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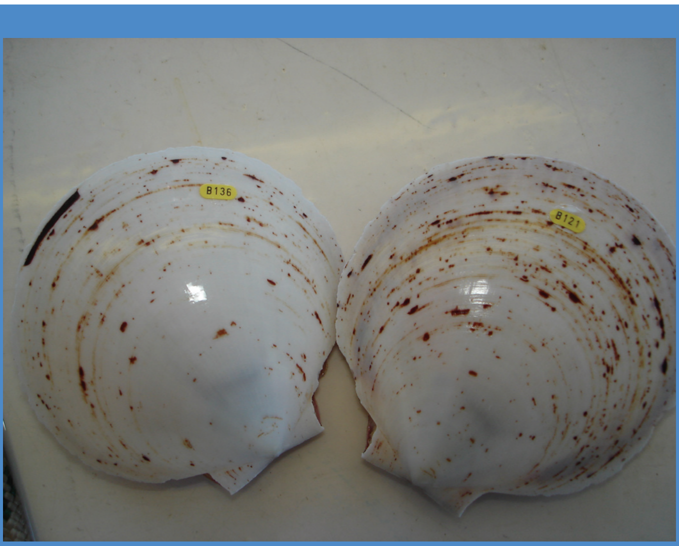

Harvest strategy evaluation to optimise the sustainability and value of the Queensland scallop fishery

FRDC Project No 2006/024

M. J. Campbell, A. B. Campbell, R. A. Officer,
M. F. O'Neill, D. G. Mayer, A. Thwaites,
E. J. Jebreen, A. J. Courtney, N. Gribble,
M. L. Lawrence, A. J. Prosser and S. L. Drabsch

Australian Government
Fisheries Research and
Development Corporation

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Government

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Final Report
May 2010

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Authors:
M J Campbell, A B Campbell, [1]R A Officer, M F O'Neill, D G Mayer, A Thwaites, [2]E J Jebreen, A J Courtney, N Gribble, M L Lawrence, A J Prosser and S L Drabsch

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[1] R A Officer was the Principal Investigator until July 2007
[2] E J Jebreen replaced A Thwaites as Trawl Manager

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2006/024 Harvest strategy evaluation to optimise the sustainability and value of the Queensland scallop fishery

PRINCIPAL INVESTIGATOR: Matthew Campbell[3]
ADDRESS: Department of Employment, Economic Development and Innovation
Bribie Island Research Centre
PO Box 2066
Bribie Island Qld 4507
Phone: (07) 3400 2051 Fax: (07) 3408 3535

OBJECTIVES:

1. Measure spatial and temporal trawl frequency of scallop grounds using VMS data. This will provide a relative measure of how often individual undersized scallops are caught and graded using a "tumbler".
2. Estimate discard mortality and growth rates for saucer scallops using cage experiments.
3. Evaluate the current management measures, in particular the seasonal closure, rotational closure and seasonally varying minimum legal sizes using stock assessment models. Recommend optimal range of management measures to ensure long-term viability and value of the scallop fishery based on a formal management strategy evaluation.

1 Non-technical summary

OUTCOMES ACHIEVED TO DATE

1. Improved understanding of the survival rates of discarded sub-legal scallops;
2. Preliminary von Bertalanffy growth parameters using data from tagged-and-released scallops;
3. Changing trends in vessels and fishing gear used in the Queensland scallop fishery and their effect on scallop catch rates over time using standardised catch rates quantified;
4. Increases in fishing power of vessels operating in the Queensland scallop fishery quantified;
5. Trawl intensity mapped and quantified for all Scallop Replenishment Areas;
6. Harvest Strategy Evaluations completed.

Using methods developed in the FRDC Project *Innovative stock assessment and effort mapping using VMS and electronic logbooks* (Good, Peel *et al.* 2007), trawl position data supplied by the Queensland Government's Vessel Monitoring System (VMS) Unit were

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[3] Matthew Campbell replaced Dr Rick Officer as Principal Investigator in July 2007

mapped in order to determine trawl intensity within Queensland's Scallop Replenishment Areas (SRAs). To this end, the trawl intensity in the months immediately after the re-opening of closed SRAs was examined to determine the trawling intensity during elevated levels of trawl effort within these areas. To achieve this, each SRA was divided into 34 m² grids (ie. the width of a trawl track using typical scallop gear) and the number of trawls that occurred within each of these grids was calculated. This gave a measure of trawl intensity in terms of the number of trawls in each 34 m² grid in a month. The grids that received the same number of trawls were then grouped together and their total area summed, resulting in trawl intensity as a function of area within the SRAs. The results suggested that the majority of SRAs are not trawled due to unfavourable substrate or low scallop density. The maximum number of trawls that any 34 m² grid received in the month immediately after the re-opening of an SRA was 17 in the Bustard Head B SRA in 2004. For all SRAs, approximately 85-90% of the trawled area experienced four trawls or fewer in the month immediately after the SRA was re-opened to trawling.

This result informed the frequency with which an undersize scallop may be caught and discarded during periods of elevated levels of trawling effort. That is, if a sub-legal (<90 mm) scallop were located in an SRA, theoretically that scallop could be caught and discarded up to 17 times. However, it is more likely that an individual sub-legal scallop could be caught and discarded up to four times. In Queensland, scallops are graded for size using a 'tumbler', a revolving tube constructed from stainless steel rings of a size which allow sub-legal scallops to exit the device. The damage to the shells of the discarded scallops caused by the tumbler has long been the subject of much discussion among fishers, with some saying that tumbling significantly decreases survival. As such, the survival of discarded sub-legal scallops was quantified via experiments conducted within the Bustard Head B SRA. Scallops were caught and subjected to increasing levels of both trawling and tumbling before being caged for three days. After three days, the cages were retrieved and the vitality of each scallop assessed. These experiments showed that with increasing levels of tumbling, the survival of sub-legal scallops decreased significantly. Survival was found to be 20% lower for animals that were subjected to four trawls and tumbles, compared to scallops that were subjected to four trawls only. Further, the experiment suggested that survival would have reached zero after approximately 10 trawls and tumbles.

Since the introduction of mandatory logbooks in 1988, scallop fishers have become more efficient due to significant advances in vessel- and gear-related characteristics. The effect of these changes was analysed and isolated via a Restricted Maximum Likelihood (REML) model. Catch rates were standardised using various gear and vessel characteristics. Catch rates decreased during the period 1993 to 1997 and remained relatively low until 2004. In 2001, the introduction of the *Fisheries (East Coast Trawl) Management Plan 1999* resulted in major changes to the structure of the scallop trawl fleet, with smaller vessels being replaced by larger, more efficient vessels. Since 2004, catch rates have increased, particularly during

January, when SRAs re-open after being closed for 15 months. Further, catch rates have been high in November, coinciding with the end of a temporal closure and the reduction in minimum legal size from 95 mm to 90 mm. At these times, the increased catch rates have attracted vessels from other trawl sectors such as the northern Queensland tiger prawn fishery and the eastern king prawn fishery. The increased use of these larger, more powerful vessels combined with advances in net size and configuration has contributed to a 16.5% increase in fishing power in the scallop fishery in the 20 years to 2008. Fishing power has increased significantly in the last 5 years, due to the fact that these large, efficient vessels are contributing more to total catch.

After discussions with scallop fishery stakeholders, via the project Steering Committee, ten management scenarios were identified and assessed via a Harvest Strategy Evaluation (HSE). The HSE was designed to assess the effect of the management scenarios on four performance indicators; catch rate, biomass, total harvest and economic value. Ten scenarios, including the status quo scenario, incorporated a range of rotating closure regimes using the Scallop Replenishment Areas and temporal closures. Closure regimes included the total removal of SRAs; increasing closure duration from the current 15 months to 21 months, 27 months, 33 months 39 months and 45 months; the removal of the current temporal (Southern) closure; and the introduction of a winter closure. These scenarios were assessed to determine their effect on the long-term sustainability and value of the fishery. The HSE model predictions varied greatly between the scenarios for all performance indicators. This is typical of scallop fisheries, which are subject to highly variable levels of recruitment. As such, no one scenario can be identified that maximises profit and ensures the sustainability of the *Amusium balloti* stock. However, the HSE model suggests that the removal of the SRAs would be detrimental to the fishery and the closure periods of the SRAs should, in fact, be increased. This is due to the fact that the number of scallops within the SRAs increases proportionally to closure duration. Increasing closure duration to either 27 months or 33 months, from the current 15 month closure, would result in an increase in all performance indicators, assuming a weak stock-recruitment relationship. At historically high levels of fishing effort and low recruitment, increasing closure duration to 39 months or 45 months allows successive year classes to settle within SRAs resulting in higher biomass. Discard mortality of tumbled scallops was found to be between 10% and 27% of total mortality depending on harvest rate and scallop density. However, the use of square mesh codends, which reduces scallop discard mortality by approximately 50%, will be a beneficial legislative change at the conclusion of the review of the *Fisheries (East Coast Trawl) Management Plan 1999*.

KEYWORDS: scallops, *Amusium balloti*, discard mortality, growth, harvest strategy evaluation, Scallop Replenishment Area, spatial closure

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We would like to thank Mike Dredge who provided invaluable advice during the initial stages of the project and also generously shared some rare publications and insights into the fishery he studied for the best part of 25 years. The numerous journal articles he authored during the late 1980's and early 1990's have formed the basis of the management strategies used in the last 20 years and are referenced throughout this report. His pioneering work in the scallop fishery is a reminder that researchers should remove themselves from the laboratory and gain some hands-on experience in the fisheries they study.

Special thanks go to Kate Yeomans for her patience and assistance when processing the frequent requests for logbook data during the course of the project. Thanks also to Nadia Engstrom for her assistance in this area.

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Thanks go also to Mr Mike Conroy of Crab 'n' Gear for sharing his knowledge regarding the construction of the cages used in the survival experiments. His innovation, generosity and assistance were of great benefit when designing and manufacturing the cages.

3 Background

Over the last 6 years, the annual catch of scallops from the Queensland East Coast Otter Trawl Fishery has fallen dramatically to about a third of the annual catch weight and value. We propose to determine whether the current management measures are resulting in the optimum use of the resource.

The spatial management of trawl effort in Queensland's fisheries is under review over the next two years, with scallop as a key component of the review. A major aim of this review will be to determine whether it is optimal to manage the scallop sector as a separate fishery. Key to this is determining the most appropriate arrangements that will optimise yield and economic output whilst ensuring ecological sustainability.

Current management arrangements include minimum legal size (MLS), spatial and temporal closures, and gear restrictions. Imprecise estimates of discard mortality have previously been identified as a major impediment to improved stock assessment and effective harvest strategy evaluation for Queensland scallops (Proceedings of the South East Queensland Stock Assessment Review Workshop (1998) and FRDC Project #1999/120).

The long-term annual reported catch from the Queensland scallop fishery from 1988-2000 was about 1,100 tonnes (meat weight) valued at $20-30 million. Landings varied between about 600 and 2,200 tonnes and annual fishing effort has also varied between about 9,000-22,000 boat-days over the same period, with a mean of about 15,500 boat-days. The majority of the catch is exported, mainly to niche markets in south east Asia where it commands premium prices. In the last three years catch and effort have declined markedly. In 2003 the reported catch declined to around 390 tonnes from about 6,500 boat-days of effort. According to recently-developed stock assessment models of the fishery, the decline does not appear to be due to a decline in biomass or population size. Reasons for the decline are unknown, but appear to be due, in part, to the response of the trawl fleet to the *Fisheries (East Coast Trawl) Management Plan 1999* that was introduced in January 2001.

The decline has occurred concurrently with a reduction in the number of small vessels operating in the scallop fishery. Traditionally, these smaller operators provided scallops and by-product to processors and export markets throughout the year. A key initiative of the *Trawl Plan* was the allocation of a limited number of fishing nights to each vessel/operator on the Queensland east coast. This initiative brought about a dramatic amalgamation and reduction in the number of vessels from about 800 in 2000 to about 470 in 2003. Many small vessel operators, in particular, sold their allocated nights to remaining operators and simply left the industry.

In the scallop fishery ports of central Queensland (Tin Can Bay, Bundaberg, Gladstone and Yeppoon), the remaining vessels appear to allocate most of their effort to other stocks such as the eastern king prawn and the northern tiger/endeavour prawn stocks, probably because it is more profitable for them to do so. As a result, catch and effort in the scallop fishery have declined markedly. Most of the fishing effort in the scallop fishery is now applied during the months of November to January as a result of seasonal closures and seasonally varying minimum legal sizes.

Another factor that appears to have contributed to the reduced effort is related to the introduction of Turtle Excluder Devices, or TEDs, as part of the Trawl Management Plan. An important contributing factor to the profitability of small vessels trawling for scallops throughout the year prior to the introduction of the Plan was that they were allowed to retain Moreton Bay bugs, as well as scallops. The scallop fishery operates in one of the State's two most productive areas for bug landings. However, research data obtained from the FRDC-funded bycatch project (Courtney, Haddy *et al.* 2007) has shown that TEDs in the scallop fishery significantly reduce the catch rate of Moreton bay bugs. A significant decline in Bug landings is reflected in the logbook records since TEDs were introduced.

The value of the scallop harvest is largely dependent on Asian markets. Because there is now very little production of scallops for most of the year, and because most of the landings are now taken over a short period of pulsed effort from November to January, the overseas importers tend to hold off purchasing scallops until there is a glut, thus lowering the price and value of the harvest. This complex chain of events (little supply throughout most of the year and a glut from November to January) has left the marketing and the value of the scallop harvest in a very precarious state.

In 2002 the Queensland Seafood Marketer's Association Inc (QSMA) commissioned a report by Mr Warwick Lee of the DEEDI to ascertain the status of marketers in the Tin Can Bay to Gladstone region. The report (Lee 2002) confirmed a downturn in the profitability of the regional scallop processors and a significant decline in the 2002 catch. This has been accompanied by a decrease in the reported price paid to fishers, a 30% decline in value to the industry, seasonal reductions in processing staff numbers and days worked, and limited success from diversification strategies into other seafood species. Some processors have indicated that their business will be bankrupted as a result of the downturn.

The fishery currently catches and discards a high proportion of undersize scallops. This suggests that current fishing gears are not properly selective for scallops greater than the minimum legal size. Anecdotal evidence from fishers suggests that undersize discarded scallops suffer high mortality through significant chipping after grading in onboard tumblers. Fishers also suggest that the same undersize scallops are caught and processed repeatedly, leading to a further increase in mortality.

In summary, the catch and effort in Queensland's scallop fishery have declined significantly over the last 3 years and concurrently with the introduction of the Trawl Fishery Management Plan. The reported catch in 2003 estimate was about a third of the long-term average, equivalent to a reduction in value of about $14 million. The decline does not appear to be due to a similar decline in biomass, but rather due to the fleet's response to the allocation of nights, the subsequent reduction in the number of small vessel operators and the current combination of seasonal and rotational spatial closures, and seasonally-changing minimum legal sizes. The introduction of TEDs also appears to have lowered the profitability of trawler operators in the scallop fishery. The bulk of the catch now being landed over a short period each year (November to January) resulting in a subsequent glut in supply lowering the prices paid by overseas importers.

In order to increase the annual total landings of scallop meat, the central Queensland seafood processors are advocating a reduction in the minimum legal size of scallops and abolishing the rotational closures. It is likely that these measures would attract some effort back into the fishery and increase catches, although the magnitude of the increase in effort is unknown. Improved selectivity of fishing gears may mitigate the risks of adjusting the minimum legal size whilst also reducing discarding rates and discard mortality. DEEDI needs to quantitatively assess such measures before it is decided to implement change. To this end, we propose to quantitatively evaluate the current management measures and evaluate additional and alternative measures. These management strategy evaluations (MSEs) will build on the outputs of several FRDC projects including Good, Peel *et al.* (2007), Courtney, Haddy *et al.* (2007), Hall, Cao *et al.* (2000) and Haddon, Harrington *et al.* (2006), along with published, peer-reviewed articles regarding MSE frameworks including Smith (1994), Smith, Sainsbury *et al.* (1999) and Punt and Smith (1999). The MSE will consider the rotational closure models developed for the Tasmanian Scallop fishery, in addition to other rotational harvest strategies (Caddy and Seijo 1998). Field experiments will be used to estimate discard mortality and growth. An analysis of VMS trawl track data will estimate the relative frequency of undersize scallop recaptures.

There is also a need for industry and management to identify targets for the scallop fishery. That is, what is the objective of management and what is the level of risk of overfishing that industry and management are prepared to accept? These questions will be addressed in partnership with the strategic assessment of the East Coast Trawl Fishery under the EPBC Act.

4 Need

There is a need to evaluate the current management measures applied to the scallop fishery, particularly the range of minimum legal sizes, the effects of the southern closure and the rotational closures. It is important to assess whether these management measures are effective and what alterations are required to ensure the long-term sustainability of the fishery. Further, given the financial pressures exerted after the dramatic increase in fuel cost in recent years, combined with the decrease in the scallop price paid to fishers, there is a need to ensure both sustainability and economic viability in the scallop fishery. There is a need to determine whether the value of the fishery can be increased with alternative management measures within the constraints of acceptable risks of overfishing. One of the priorities of the Queensland Fishing Industry Research Advisory Council (QFIRAC) is to look at the scallop fishery and in particular the value of protected areas, sources of mortality and stock structure.

Some processors are requesting DPI&F abandon the rotational spawning stock closures and lower the minimum legal size of scallops with the intention of increasing the amount of scallops fishers can retain and market. To consider any of these changes in management that could possibly lead to overfishing it is imperative that precise estimates of key stock assessment parameters including gear selectivity and discard mortality are quantified.

The frequency with which discarded scallops are recaptured over time and space may impact on estimates of discard mortality. Using the VMS trawl track database, the frequency with which an area is trawled will be determined to guide subsequent discard mortality experiments.

5 Objectives

1. Measure spatial and temporal trawl frequency of scallop grounds using VMS data.
2. Estimate discard mortality and growth rates for saucer scallops using cage experiments.
3. Evaluate the current management measures, in particular the seasonal closure, rotational closure and seasonally varying minimum legal sizes using stock assessment and management modelling models. Recommend optimal range of management measures to ensure long-term viability and value of the Scallop fishery based on a formal management strategy evaluation.

6 Survival of discarded sub-legal scallops *Amusium balloti* in Queensland's trawl fishery

6.1 INTRODUCTION

Bycatch mitigation in demersal prawn trawl fisheries is a complex issue (see reviews by Alverson, Freeberg *et al.* 1994; Hall, Alverson *et al.* 2000; Kennelly 1995). Bycatch mitigation in prawn and scallop otter-trawl fisheries is particularly difficult. These fisheries use trawl gear that is designed to target relatively small animals and, as a result, are characterised by poor species and size selectivity. This poor selectivity, combined with the fact that prawns and scallops co-exist with a diverse range of animals that are susceptible to capture by otter-trawl gear (Andrew and Pepperell 1992), results in relatively high bycatch rates when compared to other forms of fishing.One aspect of bycatch that is of concern to the managers of demersal prawn and scallop otter-trawl fisheries is the fact that the bycatch may include target species which must be discarded because of their small size (Jenkins and Brand 2001), termed regulatory discards by Kelleher (2005). The capture, and resultant associated mortality, of these discarded animals can have significant impacts on stocks (Miller, Broadhurst *et al.* 2005), particularly with regard to recruitment, yield and biomass (Broadhurst 2000). Discard mortality is rarely known in specific fisheries and represents a large source of uncertainty in estimates of fishing mortality (Davis 2002). Although Hill and Wassenberg (2000) indicate that bivalves have high survival rates compared to other bycatch species, the estimated proportions of discarded individuals dying often greatly exceed those which survive (Broadhurst, Suuronen *et al.* 2006). The survival of discarded saucer scallops in Queensland is unknown.

As part of the *Fisheries (East Coast Trawl) Management Plan 1999*, a seasonally changing minimum legal size (MLS) of 90 mm maximum shell height (November to May) and 95 mm (May to November) was introduced for scallops in 2001. This effectively protects the spawning scallops through winter and spring when 75% of scallops over 90 mm are sexually mature (Dredge 1981). Minimum mesh size regulations (≥75 mm or 3 inch) exclude a significant proportion of sub-legal scallops from commercial catches. However, mesh selectivity is not “knife-edged” and some undersize scallops are caught, with young-of-year scallops being susceptible to trawling from July onwards each year (Dredge 1988a). Courtney, Campbell *et al.* (2008) reported that during a dedicated research charter in the scallop fishery, undersize scallops accounted for 34% of the total scallop catch rate by weight and would have accounted for a considerably higher proportion in terms of individuals.

Queensland scallop fishers use a specially-designed grading machine to separate legal and sub-legal scallops. The grading machine, or “tumbler”, consists of stainless steel rings welded together to form a tube approximately 1200 mm long and 400 mm in diameter (see Figure 6-1). The tube is inclined at approximately 15° from the horizontal and revolves via a belt driven by a small electric motor mounted to the tumbler’s frame. The sub-legal scallops fall through the rings and are washed through a chute and overboard by a deck-hose attachment. Legal-sized scallops move down the cylinder and fall into a basket under the lower exit point. The effect of this process on the survival of the sub-legal scallops is unquantified and likely adds to the effects of contact with ground chains, crushing in the codend and being dropped on the sorting tray along with the rest of the catch.


(a) (b)

Figure 6-1: The tumbler used in the survival experiments (a). This particular tumbler separated sub-legal scallops of less than 90 mm commercial shell height which fell through the stainless rings and exited the device via the shute located at the base. The legal scallops passed through the device and were collected in the basket shown in (b).

The mortality incurred by discarded scallops may be further exacerbated by the pattern of fishing effort in the fishery. The Queensland scallop fishery currently mainly occurs through the rotational harvest of “Scallop Replenishment Areas” (SRAs) (Figure 6-2). SRAs were implemented as part of the Queensland Government’s *Fisheries (Emergency Closed Waters) Declaration 1997*, and their rotational spatial closure was implemented as part of the *Management Plan* in 2000. Historically, SRAs were highly productive. It was thought that closing such areas would maintain spawning stocks for the following winter. Three of the SRAs are closed for a period of 15 months while the remaining three are open to fishing. When closed SRAs are re-opened there is a sudden influx of vessels and highly elevated levels of fishing effort. This has implications regarding the incidental trawl mortality of discarded scallops - with upwards of 50 vessels trawling intensively in a relatively small area. It is conceivable that a single sub-legal scallop could be caught, tumbled and discarded a number of times in a short period.

Improved assessment and management of the scallop fishery requires well estimated measures of discard mortality. Currently the assessment of the fishery is based on the assumption that all discarded scallops survive capture (O'Neill, Courtney *et al.* 2005). This chapter examines and quantifies the effects of multiple captures and tumbling on the survival of discarded sub-legal scallops.

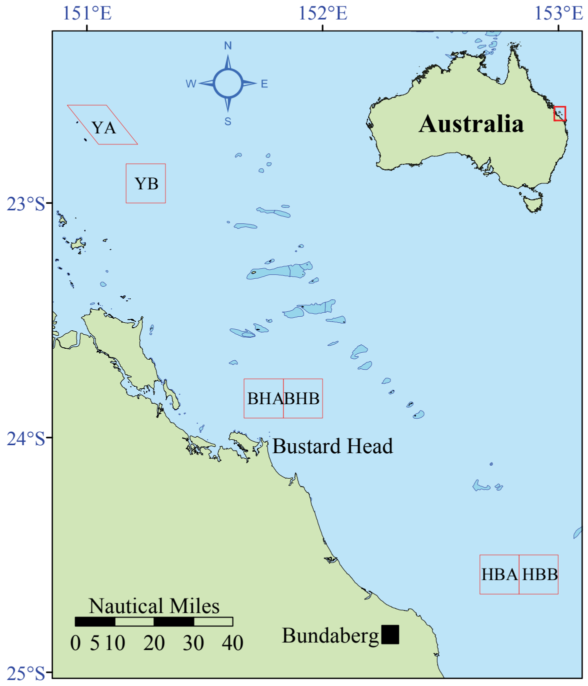

Figure 6-2: Location of Queensland's Scallop Replenishment Areas. YA = Yeppoon A, YB = Yeppoon B, BHA = Bustard Head A, BHB = Bustard Head B, HBA = Hervey Bay A and HBB = Hervey Bay B.

6.2 METHODS

The Scallop Replenishment Areas (see Figure 6-2) were mapped to determine the trawl intensity that occurred during periods of elevated trawl activity coinciding with the re-opening of the SRAs after a 15 month closure. These maps were used to estimate the theoretical maximum number of times an individual scallop may be caught during intensive trawl effort. Vessel location data were sourced from the Queensland Government's Vessel Monitoring System (VMS) Unit and, using decision rules developed by Good, Peel *et al.* (2007), trawl tracks were derived. Once the trawl tracks were developed, the SRAs were divided into 34 m^2 grids using MATLAB (2009) and the number of trawling events in each of these grids was calculated (see Appendix 3, Section 17.1.1, page 111 for the relevant MATLAB code). The grids that received the same number of trawls were then grouped together and their total area summed. This gave a measure of trawl intensity as a function of area within each SRA. From these data, the theoretical number of times that a discarded scallop could be caught and discarded during elevated levels of trawling effort were derived.

Four experiments were conducted in April 2007 (Autumn07), July 2007 (Winter07), October 2007 (Spring07) and April 2008 (Autumn08). The Bustard Head B Scallop Replenishment Area (SRA) was chosen for the first three field experiments as its closure from 20 September 2006 to 31 December 2007 allowed the experiments to be conducted in an area where there was no commercial trawling activity. Furthermore, surveys conducted as part of the Queensland Government's Long Term Monitoring Program just after the area was closed revealed that relatively high numbers of scallops could be caught, providing enough scallops to enable robust statistical analysis. From Figure 6-5, it can be seen that approximately 96.5% of the Bustard Head B SRA was trawled four times or less. Consequently, this was considered to be an appropriate number of trawling events to which the scallops should be subjected in order to quantify the effect of repeated capture and discarding. Further, four trawls per night was also considered to be practical aboard the vessel given the extra time required to complete the experiments. The fourth and final experiment was conducted within the Hervey Bay A SRA (see Figure 6-2). This SRA was chosen as it had been closed for seven months at the time of the experiment.

All short-term survival experiments were conducted aboard the Fisheries Research Vessel *Tom Marshall*, a 15 metre aluminium catamaran. The scallops were caught using a beam trawl net, with a 3.5 fathom (≈ 6.4 metre) headline and a mesh size of 2 inch (50 mm), attached to a 5 metre beam towed from the stern. The codend was 75 meshes long, constructed from 3 mm braided polyethylene (2 inch mesh) with a bottom-shooting Turtle Excluder Device (TED) installed in the forward section. A Fisheye Bycatch Reduction Device was installed 35 meshes forward of the drawstrings.

Trawling commenced each night about 30 minutes after sunset. The first trawl was approximately 90 minutes long, enabling a minimum of 800 scallops to be captured for the experiment. At the conclusion of the first trawl, the scallops and bycatch were separated and the scallops placed in 9 litre buckets, at 50 scallops per bucket. The bycatch was returned to the sea as soon as possible to maximise survival. In order to isolate the effects of tumbling, all other factors affecting survival were quantified using control animals which, apart from the tumbling, were subjected to the same handling as the tumbled scallops. 100 individuals were allocated to each of eight treatment levels – trawled-only one to four times (controls) and trawled-and-tumbled one to four times (treatments).

Once 800 scallops had been removed from the catch and placed in buckets, approximately 400 scallops were graded using the commercial tumbler. These scallops were placed into the tumbler one bucketful at a time and were kept separate throughout the night. Once all the tumbled scallops had passed through the tumbler, approximately 50 individuals, both legal and sub-legal, were placed in each of two cages. The cages were constructed from a tube of #15 ply, 32 mm polyethylene trawl mesh, 158 meshes round and 45 meshes deep, laced to two galvanised steel hoops 900 mm in diameter (see Figure 6-3). The two hoops were held 150 mm apart by 4 aluminium risers. The remaining tumbled scallops were placed in labelled catch bags (see Figure 6-4), at approximately 50 scallops per bag, constructed from the same material as the cages. Both treated and control scallops were held on the deck of the vessel while tumbling occurred. This ensured that control and treated scallops were exposed to the air for equal amounts of time in order to minimise variation in survival due to this factor.

Figure 6-3: Cages used to house scallops during the survival experiments conducted in the Bustard Head B and Hervey Bay A SRAs.

Approximately 50 control scallops were placed in each of two cages with the remainder placed in catch bags (50 scallops per bag). All cages and catch bags were then placed in a one-tonne recirculating tank while steaming to a pre-determined area for cage deployment, approximately 0.5 nautical miles east of the trawl ground.

The cages were deployed along the seabed on a 125 metre length of 8 mm diameter polyethylene longline, via lanyards and shark clips. A cement block was also attached to the longline to prevent movement of the cages on the sea floor. Each longline was marked with a float and assigned a number. Once the longline had been deployed, the vessel returned to the trawl grounds. On arrival at the trawl grounds, the catch bags were removed from the recirculating tank and placed in the codend of the trawl. The net was then deployed and readied for trawling.

Successive trawl times were 60 minutes, at the conclusion of which, the catch bags were removed from the codend and the treated scallops were subjected to further tumbling. Approximately 100 tumbled and 100 control scallops were removed to cages and deployed on longlines. This process was repeated until all scallops had been removed to cages with 16 cages deployed, each containing approximately 50 scallops.

Figure 6-4: Catch bags used during the survival experiments. Approximately 50 scallops were placed in each catch bag for successive trawls after being caught in the first trawl shot of each night. Treated scallops were removed from the catch bags and tumbled before being returned to the same catch bag.

This procedure was repeated on the second and third nights of the field work, allowing the cages to ‘soak’ for approximately two-and-a-half days after which the cages were retrieved. This soak time was chosen after discussions with researchers involved in scallop ranching in Bundaberg, Queensland, who suggested that the mortality of broodstock scallops sourced from commercial trawlers is highest in the first three to five days (R Dean, Queensland Sea Scallops, *personal communication*). This was confirmed by earlier results reported by Wassenberg and Hill (1993), who found that most otter-trawl gear bycatch mortality occurred within three days of capture, with little mortality occurring after four days. Further, it was necessary to limit the soak time of the deployed cages to minimise the risk of entanglement of large fauna, such as sea turtles and whales, in the gear.

Once each longline had been retrieved, the nominal shell height (NSH, in mm) of each scallop was measured as per Williams and Dredge (1981) and vitality was assessed. Each live scallop was tagged with a Shellfish Tag[4], using cyanoacrylate glue[5]. After tagging, the scallops were released in the Bustard Head B SRA. The next longline was then retrieved and the above process repeated.

Generalised linear modelling (GLM) using GenStat (2007) statistical software was used to examine the variation in survival according to the number of tumbles and/or trawls. A binomial distribution with logit link function was used to estimate the proportion of scallops surviving where treatment level (the number of tumbles and/or trawls), experiment

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[4] 4 x 8 x 0.15 mm, Hallprint Pty Ltd, South Australia – see Ross KA, Thorpe JP, Norton TA, Brand AR (2001) An assessment of some methods for tagging the great scallop, *Pecten maximus*. *Journal of the Marine Biological Association of the United Kingdom* **81**, 975-977.

[5] Selleys® Quick Fix™ Supa Glue Non-Drip Gel

(Autumn07, Winter07, Spring07 and Autumn08) and size class (legal (CSH ≥ 90 mm) and sub-legal (CSH < 90 mm)) were added as factors. The number of scallops per cage was added as a co-variate to assess the effect of stocking density on survival. Several interactions of these factors were tested and excluded from the model if the deviance ratio of the interaction was an order of magnitude lower than the deviance ratio of the main factors alone.

To minimise the duration of exposure to air, the scallops were measured at the end of the experiment, rather than at first capture. Changes in NSH after successive tumbling events due to chipping of the outer margin of the valves were estimated by a separate experiment in which 500 scallops, extraneous to the survival experiments, were tagged and tumbled four times. After each tumble, the tag number and NSH of each scallop were recorded. The effect of tumbling on NSH was assessed using Paired T-tests. Linear regressions were then performed in (GenStat 2007) to estimate the NSH of each scallop corrected for each tumbling event. These regressions were then used to back calculate the size of each scallop prior to tumbling. The NSH was converted to commercial shell height (CSH, in mm), the maximum width of the shell and the measurement used by commercial fishers, using the following formula:

$$CSH = 1.02(NSH) + 0.64$$

In December 2007, the Bustard Head B SRA was re-sampled over a two-day period, prior to it's opening to commercial activity. The same trawl gear was employed to recapture the scallops aboard the FRV *Tom Marshall*, with 20 individual 25-minute trawls completed in two days. At the end of each trawl, the tag number and NSH of each recaptured scallop were recorded. As with short-term mortality, generalised linear modelling using GenStat (2007) was used to examine the variation in recapture rate (ie. the number of scallops recaptured compared to the numbers released). Once again, the effects of treatment level, experiment, size class and the number of scallops per cage were assessed, to determine their effect on recapture rate.

6.3 RESULTS

6.3.1 Trawl intensity within SRAs

Of primary concern for the survival experiments was the trawl intensity within the Bustard Head B SRA. It was found that 96.5% of the area within the SRA received 4 trawls or less during January, 2004 (Figure 6-5). Approximately 59% of the SRA received no trawling effort. For the entire month, the average trawl frequency for the SRA was less than 1 suggesting that for the most part, trawl tracks do not intersect. The results also suggest that the majority of discarded scallops are unlikely to be re-caught and tumbled more than 4 times in one month.

Further analyses were undertaken for all of the SRAs, which can be found in Appendix 3, Section 17.1.2 on page 114.

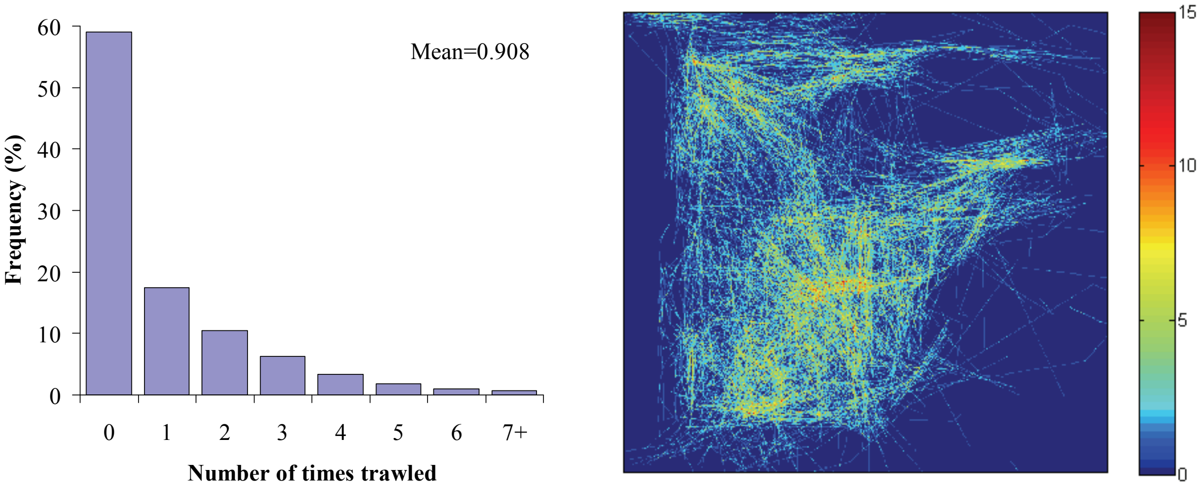

Figure 6-5: Trawl frequency within the Bustard Head B SRA during January, 2004. Note the large area within the SRA that received no trawl effort.

6.3.2 *Effect of tumbling on nominal shell height*

484 scallops with an original mean NSH of 90 mm (s.e. = 0.44 mm) were tumbled four times. Paired T-tests revealed that the mean NSH became significantly smaller ($P < 0.001$) after successive tumbling except after the third tumble when the mean NSH did not change significantly ($P = 0.668$). These changes in NSH were corrected via linear regression equations generated in GenStat (2007) to ensure the scallops were correctly divided into either legal or sub-legal prior to being tumbled. All of the following analyses were performed using this corrected NSH and the resulting CSH.

6.3.3 *Effect of tumbling on short-term survival*

A total of 8,868 scallops were caught during the experiments (Table 6-1), ranging in CSH from 32 mm to 117 mm (mean = 95 mm, s.e. = 0.12 mm). Of these, 2,056 (23.2%) were smaller than the minimum legal size of 90 mm (see Figure 6-6). Kolmogorov-Smirnov tests revealed that there was no significant difference (ie. $P > 0.05$) between the CSH size distributions for each treatment level (the number of tumbled and/or trawls).

Although 800 scallops per night, or 2,400 per experiment, was the intended target, at times this number of scallops was not always obtainable due to weather or other constraints (Table 6-1). During the first experiment, suitable numbers of scallops could not be located until the second night, resulting in a lower total number caught, while weather forced the abandonment of the third night of trawling during the final autumn experiment. The largest scallops were caught during the Spring07 experiment, with a mean CSH of 101 mm (s.e. = 0.14), while the smallest scallops were caught during the Autumn08 experiment with a mean CSH of 82 mm (s.e. = 0.33).

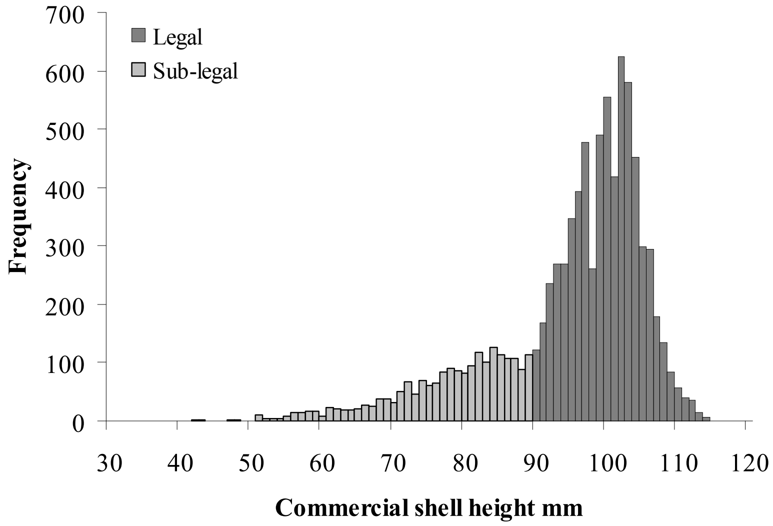

Figure 6-6: Commercial shell height (in mm) frequency histogram for the 8,868 *A. balloti* caught during the four survival experiments.

Table 6-1: Number, commercial shell height (CSH) size range and mean commercial shell height (standard error) of *A. balloti* in each trial and experiment.

Treatment level/ Experiment	*n*	CSH Range mm	Mean CSH mm (s.e.)
1 trawl, 0 tumbles	1185	51 – 117	95.5 (0.30)
1 trawl, 1 tumble	1255	47 – 114	93.5 (0.34)
2 trawls, 0 tumbles	1021	50 – 113	95.0 (0.33)
2 trawls, 2 tumbles	1018	42 – 113	94.5 (0.31)
3 trawls, 0 tumbles	1192	40 – 116	94.9 (0.31)
3 trawls, 3 tumbles	1208	45 – 117	96.7 (0.32)
4 trawls, 0 tumbles	1002	32 – 112	93.4 (0.34)
4 trawls, 4 tumbles	987	42 – 115	96.4 (0.32)
Autumn07	1966	49 - 117	92.7 (0.22)
Winter07	2960	50 - 115	99.2 (0.10)
Spring07	2293	40 - 117	100.9 (0.14)
Autumn08	1649	32 - 113	81.8 (0.33)

The GLM indicated that both treatment level and experiment had a highly significant ($P < 0.001$) effect on scallop survival. Further, the number of scallops in each cage significantly affected scallop survival ($P < 0.05$), while size class (legal or sub-legal) had no significant effect (ie. $P > 0.05$). Hereafter, results relate to sub-legal scallops only as all legal scallops would have been retained by fishers.

Survival of treated and control sub-legal scallops decreased significantly ($P < 0.001$) with successive trawls (Figure 6-7) but the survival of tumbled scallops was significantly lower ($P < 0.001$) than that of the control animals after each trawl. Survival ranged from 98.5% (s.e. = 0.38) after one trawl to 83.0% (s.e. = 1.57) after four trawls for the control scallops and from 96.7% (s.e. = 0.47) after one trawl to 64.4% (s.e. = 2.18) after four trawls for treated scallops.

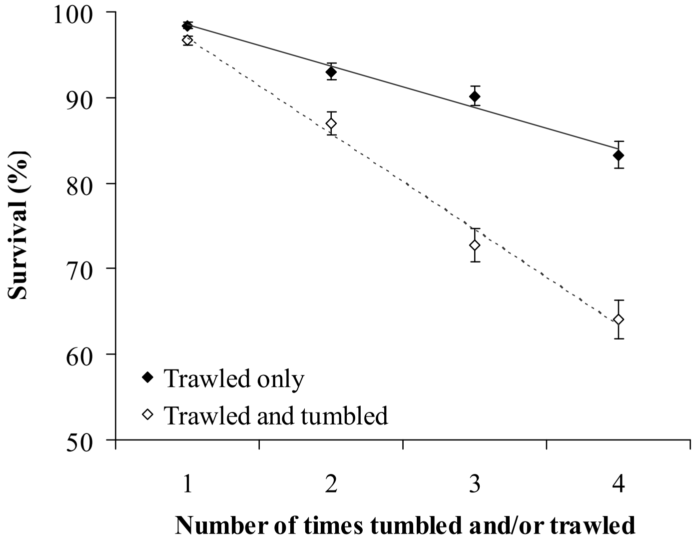

Figure 6-7: Adjusted overall mean survival (± standard error) of sub-legal *A. balloti* after various levels of tumbling and/or trawling.

There was no significant difference (*P* = 0.258) in survival between the Winter07 experiment and the Autumn08 experiment (see Figure 17-11, page 119). However, survival rates during these experiments were significantly higher (*P* < 0.001) than those of the other two experiments. Scallop survival was lowest (*P* < 0.001) during the Autumn07 experiment, with survival of tumbled animals decreasing from 93.9% (s.e. = 0.99) survival after one trawl to 46.3% (s.e. = 2.78) after four trawls. Further, survival was significantly higher (*P* < 0.001) during the Autumn08 experiment compared to the Autumn07 experiment.

6.3.4 Effect of tumbling on recapture rate

A total of 6,239 live scallops were tagged-and-released during the first three experiments conducted in the Bustard Head B SRA. Of these, 1,428 (22.9%) were re-caught in December, 2007. Both experiment (*P* < 0.001) and size class (*P* < 0.05) affected the recapture rate of scallops (Figure 6-8), while treatment level had no significant effect (*P* = 0.451). Recapture rates differed significantly between each experiment (*P* < 0.05), with 17.6% (s.e. = 1.07) of those scallops released during the Autumn07 experiment being re-caught, 22.2% (s.e. = 0.83) from the Winter07 experiment and 25.2% (s.e. = 1.08) from the Spring07 experiment. Further, the recapture rate of sub-legal scallops was significantly higher than that of legal scallops (*P* = 0.02).

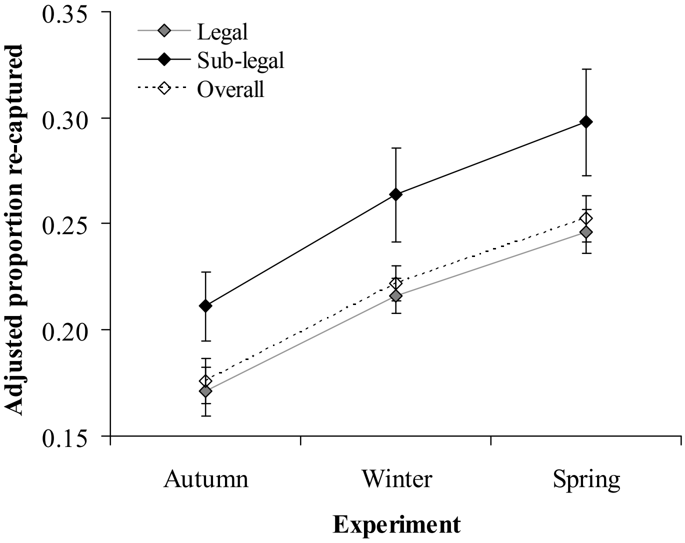

Figure 6-8: Adjusted mean percentage (± standard error) of recaptured legal and sub-legal *A. balloti* tagged-and-released during each experiment (all treatments combined). Average days-at-liberty for the Autumn07, Winter07 and Spring07 experiments were 236, 133 and 45, respectively.

6.4 DISCUSSION

The aim of this study was to determine the effect of tumbling on the relative survival of sub-legal *A. balloti*. Given that sub-legal *A. balloti* endure being captured, with resultant stresses related to emersion, it is important to know the added effect of the tumbling process on survival. Tumbled and control scallops were subjected to the same handling and therefore endured the same levels of stress from other factors that may effect survival such as sorting time, air temperature, tow duration and time on deck (eg. Bergmann and Moore 2001; Broadhurst, Suuronen *et al.* 2006; Castro, Araujo *et al.* 2003; Gaspar and Monteiro 1999; Hill and Wassenberg 1990; Kennelly 1995; Pikitch, Erickson *et al.* 1996). The difference in survival between tumbled and control *A. balloti* represents the effect of tumbling alone (ie. relative survival) and is not a representative, absolute estimate of survival.

Dead *A. balloti* were easily identified as only the valves remained for the majority of animals classified as dead. Isopods, locally known as sea-lice, were able to enter the cages through the small mesh and consume all but the valves of dead scallops. Very few (<1%) animals appeared moribund but were classified as alive if the valves were closed after stimulation of the mantle with forceps. The only apparent damage to scallops was the chipping of the outer edge of the valves, while crushed scallops or those with cracked valves were rare. The majority of mortalities, as observed by scallop ranchers relying on broodstock from trawl operators, occur when the mantle is damaged by the valve-edges of other scallops during trawling (R Dean, Queensland Sea Scallops, personal communication), a phenomenon also observed during the present study. Live scallops were typically active, adducting periodically while in seawater prior to tagging.

In accord with anecdotal evidence, the survival of sub-legal *A. balloti* decreased with increased levels of tumbling. The GLM showed significant differences in the survival of tumbled and control sub-legal *A. balloti* even after one trawl. Valero and Lasta (2008) re-analysed data reported by Bremec, Lasta *et al.* (2004) and found lower survival rates of discarded undersized (< 55 mm) *Zygochlamys patagonica*, compared to un-graded animals, after grading using a machine similar to that used to grade *A. balloti*, a result comparable to that found in the present study.

The relatively high survival rates achieved by both tumbled and control scallops after one trawl are consistent with previously published information on the survival of discarded bivalve molluscs. Broadhurst, Suuronen *et al.* (2006) state that bivalves are least affected by emersion and consequently incur lower mortalities than other species such as teleosts and cephalopods. Kaiser and Spencer (1995) reported 100% survival ($n = 65$) after four days for *Pecten maximus* after a single 30 minute tow with a beam trawl. Survival rates of 98% ($n = 50$) after 60 hours and 90% ($n = 10$) after 144 hours were observed for the scallop *Aequipecten opercularis* during the same experiment. In an experiment conducted in Queensland’s Moreton Bay (27º11’S, 153º03’E), Wassenberg and Hill (1993) reported that the survival of the scallop *Annachlamys flabellata* caught using otter-trawl gear was 100% ($n = 48$) after seven days.

