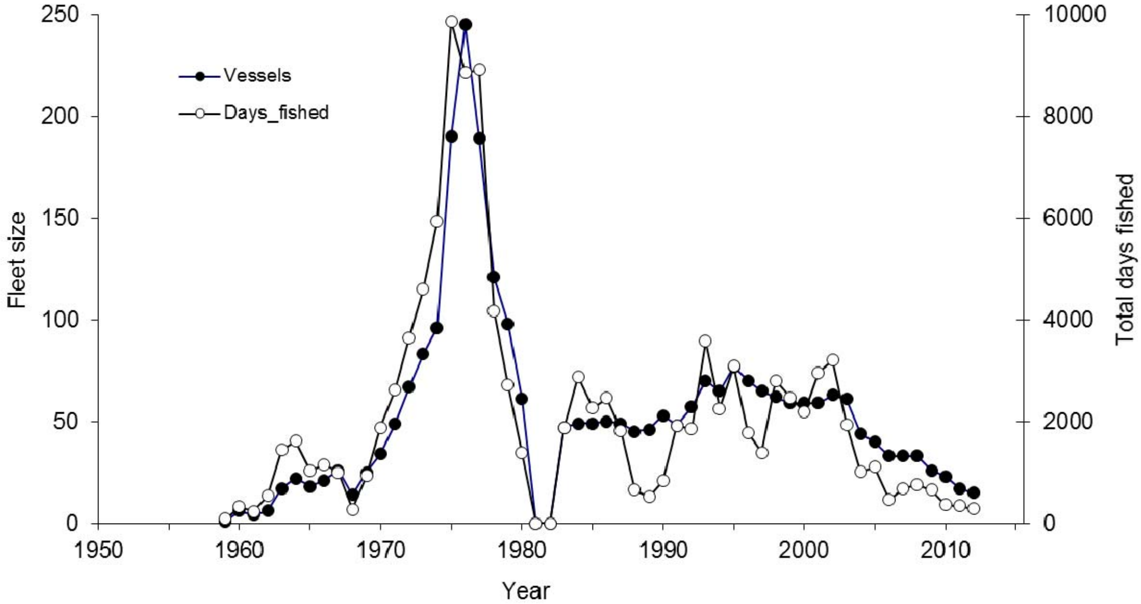


Figure 6: The number of vessels fishing and vessel days fished annually between 1959 and 2012.

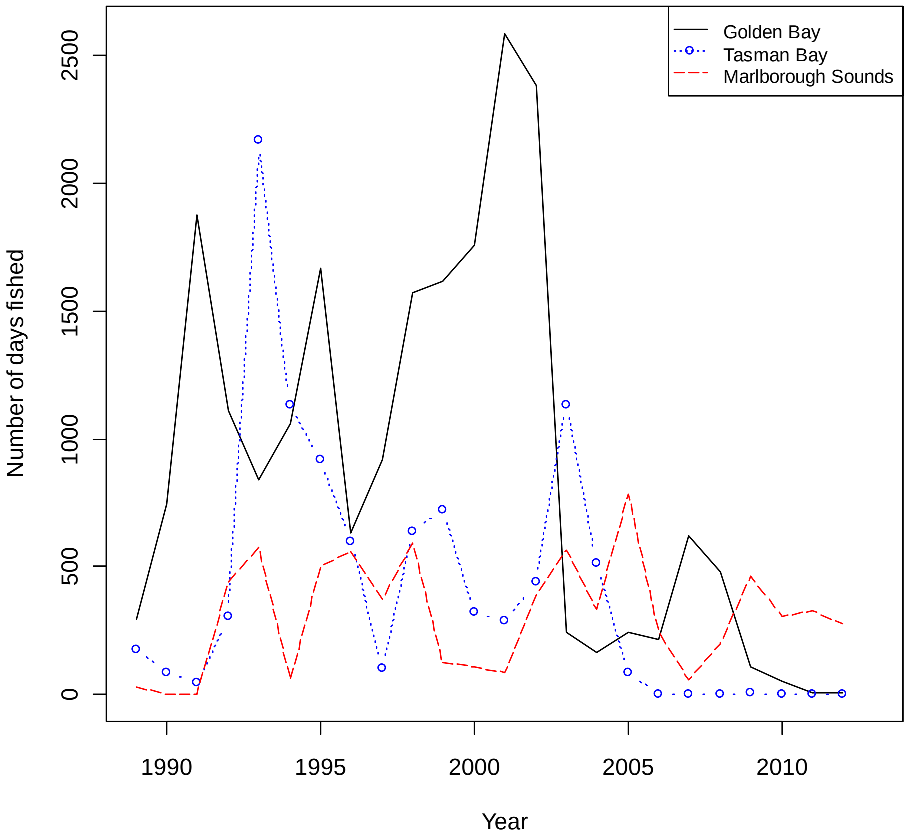


Figure 7: Number of vessel days fished annually in the three substocks of SCA 7 between 1989 and 2012.

The reported landings (in meatweight i.e., processed weight, being the adductor muscle plus attached roe) from the three regions of SCA 7 have also varied considerably over the last 50 years (Figure 8; Table 1 and Table 2). Over this time, most of the landed catch was taken from the Tasman Bay/Golden Bay area, although since about 2003 the fishery has become almost completely reliant on the Marlborough Sounds fishery because of the scallop population declines observed in Golden Bay and Tasman Bay.

In Golden Bay and Tasman Bay, landings increased as the fishery developed in the 1960s, with a small peak in the mid 1960s followed by a decline, then a rapid increase to very high levels in the late 1970s followed by a rapid decline that led to fishery closure in 1981 and 1982. After the fishery reopened in 1983, landings were moderate in the 1980s, rose to a high levels in the early 1990s and had declined again by the mid 1990s. Subsequently, Golden Bay landings rose to high levels in the early 2000s followed by a very rapid decline to low levels, and a subsequent minor peak in landings occurred around 2007 but declined to very low levels afterwards. In Tasman Bay, following the decline in landings from high levels in 1993 and 1994 to a very low level in 1997, there were two small peaks followed by declines in landings in 1999 and 2003, and there has been no commercial scallop fishing there since 2005.

In the Marlborough Sounds, landings have fluctuated at a relatively low level over the entire fishery history, but in general have been more consistently taken in most years compared with landings in Golden Bay and Tasman Bay.

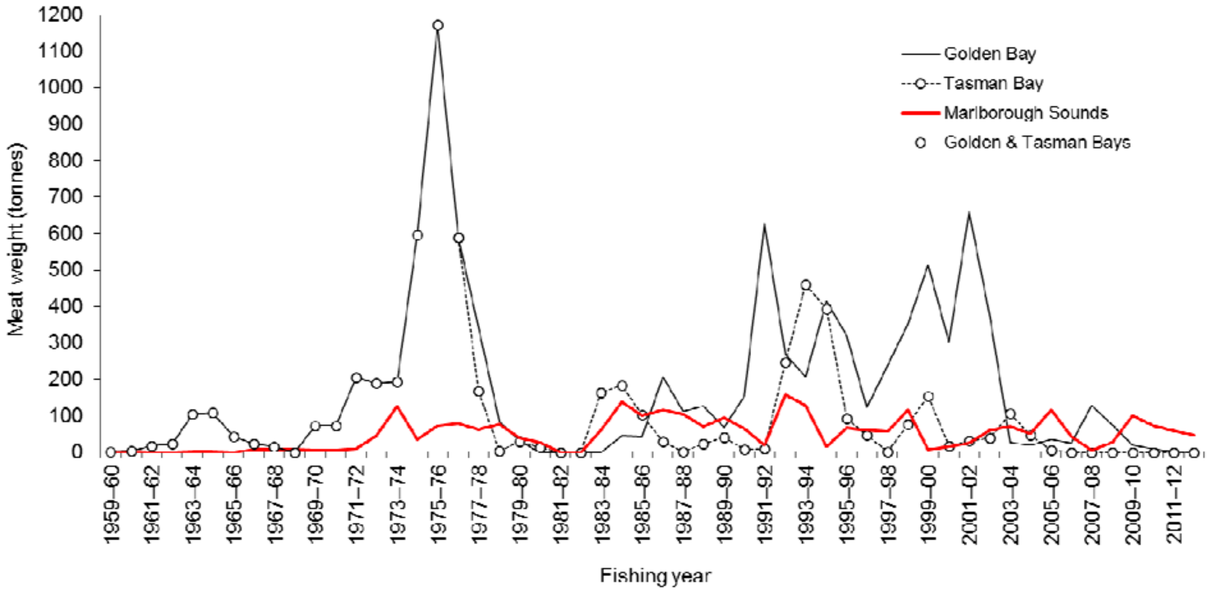


Figure 8: Annual landings by region by fishing year.

Table 1: Reported landings (t, meatweight) of scallops from SCA 7 from 1959–60 to 1982–83. The fishery was closed in the 1981–82 and 1982–83 scallop fishing years. Landings are presented by region (GB, Golden Bay; TB, Tasman Bay; MS, Marlborough Sounds) and total, except before 1977 landings were reported by the Golden Bay and Tasman Bay combined area (Gold/Tas). Data source: King & McKoy (1984).

Year	Gold/Tas	GB	TB	MS	Total	Year	Gold/Tas	GB	TB	MS	Total
1959–60	1	–	–	0	1	1971–72	206	–	–	10	215
1960–61	4	–	–	2	7	1972–73	190	–	–	46	236
1961–62	19	–	–	0	19	1973–74	193	–	–	127	320
1962–63	24	–	–	< 0.01	24	1974–75	597	–	–	36	632
1963–64	105	–	–	2	107	1975–76	1172	–	–	73	1244
1964–65	108	–	–	2	110	1976–77	589	–	–	79	668
1965–66	44	–	–	< 0.5	44	1977–78	–	342	168	63	574
1966–67	23	–	–	8	32	1978–79	–	86	4	76	166
1967–68	16	–	–	7	23	1979–80	–	32	30	40	101
1968–69	1	–	–	8	9	1980–81	–	0	14	27	41
1969–70	72	–	–	6	78	1981–82	–	–	–	–	–
1970–71	73	–	–	7	80	1982–83	–	–	–	–	–

Table 2: Reported landings and catch limits (t, meatweight) of scallops from SCA 7 since 1983–84. The fishery was closed for the 1981–82 and 1982–83 scallop fishing years, and was subsequently managed under a rotationally enhanced regime. Catch limits: TACC, Total Allowable Commercial Catch; MSCL, Marlborough Sounds catch limit (a subset of the TACC, or a subset of the Annual Allowable Catch in 1994–95). Data sources: FSU, Fisheries Statistics Unit; MHR, Monthly Harvest Returns (Quota Harvest Returns before October 2001); CELR, Catch Effort Landing Returns; CSEC, Challenger Scallop Enhancement Company. Landings are presented by region (GB, Golden Bay; TB, Tasman Bay; MS, Marlborough Sounds) and best total (believed to be the most accurate record) for the SCA 7 stock. –, no data.

	Catch limits		Landings				Landings by region and best total				
Year	TACC	MSCL	FSU	MHR	CELR	CSEC	GB	TB	MS	Best total	Source
1983–84	–	–	225	–	–	–	< 0.5	164	61	225	FSU
1984–85	–	–	367	–	–	–	45	184	138	367	FSU
1985–86	–	–	245	–	–	–	43	102	100	245	FSU
1986–87	–	–	355	–	–	–	208	30	117	355	FSU
1987–88	–	–	219	29	–	–	113	1	105	219	FSU
1988–89	–	–	222	228	–	–	127	23	72	222	FSU
1989–90	–	–	–	205	125	–	68	42	95	205	Shum. & Pars. (2006)
1990–91	–	–	–	237	228	–	154	8	66	228	CELR
1991–92	–	–	–	655	659	–	629	9	20	659	CELR
1992–93	–	–	–	712	674	–	269	247	157	674	CELR
1993–94	*1 100	–	–	805	798	–	208	461	129	798	CELR
1994–95	*850	70	–	815	825	–	415	394	16	825	CELR
1995–96	720	73	–	496	479	–	319	92	67	479	CELR
1996–97	#720	61	–	238	224	231	123	47	61	231	CSEC
1997–98	#720	58	–	284	265	299	239	2	58	299	CSEC
1998–99	#720	120	–	549	511	548	353	78	117	548	CSEC
1999–00	720	50	–	678	644	676	514	155	7	676	CSEC
2000–01	720	50	–	338	343	338	303	19	16	338	CSEC
2001–02	720	76	–	697	715	717	660	32	25	717	CSEC
2002–03	747	–	–	469	469	471	370	39	62	471	CSEC
2003–04	747	–	–	202	209	206	28	107	71	206	CSEC
2004–05	747	–	–	117	112	118	20	47	51	118	CSEC
2005–06	747	–	–	158	156	156	35	5	116	157	CSEC
2006–07	747	–	–	67	66	68	26	0	43	68	CSEC
2007–08	747	–	–	134	183	134	128	0	6	134	CSEC
2008–09	747	–	–	103	137	104	76	0	28	104	CSEC
2009–10	747	–	–	120	120	–	19	0	101	120	CELR
2010–11	747	–	–	85	85	–	10	0	74	85	CELR
2011–12	747	–	–	62	61	–	1	0	60	61	CELR
2012–13	747	–	–	48	48	–	0	0	48	48	CELR

*Annual Allowable Catch (AAC); TACCs came into force 1 October 1995.
#Initial industry controlled catch limit was 350 t in 1996–97, 310 t in 1997–98, and 450 t in 1998–99.

The spatial intensity of fishing within each of the Golden Bay, Tasman Bay, and the Marlborough Sounds regions probably differed from year to year, as fishers adapted their behaviour in response to localised fishing success. A fine scale spatial description of the fishery is not possible for the first 33 years, however, because of the varying reporting regimes implemented over this period (as discussed in the previous section). The current spatial definitions have been in consistent use since 1 April 1993 (see Figure 3), which provides some insight into the dynamics of the fishery.

A rotational fishing regime was introduced in 1989, which theoretically maximises the productivity of an enhanced stock by protecting a significant proportion of the spawning stock in any one year while minimising the disturbance of seeded juveniles and benthic scallop habitats (Breen & Kendrick 1997). The extent to which this regime was implemented is described in Section 2.8 and discussed in the context of recent management practices in Section 5.1. It is clearly evident from Figure 9, however, that the three sectors 7AA to 7CC in Golden Bay especially, were frequently, and sometimes consistently, fished in consecutive years. Most of the landings have been from sector 7BB. Close examination of the catch records suggests that rotational fishing may have occurred at the sub sector level, but the extent to which this has occurred is not clear, and Tuck & Williams (2012a) showed that over half the area was open to fishing in consecutive years. The intensity of fishing in Golden Bay may have been in response to low biomass levels in Tasman Bay, from which relatively few landings have been made. In the Marlborough Sounds, most of the annual landings have been from area 7KK, and are remarkably consistent for a scallop fishery.

There has also been a marked change in the seasonality of the commercial fishery since its inception in 1959 (Figure 10). Landings initially occurred throughout the year, at very low level, but a closed five month season was introduced in 1968. The intensity of fishing increased rapidly in the following years, and the season ended earlier in the late 1970s as the fishery rapidly declined. Since the fishery reopened in 1983, the core period of fishing each year has generally been from September to November, although in the late 1990s and early 2000s fishing continued through early summer. The period of fishing in recent years has been short, occurring from September to October.

2.6 Recreational and customary fisheries

Recreational and customary non-commercial fishers harvest scallops from SCA 7 by dredge and by diving, although there is limited information on the level of customary take. In October 1995 the recreational bag limit was increased from 20 to 50 scallops, and the minimum legal size was reduced from 100 mm to 90 mm, as part of the statutory enhancement programme agreement. Recreational fishers have access to both the wild and enhanced scallop populations, and are not subject to the area closures experienced by the commercial fishery. Estimates of annual recreational scallop harvest from SCA 7 are shown in Table 3; note that the estimates provided by telephone diary surveys are no longer considered reliable for various reasons (for more information, see Ministry for Primary Industries 2013: pp 1101-1105 of the snapper section of the Fisheries Assessment Plenary 2013). The estimates from a creel survey in 2003–04 (Cole et al. 2006) and a panel survey in 2011–12 (Wynne-Jones et al. 2013) equate to about 7–18% of the commercial harvest in the areas surveyed in those years. The annual recreational harvest level is likely to vary substantially through time.

Table 3: Estimates of the annual recreational harvest of scallops from SCA 7. GB/TB, Golden Bay/Tasman Bay. The estimates provided by telephone diary surveys are no longer considered reliable for various reasons. The 2011–12 estimate assumes a 12.5% recovery of meat from greenweight; note that the panel survey was still under review at the time that this report was written, but appears to provide plausible results.

Year	Area	Survey method	Number harvested	CV	Meat weight (t)	Reference
1992–93	SCA 7	Telephone diary	1 680 000	0.15	21.8	Teirney et al. (1997)
1996	SCA 7	Telephone diary	1 456 000	0.21	18.9	Bradford (1998)
1999–00	SCA 7	Telephone diary	3 391 000	0.20	44.1	Boyd & Reilly (2002)
2000–01	SCA 7	Telephone diary	2 867 000	0.14	37.3	Boyd et al. (2004)
2003–04	GB/TB	Creel survey	860 000	0.05	9.4	Cole et al. (2006)
2011–12	SCA 7	Panel survey	796 164	0.23	11.0	Wynne-Jones et al. (2013)

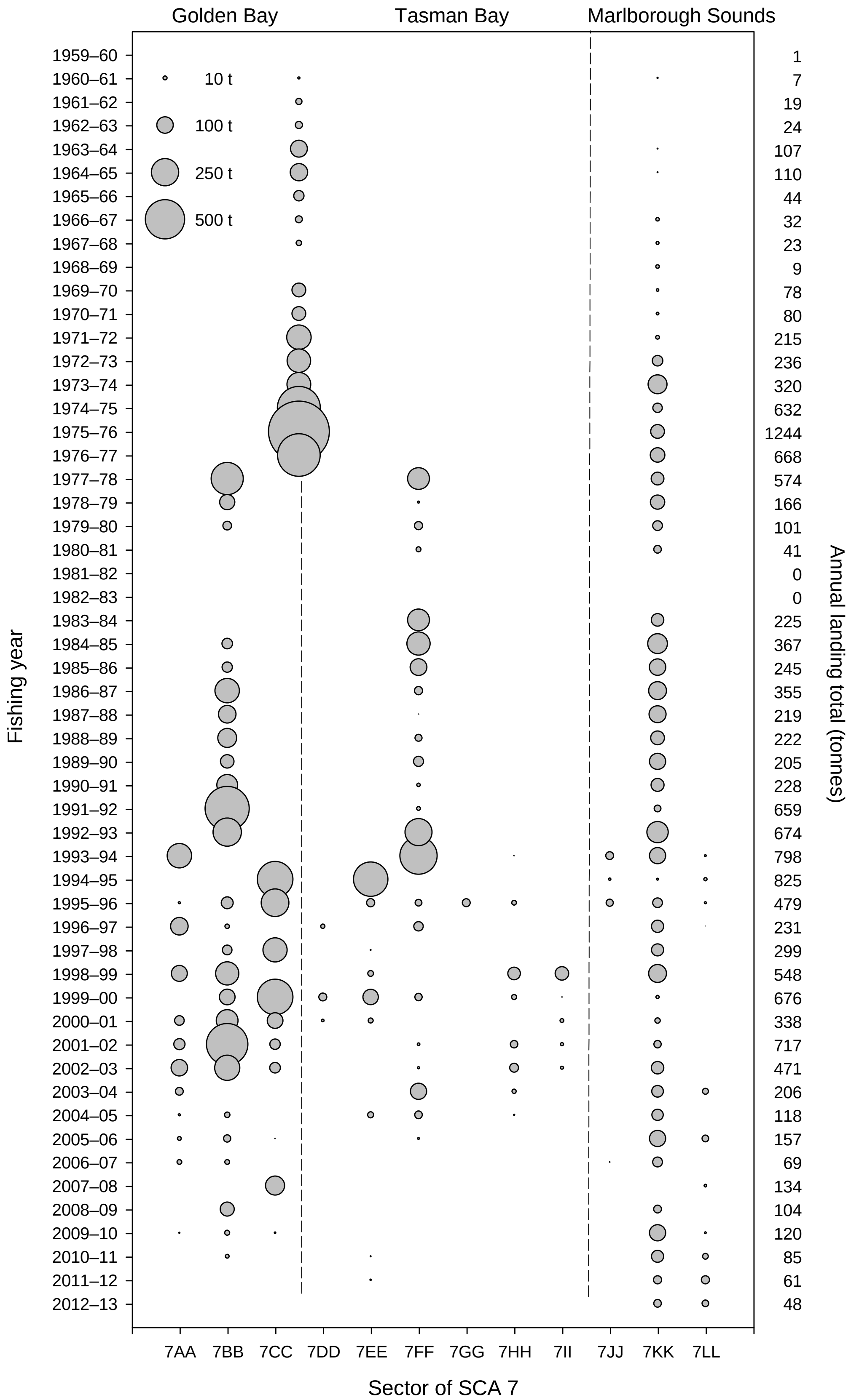


Figure 9: Spatial distribution of harvest by region, and for the period 1993–94 to 2011–12, by sector (statistical reporting area).

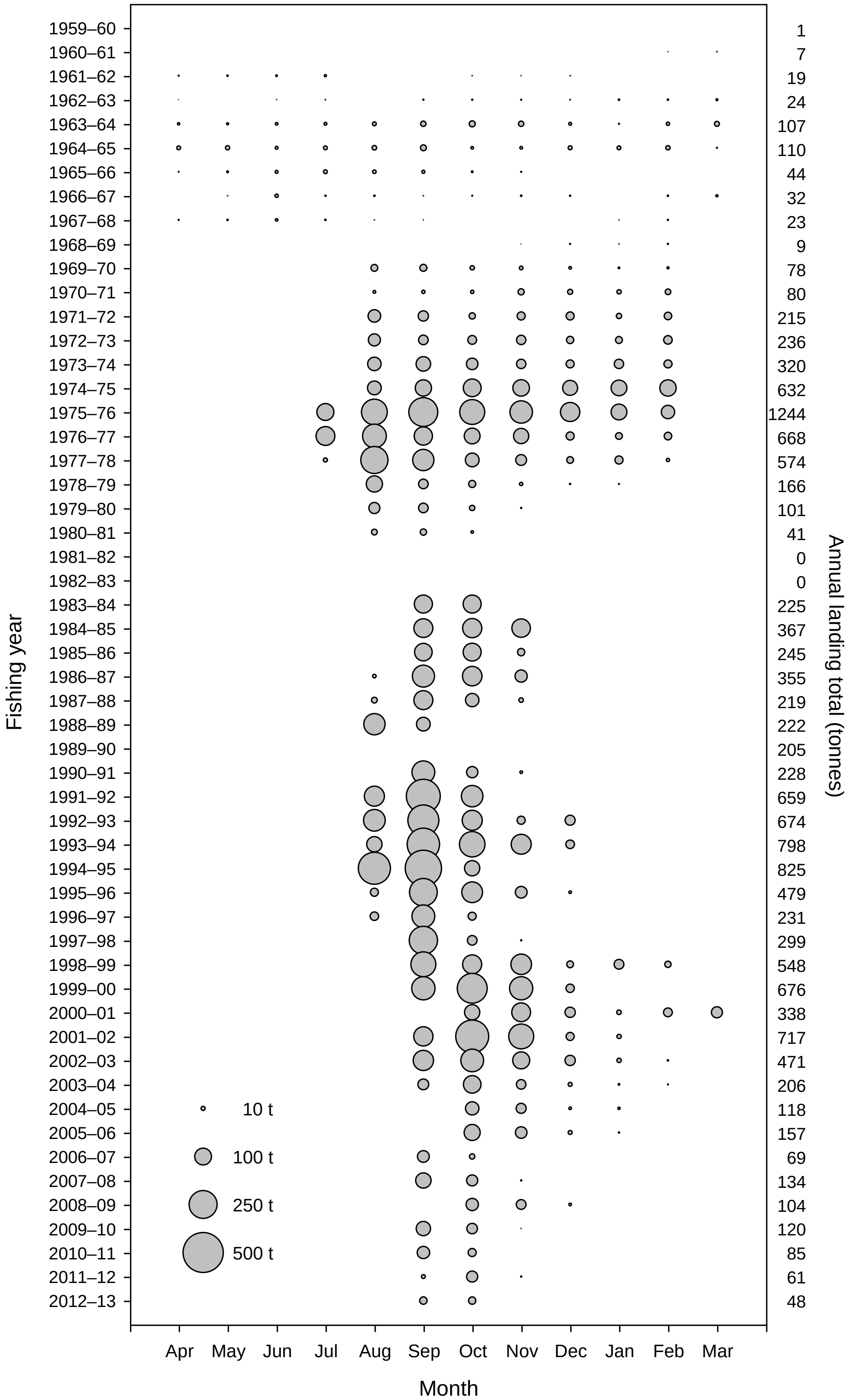


Figure 10: Monthly distribution of landings from SCA 7 since 1959.