Higher discard mortality rates of bivalves have been observed where a dredge was used for capture (Gaspar and Monteiro 1999; Gruffydd 1972; Medcof and Bourne 1964; Meyer, Cooper *et al.* 1981), possibly due to the mechanics of each trawling method. The otter trawls used to catch *A. balloti* rely on swimming and escape behaviour. That is, individuals caught by the otter trawls are in the water column, having responded to the oncoming trawl by “swimming” off the bottom (Joll 1989b). Dredges, however, dig into the substrate and force scallops into the mouth of the dredge and back into the collection area. Generally, dredges have more hard surfaces, compared to otter trawls, which can damage scallops and cause increased mortality of discarded individuals. An exception to this was reported by Gaspar, Dias *et al.* (2001), who found mortality of *Callista chione* caught with two dredge types in Portugal was less than 10.9%. However, the authors only used the damage to individuals as a measure of mortality, rather than dedicated survival studies. For example, all animals that were classified as severely damaged were assumed to have died, while those that were lightly damaged were assumed to have lived.

Estimates of scallop survival following repeated trawls have not been described previously due to logistical difficulties (Bremec, Lasta *et al.* 2004) although the present study found decreased survival of both tumbled and control sub-legal *A. balloti* after repeated trawls. Maguire, Jenkins *et al.* (2002) found that repeated simulated dredging did not have a significant cumulative effect on the level of the stress indicator adenylic energetic charge (AEC) or behavioural activity of undersize (< 110 mm shell height) *Pecten maximus*. The authors state that this was because the period between dredge simulations (24 hours) was sufficient for the scallops to recover. In the present study, recovery time was limited due to time and logistical constraints. Ideally, to reflect real-world conditions, all scallops should have been released on the trawl grounds and allowed to recover for some period before being re-trawled. However, this would have resulted in the loss of experimental control, with the possibility of insufficient numbers being re-caught to enable robust statistical analysis. Given the results reported by Maguire, Jenkins *et al.* (2002), it is conceivable that the results of the current study may under-estimate the survival of sub-legal *A. balloti* after repeated trawls. It is difficult to determine whether the estimates of the survival of tumbled, sub-legal *A. balloti* in the present study were confounded by the lack of recuperation time. In reality, a discarded individual will recuperate for some period of time, during which it will not be prone to capture by an otter trawl as it may not have the ability to swim into the water column.

The number of tumbles and/or trawls had no significant effect on the recapture rate of tagged scallops, while experiment and size-class (legal/sub-legal) both had a significant effect. This suggests that although tumbling affects scallop survival in the short-term, the longer-term effects of tumbling are negligible. This statement must be qualified by assuming that factors such as natural mortality, dispersion of animals away from the release sites and the selectivity of the gear used for recapture are constant for each tagged-and-released scallop, irrespective of treatment. For the purposes of this discussion, we have assumed that these factors are constant for all released *A. balloti* from all experiments.

The scallops were recaptured in the present study during field work where trawl effort was concentrated around the release sites. As such, those scallops that had moved away from the release sites were less likely to be recaptured. Given that the recapture rates of sub-legal *A. balloti* were significantly higher than those of legal animals, it is likely that there was greater dispersion away from the release sites for larger (legal) animals, while the smaller animals tended to remain in the same area. The fact that significantly more sub-legal *A. balloti* were re-caught suggests that the selectivity of the gear had little effect on recapture rate. The significantly higher recapture rates for scallops released during later experiments are further evidence of the dispersion of animals away from the release sites.

During this study, scallop survival was not affected by size. Small individuals (CSH < 60 mm) were selected by the tumbler quite quickly, while larger, nearly-legal (≈ 80-89 mm) scallops remained in the tumbler for a longer period before dropping out. These observations prompted the hypothesis that the smaller size classes would survive the tumbling process better than the nearly-legal scallops, however, this was not the case.

Several studies have shown that lower air temperatures result in higher post-trawl survival rates of various species (Castro, Araujo *et al.* 2003; Davis and Olla 2001; Gamito and Cabral 2003; Giomi, Raicevich *et al.* 2008; Medcof and Bourne 1964; Pikitch, Erickson *et al.* 1996;

van Beek, Van Leeuwen *et al.* 1990). It is difficult to ascertain whether the differences in the survival of sub-legal *A. balloti* in the present study can be attributed to a seasonal (ie. temperature) effect or another factor. Although every attempt was made to ensure the variability in factors that influence discard survival, such as time-on-deck and sorting time, were minimised, it is unlikely that such factors were absolutely consistent from one experiment to another. The variation in survival attributable to changes in these factors is not independent of season in the present study and are, therefore, difficult to isolate. However, these variations are of less importance as relative survival was of primary concern.

The use of cages to house the scallops during the short-term mortality experiments effectively excluded the influence of predation on mortality. Predation of discarded scallops is difficult to quantify but is likely to occur based on studies of other discarded bivalves (Maguire, Coleman *et al.* 2002; Veale, Hill *et al.* 2000). If *A. balloti* were to exhibit the same vulnerability to predation as other scallop species, the survival rates derived in the current study would be over-estimated. Further studies could therefore incorporate some estimate of the mortality of discarded *A. balloti* attributable to predation and also determine whether the tumbling process leaves discarded animals more vulnerable to predation compared to non-tumbled animals.

In reality, the sorting process may confound the effect of predation. Barbeau, Scheibling *et al.* (1998) reported that predation by crabs and sea stars on juvenile *Placopecten magellanicus* increased significantly with scallop density. When sub-legal *A. balloti* are tumbled aboard commercial vessels, a large number of individuals may be discarded in a very small area. The increased predatory response reported by Barbeau, Scheibling *et al.* (1998), combined with an increase in response time and a decrease in swimming ability, may result in decreased relative survival of tumbled *A. balloti*. Additionally, given that predators, such as starfish, are often found in the bycatch, the sorting process may result in a large number of predators being discarded along with the tumbled, sub-legal scallops, exacerbating the effect of predation.

The cages used in the present study were seen as a better alternative to storing the animals in tanks or other storage systems so as to avoid any confounding effects due to confinement in such systems. A number of studies have been conducted on the post-trawl survival of various species using cages or similar apparatus to hold animals adjacent to fishing grounds (eg. Bergmann and Moore 2001; Castro, Araujo *et al.* 2003; Erickson, Pikitch *et al.* 1997; Macbeth, Broadhurst *et al.* 2006; Mandelman and Farrington 2007; Metin, Tokac *et al.* 2004; Pikitch, Erickson *et al.* 1996; Soldal and Engas 1997; Suuronen, Erickson *et al.* 1996; Suuronen, Turunen *et al.* 1995). Caging may not only over-estimate survival rates due to the exclusion of predators, it may also under-estimate survival due to factors such as crowding and starvation within cages or tanks. However, the present study was concerned primarily with the effect of tumbling on survival rather than the absolute estimation of survival. Cages, therefore, represented a practical method of containing the scallops and were appropriate for the estimation of relative survival (Pikitch, Erickson *et al.* 1996). Given the number of scallops required for robust analyses, the recirculating sea water systems required to hold the scallops would have been far too large and cumbersome for the available deck space on the vessel.

As tumbling has been shown to affect the survival of discarded sub-legal *A. balloti*, it is prudent to consider alternate methods of excluding sub-legal animals from commercial catches. Recent research has shown that square mesh codends can reduce the catch rate of sub-legal *A. balloti* by 32%, compared to a net without a square mesh codend (Courtney, Campbell *et al.* 2008). Despite this, fishers may be reluctant to use the devices as a proportion of the marketable by-product such as scyllarid lobsters (*Thenus australiensis* and *T. parindicus*), blue swimmer crabs (*Portunus pelagicus*) and cuttlefish (*Sepia* spp.) are effectively excluded depending on the mesh size used. Also, some grading will still occur when using square mesh codends as the devices do not exhibit knife-edge selectivity, with Courtney, Campbell *et al*. (2008) reporting that 68%, by weight, of sub-legal scallops are retained using a square mesh codend.

Another method to reduce tumbling is to target specific areas where catch rates of sub-legal animals is low. The Bass Strait scallop (*Pecten fumatus*) fishery, for example, prohibits trawling in areas where the discard rate exceeds 20% (Zacharin 1994). Such legislation would be difficult to police in the Queensland scallop fishery given the number of vessels and considerable area of the fishery. A more practical solution may be fishery-independent surveys to identify areas of proportionately low sub-legal scallop catch rates. Surveys conducted between 1997 and 2000 by the Queensland Department of Primary Industries and Fisheries as part of its' Long Term Monitoring Program (O'Sullivan S, Jebreen E *et al.* 2005) resulted in the production of maps that displayed standardised scallop catch rates by location and size class. Such data could be used to close areas where there is a high catch rate of sub-legal scallops, thereby reducing potential discard mortality.

The differential rates of discard mortality derived in this chapter will be used in Chapter 9 in order to provide an accurate measure of total fishing mortality.

7 Growth of discarded scallops in Queensland's trawl fishery

7.1 INTRODUCTION

The growth of any animal is an essential aspect to consider when developing a Harvest Strategy Evaluation, given that the stock biomass vulnerable to fishing is partly reliant on the growth of the individuals in the population (Haddon 2001). The most widely used model of growth in length is one described by von Bertalanffy (1938), where the ages (t) and lengths-at-age (L_t) of individuals in a population are related via an exponential growth curve with a slope (≈ growth rate), k, and an asymptotic, theoretical maximum size (L_∞). In many fish species, hard-parts (mostly otoliths) are examined to determine the age of the individual.

Once this process is completed for a number of individuals, the lengths and ages are plotted to produce a growth curve, via a line-of-best-fit.

Growth in bivalves has been described by many authors. Although hard-part (ie. shell) analysis has also been used in the growth determination of bivalves (eg. Lomovasky, Lasta *et al.* 2008; Stevenson and Dickie 1954; Varfolomeeva, Artemieva *et al.* 2008), a common method of deriving relevant growth parameters for bivalves is by mark-recapture studies (eg. Laudien, Brey *et al.* 2003; Mitchell, Crawford *et al.* 2000; Peharda, Soldo *et al.* 2003; Wolf and White 1995).

A previous study by Williams and Dredge (1981) described the growth of *A. balloti* using tag-recapture data to estimate the von Bertalanffy growth parameters, L_∞ and k. The authors used methods described by Fabens (1965) to estimate the growth parameters. Although this model is somewhat restrictive, in that it assumes that any variation in growth from the model is independent with a mean equal to zero and the variance constant for all ages, it is straight-forward and easily understood. Several authors (eg. Francis 1988; James 1991; Wang 1998) have developed improved methods to analyse tag-recapture data to determine the von Bertalanffy growth parameters. However, given the fact that a previous study detailing the growth of *A. balloti* used the Fabens method, it was decided to compare the results from this study to those achieved from the current study using similar methods.

The objective of this experiment was to estimate the von Bertalanffy growth parameters for scallops tagged-and-released during the survival experiments described in Chapter 6. These growth parameters will then be used in the stock assessment and Harvest Strategy Evaluation described in Chapter 9. For the purposes of this report, growth in *A. balloti* will be described as a function of nominal shell height (NSH, mm), the distance between the hinge and outer edge of the lower (white) valve (see Figure 7-1).

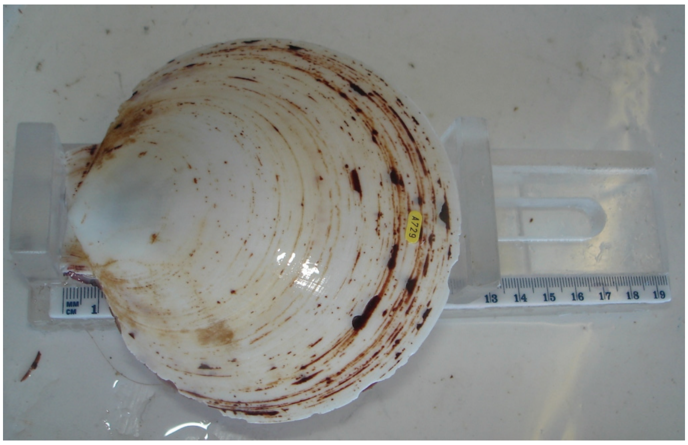

Figure 7-1: Method for measuring nominal shell height NSH in scallops. Note that the ventral (white) valve is measured and the tag attached toward the outer edge.

7.2 METHODS

Scallops tagged during the survival experiments (as detailed in Section 6.2, on page 11) were recaptured during a dedicated charter aboard the Department of Employment, Economic Development and Innovations' research vessel, the FRV *Tom Marshall* during December 2007. The recapture field work was conducted at this time due to the fact that the Bustard Head B SRA was due to re-open on 1 January, 2008. 6,239 individual scallops were released as part of the survival experiments at two pre-determined release sites within the Bustard Head B SRA. During the recapture field work, the release sites were targeted in order to maximise the number of recaptures. As stated earlier, 20 individual 25-minute trawls were conducted within the Bustard Head B SRA using the beam trawl used to capture the animals for the post-release survival experiments detailed in Chapter 6. On recapture, all tagged scallops were separated from the catch before the shell height and tag number (see Figure 7-1) of each scallop was recorded.

7.2.1 Analyses and model development

The tag-recapture data were analysed using the standard von Bertalanffy (1938) growth equation, which is as follows:

$$L_t = L_\infty\left(1 - e^{-k(t-t_0)}\right) \qquad \text{Equation 7-1}$$

where L_t is the length of the animal at time *t*, L_∞ is the theoretical asymptotic maximum length of the animal, *k* is the average growth rate and t_0 is the age when length is zero. Fabens (1965) altered Equation 7-1 in order to estimate growth rate, *k* and the theoretical maximum length, L_∞, of the tagged-and-released animals from the change in length during the time in which the animals were at liberty thusly:

$$L_2 - L_1 = \left(L_\infty - L_1\right)\left(1 - e^{-kt}\right) \qquad \text{Equation 7-2}$$

where L_2 is the length at recapture, L_1 is the length at release, and *t* is the time at liberty. Fabens (1965) used a least-squares method to minimise the difference between the predicted change in length, ΔL $\left(L_2 - L_1\right)$, and the observed ΔL by iterating various values of *k* and L_∞. This equation can be re-arranged in order to fit tag-recapture data (as reported by Laudien, Brey *et al.* 2003) with the length at recapture, L_2, being the response variable, thus:

$$L_2 = L_1 + \left(L_\infty - L_1\right)\left(1 - e^{-kt}\right) \qquad \text{Equation 7-3}$$

Using GenStat (2007), the tag-recapture data were modelled using Equation 7-3 (see Appendix 17.3 on page 120). Initial values of $k = 0.005\text{day}^{-1}$ and $L_\infty = 110\text{mm}$ were used. A third parameter was added to the model described by Equation 7-3 that quantified a period of slow or no growth (t_2 in the model, Appendix 17.3, page 120) immediately after being tagged and released. Effectively, the addition of this parameter removes the period of zero or slow growth immediately after release from the time-at-liberty, *t*, and restricts *t* to when growth occurred. As such, Equation 7-3 was changed to incorporate this parameter, thus:

$$L_2 = L_1 + (L_\infty - L_1)\left(1 - e^{-k(t-t_2)}\right) \qquad \text{Equation 7-4}$$

In order to quantify the effect of tumbling on the period of slow or no growth, a parameter (t_n in the model, Appendix 17.3, page 120) was incorporated into the model. This parameter was multiplied by the number of tumbles as a linear term (0-4). Equation 7-4 was altered to incorporate this parameter thus:

$$L_2 = L_1 + (L_\infty - L_1)\left(1 - e^{-k(t-(t_2+t_n \times tumbles))}\right) \qquad \text{Equation 7-5}$$

This parameter quantified the additional number of days added to the period of slow or no growth due to increased levels of tumbling. At each step of model development, 50 iterations using various values of the parameters were trialled. Increasingly complex models were tested and ignored if further significant improvements were not detected. These methods are similar to those used by Robins, Mayer *et al.* (2006) to determine the growth of barramundi (*Lates calcarifer*) from tag-recapture data.

7.3 RESULTS

As stated in Section 6.3.4, a total of 6249 scallops were tagged and released during the first three mortality experiments conducted in the Bustard Head B SRA. Of these, 1428 were recaptured during field work conducted in December, 2007 (see Table 7-1). Approximately 25% of those animals released as part of the third (spring) survival experiment were recaptured while approximately 20% of the tagged scallops from the first (autumn) experiment were recaptured.

Estimates of the model parameters are given in Table 7-2. Model 1 provided a good fit to the data with 75.5% of the variation between the fitted L_2 and observed L_2 explained. This model generated values of $L_\infty = 103.55$ mm and k = 1.60 yr^{-1}. The addition of the parameter describing the time of slow or zero growth, t_2 in Equation 7-4, significantly improved the model. That is, the model improved the correlation co-efficient (R^2) by approximately 0.035 which represented 14% of the variation that was unexplained by the initial model. This model generated values of $L_\infty = 104.31$ mm and k = 2.02 yr^{-1} and indicated that the period of slow or no growth immediately after release was $t_2 = 44.57$ days.

Finally, the addition of the parameter to describe the additional time of slow or no growth immediately after release due to repeated tumbling events (t_n in Equation 7-5) improved the model. This is indicated by the improvement in the correlation co-efficient to 0.792 or 79.2%. Model 3 generated values of L_∞ and k of 104.29mm and 2.05 yr^{-1}, respectively. The model indicated that the period of slow or no growth immediately after release was approximately 41.5 days and that this value would increase by 3.27 days for every tumbling event endured. A plot of the standardised residuals generated from Model 3 shows a homogenous scatter for all fitted values of L_2 and is evidence of the appropriateness of this model (see Figure 17-12).

A comparison of the relevant von Bertalanffy growth curves, generated from the respective models are shown below in Figure 7-2.

Table 7-1: Number of scallops released and recaptured as part of the first three mortality experiments conducted in the Bustard Head B SRA.

Season/Treatment	Number released	Number recaptured	% recaptured
Autumn	1581	320	20.24
Winter	2725	631	23.16
Spring	1933	477	24.68
1 trawl, 0 tumbles	1002	233	23.25
1 trawl, 1 tumble	1013	251	24.78
2 trawls, 0 tumbles	770	168	21.82
2 trawls, 2 tumbles	700	146	20.86
3 trawls, 0 tumbles	892	210	23.54
3 trawls, 3 tumbles	689	142	20.61
4 trawls, 0 tumbles	674	154	22.85
4 trawls, 4 tumbles	499	124	24.85

Table 7-2: Estimates of the von Bertalanffy parameters from tag-recapture data generated from the survival experiments described in Chapter 6. The data were generated from the models described in Appendix 17.3 using (GenStat 2007). NSH_∞ relates to L_∞ in Equations 7-3, 7-4 and 7-5.

Model	Equation	NSH_∞ (mm)	CSH_∞ (mm)	k (yr^{-1})	t_2 (days)	t_n (days)	R^2
1	7-3	103.55	106.26	1.60	-	-	0.755
2	7-4	104.31	107.10	2.02	44.57	-	0.790
3	7-5	104.29	107.01	2.05	41.47	3.27	0.792

It should be noted that the terms “Days Out” (t in the models) and “Trip” or “Season” were not independent due to the fact that the release dates for all scallops were grouped within a 2 day period during each experiment. As such, “Trip” significantly affected growth in all models. The number of tumbles endured was found to have had no significant effect (i.e. $P > 0.05$) on the growth rate, k.

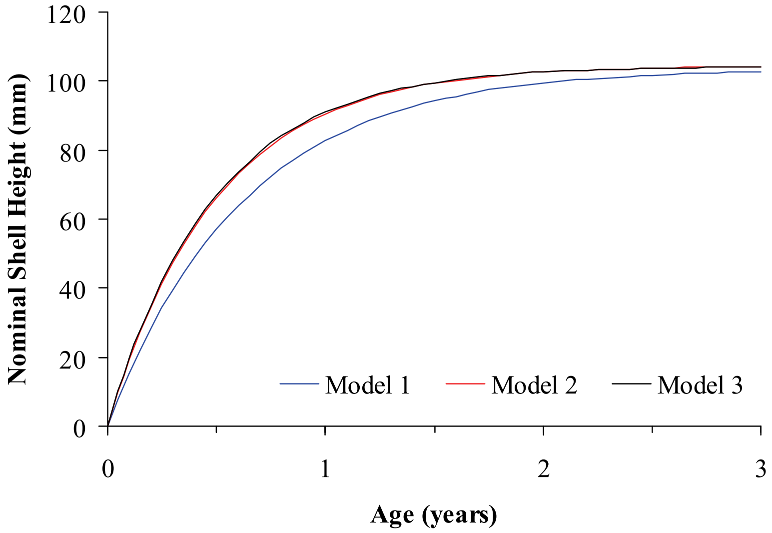

Figure 7-2: von Bertalanffy growth curves generated from each of the three models used in the analysis, the parameters for which are shown in Table 7-2. Note: these curves are based on Equation 7-1, with $t_0 = 0$.

7.4 DISCUSSION

The von Bertalanffy growth parameters generated during the current study are comparable to those reported by Williams and Dredge (1981). The authors reported NSH_∞ and *k* for scallops in the Bustard Head area from tagging studies conducted in 1976, 1977 and 1978. The values of NSH_∞ generated during the present study are within the 90% confidence limits reported by Williams and Dredge (1981) for scallops recaptured in 1977. However, the values reported for 1976 and 1978 are higher than those from the present study. Similarly, the values of *k* reported by Williams and Dredge (1981) are higher than those from the current study.

The fact that Model 3 generated a value for t_n of 3.27 days suggests that increased levels of tumbling causes a longer period of slow or no growth immediately after release. In reality, discarded *A. balloti* would remain inactive for some period (as described by Maguire, Jenkins *et al.*, 2002). During this time, these animals would be unable to exhibit the necessary response to an on-coming trawl by swimming up into the water column and would not be caught. However, once this period of slow or no growth has passed, the growth of *A. balloti* is not significantly affected by tumbling.

The reduced growth rates derived in the current study are not unexpected as growth in scallops and other molluscs has been shown to vary due to several factors. The most common cause of variable growth among individuals of the same bivalve species is water temperature. For example, Haynes (1971), Broom and Mason (1978), Miyaji, Tanabe *et al.* (2007), Richardson, Taylor *et al.* (1982) and Rupp, Parsons *et al.* (2005) cited temperature as the most significant factor influencing the growth rates of bivalves such as *Patinopecten caurinus*, *Chlamys opercularis*, *Phacosoma japonicum* and *Nodipecten nodosus*.

Further, the interaction of temperature and water depth, with shallower water warming faster, has been shown to influence growth. Mason (1957) reported that scallops *Pecten maximus* inhabiting shallower areas grew faster than those from deeper water, most likely due to higher temperatures in the shallow water (20 metres as opposed to 53 metres) when growth rate is at a maximum (May to August adjacent to the Isle of Man). Williams and Dredge (1981) reported faster growth rates in *A. balloti* in experiments conducted in water depths of 30 to 40 metres compared to those in the current study, where water depth was 40 to 42 metres.

Another common source of differential growth within a bivalve species is water current. Harris and Stokesbury (2006) stated that greater flow velocities can limit feeding in *Placopecten magellanicus* leading to growth retardation. Further, Kirby-Smith (1972) suggested that water current is an important factor when assessing the growth of the bay scallop *Argopecten irradians concentricus*. In large populations of these animals it is thought that in low current areas, food depletion could occur and may affect the growth of individuals. Additionally, Ciocco (1991) reported a difference in growth rates between neighbouring populations of the scallop *Chlamys tehuelcha* and attributed this to gradients in food availability. The interaction between water current and food availability is an obvious source of growth variability in the same species over time and could account for the differences in growth rate between the animals used in the current study compared to those used by Williams and Dredge (1981).

These abiotic factors have influenced the growth rate of *A. balloti* and may have accounted for the slower growth rates in the current study when compared to those from Williams and Dredge (1981). Given that these authors conducted their experiments 30 years before the present study, it is not unreasonable to suggest that current climatic conditions differ from those in the late 1970's, with resultant changes to growth of *A. balloti*.

Additionally, several other factors may explain the changes in growth rate. Given that the animals used in the current study were captured within a closed area that has been shown to hold large populations of *A. balloti*, the growth of individuals may have been affected by competition for food and other factors associated with high density. A large number of scallop species are used in aquaculture throughout the world and several studies have shown that the density at which scallops are stocked has a significant effect on the growth of individuals. For example, Louro, Christophersen *et al.* (2007) reported that stocking density was the main factor affecting the growth of juvenile *Pecten maximus* in suspension culture, with animals stocked at lower densities obtaining higher growth rates than those stocked at high densities. Further, Velasco, Barros *et al.* (2009) reported that stocking at higher densities had a negative effect on growth of *Argopecten nucleus* and *Nodipecten nodosus*. In this instance, competition for food was seen as the reason for the negative effect on growth.

A further consequence of high scallop densities is parasitism and the effects of parasitism on the growth of individuals within a population. The presence of the parasitic ascaridoid nematode *Sulcascaris sulcata* was reported in *A. balloti* in Queensland by Cannon (1978) and these animals were found in some individual *A. balloti* during the current study. Breeding loggerhead turtles, *Caretta caretta*, inhabit the waters of the southern Great Barrier Reef during the November breeding period and consume *A. balloti* and other molluscs infected with *S. sulcata* during this time. *C. caretta* spread viable *S. sulcata* eggs from which larval *S. sulcata* hatch before infecting more scallops. *S. sulcata* are generally found to be present in areas where scallop density is high, particularly within SRAs (T. Wittingham, personal communication). The effect of *S. sulcata* on an individuals' growth is unknown, however, their presence may inhibit the growth of animals within SRAs and may be another reason why the growth rate parameter from this study is lower than that from the previous study by Williams and Dredge (1981), when SRAs were not in operation. Evidence of parasitism affecting growth has been reported by Haynes (1971), who suggested that the presence of the polycheate *Polydora* restricted growth in the giant Pacific sea scallop *Patinopecten caurinus*.

The growth parameters in the current study were derived from animals that were at-large for less than one year. That is, for example, those animals caught in the Winter07 experiment were at-large during the spawning period (Dredge 1981). This would result in a reduction in the growth parameter *k* for these animals and a consequent reduction in the population *k*. Further, those animals released during the Spring07 experiment had no time in which to grow which resulted in very low growth rates for these animals. The animals released during the Spring07 experiment exhibited zero growth, with most (>75%) recaptured animals showing signs of reparation to damage in the outer margins of both valves. This reparation was characterised by areas of darker shell (note the bands of darker shell observed on the valve in Figure 7-1) and has been observed in other studies (Dredge 1988a; Joll 1988). Dredge (1985b) stated that handling and chipping during tagging may lead to growth retardation in tagged *A. balloti*. However, the addition of the parameters t_2 and t_n in Equation 7-5 accounted for this period of slow growth and effectively restricted the time-at-liberty, *t*, to the period where growth actually occurred. This method somewhat overcame the problems associated with restricting time-at-liberty to less than 8 months. However, the growth parameters derived in the current study are compromised because of this restriction and, as such, the growth parameters derived by Williams and Dredge (1981) will be used in Chapter 9.

8 Fishing power and catch rates in the Queensland scallop fishery

8.1 INTRODUCTION

Stock assessment models generally use commercial catch rate data or catch-per-unit-effort (CPUE), as an index of the abundance of the target species. That is, for example, a reduction in the number of animals will result in a lower CPUE, given that stock size and CPUE are correlated. However, CPUE is only an accurate measure of abundance whilst the catchability of the species, the extent to which a stock is susceptible to fishing, is constant over time (Marchal, Ulrich *et al.* 2002). The catchability of commercially targeted species may vary due to natural factors such as migration, seasonal fluctuations or lunar phase. For example, Courtney, Die *et al.* (1996) reported varying catch rates of eastern king prawns *Melicertus plebejus*, with declining catch rates evident in commercial logbook data in the seven days after a full moon.

Although the influence of these natural factors on CPUE is an important consideration, it also necessary to quantify the effects of changes to fishing gear and practices on a nominal fishing effort unit. In the scallop fishery, a fishing day is the nominal unit of fishing effort and, in effect, a unit of fishing effort in 1988 is the same as it is in 2009. However, changes to the fishing gear and recent advances in fishing-related electronics have resulted in increased efficiency of the vessels operating in the fishery. This leads to an increase in catchability over time and a resultant diversion from correlation between CPUE and abundance. Factors such as vessel size (Battaile and Quinn 2004), engine size (Marchal, Ulrich *et al.* 2002) and the use of GPS/plotters (Robins, Wang *et al.* 1998) have been shown to have a significant effect on catchability due to an increase in the effectiveness of each unit of nominal effort.

These technology-dependent variations in catchability not only occur over time but can vary within fisheries, especially in those fisheries where the fishing gear and vessel types employed are variable (Battaile and Quinn 2004). This is certainly the case in the Queensland scallop fishery, where factors such as vessel size, engine size and net configuration vary considerably (O'Neill and Leigh 2006). As such, in order to derive accurate CPUE data and resultant indices of abundance over time, the effect of both the natural and technology-dependent variations in catchability must be quantified.

To achieve this, several methods have been used. Salthaug and Godø (2001) used a comparison of catch rates between two vessels fishing in close proximity to assess fishing power relative to a ‘standard’ vessel in the Norwegian bottom trawler fleet. This method was also used by O'Sullivan, Jebreen *et al.* (2005) to standardise catch rates by several vessels during a fishery-independent survey conducted to quantify recruitment in the *A. balloti* fishery.

Several authors have used generalised linear models (GLMs) to standardise catch rates. Battaile and Quinn (20040, Glazer and Butterworth (2002), Mahévas, Sandon *et al.* (2004), Marchal, Nielsen *et al.* (2001) and Robins, Wang *et al.* (1998) used GLMs to standardise CPUE data for a range of trawl fisheries. GLMs quantify the effect of a linear combination of explanatory variables on the expected value of the response variable (Maunder and Punt 2004), in this case catch rate. However, the use of GLMs for the standardisation of catch rate data can be problematic when vessel identifiers, such as boat mark, are added to the model.

This is because the GLM estimates parameters for each factor level which in the case of the scallop fishery, where there are in excess of 850 levels, would be computationally prohibitive.

To remedy this, vessel identifiers can be incorporated into a linear mixed model, via a Restricted (or Residual) Maximum Likelihood (REML) model, as a random term. REML analysis allows the use of both fixed and random terms, where the random terms are drawn from a large homogenous population, and takes into account the fact that the mean parameters are estimated from the data (Bishop, Venables *et al.* 2004). O'Neill and Leigh (2006) reported that the inclusion of the vessel identifiers as a random term in an REML analysis increase the accuracy of the gear and technology parameters that describe the effects of these factors on catch rate. Further, the addition of vessel identifier as a random term may be able to quantify further increases in fishing power due to unknown factors such as fisher knowledge.

Since the completion of the project *Fishing power and catch rates in the Queensland east coast trawl fishery* (O'Neill and Leigh 2006), the scallop fishery has experienced dramatic reductions in fishing effort. This has been a result of reductions in the wholesale price paid to fishers and an increase in the cost of fuel, with fishing effort being redirected primarily toward the eastern king prawn (*Melicertus plebejus*) fishery. It was therefore prudent to update the results of the catch rate standardisation and fishing power analyses performed by O'Neill and Leigh (2006) as a precursor to the Harvest Strategy Evaluation. As such, the methods reported by O'Neill and Leigh (2006) were used in the current project to standardise catch rates for a range of factors such as lunar cycle, hours trawled, net size and engine power. This method is required to ensure that catch data are adjusted for efficiency changes in effort, giving more accurate measures of catch rate and relative abundance.

8.2 METHODS

8.2.1 Catch data

Logbook data were sourced from the Assessment and Monitoring Unit of Queensland Primary Industries and Fisheries. All daily catch records were sourced from both the voluntary (1975-1987) and mandatory (1988-2008) logbooks. This represented in excess of 264,000 daily catch records. This data gave information regarding vessel name, vessel identifier (boat mark), date, location and catch in baskets of scallops. These data were matched to lunar phase information and used to standardise long-term catch rates.

Further, O'Neill, Courtney *et al.* (2005) and O'Neill and Leigh (2006) conducted surveys of fishers operating in the QECOTF to determine vessel and gear characteristics up to 2004. These data were matched to daily catch records from the logbook data in a Microsoft® Access database. After 2004, vessel and gear characteristics data were sourced from the logbook (see Figure 17-15) and matched to daily catch records and appended to the Access database. This resulted in approximately 95,000 daily catch records with reliable vessel and gear data.

Vessel and gear characteristics data supplied by both the survey conducted by O'Neill and Leigh (2006) and the commercial logbooks included:

- Vessel characteristics – engine power, trawl speed, presence of propeller nozzle;
- Navigation equipment – presence of GPS, plotter, etc;
- The use of try-gear;
- The use of TEDs and/or BRDs; and
- Net configurations – number of nets, total headline length, ground gear configuration, board-type and size.

8.2.2 Data Analysis

Firstly, total harvest and effort south of 22° were calculated for all data submitted via commercial logbooks.

Catches were standardised using methods described by O'Neill, Courtney *et al.* (2005) and O'Neill and Leigh (2006) and this report should be sourced by the reader in order to gain a thorough understanding of the methods used in the current report. In summary, a linear mixed model using Restricted (or Residual) Maximum Likelihood (REML) was used to standardise catch rates in the scallop fishery (see 17.4.2 on page 121). The model was defined as:

$$\log_e \mathbf{C} = \mathbf{X}\boldsymbol{\alpha} + \mathbf{Z}\boldsymbol{\gamma} + \boldsymbol{\varepsilon} \qquad \text{Equation 8-1}$$

where $\mathbf{C}$ is the vector of catches; $\boldsymbol{\alpha}$ is a vector of fixed terms including a) β_0, a scalar intercept, b) $\boldsymbol{\beta}_1$, an abundance vector consisting of terms that categorised location (CFISH grid), year and month and their two-way interactions; c) $\boldsymbol{\beta}_2$, a catchability vector describing vessel and gear characteristics, d) $\boldsymbol{\beta}_3$, a vector describing the effect of lunar phase, and e) $\boldsymbol{\beta}_4$, a vector describing the associated prawn catch for each day; matrix-multiplied by data $\mathbf{X}_1$, $\mathbf{X}_2$, $\mathbf{X}_3$ and $\mathbf{X}_4$; $\boldsymbol{\gamma}$ is a vector of random vessel terms with design matrix $\mathbf{Z}$, indicating which daily catches belong to each vessel and $\boldsymbol{\varepsilon}$ is a normally distributed error term. The analysis was performed in GenStat (2007). Interactions were limited to two-way to ensure computational efficiency. Wald statistics were calculated by dropping fixed terms from the full model and were used to assess the importance of the individual terms. A similar model was used to standardise long-term catch rates (see 17.4.1 on page 121).

Relative fishing power was determined as a proportional change in fishing power from year to year under standard conditions. Thus the expected catch was determined as follows:

$$\mathbf{c} = e^{(\mathbf{X}\boldsymbol{\alpha} + \mathbf{Z}\boldsymbol{\gamma})} \qquad \text{Equation 8-2}$$

where $\mathbf{c}$ is the vector of expected catches under standard conditions for each vessel and day fished; $\mathbf{X}$, $\boldsymbol{\alpha}$, $\mathbf{Z}$ and $\boldsymbol{\gamma}$ are the same as in Equation 8-1. Within $\mathbf{X}\boldsymbol{\alpha}$, the terms represented by β_0, $\mathbf{X}_1\boldsymbol{\beta}_1$, $\mathbf{X}_3\boldsymbol{\beta}_3$, and $\mathbf{X}_4\boldsymbol{\beta}_4$ were held constant in order to isolate changes in fishing power according to the vector $\mathbf{X}_2\boldsymbol{\beta}_2$ only, which represents the changes in gear and vessel characteristics of interest. An average catch $\overline{c}$ was determined and compared to the catch in

1989, c_{1989}, so that fishing power is defined as:

$$\mathbf{f}_y = \frac{\bar{c}_y}{c_{1989}} \qquad \text{Equation 8-3}$$

where $\mathbf{f}_y$ is the vector of proportional change in average catch relative to 1989 and $\bar{c}_y$ is the annual catch under standard conditions.

8.3 RESULTS

8.3.1 Harvest and Effort Summary

Since the introduction of the *Fisheries (East Coast Trawl) Management Plan 1999* in January 2001, effort in the scallop fishery has decreased significantly (Figure 8-1) to around 5500 boat days per year. This reduction in effort is a result of a combination of several factors including:

1) An increase in the cost of fuel;
2) A reduction in the price paid to fishers for scallops; and
3) A buy-back of smaller vessels that fished year-round prior to the introduction of the *Trawl Plan*.

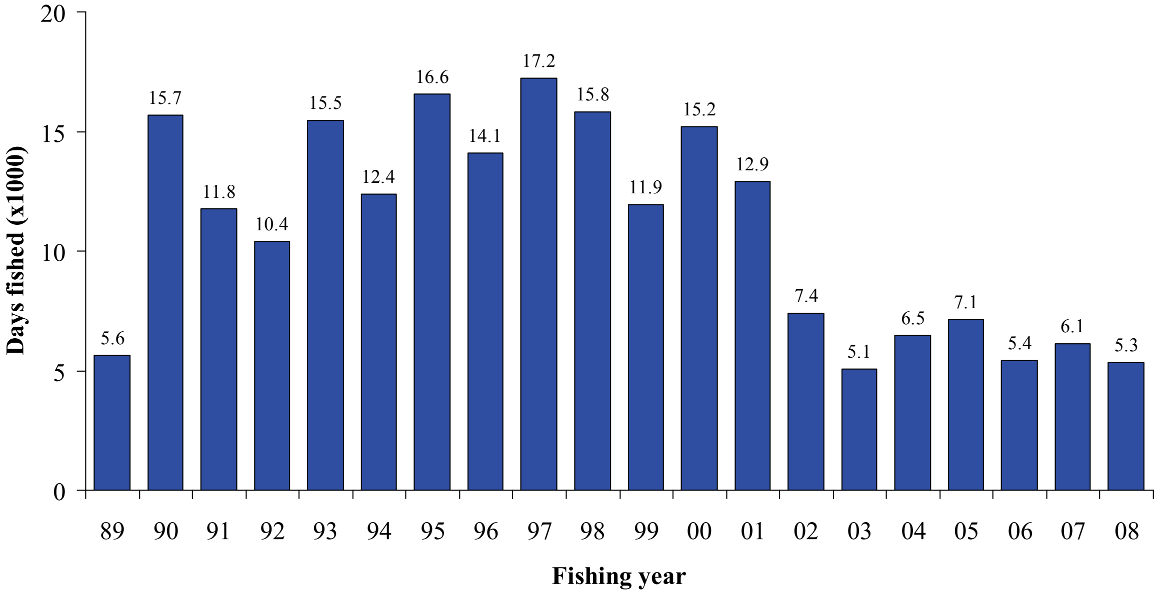

Figure 8-1: Total annual fishing effort south of 22°S in boat days using all logbook data, rounded to the nearest hundred days.

At the time the *Trawl Plan* was introduced, fishers were routinely paid in excess of $300 per basket for scallops but presently receive approximately $125 per basket. Further, where a vessel may have spent $400 - $450 per night for fuel in 2001, that same vessel would likely pay in excess of $800 at the time of writing. Such factors have forced scallop fishers to target high value species such as eastern king prawns (*Melicertus plebejus*) throughout the year.

Most trawl activity in the scallop fishery now takes place in conjunction with a) the re-opening of the SRAs on 1 January (3 January as of 2009) and b) the resumption of fishing after the southern closure period (20 September – 31 October), with a reduction in the minimum legal size from 95 mm to 90 mm (see Figure 8-2). There is nominal trawl effort throughout the winter months, with some vessels targeting Moreton Bay bugs (*Thenus* spp.) on the scallop grounds between Gladstone and Bundaberg during this time and recording mostly incidental scallop catch. Some fishers continue to target scallops during winter. Fewer days are fished during the April/May/June period which coincides with spawning (Dredge 1981), with a resultant decrease in meat quality. Further, April/May/June is also the time when the catch rate of large eastern king prawns increases, attracting fishers into that fishery. Before the introduction of the *Trawl Plan* in 2001, effort increased through the spring months, with maximum effort observed during October and November (see Figure 8-2).

As expected, scallop catch decreased immediately after the introduction of the *Trawl Plan* in 2001 (see Figure 8-3 and Figure 8-4). Although effort was maintained in 2006, catches were poor. In contrast, 2007 was characterised by a very good catch compared to the preceding year.

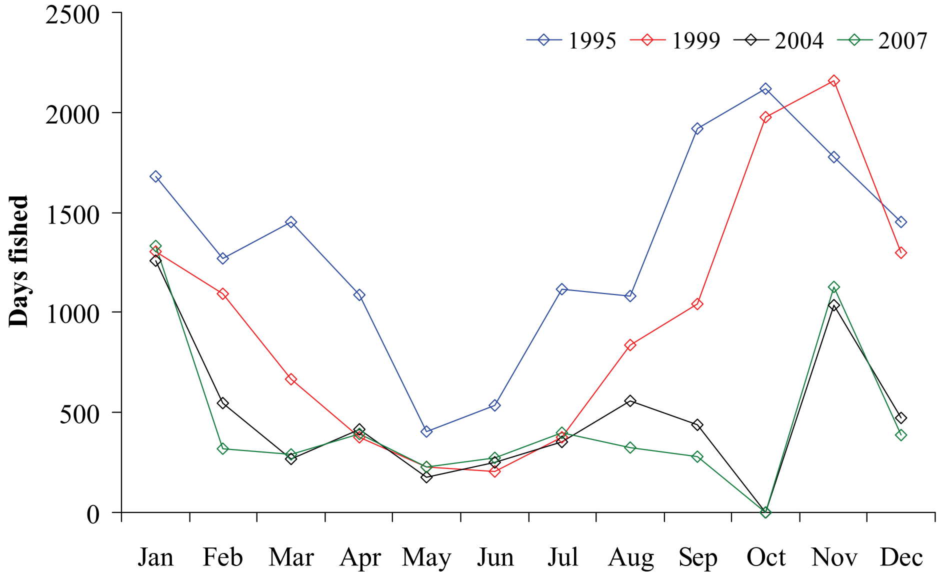

Figure 8-2: Number of days fished per month for the years 1995, 1999, 2004 and 2007 in the scallop fishery south of 22°S. Note the overall reduction in effort since 1995, with pronounced spikes occurring in January and November in 2004 and 2007.

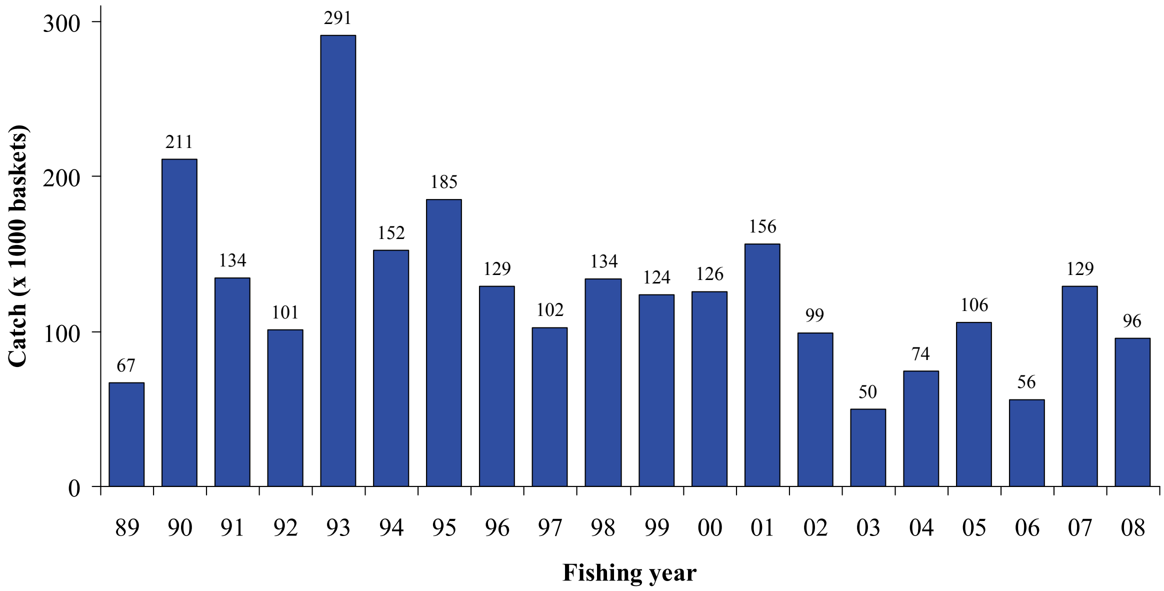

Figure 8-3: Total annual scallop catch for fishing years 1989 to 2008, south of 22°S in thousands of baskets using all logbook data, rounded to the nearest thousand baskets.

From Figure 8-5, it can be seen that the catch throughout the winter months has traditionally been poor. The introduction of the *Trawl Plan* has further reduced the catch of scallops throughout the winter months. Both the reduction in minimum legal size (MLS) to 90 mm after the southern closure period (November) and the re-opening of closed SRAs (January) result in significant increases in catch compared to preceding and subsequent months.

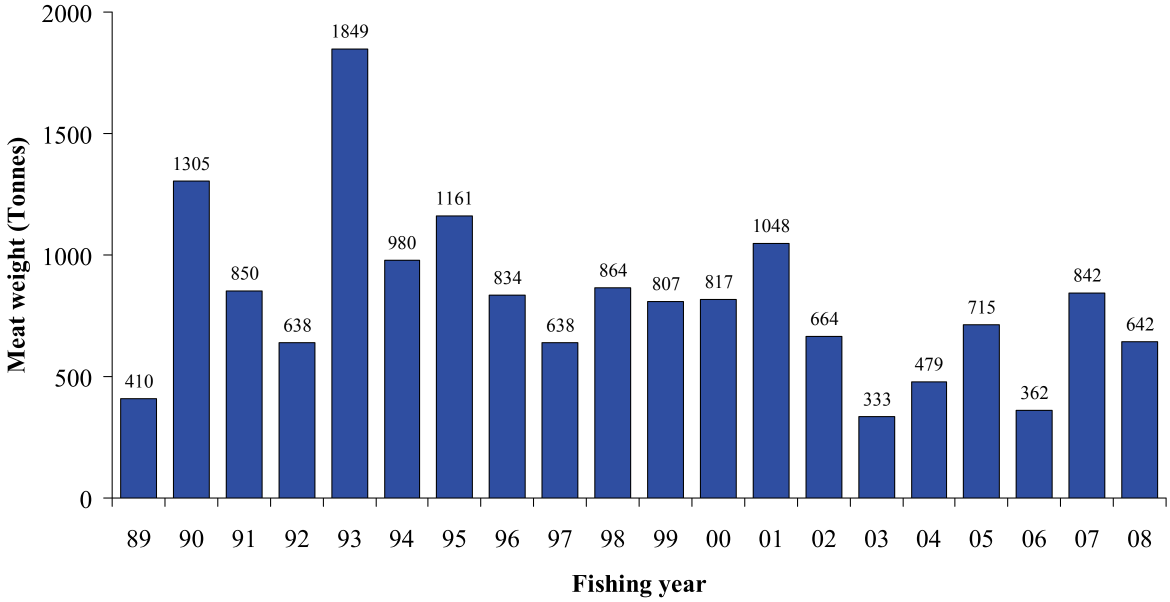

Figure 8-4: Total annual scallop catch south of 22°S in tonnes of meat using all logbook data, rounded to the nearest tonne.