2.7 Enhancement

Bull (1990b) reviewed the early work (1970s to 1980s) on scallop enhancement in New Zealand and described the knowledge of the methodology for seabed culture of scallops as at 1989. The methodology was based principally on experience gained from a three year pilot scale operation established in 1983 by MAF in conjunction with a Japanese organisation (The Overseas Fishery Co-operation Foundation) and on subsequent seeding work carried out by MAF. The work on New Zealand scallop enhancement was initiated following a brief study tour of scallop farming areas in northern Japan (Bull 1982).

In the New Zealand context, scallop enhancement is the collection of scallop larvae on synthetic mesh spatbags which are suspended in the water column and act as artificial settlement material which scallop larvae settle on and attach to. The larvae are grown through to small juvenile scallops (spat) and then released into the wild. Primary enhancement refers to the release of the spat (up to about 30 mm) from the spatbags. Secondary enhancement refers to the dredging of larger juveniles from areas beneath spat catching gear and their transfer to and release at other sites.

Scallop enhancement has been almost exclusively confined to Golden and Tasman Bays, although small scale trial enhancements were carried out in a number of small areas in Pelorus Sound. Bradford-Grieve et al. (1994) documented chronological details of pre-enhancement (1959–1983) records and observations relating to scallops in Tasman and Golden Bays. Test collectors (spatbags) were used by MAF in 1977, and in each year thereafter, as a method of assessing scallop spat abundance. Bulk collectors (longlines of spatbags) were used by Talleys Fisheries Ltd. in Golden Bay in the summer of 1981–82 and caught good numbers of spat (about 1600 per bag). Bulk collectors were set again in the summer of 1982–83, and subsequently were used routinely as part of the enhancement programme.

Bradford-Grieve et al. (1994) also summarised spat catches, areas seeded, survival records, harvests, and general observations for the first ten years of the enhancement programme (1983–84 to 1992–93). The first primary enhancement activity (collection and release of scallop spat from spatbags) was trialled over the summer of 1983–84: the bulk collectors set in late 1983 caught about 2000 spat per bag, and about 35 million of the spat were released into three small enhancement plots in sectors B and C (combined 3.2 km^2 area) in 1984. Subsequently, similar relatively small-scale enhancement trials were conducted each year in various areas of the two bays until 1990 when the scale of the operation was increased, followed by much larger scale enhancement operations conducted at the sector level in the early 1990s (Figure 11).

Tuck & Williams (2012a) examined various CSEC internal reports to extract data on spat monitoring, harvest, reseeding and transfer activities. Details of all scallop enhancement activities (spat collection, and levels of enhancement from primary spat harvest and secondary spat transfer) are available at a 0.5×0.5 minute grid resolution, the scale at which enhancement activities have been conducted. These were used to generate maps of the distribution of enhancement activities in Golden Bay and Tasman Bay from 1993 to 1997 (Tuck & Williams 2012a), which show that the large scale enhancement at the sector level initiated in 1991 continued at that level until about 1996, after which time the scale of enhancement decreased.

The areas that have received the most enhancement activities in the period 1992–2007 have been in the inshore waters of Golden Bay (particularly in sector B) and Tasman Bay (particularly at the eastern end of the bay) (
Figure 12). There was no enhancement in Golden Bay in 2000 or 2001, or in Tasman Bay in 2003 or since 2005. The overall area of seabed enhanced in Golden Bay and Tasman Bay has generally decreased since the mid 1990s except for a high level of (secondary spat) enhancement in Tasman Bay in 2002 (Figure 13).

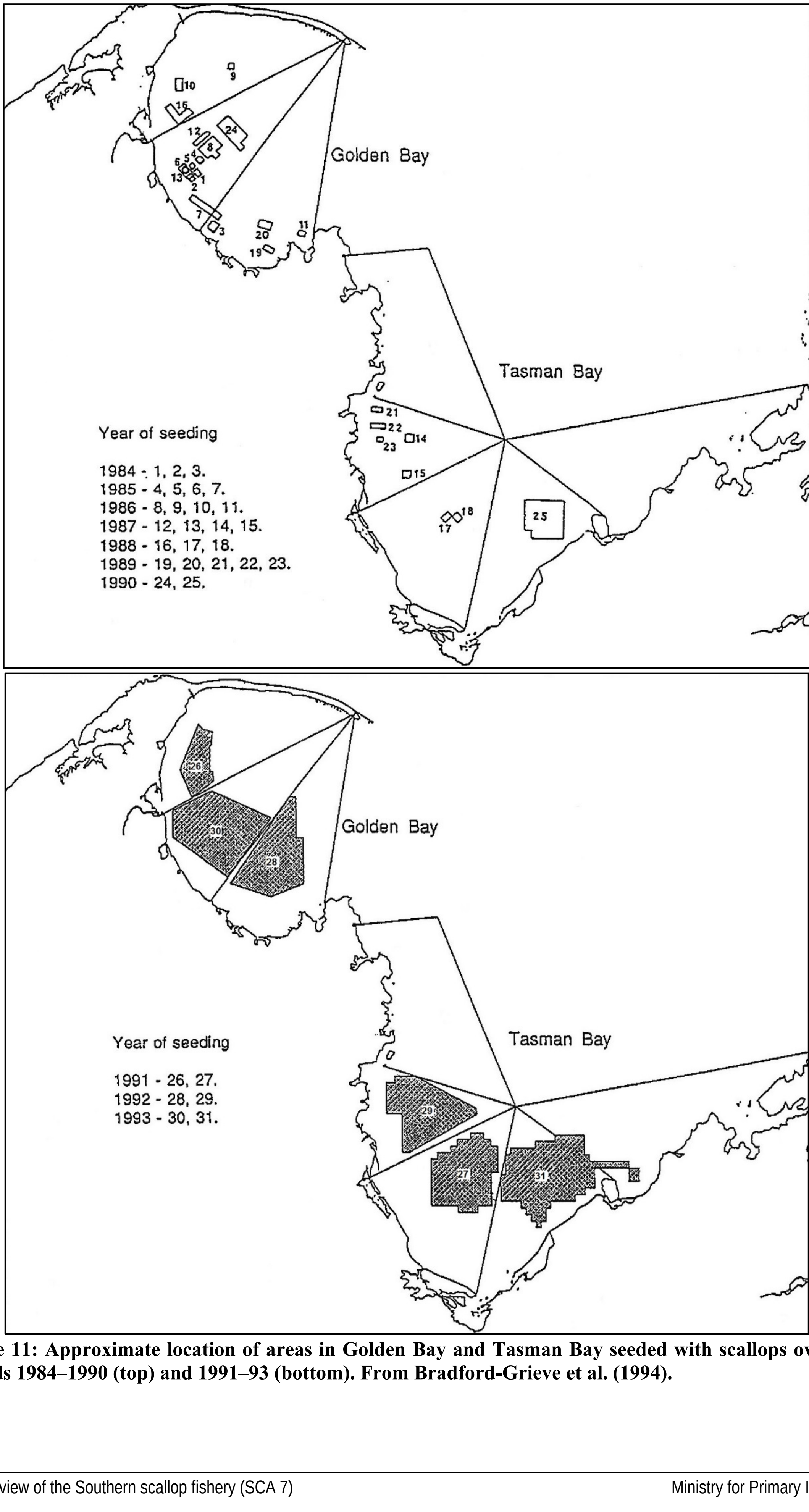


Figure 11: Approximate location of areas in Golden Bay and Tasman Bay seeded with scallops over the periods 1984–1990 (top) and 1991–93 (bottom). From Bradford-Grieve et al. (1994).

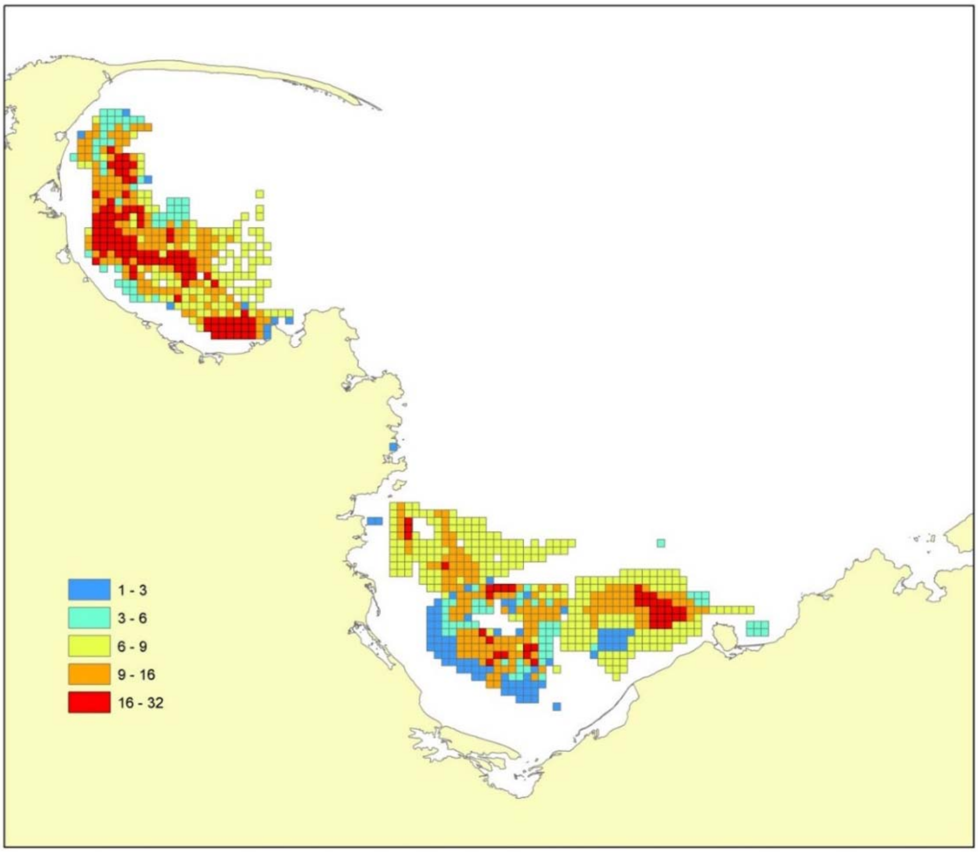


Figure 12: Number of scallop spat enhancement activities by area, 1992–2006. The shading in each grid cell represents the total number of times that cell experienced primary or secondary enhancement activities during the time period.

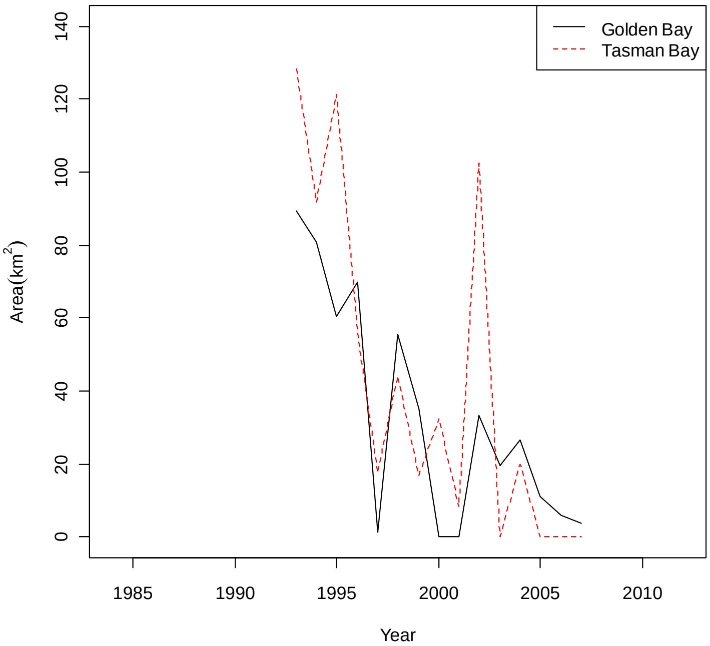


Figure 13: Area of seabed enhanced with scallops (through primary spat release and secondary spat transfer) in Golden Bay and Tasman Bay, 1993–2007. Data from CSEC reports.

Data were provided by CSEC on the amount of spat catching gear set over summer from 1990–91 to 2007–08 (Figure 14). The number of spatbag lines used in Golden Bay and Tasman Bay combined was high from 1990–91 to 1996–97 (mean = 140 lines set), moderate from 1997–98 to 1999–2001 (mean = 70), and low from 2001–02 to 2003–04 (mean = 28, lowest = 15 lines in 2003–04). The number of lines used was moderate again from 2004–05 to 2006–07 (mean = 62), accompanied by a shift in the type of spat catching gear used from spatbag lines to Xmas tree mussel rope lines, but the amount of gear used was lower again in 2007–08 (24 lines set). The use of spat catching gear has continued since then but data on the numbers of lines set were not available at the time of writing this report.

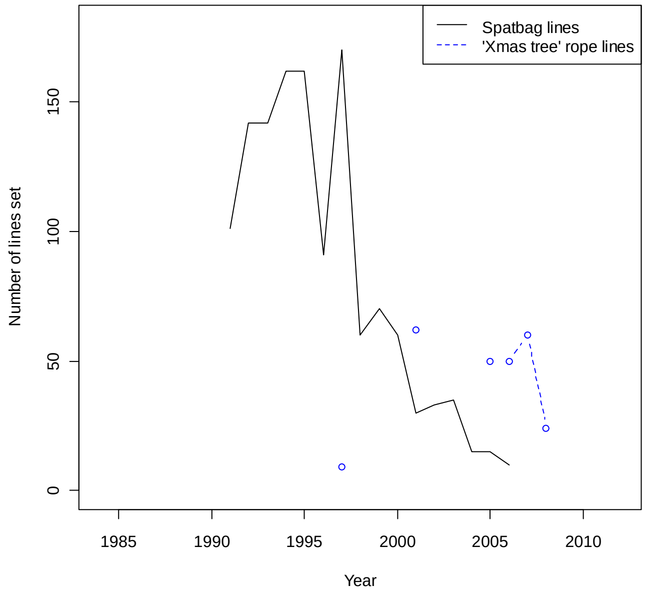


Figure 14: Total number of spat catching lines set in SCA 7 over the summers of 1990–91 to 2007–08. Two types of lines were set: spatbag lines and 'Xmas tree' rope lines. Data from CSEC.

Data on the number of primary and secondary spat harvested and released (Figure 15) were sourced from various CSEC reports The level of primary enhancement (direct collection and release of spat from spat catching gear) gradually increased in the 1980s during the initial enhancement trials period, and rapidly increased in the early 1990s as enhancement was upscaled to a commercial operation. In Golden Bay the highest levels of primary enhancement were achieved in 1992 and 1993 (mean = 605 million spat harvested and released, respectively), with medium levels in 1995, 1996, 1998 and 1999 (mean = 290 million), and a notably low level in 1997 (22 million). In 1998, spat catches were very high, and the spat harvested were released in sectors 7A and 7C (Tuck & Williams 2012a). Overall, Tasman Bay has followed a broadly similar trajectory to Golden Bay, except that primary enhancement in Tasman Bay was particularly high in 1993 (760 million) and 1995 (625 million). Like in Golden Bay, primary enhancement was also low in Tasman Bay in 1997. The levels of secondary enhancement (dredging of juvenile scallops from spat catching areas and transfer elsewhere) in both bays have in general been much lower than those of primary enhancement, and appear to have occurred in years when primary spat harvests were high (e.g., 1992 and 1998), but also when the general abundance of scallops was high (i.e. in 2002).

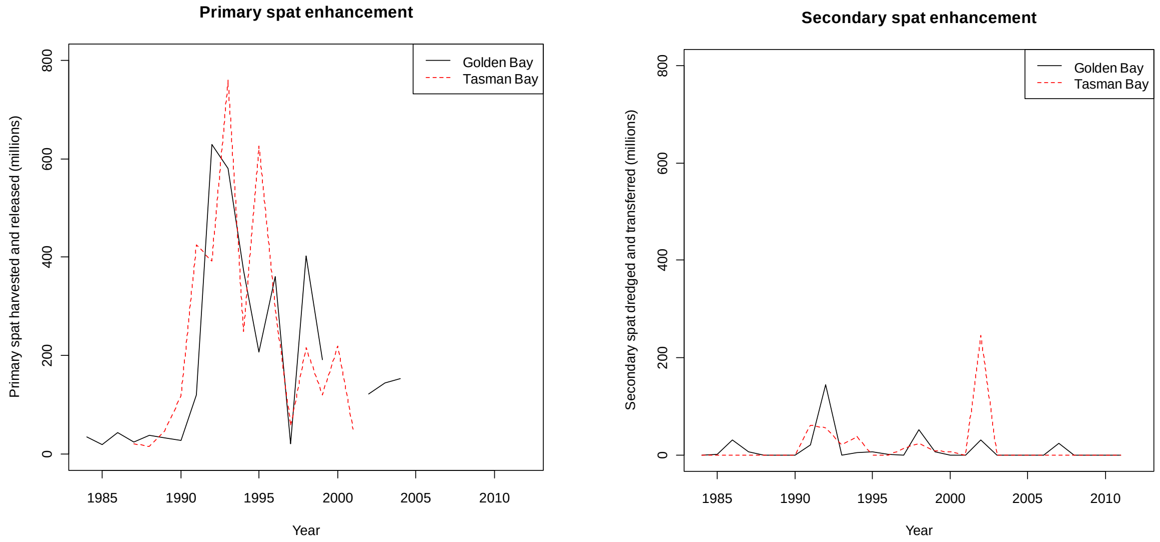


Figure 15: Number of scallop spat harvested and released in Golden Bay and Tasman Bay. Primary spat were collected in spatbags and released in reseeding areas, secondary spat were dredged from spat catching areas and transferred elsewhere. Data from various CSEC reports.

Data on the estimated mean number of spat per bag from 1984 to 2003 were also sourced from various CSEC reports (Figure 16). These data provide a coarse measure of the success of larval settlement onto the artificial collectors held in the water column in Golden Bay and Tasman Bay, although the potential effects of several other factors (such as the timing of setting and retrieving the gear, other organisms settling in the bags, water depth, and the method used to select spatbags for processing) may have resulted in these estimates not reflecting the true scallop larval abundance and settlement. Uncertainty in the estimates has not been accounted for, and it must be noted that these estimates may not be related to the levels of natural scallop settlement to the seabed. However, acknowledging these limitations, the magnitude of changes in the number of spat per bag over time suggests episodic larval settlement has occurred (Figure 16).

In Golden Bay, for example, the mean number of spat per bag decreased from about 2000 in the mid 1980s to about 300 in 1990, increased to about 4000 in 1992 followed by a decrease to about only 100 in 1997, peaked to about 4600 in 1998, and decreased to about 1700 in 1999. Spatbags were not deployed in Golden Bay in 2000 or 2001, but deployments resumed again in 2002 and 2003, with spat bag catches of about the level of the time series mean (about 1700 per bag). The estimates of mean spat per bag for Tasman Bay generally follow a broadly similar trajectory, although the timing and magnitude of the peaks and troughs in spat abundance are not entirely consistent (e.g. there is a peak in 1995 not observed in Golden Bay). Interpreting these data as a coarse measure of spat recruitment, there appear to have been two main peaks of spat recruitment in Golden Bay, in 1992 and 1998. Two similar peaks are also apparent in the Tasman Bay estimates (1991–93 and 1998) plus an additional peak in 1995 not observed in Golden Bay. Data on the mean number of spat per bag were not available after 2004, but spat catches in spatbags in Golden Bay were very high in 2012 (J. Williams, NIWA, pers. obs.), suggesting that spat recruitment (presumably resulting from an abundance of larvae) was high despite the low scallop biomass present in Golden Bay and Tasman Bay at that time.

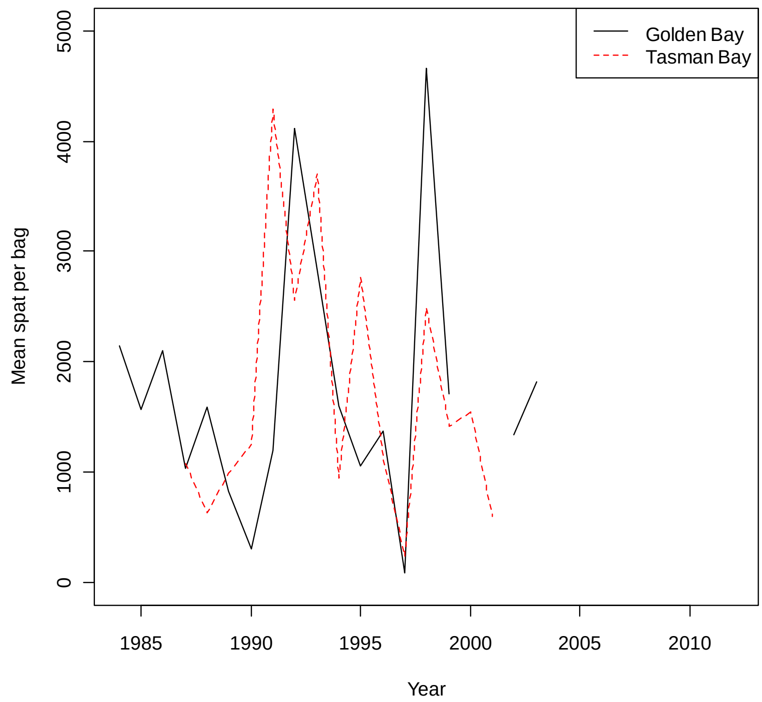


Figure 16: Mean number of spat per bag in spatbags in Golden Bay and Tasman Bay. Data from various CSEC reports.

Except for the monitoring of spat enhancement conducted during the 1980s trials (Bull 1990b), there have been no formally designed scientific studies to examine factors affecting the effectiveness of spat enhancement. The enhancement data described above were analysed by Tuck & Williams (2012a) in relation to fishing patterns and survey catches, to investigate the effects of scallop spat enhancement on scallop catches in Golden Bay and Tasman Bay. The linear modelling approach conducted suggested that primary enhancement had a significant effect on survey catches, although increased catches of recruited scallops ('commercial' size scallops of 90 mm shell length or larger) occurred two years after enhancement in Golden Bay and four years after enhancement in Tasman Bay. Secondary enhancement (release of spat collected by dredge from under spat collection sites) did not have a detectable effect on survey catches. The fishing history of an area did not appear to affect survey catches, but the rotational nature of enhancement followed by fishing may have confounded the detection of a fishing effect.