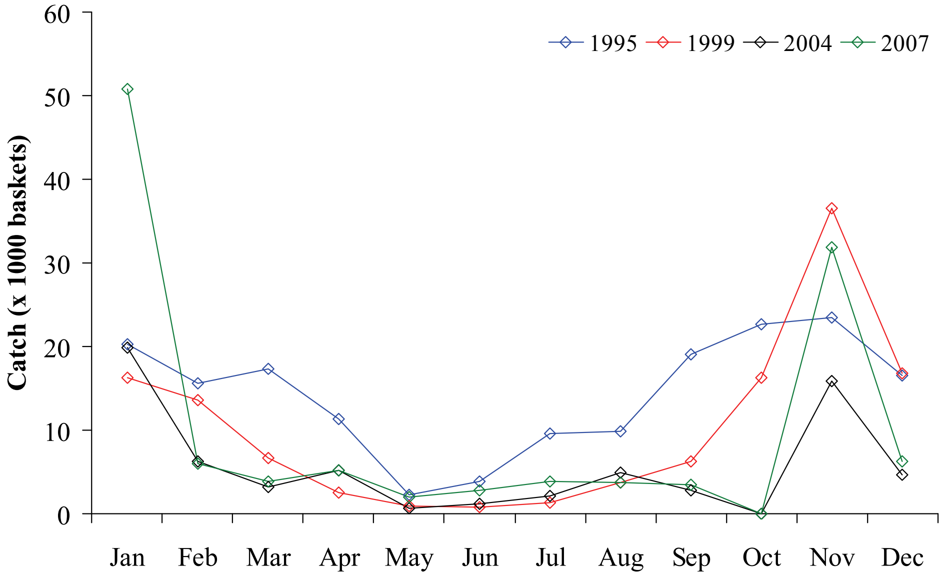

Figure 8-5: Total monthly catch (in 1000's of baskets) for the years 1995, 1999, 2004 and 2007 in the scallop fishery south of 22°S.

8.3.2 *Trends in fishing vessels and gear*

The following results are trends generated from the generalised linear model, the Genstat (2007) code for which can be found in Appendix 17.3.

8.3.2.1 Changes in vessel characteristics

Since 1988, average engine power in the scallop fishery has increased, with a peak of 315 horsepower occurring in 2001 (Figure 8-6). O'Neill and Leigh (2006) reported that engine power would reach approximately 340 horsepower in 2004, however, these results were based on an incomplete data set, with the engine power rating in 2004 adjusted to approximately 295 horsepower in the present project. Since 2001, average engine power has decreased to approximately 300 horsepower.

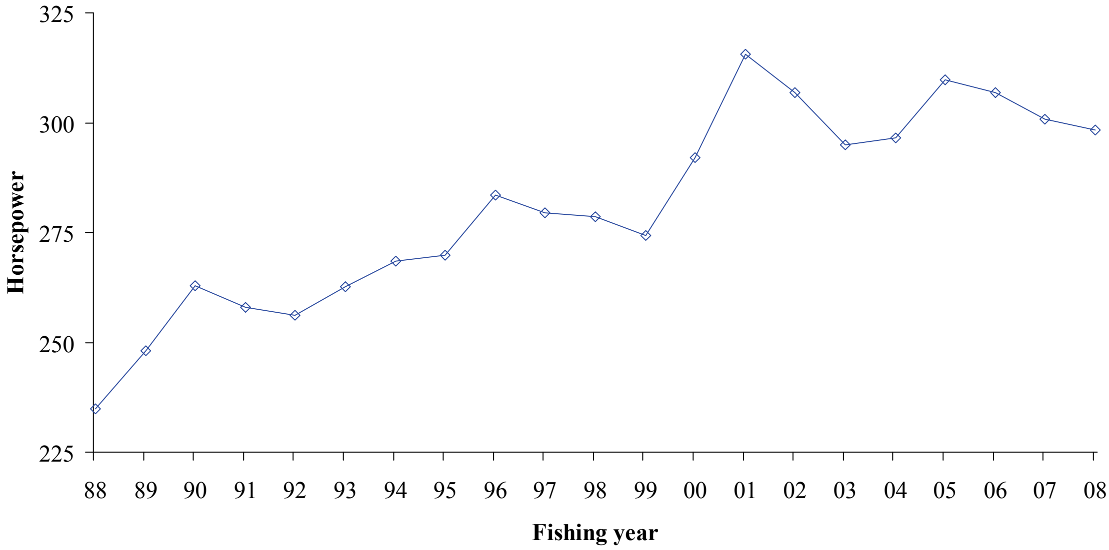

Figure 8-6: Adjusted engine power rating (horsepower) for vessels operating in the Queensland scallop fishery from 1988 to 2008. Data were sourced from mandatory log books.

All vessels operating in the scallop fishery now use Global Positioning Systems (GPS), while few have Sonar (Figure 8-7). Approximately 80% of the boat days in the scallop fishery in 2008 were recorded by vessels with a Kort nozzle installed.

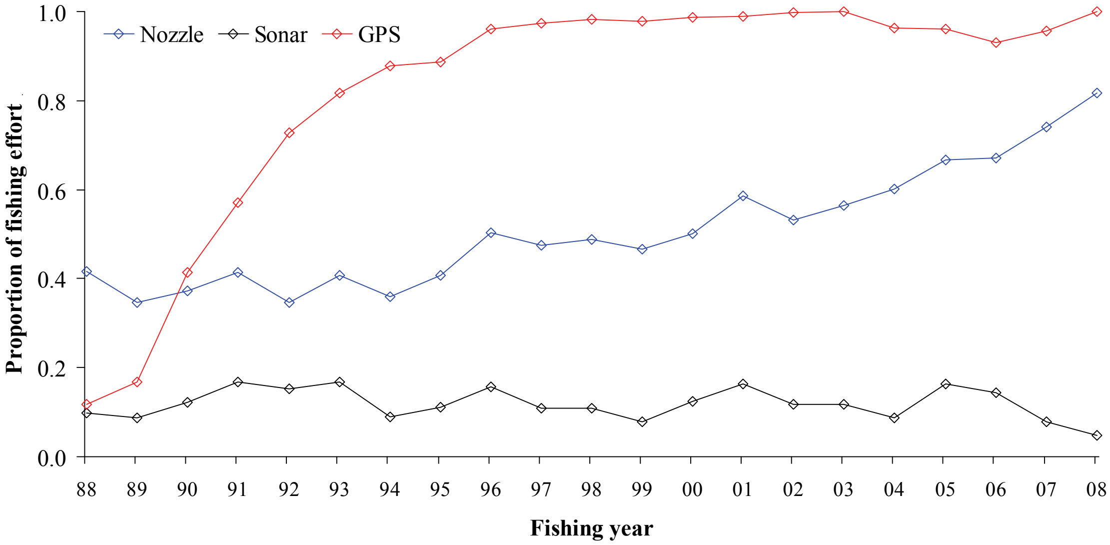

Figure 8-7: Adjusted proportion of days fished in the Queensland scallop fishery where a Kort Nozzle, Sonar and GPS were used.

The number of hours fished per day has increased since 1992 and reached approximately 14 hours in 2001 (see Figure 8-8). Since 2001, the number of hours fished per day has remained relatively stable with a slight decrease observed in 2008.

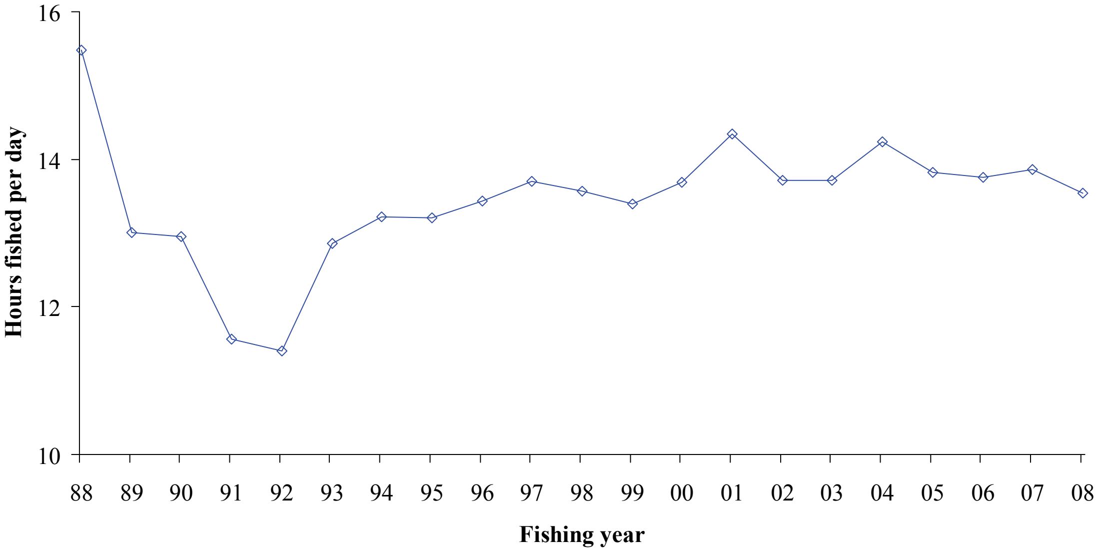

Figure 8-8: Adjusted number of hours fished per day in the scallop fishery.

8.3.2.2 Changes in fishing gear characteristics

The use of quad-rigged nets has increased in recent years with approximately 70% of effort days in the scallop fishery recorded by quad-rigged vessels (Figure 8-9). The use of quad-rig has increased steadily since 1988, with a sharp rise in 2007, whilst the use of triple-rig has decreased. Since 2001, the number of triple- and quad-rigged vessels remained steady, with a significant increase in quad-rigged vessels in 2007, compared to the previous year. In 2008, most vessels fishing in the scallop fishery were using quad-gear, while there was a further decline in those vessels using triple-rig.

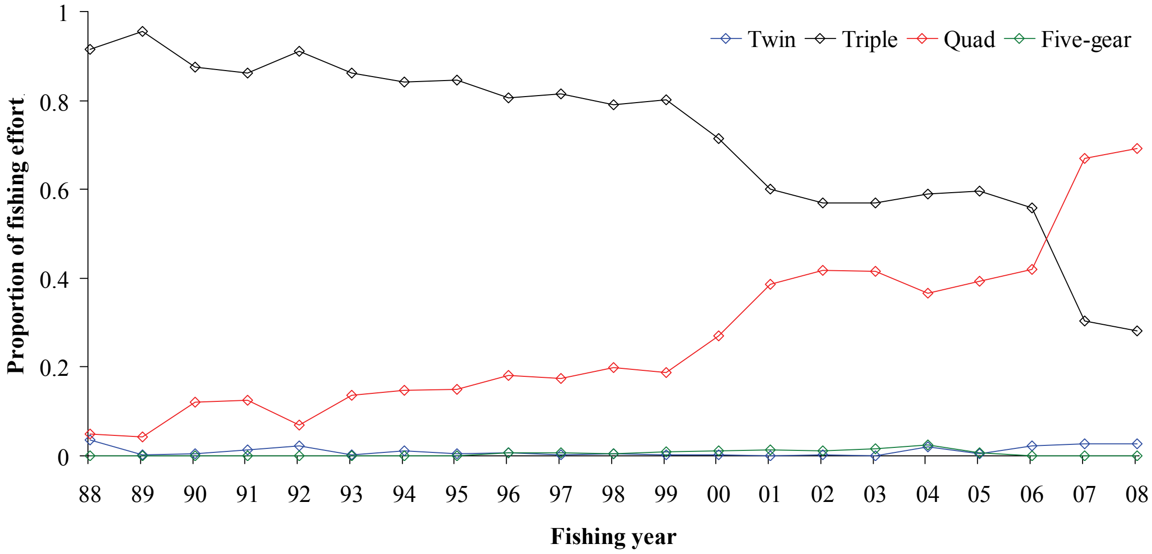

Figure 8-9: Gear type employed in the scallop fishery as a proportion of annual fishing effort (in boat days).

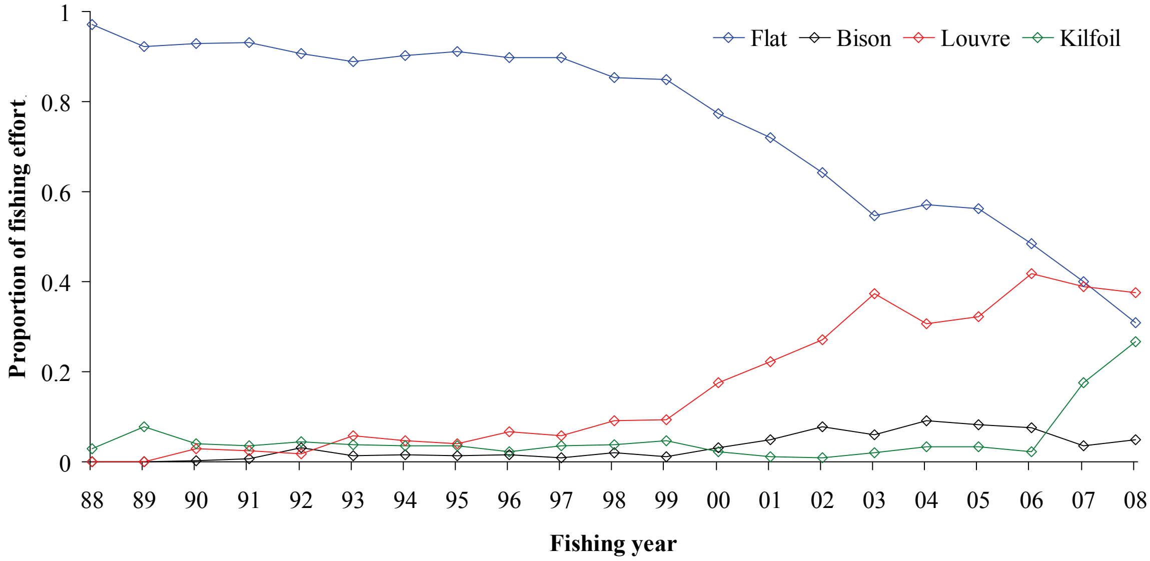

Figure 8-10: Otter board designs used in the Queensland scallop fishery as a proportion of annual fishing effort (in boat days).

With the introduction of the *Trawl Plan*, the use of standard, flat “barn-door” otter-boards decreased, while the use of louvre-type boards, including Kilfoils, increased (Figure 8-10). As with the use of triple-rig, the reduction in the number of older, smaller vessels resulted in a reduction in the use of the older-style flat boards. The remaining boats used otter-boards that utilised hydro-dynamic properties rather than ground shear to spread the nets.

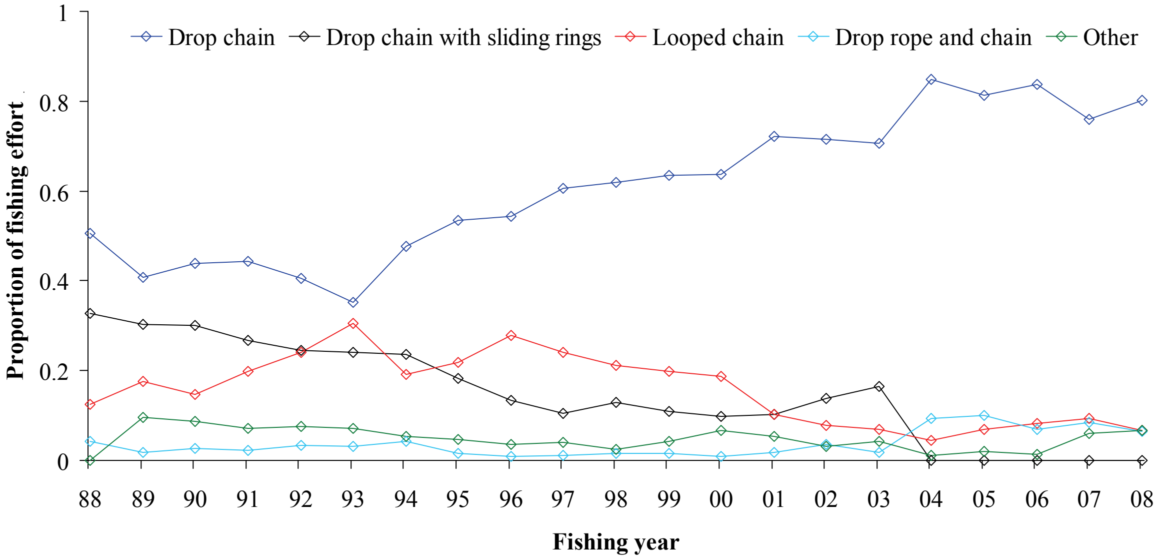

Figure 8-11: Ground chain arrangement employed by fishers in the scallop fishery as a proportion of annual fishing effort (in boat days).

Most of the vessels in the scallop fishery use similar ground gear to that used in the king prawn fishery. Although the looped chain arrangement and the drop chain with sliding rings arrangement were popular in the early 1990's (Figure 8-11), the drop chain arrangement is the most widely employed ground gear arrangement in recent years.

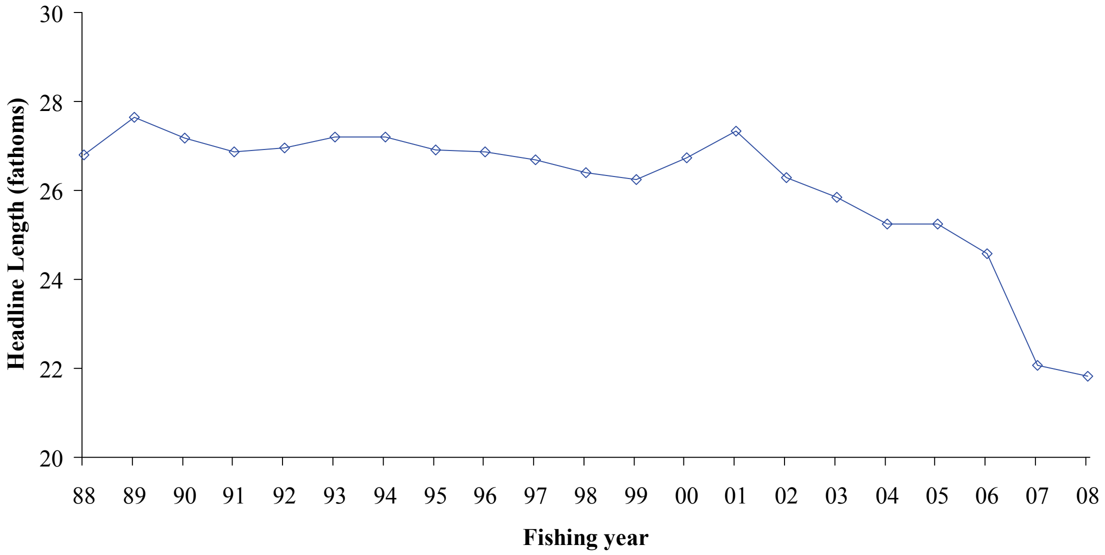

Figure 8-12: Adjusted headline length of nets used in the Queensland scallop fishery from 1988 to 2008.

The use of try-gear nets, smaller nets used to indicate the catch rates being achieved by the 'main' gear, increased steadily from 1988 to 2001 (Figure 8-13). Since the introduction of the *Trawl Plan* in 2001, the scallop fishery has been dominated by pulse fishing in re-opened SRAs, where try-gear is not required to catch scallops by some fishers as they fish close to other, more effective fishers. TEDs and BRDs were progressively mandated in the scallop fishery during 2000-01, with full compliance required by July 2001. Since 2004, all vessels reporting scallop catch south of 22°S have had TEDs and BRDs installed (Figure 8-13).

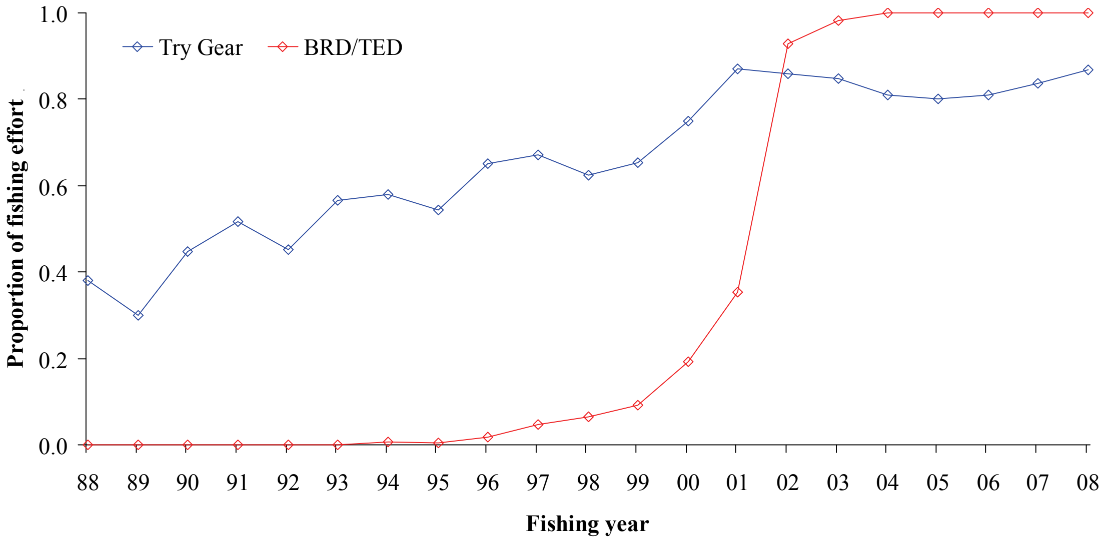

Figure 8-13: Adjusted proportion of days fished in the Queensland scallop fishery where try-gear and TEDs/BRDs were used. TEDs were progressively introduced after 2000 and were made mandatory in 2001.

The size of the vessels operating in the scallop fishery affected some of the vessel or gear characteristics Table 8-1. Horsepower, an index of vessel size (O'Neill and Leigh, 2006 reported that vessel length and horsepower were highly correlated), was positively correlated with the use of Kort nozzles, try gear and headrope length. This suggests that the larger vessels were more likely to employ try gear and Kort nozzles, reflected in the positive correlation between these characteristics, whilst towing larger nets. The low correlation between horsepower and the use of TEDs and BRDs suggests that vessels are employing these devices irrespective of size, which accurately reflects their mandatory use in the scallop fishery.

Table 8-1: Linear correlations between select scallop vessel and gear characteristics.

	Horsepower	Nozzle	Sonar	GPS	Try gear	TED/BRD	Headrope length
Horsepower	1.000						
Nozzle	0.457	1.000					
Sonar	0.294	0.291	1.000				
GPS	0.205	0.192	0.093	1.000			
Try gear	0.526	0.423	0.178	0.237	1.000		
TED/BRD	0.089	0.127	-0.013	0.182	0.208	1.000	
Headrope length	0.407	0.135	0.142	0.028	0.159	-0.157	1.000

8.3.3 Standardised catch rates 1977–2008

The lack of reliable vessel characteristics and gear data for the pre-1988 period resulted in a model that incorporated fewer factors and co-variates to adjust catch rates for standardisation purposes. As such, hours fished, fishing year, month, CFish grid, prawn catch and lunar phase, were used to standardise the long-term catch rate data (see Section 17.4.1 on page 121). The data used in the standardisation were those where most of the above factors were present and were representative of the overall observed dataset (see Figure 17-13, page 122). The pre-1988 catch rates were significantly higher than those from the post-1988 period (see Figure 8-14), with standardised catch rates exceeding 50 baskets per vessel per day on a number of occasions. However, whether this is an accurate measure of abundance is disputable, given the data used to generate Figure 8-14 were based on voluntary logbooks. As such, only those fishers that wanted to participate in the logbook scheme submitted catch data. It is, therefore, difficult to ascertain whether these data are based on an 'average' vessel. Anecdotal evidence suggests that only 'good' fishers participated in the voluntary logbook scheme, which may have artificially inflated catches during the pre-1988 period.

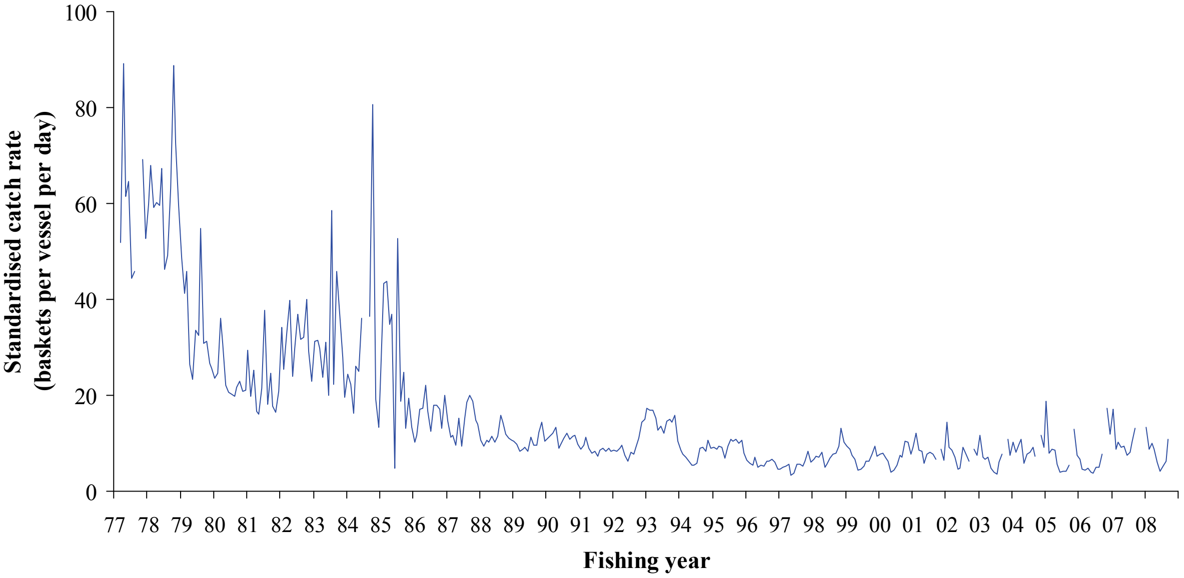

Figure 8-14: Standardised scallop catch rates for the fishing years 1977 – 2008 inclusive. Catch rate data derived from both mandatory and voluntary logbooks. Mandatory logbooks were introduced in 1988. Note: catch rate data from October are excluded from 2000 to present due to the effect of the temporal closure which occurs from 15 September to the 31 October, annually.

8.3.4 Standardised catch rates 1988 – 2008

Average monthly catch rates showed a downward trend from 1988 through to 1997, with catch rates over 20 baskets per vessel day being recorded in 1988 and 1993 (see Figure 8-15). Since 2004, catch rates have increased, with catch rates in January 2007 exceeding 20 baskets per vessel per day. Since 2001, catch rates have been highest in November and January, corresponding to a reduction in the MLS and the re-opening of closed SRAs, respectively. Catch rates in the winter months, which coincide with the increase in MLS from 90 mm to 95 mm, are lowest.

8.3.5 Proportional change in fishing power

Parameter estimates of the effects of individual components on the number of baskets caught can be found in Appendix 17.4.4. From Figure 8-16, it can be seen that fishing power has increased by approximately 20% since 1989. O'Neill and Leigh (2006) quoted a 5% increase from 1989 to 2003, although the 2004 figure of approximately 15% was for an incomplete data set. The complete data set used in the present report shows that the actual fishing power increase was approximately 10% between 1989 and 2004.

Since 2003, fishing power reached a maximum level 18% higher than the 1989 baseline level in 2007. In 2008, fishing power decreased slightly and was found to be 16.5% higher than the 1989 level. Overall fishing power increased from the 1989 baseline through until 1996, driven primarily by changes in vessel characteristics such as engine power. Between 1996 and 1999, overall fishing power decreased, again driven by vessel-related changes, particularly engine power. Both vessel- and gear-related factors such as engine power, headline length, hours fished per day and the increased use of quad-rig, caused an increase to overall fishing power from 1999 through to 2002, while decreases in engine power caused a decrease in 2003. Since 2003, vessel-related factors have caused increases in overall fishing power.

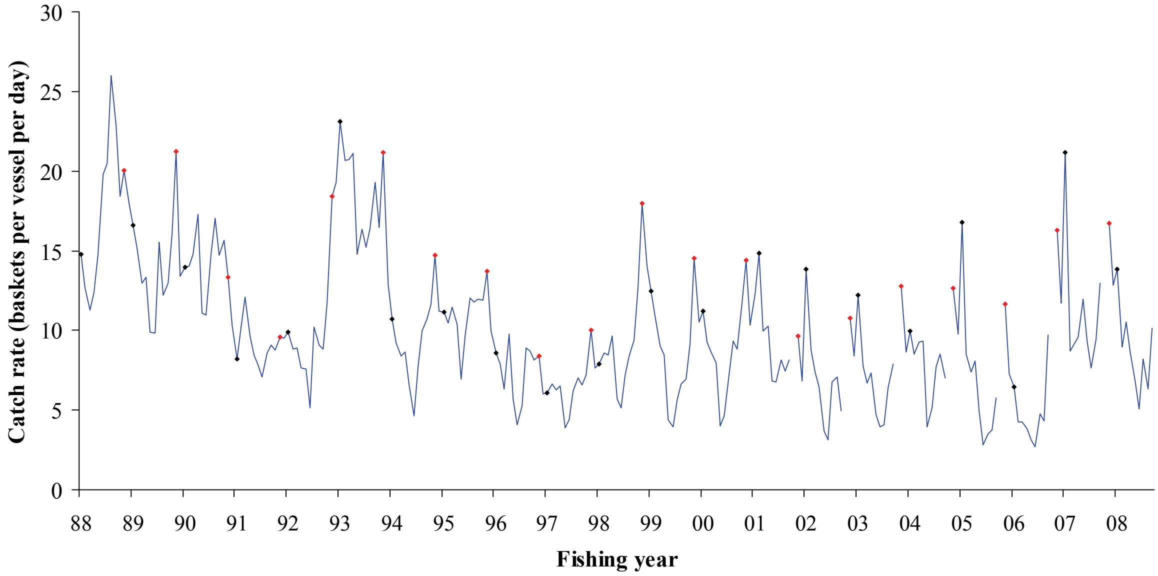

Figure 8-15: Standardised monthly scallop catch rates south of 22°S in Queensland. The x-axis tick marks and the black diamonds correspond to January of each fishing year; the red diamonds correspond to November of each fishing year. See O'Neill and Leigh (2006) for methods and procedures for generating this figure. Catch rate data derived from mandatory logbooks. Note: catch rate data from October are excluded from 2000 to present due to the effect of the temporal closure which occurs from 15 September to the 31 October, annually.

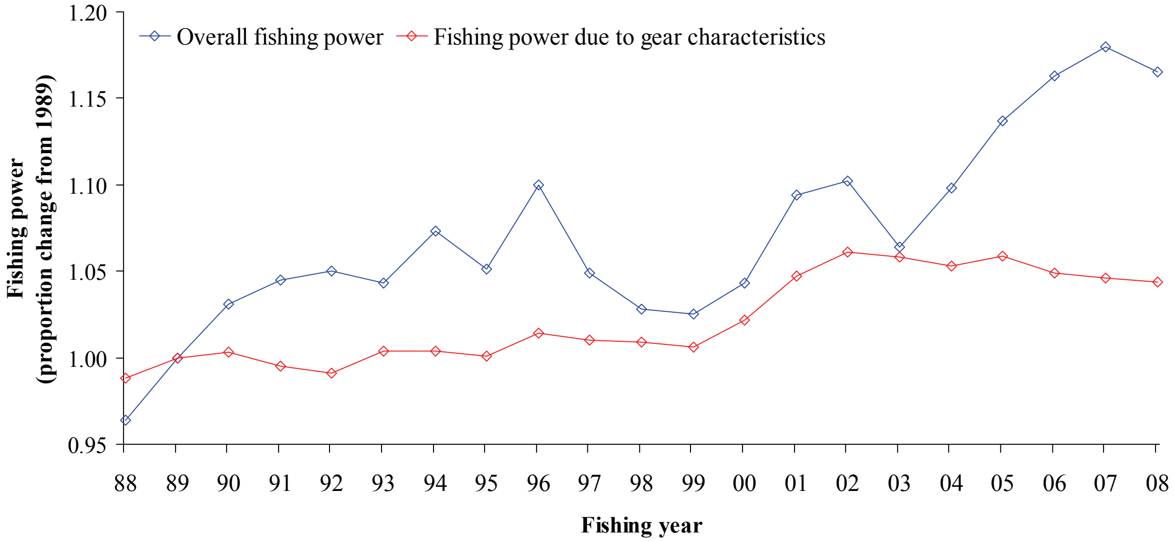

Figure 8-16: Annual change in fishing power for saucer scallops as calculated from the mixed linear model described by O'Neill and Leigh (2006). The proportion change is a comparison to fishing power in 1989. The blue line categorises changes in fishing power attributable to both vessel- and gear-related factors, while the red line categorises changes in fishing power attributable to gear-related factors only.

8.4 DISCUSSION

The use of technology that impacts on the catchability of scallops has increased significantly since the mandatory logbook system was introduced in 1988, with resultant increases in the fishing power of the scallop trawl fleet.

Firstly, engine power has increased significantly. From the REML analysis, engine power was found to have had the most significant effect on catch rate ($F = 86.99$, $P < 0.001$, see Table 17-1), when compared to the other gear- and vessel-related factors examined in the analysis. Further, engine power was found to have had a strong positive effect on catch rate (see Table 17-2). Increases in engine power have been reported as a factor that contributes to an increase in the fishing power of trawler fleets. For example, Mahévas, Sandon *et al.* (2004) reported that engine power was one of the most important variables in explaining the differences in fishing power in a bottom-trawl fishery targeting anglerfish (*Lophius* spp.) in France. Further, (Marchal, Ulrich *et al.* 2002) reported that “the fishing power of towed-gear fleets increases with horsepower”. Average engine power has decreased since 2005 from approximately 310 horsepower to 298 horsepower in 2008.

In Queensland, engine power and vessel size are highly correlated (O'Neill and Leigh 2006) and, as such, the increasing trend in engine power has occurred concurrently with an increase in vessel size. Since the introduction of the *Fisheries (East Coast Trawl) Management Plan 1999*, the operators of the smaller vessels that operated year-round surrendered their boats during the period when the vessel buy-back scheme and effort unitisation were in operation. At this time, the wealthier operators in the fishery saw the opportunity to increase capital in the ECOTF and purchased the smaller vessels and their effort units and constructed the large boats operating in the fishery at present. A substantial proportion of these vessels are dual-endorsed to operate in the Torres Strait Prawn Fishery and, as a result, are manufactured to hold a significant volume of product as they were only serviced every two weeks by the barges that unloaded their catch. These larger vessels and those from northern Queensland have fished for scallops in recent years due to economic pressures chiefly due to increasing fuel costs and competition with imported farmed prawns from south-east Asia. The observed increase in engine power should result in an increase in trawl speed, however, scallops are best caught at slower trawl speeds compared to the prawn sectors (see O'Neill and Leigh, 2006, page 87). This is a result of scallop behaviour when encountering an oncoming trawl – if the trawl speed is too fast, the scallops are unable to swim high enough into the water column, above the footrope, to be caught. As such, where a vessel may trawl at speeds in excess of 3.5 knots in the tiger prawn fishery in northern Queensland, trawl speed is around 2.1-2.4 knots when targeting scallops. This suggests that the engine power itself is not the only factor contributing to increases in fishing power but that the size of these vessels are also having an effect. That is, larger vessels generally have more crew, enabling greater processing capacity. Further, larger vessels have more storage capacity with superior refrigeration, allowing for the efficient processing of very large catches associated with the January and, too a lesser extent, the November peak periods. In contrast, smaller vessels are forced to regulate catches according to storage and refrigeration limitations. Also, the larger vessels can use much larger TEDs which are much more efficient than the devices used by smaller vessels, which have limited deck space, making large TEDs impractical. The fact that the use of propeller nozzles (Figure 8-7) was found not to have any effect on catch rate (see Table 17-2) is further evidence that it may be vessel size, rather than engine power, contributing to increases in fishing power in the scallop fishery.

However, increased engine power combined with the increasing use of propeller nozzles can be advantageous when targeting scallops. Scallop catch can be associated with a diverse range of flora and fauna with a bycatch to catch ratio by weight of more than 15:1 being reported by Courtney, Haddy *et al.* (2007). This can result in substantial accumulated catches in the codends of scallop trawls. Further, the targeting of dense aggregations of scallops can result in very large catches of scallops accumulating in the codends, resulting in increasing net drag over time. Vessels having more available thrust via large engines and propeller nozzles are able to maintain optimum trawl speed over the length of a trawl by increasing engine revolutions, where smaller vessels with lower engine power gradually decrease speed with the increasing accumulated catch and resultant increasing net drag. In these situations, smaller vessels will, generally, decrease trawl shot time to ensure the gear is operating efficiently and to avoid wear.

The increases in the use of quad-rig (Figure 8-9) in recent years are also a result of the influx of large boats from northern Queensland. Vessels operating in the northern tiger prawn fishery employ quad-gear predominantly (see O'Neill and Leigh, 2006, page 42) and retain this gear-type when moving to the scallop fishery. The number of nets was found to significantly affect (F=13.38, P<0.001) the catch rate of scallops (see Table 17-1), with most (≈ 69%) scallop fishers now using quad-rigged nets. Mahévas, Sandon *et al.* (2004) reported that the transition from a single net to twin-gear resulted in a 30% increase in efficiency, which contributed significantly to increases in overall fishing power in a trawl fishery in South-Brittany, France. However, the potential benefits associated with quad-gear, including reduced drag and resultant increase in trawl speed for a given headline length, are somewhat negated in the scallop fishery with regard to trawl speed, as explained above. This is further evidenced by the fact that both triple-gear and quad-gear only had a very marginal positive effect on catch rates (see Table 17-2). Most of the vessels based in the southern ports of Queensland also target eastern king prawns and, as such, employ triple-rig. This is due to the fact that quad-rig cannot be used in deeper water for safety reasons, with trawl blocks located at the end of trawl booms causing considerable instability should a vessel hook-up on an obstacle, especially when retrieving the snagged gear. As such, most vessels based in southern ports continue to fish with the triple-rig configuration in the scallop fishery, although there are certainly some fishers converting to quad-rig.

The increased uptake of quad-gear has coincided with a decrease in headline length (Figure 8-12). Headline length was found to have had a significant positive (β_2=0.172, see Table 17-2) effect on catch rate (F=77.01, P<0.001, see Table 17-1). Fishers operating in the scallop fishery are required to limit the combined head- and foot-rope length to 109 metres (60 fathoms). The increased uptake of quad-rigged nets has resulted in a large proportion of vessels towing four 5- to 5½-fathom nets, resulting in a total headline length of 20-22 fathoms. For the most part, vessels operating in the scallop fishery are restricted to using nets of this size due to the length of the trawl ‘arms’ or ‘booms’ and the resultant trawl-block width. That is, if larger nets were used, the inside trawl boards would become entangled. Further, the use of “Siebenhauser” nets (Davies 1992) allowed fishers to tow nets with up to 28 fathoms of headline in triple-rig configuration as both head- and foot-ropes are similar in length due to the fact that scallops do not require lead-ahead. Since the *Fisheries (East Coast Trawl) Management Plan 1999* was introduced, fishers have favoured Florida Flyer-style nets (see Davies 1992 for a detailed description), partly due to the introduction of TEDs, which perform better when installed into this style of net. In short, “Flyers” have equal tension around the circumference of the throat of the net, compared to Siebenhauser nets which are characterised by ‘slack’ net top and bottom. The ‘slack’ net results in TEDs performing very poorly due to drastic changes in TED angle. Florida-flyers incorporate lead-ahead, which results in longer foot-ropes and a resultant reduction in headline length. The negative correlation between the use of TEDs/BRDs and headline length (-0.157, see Table **8-1**) suggests that fishers are moving to Florida Flyer-style nets, with smaller headlines, in order to ensure the efficient use of these devices.

Interestingly, Sterling (2000) reported that, at low speeds, triple gear exhibits higher swept areas for a given headline length. This is due to the fact that the optimum spread ratios are higher for triple-rig compared to quad-rig. This allows for more ground to be trawled by a triple-rigged vessel, compared to a quad-rigged vessel. The fact that the REML analysis implies that quad-rigged nets have a slightly higher positive effect on catch rates suggests that triple-rigged vessels are generally employing nets with a similar overall headline length to quad-rigged vessels. Further, the increased swept area exhibited by triple-rig is negated due to an increase in the targeting of scallop 'patches', particularly inside the SRAs, compared to the searching behaviour where increases in swept area would be of benefit.

The REML analysis revealed that the use of global position systems (GPSs) had no significant effect on scallop catch rates (F=1.29, P=0.256). Further, GPS was found to have had a negative effect on catch rates ($\beta_2 = -0.014$). This is in contrast to Robins, Wang *et al.* (1998) and Bishop, Venables *et al.* (2008), who reported that the addition of a GPS had a significant effect on tiger prawn (*P. esculentus* and *P. semisulcatus*) catch rates in the Northern Prawn Fishery (NPF). O'Neill and Leigh (2006) also reported that the use of GPS technology had no significant effect on catch rates. However, Bishop, Venables *et al.* (2008) quantified the effects of GPS at a time when the technology was first introduced, rather than for the longer time-series of data, as there was optimal contrast in the data at this time. Using this method, the authors were able to show that the use of GPS had a significant and positive effect on catch rates of tiger prawns in the NPF. Further, Robins, Wang *et al.* (1998) used skipper experience in relation to the use of GPS to show that the technology had a significant effect on the catch rate of tiger prawns in the NPF, with an increase in time that GPS technology is used having a positive effect on catch rates. Given that GPS technology was adopted rapidly in the scallop fishery (see Figure 8-7) and has now been adopted by the whole fleet, little contrast exists in the logbook data and may be the reason that the non-significant effect occurred.

Although GPS is a generic term, the addition of technologies related to the availability of precise location data have continued to change since the completion of the report by O'Neill and Leigh (2006). Technology has evolved that allows a GPS unit to interface with the steering mechanics and mapping software that allows a fisher to follow very precise trawl tracks. Further technology has now been introduced that allows fishers to produce very detailed three-dimensional charts. This, combined with the increasing memories of on-board computers, allow fishers to save an infinite amount of detailed trawl track data. The uptake of such technologies will continue to apply upward pressure on fishing power.

The use of try-gear was also found to have not significantly affected catch rates (see Table 17-2). The use of try-gear is positively correlated with engine size (see Table 8-1) which suggests that a larger vessel is more likely to use try-gear. This reflects reality with smaller boats unable to employ try-gear. However, the use of try-gear is not as important in the scallop fishery as those vessels without try-gear are able to follow closely behind those vessels that use try-gear, a phenomenon also reported by Bishop, Venables *et al.* (2008) in the NPF. This is especially the case when the SRAs re-open, where vessels without try-gear are able to take large catches. The fact that try-gear has no significant effect on catch rates is evidence that the fishery targets large aggregations of scallops, rather than a "search and scratch" fishery. Traditionally, fishers would search scallop grounds and work their try-gear until an area with higher catch rates was found. Given that trawl effort is concentrated around the November and January peak times, most fishers now know where high concentrations of scallops are located. During the January peak period, it is a simple matter of going to the SRAs that are due to open and fishing areas that have produced large catches in previous years. Given the competition among vessels at this time, searching time is kept to an absolute minimum, with the main gear shot away and effectively used as try-gear.

The targeting of scallops during the November peak period is slightly more complicated. Those fishers that fished through the winter and found dense beds of sub-legal scallops were able to target these once the minimum legal size (MLS) returned to 90mm after the winter spawning period. The locations of these beds were passed around the fleets through word-of-mouth, allowing fishers that had fished for eastern king prawns throughout the winter to target these dense beds during the first few weeks of November. Further, the general location of scallop beds are widely known throughout the fleet, with most beds recurring annually. This has been the case up until 2009 and may change with the removal of the 95mm MLS during winter.

The REML analysis suggested that otter board-type had a significant effect (F = 18.97, $P < 0.001$) on catch rates in the scallop fishery. The use of flat, "barn-door" boards has decreased significantly (see Figure 8-7), in accordance with the reduction in the use of triple-rig (see Figure 8-9) in the scallop fishery. Generally, flat otter boards are used in the eastern king prawn fishery (O'Neill and Leigh 2006) due to their stable nature during trawling and low relative cost. In contrast, in the prawn fisheries of northern Queensland, where trawl speed is an important consideration, louvre-style boards such as Kilfoils, are employed more widely. As such, those vessels employing triple-rig continue to use the flat rectangular boards in the scallop fishery, while those vessels from northern ports are using louvre-style boards. The REML analysis suggests that Bison boards have a slight negative effect on scallop catch rate (see Table 17-2 on page 124). This result reflects reality as Bison boards are prone to instability, particularly at low speeds. Hence, Bison boards are not used in the scallop fishery despite their superior ability to spread nets compared to other board types for a given board size (Sterling 2000). The use of louvre-style boards and Kilfoils is having a positive effect on catch rates ($\beta_2 = 0.033$ and $\beta_2 = 0.130$, respectively). These boards are used in the northern prawn fisheries due to the fact that they are towed at relatively high trawl speeds and achieve gains in swept area, compared to flat rectangular boards. Further, the use of these boards is advantageous when used in conjunction with quad-rig as they reduce total overall drag and are easier to tow compared to flat rectangular otter boards, given that four boards are necessary with quad-rig (Sterling 2000). Although increasing trawl speed is of lesser importance in the scallop fishery, these styles of otter-boards are being adjusted by fishers when entering the scallop fishery so that they fish well when used in conjunction with quad-rig. However, there may be some confounding effects due to interactions between gear-type, engine size and board type. That is, the vessels employing quad-rig are generally larger in size and use louvre-style or Kilfoil boards. This interaction needs to be addressed in future studies.

Turtle excluder devices (TEDs) were mandated in the scallop fishery in 2001. The steady increase in the use of TEDs and BRDs between 1996 and 2000 (see Figure 8-13) coincides with the FRDC-funded project *Commercialisation of bycatch reduction strategies and devices within northern Australian prawn trawl fisheries* (Robins, Eayrs *et al.* 2000), during which fishers were assisted with the introduction of TEDs and BRDs before their mandatory use. The use of TEDs and BRDs was found to have had a positive ($\beta_2 = 0.038$) significant effect (F=6.91, P=0.009) on scallop catch rates. This is a somewhat surprising result as most fishers reported major problems when TEDs were introduced in 2001. At this time, ineffective devices were used that allowed a large portion of captured scallops to escape the trawl due to poor design and manufacture. The introduction of TEDs and/or BRDs into the Northern Prawn Fishery had a negative effect on prawn catch rates (Brewer, Heales *et al.* 2003) as reported by Bishop (2006) and a similar effect was expected in the current study. However, in more recent years, most fishers have developed extremely efficient TEDs and BRDs, with some devices increasing catch rates. For example, the use square mesh codends was shown to increase catch rates by Courtney, Haddy *et al.* (2007) during the FRDC-funded (Project number 2000/170) project *Bycatch weight, composition and preliminary estimates of the impact of bycatch reduction devices in Queensland's trawl fishery*. These devices are now being used by a significant portion of the scallop fleet and will be made mandatory after the review of the *Fisheries (East Coast Trawl) Management Plan 1999*, due in 2010.

Another important change that has occurred within the scallop fishery with regard to the introduction of TEDs has been the targeting of areas that have traditionally been avoided due to the large amounts of bottom debris associated with scallop catch. Anecdotal reports suggest that some of these areas contain dense scallop beds which are now accessible due to the efficient exclusion of sponges by TEDs, with resulting positive effects on catch rates. Further, the use of Florida Flyer-style nets has increased, as explained earlier, and has probably accounted for a significant reduction in scallop loss through TED escape openings. TED design has evolved since their introduction in 2001. Larger grids with very large escape openings aid in the fast and efficient exclusion of sponges and other large fauna, which is necessary in order to avoid blocking the TED and catch-loss occurring when the trawl slows at winch-up. The exclusion of sponges and other large animals by TEDs, combined with the efficient exclusion of smaller bycatch species via BRDs, may have also resulted in slight increases in swept area with a resultant positive effect on catch rates.