2.8 Rotational fishing

A system of rotational fishing, involving fishing on a three or four year rotation of the grounds, was considered as an alternative management regime for the SCA 7 fishery in the late 1980s (Bull 1990a), and was first implemented in SCA 7 in the 1989–90 fishing year (CSEC 1998). Under the intended 3-yearly rotational enhancement management regime, sectors (statistical reporting areas) were to be enhanced with spat, closed to fishing for two years, and then opened to fishing in the third year (after which the area would be enhanced again, and the cycle would be repeated). Sectors A, B and C in Golden Bay, and E, F, and G/H combined in Tasman Bay were the designated rotational fishing sectors; sectors D (Tasman Bay), I (spanning Golden/Tasman Bays), J, K, and L (Marlborough Sounds) were selected as non-rotational areas (do not form part of the rotational fishing programme in SCA 7) (CSEC 2005).

In the present study, an assessment of the level of rotational commercial scallop fishing in Golden Bay and Tasman Bay was made using the available information on catch by sector from CELR data, on areas fished from written reports (including Bradford-Grieve et al. (1994), CSEC (1998) and other internal reports provided by CSEC), and on areas designated as open or closed to fishing between 1996 and 2008 from Geographical Information System (GIS) layers (provided by CSEC).

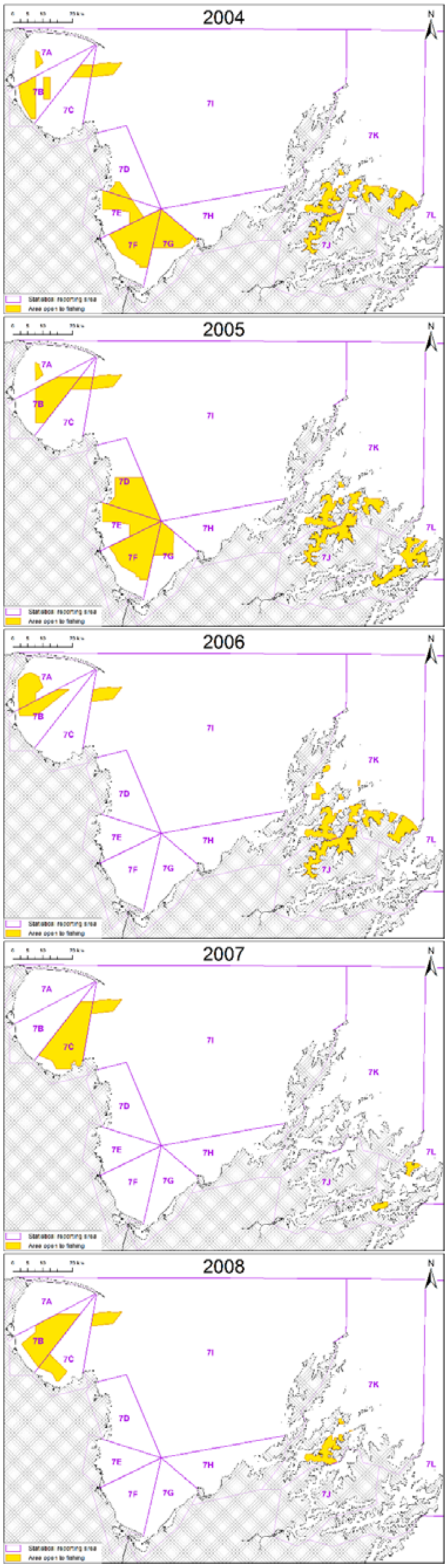
Regional landings of scallops from rotational sectors in Golden Bay (A, B, and C) and Tasman Bay (E, F, and G/H), and the proportion of the regional total landed from each rotational sector, by fishing year since 1989–90 are shown in Table 4. In the first six years of the rotational management programme, from 1989–90 to 1994–95, rotational fishing was almost entirely carried out at the sector level, with the rotation order being B, A, C in Golden Bay and G/H, F, E in Tasman Bay. Exceptions to this are that in the first year (1989) sector E was fished (rather than G/H) and in 1991–92 sector B was also fished in addition to the open sector C. For the three years from 1995–96 to 1997–98, the sector level rotation began to break down: although the majority of fishing occurred in the designated open sectors, some fishing was carried out in designated closed sectors, particularly in Golden Bay. For example, in the 1995–96 fishing year 81% of the Golden Bay landings in that year were from the designated open sector C, as per the 3-year rotation plan, 17% and 1% of reported landings were from areas B and A, respectively (which should have been closed); similarly, in Tasman Bay, fishing in 1995–96 occurred in all of the rotational sectors E–H. From 1998–99, especially in Golden Bay, sector level rotation did not occur.

Maps of the areas open to commercial scallop fishing between 1996 and 2008 also show that fishing has generally not occurred on a 3-yearly rotational basis at the sector level over this time period (Figure 17). The 3-year rotation initially intended was not followed, but instead was replaced with a practice of opening and closing different areas within multiple sectors. Such sub-area rotation has occurred in some years, but in others there was no rotational fishing at all. For example, for three years from 2000–01 to 2002–03 all three sectors (A, B, and C) in Golden Bay were open to fishing. Some sectors in particular, such as sector B in Golden Bay, have been consistently fished in most years. Note that following the decline of the scallop stock in Tasman Bay, all areas of Tasman Bay were closed to commercial scallop fishing in 2006 and have remained closed since.

Table 4: Regional landings of scallops (t meatweight) from rotational sectors in Golden Bay (A, B, and C) and Tasman Bay (E, F, and G/H), and the proportion of the regional total landed from each rotational sector, by fishing year since 1989–90. Sectors D (Tasman Bay), I (Golden/Tasman combined), J, K, and L (Marlborough Sounds) are not part of the rotational fishing programme in SCA 7. Cells outlined with a black border indicate sectors that would have been open to fishing if three yearly rotational fishing had continued at the sector level since it was initiated in 1989-90. Values in cells without a black border represent fishing that occurred out of sequence with the planned sector level rotation. Density of red shading highlights the proportional magnitude of landings in the rotational sectors.

Fishing	Regional landings from rotational sectors (t meat)		Proportion of Golden Bay rotational sector landings			Proportion of Tasman Bay rotational sector landings				3 year rotation?	
Year	Golden	Tasman	A	B	C	E	F	G	H	Golden	Tasman
1989–90	–	–	0.00	1.00	0.00	1.00	0.00	0.00	0.00	Yes	No
1990–91	–	–	1.00	0.00	0.00	0.00	1.00	0.00	0.00	Yes	Yes
1991–92	–	–	0.00	0.50	0.50	1.00	0.00	0.00	0.00	No	Yes
1992–93	–	–	0.00	1.00	0.00	0.00	0.00	0.50	0.50	Yes	Yes
1993–94	208	460	1.00	0.00	0.00	0.00	1.00	0.00	0.00	Yes	Yes
1994–95	415	394	0.00	0.00	1.00	1.00	0.00	0.00	0.00	Yes	Yes
1995–96	319	92	0.01	0.17	0.81	0.33	0.23	0.31	0.14	No	No
1996–97	123	36	0.90	0.10	0.00	0.00	1.00	0.00	0.00	No	Yes
1997–98	239	2	0.00	0.17	0.83	1.00	0.00	0.00	0.00	No	Yes
1998–99	281	78	0.33	0.67	0.00	0.22	0.00	0.00	0.78	No	No
1999–00	513	127	0.00	0.18	0.82	0.70	0.20	0.00	0.10	No	No
2000–01	294	13	0.13	0.56	0.31	1.00	0.00	0.00	0.00	No	Yes
2001–02	653	32	0.08	0.86	0.07	0.00	0.19	0.00	0.81	No	No
2002–03	363	39	0.27	0.60	0.13	0.01	0.11	0.00	0.88	No	No
2003–04	28	107	0.99	0.00	0.00	0.00	0.90	0.00	0.10	No	No
2004–05	20	47	0.21	0.79	0.00	0.38	0.57	0.00	0.06	No	No
2005–06	35	5	0.27	0.69	0.04	0.09	0.77	0.00	0.14	No	No
2006–07	26	0	0.50	0.50	0.00	0.00	0.00	0.00	0.00	No	NA
2007–08	128	0	0.00	0.00	1.00	0.00	0.00	0.00	0.00	No	NA
2008–09	76	0	0.00	0.99	0.01	0.00	0.00	0.00	0.00	No	NA
2009–10	19	0	0.12	0.69	0.19	0.00	0.00	0.00	0.00	No	NA
2010–11	10	0	0.00	1.00	0.00	0.00	0.00	0.00	0.00	Yes	NA
2011–12	1	0	0.00	0.47	0.53	0.00	0.00	0.00	0.00	No	NA
2012–13	0	0	1.00	0.00	0.00	0.00	0.00	0.00	0.00	No	NA

Figure 17: (also continued on next page) Areas open to scallop harvest in SCA 7. Maps were generated using information and maps supplied by CSEC and contained within CSEC scallop fishery performance reports. No area data were available for the years 1994–95 and 2009–13.



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3 STOCK INFORMATION

3.1 Early surveys and research

The first investigation of the scallop resource in SCA 7 was in Tasman Bay in 1959, and was documented by Choat (1960). Scallop surveys in the Nelson and Marlborough regions from 1960–82 were carried out by several workers, and the data were documented by Doonan et al. (1985) and, as stated in Bradford-Grieve et al. (1994), in unpublished MAF reports by Bull from 1978–93. These early survey data have not been analysed in the present study, which focused on the more readily available data from annual dredge surveys of SCA 7 carried out since 1994. Bradford-Grieve et al. (1994) also noted that an intensive study on scallop population dynamics (reproductive biology, larval ecology, spat settlement, and adult growth and mortality) was carried out by MAF in the period 1982–86 using Croisilles Harbour as a base, but that work remains unpublished. The data from that work were backed up to tape, but difficulties have been encountered trying to access these data.

3.2 CSEC surveys overview

The Challenger Scallop Enhancement Company (CSEC) conducts an annual stratified random biomass survey for scallops (*Pecten novaezelandiae*), and since 1998, for dredge oysters (*Ostrea chilensis*), in the Challenger fishery area (i.e., Golden Bay, Tasman Bay, and the Marlborough Sounds) (Table 5). The stratified random survey design is orthodox and well-documented, and is used to estimate resource size in other New Zealand scallop fisheries (e.g., see Cryer & Parkinson 2006, Williams et al. 2013b). Following a survey designed and conducted in 1994 by MAF (Drummond 1994), surveys have been undertaken annually through collaboration between research providers and CSEC; research providers usually assist with the survey design and sampling methods, and by carrying out analysis of the data provided by CSEC, who conduct the survey fieldwork. The survey is required by the Ministry for Primary Industries (MPI, formerly Ministry of Fisheries, MFish) under a Memorandum of Understanding agreement with CSEC (MFish & CSEC 1998), and information from the survey is used by CSEC for the development of spatial fishing strategies and consultation with other end users. Survey coverage (i.e., sample extent) for the 1994 to 1997 surveys was limited to particular areas of interest at that time, but survey coverage from 1998 to 2013 has been consistent, in that the same overall area was sampled each year, except that neither Golden Bay nor Tasman Bay were surveyed in 2013.

Following a meeting in December 2007 held at the Nelson office of MFish between representatives from CSEC, MFish, and NIWA, a number of areas within the existing SCA 7 scallop survey analytical methodology were identified where there was potential to improve the analytical workup. These areas included meatweight conversion factors, dredge efficiency, growth parameters, the propagation of variance, and calculation of Current Annual Yield (CAY) for the Marlborough Sounds area (Tuck & Brown 2008). Consequently, the SCA 7 survey workup methodology was revised by using an adaption of the approach employed for the workup of the Coromandel and Northland scallop surveys (Cryer & Parkinson 2006). The revised workup methodology was used for the 2008–13 SCA 7 survey analyses (Tuck & Brown 2008, Williams 2009, Williams et al. 2010, Williams & Michael 2011, Williams & Bian 2012), and in the present study it was used to re-estimate scallop biomass for the years 1998–2007, thus providing more robust estimates of scallop biomass since extensive surveys (comparable survey coverage) began in 1998.

Table 5: List of reports documenting the SCA 7 dredge surveys, 1994–2013.

Year	Reference
1994	Drummond (1994)
1995	Vignaux et al. (1995)
1996	Cranfield et al. (1996)
1997	Cranfield et al. (1997)
1998	Osborne (1998)
1999	Breen & Kendrick (1999)
2000	Breen (2000)
2001	Horn (2001)
2002	Horn (2002)
2003	Horn (2003)
2004	Horn (2004)
2005	Horn (2005)
2006	Horn (2006)
2007	Brown (2007)
2008	Tuck & Brown (2008)
2009	Williams (2009)
2010	Williams et al. (2010)
2011	Williams & Michael (2011)
2012	Williams & Bian (2012)
2013	Williams et al. (2013a)

3.3 Survey objectives

The MoU agreement between the Ministry and CSEC (MFish & CSEC 1998) specifies that the SCA 7 survey should provide estimates of:

- the population structure, distribution and abundance (numbers and biomass) of scallops one year and older in all survey strata areas;
- the meatweight of recruited scallops above a commercial threshold density;
- for the Marlborough Sounds, numbers, biomass, and density of recruited scallops.

Recruited scallops are those of 90 mm or larger in shell length, and pre-recruit scallops are those measuring 89 mm or smaller. Breen (1995) used data from Bull (1976) on the length and estimated age of scallops in Pelorus Sound to model scallop growth: the resulting von Bertalanffy growth curve predicts that scallops reach about 50 mm in length at age one (however, estimates of pre-recruit scallop abundance from the SCA 7 dredge surveys have not distinguished between those larger than or smaller than this size: instead, the pre-recruit estimates are for all scallops less than 89 mm). The MoU agreement also specifies that strata are to be no larger than sectors (statistical reporting areas) and that the target CV on biomass estimates should be 10–20%.

Additional objectives for the survey are usually to:

- estimate the meatweight biomass of scallops at the start of the season, using a range of commercial density thresholds from 0.00 to 0.20 recruited scallops per square metre;
- determine the population structure, distribution, and relative abundance of oysters within the Nelson-Marlborough dredge oyster fishery;
- estimate a Current Annual Yield (CAY) for scallops in the Marlborough Sounds from absolute abundance estimates;
- collect additional data on scallop meatweight recovery and bycatch composition.

Before each survey, specific CV targets were set for the areas where CSEC proposed to conduct scallop harvesting in the coming fishing year. Surveys up to 1999 attempted to meet a CV target of 10–20% for each estimate (biomass or numbers) for each size (recruited or pre-recruit) for each species (scallops and oysters) in each sector – a very difficult optimisation given the patchy distribution of scallops (i.e., large variability in shellfish density and size within sectors). Specifying a smaller subset of targets at more rigorous levels permits a more efficient survey (Breen & Kendrick 2000); such a methodology has been used in surveys since 2000.

3.4 Survey methods

3.4.1 Survey design

The SCA 7 survey has used a 2-phase stratified random dredge survey design, although the second phase of sampling has not been conducted in surveys since 2011. Strata have usually been defined in each survey year based on the results of previous surveys, knowledge about the previous year's fishing patterns, pre-release surveys in areas of spat reseeding, spat reseeding activity, and monitoring of reseeded stocks. In 2012, NIWA provided a new stratification for the survey based on a review of the available data on scallop distribution from past surveys and information provided by fishers. The same stratification was used again in the 2013 survey of the Marlborough Sounds, although Golden Bay and Tasman Bay were not surveyed because of the expected low scallop abundance.

In 1998, the scallop dredge survey was extended to include dredge oysters, which are found in the same general areas as scallops in Tasman Bay and Golden Bay, and also in deeper areas in these bays. Since 2005 the surveys have included additional strata in an attempt to achieve more precise estimates of relative oyster biomass, but until the 2012 survey, strata had not been optimised for the distribution of oyster density; in 2012 the strata in Tasman Bay were designed primarily to optimise the precision of oyster estimates. However, estimates of dredge oysters were not produced in 2013 because neither Tasman Bay nor Golden Bay were surveyed.

Survey coverage (sample extent) in the past has varied among years somewhat, because the aim of those surveys was to assess the status of the main scallop beds likely to be fished in the coming season, rather than for the survey coverage to encompass the main beds of the whole stock to provide an index of abundance representative of the status of the overall population. Surveys since 1998 are generally comparable in that they covered the same overall area. The overall extent of CSEC surveys to 2011 is shown in Figure 18.

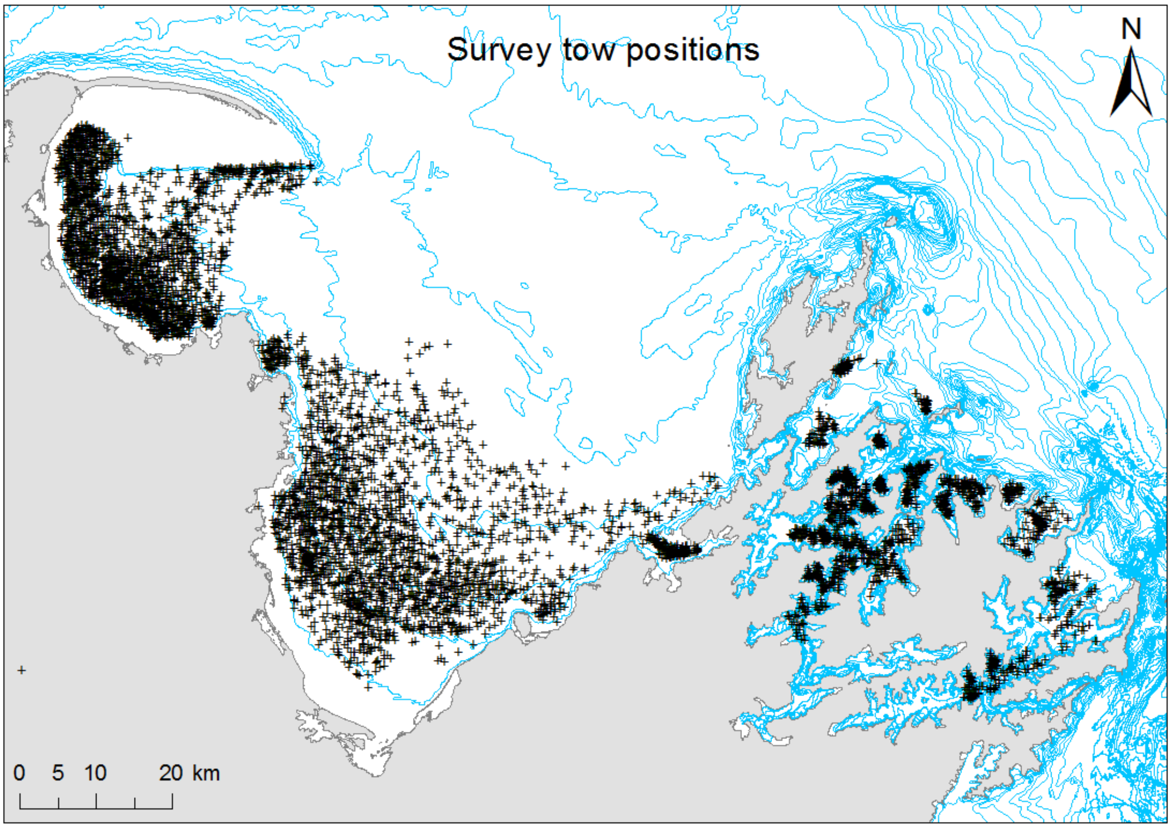


Figure 18: Survey coverage (sample extent) for the CSEC surveys, 1994–2011. Crosses indicate the mid-points of survey dredge tows (all years), with 10 m depth contours shown overlaid.

In reviewing the purpose of the SCA 7 surveys, the MPI Shellfish Fisheries Assessment Working Group agreed in 2012 that important aspects of the survey are consistency of survey coverage (sample extent) among years to maintain a standard series, and the ability to provide biomass estimates by region. In designing the 2012 survey therefore, special consideration was given to reviewing the available data on scallop distribution from past surveys and information provided by fishers, to ensure that the 2012 survey coverage included the main areas surveyed historically, together with any other areas that are known or expected likely to contain substantial scallop beds. Consequently, the 2012 survey coverage was more extensive than used previously, with the stratification comprising 'main' strata (those surveyed and fished consistently in the past), and 'deep' strata (those in deeper areas in the outer parts of Golden and Tasman Bays that have never been surveyed before) (Williams & Bian 2012). Strata for the 2013 survey of the Marlborough Sounds were unmodified from those used in the 2012 survey of that region.

Surveys were usually optimised to achieve the target CV of 10–20% on the estimate of recruited biomass. For example, in the 2013 survey project, a theoretical optimum station allocation was generated using the R function *allocate* on the basis of the 2011 and 2012 survey data (a minimum of three stations per stratum was specified). This allocation was then modified to produce the final allocation by considering operational and logistical constraints on the survey, including the maximum number of dredge tows possible in a sampling day and the time required to steam between stock regions. Strata that were sufficiently close together to tackle in a single day were grouped. Up to about 20 shots can be completed in a problem-free day with little steaming, so the number of stations allocated to strata within regions from the optimisation was adjusted according to their relative stratum sizes and a semi-quantitative understanding of historical performance. The positions of stations within strata were randomised using ArcGIS® software by ESRI, constrained to keep all stations at least 200 m apart; this software estimates the area of each stratum, and gives the latitude and longitude of each random station.

3.4.2 Dredging and catch sampling procedure

The surveys were carried out by CSEC in May–June each year. All sampling was undertaken using the same dredge (Challenger standard ring-bag dredge 2.4 m wide) and whenever possible using the same vessel and key staff as used in previous surveys. Dredging operations were also consistent with the following standard procedure. The vessel was positioned at the random station with non-differential GPS, giving accuracy to within a 30 m radius about 95% of the time. The dredge was deployed from a winch at the stern, using a warp with length three times the water depth. The tow began when the brakes were set, and ended when winching began. The normal target tow length was 0.4 n.miles, but this was reduced to 0.2 n.miles where very high catches (of scallops, by-catch, and/or sediment) were expected based on adjacent station results. The actual tow length was calculated with plane geometry from the logged GPS positions at the beginning and end of the tow. The tow direction was taken from a list of random compass bearing directions, although it was permitted to vary at the skipper's discretion if required (e.g., to avoid stratum boundaries, foul ground, obstructions).

The survey catch was sampled by CSEC personnel. Sampling procedures were largely the same as those described in a catch sampling manual supplied by NIWA (Breen & Kendrick 2000), except for some important modifications in 2009 to ensure that the survey data collected were in the form required by the revised analytical approach (used in SCA 7 for the first time in 2008; see Tuck & Brown (2008)).

In surveys before 2009, when contents of the dredge were not too large for the entire catch to be sorted, all scallops and oysters were removed from the catch. When the dredge catch was too large to permit this, dredge contents were loaded into fish cases and weighed with a motion-compensated balance tared for the average fish case weight. Contents in a sub-sample of these cases was sorted, and a scaling factor calculated as the total catch weight divided by the subsample weight. Numbers and weights of oysters and scallops were then scaled up by this factor from the subsample to the entire catch at the data analysis stage. Scallops and oysters were then sorted by size into recruited and pre-recruit fractions and both fractions were counted and weighed. Recruited scallops are those that have a length of at least 90 mm; recruited oysters are those that cannot be passed through a ring of 58 mm inside diameter. From each tow, for scallops, a random selection of each of the pre-recruit and recruited fractions was made, in rough proportion to their relative abundance in the sample, and up to 100 scallops were measured for shell length. Up to 50 oysters were selected and measured for shell length, shell width, and shell depth.

In surveys since 2009, the entire contents of the dredge were sorted and all scallops and oysters were removed from the catch and placed into fish bins. There was no sub-sampling of the unsorted catch (and, therefore, in contrast with surveys before 2009, there was no need to apply a catch 'scaling factor' during the data analysis). All scallops in the catch were counted. There was no direct weighing of the scallop catch, unlike most previous surveys. Usually, all scallops were measured for length (along the anterior–posterior axis) rounded down to the next whole millimetre below actual length. Very large catches were subsampled for length: all scallops from the random subsample were measured for shell length, and all unmeasured scallops were counted.

During most surveys before 2008, from most tows containing more than 20 scallops, a sample of up to 50 individuals was retained and shucked by experienced shellfish openers within 24 hours of capture to calculate a time of survey greenweight to meatweight conversion factor for predicting biomass in meatweight. CSEC did not undertake time of survey meatweight sampling during the 2008–13 surveys. Instead, historical data on meatweight recovery were used to estimate meatweight biomass.

In addition to scallop and oyster sampling, large starfish (suspected to be *Coscinasterias* sp.) were also sorted from the catch and counted and/or weighed, and the nature of remaining bycatch at each station was also characterised: the total number of cases of bycatch and the percentage in each bycatch category (green-lipped mussels, coral, shell, algae, bryozoa, other starfish, horse mussels, hermit crabs, volutes, and other gastropods) was visually estimated and recorded. Not all bycatch categories were used in all surveys, and between 2004 and 2008, counts and weight of green-lipped mussels were recorded instead of the estimated mussel percentage composition of the catch. These bycatch data have been used to produce preliminary estimates of survey bycatch abundance (Appendix 1), but detailed analysis of these data was beyond the scope of the present study.

Data were recorded on pre-printed waterproof forms. Details of each tow (date, tow start and finish times and positions, sea state, depth) and the results of catch sampling (scallop numbers and lengths; oyster, green-lipped mussel, and starfish numbers, data on the composition and relative abundance of other components of the bycatch and sediment characteristics) were recorded and entered into a spreadsheet. CSEC checked the entered data against the vessel's GPS log and verified all other data against the station sheets. Responsibility for error checking fell primarily with CSEC, and the data were forwarded to NIWA for analysis. Before embarking on the analysis, NIWA also undertook routine data checking and verification, and suspected errors identified were referred back to CSEC to resolve.

3.4.3 Survey data analysis

The revised analytical approach to estimating start-of-season recruited biomass for scallops was modified from that developed during the 2002 and 2003 Coromandel and Northland scallop stock assessments, and used subsequently (Cryer & Parkinson 2006). This approach is based on raised length distributions of scallops, and was used to analyse SCA 7 survey data for the first time in 2008 (Tuck & Brown 2008). In brief, the approach contains the following ten 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 ($W = 0.00037 \times L^{2.690}$). 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. A CV of 0.065 is assumed for 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. Biomass was estimated above five commercial density thresholds (0.00, 0.04, 0.08, 0.16 and 0.20 recruited scallops m^{-2}). These are assumed densities below which commercial fishers would stop fishing.
10. The final step in the analysis is the prediction of meatweight from expected start-of-season greenweight. Analysis of recovery of meatweight from greenweight in SCA 7 in 13 previous

fishing seasons (1996 to 2008) suggests that seasonal recovery varies among regions from about 10% to about 15%, with an overall mean of about 13%. Uncertainty in predicting meatweight recovery is incorporated for each region of SCA 7 by selecting one of the 13 seasonal averages for each bootstrap estimate of start-of-season recruited biomass (in greenweight).

3.4.4 Use of SCA 7 parameters in survey workup

3.4.4.1 Dredge efficiency

An estimate of mean dredge efficiency (0.70, Cranfield et al. 1996) was used to produce estimates of absolute scallop abundance from 1996 to 2003 (Cranfield et al. 1996, Cranfield et al. 1997, Osborne 1998, Breen & Kendrick 1999, Breen 2000, Horn 2001, 2002, 2003). New (lower) estimates of mean dredge efficiency (0.34–0.56, depending on substrate type and depth) derived by Handley et al. (2004) were used to produce estimates of absolute scallop abundance from 2004 to 2006 (Horn 2004, 2005, 2006). In 2007, Brown (2007) produced estimates of absolute scallop abundance by correcting for dredge efficiency using averaged efficiency values from both studies (Cranfield et al. 1996, Handley et al. 2004). However, whilst correcting for dredge efficiency using simple scalars of mean efficiency can produce reliable estimates of absolute scallop abundance, uncertainty in the estimates is grossly underestimated because that approach does not account for additional variability associated with dredge efficiency. Consequently, Tuck & Brown (2008) reanalysed the available data from concurrent dredge and diver abundance surveys from both studies (Cranfield et al. 1996, Handley et al. 2004) to provide more robust estimates of dredge efficiency and associated variance. Their analytical methodology was adapted from the non-parametric bootstrap (resampling with replacement) procedure used for the northern scallop fisheries (Cryer & Parkinson 2006), and was applied in the analysis of SCA 7 survey data from 2008 to 2013 (Tuck & Brown 2008).

Within the current approach (used since 2008), data from concurrent dredge and diver abundance surveys were used by Tuck & Brown (2008) to provide estimates of dredge efficiency and associated variance. The efficiency of a dredge can be calculated as the number of scallops retained by the dredge divided by the number of scallops collected by divers in the same location. To do this, it is necessary to compare densities rather than actual counts, as the areas swept will differ, and to assume that the divers have collected all scallops present in the area they sweep (i.e., divers are 100% efficient).

Dredges are expected to be more efficient at catching larger scallops than smaller ones, and it is therefore necessary to partition the data into meaningful size bins, yet take associated sample sizes into account. In their study, Tuck & Brown (2008) were subject to the constraint that most of the length frequency data available were grouped into irregular sized length bins, and were not available in the form of individual scallop measurements. They were, therefore, compelled to calculate efficiencies for the length classes: 0–83 mm, 84–88 mm, 89–99 mm, and 100 mm or larger.

In SCA 7, concurrent dredge and diver count data are available from two studies (Cranfield et al. 1996, Handley et al. 2004). In the Cranfield study, data were available from three areas (Golden Bay, Tasman Bay and the Marlborough Sounds), which Tuck & Brown (2008) considered as three separate treatments. These data are useful in that they potentially cover a range of habitat types, although unfortunately length data are only available for the length classes described above. The more recent Handley et al. (2004) study provided data recorded in millimetre length bins, but diver counts were only available from the Tasman Bay area. Tuck & Brown (2008) considered these data to be a further single treatment. Video camera counts are also available from the Handley et al. (2004) study, for other areas, but the efficiency of this method is poorly understood and unlikely to be comparable to that of divers.

Variance estimates were generated for each length bin (Tuck & Brown 2008) following the bootstrapping procedure used for the northern scallop fisheries from 2004 until 2010 (Cryer & Parkinson 2006). In each bootstrap, dredge tow and diver transect density estimates from each treatment (three from 1996 (Cranfield et al. 1996) and one from 2004 (Handley et al. 2004)) were sampled with replacement. These were used to generate an estimate of average dredge efficiency for each treatment; i.e., the average density of scallops taken by dredge, divided by the average density of scallops taken by divers.

These bootstrap estimates of dredge efficiency for each of the four treatments were then sampled with replacement, and used to derive a weighted average dredge efficiency estimate. The weighting applied to each treatment estimate was the log (N+1), where N is the minimum number of scallops taken by either divers or from the dredge in each treatment. Four thousand bootstrap estimates of average weighted dredge efficiency were generated for each length bin. Mean (bootstrapped) dredge efficiency at length ranged from 0.51 to 0.90, but variability in efficiency was high (Figure 19). The inverse of these efficiency estimates were then used to scale up dredge estimates from the survey, to account for scallops not taken by the dredge.

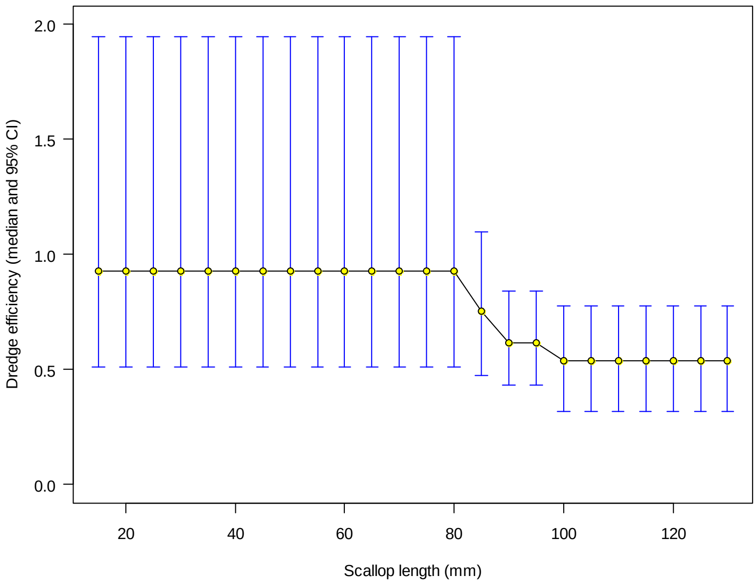


Figure 19: Estimated dredge efficiency at length for scallops in the SCA 7 stock. Estimates were generated by Tuck & Brown (2008) using historical diver and dredge data on scallop density and a non-parametric resampling with replacement approach to estimation (4000 bootstraps). The modelled dredge efficiency for box dredges in northern New Zealand is shown in Figure 20 for comparison.

The resulting dredge efficiency curve for scallops in the SCA 7 stock (Figure 19) looks unusual: the highest efficiencies predicted are for the smallest (0–83 mm) length bin, and a there is a trend of decreasing efficiency with length. This is the opposite of the expected trend of increasing efficiency with length. For large (recruit-sized) scallops the estimated efficiencies (about 50–60%) and corresponding uncertainties appear comparable with those estimated for other scallop dredges (e.g., those used in SCA CS and SCA 1 stock surveys). For smaller (pre-recruit) scallops, the estimated efficiency and uncertainty seem to be too high. Using the estimates of efficiency for SCA 7 generated from this bootstrapping approach is therefore likely to underestimate the abundance of small (pre-recruit) scallops, although these do not contribute to estimates of commercial biomass.

While the non-parametric dredge efficiency method (2008) is an improvement on the simple scalar approach used previously (in survey analyses before 2008), the available data which could be used in the analysis are very limited and may not be representative of average dredge efficiency throughout all areas of the fishery.

Recently, the efficiency of box dredges used in northern New Zealand scallop fisheries has been determined using a parametric model (Bian et al. 2012), that is considered a more appropriate method. Results suggest that the non-parametric approach (described above) underestimated efficiency and overestimated biomass when applied in analyses of northern scallop survey data. It is unknown whether a similar effect exists with the estimates produced from dredge surveys of SCA 7, but the potential for this effect must be considered when assessing the scallop abundance and biomass estimates, and estimates of exploitation rates generated using such biomass estimates. Furthermore, while the estimates of dredge efficiency for recruited scallops (90 mm or larger) appear credible, as do the estimates of recruited biomass, the estimated dredge efficiency for pre-recruits smaller than about 85 mm does not seem appropriate, and estimates of abundance for those pre-recruits may be underestimates. Our knowledge of the efficiency of ring-bag dredges used in SCA 7 is very limited, and the estimated dredge efficiency is a major source of uncertainty in the estimates produced from these dredge surveys, which should therefore be interpreted cautiously.

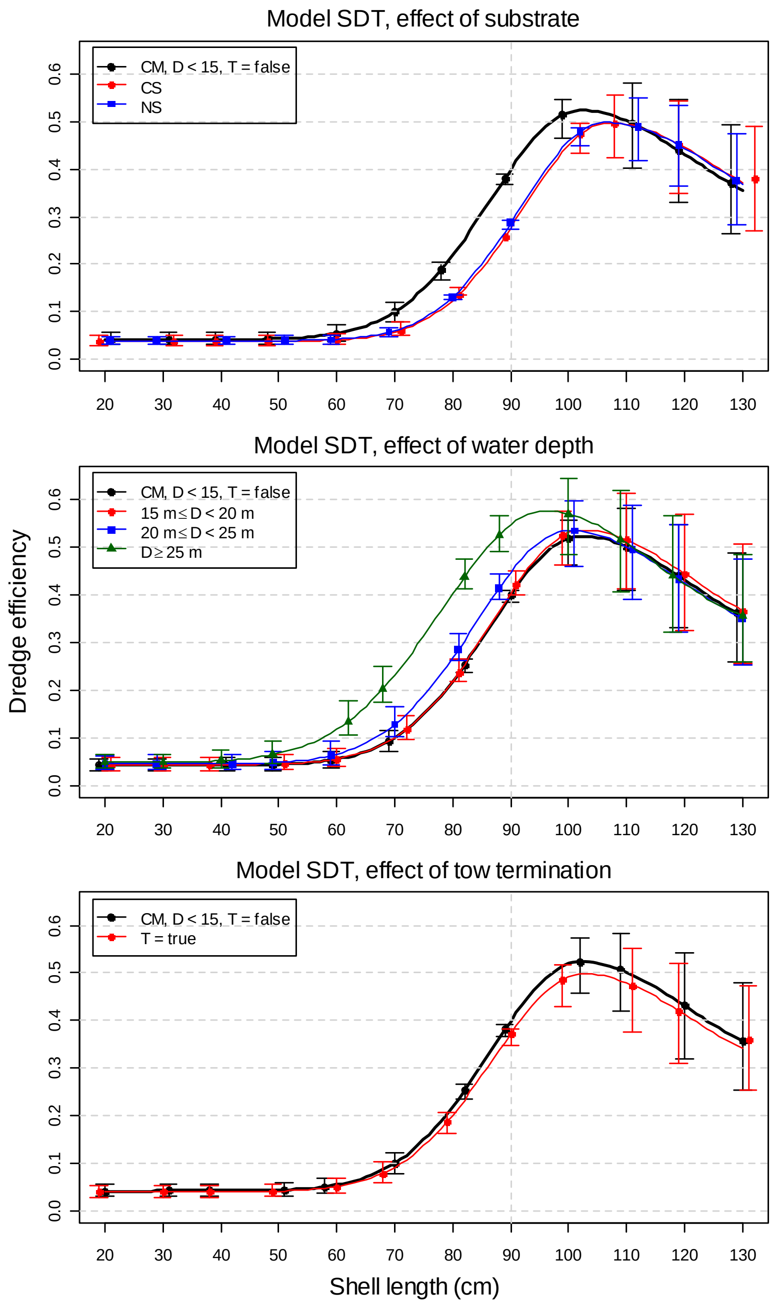


Figure 20: Efficiency of 'box' dredges used in the northern New Zealand commercial scallop fisheries (SCA 1 and SCA CS), modelled using model 'SDT' which includes the covariates substrate (S), depth (D) and tow termination (T). From Bian et al. (2012). The effect of these covariates on estimated dredge efficiency are shown in the three panels (vertical lines are 95% confident intervals). Top panel: effect of substrate, categorised as Coromandel mud (CM), Coromandel sand (CS) or Northland sand (NS). Middle panel: effect of depth (D), categorised as four levels (D<15 m, 15 m ≤D < 20 m, 20 m ≤ D < 25 m, and D ≥ 25 m). Bottom panel: tow termination (whether a tow had been hauled early before the completion of the planned tow distance), treated as a binary covariate (not terminated T = false, or terminated T = true).

3.4.4.2 Predicting greenweight from length

The revised workup approach involves predicting scallop weight from shell length data collected during the survey, using a length weight relationship. This differs from the previous approach used before 2008, when the aggregate weight of the scallop catch was weighed on board and recorded in two size categories (pre-recruits and recruits). Surveys between 1995 and 2010 weighed the catch in this way. For those years and tows in which scallop length frequency data were also recorded, catch weight can also be predicted using the length data and a length to green weight relationship:

$$Predicted\ catch\ weight = \sum N_L . aL^b$$

where N_L = number of scallops at length L (in mm) and W = weight (in g) at length L, and a and b are the estimated intercept and slope parameters of a least squares linear regression between weight and length. These parameters were estimated using length and weight data for scallops from the Coromandel stock (a = 0.00037 and b = 2.69). Examination of the SCA 7 survey data suggests that there is a close relationship between the recorded and predicted catch weight (Figure 21). Recorded catch weights are generally slightly higher than predicted weights, which may be because of the extra weight of sediment and water trapped on or in the scallops at the time of weighing.

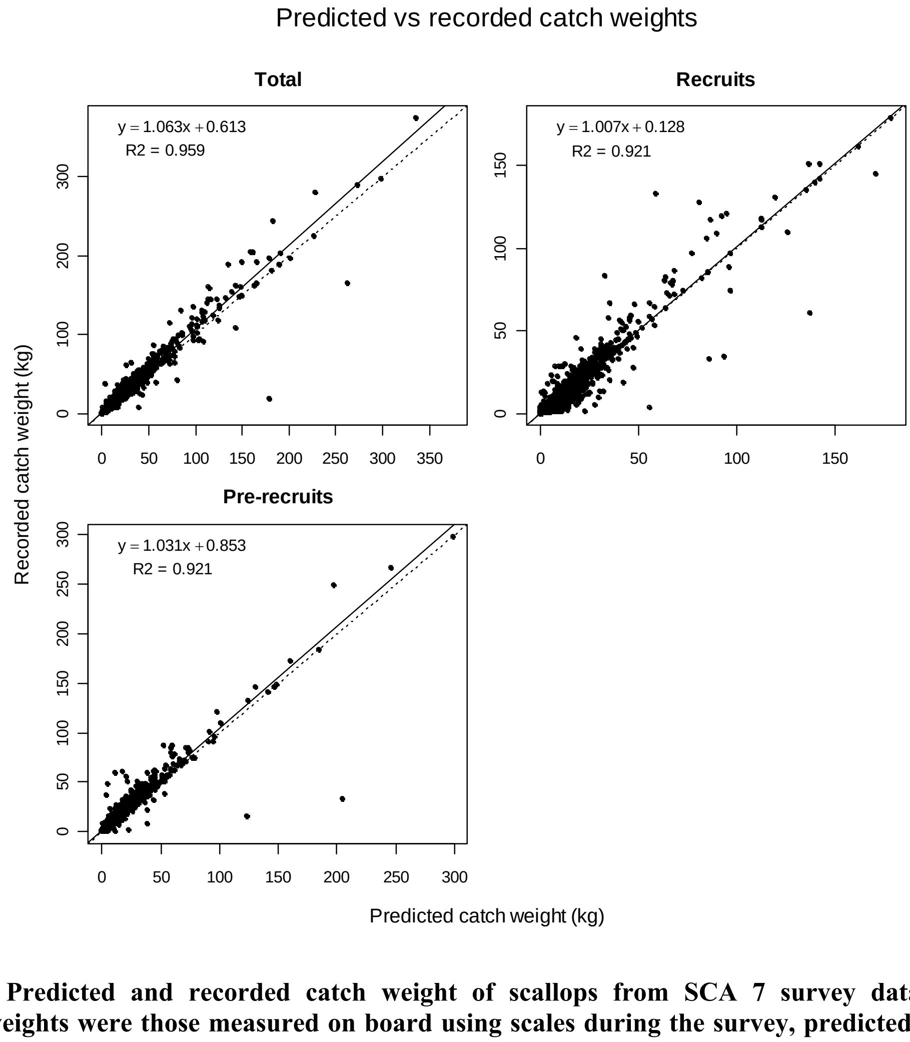


Figure 21: Predicted and recorded catch weight of scallops from SCA 7 survey data, 1997–2010. Recorded weights were those measured on board using scales during the survey, predicted weights were estimated using the survey data on scallop length frequency and a length to weight relationship). No length frequency data were available for surveys before 1997, and catch weights were not recorded after 2010. The dotted lines represents the 1:1 proportional relationship shown for reference, solid lines and equations indicate least squares linear regression fits to the data.

3.4.4.3 Growth

The previous SCA 7 survey workup approach (before 2008) assumed that near legal-sized scallops grow 3 mm between the time of survey and the start of season (1st September), based on the recapture of 17 tagged scallops from Tasman/Golden Bays in 2003/2004, although, in some strata, no allowance for growth was made. Growth in the 17 tagged scallops was examined in the same way as has been conducted previously for the northern populations. Over the scallop sizes available, expected growth increments (between survey and season) were within the range of those observed for SCA CS (Coromandel scallops over the same time duration) (Figure 22). For the revised SCA 7 survey workup approach (used since 2008), therefore, the Coromandel growth transition matrix was used (Cryer & Parkinson 2006).

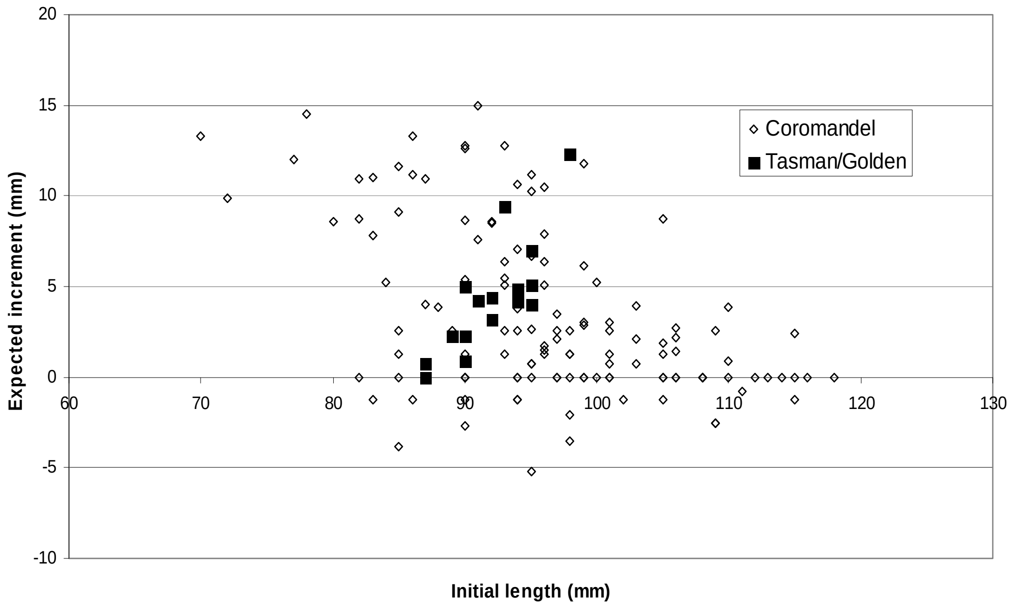
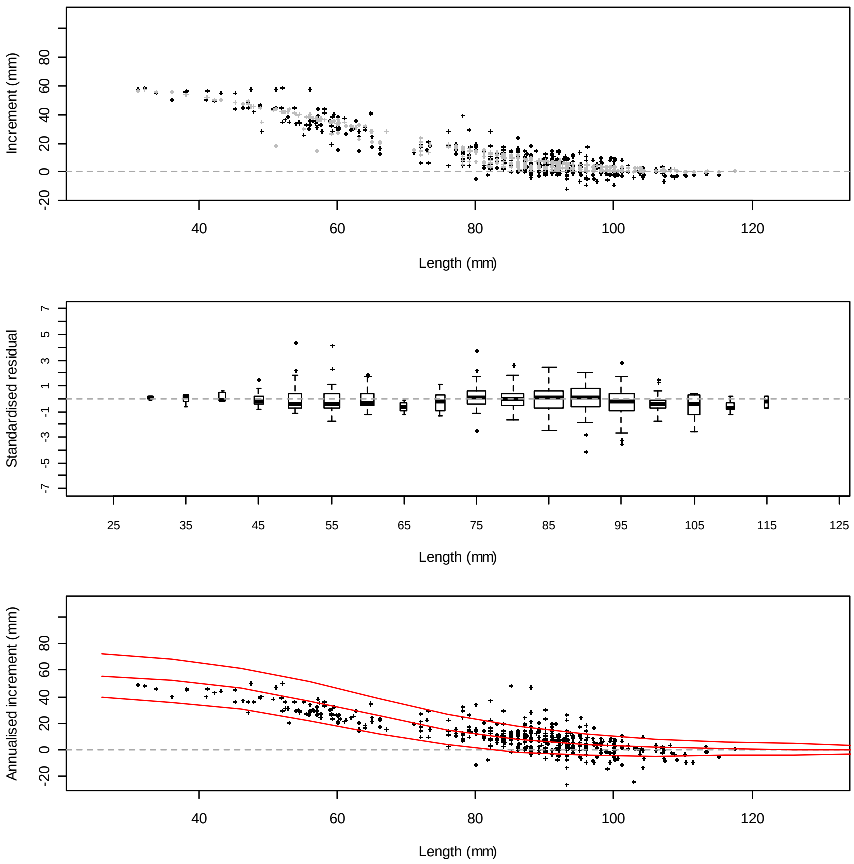


Figure 22: Initial versus expected length increment for recaptured tagged scallops from SCACS and SCA 7 before 2010. Expected increment is based on an assumed 16 week interval between survey and fishing season.