The addition of prawn catch as a co-variate in the model provided a measure of whether those fishers reporting scallop catch in their logbooks were actually fishing for scallops or had caught scallops incidentally whilst trawling for prawns. The REML analysis determined that prawn catch had a highly significant negative effect on scallop catch (F=8953.08, P<0.001; $\beta_2 = -0.242$). This was an expected result as higher prawn catch rates will generally correspond to very low scallop catches. There are some areas where scallops are caught by fishers targeting prawns such as the Wide Bay Bar area. In this location, fishers target a mix of tiger and king prawns, whilst retaining scallops as a bycatch. The inclusion of prawn catch as a co-variate allows low scallop catches, caught as a bycatch during prawn trawling operations, to be included in the analysis and goes some way to explaining a low catch rate. That is, if the prawn catch were excluded from the analysis, a reported catch of, for example, one basket of scallops caught in conjunction with 300 kg of prawns would be interpreted as a low scallop catch rate by the model rather than as a bycatch of prawn trawling. Furthermore, a low scallop catch reported in conjunction with a zero prawn catch indicates a legitimately low scallop catch.

The changes in these factors have resulted in a significant increase in fishing power in the scallop fishery (Figure 8-16). Such increases in fishing power have occurred in other demersal trawl fisheries, for example the Northern Prawn Fishery (Bishop, Die *et al.* 2000; Bishop, Venables *et al.* 2008; Bishop, Venables *et al.* 2004; Dichmont, Bishop *et al.* 2003; Robins, Wang *et al.* 1998), the South African west coast hake (*Merluccius* spp.) trawl fishery (Glazer and Butterworth 2002) and the demersal trawl fisheries of the North Sea (Marchal, Ulrich *et al.* 2002). Further, previous work by O'Neill and Leigh (2006) and O'Neill, Courtney *et al.* (2003) showed increases in fishing power in the Queensland scallop fishery for the years 1989-2004 and 1989-2009, respectively.

In contrast to O'Neill and Leigh (2006), who found that net configurations (eg. triple-rig, quad-rig) were more important than other factors in determining scallop fishing power, the current analysis suggests that engine size and headline length were the most important factors affecting changes in fishing power. This is in agreement with Robins, Wang *et al.* (1998), who also reported that average headline length and average boat length had the highest positive effect on relative fishing power in the NPF for the years 1988 to 1992.

The increase in overall fishing power in the current study for the period 1989 to 1996 occurred concurrently with a 14% increase in average adjusted horsepower. During this time, gear characteristics such as headline length and the use of quad-rig remained relatively constant, hence fishing power changes due to these characteristics were minimal. From 1999 through to 2002, overall fishing power was influenced by the increased use of large vessels employing quad-rig, with gear-related fishing power increasing by around 5% during this time. In addition, the vessels entering the fishery at this time were powered by larger engines, with significant increases in average adjusted horsepower in the period 1999-2001 due to reasons explained earlier. Beyond 2003, fishing power changes due to gear-related factors have decreased while overall fishing power has increased significantly. This suggests that the larger, efficient vessels have contributed a higher proportion of the total catch since 2003.

One important factor that influences fishing power is skipper experience and knowledge. This factor is particularly difficult to quantify (Bishop, Venables *et al.* 2004; O'Neill and Leigh 2006). Robins, Wang *et al.* (1998) quantified the effect of skipper experience with regard to the use of GPS and plotter technology and found that increased use of this technology resulted in an increasingly positive effect on catch rate. Specifically, fishing power increased by 7% during a fisher's first year of using a plotter, and increased to 12% after the third year of plotter use. This goes some way to quantifying the effect of skipper experience in a fishery and its effect on fishing power. Logically, the more experience a fisher has within the scallop sector, the higher the probability that scallop catch rates will increase. Since the introduction of the *Fisheries (East Coast Trawl) Management Plan 1999*, and the resultant decrease in the number of vessels operating in the fishery, the number of experienced skippers has decreased substantially. These experienced skippers generally operated the smaller vessels in the fishery that operated year-round. Most of these operators saw the vessel buy-back scheme and effort unitisation, where days fished became a commodity to be bought and sold, as a way of exiting the fishery in what was a volatile and uncertain time.

The effect of the rotational closure system in use after the introduction of the *Trawl Plan* allowed fishers with no experience in the scallop fishery to catch large volumes of scallops by targeting SRAs, effectively informing fishers about where to trawl. This provides all fishers with the ability to target very dense aggregations of scallops without having any prior knowledge of the fishery. Hence, large vessels from northern ports with operators lacking experience in the fishery can enter the scallop sector and catch more than a fisher with a smaller vessel and 15 years experience. This is in direct contrast to previous years, when fisher knowledge was a significant factor in determining catch rates. Experienced skippers could identify trawlable areas after years of fishing in the scallop sector and direct effort at those areas where scallop catch rates were high.

In conclusion, high trawl speeds do not equate to improved scallop catch rates. Technological changes relating to increased thrust can improve catch rates by maintaining optimum trawl speed for longer periods. The increase in engine power equates to an increase in average vessel size, the advantages of which include the ability to process large catches during the peak November and January periods. This results in higher catch rates compared to smaller vessels with less crew and inferior storage capacity and refrigeration. The larger vessels are able to use efficient TEDs that exclude large volumes of sponges and other bottom debris quickly, resulting in the retention of a higher proportion of caught scallops. These large vessels are able start trawling in productive areas with very little searching required. All of these factors combined have resulted in increasing catch rates in recent years and has had a significant effect on fishing power in the Queensland scallop fishery.

9 Harvest Strategy Evaluation

9.1 INTRODUCTION

The Queensland East Coast Otter Trawl fishery (QECOTF) is the largest demersal trawl fishery in Australia, with 330 licensed vessels reporting catch in 2008, with approximately 40,000 boat days of effort expended in 2007. Fishers are permitted to target prawns, scallops, Moreton Bay bugs and squid with otter trawl gear from Cape York (≈11°S) to the Queensland/New South Wales border (≈28°S). In 2007, the Gross Value of Production (GVP) was estimated at $76 million after reaching in excess of $120 million in the late 1990's (Zeller 2009). Whilst prawns (including *Melicertus* spp., *Penaeus* spp., and *Metapenaeus* spp.) are the major target of fishers operating in the QECOTF, the saucer scallop (*Amusium balloti*) is the basis of a significant fishery, with 920 tonnes of scallop meat (adductor muscle) landed in 2007, worth approximately $14 million (L. Williams, personal communication). *A. balloti* are fished predominantly between Yeppoon (22°S) and southern Hervey Bay (25°S) inside, or to the south of, the Great Barrier Reef, although some significant catches are reported outside of this range.

A. balloti were first trawl-caught during the 1950's, with a fishery established in the late 1960's (Dredge 1988b). During this time, scallops were an off-season target for prawn trawl fishers until regular markets were established in south-east Asia and the United States during the 1970's (Dredge 1994). The Queensland Fisheries Management Authority introduced the first management measures in 1984. These measures were the introduction of a minimum legal size of 80 mm designed to maximise yield per recruit, 109 metre combined head and footrope and 82 mm mesh size. However, as increased levels of fishing effort were directed at the scallop fishery in the late 1980's, emphasis was placed on managing to protect spawning stocks (Dredge 1994) with the MLS increasing from 80 mm to 90 mm in 1987. Further to the increased MLS, three small (10 minute x 10 minute) areas were closed to fishing as a trial to protect spawners in 1989 and, in the same year, MLS varied seasonally with a 95 mm MLS introduced during the winter months when spawning is known to occur (Dredge 1981). In 1990, a daylight trawling ban was introduced permanently and the trial closures were removed in 1990.

These measures were used, with slight temporal variations to the seasonally varying MLS, throughout the 1990's until 1997 when three Scallop Replenishment Areas (SRAs) were implemented as part of the Queensland Government's *Fisheries (Emergency Closed Waters) Declaration 1997*. This was due to concern among fishers and managers after low catch rates during 1996 and 1997 (O'Sullivan, Jebreen *et al.* 2005). These areas were historically very productive and it was thought that closing these areas would maintain spawning stocks for the following winter. With the introduction of *Fisheries (East Coast Trawl) Management Plan*

1999 in 2000, a temporal closure (the Southern Closure) was introduced from 20 September to 31October, annually. In 2004, the MLS was adjusted to 90 mm from 1 November to the following 30 April and 95 mm from 1 May until the end of the Southern Closure. In 2001, the SRAs were divided into 10 separate areas (see Figure 17-1) before being simplified in 2003 (see Figure 6-2). A rotational opening strategy was also introduced in 2003, whereby the SRAs remained closed for 15 months and open for 9 months over a two-year period.

The significant reduction in trawl effort associated with the introduction of *Fisheries (East Coast Trawl) Management Plan 1999*, combined with increased fuel costs and the reduction in scallop price, has prompted fishery stakeholders to question the management strategies employed by the Queensland government. As stated earlier, the current management arrangements attract elevated levels of trawl effort in November and January each year, resulting in an over-supply of product and a significant reduction in unit price. Further, processors are required to store large quantities of scallop during peak fishing times, adding unwanted costs. The relatively short shucking season also results in difficulties retaining trained casual staff to shuck scallops throughout the year. Apart from these practical considerations, the management of the scallop fishery in Queensland is also required to comply with the current suite of conservation-driven policies that are designed to ensure the ecologically sustainable use of fisheries resources. Through the Department of Environment, Water, Heritage and the Arts and the *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act), the Australian federal government promote ecologically sustainable management. Among other important legislation outlined in the EPBC Act, Fisheries Queensland (formerly the Fisheries Business Group) are required to demonstrate that the scallop fishery is operating in a way that ensures the long-term sustainability of target and non-target species as well as the ecosystems in which the fishery occurs. Further, given that the scallop fishery is located within the World Heritage listed Great Barrier Reef Marine Park, it is necessary to manage the fishery accordingly and ensure its impact is minimal on the environment.

To this end, in 2009, the Queensland government via Fisheries Queensland released its Fisheries Strategy. This document (Anon 2009) details the objectives of Queensland’s future fisheries management policies and outlines strategies to manage fisheries in the areas of sustainable habitat use, sustainable harvest and maximum value. These policies require that fisheries managers reform existing legislation and incorporate more flexible and responsive management of fisheries resources. The implementation of such policies can be approached through the use of Harvest Strategy Evaluations (HSEs), to determine the optimum use of fisheries resources in Queensland.

HSEs, also known as management strategy evaluations and management procedure evaluations, are designed to examine alterations in the management policies of a fishery and their effect on selected performance indicators. HSEs utilise available data and knowledge of a resource to provide an indication as to future levels of performance indicators, such as abundance and productivity, through simulation (Butterworth 2007). As such, HSEs provide an objective basis for decision making by evaluating the performance of management policies according to management objectives (Smith, Sainsbury *et al.* 1999). HSEs allow fisheries managers to evaluate the relative performance of management strategies that have been formulated in consultation with stakeholders.

HSEs can be as complex or as simple as the available input data allows, although a major benefit of HSEs is that provision can be made to estimate those parameters that may be lacking for any given fishery, along with any uncertainty around the estimation of such parameters. Given the increasing need for ecosystem-based management, more complex HSEs, that incorporate the effect of fishing on the ecosystem, are becoming more commonplace. Ecosystem-based HSEs can incorporate parameters to describe the effect of a fishery on groups such as bycatch or marine predators in order to ensure that biodiversity is maintained at all biological levels (Sainsbury, Punt *et al.* 2000). HSEs have been used extensively during the last decade in Australia for a range of species including southern bluefin tuna (Polacheck, Klaer *et al.* 1999), gemfish (Punt and Smith 1999), school and gummy sharks (Punt, Pribac *et al.* 2005), tiger prawns (Dichmont, Deng *et al.* 2006), and the southern rock lobster (Punt and Hobday 2009).

For the purposes of the current project, a relatively simple single-species HSE was formulated for the Queensland scallop fishery. This research is timely in that the *Fisheries (East Coast Trawl) Management Plan 1999* is under review. As such, the current project has a unique opportunity to contribute significantly to the formulation of fisheries legislation in relation to the scallop fishery. Relevant stakeholders, through the projects' Steering Committee, provided a suite of potential management strategies and identified the criteria on which their relative performance was evaluated.

9.2 METHODS AND DATA

9.2.1 Basic Population Dynamics

The population dynamics were based on the model used in O'Neill, Courtney *et al.* (2005), with numbers of scallop in month *m*, and at age *a* given by:

$$N_{m,a} = \begin{cases} R_m & \text{for a=1} \\ N_{m-1,a-1} e^{-(M + S_{m-1,a-1} F_{m-1})} & \text{for a=2,...,48} \end{cases}$$

where R_m was recruitment for month *m*, $S_{m,a}$ was the selectivity (incorporating changes in minimum legal size over time), *M* the monthly natural mortality rate and F_m the fishing mortality, calculated as qE_m with *q* a catchability coefficient and E_m effort (in boat days) in month *m*.

Recruitment in each month was calculated as $R_m = R_y \Phi_m$ where Φ_m is a monthly weighting (proportion) of the annual recruitment which follows a von Mises distribution:

$$\Phi_m = \frac{e^{\kappa \cos(m-(\bar{r}/12)2\pi))}}{2\pi I_0(\kappa)}$$

where $I_0(x)$ is the modified Bessel function of order 0 and κ and $\bar{r}$ are parameters (analogous to the mean and variance of a distribution) to be estimated (Mardia and Jupp 2000).

Annual recruitment, R_y, is a product of the overall mean recruitment and an annual log-normally distributed residual:

$$R_y = e^{\chi + \zeta_y}$$

where χ and ζ_y are estimable parameters that measure the geometric mean recruitment and inter-annual variation respectively. Initial numbers of scallop in November 1988 (the first month of the model) for ages 2 to 48 months were calculated as follows:

$$N_{1,2..48} = e^{\chi'} \Phi'_m \, e^{-(\mathbf{M}(a-1))}$$

where $e^{\chi'}$ was the estimated average recruitment for the fishing-years 1985 to 1988, Φ'_m was the vector of birth patterns for each cohort occurring up to the previous 47 months *m*, and **M** was the vector of assumed average monthly natural mortality for each cohort up to the previous 47 months.

9.2.2 Spatial Extension

Nearly sessile adult behaviour, combined with pelagic larvae dispersal tend to make scallop fisheries spatially complex (Orensanz, Parma *et al.* 2006). Even without targeted fishing, scallops naturally tend to be distributed in patches that have some persistence over time. Using the terminology of Orensanz, Parma *et al.* (2006), at the macroscale one has 'metapopulations' that are spatially disjoint but connected through the dispersal of larvae. At the mesoscale each population is composed of a number of subpopulations; this is typically the scale of fishing 'beds'. As can be seen from Figure 9-1, this conceptual model is a good match for the east coast scallop fishery.

Spatial management strategies notwithstanding, such complexity has an immediate implication for the interpretation of fishery catch rate data. In particular, one must take into account the 'resource concentration profile'. As discussed in Smith and Rago (2004), if the resource is distributed such that there is an inverse relationship between the density of a (uniform size) patch and its frequency of occurrence (that is, there are incrementally more lower density areas as density decreases), then it is reasonable to assume that fishers will target the high density regions first and gradually work out to other areas as these regions are fished down. If this is the case then catch rates will initially decline more rapidly as the high density regions are fished down quickly (but the stock as a whole is not). Anecdotal evidence suggests this fish-down behaviour is certainly true of the east coast fishery, and catch and effort derived from Vessel Monitoring System data also support this (Good, Peel *et al.* 2007) (see also the catch-rate plots below).

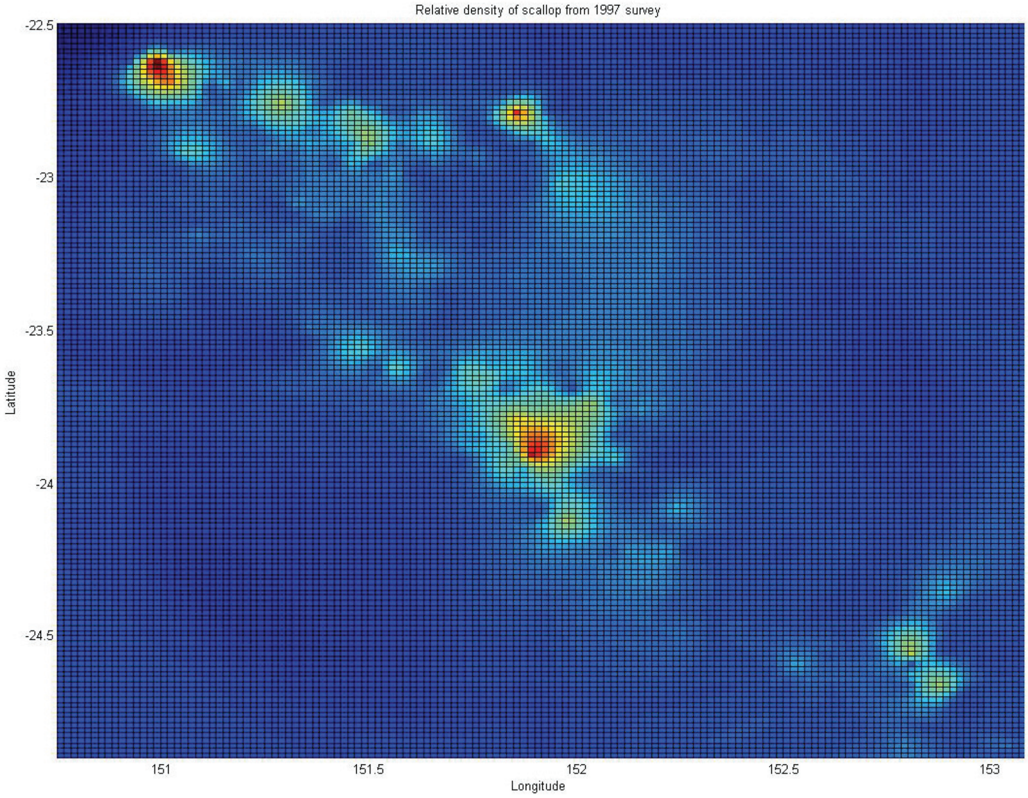

Figure 9-1: Spatially kriged scallop densities from 1997 survey data, suggestive of three distinct metapopulations. The fourth metapopulation, Region 4, was not surveyed and is represented by all fishing grounds south of 25°S.

In order to deal with the potential for strong nonlinearity between catch rates and abundance, and to better understand how abundance patchiness affects the spatio-temporal targeting of fishing effort, a third dimension is brought into the model:

$$N_{m,a,s} = N_{a-1,m-1,s} e^{-(M + S_{a-1,m-1} F_{m-1,s})}$$

where s is a spatial gradient along which scallop density and effort is distributed (Ellis and Wang 2007).[6] Fishing mortality in each element of s is then calculated as $F_{m,s} = q_s E_{m,s}$ where catchability in s is proportional to scallop density, $q_s \propto N_s / N$.[7] The extent to which the effort distribution over s tracks the catchability (or equivalently, density) distribution is captured through a power relationship $E_s \propto (N_s / N)^{\gamma}$ – higher values of the estimable parameter γ provide more effort in higher density areas and result in greater catches (Cressie

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[6] The modelling framework that follows is inspired by the approach of Ellis N, Wang YG (2007) Effects of fish density distribution and effort distribution on catchability. *ICES Journal of Marine Science* **64**, 178-191. and can be thought of as a grid-based (and region-stratified) implementation of their integral equations.

[7] Notational convention: dropping a subscript(s) implies a sum over the absent dimension(s).

1993) we refer to γ as the ‘knowledge’ parameter). The simplest way to implement these proportionality expressions is as follows:

$$q_s = \tilde{q}\frac{N_s^{\gamma}}{\sum_s N_s^{\gamma}} \times |s|, \; E_s = E\frac{N_s^{\gamma}}{\sum_s N_s^{\gamma}}$$

where $\tilde{q}$ is an estimable parameter analogous to the instantaneous catch rate in Ellis and Wang (2007), and $|s|$ indicates the number of elements (ie. grid cells) of the spatial gradient dimension *s*.

In the model described so far there is no direct mapping between an element of *s* and a particular spatial region of ocean. However, it *is* necessary to explicitly stratify this dimension in order to effectively model the complex history of spatial closures, and to simulate future closure strategies. Eleven regions of the ocean in three spatially distinct groups have been off-limits to fishing in various spatial configurations over time. These restricted areas are known as Scallop Replenishment Areas (SRAs); they correspond to the red boxes in Figure 9-2. In addition to this somewhat fine-scale stratification (loosely a ‘mesoscale’ from Orensanz, Parma *et al.* 2006) it was decided to also stratify on a broader scale, separating the stock latitudinally into four ‘metapopulations’, numbered one to four from north to south. Spatial patterns of catch and effort, and survey abundance, all pointed clearly to four distinct aggregations. Regions twelve through fifteen in Figure 9-2 refer to ‘everything outside of the SRAs’ within each metapopulation (eg. metapopulation one is the sum of regions nine, ten and twelve). The latitude cut-offs were chosen based on careful study of spatial catch distributions from VMS data and surveys.

Ideally one would have a relatively large number of grid cells along the spatial gradient dimension, and each region according to the above stratification would map to the appropriate number of these cells according to area. However, due partly to computational considerations, it was decided that the above spatial stratification was already a sufficient level of spatial complexity (that is, enough to capture any nonlinearity in the abundance-catch rate relationship due to non-uniform catchability and fish-down targeting). This however required a small adjustment to the catchability and spatial effort allocation model to be appropriate for a third dimension which has ‘cells’ that are not all the same size. We highlight this by giving the third dimension an ‘r’ subscript (for ‘region’, instead of ‘s’). Firstly, calculate the region density and mean density:

$$\rho_r = \frac{\sum_a S_a N_{a,r}}{A_r}, \; \bar{\rho} = \frac{\sum_r \sum_a S_a N_{a,r}}{\sum_r A_r}$$

where A_r is the area of region r (clearly the estimation of area for regions twelve to fifteen is an important variable; see section Spatial Catch Patterns from VMS Data). Then regional catchability for the fifteen regions is given by:

$q_{m,r} = \tilde{q}(\rho_{m,r} / \bar{\rho}_m) \times 15$

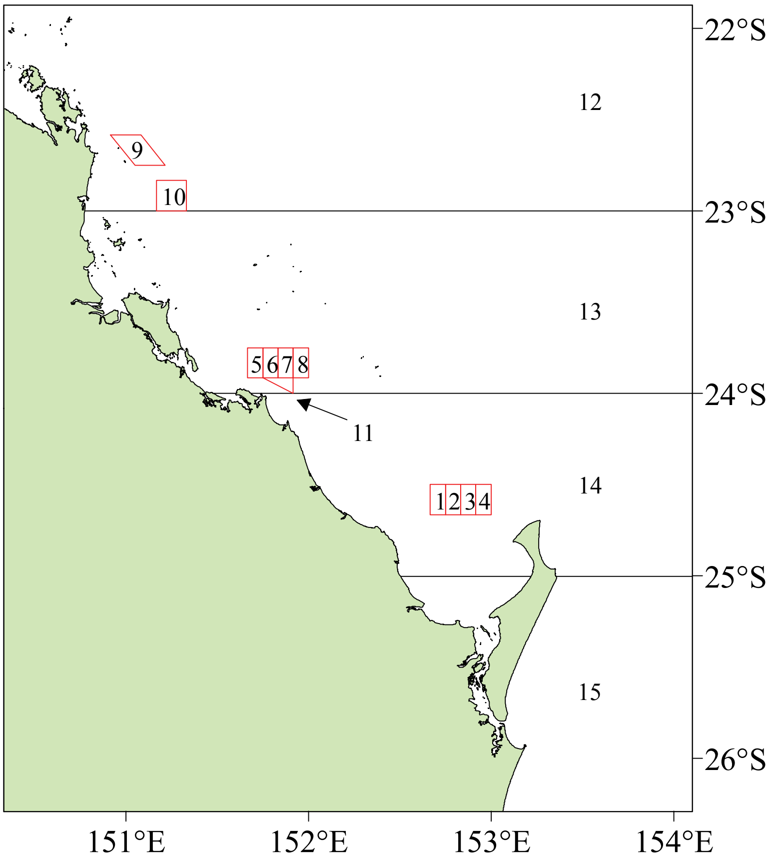

Figure 9-2: Regional stratification of the scallop fishery for the purposes of the MSE.

Regional effort needs to be area-weighted and is given by:

$$E_{m,r} = E_m \frac{(\rho_{m,r} / \bar{\rho}_m)^\gamma A_r}{\sum_r (\rho_{m,r} / \bar{\rho}_m)^\gamma A_r}$$

The only biological ingredient yet to be specified spatially is recruitment. Given that we have at our disposal a significant quantity of high resolution spatio-temporal information from both the fishery and surveys (six years of catch and effort derived from VMS data and ten years of survey data; see sections Spatial Catch Patterns from VMS Data and Recruitment Indices from Survey Data for details), it was decided that it would be reasonable to estimate a spatial proportion parameter, p_r , for each region:

$$R_{m,r} = R_m p_r$$

(For the harvest strategy simulations, a stock-recruitment function was fitted to the estimated annual recruitment; see below).

Finally we add spatial closures to the model. Given the detailed spatial stratification, closures can be represented in the model very simply: $\Gamma_{m,r}$ is a zero if region *r* is closed in month *m*, and a one otherwise. The only equation to redefine is spatial effort allocation:

$$E_{m,r} = E_m \frac{(\rho_{m,r} / \bar{\rho}_m)^{\gamma} A_r \Gamma_{m,r}}{\sum_r (\rho_{m,r} / \bar{\rho}_m)^{\gamma} A_r \Gamma_{m,r}}$$

After exploratory parameter estimation and simulations it was decided that the knowledge parameter should be split into two values, γ_1 and γ_2. γ_1 being used for the earlier, pre-SRA period of the fishery, γ_2 for the fishery since SRAs have been introduced. The motivation for this is that when the SRAs open in January, there is a massive influx of fishing effort into this known high density scallop region. This significantly reduces the requirement for the fishers to search for good trawling grounds, and was hypothesised to represent a different regime with respect to the knowledge parameter.

The main assumptions of this model are:

- Within each region, catchability is proportional to abundance.
- Given catchability, standardised catch rate is proportional to abundance.
- Effort allocation to each region is proportional to abundance to the power of the knowledge parameter.
- Constant natural mortality and scallop growth.
- No systematic bias in the reporting of commercial catches.
- Spatial closures have a monthly temporal resolution, no finer.
- There has been no slow drift in the spatial extent or mean location of the fishery (Walter's ‘fantasy’ problem in Walters 2003).
- No discard mortality. Discard mortality is considered in a separate model, detailed in the next section.

Table 9-1: Symbology and parameter definitions as used throughout this chapter.

Symbol	Meaning
χ	(log) geometric mean recruitment 1989 to 2008
χ'	(log) geometric mean recruitment 1985 to 1988
κ	von Mises ‘concentration’ parameter
$\overline{r}$	von Mises ‘location’ parameter
$\tilde{q}$	‘instantaneous’ catchability
γ_1, γ_2	Pre-SRA and post-SRA knowledge parameters
ζ_y	recruitment deviation in year *y*
p_r	proportion of overall recruitment allocated to region *r*
$N_{m,a,r}$	numbers of scallop of age *a* in region *r* during month *m*
$E_{m,r}$	effort in month *m* and region *r*
$S_{m,a}$	selectivity in month *m* at age *a*
$F_{m,r}$	fishing mortality in month *m* and region *r*
$q_{m,r}$	catchability in month *m* and region *r*
ρ_r	density of scallop in region *r*
A_r	area of region *r*
W_a	weight of scallop at age *a*
$\Gamma_{m,r}$	closure multiplier for month m and region *r* (zero if closed, one if open)
$C_{m,r}$	catch (in numbers) in month *m* and region *r*
$P_{m,r}$	mid-month exploitable numbers in month *m* and region *r*
U_m	model-predicted catch per unit effort in month *m*
U_m	observed (standardised) catch per unit effort in month *m*
$N_{l,t,g}$	number of scallop in size class l at trawl number *t* and in discard group *g*
S_l	overall selectivity for size class l
U	harvest rate
S_l^d	discard selectivity for size class l
$Surv_g$	survival rate of *tumbled* discards going into discard group g
$Surv_g\,'$	survival rate of discards going into discard group g
F_s	number of patches of ground with the same total number of trawls

9.2.3 Discard Mortality Model

As reported in Chapter 6, high trawl intensity can result in increasing levels of discard mortality. In order to determine whether this discard mortality should be incorporated into the HSE, it was prudent to model discard mortality to quantify its effect on total fishing mortality. This section details the methods used to describe discard mortality as a proportion of total mortality.

The model for a patch of ground that is trawled a given number of times:

$$N_{l,t,g} = \begin{cases} N_{init} & \text{for t=0, g=0} \\ N_{l,t-1,g} - N_{l,t-1,g} * S_l * U & \text{for } g = 0, t = 1..T \\ N_{l,t-1,g} - N_{l,t-1,g} * S_l * U + N_{l,t-1,g-1} * S_l^{\,d} * U * Surv_g & \text{otherwise} \end{cases}$$

where $N_{l,t,g}$ is the number of scallop in size class l at trawl number t and in discard group g, S_l is overall selectivity for size class l, U is the harvest rate, $S_l^{\,d}$ is discard selectivity, and $Surv_g$ is the survival rate of discards going into discard group g (ie. those that have already been caught and discarded $g-1$ times). This equation is iteratively applied the number of times that the patch is trawled during the analysis period. Think of the model as a matrix which holds a size-structured population in each cell. The row and column of this matrix refer to a population that has been trawled row times, and discarded column times (assume zero-based indexing). So the upper left cell (0,0) is the 'virgin' population, the cell below it (1,0) is the population that remains untouched after one trawl, the cell below and to the right (1,1) is the discards from that first trawl that have survived etc.

From the VMS we have an estimate of the total number of trawls for a patch of ground at the scale of 34m^2 patches. The spatial index s has been suppressed above: we actually need to consider $N_{l,t,g,s}$, where s does not index the totality of spatial patches but rather the set of equivalence classes such that all patches in a class have been trawled the same number of times. We then have T_s, the number of trawls for that equivalence class ('trawl class'), and F_s, the size of the trawl class (number of patches of ground with the same total number of trawls.

We then calculate total discard mortality for the entire study period/area as:

$$DiscM = \sum_{s=1}^{S} \left(\sum_{t=1}^{T_s} \sum_{g=1}^{T_s} \sum_{l} N_{l,t,g,s} S_l^d U (1 - Surv_g) \right) F_s$$

Total catch mortality is:

$$CatchM = \sum_{s=1}^{S} \left(\sum_{t=1}^{T_s} \sum_{l} N_{l,t,0,s} S_l^c U \right) F_s$$

The overall discard effect is:

$$\frac{DiscM}{DiscM + CatchM}$$

$N_{.,0,0,s}$ (ie. the initial number of scallop for all lengths) is set arbitrarily at 100 for patches in the first trawl class (trawled only once). For patches that are trawled t times, the initial number is equal to $100 * \alpha^{t-1}$ where α is a parameter responsible for enforcing the general rule that patches which are trawled many times probably had a higher initial population. α should be pretty close to 1, but we will test a range of scenarios from 1 to 1.5. With α =1.2, a fifteen-trawl patch will have roughly 15 times the initial number of scallop as a 0 trawl patch. With α =1.5 the same patch will have 438 times the number of scallop.

The study period/area is January 2004, Bustard Head B (first month of the opening of the closure). This closure was chosen for this analysis as the Bustard Head closures are popular among scallop fishers given recruitment is relatively high each year (O'Sullivan, Jebreen *et al.* 2005). Up to 55 vessels targeted this closure during January 2004 and, as such, trawl intensity levels were highest of all the SRAs evaluated in Chapter 6 (see Appendix 17.1.2 on page 114). Trawl tracks generated by these vessels are displayed in Figure 9-3, below.

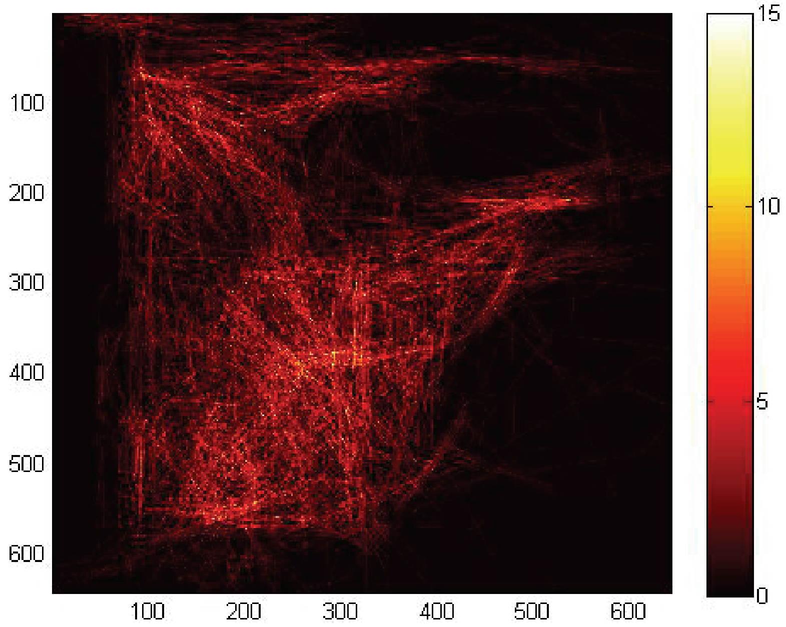

Figure 9-3: Spatial intensity of fishing during January 2004 in the Bustard Head B region. Colour represents an estimate of the number times a 34 m^2 cell has been trawled. The vertical and horizontal axes index latitude and longitude respectively.

The tumbling experiments give us two values for $Surv_g$, one with tumbling and one without, the latter we will label $Surv_g'$. Values for T_s, F_s, $Surv_g$ and $Surv_g'$ are given in Table 9-2, below.

Two selectivity curves were used: one that represents the selectivity of the fleet with 90 mm mesh and a 'TED' (Turtle Excluder Device), and one that additionally has a 'SMC' (Square Mesh Codend'). The SMC curve is more selective and will be denoted $smcS_l$ (the TED, which is the 'base case', will remain S_l). See Figure 9-4 for details of these curves, also for comparison to reference size frequency data from all LTMP scallop surveys as reported by O'Sullivan, Jebreen *et al.* (2005) and the bycatch charter conducted by Courtney, Haddy *et al.*

(2007) (3.5inch 88 mm diamond mesh). Note that S_l is just an element-wise addition of S_l^d and S_l^c.

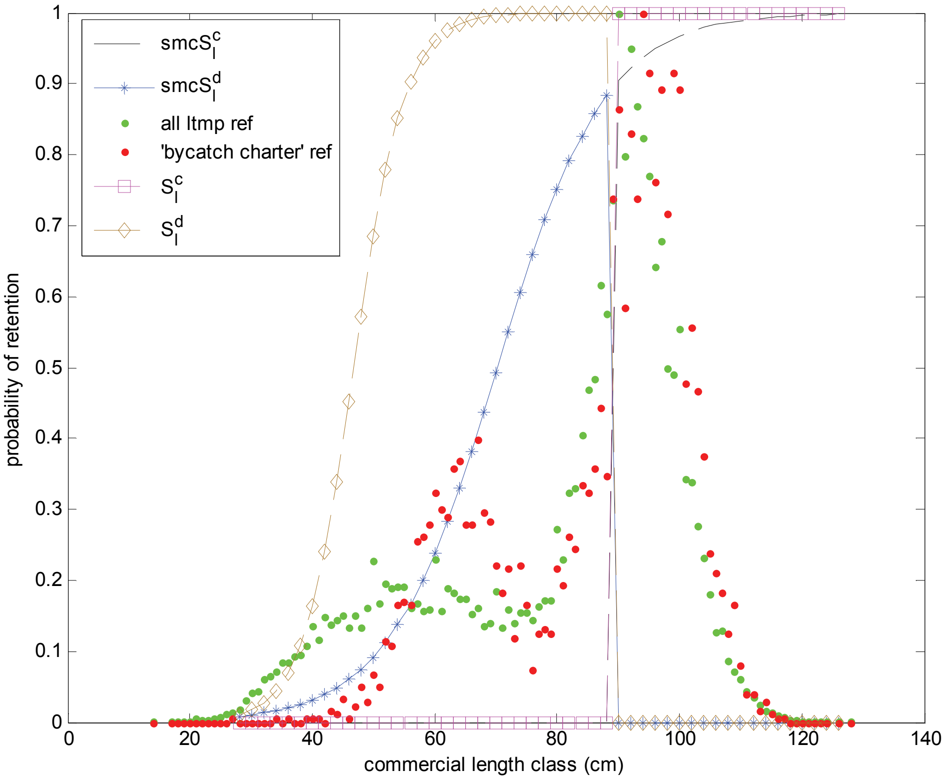

Figure 9-4: Selectivity curves for 90mm mesh and a Turtle Excluder Device (TED – brown line), TED plus a Square Mesh Codend (SMC – blue line). The red dots represent the length frequency data for all LTMP data recorded during recruitment surveys reported by O'Sullivan, Jebreen *et al.* (2005), while the green dots represent length frequency data reported by Courtney, Haddy *et al.* (2007) in a dedicated research charter.

Main assumptions:

1. The population is closed to additions from recruitment and immigration and to losses from natural mortality and emigration during the study period.
2. Every 34 m^2 patch of ground that the trawl track passes over has been trawled (is subject to the given harvest rate).
3. The harvest rate remains constant regardless of how many times the patch has been trawled.
4. Discarded scallops are no more or less likely to be caught than scallops that have never been caught.
5. The tumbling experiments should be interpreted as having measured the effect of trawling t times on survival, and trawling plus tumbling t times.
6. It is possible to extrapolate these experiments from 4 to 16 using a linear model.
7. Discard selectivity is everything less than legal size in the fishery selectivity curve, retained selectivity is everything greater than or equal to legal size.
8. The initial population size structure is flat: every size class has the same number of scallops.

9. Scallops don't move between spatial cells at any point.
10. Scallops don't change size classes over the 'study period' (in this case one month), ie. no growth occurs during the study period.

Whilst the second assumption is crude, the fact we are concerned with the *ratio* of discard mortality to total mortality should lessen its impact. It is not clear whether the impact will exaggerate or diminish the overall effect. The third assumption most likely exaggerates the overall effect as harvest rate will likely decline with increasing trawls.

Table 9-2: Values for T_s, F_s, $Surv_g$ and $Surv_g'$

s/g	T_s	F_s	$Surv_g$	$Surv_g'$
1	0	243124	0.9421	0.9792
2	1	71657	0.881	0.9549
3	2	43183	0.7736	0.9057
4	3	25567	0.6158	0.8152
5	4	14087	0.4311	0.6731
6	5	7649	0.2625	0.493
7	6	3764	0.1412	0.3144
8	7	1781	0.0697	0.1756
9	8	796	0.0327	0.0888
10	9	322	0.015	0.0422
11	10	139	0.0068	0.0194
12	11	49	0.003	0.0088
13	12	28	0.0014	0.004
14	13	9	0.0006	0.0018
15	14	7	0.0003	0.0008
16	15	2	0.0001	0.0004

9.2.4 *Model Inputs and Fitting Indices*

9.2.4.1 *Standardised Catch Rate and Historical Effort*

For the purposes of the HSE, catch rate data were standardised in accordance with the methods described in Chapter 8. However, the abundance vector, $\boldsymbol{\beta}_1$, was altered to incorporate a location parameter according to 4 regions as described in Figure 9-2, rather than the CFISH grid codes used earlier.

The four regions of interest for the catch rate standardisation for the purposes of the HSE from Figure 9-2 are regions 12, 13, 14 and 15, including all catches from the relevant SRAs.

As such, the logbook data described in Section 8 were related to the relevant Region and the GenStat (2007) code altered as per Section 17.5.1 on page 126.

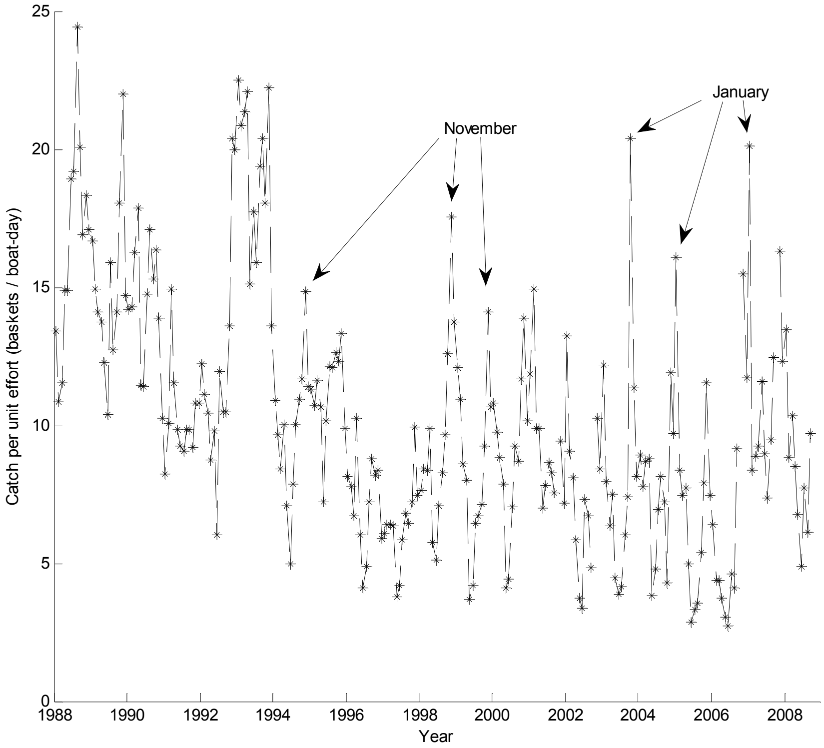

Figure 9-5: Standardised catch per unit effort. Peaks in November and January are highlighted to aid interpretation of the series. Note that the January peaks since 2003 coincide with the opening of SRAs. Prior to the SRA period the peak month was November.

Historical effort levels used in the HSE were derived from logbook data as reported in Section 8.3.1 on page 34.

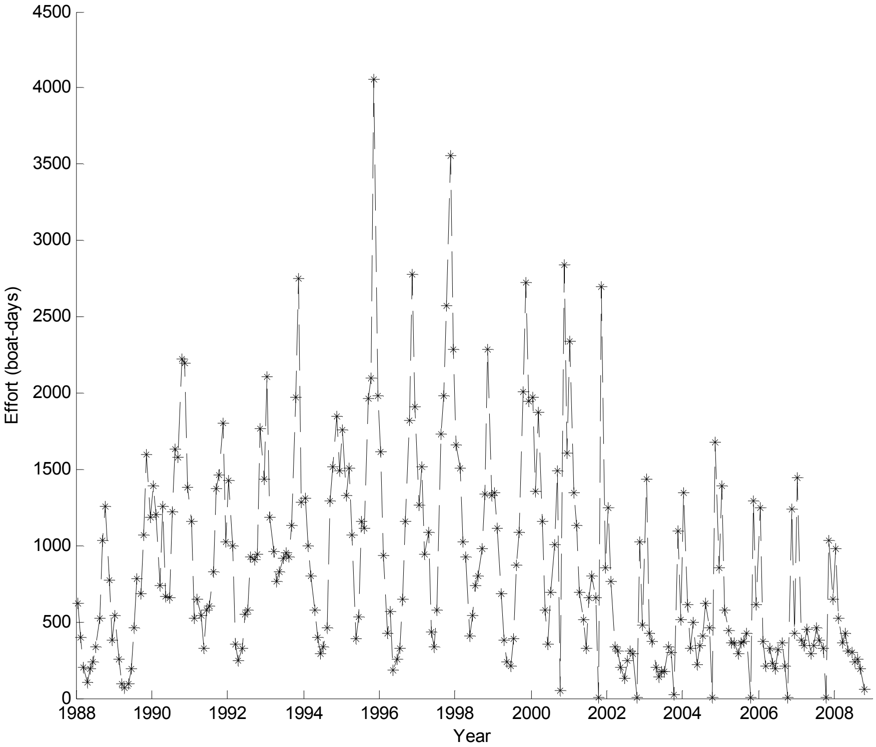

Figure 9-6: Monthly effort pattern in the scallop fishery for the period January 1988 to December 2008.

9.2.4.2 Biological Parameters and Selectivity

The only biological parameter used directly in the model is natural mortality, *M*, which was set at 0.09 per month. The estimation of this parameter is described in Dredge (1985a). Length-age (Figure 9-7) and weight-age (Figure 9-8) relationships were used for selectivity calculations and to estimate catch weights. Values for these parameters were taken from O'Neill, Courtney *et al.* (2005).

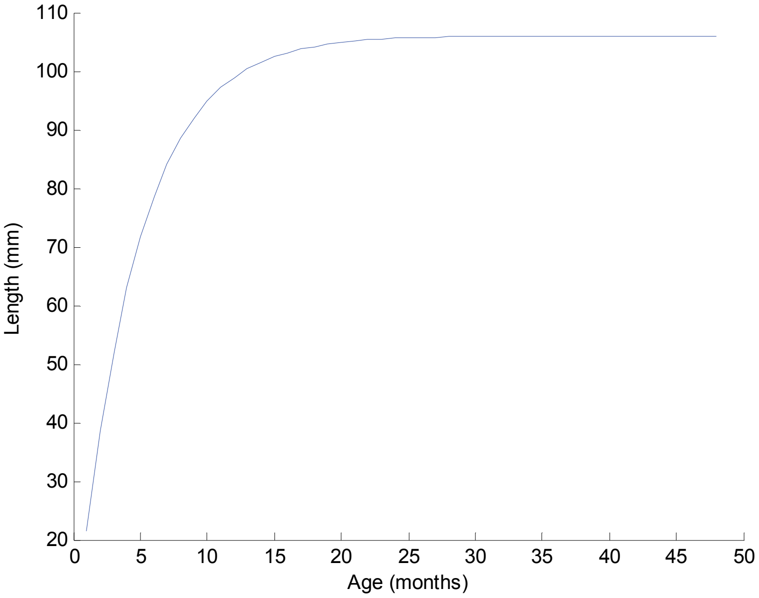

Figure 9-7: Length-age relationship (median length-at-age) for *A. balloti*.

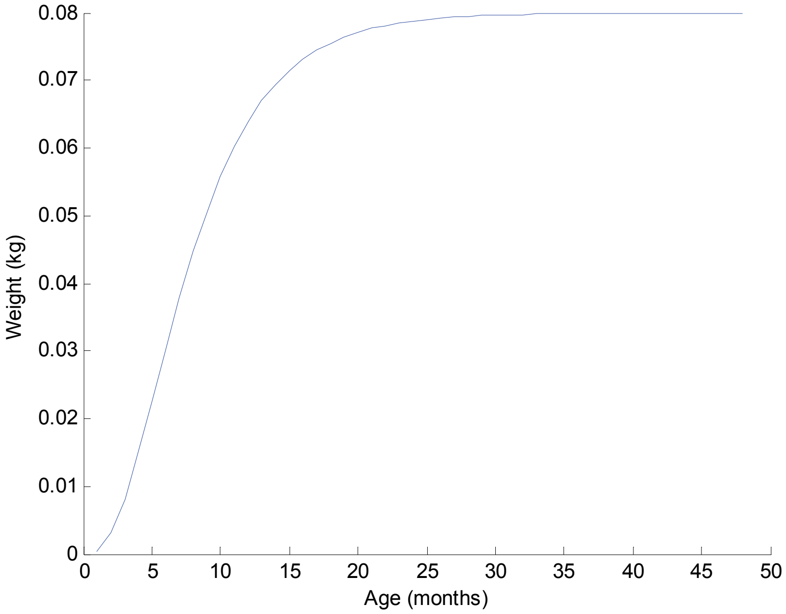

Figure 9-8: Weight-age relationship (median weight-at-age).