More recent tagging and release of scallops in SCA 7 was conducted in June 2010 as part of a national study on scallop growth (Tuck & Williams 2012b). Scallops were tagged and released at two sites in Golden Bay (*n* = 500 and 498 scallops) and three sites in the Marlborough Sounds (Guards Bay, *n* = 500; Ketu Bay, *n* = 499; Long Island, *n* = 506), and the subsequent recapture of 41 tag returns in the 2010–11 fishing year provided new data on growth specific to SCA 7 (recaptures reported to NIWA up to 1 September 2011: 1 from Golden Bay, 19 from Guards, 3 from Ketu, and 18 from Long Island). These data were analysed, together with other available data on *P. novaezelandiae* growth from the Coromandel (SCA CS) and Northland (SCA 1) stocks, using an inverse-logistic growth model (Tuck & Williams 2012b). The available tag recapture data from SCA 7 were all from the 2000s decade, so for the modelling these data were combined with tag recapture data from other areas (five locations in SCA CS) in the same 2000s period. There were no consistent patterns in the residuals between the SCA 7 and SCA CS areas, suggesting that the estimated model parameters appropriately describe scallop growth in each of the areas, and there is no evidence that growth varies between the sites used for the tagging and recapture work (Tuck & Williams 2012b).



Plot of observed (black dot) and estimated (grey dot) growth increment (upper plot), boxplots of the standardised residuals (middle plot) and annualised increment (black dot) and estimated annual increment ± 2 s.d (lines) (lower plot) against initial length for the fit of the seasonal inverse-logistic growth model to the tag recaptures from the 2000s. From Tuck & Williams (2012b).

3.4.4.4 Natural mortality

Natural 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 with an assumed CV of 0.065. This assumed rate of (and uncertainty in) M is based on the following mortality studies. From studies of the ratio of live to dead scallops and the breakdown of the shell hinge in dead scallops, Bull (1976) estimated the annual natural mortality rate for two populations of adult scallops in the Marlborough Sounds (Forsyth Bay and North West Bay in Pelorus Sound) to be 23% (M = 0.26) and 39% (M = 0.49). From a tagging study conducted in Golden and Tasman Bays from 1991 to 1992, Bull & Drummond (1994) estimated the mortality of 0+ and 1+ scallops to be about 38% (M = 0.21) per year, and the mortality of 2+ scallops to be 66% (M = 0.46). These estimates of M for commercial size scallops in SCA 7 are similar to those for commercial sized scallops in SCA CS in northeastern New Zealand, and suggest that the natural mortality of *Pecten novaezelandiae* is quite high.

3.4.4.5 Greenweight to meatweight conversion

The previous workup approach (before 2008) used an average meatweight per individual (for time of survey estimates), or the mean survey meatweight plus an estimated growth percentage, calculated from previous years (for start of season estimates). That approach in meatweight estimation allowed for different meatweight between areas, but took no account of uncertainty. Meatweight was not measured during the 2008–13 surveys, so time of survey estimates of recruited biomass are presented in greenweight only. For the projected start of season estimates, meatweights were predicted by taking the projected greenweight estimates for the start of season and applying estimates of historical mean greenweight to meatweight conversion factors (generated using fishing season meatweight recovery data provided by CSEC (Table 6) for each region of the SCA 7 stock in each scallop fishing year from 1996–97 to 2008–09).

Table 6: Mean recovery (%) of meatweight from greenweight for SCA 7 fishing seasons 1996–97 to 2008–09. Values were estimated based on the ratio of measured meatweight to measured greenweight, using data supplied by CSEC. –, no estimate.

Fishing year	Golden Bay	Tasman Bay	M. Sounds	SCA 7
1996–97	15.1	13.1	11.9	13.5
1997–98	13.5	13.1	14.4	13.7
1998–99	13.2	11.3	12.9	12.7
1999–2000	13.2	11.8	13.1	12.8
2000–01	11.5	11.4	13.1	11.6
2001–02	13.1	12.4	13.9	13.0
2002–03	13.1	10.2	13.0	12.7
2003–04	14.0	12.1	12.5	12.4
2004–05	14.5	11.1	14.0	12.8
2005–06	14.8	11.2	13.9	13.9
2006–07	14.8	–	12.7	13.7
2007–08	14.8	–	14.2	14.8
2008–09	13.4	–	12.0	13.0

3.5 Survey results

3.5.1 Scallop distribution

In general, the survey data suggest that scallops have been distributed in particular areas within the three regions (Figure 23), although the densities observed have changed dramatically over the time series (Figure 24).

In Golden Bay, the highest densities of recruited scallops (‘commercial size’ scallops, 90 mm or larger) have tended to be in waters between 10 and 20 m depth throughout the curvature of the bay and on a bank to the south of Farewell Spit, with moderate densities between 20 and 30 m depth, and lower densities in deeper water (although high densities of recruited scallops have been observed in 20–30 m depths in sectors B and C in 1994 and 1995 following enhancement of those areas in 1992 and 1993). Similarly, recruited densities in Tasman Bay have been found mainly in depths between 10 and 20 m, but perhaps more so in the western half of the bay, plus in a small area within Croisilles Harbour. Recruited scallops have been distributed in many of the different bays and inlets in the Marlborough Sounds, and the best densities have usually been in certain small bays in the outer Sounds (e.g., Ketu Bay, Guards Bay, Forsyth Bay, Ships Cove).

The distribution of pre-recruit sized scallops generally matches that of recruited (commercial size) scallops, but densities of pre-recruits have been notably higher than those of recruited scallops in some deeper areas (30–40 m depth) in Tasman Bay.

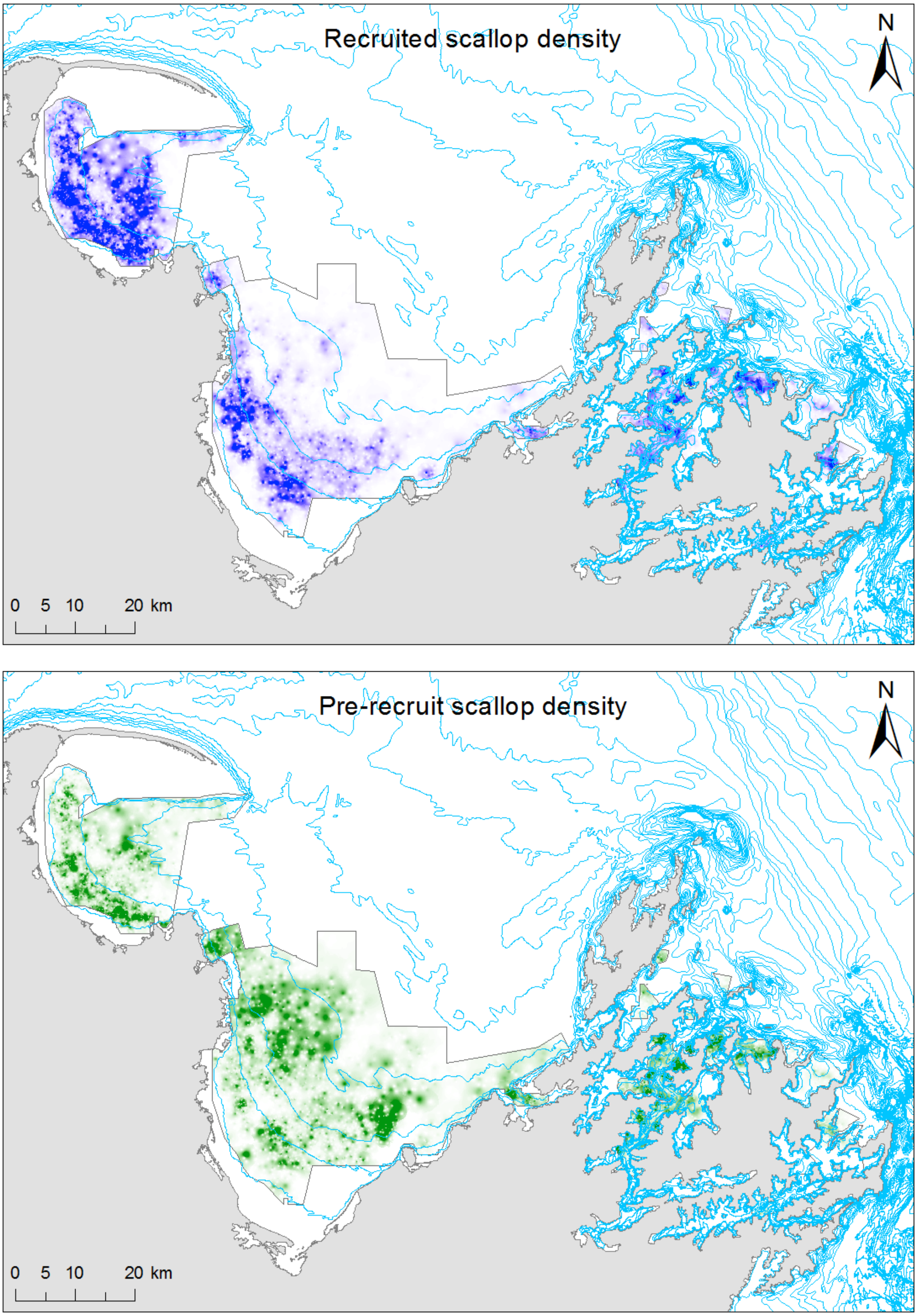


Figure 23: Spatial density of recruited (top) and pre-recruit (bottom) scallops in SCA 7 from an inverse density weighted (IDW) interpolation of SCA 7 survey estimates to 2011. Depth contours at 10 m intervals are shown overlaid for reference.

The spatial distribution of scallop density from surveys between 1994 and 2013 is shown in Figure 24. Plots for 1994–97 illustrate how the survey coverage was limited to specific sectors. For example, in 1994, sector C in Golden Bay and sector E in Tasman Bay were surveyed because they were the two main zones to be fished in the 1994 season following the 1992 seeding of those areas with spat (Drummond 1994). It was not until 1998 that the survey had consistent and comparable coverage (sample extent) throughout the main areas of SCA 7 stock.

In some years, scallops have exhibited a wider than ‘normal’ distribution throughout the bays and the Sounds, such as between about 2000 and 2003. Tasman Bay has typically held a smaller proportion of recruited (commercial size) scallops than Golden Bay or the Marlborough Sounds.

Examining temporal trends in the spatial distribution, scallops were distributed widely in high densities in Golden Bay and Tasman Bay between 2000 and 2003, probably resulting from widespread natural spat settlement in the late 1990s (indicated by a peak in spatbag catches in 1998, followed by the subsequent appearance and successive increase in size of juvenile scallops in the survey length data). Golden Bay held greater densities of recruited scallops during this time than Tasman Bay. Since then, the spatial distribution of the scallop population in Tasman Bay appears to have contracted in towards the central to western part of the bay, with densities and spatial extent steadily decreasing. Very low densities of scallops have persisted in Tasman Bay since 2007. Scallop densities increased again in Golden Bay from about 2005 to 2007, particularly in sectors B and C, but a similar contraction in the spatial distribution has occurred there since then. The 2012 survey found only very small low density beds of scallops in Golden Bay and none in Tasman Bay, except for Awaroa Bay and the non-commercial area in Croisilles Harbour.

Golden Bay and Tasman Bay were not formally surveyed during the May 2013 survey, but informal surveys conducted by CSEC in June 2013, using a fine mesh liner in the dredge, found some spat up to a size of about 40 mm in areas of Golden Bay that were seeded with spat in March 2013: these spat had a shell ring at about 20–30 mm, which potentially indicates some growth since the spat were seeded; no ‘naturally settled’ spat were found within the main part of Golden Bay, but some were caught on tows just inside Farewell Spit (R. Green, CSEC, pers. comm.).

In the Marlborough Sounds, the spatial distribution and densities in the outer Sounds areas have been fairly similar through time, but it appears that the inner Sounds areas supported a greater proportion of recruited scallops in the mid to late 1990s. In 2013, the distribution of scallops surveyed in the Marlborough Sounds was similar to that in recent years; most of the recruited population was held in a few small areas of the outer Sounds, where densities were relatively high.

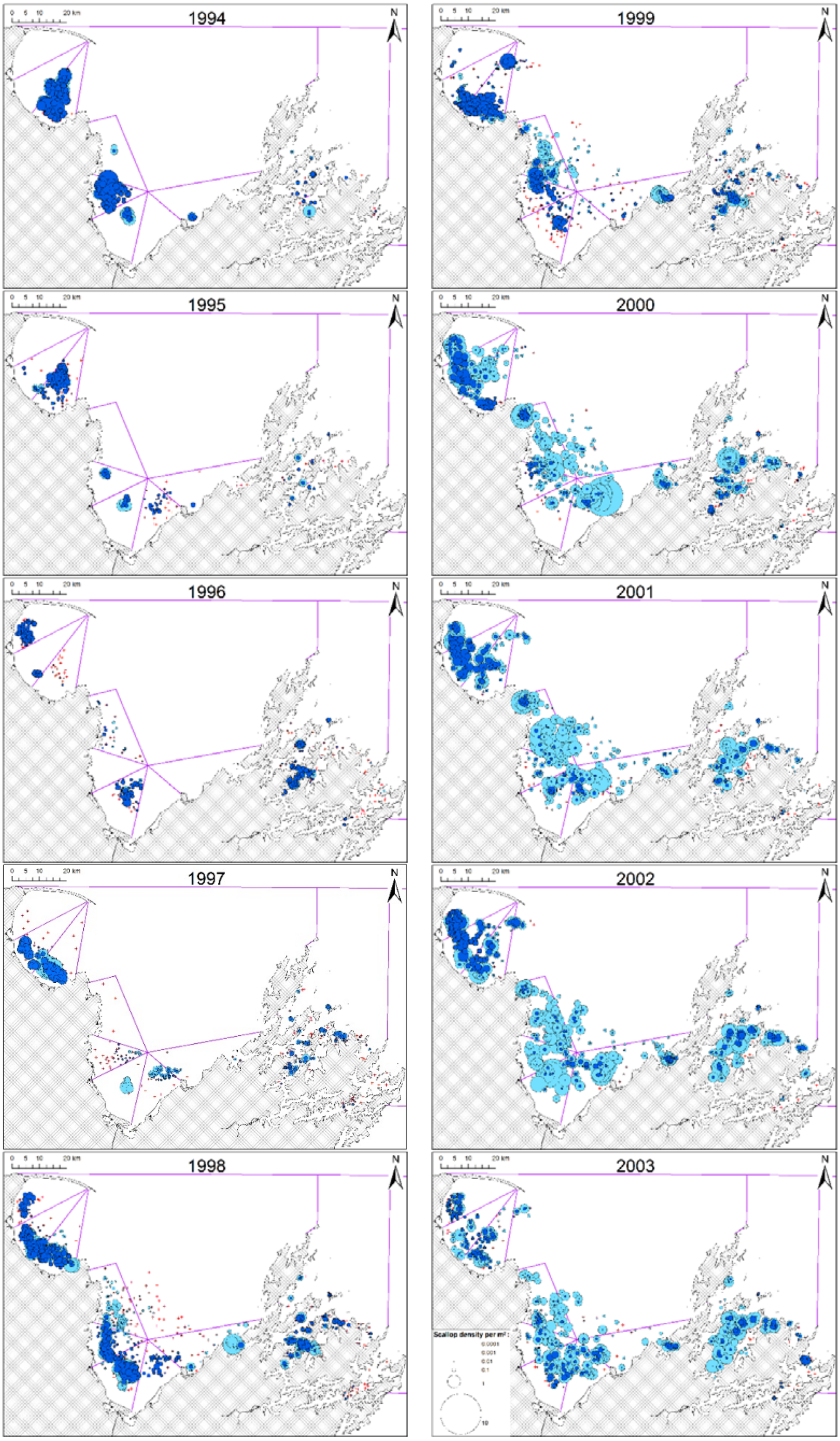
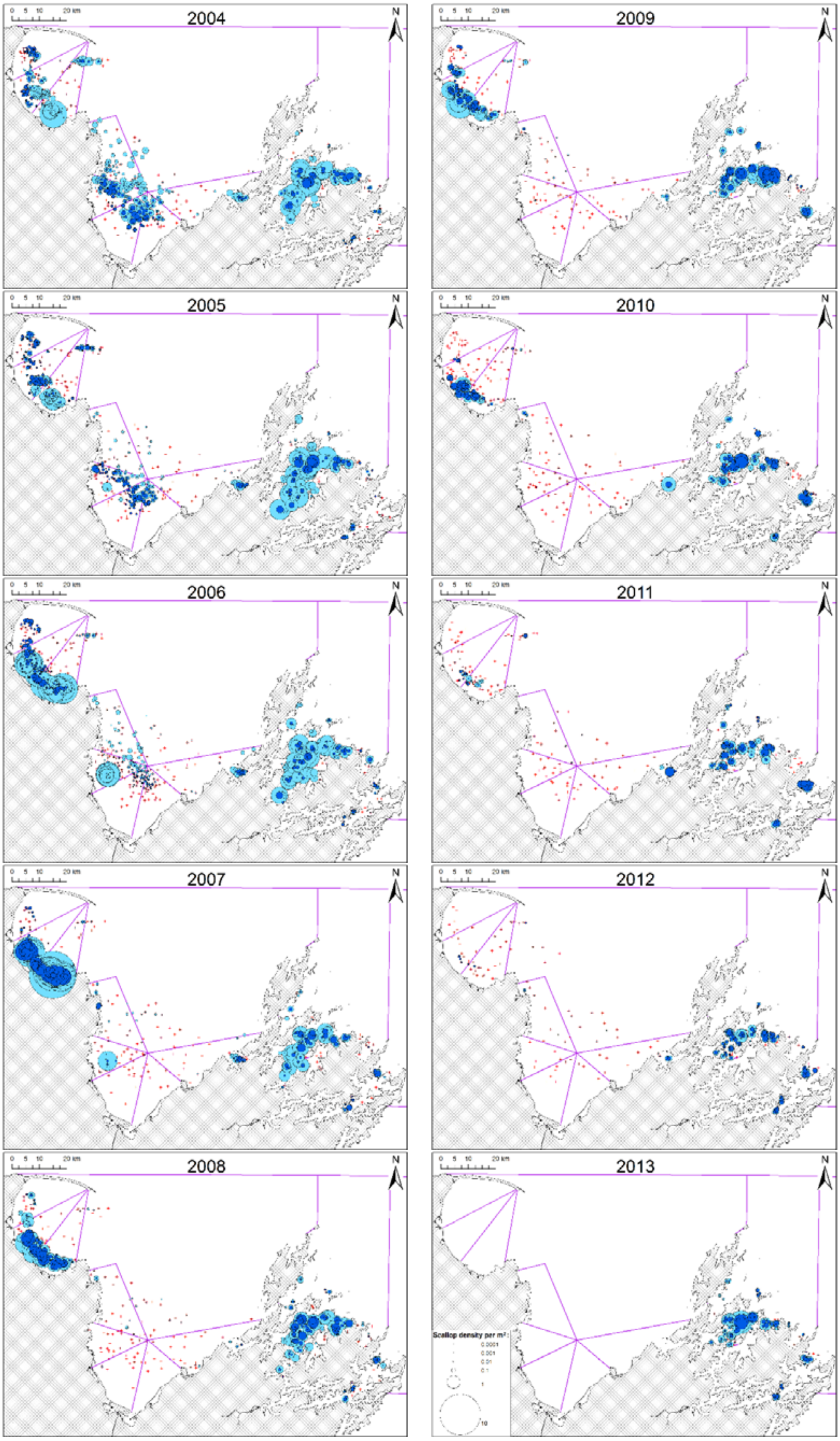


Figure 24: Spatial density of scallops in SCA 7 from survey estimates, 1994–2013 (figure continued on next page). Circle area proportional to density (scallops.m^{-2}), uncorrected for dredge efficiency. Total (light blue circles) and recruited (≥90 mm, dark blue circles) densities, and station positions sampled (red crosses), are shown.



(figure continued from previous page)

3.5.2 Scallop biomass

The recruited biomass trajectories from the revised analytical approach to estimation were similar to those from the previous approach (used in survey analyses before 2008), but the uncertainty in the estimates was greater in the revised approach which incorporates uncertainty at all stages of the work-up process by resampling with replacement (bootstrapping) (Figure 25).

The first survey with extensive coverage of the entire SCA 7 fishery area was in 1998. In all three regions of SCA 7, recruited scallop biomass generally increased from the late 1990s to reach peak levels in 2001–02 in Golden Bay and 2002–03 in Tasman Bay and the Marlborough Sounds. Since then there has been substantial biomass declines in both Golden Bay and Tasman Bay; biomass in both regions in 2012 was at historically low levels, but the level in 2013 was unknown because only the Marlborough Sounds region was surveyed in 2013. In contrast with Golden and Tasman Bays, biomass in the Marlborough Sounds has remained relatively stable over much of the same period, although there was evidence of a decline there between 2009 and 2012. The 2013 survey of the Marlborough Sounds suggested the biomass was approaching the level observed in 2010 and 2011. Examining the estimates at the SCA 7 stock level, recruited biomass increased from the late 1990s to reach a major peak around 2001 and 2002, declined steeply to a low level in 2006, showed a minor peak in 2007, and gradually declined to a very low level in 2012. The 2013 biomass was slightly higher than in 2012, even though the estimate did not include Golden and Tasman Bays because they were not surveyed in 2013.

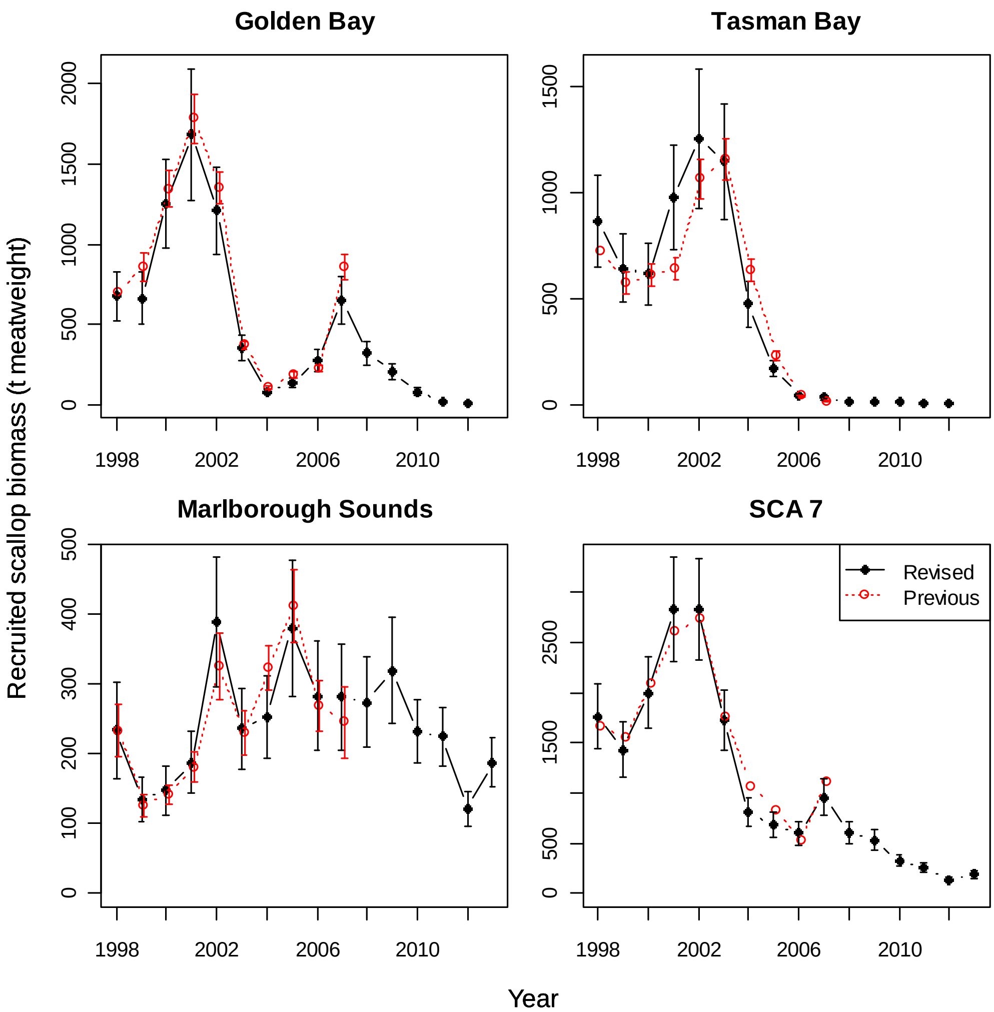


Figure 25: Trends in biomass estimates for recruited scallops produced from two analytical approaches: 1) revised approach based on survey length data and length-weight regression, with uncertainty incorporated by bootstrapping; and 2) previous approach based on survey weighed catches and simple projection (values offset slightly to the right to allow comparison). The revised approach has been used since 2008.

3.5.3 Scallop length frequency

Absolute length frequency distribution time series were constructed for the three substocks of SCA 7 (Figure 26). Proportional length frequency plots were also produced to aid data interpretation when comparing areas and years with contrasting abundance (Figure 27). In both figures, the values plotted are adjusted for average dredge efficiency by length bin, which should have produced credible estimates of recruited scallops (harvestable size, 90 mm or larger) but has probably resulted in the number of pre-recruit scallops being underestimated. Producing the same figures with values uncorrected for dredge efficiency, and at finer spatial scales, could help in assessing patterns further in future work. In describing the patterns below, the presence of spat (scallops smaller than 50 mm) is interpreted as evidence of successful settlement, initial growth and survivorship within one year preceding the survey. The presence of pre-recruits (scallops smaller than 90 mm) and recruited scallops (larger than 90 mm) indicate that growth and survivorship has occurred in the two or more years preceding the survey.

In Golden Bay, the population appears to be strongly driven by episodic recruitment, shown by the appearance and progression of spat, pre-recruit, and recruited size scallops over time. The numbers of recruited scallops tends to increase or decrease about one year after the numbers of large pre-recruits increases or decreases, respectively. Two notable periods of recruitment have occurred during the time series, which relate to the two obvious peaks and declines observed in the recruited biomass (see Figure 25). The first and largest recruitment period was in the early 2000s: scallop spat were detected in the 1998–2000 surveys, followed by a dominance of pre-recruits in 2000–2002, and elevated numbers of recruited scallops from 2000 to 2003, after which they declined. The contribution of enhancement to this recruitment episode is unknown, but given that enhancement was confined to relatively specific areas yet spat settlement and later distribution of larger scallops was extensive, it seems that the recruitment stemmed at least partly from natural settlement in addition to any influence of enhancement. Interestingly, the sudden increase in recruited scallops between 1999 and 2000 occurred even though few large pre-recruits were caught in the survey the year before. The second, and much smaller, recruitment period in Golden Bay occurred in the mid to late 2000s: spat were detected in the 2004–06 surveys (Figure 27), a clear mode of pre-recruits appeared in 2006, and by 2007 recruited scallops dominated the population, followed by a decline. There is some indication of a significant settlement event in 2012, when spat were present in modes of about 30 and 45 mm, but it is unknown whether these progressed into pre-recruit modes because Golden Bay was not surveyed in 2013.

In Tasman Bay during the same time series, there was only one clear episode of recruitment, which occurred in the early 2000s and relates to the peak and subsequent decline in Tasman Bay recruited biomass (see Figure 25). The timing of this episode is similar to that observed in Golden Bay, except that recruitment to the harvestable size was slightly later in Tasman Bay than in Golden Bay. Some spat were detected in Tasman Bay in 1998, and there was a particularly clear spat mode in 1999, followed by a very large increase in the numbers of pre-recruit scallops in 2000, which persisted until about 2003. Progression of these pre-recruits to the recruited size occurred between 2000 and 2004, but despite the exceptionally high abundance of pre-recruits in Tasman Bay in the early 2000s, the abundance of recruited scallops was relatively low, especially compared with Golden Bay. The number of pre-recruits dropped progressively lower from 2004 and the recruited population subsequently declined to a very low level. Although overall numbers were very low in 2012, the proportional frequency plots (Figure 27) suggest that there was a clear mode of 30 mm spat in Tasman Bay in 2012, as in Golden Bay.

In contrast to Golden and Tasman Bays, the size composition of the scallop population in the Marlborough Sounds appears to have been more consistent through time, and recruitment ‘events’, indicated by the rapid appearance and progression of size modes, are not as obvious. Trends in recruitment in the Marlborough Sounds, although less dramatic than in the other regions, are still evident however, with numbers of pre-recruits gradually increasing from lower levels in the late 1990s, broadly peaking in the mid 2000s (2002–2006) and gradually reducing in the late 2000s.

However, there appears to be no clear link between the numbers of large pre-recruits in one year and the abundance of recruited scallops in the following year: in fact, the numbers of recruited scallops in the overall Marlborough Sounds substock appears to have been relatively stable through the time series.

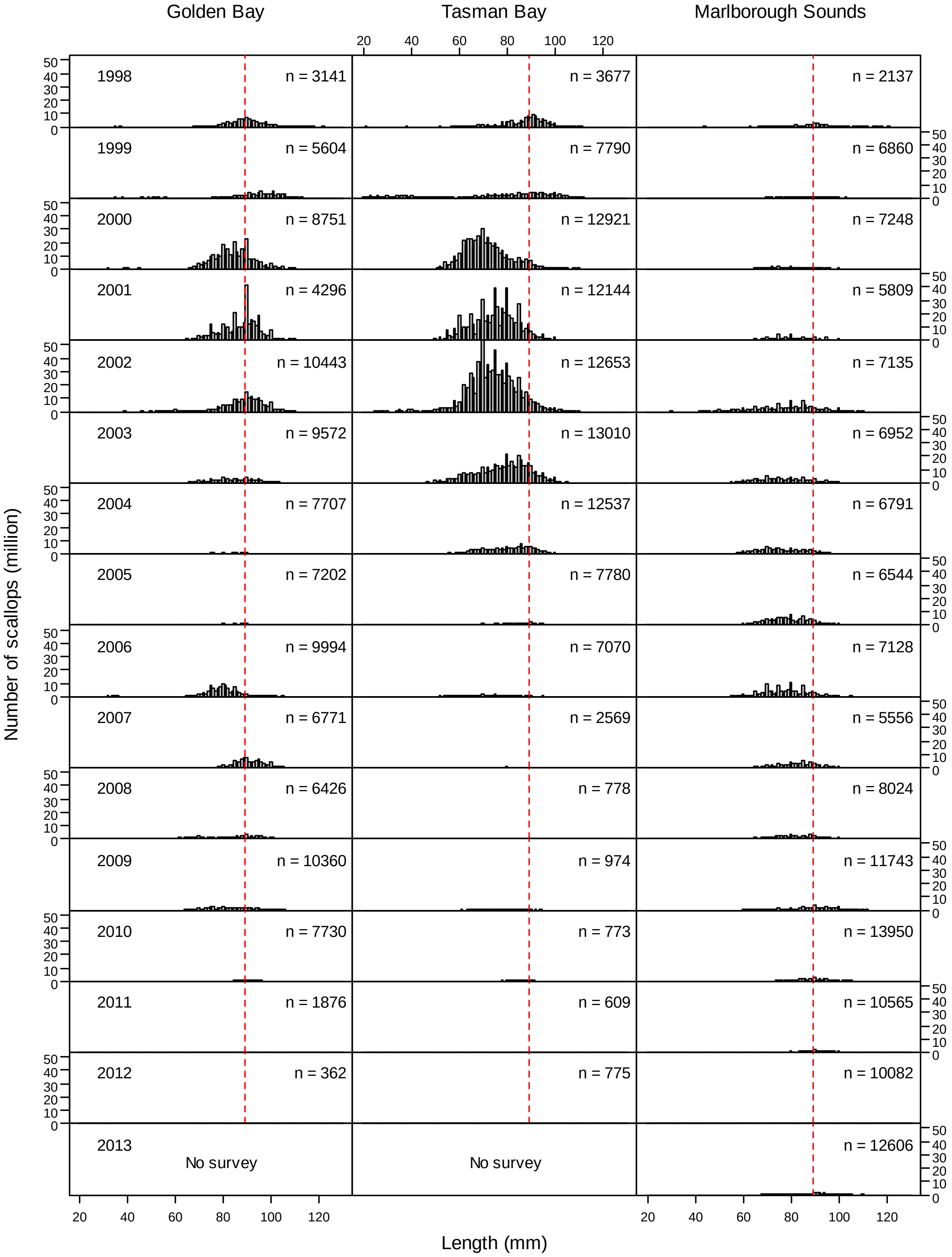


Figure 26: Length frequency distributions for scallops in Golden Bay, Tasman Bay, and the Marlborough Sounds, 1998–2013. Survey shell length data were corrected for sampled fraction, area swept by the dredge, and historical average dredge efficiency; stratum mean length frequencies were scaled by the stratum areas, and summed to produce population estimates for each of the three substocks shown. Note that the abundance of pre-recruit scallops smaller than about 80 mm is likely to have been

underestimated because of the limited estimates of dredge efficiency for small scallops. Red dashed lines show the minimum legal size (90 mm shell length).

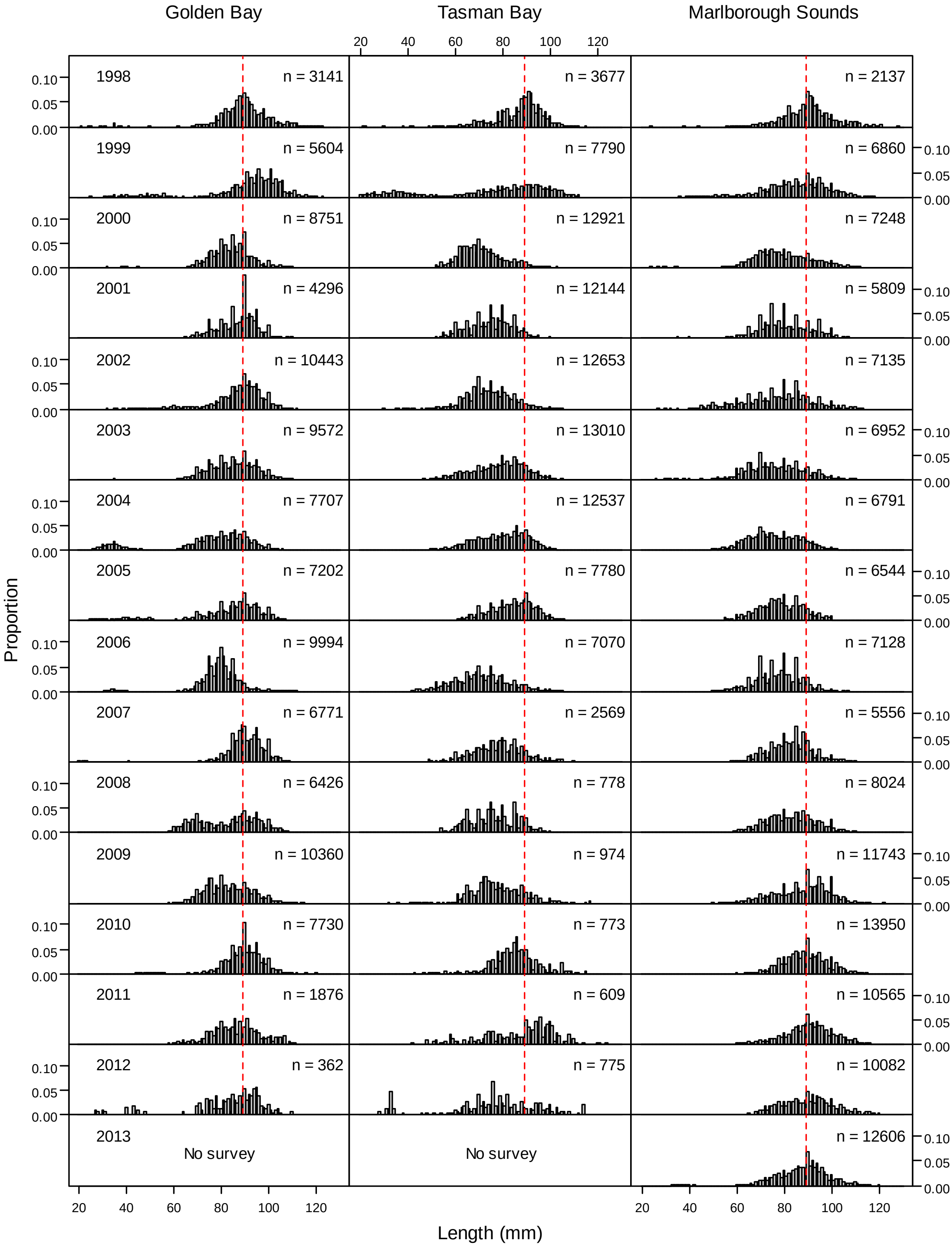


Figure 27: Proportional length frequency distributions for scallops in the three substocks (Golden Bay, Tasman Bay, and the Marlborough Sounds) of the SCA 7 stock, 1998–2013. Scaled shell length frequency data plotted in Figure 26 were converted to proportional frequencies for this plot. Red dashed lines show the minimum legal size (90 mm shell length).

4 YIELD AND EXPLOITATION RATE

4.1 Current Annual Yield

Current Annual Yield (CAY) is the potential catch for one year, calculated by applying a reference rate of fishing mortality, F_{ref}, to an estimate of the fishable biomass at the beginning of the fishing year. Management of scallops in the Marlborough Sounds is based on a CAY approach (as it is in the SCA 1 and SCA CS scallop stocks in northeastern New Zealand), and CAY was calculated for this substock in each survey year. Although the Golden Bay and Tasman Bay regions of the SCA 7 stock are not managed using a CAY approach (instead the management is based on a rotational fishing and enhancement approach), in the present study we also calculated CAY retrospectively for all three substocks (Golden Bay, Tasman Bay, and the Marlborough Sounds) to enable comparison of scallop landings with estimates of yield. CAY for SCA 7 was calculated using a standard equation from the Fisheries Assessment Plenary Report (Ministry for Primary Industries 2012b):

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

where B_{beg} is the estimated start of season recruited biomass and F_{ref} is a reference rate of fishing mortality. This equation is appropriate where fishing occurs over a short period of the year (Ministry for Primary Industries 2012b). For B_{beg} the projected (i.e. 1 September) estimates of recruited biomass (t meatweight) were used. For F_{ref}, the standard fisheries target reference point $F_{0.1}$ was used. Breen & Kendrick (1999) used a yield per recruit model constructed by Breen (1995) to estimate $F_{0.1}$ for SCA 7. With a minimum shell length of 90 mm and assumed instantaneous rates of natural mortality of $M = 0.40$ and 0.50, estimates of $F_{0.1}$ were 0.553 and 0.631, respectively. Consequently, CAY was calculated using the range of projected recruited meatweight biomass for B_{beg}, and the range 0.55 to 0.63 for F_{ref}. Note that these estimates of reference fishing mortality were generated by Breen & Kendrick (1999) using slightly different estimates of dredge efficiency than those used to estimate biomass in the present study.

Expressing each of the two estimates of CAY for SCA 7, derived from using F_{ref}. = 0.55 or 0.63, as a proportion of the recruited scallop biomass equates to 'target' fishery removal exploitation rates (catch divided by biomass) of 0.42 and 0.47, respectively. These are higher than the equivalent reference rates estimated for the SCA CS and SCA 1 fisheries.

4.2 Comparison of CAY and landings

Although the trends in scallop landings from Golden Bay and the Marlborough Sounds have broadly followed the calculated CAY trajectories (which correspond proportionally to changes in biomass), in general the actual level of landings has been lower than the calculated CAY (Figure 28). Landings were always lower than the CAY in all regions and years, except for in 1998 and 1999 in Golden Bay, and in 1998 in the Marlborough Sounds. Landings in the Marlborough Sounds in 2012–13 were very close to the level of the CAY. Overall, landings in Golden Bay have been much closer to the CAY than in Marlborough Sounds or Tasman Bay, and landings in Tasman Bay in particular have been substantially lower than the CAY.

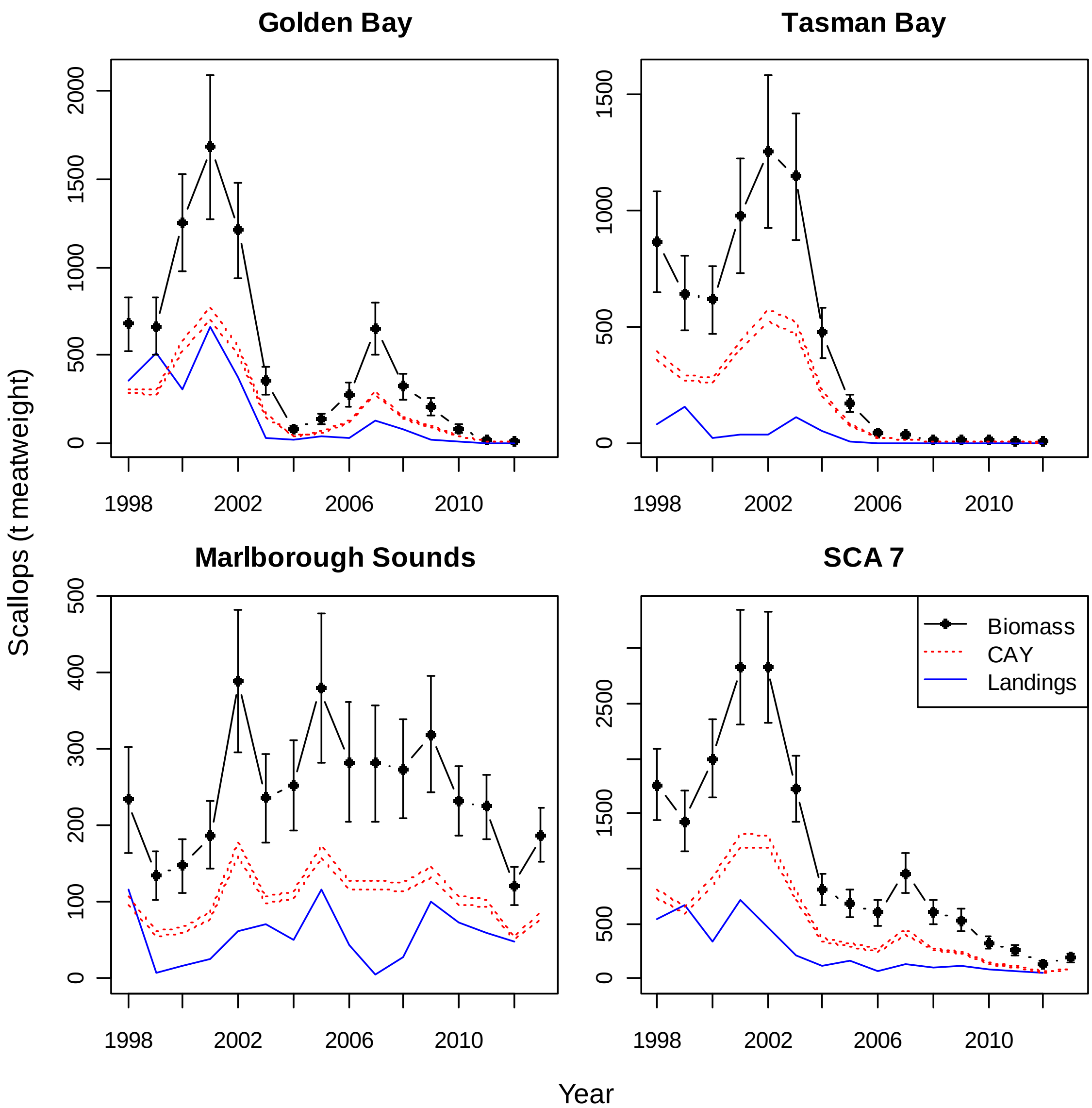


Figure 28: Trends in the SCA 7 stock from 1998–2013. Plots show start of season recruited scallop biomass estimates and CVs (closed symbols with error bars joined by solid black line), CAY estimated retrospectively using $F_{0.1}$ = 0.553 (lower dotted red line) and $F_{0.1}$ = 0.631 (upper dotted red line), and reported landings (solid blue line) by region and for the overall SCA 7 stock. All values in t meatweight. Golden Bay and Tasman Bay were not surveyed in 2013.

4.3 Exploitation rate

The estimated exploitation rate (catch to recruited biomass ratio) for scallops in SCA 7 since 1998 has varied among regions, but, with the exception of 1998–99 and 1999-2000 in Golden Bay and 1998–1999 in the Marlborough Sounds, it has always been below the 'target' exploitation rate (0.42–0.47) that equates to fishing at the level of the calculated CAY (Figure 29). In Golden Bay, the exploitation rate was very high (0.54–0.80) in the period 1998–99 to 1999–2000, followed by a decreasing trend with fluctuation from 2000–01, and was low (0.05) in 2011–12. In Tasman Bay, the peak exploitation rate in the time series was 0.25 in 1999–2000 but otherwise has been relatively low, and no commercial scallop fishing has occurred in Tasman Bay since 2005–06. In the Marlborough Sounds, the exploitation rate was high (0.51) in 1998–99 but low (0.05) in 1999–2000, followed by a general increase to reach 0.31 in 2005–06. The exploitation rate in the Marlborough Sounds had decreased to only 0.02 in 2007–08, but there was an increasing trend in the following years, reaching a high of 0.39

in the most recent fishing year 2012–13 that is very close to the 'target' exploitation rate of the calculated CAY.