The fishing selectivity $S_{m,a}$ was not assumed to be knife-edge and was smoothed with a 10% standard deviation (O'Neill, Courtney *et al.* 2005) on both the 90 mm and 95 mm minimum commercial legal sizes. The selectivity vector for the 90 mm minimum commercial legal size across all ages *a* was given by:

$$S_a=[max(normcdf(L_{a=1\ldots7},87.6,8.8),0)\ max(normcdf(L_{a=8\ldots48},87.6,8.8),1)],$$

and for the 95 mm minimum commercial legal size by:

$$S_a=[max(normcdf(L_{a=1\ldots9},92.5,9.3),0)\ max(normcdf(L_{a=10\ldots48},92.5,9.3),1)],$$

where *max* was a MATLAB (2009) function to return the largest elements of the array, *normcdf* function computed the normal cumulative distribution function (cdf) at each of the average scallop shell height sizes at age using the corresponding minimum legal shell height size and 10% standard deviation (O'Neill, Courtney *et al.* 2005), and L_a was the average scallop shell height at age calculated using a von Bertalanffy growth curve.

The minimum legal sizes (MLSs) of scallops have varied historically. From 1988 to December 1999 minimum legal sizes were set at 90 mm from November to April and 95 mm for May to October inclusive. In January 2001 sizes changed to 90mm from January to April, and 95 mm for May to December, inclusive. The selectivity curves for both MLSs are given in Figure 9-9.

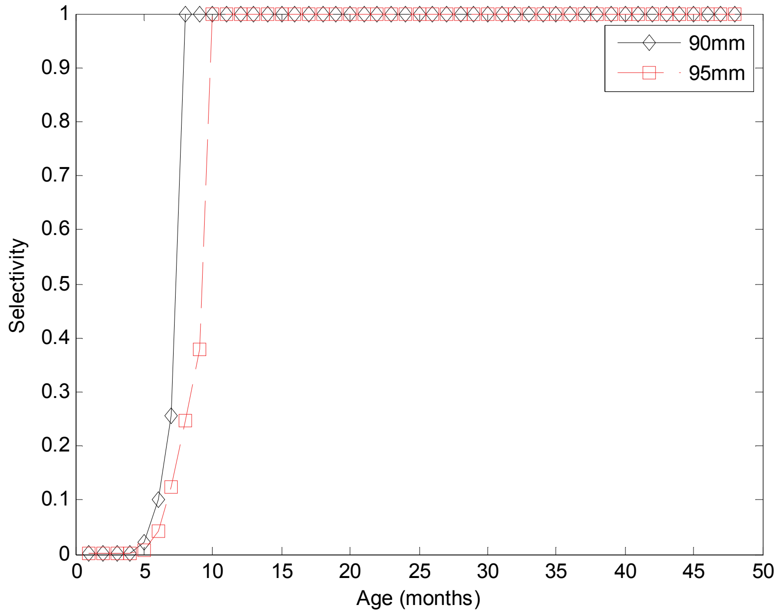

Figure 9-9: Selectivity curves for the 90 mm MLS and 95 mm MLS.

9.2.4.3 Recruitment Indices from Survey Data

Abundance indices were reconstructed from the survey data as follows. Firstly, the density (in numbers per square metre) was estimated for each trawl $i = 1..n$ from the swept area s_i and the distance travelled d_i:

$$\rho_i = n_i / d_i s_i$$

These observed densities were approximated as point densities and geo-referenced using the midpoint of the trawl start and end locations, so that ρ_i occurs at location x_i. The spatial distribution of scallop $Z(x)$ could then be estimated using kriging, which uses a linear combination:

$$\hat{Z}(x_0) = \sum_{i=1}^{n} w_i(x_0) Z(x_i)$$

of the observed values $\rho_i = Z(x_i)$ to find the value at new location x_0 with weights $w_i(x_0)$ chosen such that the variance is minimised subject to an unbiasedness condition (see any spatial statistics text, eg. Cressie 1993). Semi-variograms were specified using estimates from experimental semi-variograms. Numbers in each region were then estimated by integrating density over area:

$$\mathrm{N}_r = \int_{x \in x(r)} \hat{Z}(x) dx$$

where $x(r)$ is region r. In practice this is calculated using:

$$\mathrm{N}_r = \sum_{x_{j=1..J} \in x(r)} \hat{Z}(x_j) a_J dx$$

where j indexes a suitably fine mesh and a_J is the area covered by one grid of that mesh. Variance for the region is calculated by combining the variances of each kriging predictor in the mesh.

The recruitment index was constructed using the above kriging approach, but restricting the analysis to the 'zero-plus' group of animals, defined as 78mm length or smaller (Jebreen, O'Sullivan *et al.* 2006). The numbers of zero-plus animals in each trawl was calculated by multiplying the total number caught by the proportion of those measured that were in the zero-plus group; this is shown in Figure 9-10. The number of trawl surveys in each region and for each year are given in Table 9-3.

Table 9-3: Number of shots in each region by survey year; 'OTH' is other, outside the SRAs.

	HBA	HBB	HBC	HBD	BHA	BHB	BHC	BHD	YPA	YPB	OTH
Oct-97	1	6	4	2	4	6	5	0	10	11	348
Oct-98	1	9	2	5	3	6	6	4	15	7	340
Oct-99	2	11	10	6	4	5	8	1	13	11	334
Oct-00	1	5	10	3	6	4	5	1	10	7	318
Oct-01	8	8	8	7	16	14	10	7	16	15	44
Oct-02	8	8	7	8	16	10	9	7	15	18	68
Oct-03	8	9	8	8	15	8	8	8	15	15	57
Oct-04	7	5	4	9	16	11	8	7	16	15	62
Oct-05	8	8	8	8	13	10	11	7	15	16	64
Oct-06	9	8	8	8	15	14	8	7	14	17	55

9.2.4.4 Spatial Catch Patterns from VMS Data

Vessel Monitoring System data was used to estimate monthly catch and effort levels at the half-minute scale from December 2000 to December 2006 inclusive. This was summed for each of the fifteen regions to provide estimates of the proportion of catch taken from each region. The model was fit against these proportions only for January of 2000, January of 2001, through to January of 2005 (see Figure 9-11). The idea behind using this spatially fine-scale data was primarily to attempt to capture the pulse fishing behaviour that occurs when the closures open in January which is why only that month was the focus.

This data was also used to determine the metapopulations, and to estimate the fishery area A_r for each region. The total area was taken to be the combined area of all half-minute grid cells that contained 99% of the total catch (summed over all the available VMS data), and A_r was the component of this total in each region.

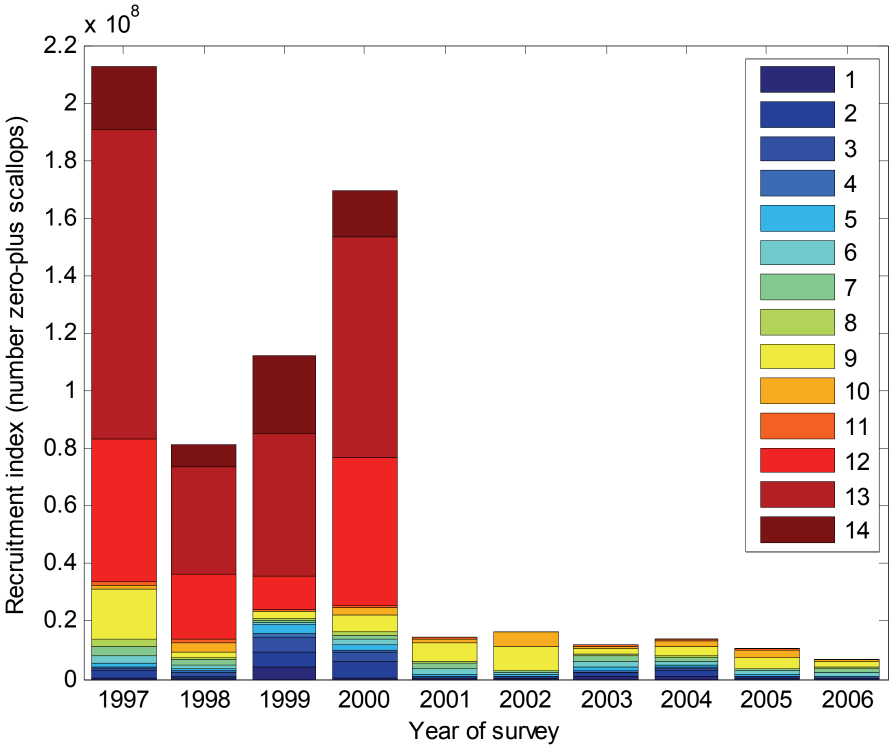

Figure 9-10: Recruitment index (in number of zero-plus scallops) for each region as estimated from surveys performed in October of 1997 through 2006. In 2001 through 2006 the surveys were only conducted in the SRAs (regions one through eleven).

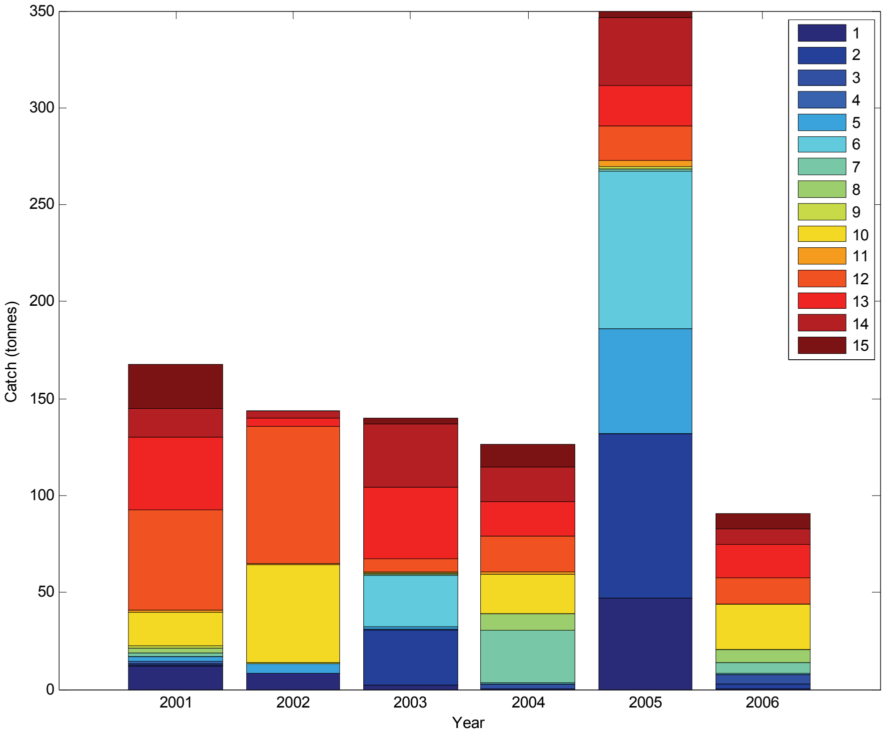

Figure 9-11: Catch by region in January of 2001 through 2006.

9.2.5 Spatial Closures

The historical closure pattern is given in Figure 9-12.

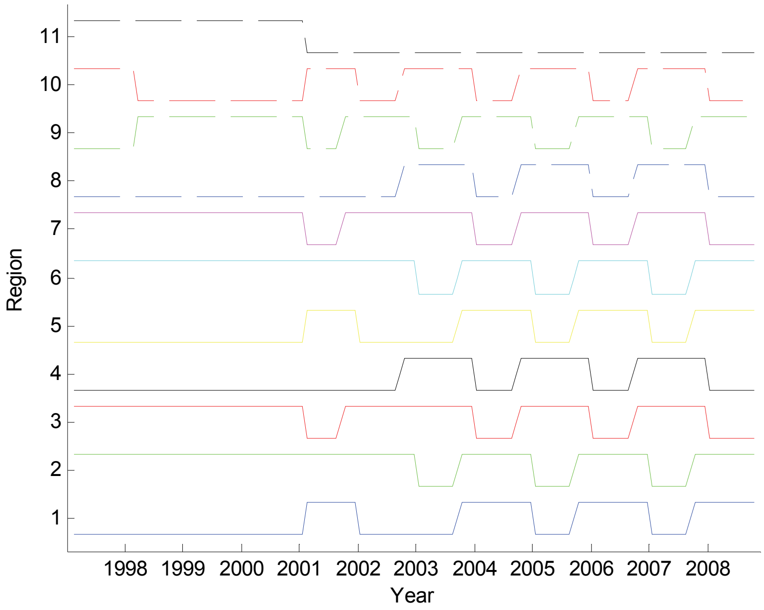

Figure 9-12: Historical SRA closure pattern. Raised value for a region indicates closure, not raised indicates open to fishing.

In addition the southern closure closes the whole fishery from the 15 September to 31 October every year since 2000.

9.2.6 Parameter Estimation

Likelihoods were constructed to fit the model to whole-fishery catch rates, metapopulation-level catch rates, survey recruitment indices and VMS spatial catch proportions. Define catch (in numbers) in month m and region r as:

$$C_{m,r} = q_{m,r} E_{m,r} \sum_a S_{m,a} N_{m,a,r}$$

and mid-month exploitable numbers as:

$$P_{m,r} = (\sum_a S_{m,a} N_{m,a,r}) - C_{m,r} / 2$$

then model-predicted catch per unit effort (CPUE), U_m, is:

$$U_m = \frac{\sum_r q_{m,r} E_{m,r} P_{m,r}}{E_m}.$$

A likelihood ℓ_u is calculated from this and the standardised CPUE U_m based on the normal distribution using Haddon (2001):

$$-\log \ell_u = \frac{n}{2}\left(\log(2\pi) + 2\log\left(\sqrt{\left(\frac{1}{n} \sum_m \left(\log(\mathrm{U}_m) - \log(U_m) \right)^2 \right)} \right) + 1 \right)$$

where n is the number of months. As well as fitting to this overall catch per unit effort, the same approach is used to calculate likelihoods for the individual metapopluations (ie. fitting to $\mathrm{U}_{m,h}$ where h refers to metapopulations 1 through 4).

The survey data and the VMS data were both used as proportions only (not absolute numbers) as they were used to provide contrast for the spatial aspects of the model (eg. the knowledge parameter γ and the spatial recruitment proportions p_r). Therefore they were fitted using a multinomial formulation. For the recruitment likelihoods, first define the regional proportion of recruits $\eta_{m,r}$ as:

$$\eta_{m,r} = \frac{N_{m,a_r,r}}{\sum_r N_{m,a_r,r}}$$

where a_r is the recruiting age. The kriged survey abundances are converted to proportions also:

$$\phi_{m,r} = \frac{\mathrm{N}_{m,r}}{\sum_r \mathrm{N}_{m,r}}$$

and the recruitment likelihood ℓ_r for an individual month is calculated as (Haddon 2001):

$$-\log \ell_r = -\sum_r \phi_{m,r} \log \eta_{m,r}$$

This likelihood calculation was applied to every month and region-set combination for which survey data was available. This includes regions one through to fourteen, as no survey data exists for region 15, for the month of October in years 1997 through to 2000, and then for regions one through eleven (SRAs only) for years 2001 through 2006.

For the VMS likelihoods define the proportion of observed catch in each region as

$$v_{m,r} = \frac{\mathrm{C}_{m,r}}{\sum_r \mathrm{C}_{m,r}}$$

where $\mathrm{C}_{m,r}$ is the total VMS catch in month m and region r. The model predicted catch by region is:

$$C_{m,r} = q_{m,r} E_{m,r} \sum_a S_{m,a,r} N_{m,a,r}$$

and define the proportions as $\psi_{m,r}$. Then the VMS likelihood ℓ_v is:

$$-\log \ell_v = -\sum_r v_{m,r} \log \psi_{m,r} .$$

As mentioned above, the model was fit against these proportions only for December and January of 2000 to December and January of 2005, plus December of 2006.

The total negative log likelihood for the model was a weighted sum of the negative log likelihoods for the five catch rate likelihoods (overall and metapopulations one to four), plus the likelihoods from the survey and VMS data. The weighting was devised such that each likelihood component contributed an approximately equal amount to the total likelihood. This was minimised using the MCMC algorithm described in Punt and Kennedy (1997) and Punt and Hilborn (2001). In all, 42 parameters were estimated:

$$\chi, \chi', \kappa, \bar{r}, \tilde{q}, \gamma_1, \gamma_2, \zeta_{1\ldots20}, p_{1\ldots15}$$

The MCMC approach requires either that priors are provided for each parameter, or at least suitable bounds (equivalent to uniformly distributed priors). As this approach was being used in the spirit of frequentist parameter estimation (there was no Bayesian intent) we opted to set bounds wide enough such that the ‘posteriors’ did not interact with them. In the case of the first seven parameters, and the twenty recruitment anomalies the application of the MCMC algorithm was straightforward. However, the fifteen spatial recruitment parameters must at all times satisfy the constraint that they sum to one and therefore cannot be treated independently in the algorithm (as is the case with the other parameters). Essentially one requires an algorithm such that in the MCMC ‘jump’ step these parameters perform a random jump on a simplex. An efficient algorithm that achieves this is detailed in Fernandes and Atchley (2008)[8].

9.2.7 Stock and Recruitment

A post parameter-estimation analysis of the stock recruitment relationship was performed. Egg production in year y was calculated as:

$$E_y = \sum_{i=November}^{October} \beta_i \frac{1-e^{-Z_i}}{Z_i} \sum\nolimits_{a,r} 0.5 N_{i,a,r} mat_a fecund_a$$

The relationship between this spawning index and the annual estimated recruitment series was fitted with a Beverton-Holt stock-recruitment function:

$$\hat{R}_{y+1} = \frac{E_y}{\alpha + \beta E_y}$$

Parameter estimation was carried out using MATLAB (2009) *nlinfit* function, which performs a robust nonlinear regression by iteratively re-weighting response values and recomputing a least squares fit. Fitting was performed on log recruitments (predicted and observed). *nlinfit* returns a mean-squared-error, $\hat{R}_{\text{mse}}$, and a covariance matrix which is used to generate 1000 samples of $\{\alpha, \beta\}$ pairs (only retaining samples for which α and β are both positive). From this set, two alternate future scenarios for stock and recruitment were generated – a 'weak' relationship and a 'strong' relationship. The weak relationship used the 5th percentile of α, and β averaged over the values it takes between the 0th and 10th percentile of α. The strong relationship used the 95th percentile of α, and β averaged over the values it takes between the 90th and 100th percentile of α.

9.2.8 Harvest Strategy Evaluation

The harvest strategy evaluation was focused on evaluating the relative merits of various spatial and temporal closure options. These options were discussed during Steering Committee meetings held at the Southern Fisheries Centre on 21 July 2007 and 22 April 2008. The options were discussed further by project staff in order to determine what could be achieved with the resources available. From these discussions, the overarching objective of the HSE was to determine whether there would be any benefit (biologically and/or economically) to 1) increasing the length of the SRA closures from their current duration of 15 months, and 2) changing the 'Southern Closure' (entire fishery closed from 15 September to 31 October) to a 'Winter Closure' – entire fishery closed from 15 April to 15 August. The scenarios tested are detailed in Table 9-4.

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[8] According to the author's blog, this reference contains an error and the correct algorithm is given in the "random walk" section of Simplex. (2010, February 2). In Wikipedia, The Free Encyclopedia. Retrieved 03:59, February 3, 2010, from http://en.wikipedia.org/w/index.php?title=Simplex&oldid=341508129; the latter is what was implemented.

Table 9-4: Periodicity of closed SRAs in months for a given cycle. 'Southern' relates to the presence or absence of the southern temporal closure (20 Sept to Oct 31) and 'Winter' relates to the presence or absence of a winter closure (15 April to 15 August).

Scenario	SRA Closed	SRA Open	Cycle Length	Southern	Winter
1	15	9	24	Yes	No
2	0	24	24	Yes	No
3	9	15	24	Yes	No
4	21	3	24	Yes	No
5	27	9	36	Yes	No
6	33	3	36	Yes	No
7	39	9	48	Yes	No
8	45	3	48	Yes	No
9	15	9	24	No	Yes
10	0	24	24	No	Yes

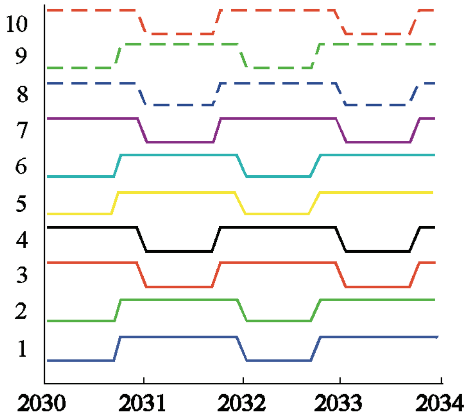
The closure strategies were simulated for 40 years starting from November 2008 (October 2008 being the last month to which data was fitted). They consisted of the following steps:
For each scenario and each future reality:

1. Construct a monthly effort pattern tailored to the scenario.
2. Construct a set of 40 annual recruitment deviations by drawing from a normal distribution with mean 0 and standard deviation $\hat{R}_{\text{mse}}$.
3. Draw a sample from the MCMC-estimated posterior parameter distribution for all parameters excluding the recruitment deviations.
4. Run the model from November 1988 to October 2048, driving it with the chosen parameters, real historical effort and scenario-generated future effort and closure schedules.
5. Use the last five years of the model to calculate performance indicators.
6. Repeat steps 2 to 5 1000 times to obtain distributions for the indicators.

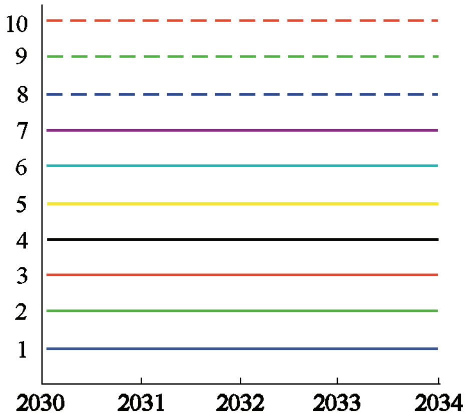
Four future realities were considered, consisting of the combination of two stock-recruitment scenarios with two future effort levels. Stock recruitment scenarios are 'weak' and 'strong', as described in the above section. Future effort scenarios are either a) average of last 5 years, 6076 nights, or b) maximum effort level ever attained, 17 110 nights.

9.2.8.1 Future Closure Schedules

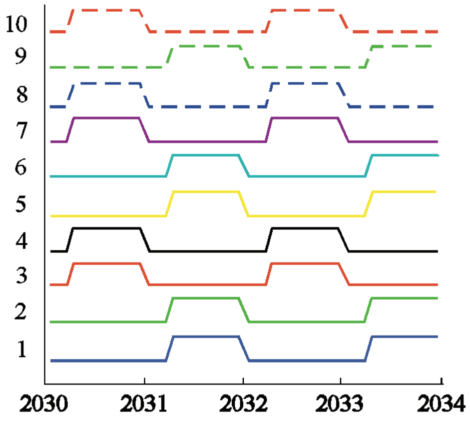
Table 9-4 describes the general closure timing for each scenario, however there are a number of ways this can be implemented in terms of the ten SRAs. For example, for the three and four-year cycles it makes sense to stagger the cycles so there is always at least one SRA opening each year. The specific future closure schedules for the ten SRAs (see Figure 9-2 on page 58 and Figure 17-1 on page 111 for the location of each SRA) are given below for each scenario (note: Scenario 9 has the same closure pattern as Scenario 1 and Scenario 10 excludes the use of the SRAs).



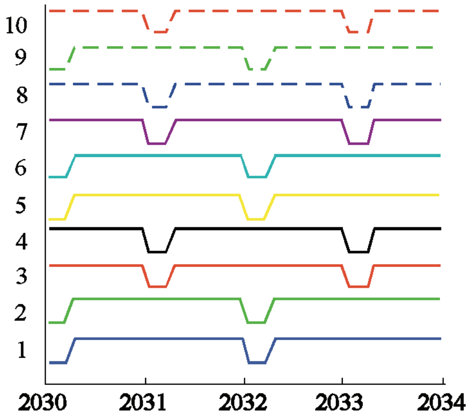
Scenario 1



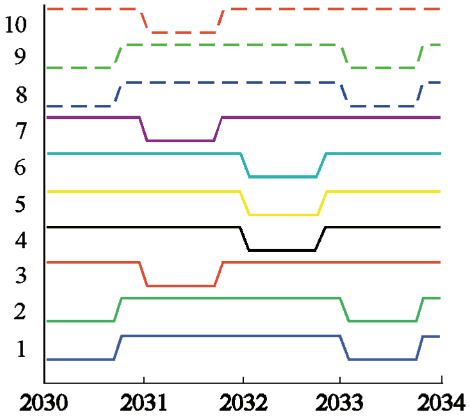
Scenario 2



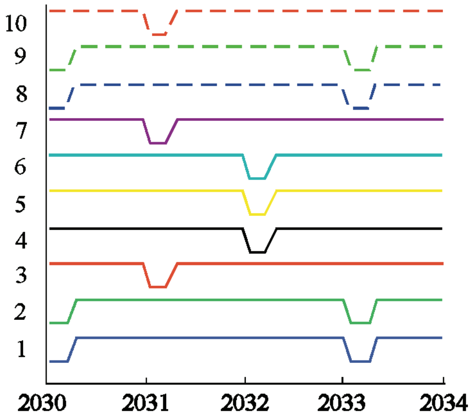
Scenario 3



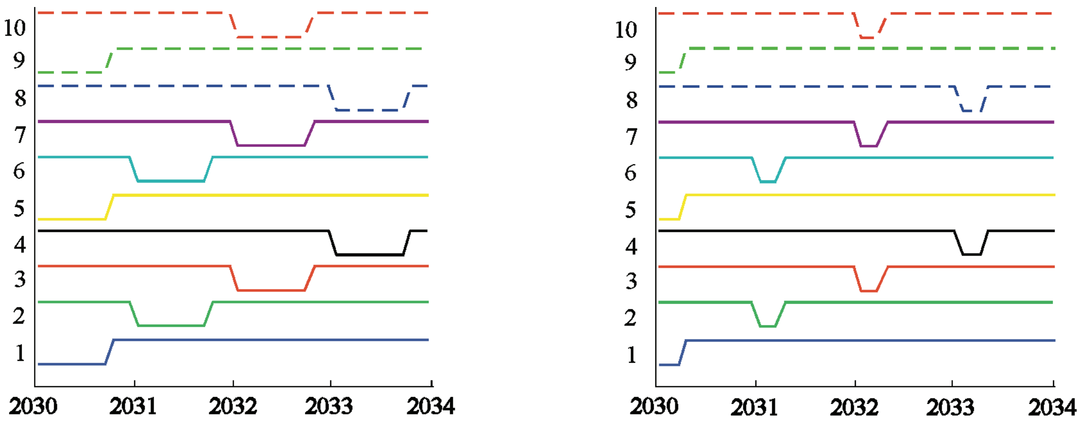
Scenario 4



Scenario 5



Scenario 6



Scenario 7

Scenario 8

9.2.8.2 *Future Monthly Effort Patterns*

While the spatial recruitment proportions and the knowledge parameter take care of the spatial distribution of fishing effort, it is necessary to specify monthly effort patterns for the various future closure scenarios. These are given in Figure 9-13.

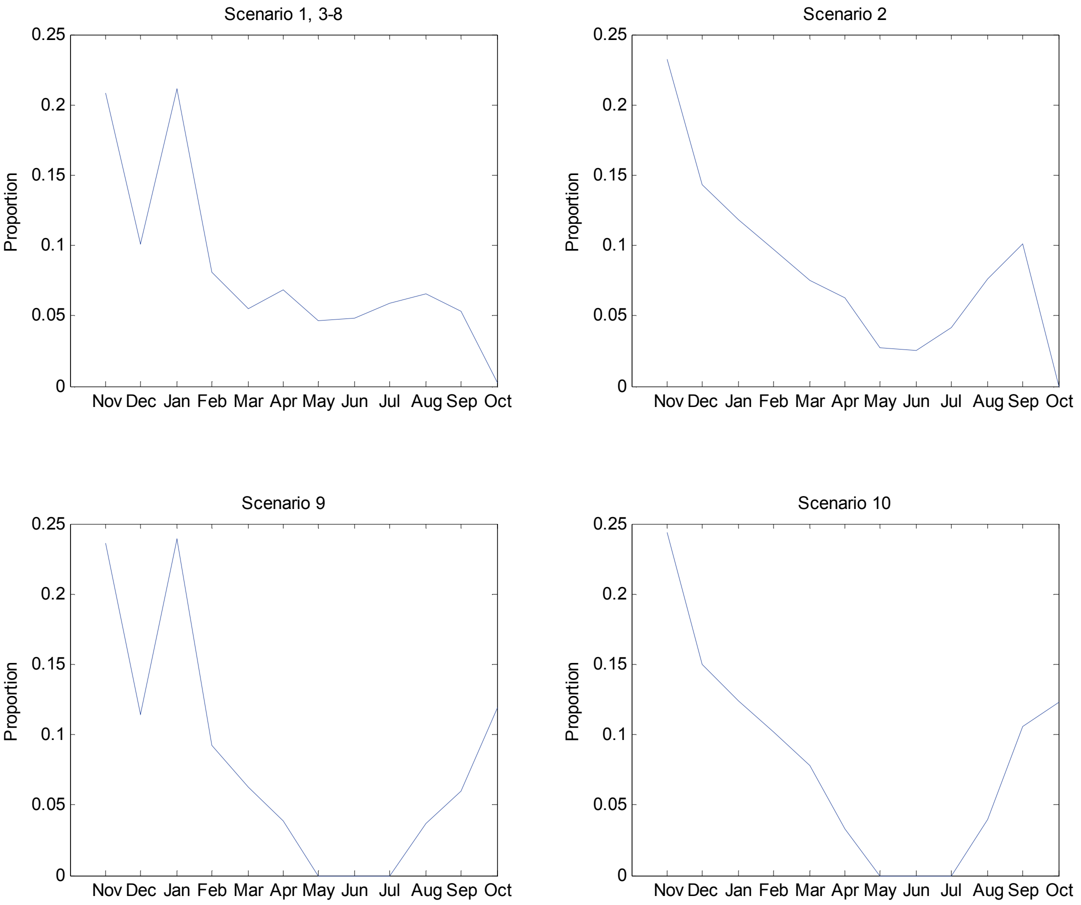


Figure 9-13: Future monthly effort patterns for scenarios 1 to 10.

9.2.8.3 Performance Indices

The performance of each harvest strategy was assessed in terms of four indicators: CPUE, biomass, total catch and economic value. The first three were calculated as follows:

$$I_{cpue} = \sum_{m=November}^{October} \sum_{r} \left(\frac{C_{m,r}}{E_{m,r}} \right) \frac{E_{m,r}}{\sum_{m=November}^{October} \sum_{r} E_{m,r}}$$

$$I_{biomass} = \sum_{m=November}^{October} \sum\nolimits_{r} \sum\nolimits_{a} N_{m,a,r} W_{a}$$

$$I_{catch} = \sum_{m=November}^{October} \sum\nolimits_{m,r} C_{m,r}$$

The above formulas provide an annual indicator of performance (note that the CPUE indicator is weighted by monthly and regional effort). In order to ensure fair comparison across management strategies with differing temporal patterns it is important to consider annual performance over a number of years in the simulation. The last twelve years were chosen for this purpose as this is the smallest number that is a common multiple of every strategy's cycle length. The indicators over this period were used in two different ways in the estimation of uncertainty. The first was a simple average (median) of the value of the indicator over the period, thus the 1000 samples from the posterior of the parameters led to a distribution of 1000 values of the indicator for a given management strategy and future scenario. The second was to include each year's value directly in the summary distribution, ie. for each indicator we obtain a distribution of 12 000 values. These approaches have different implications for the interpretation of the intra- and inter-scenario variability: the first approach averages out the variability due to inter-annual closure patterns, while the second does not (therefore we expect the second approach to have a broader distribution).

In order to determine economic value, meat count data were sourced from Urangan Fisheries. Approximately 700 processing records, incorporating 25 months (November 2005 to December 2007) of scallop shucking data, were obtained. During this period, the processing records revealed that more than 402 tonnes of scallop meat were processed. Each processing record contained information regarding the amount, in kilograms, of each meat count (number of meats per kilogram) landed by vessels unloading to Urangan Fisheries. These data are summarised in Table 9-5. It should be noted that there were no scallops processed during October 2006 and October 2007 due to the Southern Closure being in operation during this time. O'Sullivan, Jebreen *et al.* (2005) published a meat condition index and reported that the meat condition for October was the same as that in May and, as such, we have used the meat grades observed in May to provide data for October for Scenario 9 and Scenario 10 in the HSE.

Table 9-5: Meat grade, in number of individual meats per kilogram, as a percentage of total catch by month from Urangan Fisheries processing records November 2005 to December 2007.

Month	Meat count									
	U65	U70	U75	U80	U85	U90	U95	U100	U110	U120
Jan	1.88	4.54	7.12	9.94	4.60	6.33	60.23	2.96	2.19	0.22
Feb	0.00	6.08	20.42	15.29	18.26	18.07	14.75	3.98	2.67	0.48
Mar	0.00	0.00	0.00	3.38	1.71	21.50	21.41	10.66	41.35	0.00
Apr	0.49	1.95	3.89	8.50	0.00	13.11	0.54	20.55	30.49	20.49
May	0.00	0.00	3.70	17.33	1.97	5.48	6.15	12.45	52.70	0.21
Jun	0.62	0.00	0.44	0.00	2.29	6.41	28.28	28.37	33.35	0.24
Jul	0.10	0.34	0.02	0.00	1.96	4.63	2.14	1.09	9.02	80.71
Aug	0.00	0.00	1.10	1.88	0.00	11.16	10.62	12.99	27.24	35.01
Sep	0.00	0.00	0.00	0.00	0.00	1.16	0.00	19.09	43.78	35.96
Oct*	0.00	0.00	3.70	17.33	1.97	5.48	6.15	12.45	52.70	0.21
Nov	0.92	3.22	1.91	4.32	6.47	14.86	15.95	15.71	20.37	16.27
Dec	2.04	3.83	10.93	6.51	13.28	27.13	6.45	12.93	9.40	7.49

To determine the economic return, in dollars, of the catch in the HSE, each grade is given a value. This value relates to the price per kilogram paid to fishers and, therefore, represents the beach price. The price per kilogram paid to fishers was sourced from Urangan Fisheries' marketing manager, Paul Hodgson, and was accurate at the time of writing (22 January 2010). As such, the value performance indicator was calculated as follows:

$$I_{value} = \sum_{m=November}^{October} \left(\sum_{g} Meat_{m,g} Vmeat_{g} \left(\sum_{r} C_{m,r} \right) \right)$$

where $Meat_{m,g}$ is the proportion of the catch in month m of grade g, given in Table 9-5, and V_{Meat} is the price per kilo paid to fishers for each meat count grade, given in Table 9-6, below.

Table 9-6: Price per kilo of scallop meat paid (ie. landed price) to fishers by Urangan Fisheries. Data is current as at 22 January 2010. Grade relates to the number of individual meats per kilogram ie. U70 equates to less than 70 meats per kilogram.

Grade	Price per kilo
U65	\$20.50
U70	\$19.00
U75	\$18.00
U80	\$17.50
U85	\$17.00
U90	\$13.00
U95	\$12.00
U100	\$11.50
U110	\$10.50
>U110	\$9.00

9.3 RESULTS

9.3.1 Tumbling-Induced Mortality

Figure 9-14 shows the overall 'tumbling effect' – subtracting the discard mortality effect in the case of trawl only from the discard mortality effect in the case of trawl plus tumble. Discard mortality plots are given in Appendix 17.5.5 on page 139. With a SMC the effect looks to be about 3-5%, without an SMC (TED only) the effect is higher, around 6-9%. Note that in these plots more weight should be given to the lower values of alpha, perhaps $\alpha = 1$ to $\alpha = 1.2$, as values larger than this are probably not plausible (although they do serve to provide a useful upper bound). Alpha governs the exponential rate at which patches that are trawled multiple times had higher initial densities (see Chapter 6). $\alpha = 1.2$ means a patch which is trawled 15 times has 15 times the initial number of scallop as a 0 trawl patch. With $\alpha = 1.5$ the same patch will have 438 times the number of scallop. While scallop are indeed highly aggregated, the degree to which the trawl track intensity matches this aggregation is not total, and may be quite poor.

Given the relatively small effect of tumbling, during a period of particularly intense fishing, it was decided unnecessary to incorporate tumbling-induced mortality model into the full HSE.

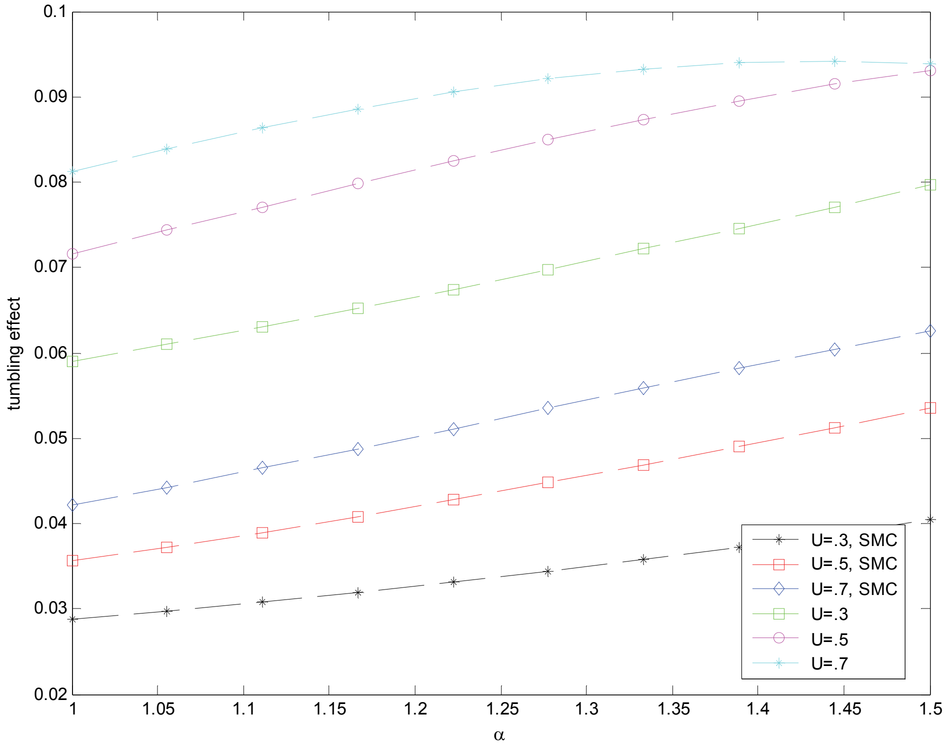


Figure 9-14: Proportion of total mortality attributable to tumbling over three harvest rates scenarios (U), two selectivity curve scenarios (SMCs or no SMCs), and a range of 'spatial aggregation' scenarios (α). See text for details.

9.3.2 Parameter Estimation

Posterior distributions for the seven ‘primary’ model parameters are given in Figure 9-15. Posteriors for the recruitment anomalies and the spatial recruitment proportions are given in the Appendix 17.5.2 on page 126 in Figure 17-16 and Figure 17-17 respectively.

As expected, γ_2 rose significantly above γ_1 once the knowledge parameter was split, and this coincided with a significant increase in overall model likelihood (Figure 9-16). As a consequence, the model was able to capture the pulse-fishing behaviour generated by the opening of the SRAs in January in the last five or so years of the fishery. Goodness of fit plots and diagnostics for the overall fishery CPUE (metapopulations combined) are given in Figure **9-17**. For the individual metapopulations, goodness of fit plots and diagnostics are given in Appendix 17.5.2 on page 126 (Figure 17-18 to Figure 17-21). Goodness of fit for the average spatial recruitment pattern is given in Figure 9-18. Goodness of fit for the individual year’s spatial recruitment patterns, and for fit to VMS data are given in the Appendix 17.5.3 on page 131 and Appendix 17.5.4 on page 137, respectively.

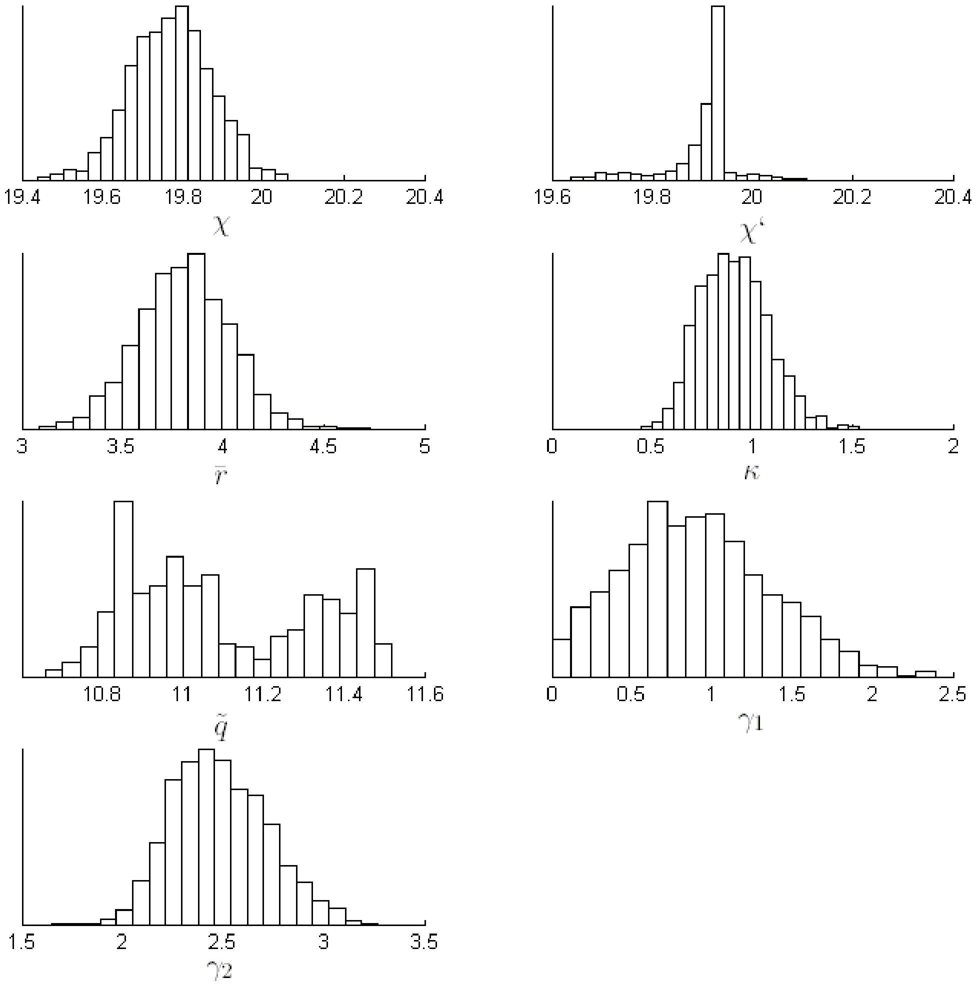


Figure 9-15: Posterior distributions for the seven ‘primary’ model parameters. Note that γ_2 is in general greater than γ_1, implying greater targeting ability during the SRA period of the fishery.

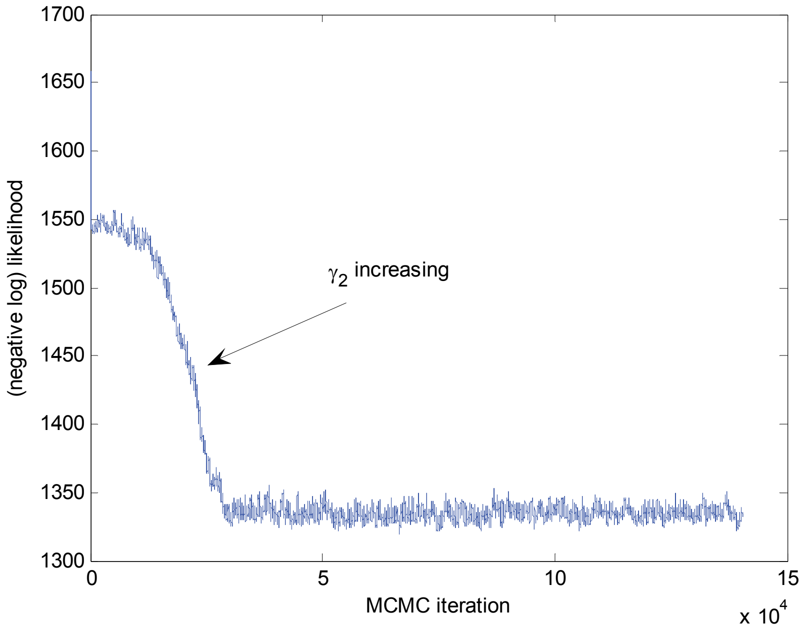


Figure 9-16: Model likelihood. Overall likelihood increased (equivalently the negative log likelihood decreased) until around iteration 3500, and during this period γ_2 separated from γ_1 (they had identical initial values), moving higher.

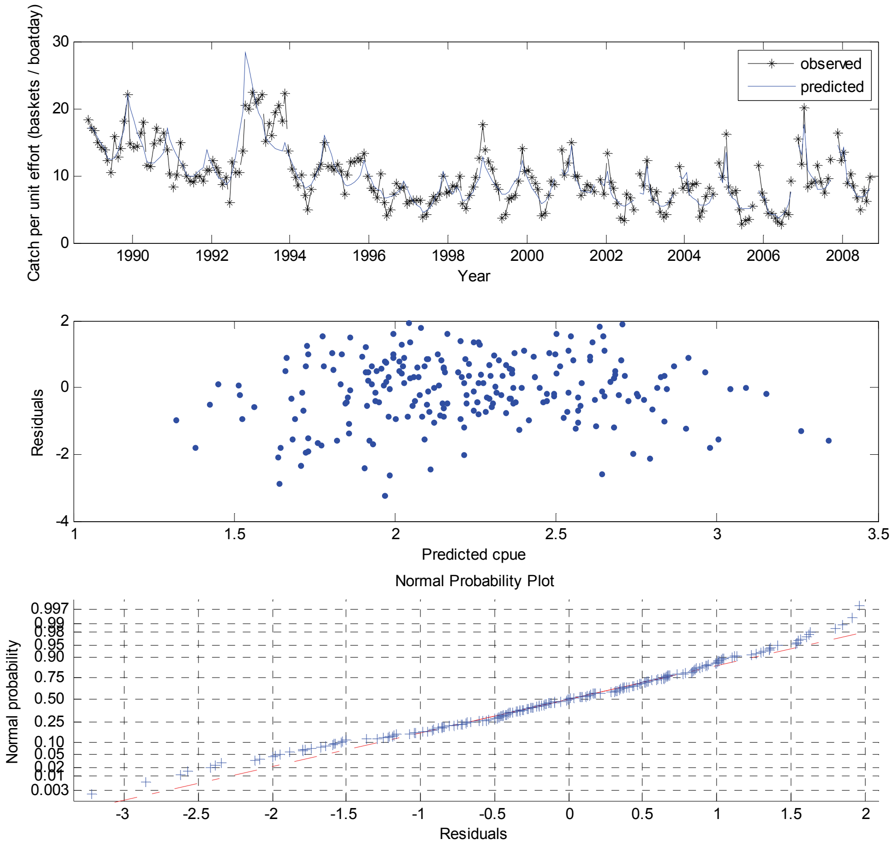


Figure 9-17: Goodness of fit plot and diagnostics for overall (all regions/metapopulations) CPUE.