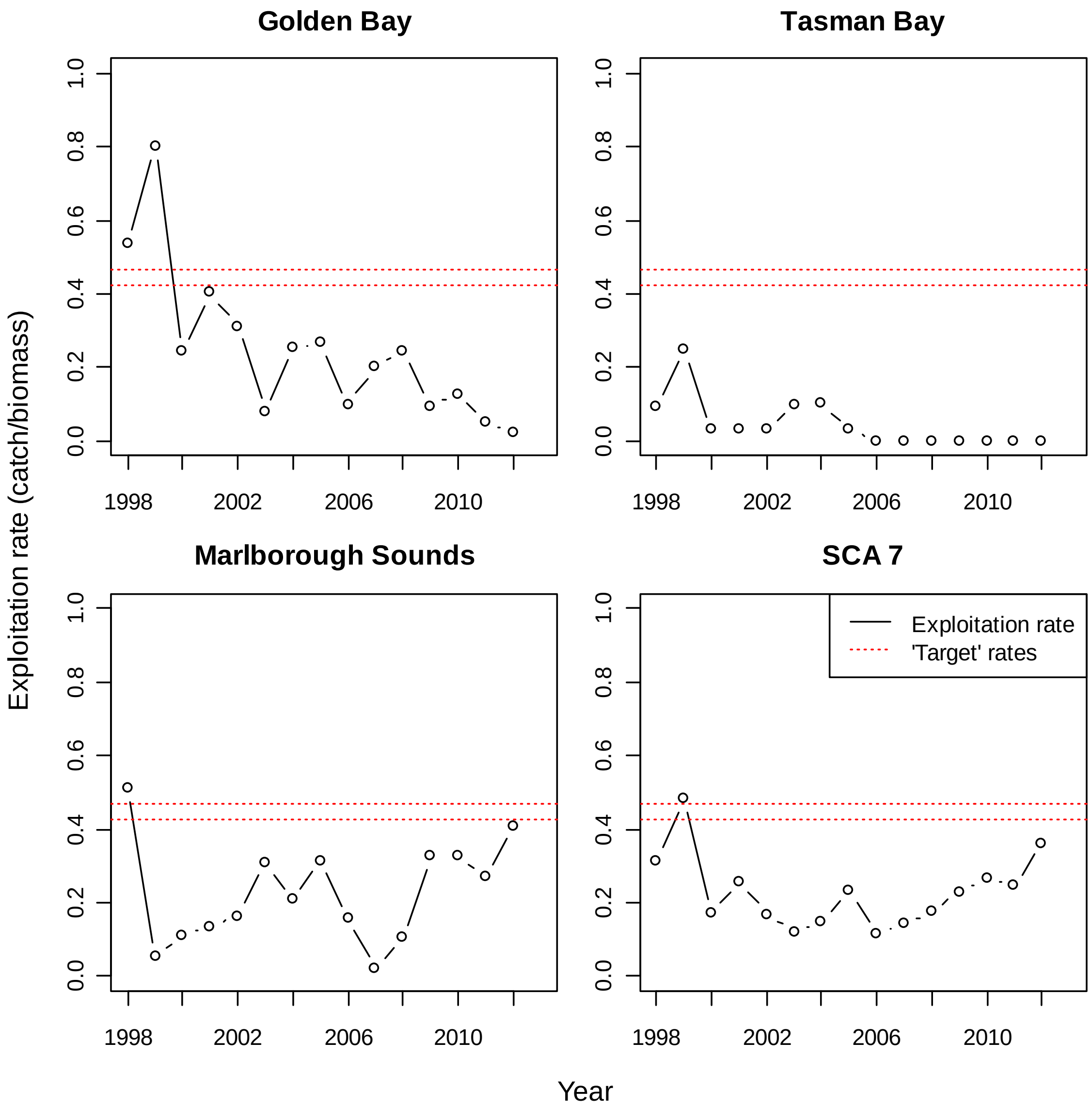


Figure 29: Exploitation rate (catch divided by biomass) trends for recruited scallops by region and for the overall SCA 7 stock (solid black lines). Horizontal lines show two 'Target' exploitation rates of 0.42 (lower dotted red line) and 0.47 (upper dotted red line) representing two estimates of CAY expressed as proportions of the recruited biomass. The two estimates of CAY were calculated retrospectively for all areas using target fishing mortalities of $F_{0.1}$ = 0.553 and $F_{0.1}$ = 0.631 based on assumed natural mortality rates of M = 0.4 and M = 0.5, respectively. It has been recognised that these estimates of the target fishing mortality F0.1 used in the calculation of CAY may be too high.

5 DISCUSSION

5.1 Fishery performance

Most landings in the Southern scallop fishery over time have been from Golden Bay and to a lesser extent Tasman Bay, except for in recent years when fishery performance in those areas has been very poor and consequently the majority of landings have been from the Marlborough Sounds. The level of landings appears to have undergone much larger fluctuations in Golden and Tasman Bays, reflecting the apparently large changes in recruitment, than in the Marlborough Sounds which has produced a smaller but more consistent level of landings over time. These differences in fishery performance among the three regions are reflected by patterns in the distribution, abundance, and size structure of their scallop populations, which, in turn, are likely to be related in part to differences in the processes affecting scallop productivity among the regions and also to the different management regimes applied. The large declines that have been observed have occurred in Golden and Tasman Bays which have been managed by a rotational fishing and enhancement regime, but not in the Marlborough Sounds which received only minimal enhancement activity and was managed as a ‘wild’ fishery using a CAY approach to inform appropriate catch limits.

The initial intention of the rotational fishing and enhancement management regime in Golden and Tasman Bays was to fish an area, enhance with scallop spat after the fishing season, close the area to fishing for two years, and then open the area to fishing again in the third year. This intended 3-year rotation was to be applied at the sector level in Golden Bay and Tasman Bay (but not in the Marlborough Sounds). The primary mechanism for ensuring sustainability of the Southern scallop fishery since the 1990s has been the rotational fishing and enhancement programme (CSEC 1998), which permitted a high TACC to be set. Simulation modelling showed that rotational harvesting is highly stabilising, with enhancement further improving catch, biomass, and safety (the avoidance of fishery collapse, which occurs when the biomass falls to a small percentage of the virgin biomass and remains there), and slightly reducing population variability (Breen & Kendrick 1997).

The rotational opening and closing of sectors to fishing was generally carried out in the early 1990s as initially intended, but the sector level rotation broke down from about 1996 onwards. Fishing of enhancement plots has been rotated to a certain degree (i.e. these plots were generally not fished in the first year after enhancement), although not strictly on a three yearly rotation. Other parts of sectors were fished consistently from year to year. Even at a fine spatial scale (at the level of 0.5 × 0.5 minute grid cells), there does not appear to have been very effective rotation: ‘while some level of rotation in the fishing activity has occurred in all sectors (since not all areas were fished every year), for most sectors, when a grid cell was fished, it had been fished in the previous year (0 years rotation) in over 50% of cases’ (Tuck & Williams 2012a). This activity of patch fishing ‘out of rotation’ was permitted under the MoU (MFish & CSEC 1998), but is quite different to the sector level approach to rotational fishing simulated in the modelling evaluation of fishing strategies for the fishery (Breen & Kendrick 1997).

In theory, the intended system of rotational fishing in SCA 7 assumed that the scallop grounds in each bay can be divided into sectors that have the same area of suitable habitat that supports scallops, but this is probably an invalid assumption. In reality, the distribution of scallops within each of the bays is not homogeneous. For example, the Golden Bay sectors 7BB and 7CC have larger areas that supported higher densities of scallops compared to the smaller area within sector 7AA.

The different fishery areas received widespread and abundant settlement of spat in 1998 and 1999, and the majority of all sectors in Golden Bay and Tasman Bay were open to fishing in the early 2000s. Given the broad coverage of fishing and its high intensity at that time, the disturbance of scallops and their benthic habitats during that period was potentially high and could have resulted in elevated levels of incidental mortality that might have contributed to the observed subsequent declines in the scallop populations.

5.2 Stock status

The estimated current status of the SCA 7 stock in 2013 (despite assuming zero biomass for Golden Bay and Tasman Bay which were not surveyed) is slightly higher in terms of recruited biomass than in 2012, the latter being the lowest recorded level since stock-wide surveys began in the 1998; landings in 2012–13 were the lowest recorded since the closure of the fishery in the early 1980s (Figure 30). The distribution of the current recruited biomass is restricted mainly to small areas of the Marlborough Sounds, with little biomass in either of Golden or Tasman Bays. There is some evidence of a recent increase in the number of juveniles in the Marlborough Sounds from the 2013 survey. The status of the SCA 7 stock in relation to the target reference rate of fishing mortality, $F_{0.1}$, has not been examined, but our examination of exploitation rates in relation to that which equates to the calculated CAY suggests that fishing mortality is lower than the target rate in Golden and Tasman Bays, and at the level of the target in the Marlborough Sounds. The SCA 7 stock status in relation to limit reference points is unknown because appropriate limits have not been defined.

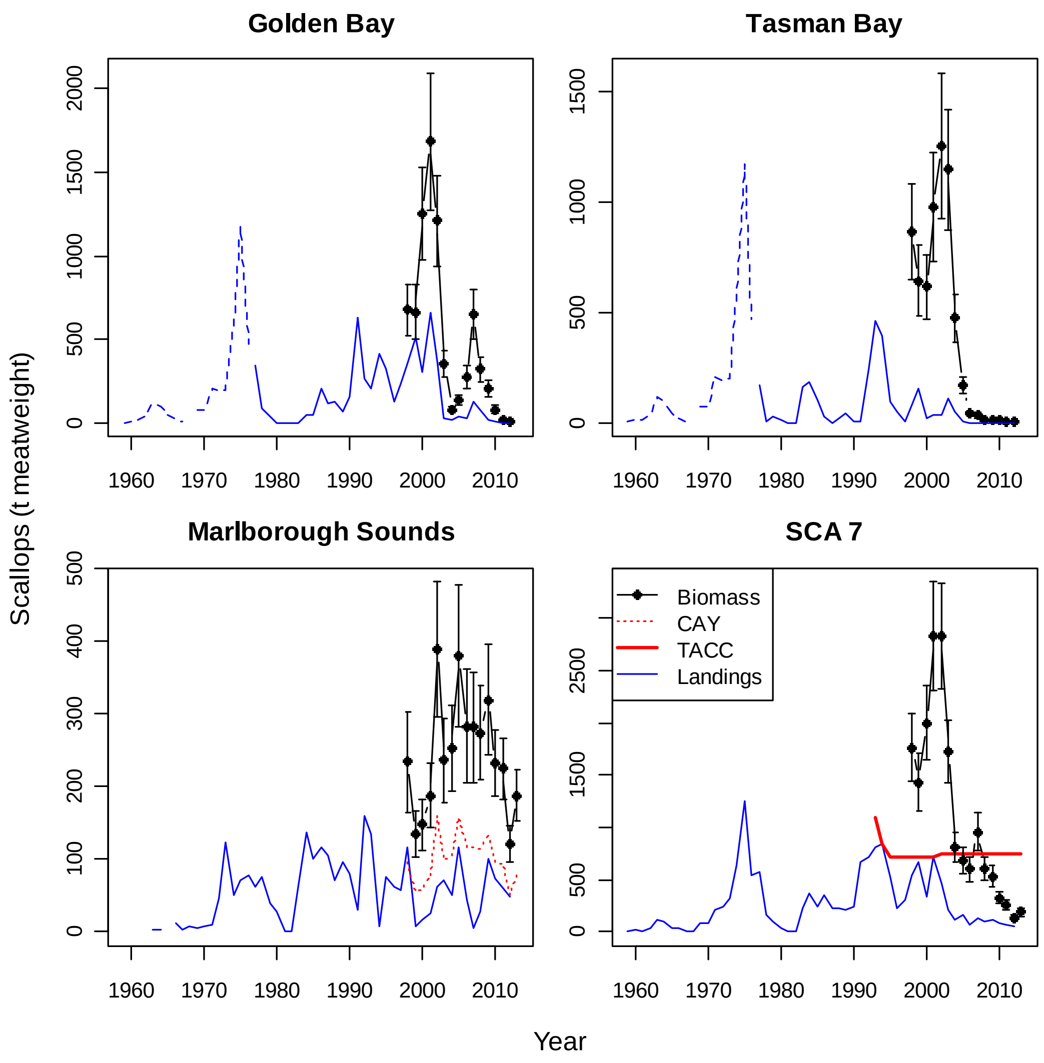


Figure 30: Historical SCA 7 stock status. Recruited (scallops 90 mm or more shell length) mean (and C.V. of) biomass estimates (closed symbols with error bars joined by solid black line), TACC (solid red line), and reported landings (solid blue line) in t meatweight for the three regions of the fishery and the overall SCA 7 stock since 1959 (landings before 1977 from Golden and Tasman Bays were reported as combined values from the two bays, shown as a dotted blue line). CAY (using F 0.1 = 0.553) for the Marlborough Sounds since 1998 is also shown (dotted red line). Estimates of biomass from surveys before 1998 are not presented because the surveys did not cover the full extent of the SCA 7 fishery. Scale differs between plots. Note the fishery was closed for the 1981–82 and 1982–83 scallop fishing years, and was subsequently managed under a rotationally enhanced regime.

A major source of uncertainty in the biomass estimates is associated with correcting survey catches for dredge efficiency. The estimated efficiency of the ring-bag dredge used on the survey is based on limited data, which we have assumed are representative of the average efficiency of the dredge for all areas of the fishery. Underestimating the average efficiency of the survey dredge would result in overestimating biomass. Recent work by Bian et al. (2012) on modelling the efficiency of box dredges used in the northern New Zealand scallop fisheries suggests that the methodological approach used to model efficiency can produce markedly different results. Their parametric model of dredge efficiency generated substantially higher estimates of efficiency than the non-parametric ratio method used previously in northern fisheries (SCA 1 and SCA CS), and used currently in the SCA 7 survey work up. However, for scallops of recruited size (90 mm or larger), the estimated efficiency of the SCA 7 survey ring-bag dredge (using the non-parametric method dredge efficiency method) is similar to that of the box dredges used in surveys of the northern fisheries (estimated using the parametric model of Bian et al. (2012)).

Other significant sources of uncertainty in the biomass estimates include predicting rates of growth and natural mortality between the survey and the start of the season, and predicting the average recovery of meatweight from greenweight. Scallop meatweight at the start of season was estimated by projecting numbers at length at the time of survey forward by 3 months (to 1 September) allowing for natural mortality, growth (in some strata), and greenweight to meatweight conversion factors. Such projections clearly include a range of uncertainties, and when used in northern New Zealand scallop fisheries are conducted over a shorter time period of a few weeks rather than months (Cryer & Parkinson 2006).

5.3 CAY estimates

Current Annual Yield estimates can provide a useful guideline for planning harvest strategies, such as informing decisions on setting catch limits. Uncertainty in CAY would be at least as large as that associated with the biomass estimate of B_{beg} used in the calculation. Working with a range of estimates (e.g., using a confidence interval) is therefore recommended, to help in selecting an acceptable level of confidence that a particular CAY will not cause fishing mortality to exceed the target rate ($F_{0.1}$). This approach is used each year for the Marlborough Sounds when estimating CAY from the annual survey data (e.g., see Williams et al. 2013a). In addition to the uncertainty associated with estimating B_{beg} as outlined above, CAY estimates are also sensitive to uncertainty in $F_{0.1}$. These uncertainties must be considered when interpreting CAY as an estimate of sustainable yield.

Estimation of the input parameter $F_{0.1}$ requires estimates of biological (recruitment, growth, mortality, maturity at length) and fishery (selectivity, incidental effects of fishing) parameters. Uncertainty in these parameters leads to uncertainty in $F_{0.1}$. As new data are collected and our estimates of these parameters are refined, $F_{0.1}$ should be re-estimated (unless other reference points considered to be more appropriate are determined). For example, new data and modelling approaches are available on *P. novaezelandiae* growth (Tuck & Williams 2012b) and maturity at length (Williams & Babcock 2005). The estimated instantaneous rate of natural mortality of *P. novaezelandiae* used to calculate $F_{0.1}$ is quite high (M about 0.5, equating to an annual mortality rate of about 40%), which is certainly higher than that of other very similar scallop species, such as *Pecten maximus* in Europe (E. Foucher, IFREMER, pers. comm.). Overestimation of M would lead to overestimation on $F_{0.1}$.

Existing estimates of $F_{0.1}$ for SCA 7 (Breen & Kendrick 1999) are probably too optimistic because they do not take into account the incidental effects of fishing. Field experiments have shown that dredging leads to reduced growth and increased mortality of *P. novaezelandiae*, and the inclusion of these incidental effects in yield-per-recruit modelling for the Coromandel scallop fishery results in lower estimates of $F_{0.1}$ (Cryer & Morrison 1997). The $F_{0.1}$ estimate used in management of the Coromandel fishery takes these incidental effects into account. Other field studies (Thrush et al. 1998, Talman et al. 2004) and modelling work (Cryer et al. 2004) on *P. novaezelandiae* suggest that dredging reduces habitat heterogeneity, increases juvenile mortality, and decreases estimates of $F_{0.1}$ even further.

Estimates of $F_{0.1}$ may also be sensitive to the method used to generate the estimates. In New Zealand scallop fisheries, the estimates of $F_{0.1}$ were derived from yield-per-recruit modelling, but there is some concern that yield per recruit estimates of F for scallops tend to be too high (Smith & Rago 2004).

The form of the equation used to calculate CAY for SCA 7 is different to the modified form of the Baranov catch equation used to calculate CAY for the SCA 1 and SCA CS scallop fisheries (Ministry for Primary Industries 2012b). The different models produce similar results if the duration of the fishing open season is very short, but the CAY estimates decrease with increasing duration of the season with the modified form of the catch equation (which includes a ‘time’ parameter to adjust for the length of the fishing season). This should not dramatically affect the CAY estimates for SCA 7 because, at least in recent years, the open season has been fairly short (1 to 2 months), but in future a consistent approach should probably be used across all of the scallop fisheries in New Zealand.

5.4 Exploitation rate

Our comparison of CAY and landings, and examination of the corresponding exploitation rates, showed that, except for in Golden Bay and the Marlborough Sounds in the late 1990s, scallop fishery exploitation in all three regions of SCA 7 has been at or often well below the level of the calculated CAY. Despite this, the scallop populations in Golden Bay and Tasman Bay have declined. Simulation modelling by Breen & Kendrick (1997) showed that simple fishing (i.e. non-rotational, non-enhanced) with a fixed-exploitation rate, where a constant proportion of the scallops are removed each year, is safe (i.e., resulted in a low probability of population collapse), if the maximum exploitation rate is appropriate. In that model, an exploitation rate of 0.35 appeared to be safe and to give a good average catch.

The calculated CAY for SCA 7 equates to a target exploitation rate of 0.42–0.47, which is clearly higher than the 0.35 value deemed safe by Breen & Kendrick (1997). It may be that the $F_{0.1}$ reference points used to calculate CAY are not appropriate, for the reasons discussed above, and the resulting CAY ‘target’ exploitation rates of 0.42–0.47 are too high. The CAY ‘target’ exploitation rate used in the Northland scallop (SCA 1) fishery is 0.37, and the current status of that stock is apparently low (Hartill & Williams 2012). In the Coromandel scallop (SCA CS) fishery, currently there are two CAY ‘target’ exploitation rates: 0.32 and 0.22; the former includes the effects of dredging on the scallops themselves (Cryer & Morrison 1997) and the latter includes those same effects plus the effects of dredging on seabed habitats that can indirectly reduce juvenile survivorship (Cryer et al. 2004, Talman et al. 2004). At the broad spatial scale of the SCA CS stock, actual exploitation rates in the last decade have been lower than either of these target rates, and the fishery is performing well.

Internationally, the scallop *Placopecten magellanicus* supports the largest and arguably the most successful fisheries for scallops in temperate waters, and stock assessment methods are well advanced. In Canada, *P. magellanicus* fisheries in the Maritimes Region (northwest Atlantic Ocean) are assessed and managed geographically, as inshore and offshore fisheries divided into multiple smaller stock areas, using a combination of fishery removal (exploitation rate) and biomass based limit reference points (Smith & Hubley 2012, Nasmith et al. 2013). In the most important offshore fishery area (Georges Bank) the target removal exploitation rate is set at 0.25, whereas in inshore fishery areas (Bay of Fundy and the inshore areas of Nova Scotia), the target is 0.15. These rates were determined by examining changes in biomass in relation to exploitation rates for the different fisheries. For example, in the inshore fishery areas, biomass levels tended to increase where the exploitation was 0.15 or less, but tended to decrease at higher exploitation rates, excluding high recruitment years. These target removal exploitation rates for Canadian scallop fisheries are substantially lower than those represented by the CAY approach in New Zealand scallop fisheries (SCA 1, SCA CS, SCA 7).

Different fishery areas most likely require different target rates of exploitation because of the potentially different productivities of the areas. Differential productivity may relate to differences in habitat suitability and the different levels of, and responses to, the incidental effects of fishing (e.g., seabed disturbance and suspension of fine sediments in the water column). Scallop beds in more exposed and/or well-flushed areas with coarse substrates might support higher exploitation rates of commercial scallop dredging than those in sheltered areas with silt or mud substrates because the latter may be more vulnerable to the indirect effects of fishing.

5.5 Drivers of productivity

Traditionally, scallops are considered as highly productive organisms: their biological traits of high potential fecundity and fast development to reach sexual maturity at a young age can result in very high population productivity (i.e., a fast biological turnover rate with the capacity to rebuild rapidly from low levels). Such high productivity, however, is not often realised because each of the different life history stages (larval, settlement and metamorphosis, juvenile, adult reproductive) requires quite specific conditions for success, and the probability of optimum conditions occurring at every stage, over the years between reproduction and recruitment to the spawning population, is low. Given the sporadic nature of recruitment typically observed in scallop fisheries, it appears that all of the necessary conditions may line up occasionally to produce large cohorts that survive, grow and recruit to the fishery as 'boom' years, but, for the years in between when conditions are less favourable, recruitment is relatively low, resulting in so-called 'bust' years. Patterns in productivity also vary spatially. For example, the Golden and Tasman Bays scallop substocks appear to have occasional years of high recruitment followed by years of low recruitment, whereas recruitment in the Marlborough Sounds substock appears to be more consistent (or at least changes in recruitment are more gradual). The above features of scallop productivity are characteristic of *P. novaezelandiae* in other stocks elsewhere in New Zealand, and in other species of scallop overseas such as *Placopecten magellanicus* in Canada (S. Smith, Department of Fisheries and Oceans, Dartmouth, Canada, pers. comm.) and *Pecten maximus* in Europe (Howarth et al. 2011).

The cause of the major declines in the scallop populations of Golden Bay and Tasman Bay is unknown, but our comparison of landings in relation to the CAY at the broad scale of the three substocks within SCA 7 suggests that the downturn is probably associated with factors other than simply the magnitude of direct removals of scallops by fishing. It has been recognised, however, that the estimates of the target fishing mortality $F_{0.1}$ used to calculate CAY may be too high. Nevertheless, declines in stocks of other shellfish (oysters, mussels) have also been observed (NIWA 2012). In addition to direct fishing mortality, a combination of other anthropogenic (e.g., land-based influences, indirect effects of fishing) and natural (e.g., oceanographic) drivers may have affected productivity of the SCA 7 fishery.

Habitat suitability encompasses many of the drivers of productivity. A suitable habitat for an organism can be defined as a place that has certain environmental conditions (e.g., temperature, salinity, pH, current flow, turbidity, pollutants) and resources (e.g., food, oxygen, physical space and structure) that enable the organism to occur and persist there; in addition to acceptable conditions and required resources, habitat suitability is also affected by intra- and inter-specific interactions (e.g., competition, predation) (Begon et al. 1990). Certain features of the habitats which scallops are associated with are known to influence their productivity. Scallop larval settlement requires the presence of fine filamentous emergent epifauna on the seabed, such as tubeworms, hydroids, and filamentous algae, hence the successful use of synthetic mesh spatbags held in the water column as a method for collecting scallop spat. The availability of suspended microalgae and detritus, the food sources of scallops, affects growth and condition (Macdonald et al. 2006). Survival of juveniles has been shown to vary with habitat complexity, being greater in more complex habitats (with more emergent epifauna) than more homogeneous areas (Talman et al. 2004).

Currently in the SCA 7 fishery, particularly in Golden and Tasman Bays, it appears that the suitability of benthic habitats for scallops might be lower now than in the past. While large numbers of scallop spat can still be collected in mesh spatbags held in the water column (such as in Golden Bay in 2012, despite very low spawning stock biomass in the surveyed area), industry surveys by diver and lined dredge suggest few spat are settling naturally onto the seabed and the survival of spat released from spatbags has been poor (M. Campbell, CSEC, pers. com.). This suggests first that settlement success may be limited more by the availability of suitable substrates to settle on rather than by larval supply, and second that the survival and growth of settled spat are affected by other inadequate aspects of habitat suitability (e.g., poor quality conditions, low food availability, inadequate habitat structure, abundant predators).

Suspended sediment is one aspect of habitat suitability that has been implicated in the scallop population declines: while sediment flows into Golden and Tasman Bays from flood events have been lower in the last decade than the historical average, near bottom turbidity from suspended fine sediments is considered to have increased (NIWA 2012). Suspended sediments can reduce rates of respiration and growth in scallops, the latter by 'diluting' the food available: scallops regulate ingestion by reducing clearance rates rather than increasing pseudofaeces production. Laboratory studies have demonstrated that suspended sediments disrupt feeding, decrease growth and increase mortality in scallops (Stevens 1987, Cranford & Gordon 1992, Nicholls et al. 2003). Suspended sediments can also reduce light levels near the seabed, potentially reducing production of benthic microalgae, which, when suspended in the water column, can form an important dietary component for scallops (Macdonald et al. 2006). Sediments can be suspended in the water column by natural hydrodynamic processes and by anthropogenic activities including fishing with mobile bottom-contact gears such as dredging and trawling.

It is well known that dredging and trawling do have impacts on benthic populations, communities, and their habitats (e.g., see Kaiser et al. 2006, Rice 2006). The effects are not uniform, but depend on at least: "the specific features of the seafloor habitats, including the natural disturbance regime; the species present; the type of gear used, the methods and timing of deployment of the gear, and the frequency with which a site is impacted by specific gears; and the history of human activities, especially past fishing, in the area of concern" (Department of Fisheries and Oceans 2006). The effects of dredging and trawling on scallops and their habitats are well-studied. In New Zealand specifically, field experiments have shown that physical disturbance from dredging (either in scallops caught and released, or those not caught but contacted by the dredge) leads to reduced growth and increased mortality of *P. novaezelandiae* (Cryer & Morrison 1997). Dredging is also focused on high density beds of scallops, which are disproportionately more important for fertilisation success during spawning (Williams 2005). Observational monitoring of *P. novaezelandiae* spat released in the first three years of enhancement (1984–86) in Golden Bay suggested that spat survival was higher in areas closed to trawling (Bradford-Grieve et al. 1994). The results of several studies on the effects of fishing carried out in scallop fishery areas in northern New Zealand (Thrush et al. 1995, Thrush et al. 1998, Cryer et al. 2000, Tuck et al. 2009, Tuck & Hewitt 2012) and the Golden/Tasman Bay region (Tuck et al. 2011) are consistent with the global literature: generally, with increasing fishing intensity there are decreases in the density and diversity of benthic communities and, especially, the density of emergent epifauna that provide structured habitat for other fauna (Ministry for Primary Industries 2012a).

Suspended sediments and the effects of fishing are two drivers of productivity that might have affected the performance of the Southern scallop fishery. The problem appears to be complex, however, with multiple influences on the system. To address this complexity, NIWA have been engaging with fishery end users to inform the development of an ecosystem model, working towards an ecosystem approach to fisheries management (EAFM) for Golden and Tasman Bays, with a view to potentially restoring sustainable fisheries production in the long term. As a first step, a workshop with stakeholders and iwi was held in February 2012, which determined the participants' shared vision of maintaining healthy, productive, and sustainable fisheries. A review of information on drivers of shellfish fisheries production in Golden and Tasman Bays and knowledge gaps was coordinated by NIWA and presented to two further workshops in August 2012 and August 2013 (NIWA 2012). That review outlines the various life history stages important to successful shellfish production, and identifies multiple drivers that include oceanographic influences on primary productivity and water circulation, sedimentation (particularly the effects of suspended sediments), effects of fishing (dredging and trawling), pollution, and disease. Further engagement with end users is ongoing to develop conceptual models for the shellfish fisheries, which forms part of NIWA's work on ecosystem modelling.

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8 APPENDIX

8.1 Preliminary estimates of survey bycatch

Dredge surveys of SCA 7 have been carried out annually since 1994 (see Table 5 for a list of the survey reports). The primary aim of the annual survey was to provide data for estimating scallop biomass, but data on the survey bycatch data were also recorded. As part of the survey catch processing methodology, scallops and oysters (of pre-recruit and recruited commercial size) and large starfish (*Coscinasterias* sp.) were sorted from the catch and the numbers of each were recorded. These data were used in the present study to estimate the standardised abundance of each of these species per tow:

Abundance = number recorded / area swept

An estimate of the total number of cases of the remaining bycatch was also recorded for each tow, and the percentage composition for each of up to 10 bycatch categories was visually estimated. These data were used to estimate the volume of each bycatch category per tow:

Bycatch volume = number of cases × bycatch category proportion × case volume / area swept

For green-lipped mussels, the surveys used the percentage composition method until 2003, and a direct weighing method (weight of mussels sorted from the catch) from 2004 to 2008. Data from the latter were used to convert the weight per tow to an approximate volume of mussels per tow using a conversion factor of 1.6 (based on an assumed weight of 28.125 kg per 45 L fish case).

These standardised estimates of abundance per tow (numbers of scallops, oysters and starfish; volumes of other bycatch categories) were then used to generate estimates of abundance at the survey stratum level, and the stratum estimates were combined to produce preliminary estimates at the Golden Bay, Tasman Bay, and the Marlborough Sounds level. Although estimates of absolute scallop abundance can be made using information on scallop dredge efficiency, estimates of dredge efficiency are not available for oysters, *Coscinasterias* or the other bycatch categories, and no correction for dredge efficiency was applied in generating these preliminary estimates of bycatch abundance (assumed 100% dredge efficiency, which is likely to be conservative).

The preliminary estimates of bycatch abundance for the years 1998 to 2013 are presented in Figure 31 to Figure 34. Detailed analysis of these bycatch data was beyond the scope of the present study, but could be of merit in future work. For example, multivariate analysis could be carried out to discern patterns or trends in catch composition in relation to other factors such as time, space, depth, bottom type, enhancement activity, and fishing intensity.

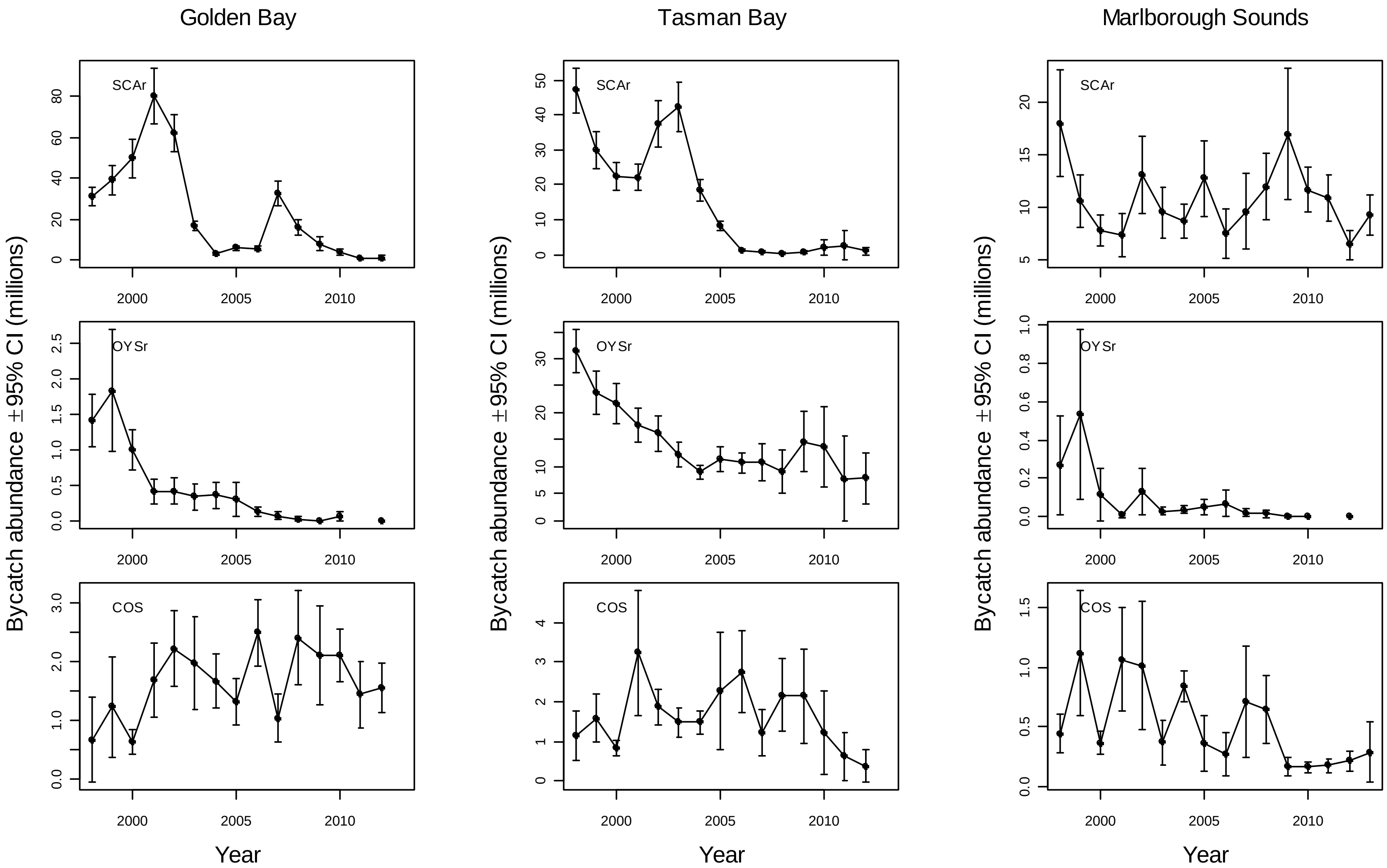

Figure 31: Estimates of abundance for recruited scallops (SCAr), recruited oysters (OYSr) and *Coscinasterias* starfish (COS) in Golden Bay, Tasman Bay, and the Marlborough Sounds from preliminary analysis of SCA 7 survey bycatch data, 1998–2013.

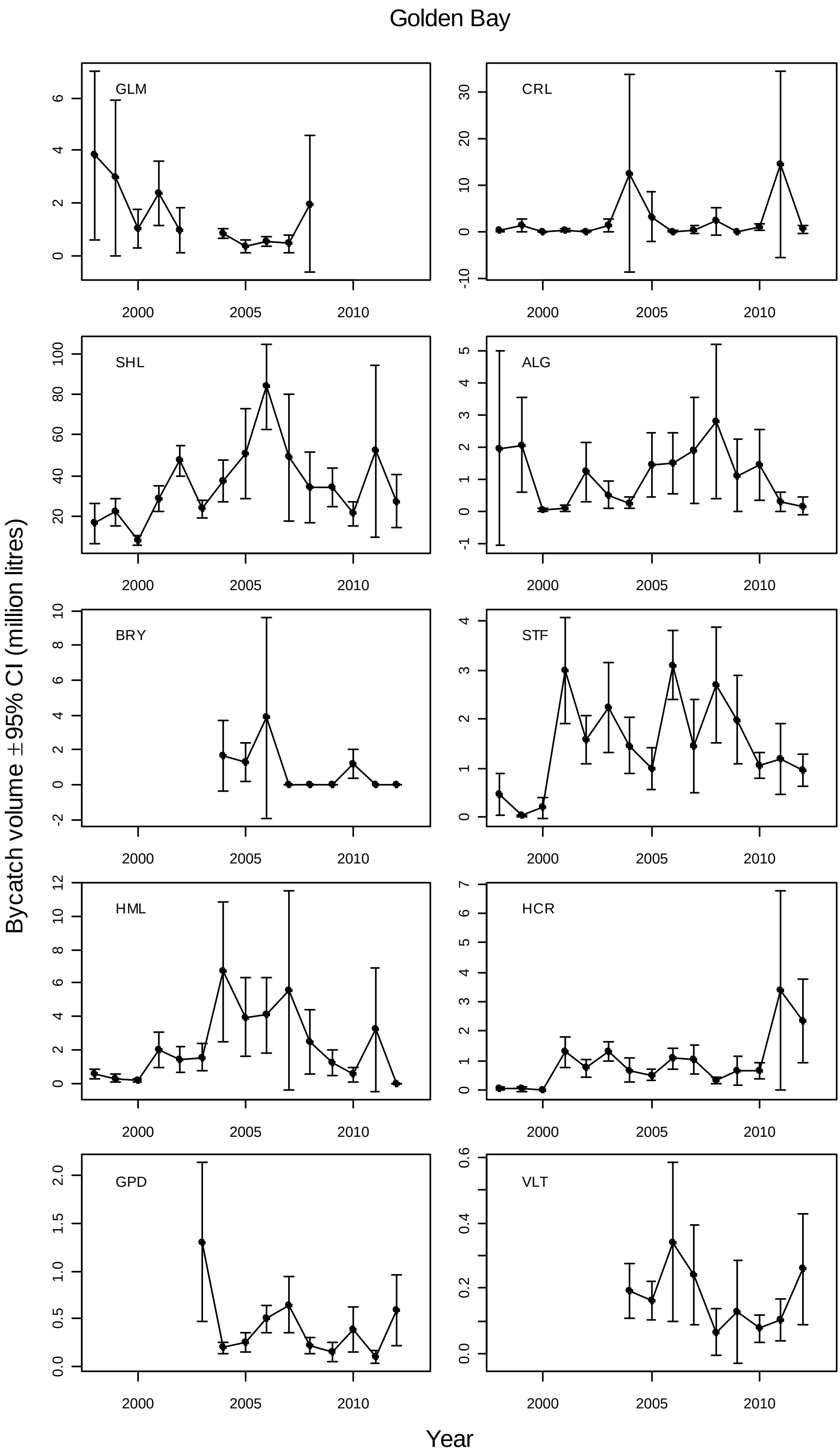

Figure 32: Estimates of abundance (volume) for various categories of bycatch in Golden Bay from preliminary analysis of SCA 7 survey bycatch data,1998–2013. Bycatch categories: green-lipped mussels (GLM), shell (SHL), bryozoa (BRY), horse mussels (HML), gastropods (GPD), 'coral' (CRL), algae (ALG), starfish (STF), hermit crabs (HCR), volutes (VLT).)

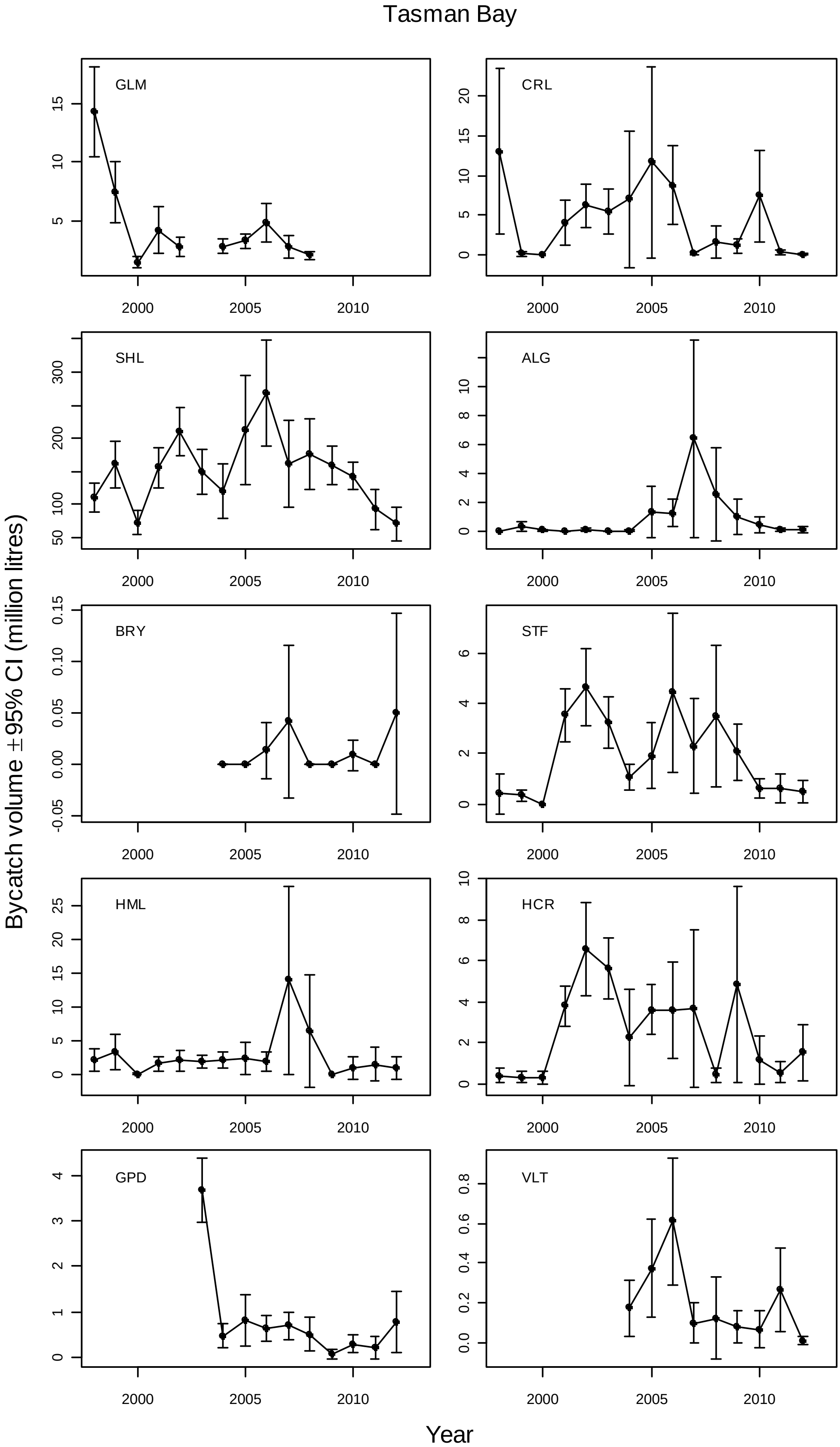

Figure 33: Estimates of abundance (volume) for various categories of bycatch in Tasman Bay from preliminary analysis of SCA 7 survey bycatch data,1998–2013. Bycatch categories: green-lipped mussels (GLM), shell (SHL), bryozoa (BRY), horse mussels (HML), gastropods (GPD), 'coral' (CRL), algae (ALG), starfish (STF), hermit crabs (HCR), volutes (VLT).)

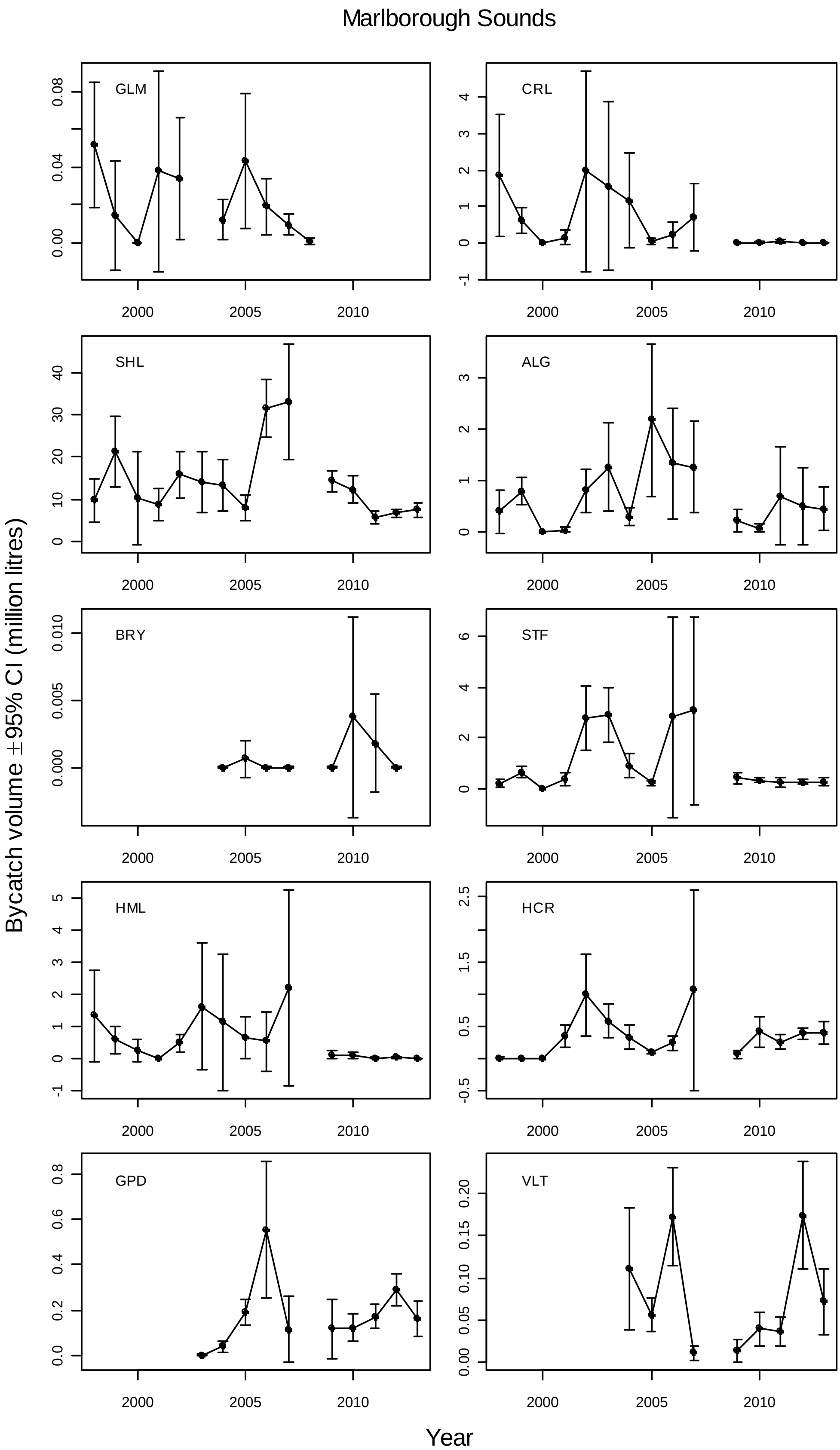

Figure 34: Estimates of abundance (volume) for various categories of bycatch in the Marlborough Sounds from preliminary analysis of SCA 7 survey bycatch data,1998–2013. Bycatch categories: green-lipped mussels (GLM), shell (SHL), bryozoa (BRY), horse mussels (HML), gastropods (GPD), 'coral' (CRL), algae (ALG), starfish (STF), hermit crabs (HCR), volutes (VLT).