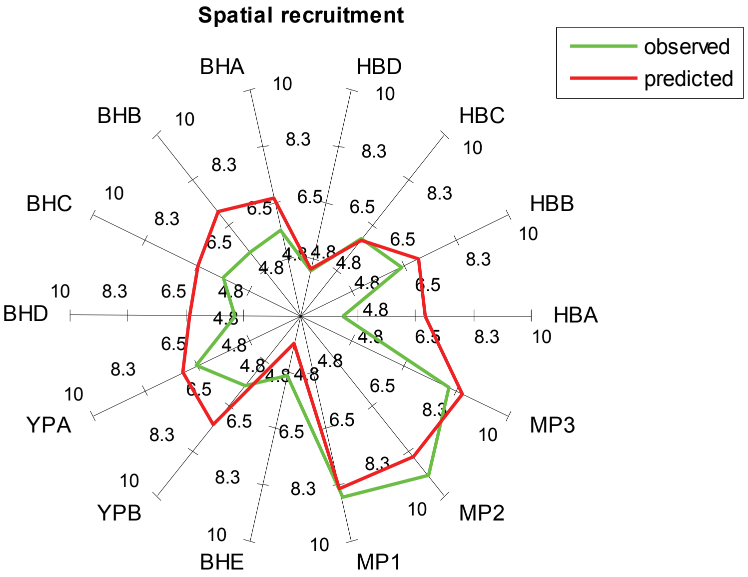


Figure 9-18 Goodness of fit for the spatial recruitment pattern. Radar plot uses a log scale to allow comparison of SRA recruitments with the recruitment to the much larger metapopulations. Response values are $10+\log(\phi_r)$ and $10+\log(p_i)$ for observed and predicted respectively, where ϕ_r is the average spatial recruitment pattern derived from the survey data for years 1997 through 2000.

9.3.3 *Stock and Recruitment*

The stock-recruitment relationship (SRR) is shown in Figure 9-19.

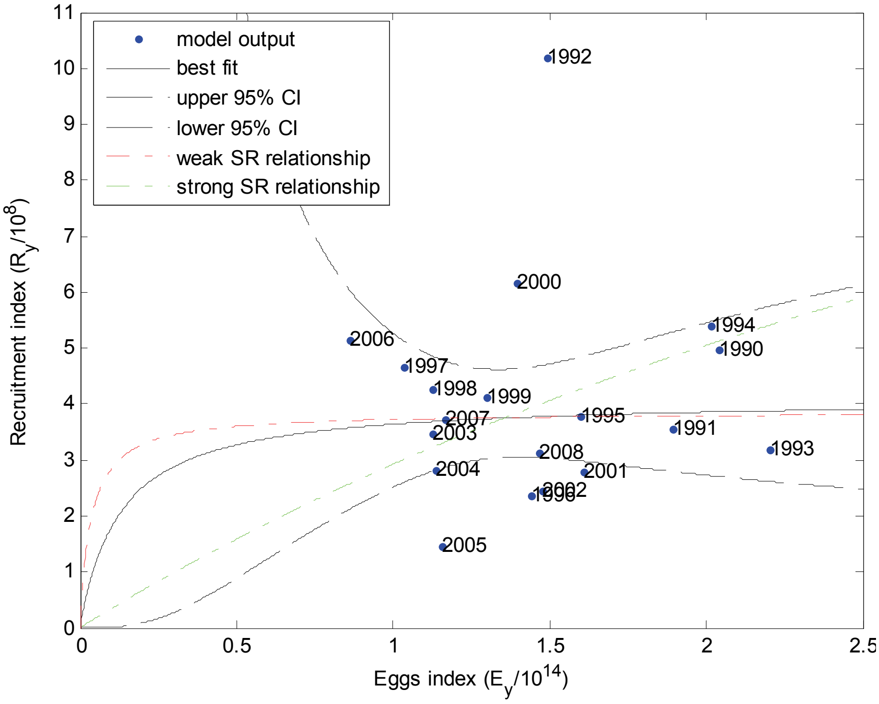


Figure 9-19: Stock-recruitment plot. Data points labelled with the year indicate estimated outputs from the model.

Table 9-7 shows the stock recruitment parameters. Neither parameter is particularly well determined by the observations, and the α value is very poorly determined (and results in the raw 95% confidence interval being biologically incorrect). This is not surprising as the observations are similarly compatible with a wide range of Beverton-Holt curves (although note that the value of recruitment at median egg production is well determined as can be seen from the best fit, strong and weak curves nearly intersecting at this point). Our concern here is not rigorous statistical support for the model, the aim is merely to identify curves that are representative of two opposing stock-recruitment hypotheses. Two quite distinct scenarios were used in the forward simulations as given by the green and red curves in Figure 9-19. The construction of these curves was discussed in section 9.2.7.

Table 9-7: Stock recruitment parameters: best fit, 'weak' relationship, and 'strong' relationship. Numbers in parentheses are standard errors. See text for a discussion of the significance of the uncertainty in these estimates.

Parameter	Estimate	Weak	Strong
α	0.0310 (0.1476)	0.0092	0.2880
β	0.2437 (0.1103)	0.2591	0.0542

9.3.4 Harvest Strategies

The performance of each of the ten harvest strategies over four alternate future scenarios are displayed in Figure 9-20 to Figure 9-23. For most performance indicators, it is only when the fishing pressure is increased dramatically from current levels (high effort scenario; bottom row plots in each figure) that it is persuasive to differentiate the strategies relative to intra-strategy variation. In these scenarios we find strategies 5 through to 8 performing the best, which is to be expected given that in this situation sustainability becomes a concern and these strategies have closure cycles in which the SRAs are closed for longer periods.

For a weak SRR at present levels of effort, the removal of the Southern Closure and an introduction of a winter closure (Scenario 9) results in slightly higher catch rates compared to Scenario 1, the status quo strategy (Figure 9-20). Further, longer closure lengths of 33 months (Scenario 6) result in similar catch rates to Scenario 9. Interestingly, closing the SRAs for periods greater than 33 months (Scenario 7 and Scenario 8) does not increase catch rates and only becomes a better option when effort levels increase significantly and a strong SRR is assumed. Removing the SRAs (Scenario 2) or increasing the period that SRAs are open to fishing (Scenario 3) result in reduced catch rates compared to those under current management scenario. At present levels of effort, catch rates are similar irrespective of assumptions concerning the SRR, although given a strong SRR catch rates are more variable consistent with variation in recruitment.

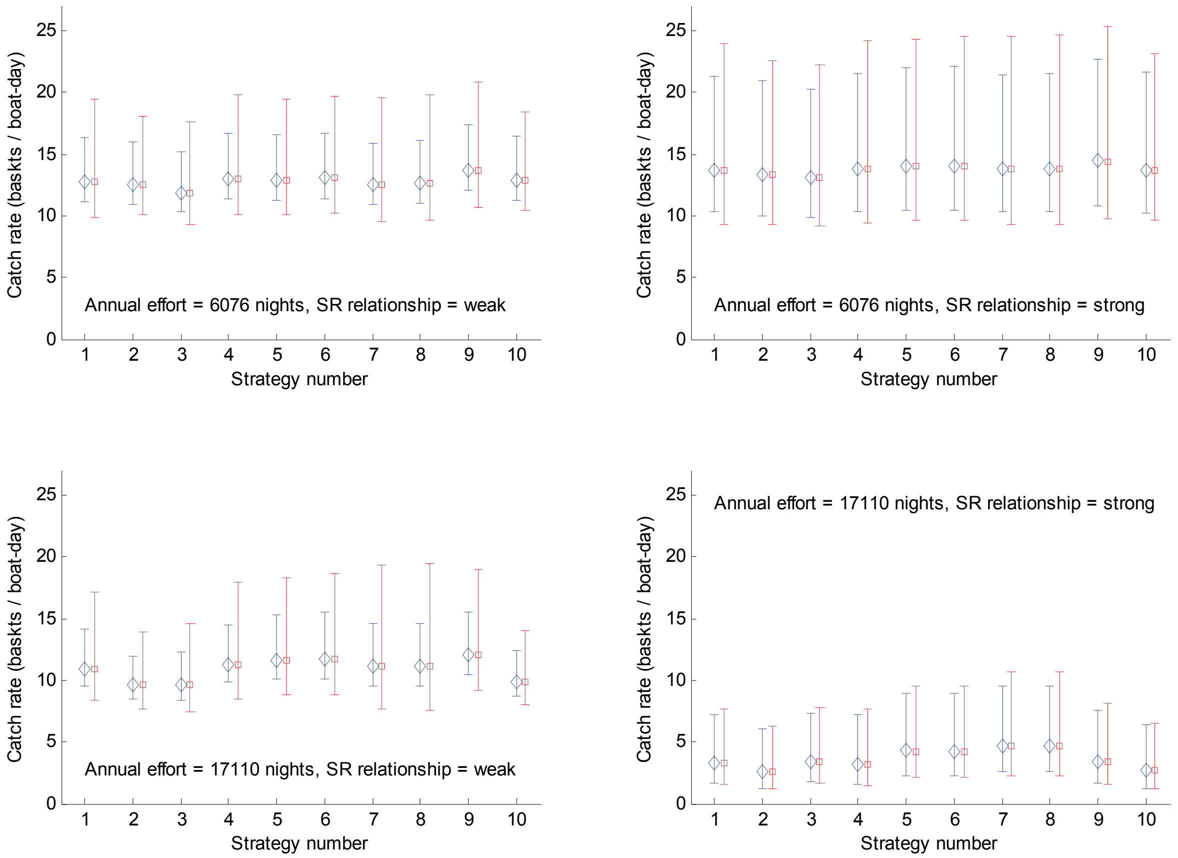


Figure 9-20: Catch per unit effort performance over ten management strategies and four alternate effort and stock-recruitment scenarios. Error bars represent 5% and 95% quantiles. Red error bars are based on the distribution which includes multiple years of the simulation as separate values; blue bars are based on an average over the simulation years (see section 9.2.8.3 for details).

At current levels of fishing effort and a weak SRR, no one scenario results in a significant change in biomass, although the model predicts slight reductions under Scenario 9 and Scenario 10 (Figure 9-21). Similar reductions in biomass result under Scenario 9 and Scenario 10 assuming a weak SRR at high levels of fishing effort. At present levels of fishing effort, biomass remains constant irrespective of assumptions regarding the SRR. As expected, a strong SRR at present levels of fishing effort results in highly variable levels of biomass into the future.

At high levels of fishing effort, assuming a weak SRR, biomass remains at approximately 120 000 tonnes, with Scenario 7 and Scenario 8 performing best, once again due to the fact that the SRAs are closed for longer periods. As expected, high levels of effort combined with a strong SRR results in dramatic reductions in biomass with Scenario 7 and Scenario 8 performing best. This is due to the fact that the SRAs are closed for a longer period with several age classes recruiting to these areas over three or four years. Under these conditions, biomass is reduced to very low levels of between 25,000 to 50,000 tonnes.

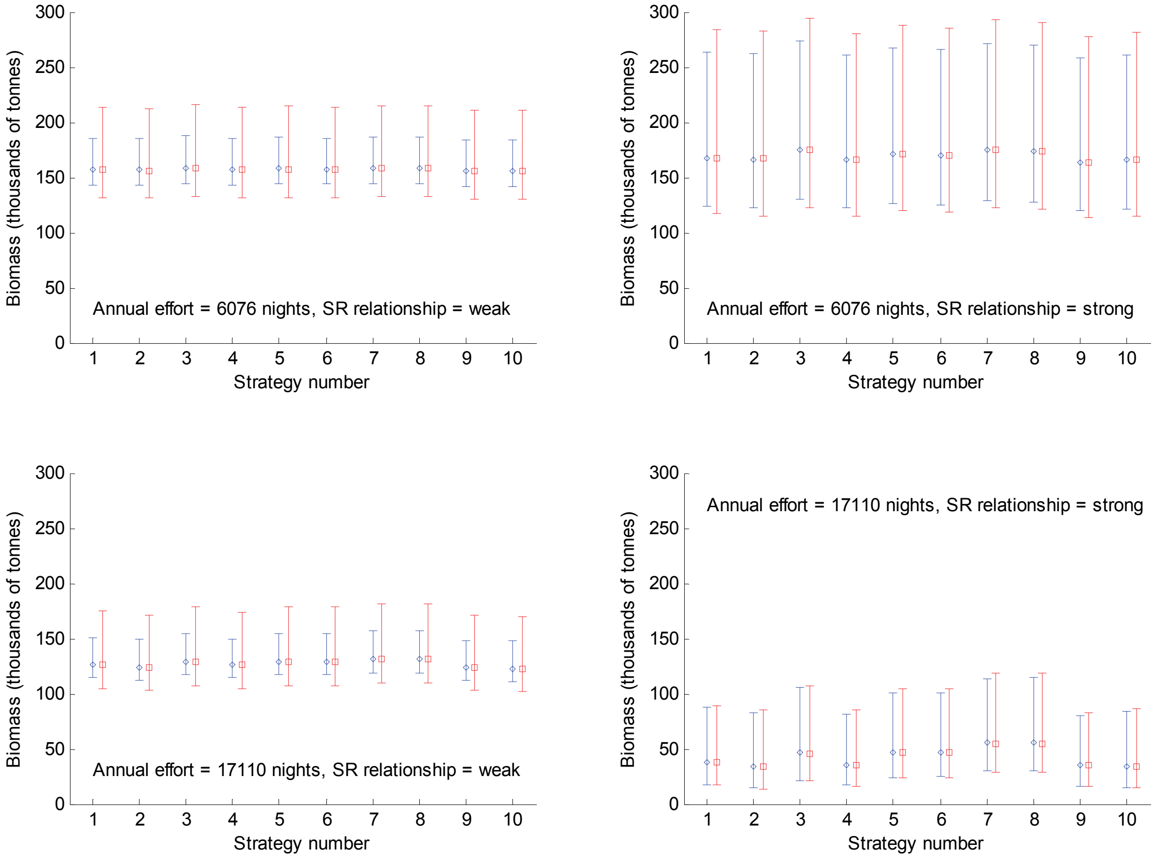


Figure 9-21: Biomass performance over ten management strategies and four alternate effort and stock-recruitment scenarios. Error bars represent 5% and 95% quantiles. Red error bars are based on the distribution which includes multiple years of the simulation as separate values; blue bars are based on an average over the simulation years (see section 9.2.8.3 for details).

Harvest levels at low levels of fishing effort are similar for each Scenario irrespective of assumptions regarding the SRR (Figure 9-22). Slight increases in harvest were predicted when closure periods of the SRAs were extended (Scenarios 4, 5 and 6) assuming a weak SRR and historically high levels of fishing effort. This was also observed when the SRR was assumed to be strong, although Scenario 7 and Scenario 8 provide for higher relative harvests. Once again, the removal of the closure appears to be detrimental with Scenario 2 and Scenario 10 resulting in the lowest harvest.

As with harvest, landed price remains constant across all Scenarios at present levels of effort irrespective of the SRR (Figure 9-23). Higher values are predicted at historically high levels of effort assuming a strong SRR, with increased closure periods of SRAs (Scenario 5 and 6) and a winter closure (Scenario 9) being of benefit. Once again, the removal of the SRAs results in decreases in total value of the fishery.

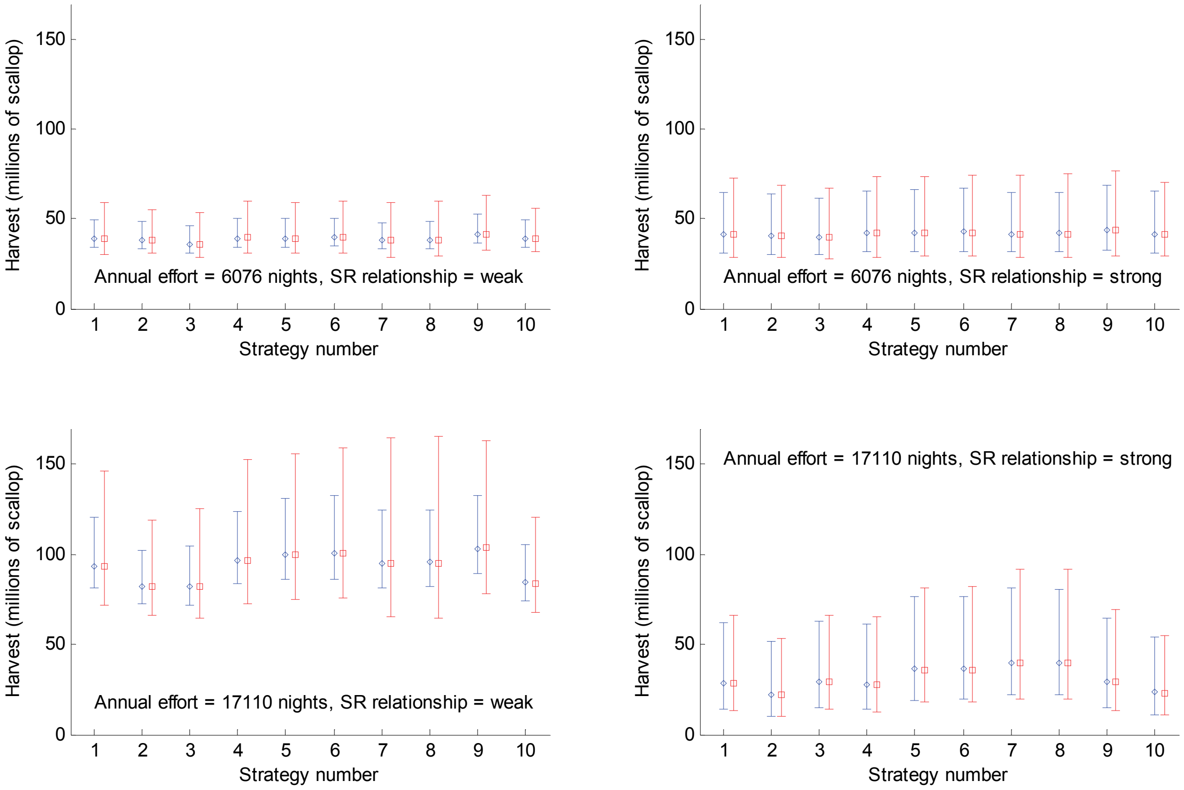


Figure 9-22: Total catch performance over ten management strategies and four alternate effort and stock-recruitment scenarios. Error bars represent 5% and 95% quantiles. Red error bars are based on the distribution which includes multiple years of the simulation as separate values; blue bars are based on an average over the simulation years (see section 9.2.8.3 for details).

9.4 DISCUSSION

The HSE model has a significant degree of spatial complexity, both in terms of the biology (four metapopulations) and the fleet dynamics (fifteen regions). Nevertheless it has limitations in relation to the treatment of stock-recruitment dynamics. The spatial pattern of recruitment has been modelled (estimated), however this relationship is fixed through time. Ideally each metapopulation would have its own stock-recruitment relationship, and the connectivity between the metapopulations would also be modelled. As the prevailing currents run north-south, it is likely that the Yeppoon metapopulation acts as a source (or ‘feeder’) for the others (Tony Courtney, *pers. comm.*). The lack of a true spatio-temporal stock recruitment relationship in the model means that the results cannot comment on whether it is more important to protect a particular local spatial region over any other. It is unlikely that there is sufficient information in the data available to estimate such a dynamic, but this possibility of inter-connected metapopulations should not be ignored as it has implications for management, in particular for the importance of the Yeppoon SRAs. This is an important direction for future work.

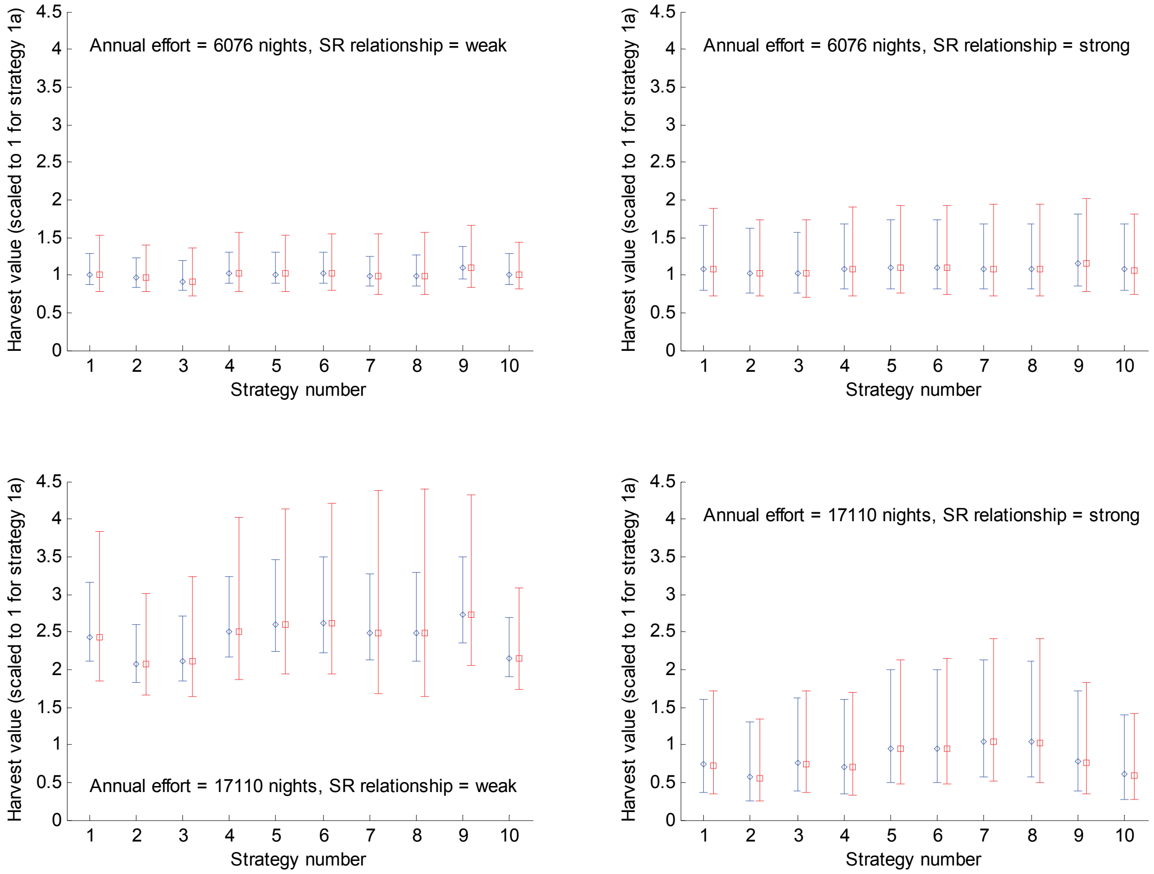


Figure 9-23: Value performance over ten management strategies and four alternate effort and stock-recruitment scenarios. Error bars represent 5% and 95% quantiles. Red error bars are based on the distribution which includes multiple years of the simulation as separate values; blue bars are based on an average over the simulation years (see section 9.2.8.3 for details). Value indicator is scaled so that strategy '1a' (strategy 1 under the low effort, weak SR relationship scenario) is equal to 1.0.

Another spatio-temporal phenomenon that has not been explicitly modelled is the spatio-temporal randomness of recruitment at fine scales. Consider Figure 17-22 on page 141, which plots the logarithm of catch rate (in numbers per 20 min shot) from all survey data against duration closed. That is, for every shot in the survey data (all years, 1997 to 2006), the plot displays (log) catch against the time (in months) that the area was closed to fishing prior to that shot being performed[9]. This plot is important in that it shows increasing closure duration is beneficial not to the expected maximum catch, which remains stable, but rather to the expected *minimum* catch, which improves steadily and significantly right out to nearly five years closure duration. As the shots are performed in a spatially random fashion, this suggests that the proportion of the area with high density scallop continues to increase with time. This in turn suggests the following stock-recruitment dynamic: spat fall occurs in a patchy fashion which varies from year to year, and over time more of the ground is occupied by recruits (which presumably also increases the likelihood of localised stock recruitment and persistence

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[9] Thus this plot is an extension of that presented in O'Sullivan S, Jebreen E, Smallwood D, McGilvray J, Breddin I, MacKenzie B (2005) 'Fisheries Long Term Monitoring Program - Summary of Scallop (*Aumsium japonicum balloti*) survey results: 1997 - 2004.' Department of Primary Industries and Fisheries, Brisbane, Queensland., the key difference being that we are plotting the full distribution of data, not just a fitted curve.

of the better spatial coverage). Thus with time, the total number of scallop in a closed area increases significantly, despite no one local patch ever increasing beyond a certain threshold density (eg. a density governed by competition for food). This hypothesis, and the evidence for it, is particularly important given that a) the HSE model is not capturing these local spatio-temporal dynamics, and perhaps consequently, b) the HSE model doesn't provide a clear justification for the utility of the SRAs (unless the fishery is being pushed with very high levels of effort). In other words, while the HSE results above are only demonstrating that the SRAs have 'sustainability value' (acting as a refuge when the fishery is pushed hard), the phenomenon just described suggests that SRAs actually continue to accumulate large numbers of scallop out to at least five years and thus may provide real economic value under 'normal' conditions.

The SRR is a large source of uncertainty within the HSE (see Section 9.3.3 on page 83). Joll (1989a) reported "...high levels of breeding stocks giving rise to small recruitments and low levels of breeding stock giving rise to large recruitments..." (page 66) in patches of *A. balloti* in Western Australia. This suggests that the SRR is closer to the "weak" situation in the current study than the "strong" situation. Joll (1994) postulated that the cause of the variability is influenced by environmental influences on the survival of larvae. Further, O'Sullivan, Jebreen *et al.* (2005) reported highly variable levels of recruitment in the Queensland *A. balloti* fishery using dedicated recruitment surveys conducted during the Southern Closure period. Interestingly, the HSE model predicts mean annual catch rates below five baskets boat-day^{-1} (Figure 9-20) at high levels of effort, assuming a strong SRR. Such low catch rates were predicted by the REML analysis in Section 8.3.4 on page 42 for the years 1997 and 1998 when effort levels were approximately 17,200 boat days and 15,800 boat days, respectively. This suggests that the SRR for these years was closer to the "strong" situation used in the HSE.

Unfortunately the large intra-strategy variation evident in the HSE outputs (Figure 9-20, Figure 9-21, Figure 9-22 and Figure 9-23) obscures the identification of the most promising management strategies.

In general terms, the removal of SRAs will result in decreases in all HSE outputs, although these decreases are not statistically significant. Further, the rotational harvest strategies generally resulted in increases in all of the HSE outputs compared to the status quo (Scenario 1). The rotational harvest of scallops has been shown to be the optimal strategy to increase yield-per-recruit (YPR) and biomass-per-recruit (O'Sullivan, Jebreen *et al.* 2005). For example, (Hart 2003) reported increases in both yield- and biomass-per-recruit for the Atlantic sea scallop (*Placopecten magellanicus*) using a rotational harvest strategy. Further, a significant gain in maximum yield-per-recruit, compared to a constant fishing mortality (ie. no closure), can be expected if the closure is timed to exploit large year classes. This may explain the good performances of Scenario 9, where a winter closure is imposed. Hart (2003) also reported that a rotational harvest strategy also protected sea scallops (*Placopecten* *magellanicus*) from growth overfishing (ie. fishing at a level higher than $F_{\max}$), with smaller reductions in yield-per-recruit compared to a situation where closures, at high levels of fishing mortality, were not in place.

The removal of the SRAs has been suggested by the marketing sector in order to provide constant supply of product year-round. The HSE model predicts that this would be detrimental. However, we have concentrated on the landed (beach or wet) price in the current project and it is necessary to develop much more comprehensive economic models to determine the consequences of any management strategies implemented. Further, the price-per-kilo used to derive the value outputs will be highly variable and subject to significant change throughout the year.

The length of the closure period of the SRAs seems to have an impact on the HSE outputs. As stated earlier, longer closure periods result in higher minimum catches inside SRAs. The extent of the benefits of the longer closure periods for the SRAs is somewhat diminished given that the outputs are averaged over 12 years. For those scenarios where the closure periods are extended, the re-opening of the closures will result in significantly higher catch rates every two or three years depending on closure length. However, in the years that the SRAs are closed, catch rates are zero, resulting in a reduction in the mean catch rate across the 12 years assessed. Catch rates were generally higher when closure length was increased to 27 months (Scenario 5) and 33 months (Scenario 6). However, any further increases in closure length resulted in reductions in catch rate, except in situations where the SRR was assumed to be strong. This suggests that the closure period is too long and too many scallops, given that biomass is proportional to closure length, cannot be accessed by fishers. This situation decreases the mean catch rate over 12 years observed in Figure 9-20.

One point regarding the winter closure is worth noting. In the HSE, the effort removed during the winter closure (Scenario 9) was redistributed among the remaining months. However, those fishers that currently fish through winter mostly fish at full capacity throughout the rest of the year. Therefore in reality it is unlikely that effort exerted during winter can be completely redistributed to the remainder of the year. Effort removed from the fishery through imposition of winter closures would therefore be removed totally from the fishery. This should be addressed in further studies and during any further economic modelling.

The scenarios modelled during the current project are only those seen to be practicable given the time restraints of the project. The model is now at a stage where more scenarios, developed in consultation with stakeholders, can be assessed. One scenario not modelled during the current project is the use of recruitment surveys. Such surveys were once conducted by QDEEDI as part of its Long Term Monitoring Program (see O'Sullivan, Jebreen *et al.* 2005; Dichmont, Dredge *et al.* 2000 and Jebreen, O'Sullivan *et al.* 2006) but were abandoned due to excessive cost. These surveys provided fishers with information regarding the location and density of scallop beds in the area from Yeppoon to Hervey Bay. Such surveys could be used in the future to determine areas of high scallop density, which could then be closed to ensure optimal harvest. This strategy would ensure the closure of areas containing high densities of recruits, compared to the current situation that relies on scallops recruiting to the SRAs which has been shown to be inconsistent from year-to-year in some instances.

Systems of pre-fishing surveys undertaken by industry have facilitated successful adaptive management in South Australia's Spencer Gulf prawn fishery and in the scallop fisheries of Tasmania and Bass Strait (Haddon, Harrington *et al.* 2006). Whilst the objectives and metrics employed in the pre-fishing surveys of these examples would be inappropriate in the Queensland scallop fishery, the principle of involving industry in real-time monitoring and adaptive management provides great opportunity to protect areas containing high densities of sub-legal scallops. However, implementation of such progressive strategies in the Queensland scallop fishery requires more flexible fisheries management legislation, and the support of industry. Achieving both presents difficulties.

The use of square mesh codends (SMCs) would significantly reduce discard mortality (see Appendix 17.5.5 on page 139). This has implications with regard to the HSE given that SMCs will be made mandatory in the scallop fishery after the review of the *Fisheries (East Coast Trawl) Management Plan 1999*. These devices were tested in a previous FRDC-funded research project (Courtney, Haddy *et al.* 2007) and were shown to reduce the capture of sub-legal scallops by approximately 50%. These reductions are comparable to those results in the current study which showed that discard mortality would decrease by approximately 50% across three harvest rates.

The values used in the discard mortality model are derived from the experiments carried out as described in Chapter 6. As stated in Chapter 6, the survival estimates of discarded tumbled scallops was likely overestimated due to the fact that the scallops used in the experiments were subjected to repeated trawling and tumbling with no time allowed for recuperation between subsequent trawling and tumbling events. However, due to an inability to "swim" high enough in the water column to be caught immediately after capture and discarding, discarded scallops are afforded some recovery time before they are again vulnerable to capture. Discard mortality is further exacerbated by repeated tumbling events which, according to the results of Chapter 7, result in longer periods of recuperation.

Further, the trawl intensity within the SRAs (see Appendix 17.1.2 on page 114) was based on the VMS data generated over the month subsequent to the SRAs reopening after a 15 month closure. As such, it is unlikely that discarded scallops would be subjected to repeated capture and discarding in a single night. This, combined with the recuperation time required, has resulted in the under-estimation of survival rates due to tumbling.

The use of square mesh codends further reduces discard mortality as a proportion of total mortality. Given that square mesh codends will be made mandatory as part of the review of the *Fisheries (East Coast Trawl) Management Plan 1999*, combined with the likely overestimation of discard survival in Chapter 6, it was deemed reasonable to exclude discard mortality from the HSE. An explicit comparison of square mesh codend versus a standard codend was not made in the current HSE but should be included in any further studies in order to quantify the effect of this change in management arrangements.

During Steering Committee meetings, members discussed the repeated trawling of high concentrations of near-legal scallops in order to remove the relatively few legal animals, particularly during the winter months. This process leads to ever-decreasing catch rates of the near-legal animals until the area is “cleaned-out”. Fishers believe that the repeated trawling and tumbling of these animals results in high discard mortality. Given the results in Chapter 6, this may be the case. It is likely that such practices are detrimental to these isolated scallop beds but, generally, the capture and discarding of sub-legal scallops will not result in sustainability issues for the entire fishery. Further, a significant proportion of the first cohort (0+ animals) is largely not selected by the trawl gear used in the fishery (see Figure 6-6 on page 17 and Figure 9-4 on page 63). This is most likely due to the fact that these animals do not, or cannot, swim high enough into the water column to be caught by the trawls - mostly animals in the 1+ cohort are caught in trawls constructed from prawn mesh used in recruitment surveys.

The use of trashing rates, where scallop beds should not be fished if 20% of scallops caught are below the MLS such as those reported by Haddon, Harrington *et al.* (2006), are not applicable to the Queensland scallop fishery. This management strategy would be difficult to monitor by the Queensland Boating and Fisheries Patrol given the spatial scale of the fishery. For trashing rates to be successful in Queensland, fishers would have to voluntarily adopt a code of practice. However, reaching unanimous agreement across the entire fishery has been difficult in the past and, as such, trashing rates would be ineffective.

In conclusion, the HSE undertaken in the current study predicts highly variable intra-scenario values for all performance indicators. This prevents the identification of a single harvest strategy which maximises profit and ensures the sustainability of the *A. balloti* stock. However, the HSE model suggests that the removal of the SRAs would be detrimental to the fishery and the closure periods of the SRAs should, in fact, be increased. This is due to the fact that the number of scallops within the SRAs increases proportionally to closure duration. As such, increasing closure duration to either 27 months or 33 months, from the current 15 month closure, would result in an increase in all performance indicators, assuming a weak stock-recruitment relationship. At historically high levels of fishing effort and low recruitment, increasing closure duration to 39 months and 45 months allows successive year classes to settle within SRAs resulting in higher biomass.

10 Benefits and adoption

Several stakeholders will benefit directly from the research undertaken during the current project. The formulation of a dynamic Harvest Strategy Evaluation model will allow Fisheries Queensland to develop optimal management arrangements for the scallop fishery. This is of particular importance at the present time given that the *Fisheries (East Coast Trawl) Management Plan 1999* will be reviewed and amended at the end of 2010 and into 2011. This represents a unique opportunity that allows the DEEDI and FRDC investment in this research to contribute significantly to the management of the scallop fishery. The positive benefits associated with SRAs and their potential to improve the value of the fishery is a significant outcome from the current research. With these results, adoption of the results by Fisheries Queensland enables the implementation of legislation regarding SRAs with additional knowledge as to their effectiveness.

The HSE model developed in the current project would also be of benefit to the Western Australian scallop fishery. Given that the fishery targets the same species and the gear and vessels used in the fishery are similar, the HSE could be tailored to assess the management arrangements employed Western Australian fishery. Project staff have informed researchers from the Western Australian Department of Fisheries regarding the results gained in the current project.

The fact that the SRAs are contributing positively to the scallop fishery is also a benefit to fishers. Discussions regarding the merits of the SRAs abound among fishers, with opinion divided about their effectiveness. The results of this research will go some way to alleviating any negative opinions about the effectiveness of SRAs.

The results regarding discard mortality are of benefit to all stakeholders. Discard mortality has been excluded from past stock assessments but is likely to represent around 10% to 20% of total mortality in a “worst-case” scenario. The implementation of legislation requiring the mandatory use of square mesh codends as part of the review of the *Fisheries (East Coast Trawl) Management Plan 1999* will reduce discard mortality by approximately 50%. These results give rise to improved stock assessment modelling which is of benefit to all stakeholders.

11 Further development

Further development of the results of the research undertaken in the current project would be advisable in the following areas:

1. As stated earlier, the benefits of a recruitment survey, which identifies areas of high scallop densities, should be investigated via the HSE. Closing such areas to fishing for two to three years would be of great benefit to the fishery in terms of catch rates and total harvest. This scenario differs from the current management arrangements because the current SRA regime relies on scallops settling within the boundary of these areas. Closing areas containing high scallop densities provide for some kind of guarantee that good catches will be possible when the area is re-opened. The Queensland government funded a recruitment survey until the mid-2000's but was deemed to expensive. Therefore, any further surveys would need to incorporate some form of collaboration among stakeholders. Hence, it is vital that the HSE provide some indication that such surveys represent a significant improvement to the results from the current HSE;

2. Although the economics of the fishery were preliminarily considered during the current project, a more intensive examination of this component of the fishery is warranted. The dynamic nature of the price paid to fishers, given the variable catches throughout the year and the resulting supply/demand situation, is difficult to quantify and is beyond the scope of the current project. Additionally, it is difficult to incorporate the price paid to wholesalers, which is largely dictated by the overseas markets.

3. We have considered a basic, single-species HSE during the current project. Given the increasing need for ecosystem-based management, more complex HSEs, that incorporate the effect of fishing on the ecosystem, are becoming more commonplace. As such, a broader, multi-species HSE that assesses more then the target species would be of benefit, especially given that the majority of effort occurs within the boundary of the Great Barrier Reef Marine Park.

12 Planned Outcomes

The primary project output is the formulation of a dynamic HSE model which allows for the assessment of a combination of management arrangements. These management arrangements can then be used by Fisheries Queensland as a basis for discussion with stakeholders. From these discussions, the most appropriate management arrangements can be applied to the fishery via legislation through the review of the *Fisheries (East Coast Trawl) Management Plan 1999*. Although the HSE does not identify specific options for the optimal management of the fishery, the primary Planned Outcome outlined in the project proposal, it highlighted two very important aspects to improve the management of the scallop fishery. Firstly, the scallop fishery is best managed using a rotating harvest strategy, involving the use of SRAs. The SRAs should be closed for between 2 and 3 years to maximise catch rates at present levels of fishing effort. Secondly, the imminent imposition of square mesh codends (SMCs) will be of great benefit to the scallop fishery, in terms of whole-of-fishery sustainability. The significant reductions in discard mortality of sub-legal scallops quantified as part of the current project, combined with the reductions in bycatch quantified during previous research (Courtney, Haddy *et al.* 2007), is an important output from the project.

Project outputs, in the form of articles in the industry magazine The Queensland Fisherman (see Appendix 17.6 on page 141), informed fishers about the survival of discarded sub-legal scallops. The articles were designed to give fishers some detail regarding the methods used and the results gained during the survival experiments conducted within the Bustard Head B SRA. Further, a second article detailing the discard survival results has been accepted by the Journal of Shellfish Research for publication in the August 2010 edition of the journal. This article was designed to disseminate information regarding the survival of discarded sub-legal scallops widely in the scientific press. Scientific journal articles detailing the results of repeated trawling and discarding are rare and, hence, the publication of the results from the current project will be of interest to researchers world-wide.

13 Conclusion

Measure spatial and temporal trawl frequency of scallop grounds using VMS data. This will provide a relative measure of how often individual undersized scallops are caught and graded using a "tumbler".

Using all available VMS data, trawl position data were mapped in order to determine trawl intensity within Queensland's Scallop Replenishment Areas (SRAs). Specifically, the period immediately after reopening was assessed to derive a worst-case measure of the frequency with which sub-legal scallops are subjected to capture and discarding. Trawl intensity was determined as a function of the total area of the SRAs. The results of this analysis suggested that the majority of the area within the SRAs is not trawled due to unfavourable substrate or low scallop density. The highest trawl intensity was observed in the Bustard Head B SRA where a single 34 m^2 grid within the SRA received 17 trawls in the month of January 2004. Of the area trawled within the SRAs, approximately 85%–90% were trawled four times or less in the month after reopening.

The trawl intensity within the SRAs was based on the VMS data generated over the month subsequent to the SRAs reopening after a 15 month closure. The use of four trawls as a measure of the number of times a single sub-legal scallop may be caught during periods of intensive trawling is, therefore, over-estimated which results in an under-estimation of discard survival.

Estimate discard mortality and growth rates for saucer scallops using cage experiments.

Increased levels of both trawling and tumbling were found to significantly decrease the survival of discarded sub-legal scallops. Whilst 83% of scallops survived repeated intensive trawling (four consecutive tows), survival fell to 64% when scallops were also graded using a commercial tumbler. Survival was high for both tumbled and control sub-legal scallops after one trawl (97% and 98%, respectively). Further analysis of these estimates revealed that discard mortality accounts for between 10% and 16% of total mortality at low harvest rates. At high harvest rates (ie. within SRAs), discard mortality accounts for between 17% and 27% of total mortality. However, the addition of a square mesh codend has a significant positive effect – discard mortality decreases to between 4.5% and 7.5% of total mortality at low harvest rates and between 7.5% and 14% at high harvest rates. The implementation of legislation requiring the mandatory use of square mesh codends in the scallop fishery as part of the review of the *Fisheries (East Coast Trawl) Management Plan 1999* will therefore reduce discard mortality significantly. Further, the survival rates of discarded sub-legal scallops are likely under-estimated in the current study due to a lack of recuperation time in the survival experiments. As such estimates of discard mortality were seen as insignificant and excluded from the HSE analysis.

The growth of *A. balloti* was assessed via a tag-recapture experiment. Animals used in the discard survival experiments were tagged-and-released inside the Bustard Head B SRA and recaptured during a dedicated research charter in December 2007. The von Bertalanffy growth parameters were generated using a modified Fabens model that incorporated parameters to isolate the effects of periods of slow growth immediately after capture and any effects due to repeated tumbling experienced by the recaptured animals. The growth model generated values of L_∞ and k of 104.29mm and 2.05yr^{-1}, respectively. These growth parameters were similar to those reported by QDPI researchers in the 1980's. However, the growth rate parameter, k, was significantly lower in the current study. This is common for scallop species, with growth rate varying according to such factors as density, water temperature, currents, food availability, etc. The most significant result from this study was that scallops required approximately 41 days of recuperation before shell growth resumed, most likely as a result of shell reparation after chipping during capture and tumbling. Additionally, for each tumbling event endured, scallops required approximately three extra days recuperation before growth resumed.

Evaluate the current management measures, in particular the seasonal closure, rotational closure and seasonally varying minimum legal sizes using stock assessment models. Recommend optimal range of management measures to ensure long-term viability and value of the scallop fishery based on a formal management strategy evaluation.

The Harvest Strategy Evaluation model predicted variable catch rate, biomass, total harvest and beach price for ten scenarios modelled, due to highly variable levels of recruitment. No one scenario was identified that maximises profit and ensures the sustainability of the fishery. The HSE suggested that the removal of the SRAs would not be beneficial and that closure periods of the SRAs should be increased. The number of scallops within the SRAs was found to increase proportionally to closure duration and an increase from the current 15 months to either 27 or 33 months would result in increases in catch rates at present levels of fishing effort. Increases in closure duration beyond this would result in decreases in mean catch rates.

The use of an extensive recruitment survey was not assessed in the current study. This scenario has been identified by several prominent scallop fishers as being useful. A fishery-funded recruitment survey could be used to determine areas of high scallop densities which could be closed for a period of time to allow the optimum utilisation of the biomass within the closed areas, similar to the current management arrangements. However, the recruitment survey scenario would result in closing areas known to hold a high biomass, whereas the current arrangement relies on scallops settling within SRAs. The survey scenario guarantees that closed areas will contain significant numbers of scallops.

Although the alternate minimum legal size of 95 mm was not assessed, the scenario of a winter closure was a substitute for the inclusion of a 95 mm winter MLS. In most instances, a winter closure resulted in increases of all performance indicators suggesting that a winter closure/95 mm MLS should be assessed further.

Any management arrangement resulting from the current study relies on fishing effort remaining relatively constant into the future at present levels. Although increases in fishing effort are unlikely to impact on sustainability, increases in total catch will result in decreases in price paid to fishers. As such, it is important to address effort limitations in the fishery via a scallop “endorsement” based on history in the fishery.

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15 Appendix 1: Intellectual Property

The information generated by this research is in the public domain and not subject to intellectual property considerations.

16 Appendix 2: Project staff

Department of Employment, Economic Development and Innovation, Queensland
Matthew Campbell (Principal Investigator from July 2007)
Dr Rick Officer (Principal Investigator prior to July 2007)
Andrew Thwaites
Alex Campbell
Dr Tony Courtney
Dr Neil Gribble
Michael O'Neill
Andrew Prosser
Mary Lawrence
Sharon Drabsch

17 Appendix 3: Additional and raw data

Following are appendices displaying raw data or analysis in addition to those displayed in the relevant sections.

17.1 ADDITIONAL DATA USED TO DETERMINE TRAWL INTENSITY

Following are the trawl intensity maps and histograms for the Scallop Replenishment Areas (SRAs). The maps and histograms were generated using decision rules described by Good, Peel *et al.* (2007). These data are based on trawl tracks with a net spread of 34 metres. The pre-2004 SRA schedule is shown in Figure 17-1. See Section 6.2 for a detailed description of the relevant methods used to generate the figures in Section 17.1.2 on page 114.

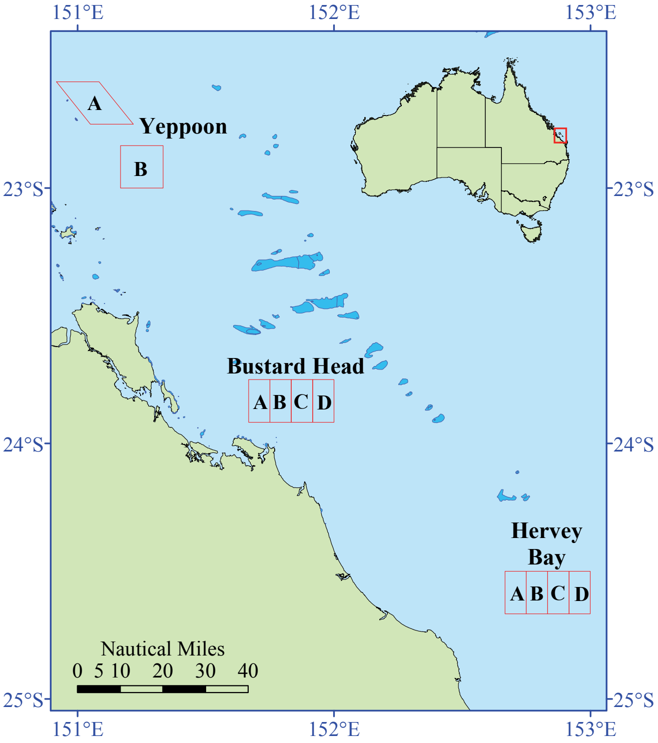


Figure 17-1: Location of Queensland's Scallop Replenishment Areas (SRAs) pre-2003.

17.1.1 Example MATLAB code used to quantify trawl intensity

Below is an example of the MATLAB code used to quantify trawl intensity and generate the figures in Section 17.1.2.

```
function TrawlIntensityGUI_OpeningFcn(hObject, eventdata, handles,
varargin)
intval=0.00031105;
handles.intval=intval;
handles.output = hObject;
guidata(hObject, handles);
function varargout = TrawlIntensityGUI_OutputFcn(hObject, eventdata,
handles)
varargout{1} = handles.output;
function area_Callback(hObject, eventdata, handles)
intval=handles.intval;
val=get(hObject,'Value');
```

```
str=get(hObject,'String');
switch str{val};
      case 'HBB04'
      handles.long=[152+50/60:intval:153]';
      handles.lat=[24+30/60:intval:24+40/60]';
      area='HBB04';
      handles.area=area;
end
guidata(hObject, handles);
function area_CreateFcn(hObject, eventdata, handles)
      if ispc && isequal(get(hObject,'BackgroundColor'),
      get(0,'defaultUicontrolBackgroundColor'))
      set(hObject,'BackgroundColor','white');
end
function load_fname_Callback(hObject, eventdata, handles)
      fname=get(handles.load_fname,'String');
      handles.filename=fname;
      area=handles.area;
      guidata(hObject,handles);
      if exist(fname,'file')
      data=xlsread(area);
      data(:,3)=data(:,3)*-1;
      handles.data=data;
      else
      error('Check the path & name of the MAT-file');
end
guidata(hObject,handles);
function load_fname_CreateFcn(hObject, eventdata, handles)
      if ispc && isequal(get(hObject,'BackgroundColor'),
      get(0,'defaultUicontrolBackgroundColor'))
      set(hObject,'BackgroundColor','white');
end
function brouse_fname_Callback(hObject, eventdata, handles)
      [filename,pathname]=uigetfile('*.xls','Pick an Excel-file');
      set(handles.load_fname,'string',[pathname,filename]);
      load_fname_Callback(handles.load_fname,[],handles);
      function calculate_Callback(hObject, eventdata, handles)
      long=handles.long;
      lat=handles.lat;
      data=handles.data;
      d=[];
      w = waitbar(0,'Process1: Calculating coordinate points. Please
      wait...');
      for i=1:length(data)-1;
      waitbar(i/(length(data)-1))
      if data(i+1,1)==data(i,1);
      dist=sqrt((data(i+1,3)-data(i,3))^2+(data(i+1,2)-data(i,2))^2); %
      distance between two points
      % trawl width = 34m= 0.00031105 decimal degree
      int=dist/0.00031105; % number of points to fit
      yrange=[data(i,3):(data(i+1,3)-data(i,3))/int:data(i+1,3)]'; % lat
      points every 34 m
      xrange=[data(i,2):(data(i+1,2)-data(i,2))/int:data(i+1,2)]'; % long
      points every 34m
      if data(i,3)==data(i+1,3); % for points in same latitude (horizontal
      line)
      yrange=data(i,3).*ones(length(xrange),1);
end
if data(i,2)==data(i+1,2);% for points in same longitude (vertical line)
      xrange=data(i,2).*ones(length(yrange),1);
end
p=[xrange yrange];
% d=data matrix for all coordinate points
```

```
d=[d;p];
%     scatter(xrange,yrange,'.')
%     hold on
clear xrange yrange p
end
end
close(w)
%calculating trawling time by counting number of points within 34*34m^2
grid
ww = waitbar(0,'Process2: Calculating trawling time. Please wait...');
      for i=1:length(long)-1; % index number for x (longtitude)
      for j=1:length(lat)-1; % index number for y (latitude)
      x=(d(:,1)>long(i)).*(d(:,1)<=long(i+1));
      y=(d(:,2)>lat(j)).*(d(:,2)<=lat(j+1));
      m(j,i)=sum(x.*y); % matrix of trawling time
end
waitbar(i/(length(long)-1))
end
close(ww)
handles.d=d;
handles.m=m;
guidata(hObject, handles);
function saveresults_Callback(hObject, eventdata, handles)
      area=handles.area;
      m=handles.m;
      [filename,pathname]=uiputfile('*.mat','Save as',area);
      cd(pathname);
      s=['save ' filename]; % need to save results in -mat file.
      eval(s)
function area_Callback(hObject, eventdata, handles)
      val=get(hObject,'Value');
      str=get(hObject,'String');
      switch str{val};
      case 'BHB03' % user selects membrane
      load BHB03.mat;
      area='BHB - January 2003';
end
% guidata(hObject,handles);
function mapping_Callback(hObject, eventdata, handles)
      m=handles.m;
      figure
      figure1=imagesc(m);
      colormap hot
      set(gca,'YTick',[ ],'XTick',[ ]);
      colorbar('peer',gca);
function histgram_Callback(hObject, eventdata, handles)
      % extracting exact SRA area
      m=handles.m;
      % mm=m(55:591,54:588);
      % plotting histogram including untrawled area
      % MM=mm(:);
      MM=m(:);
      prop=[length(find(MM==0))/length(MM);length(find(MM==1))/length(MM);l
      ength(find(MM==2))/length(MM)...
      ;length(find(MM==3))/length(MM);length(find(MM==4))/length(MM);length
      (find(MM==5))/length(MM)...
      ;length(find(MM==6))/length(MM);length(find(MM>6))/length(MM)];
      figure
      bar([1:8],prop)
      set(gca,'xlim',[0.5
      8.5],'xticklabel',{'0','1','2','3','4','5','6','7+'})
      ylabel('Frequency (%)')
      xlabel('Trawling times')
```

```
    t=['Title(''Trawl Intensity in ' tt ''')'];
e
title('Trawl Intensity in BHB - January 2003')
box off
colormap gray
a={'0','1','2','3','4','5','6','7+'}';
proportion=[a num2cell(prop)]
```

17.1.2 *Trawl intensity within Queensland's SRAs*

Following are the trawl intensity maps derived using the MATLAB (2009) code in 17.1.1.

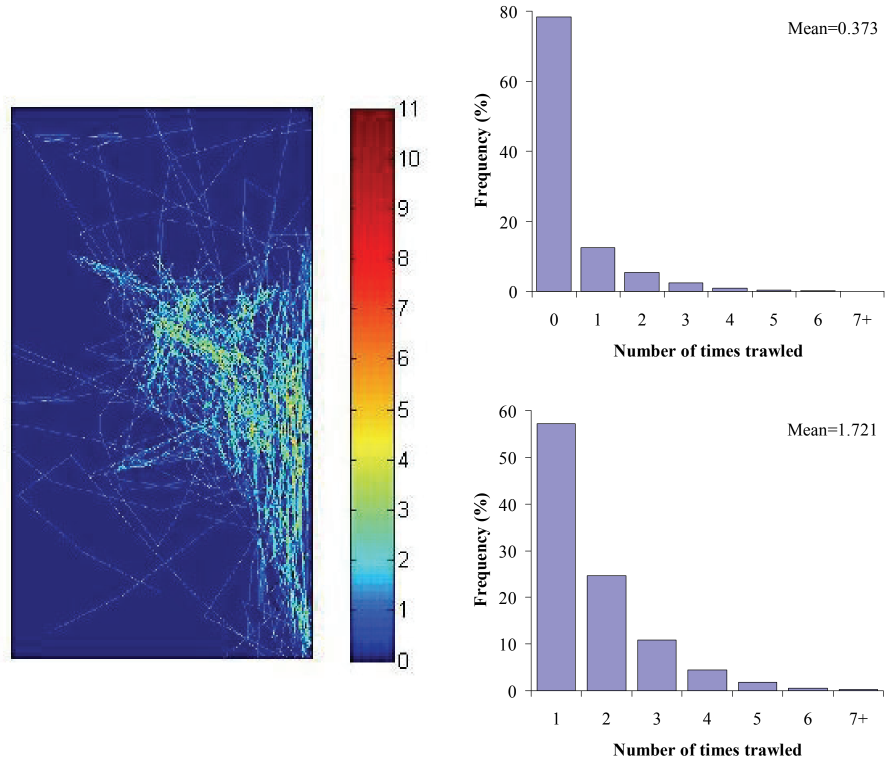


Figure 17-2: Trawl intensity within the Bustard Head A SRA in January 2002.

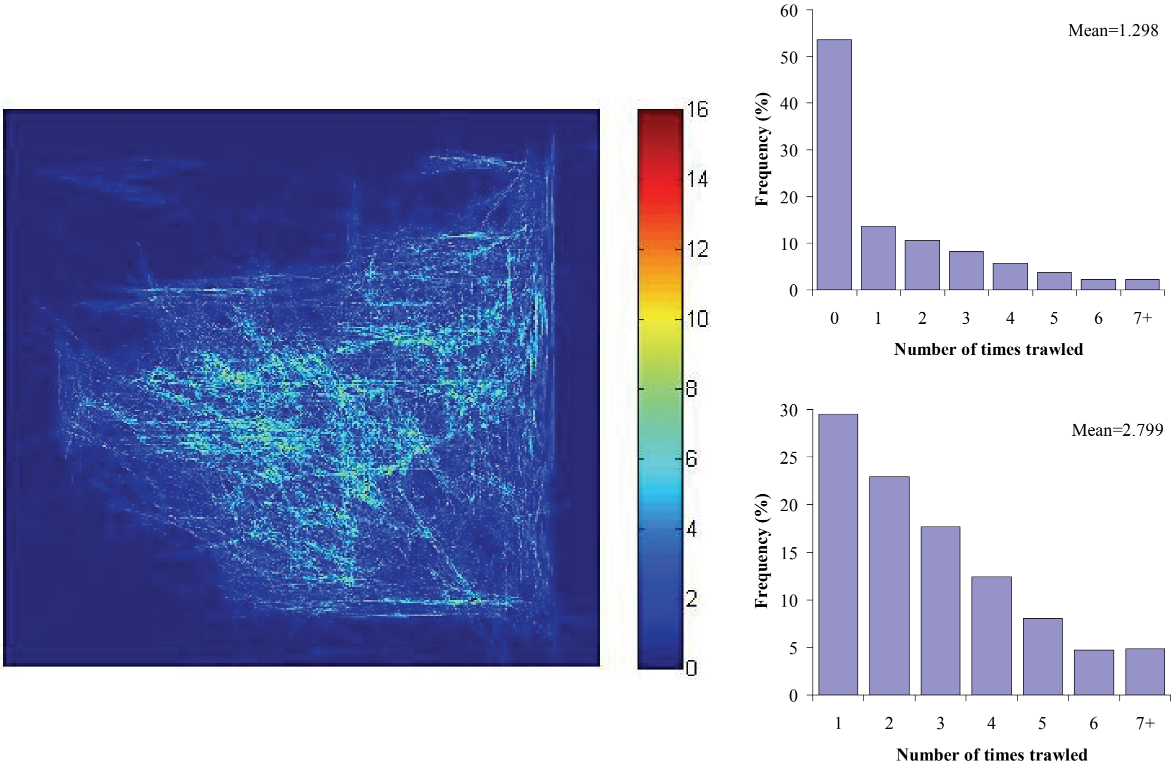


Figure 17-3: Trawl intensity within the Bustard Head A SRA in January 2005.

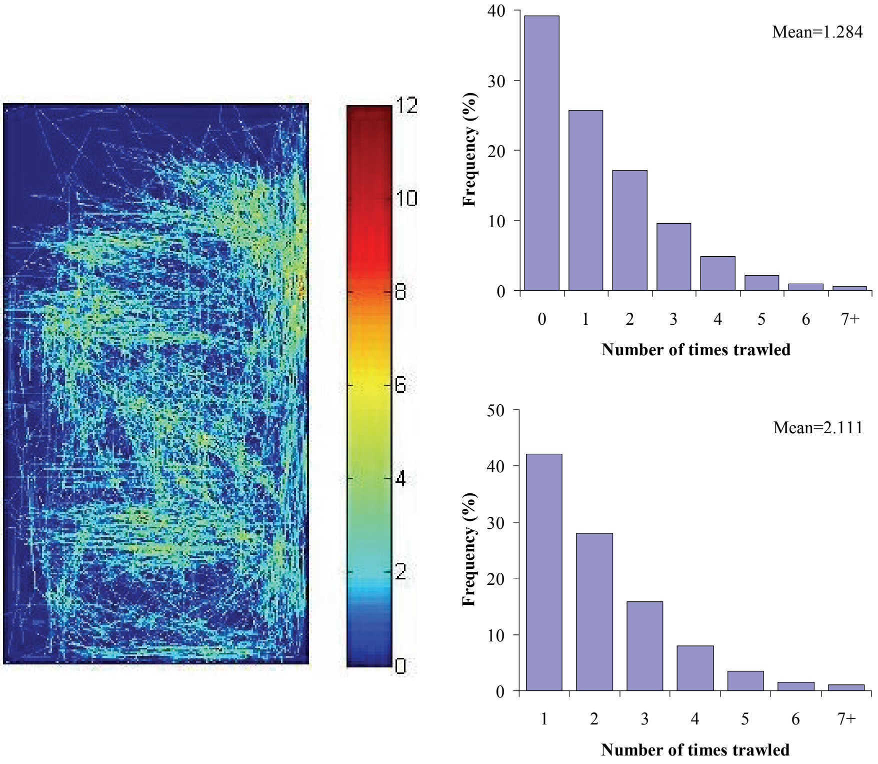


Figure 17-4: Trawl intensity within the Bustard Head B SRA in January 2003.

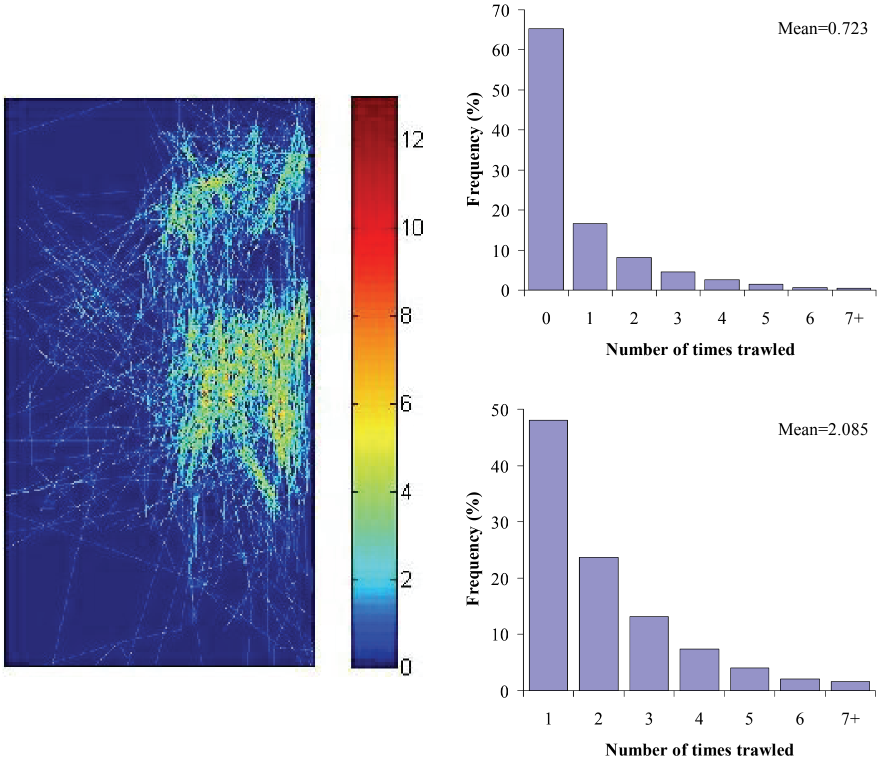


Figure 17-5: Trawl intensity within the Hervey Bay A SRA in January 2002.

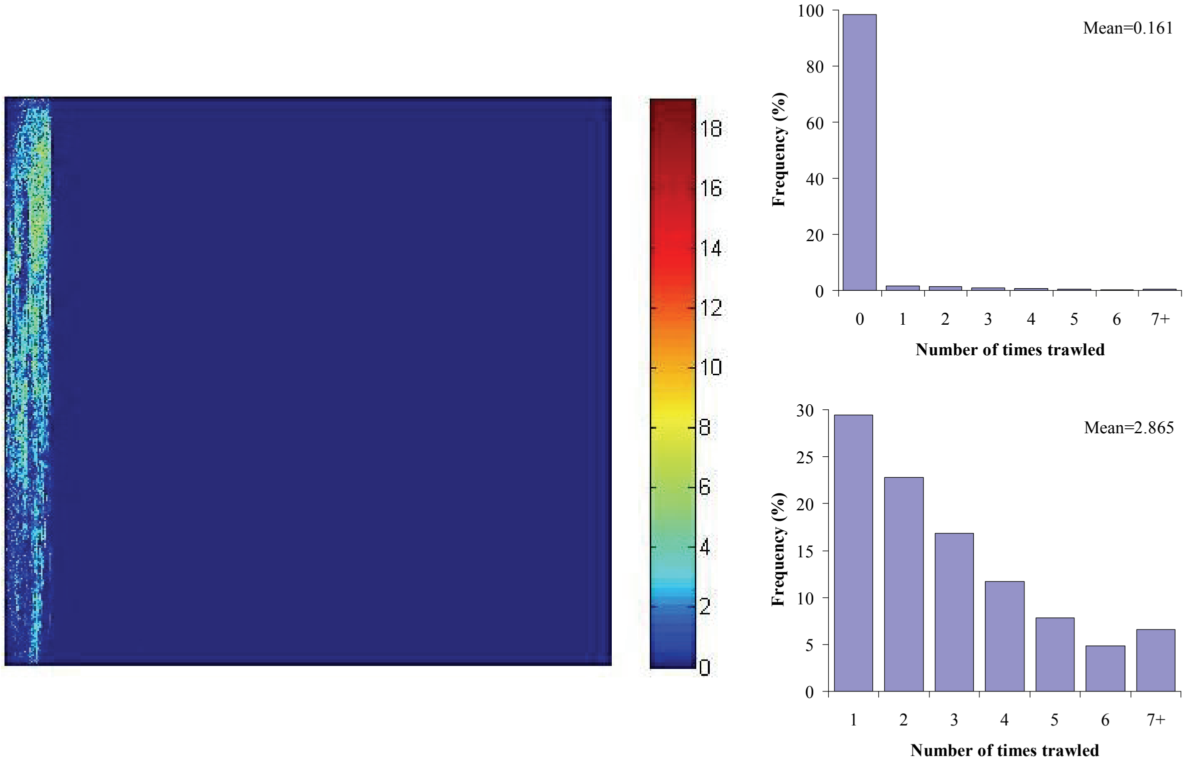


Figure 17-6: Trawl intensity within the Hervey Bay A SRA in January 2005.

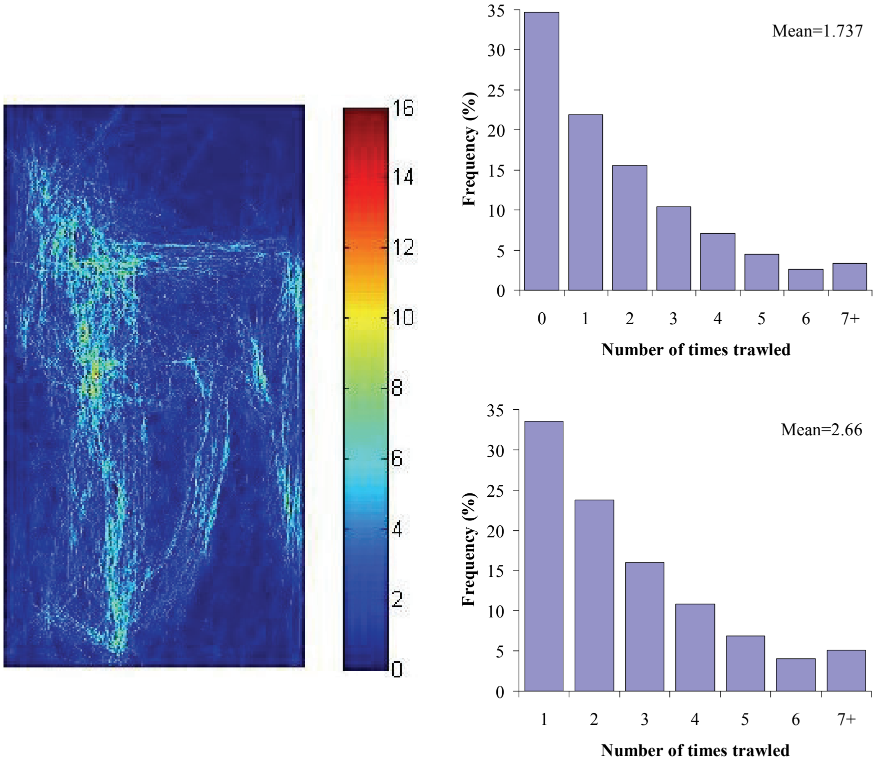


Figure 17-7: Trawl intensity within the Hervey Bay B SRA in January 2003.

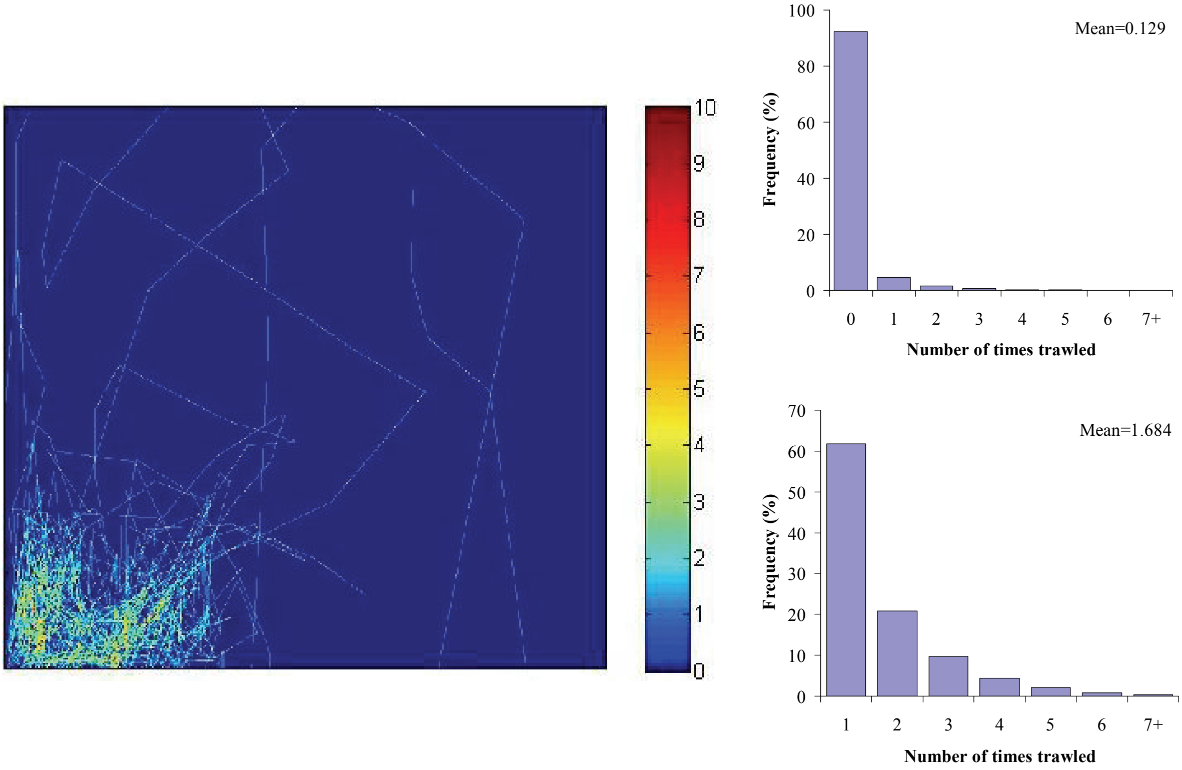


Figure 17-8: Trawl intensity within the Hervey Bay B SRA in January 2004.

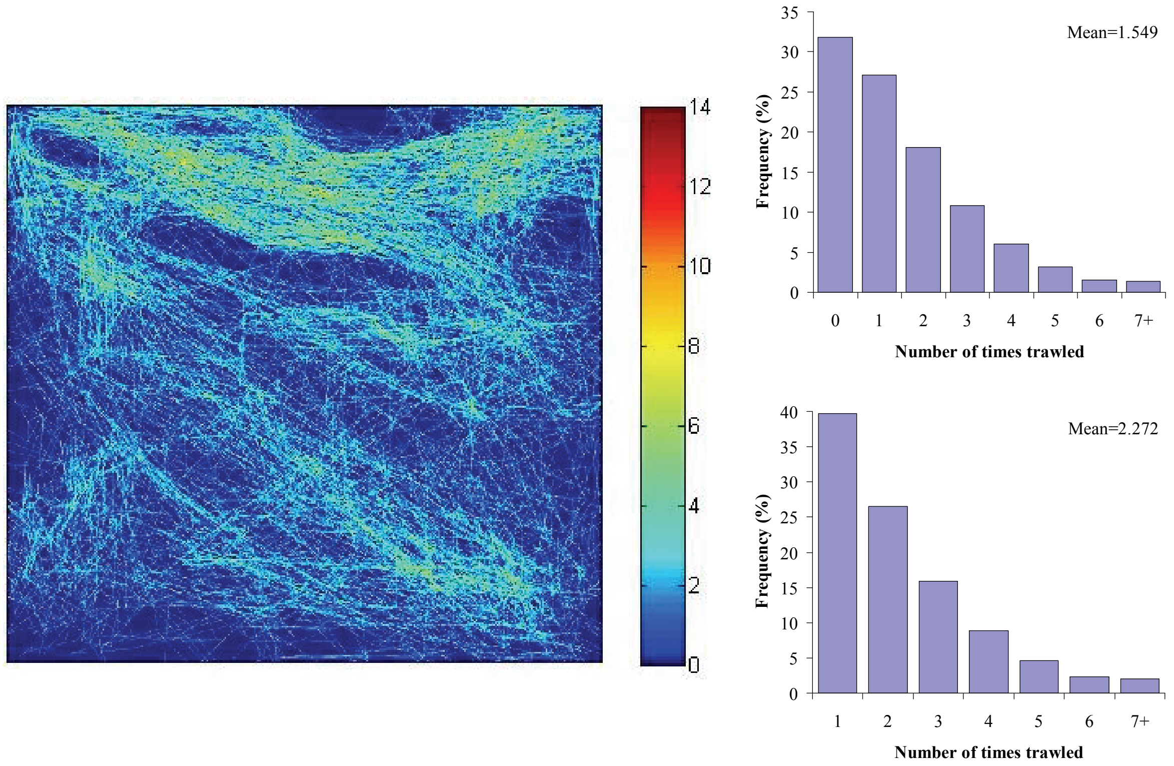


Figure 17-9: Trawl intensity within the Yeppoon B SRA in January 2002.

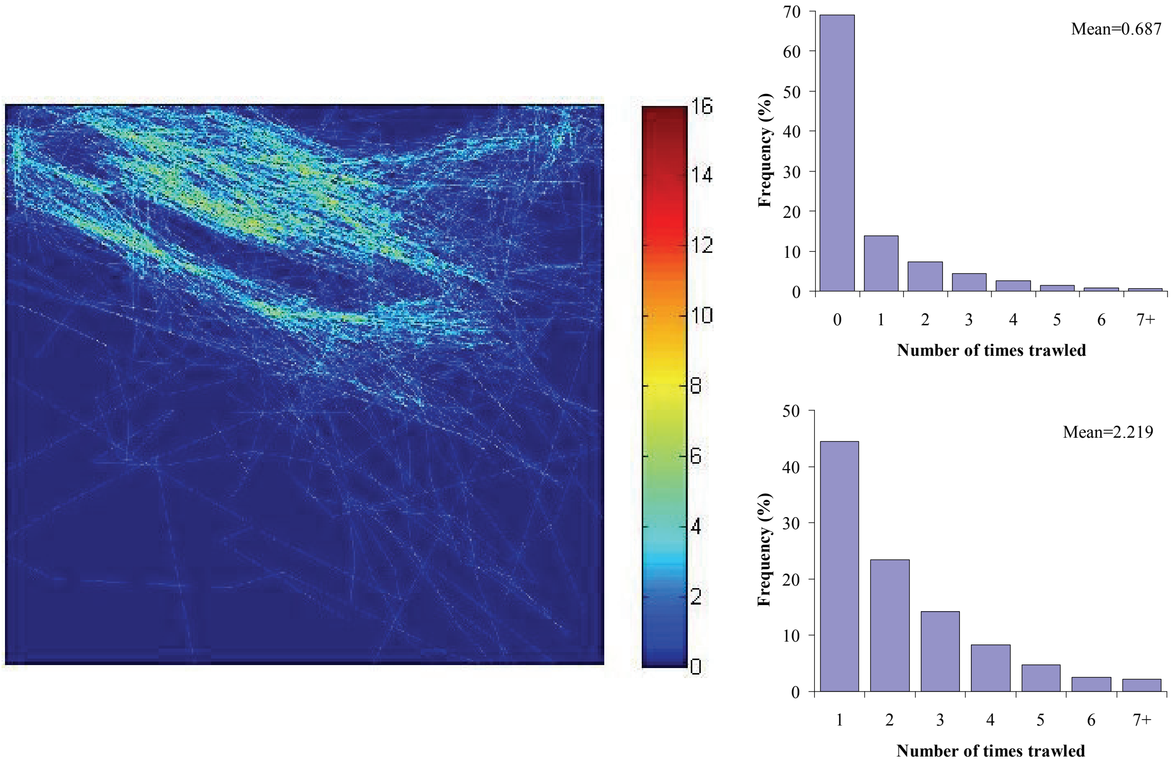
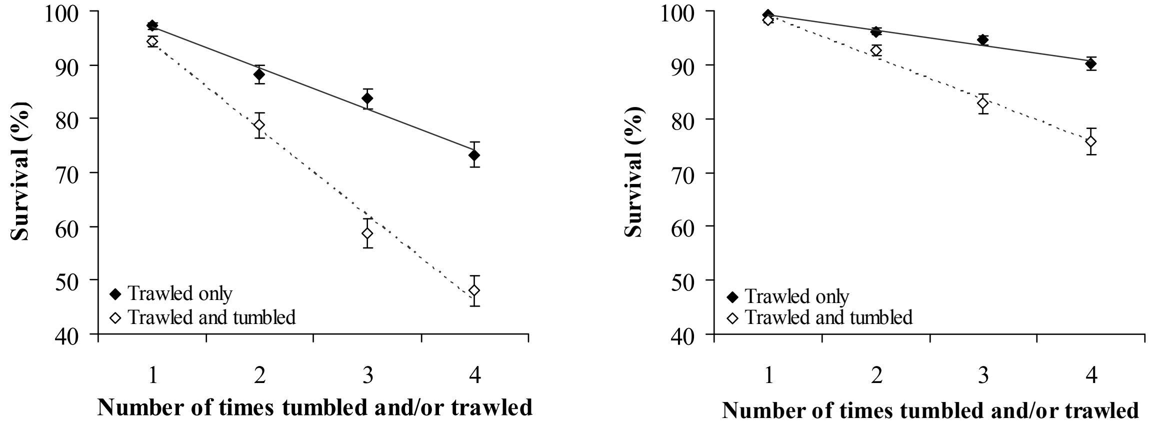


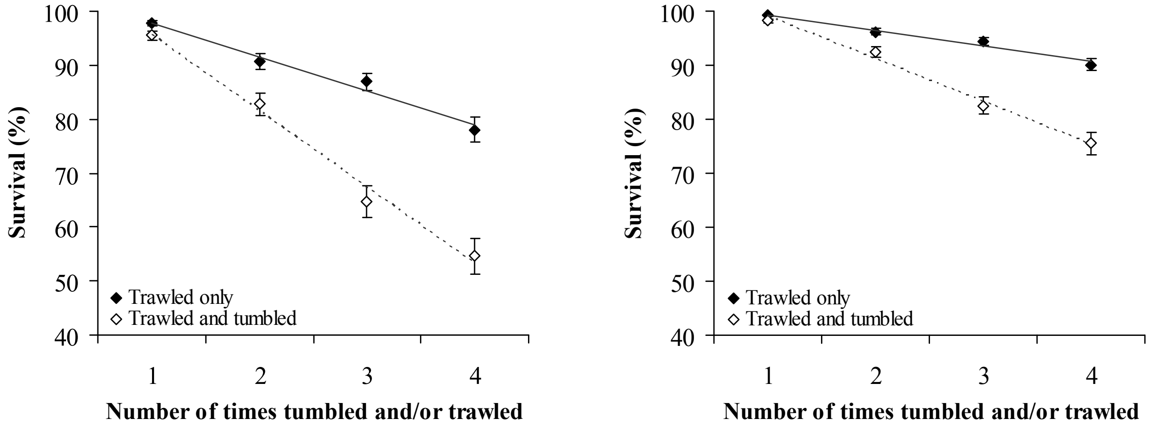
Figure 17-10: Trawl intensity within the Yeppoon B SRA in January 2004.

17.2 SHORT-TERM SURVIVAL OF DISCARDED SCALLOPS



a) Autumn07

b) Winter07



c) Spring07

d) Autumn07

Figure 17-11: Adjusted mean survival (± standard error) of sub-legal *A. balloti* for each experiment after various levels of tumbling and/or trawling.

17.3 ADDITIONAL INFORMATION FOR THE ANALYSIS OF GROWTH RATE DATA IN CHAPTER 7

Following are the GenStat (2007) code and parameter estimates used to analyse the tag-recapture data as detailed in Section 7.2.1 on page 25.

Model 1:

```
" ***** Model 1 *****"
Height2 ; fitted=fv ; residuals=rs
expression e; value=!E(fv=Height1+(Linf - Height1)*(1 - exp(-K * t )))
rcycle [maxcycle=50] Linf,K; init=110,0.005
fitnonlinear [calc=e]
```

Model 2:

```
"***** Model 2 with ' t2' *****"
expression e ;
value=!E(fv=Height1+(Linf - Height1)*(1 - exp(-K * (t-t2))))
rcycle [maxcycle=50] Linf,K, t2; init=104,0.005,38
fitnonlinear [calc=e]
```

Model 3:

```
" ***** Model 3 with ' t2 ~ linear f(tumbles)' *****"
expression e ; value=!E(fv=\Height1 + (Linf - Height1)*(1 - exp(-K *(t -
t2+ tn*NoTumbles)))))
rcycle [maxcycle=50] Linf,K, t2, tn; init=104,0.0055,38,3
fitnonlinear [calc=e]
```

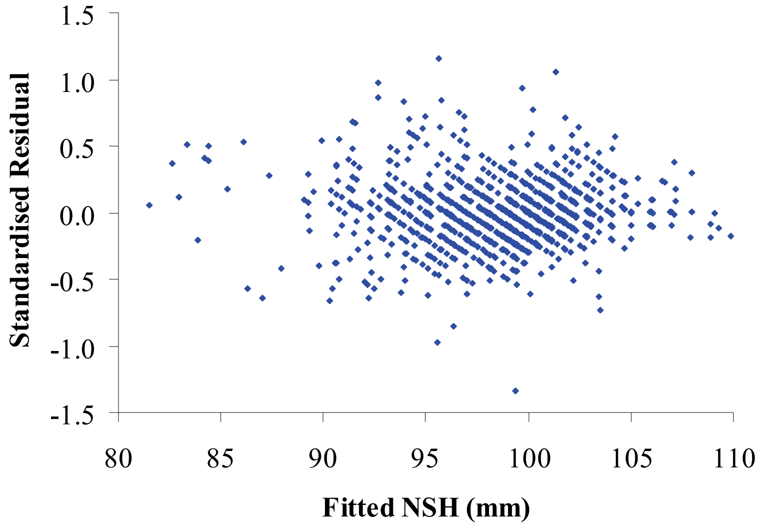


Figure 17-12: Plot of fitted values of nominal shell height in millimetres (L_2 from Equation 7-5) from Model 3 versus the standardised residuals.

17.4 ADDITIONAL INFORMATION FOR THE ANALYSIS OF CATCH RATE DATA IN CHAPTER 8

Following are the GenStat (2007) code used to analyse scallop catch rates and generate outputs in Chapter 8.

17.4.1 Long-term data 1977 - 2008

The code below was used to generate the long-term (1977-2008) standardised catch rates in Section 8.3.3 on page 41.

```
"REML model"
VCOMPONENTS [FIXED=
loghours+fish_year*month+grid+logprawns+lunar+lunar_adv;\
 FACTORIAL=2] RANDOM=boat_mark+boat_mark.fish_year;  INITIAL=1;
CONSTRAINTS=positive
REML [PRINT=model,components,effects,deviance,waldTests,means;
PSE=allestimates; MVINCLUDE=explanatory; method=ai;] logwt
vkeep [sigma2=s2]
vpredict [print=description,predictions; predictions=logcpue]
fish_year,month
calculate stand_cpue= exp(logcpue+s2/2)
```

17.4.2 Recent data 1988 - 2008

The code below was used to generate the gear and vessel characteristics data used in the REML analysis in Section 8.3.2 on page 37.

```
“General Linear Model”
for y= loghp,nozzle,sonar,gps2,tryyesno,brdted,lognet,loghours
calculate count=count+1;
MODEL [DISTRIBUTION=normal; LINK=identity; DISPERSION=*] y
FIT [PRINT=accumulated; CONSTANT=estimate; FPROB=yes; TPROB=yes;FACT=9]
fishyear
rkeep meandeviance=ems[count]
predict [predictions=predcomb[count];se=ses[count]] fishyear
endfor
"calculate gear trends for factors"
calculate count=0;
for y= ggear4,nettype,boards
calculate count=count+1;
"Gear analysis "
print count
TABULATE [PRINT=nobs; CLASSIFICATION=fishyear,y; MARGINS=no] logn
Endfor
```

The code below was used to generate the recent (1988-2008) standardised catch rate data in Section 8.3.5 on page 42.

```
VCOMPONENTS [FIXED=
fishyear*month*grid+logprawns+lunar+lunar_adv+loghp+gps2+nettype+lognet+gge
ar4+boards+brdted; FACTORIAL=2]\
RANDOM=boat_mark;  INITIAL=1; CONSTRAINTS=positive
REML[PRINT=model,components,effects,vcovariance,deviance,waldTests,covarian
cemodel,means;\PSE=allestimates; MVINCLUDE=*; method=ai;]logn
"submodel=fishyear*month*grid+logprawns] logwt"
"Monthly standardised cpue index"
vpredict [print=description,predictions;present=fishyear,grid]
fishyear,month
```

17.4.3 Comparison of observed catch rates and those used in the standardisation in Sections 8.3.3 and 8.3.4

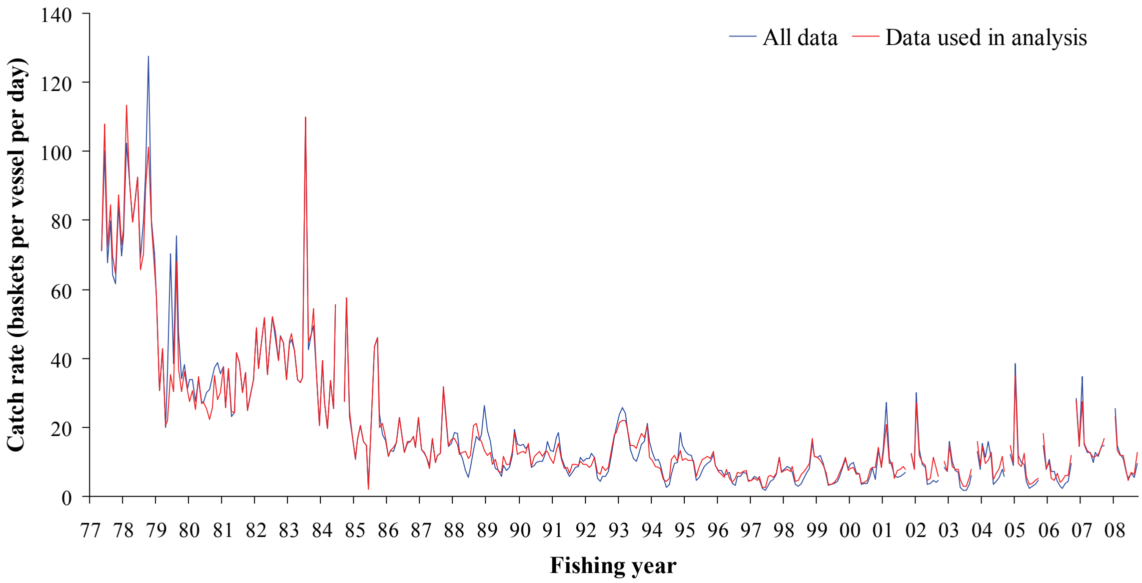


Figure 17-13: Observed monthly scallop catch rates based on both voluntary (1977–1987) and mandatory (1988–2008) logbook data compared to those data used to standardise long-term catch rates in Section 8.3.3 on page 41. Mandatory logbooks were introduced in 1988.

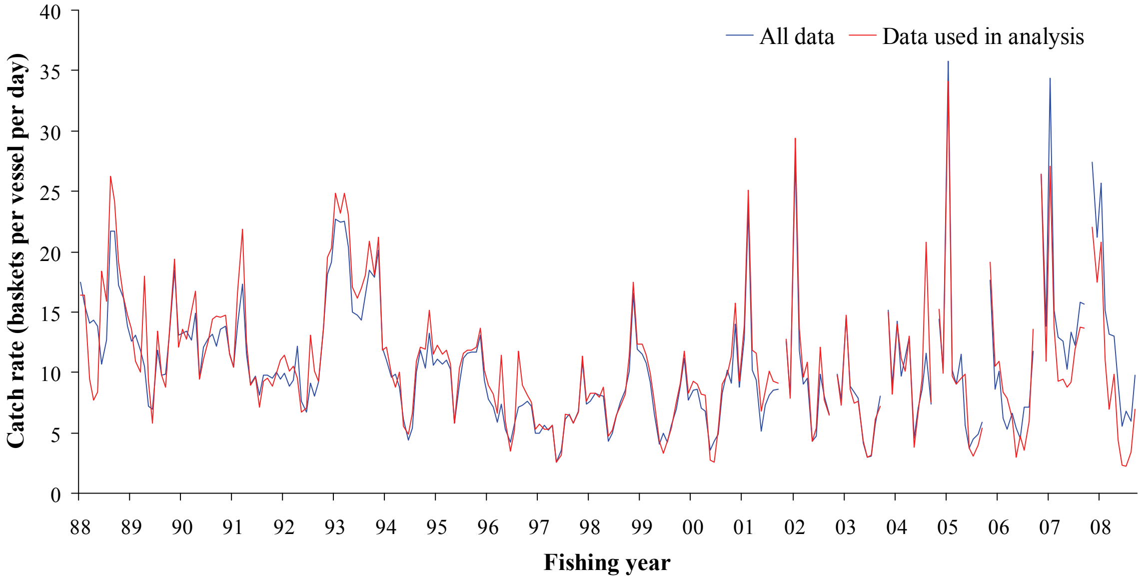


Figure 17-14: Observed monthly scallop catch rates south of 22°S based on all daily logbook data compared to those data used to standardise catch rates in Section 8.3.4 on page 42. The x-axis tick marks represent January of each year.

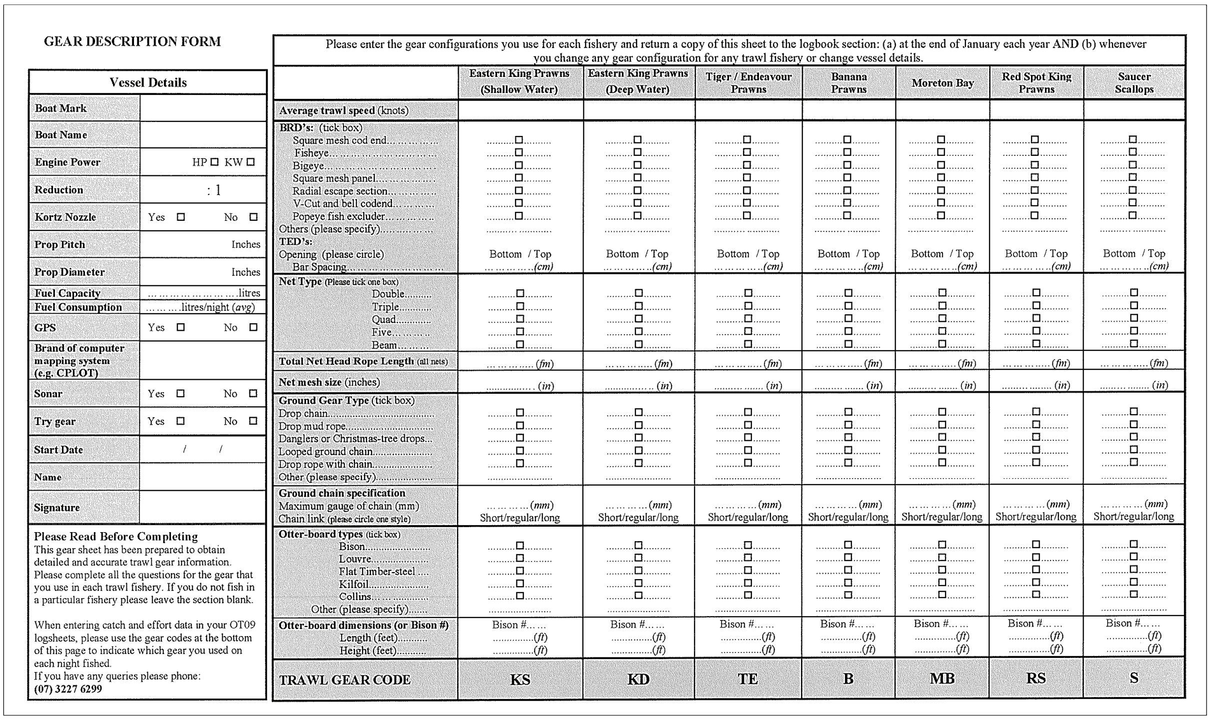
17.4.4 Wald tests for fixed effects and parameter estimates from the REML analysis in Chapter 8

Table 17-1: Wald tests for fixed effects for the REML analysis after dropping individual terms from the full-fixed model. See O'Neill and Leigh (2006) for detailed methods used to generate the data in this table.

Fixed term	Wald statistic	d.f.	Wald/d.f.	chi pr
BRD/TED	6.91	1	6.91	0.009
Board type	56.91	3	18.97	<0.001
Ground gear type	78.06	4	19.51	<0.001
Net size	77.01	1	77.01	<0.001
Number of nets	40.14	3	13.38	<0.001
GPS	1.29	1	1.29	0.256
Horsepower	86.99	1	86.99	<0.001
Lunar phase	40.33	1	40.33	<0.001
Prawn catch	8953.08	1	8953.08	<0.001
Month x CFish grid	2061.06	165	12.49	<0.001
Fish year x CFish grid	6644.66	299	22.22	<0.001
Fish year x month	6067.42	213	28.49	<0.001

Table 17-2: Parameter estimates β_2, β_3, β_4 and standard errors (in parentheses) from the mixed linear model used to standardise catch rates and estimate fishing power changes in the scallop fishery (see Chapter 8). See O'Neill and Leigh (2006) for detailed methods and explanations regarding the parameter estimates. NS = not significant.

Component	Parameter estimate
Engine power rating	0.208 (0.022)
GPS	-0.014 (0.012)
Sonar	NS
Kort Nozzle	NS
Try Gear	NS
Prawn catch	-0.242 (0.003)
Lunar phase	-0.040 (0.006)
Net type	
Twin	0
Triple	0.113 (0.039)
Quad	0.123 (0.040)
Five gear	0.539 (0.086)
Net length	0.172 (0.020)
Ground gear	
Drop chain	0
Drop chain with sliding rings	0.053 (0.016)
Loop chain	0.050 (0.013)
Drop rope	0.065 (0.021)
Other	-0.130 (0.021)
Board type	
Flat	0
Bison	-0.070 (0.022)
Louvre	0.033 (0.012)
Kilfoil	0.130 (0.020)
Presence of BRD/TED	0.038 (0.014)



GEAR DESCRIPTION FORM

Vessel Details	
Boat Mark	
Boat Name	
Engine Power	HP ☐ KW ☐
Reduction	: 1
Kortz Nozzle	Yes ☐ No ☐
Prop Pitch	Inches
Prop Diameter	Inches
Fuel Capacity	………………………litres
Fuel Consumption	………litres/night (*avg*)
GPS	Yes ☐ No ☐
Brand of computer mapping system (e.g. CPLOT)	
Sonar	Yes ☐ No ☐
Try gear	Yes ☐ No ☐
Start Date	/ /
Name	
Signature	

Please Read Before Completing
This gear sheet has been prepared to obtain detailed and accurate trawl gear information. Please complete all the questions for the gear that you use in each trawl fishery. If you do not fish in a particular fishery please leave the section blank.

When entering catch and effort data in your OT09 logsheets, please use the gear codes at the bottom of this page to indicate which gear you used on each night fished.
If you have any queries please phone:
(07) 3227 6299

Please enter the gear configurations you use for each fishery and return a copy of this sheet to the logbook section: (a) at the end of January each year AND (b) whenever you change any gear configuration for any trawl fishery or change vessel details.

	Eastern King Prawns (Shallow Water)	**Eastern King Prawns (Deep Water)**	**Tiger / Endeavour Prawns**	**Banana Prawns**	**Moreton Bay**	**Red Spot King Prawns**	**Saucer Scallops**
Average trawl speed (knots)							
BRD's: (tick box)							
Square mesh cod end…………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Fisheye…………………………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Bigeye…………………………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Square mesh panel…………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Radial escape section………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
V-Cut and bell codend………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Popeye fish excluder…………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Others (please specify)…………	…………	…………	…………	…………	…………	…………	…………
TED's:							
Opening (please circle)	Bottom / Top	Bottom / Top	Bottom / Top	Bottom / Top	Bottom / Top	Bottom / Top	Bottom / Top
Bar Spacing………………………	…………(*cm*)	…………(*cm*)	…………(*cm*)	…………(*cm*)	…………(*cm*)	…………(*cm*)	…………(*cm*)
Net Type (Please tick one box)							
Double………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Triple………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Quad………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Five………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Beam………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Total Net Head Rope Length (all nets)	…………(*fm*)	…………(*fm*)	…………(*fm*)	…………(*fm*)	…………(*fm*)	…………(*fm*)	…………(*fm*)
Net mesh size (inches)	…………(*in*)	…………(*in*)	…………(*in*)	…………(*in*)	…………(*in*)	…………(*in*)	…………(*in*)
Ground Gear Type (tick box)							
Drop chain………………………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Drop mud rope…………………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Danglers or Christmas-tree drops…	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Looped ground chain…………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Drop rope with chain…………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Other (please specify)…………	…………	…………	…………	…………	…………	…………	…………
Ground chain specification							
Maximum gauge of chain (mm)	…………(*mm*)	…………(*mm*)	…………(*mm*)	…………(*mm*)	…………(*mm*)	…………(*mm*)	…………(*mm*)
Chain link (please circle one style)	Short/regular/long	Short/regular/long	Short/regular/long	Short/regular/long	Short/regular/long	Short/regular/long	Short/regular/long
Otter-board types (tick box)							
Bison…………………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Louvre…………………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Flat Timber-steel ….	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Kilfoil…………………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Collins…………………	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……	……☐……
Other (please specify)……	…………	…………	…………	…………	…………	…………	…………
Otter-board dimensions (or Bison #)	Bison #……	Bison #……	Bison #……	Bison #……	Bison #……	Bison #……	Bison #……
Length (feet)………	…………(*ft*)	…………(*ft*)	…………(*ft*)	…………(*ft*)	…………(*ft*)	…………(*ft*)	…………(*ft*)
Height (feet)………	…………(*ft*)	…………(*ft*)	…………(*ft*)	…………(*ft*)	…………(*ft*)	…………(*ft*)	…………(*ft*)
TRAWL GEAR CODE	**KS**	**KD**	**TE**	**B**	**MB**	**RS**	**S**

Figure 17-15: Gear description data form from the commercial trawl logbook used to generate data for the REML analysis in Chapter 8.

17.5 ADDITIONAL INFORMATION FOR THE HARVEST STRATEGY EVALUATION - CHAPTER 9

17.5.1 GENSTAT code used to standardise catch rates for the Harvest Strategy Evaluation

The GenStat (2007) code below was used to generate the standardised catch rate data for Section 9.2.4.1 on page 64.

```
VCOMPONENTS [FIXED=
fishyear*month*Region+logprawns+lunar+lunar_adv+loghours+loghp+gps2+nettype
+lognet+ggear4+boards+brdted; FACTORIAL=3]\
RANDOM=boat_mark;  INITIAL=1; CONSTRAINTS=positive
REML
[PRINT=model,components,effects,vcovariance,deviance,waldTests,covariancemo
del,means;\
PSE=allestimates; MVINCLUDE=*; method=ai;]logn

vpredict [print=description,predictions] fishyear,month,Region
```

17.5.2 Posterior Distributions for relevant parameters and Goodness of Fit of predicted CPUE from Chapter 9

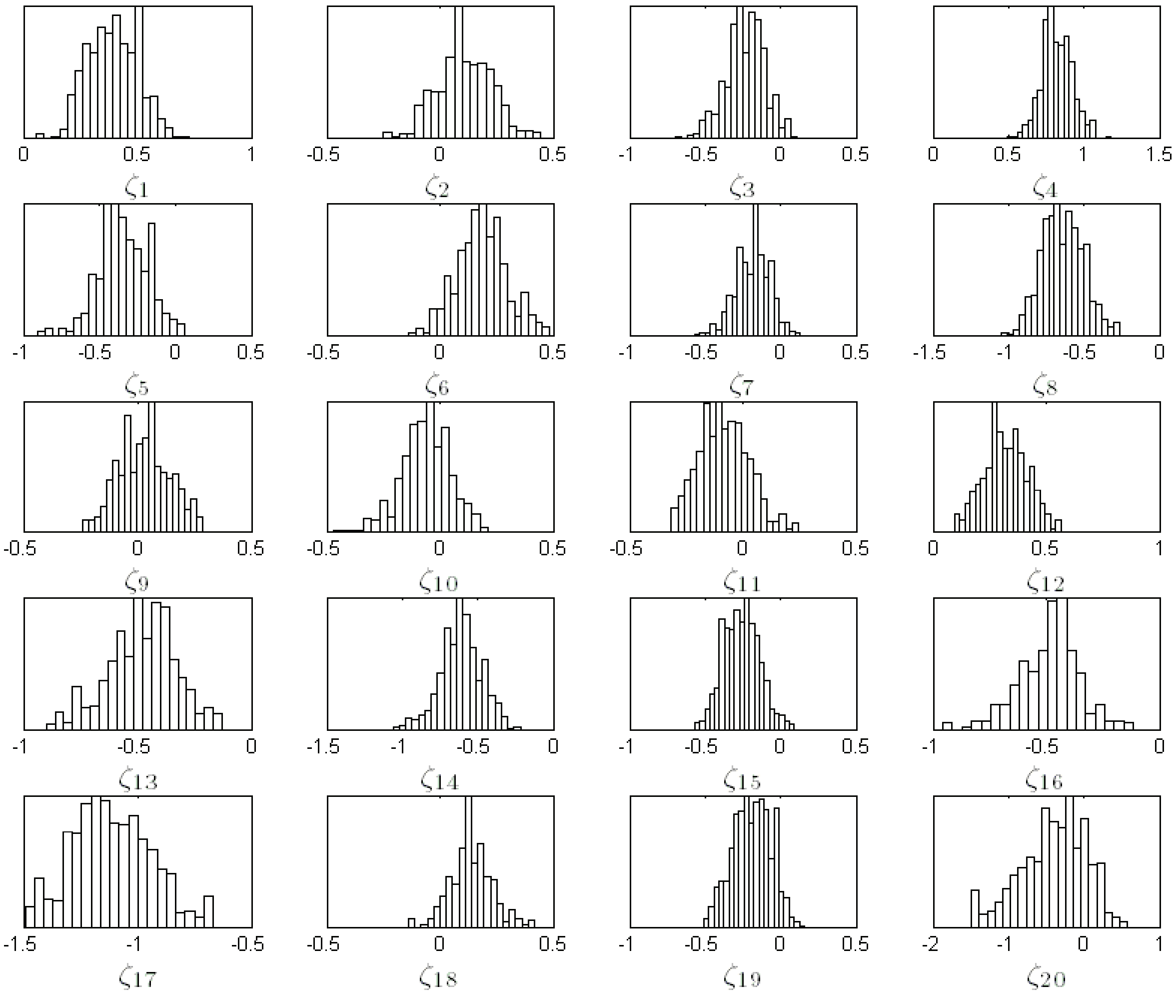


Figure 17-16: Posterior distributions for the 20 annual recruitment anomalies, representing anomalies in 1998 through 2008.

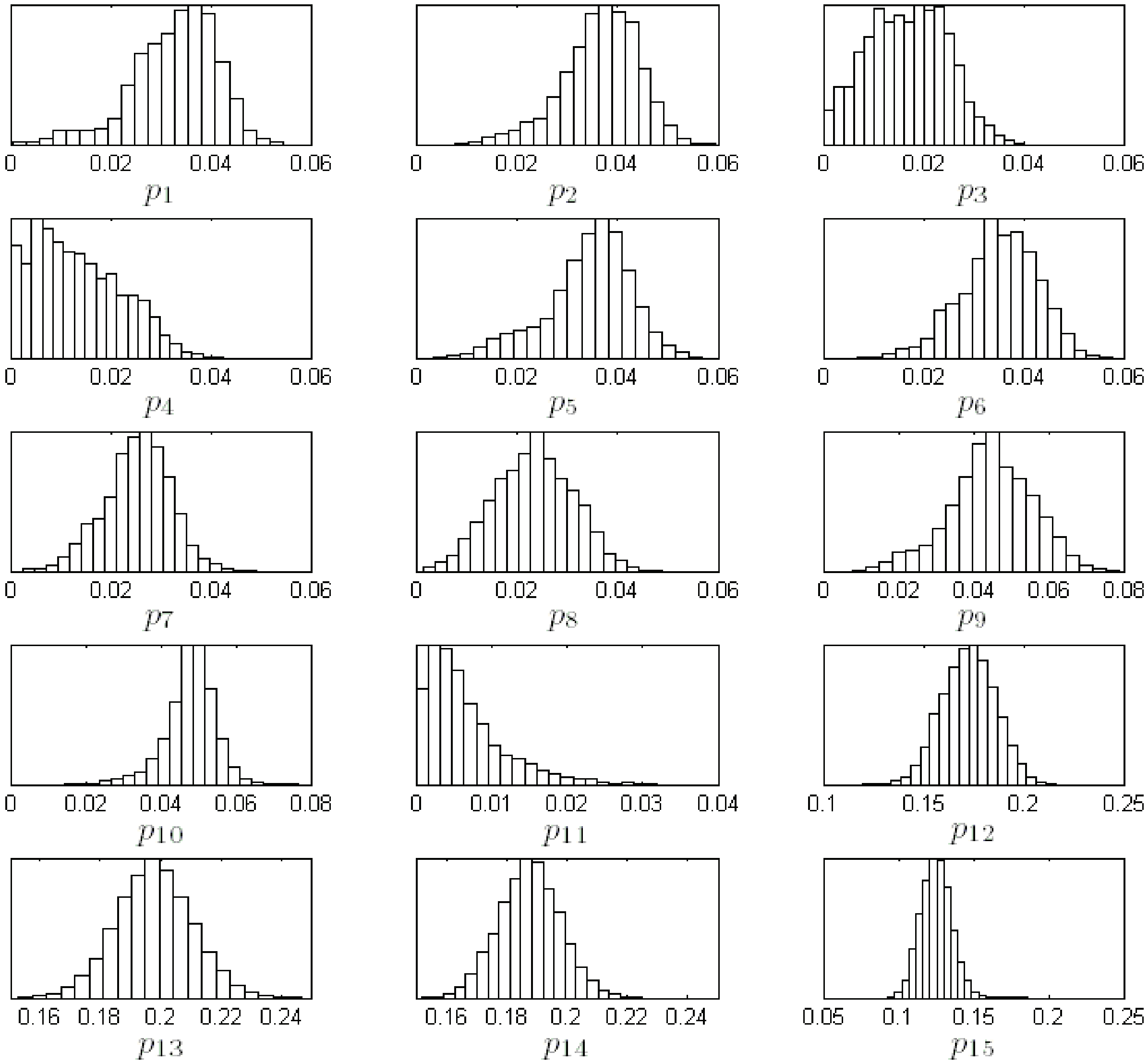


Figure 17-17: Posterior distributions from the 15 spatial recruitment proportion parameters, representing the proportion of annual recruitment allocated to regions 1 through 15.

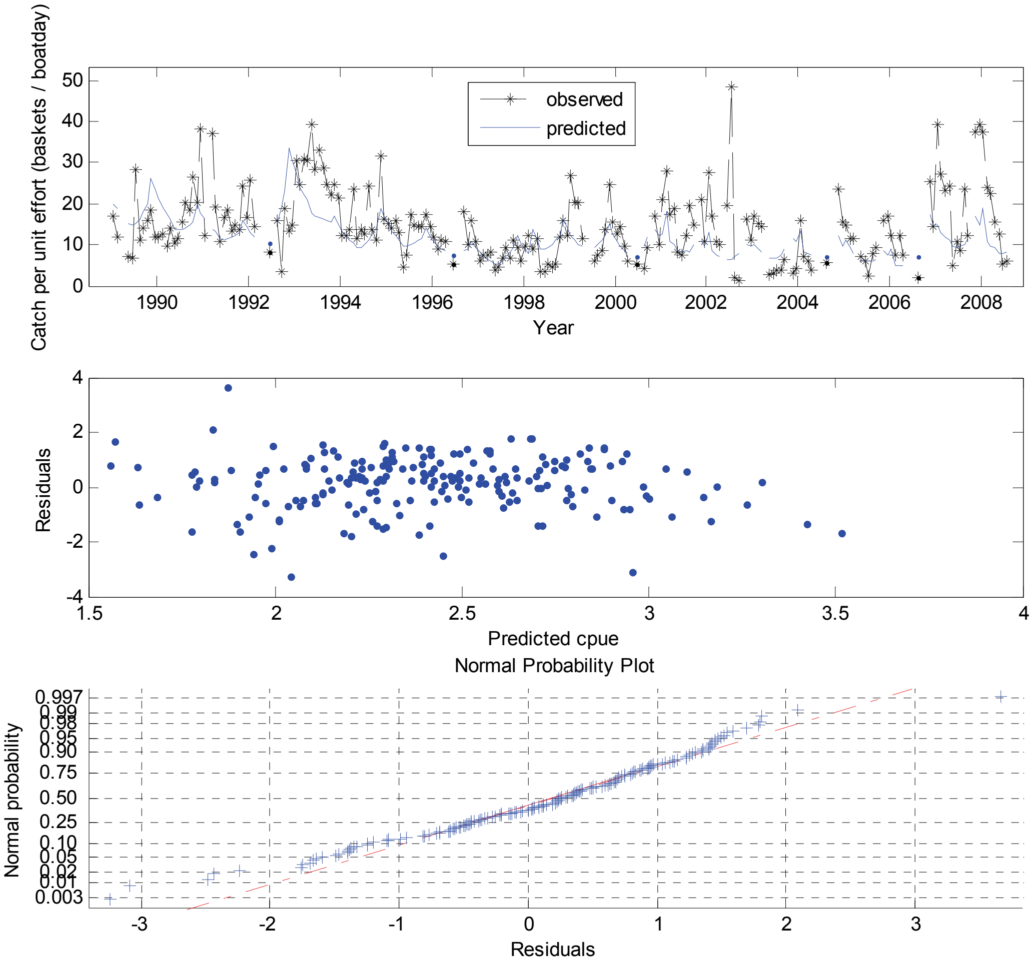


Figure 17-18: Goodness of fit and diagnostics for metapopulation one (ie. Regions 9, 10 and 12, inclusive, in Figure 9-2) CPUE.

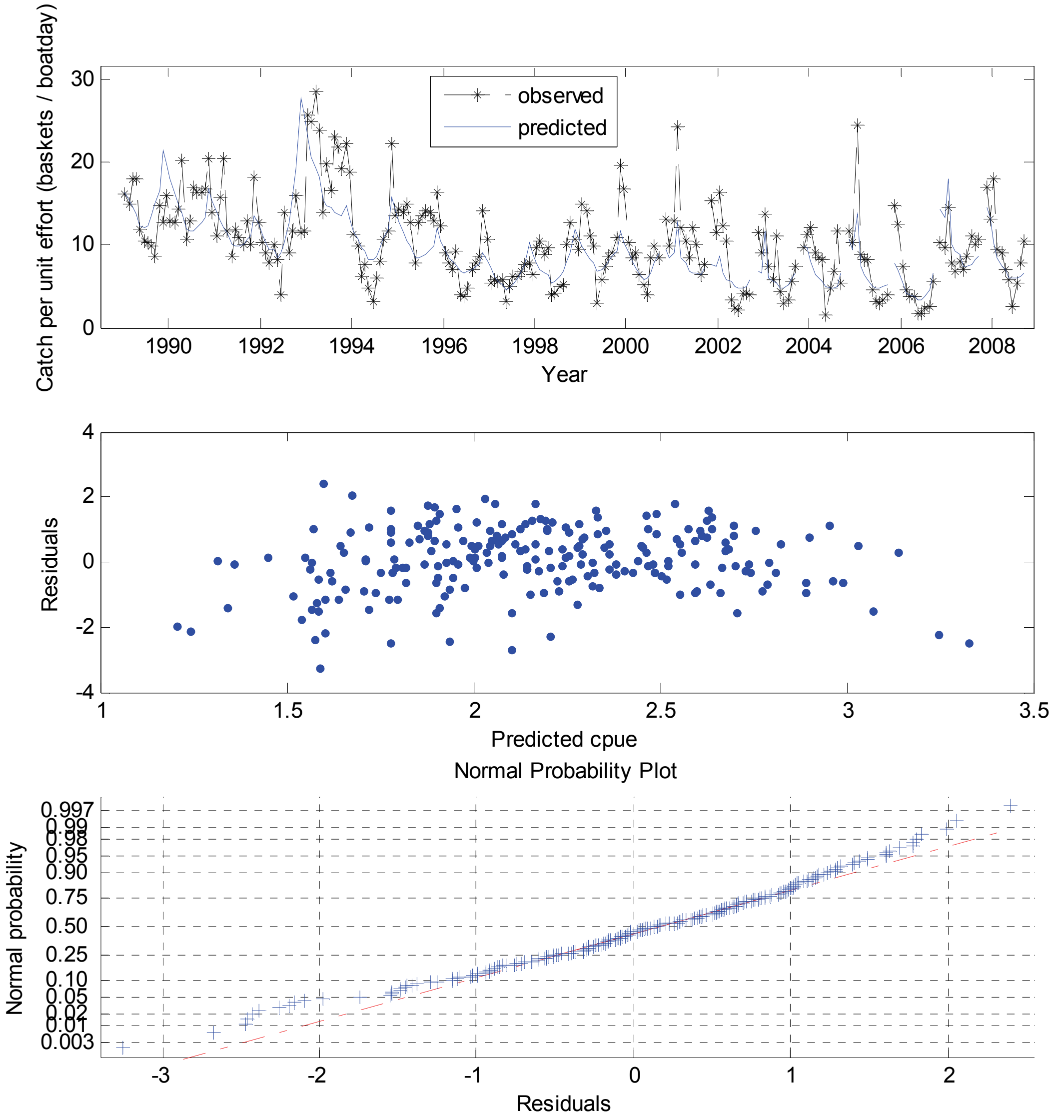


Figure 17-19: Goodness of fit and diagnostics for metapopulation two (ie. Regions 5, 6, 7, 8, 11 and 13, inclusive, in Figure 9-2) CPUE.

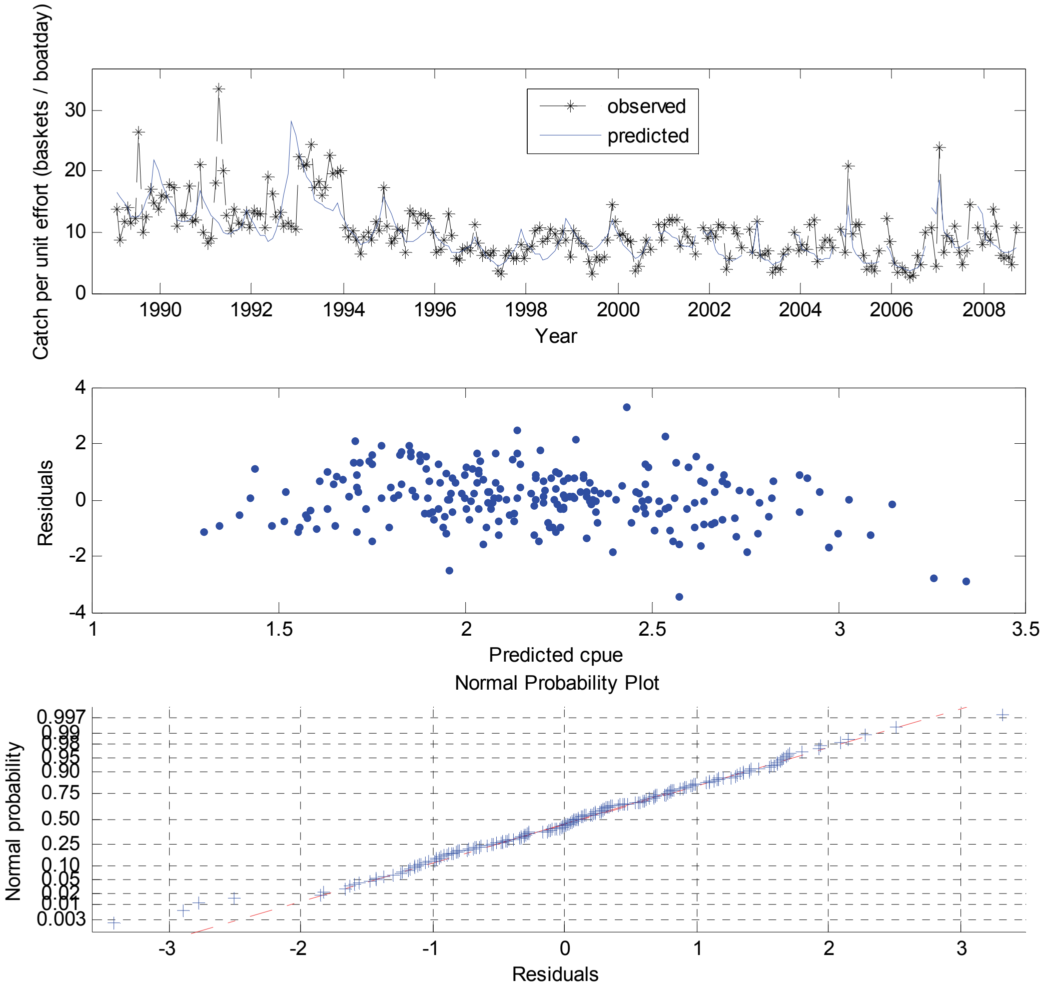


Figure 17-20: Goodness of fit and diagnostics for metapopulation three (ie. Regions 1, 2, 3, 4 and 14, inclusive, in Figure 9-2) CPUE.

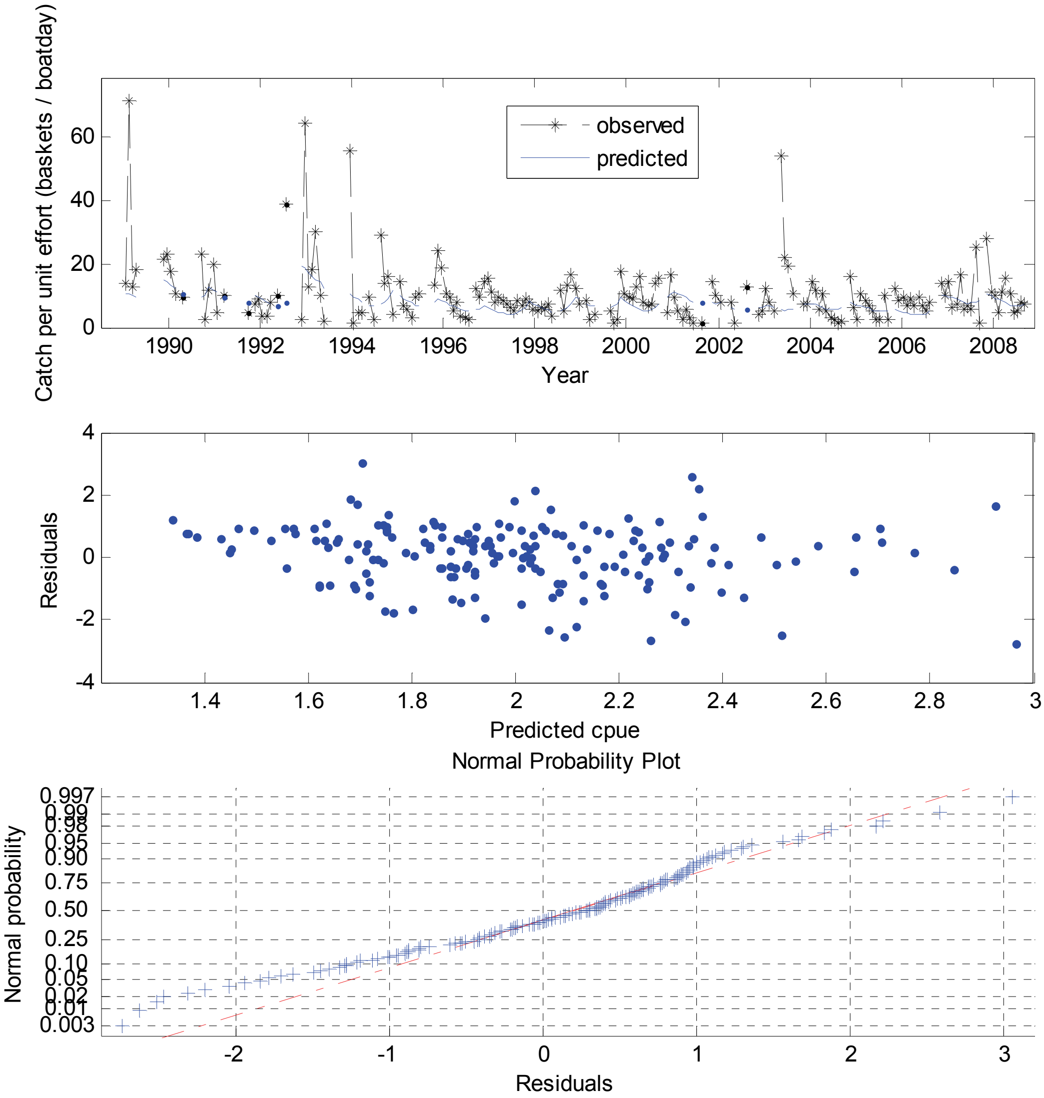
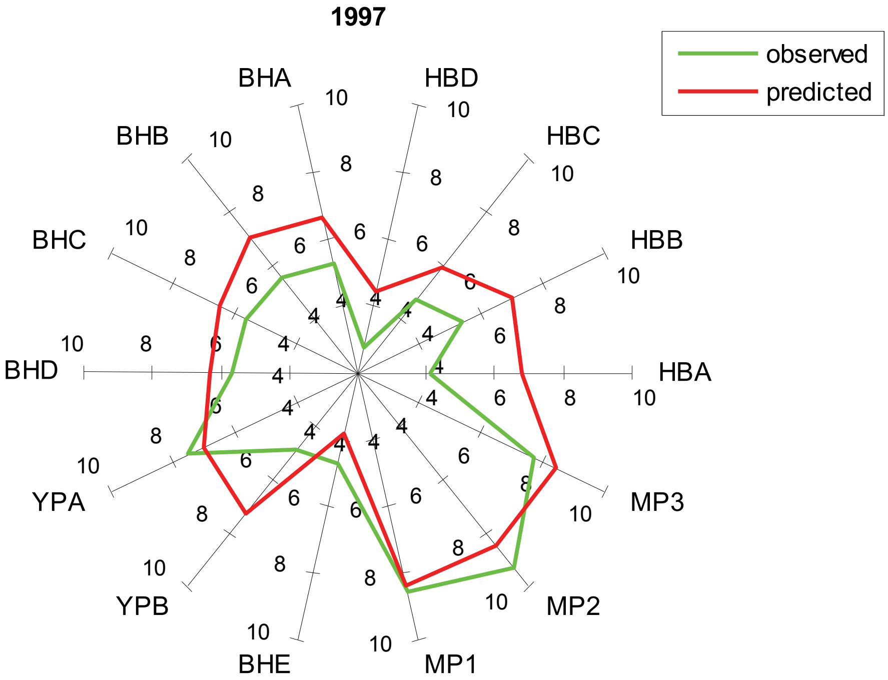


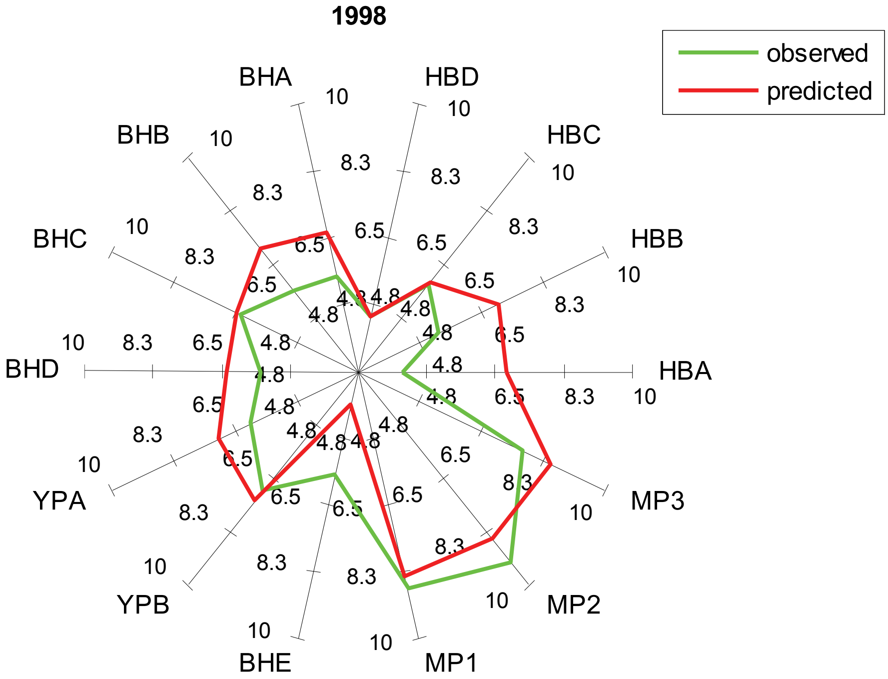
Figure 17-21: Goodness of fit and diagnostics for metapopulation four (ie. Region 15 in Figure 9-2) CPUE.

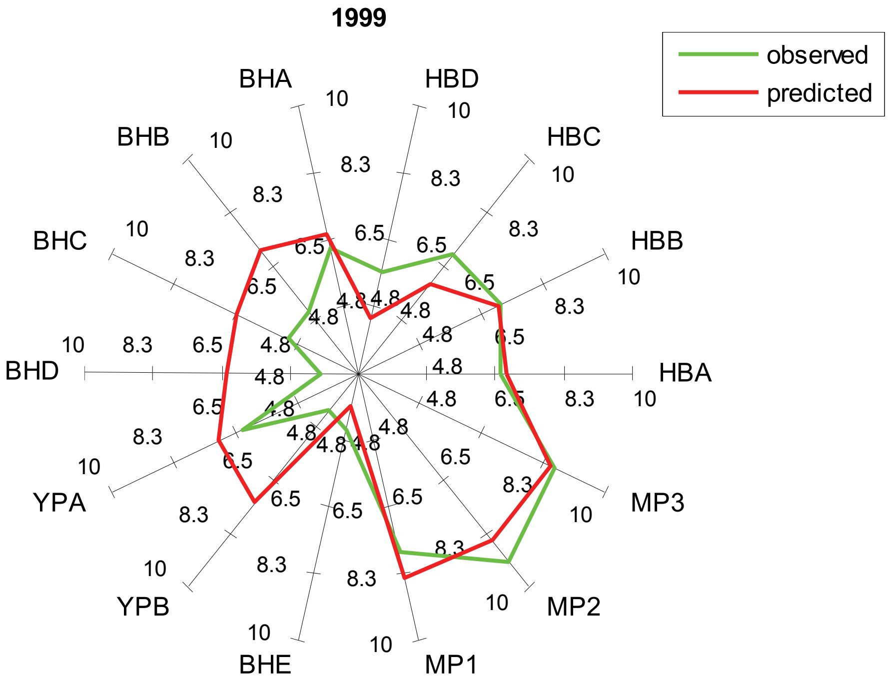
17.5.3 Goodness of Fit of predicted spatial recruitment patterns used in the HSE in Chapter 9

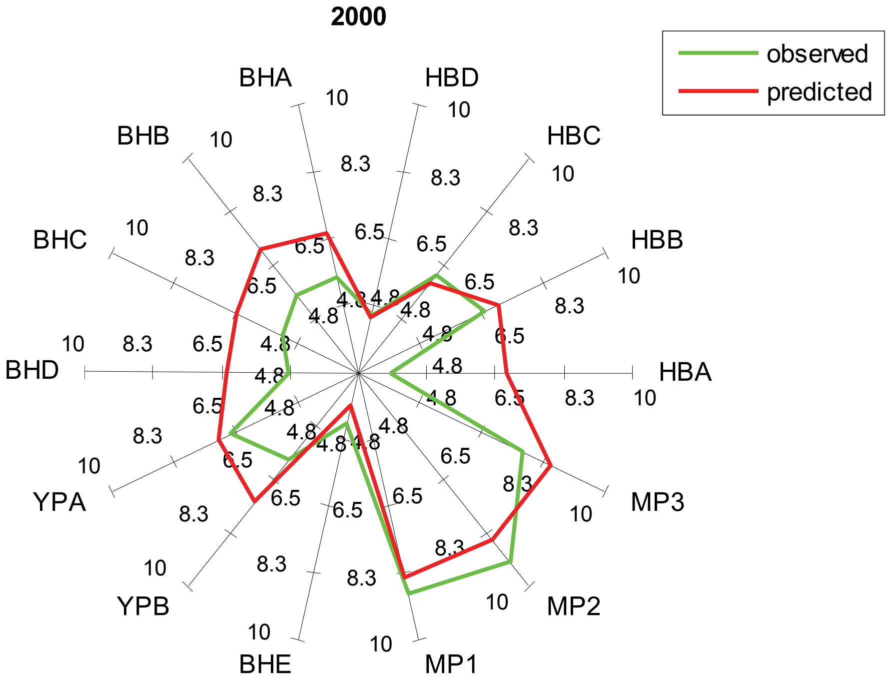
Goodness of fit radar plot of spatial recruitment patterns based on data supplied by the Long Term Monitoring Program, reported by O'Sullivan, Jebreen *et al.* (2005). See Figure 17-1 and Figure 9-2 for information relating to the location of each region. Note that only the SRAs were sampled from 2001 onwards.

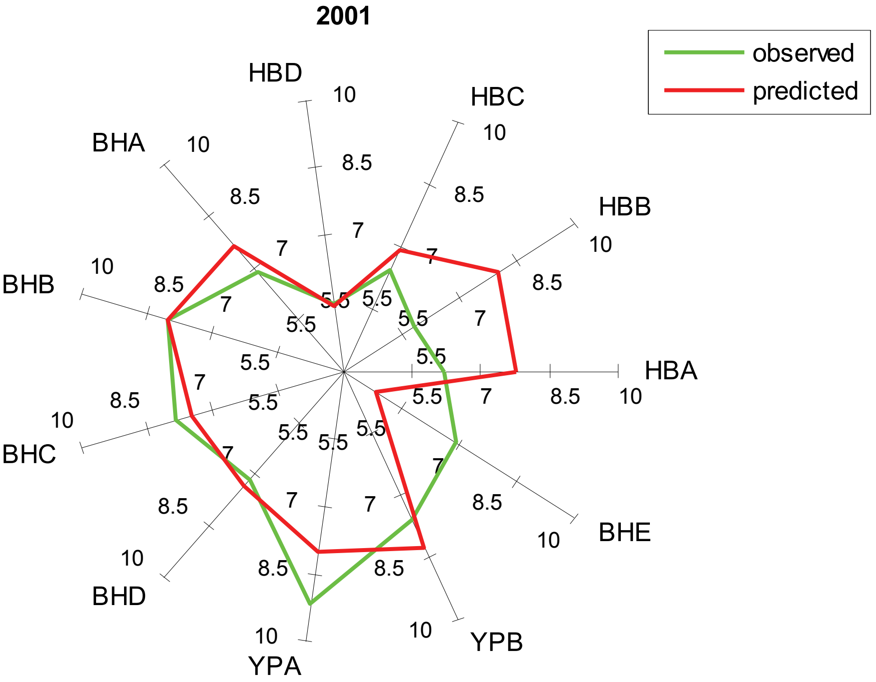
The following radar plots all use a logscale with the following equation: response = 10+log(proportion). First set of plots are spatial recruitment patterns:

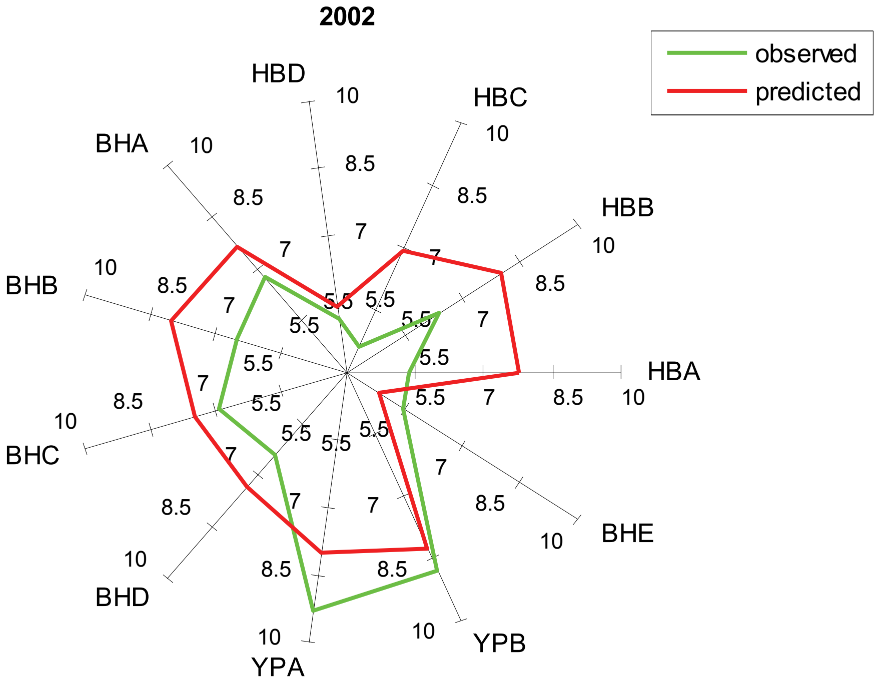


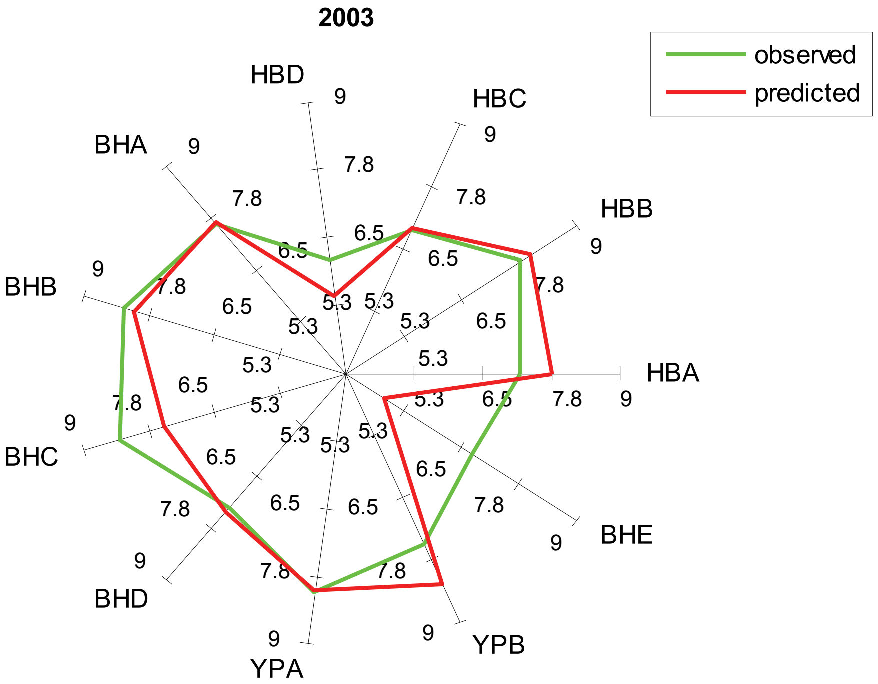


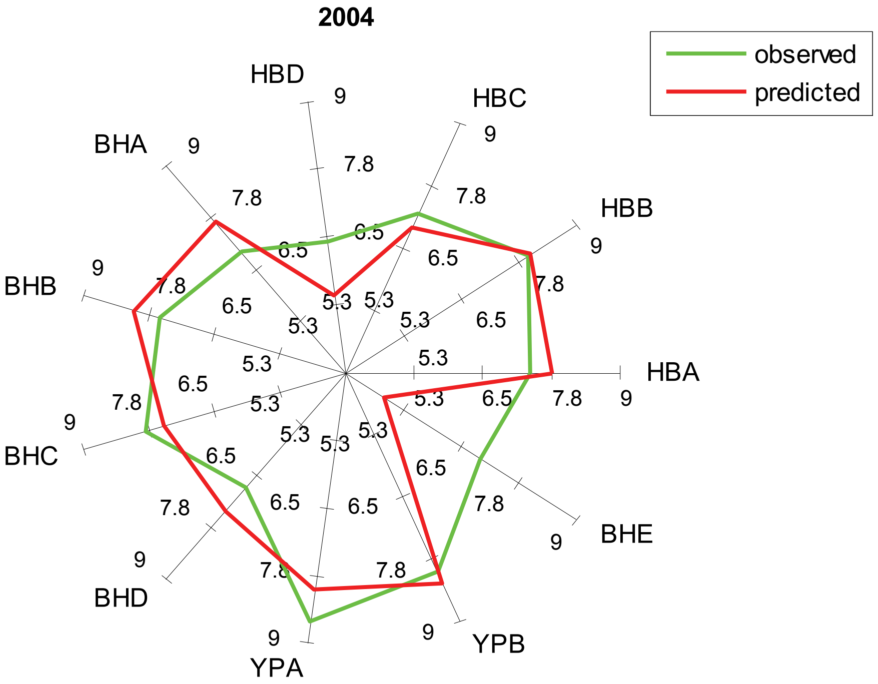

1999
observed
predicted
BHA
HBD
HBC
HBB
HBA
MP3
MP2
MP1
BHE
YPB
YPA
BHD
BHC
BHB
10
8.3
6.5
4.8

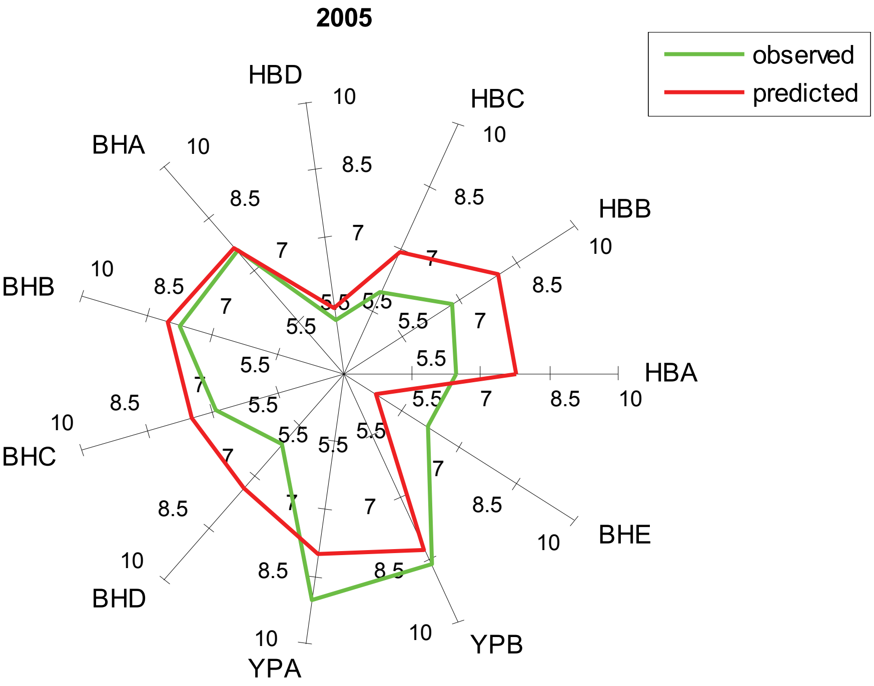

2000
observed
predicted
BHA
HBD
HBC
HBB
HBA
MP3
MP2
MP1
BHE
YPB
YPA
BHD
BHC
BHB
10
8.3
6.5
4.8

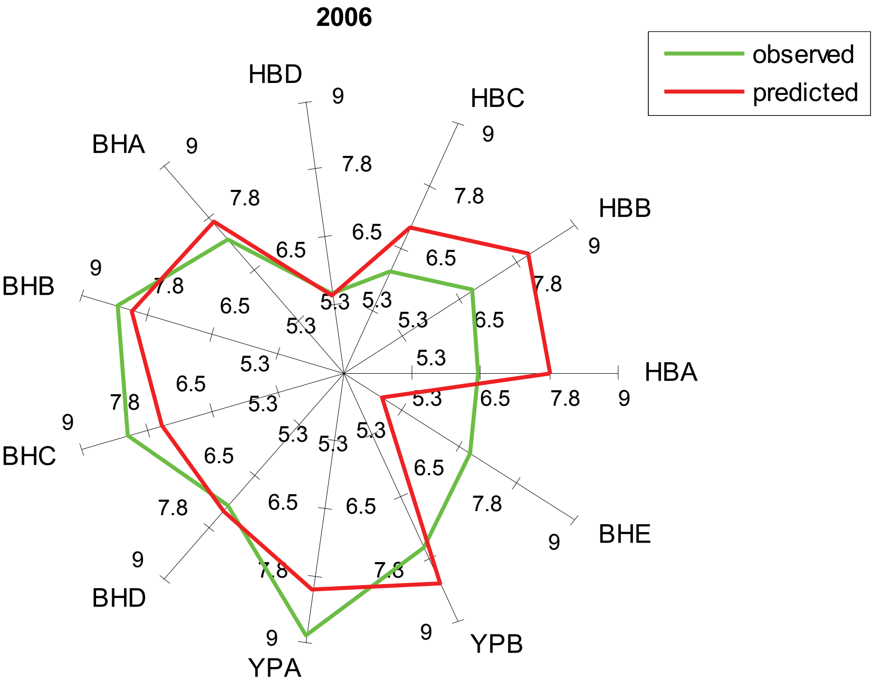

2001
observed
predicted
HBD
HBC
HBB
HBA
BHE
YPB
YPA
BHD
BHC
BHB
BHA
5.5
7
8.5
10


2002
observed
predicted
HBD
HBC
HBB
HBA
BHE
YPB
YPA
BHD
BHC
BHB
BHA
5.5
7
8.5
10


2003
observed
predicted
HBD
HBC
HBB
HBA
BHE
YPB
YPA
BHD
BHC
BHB
BHA
5.3
6.5
7.8
9

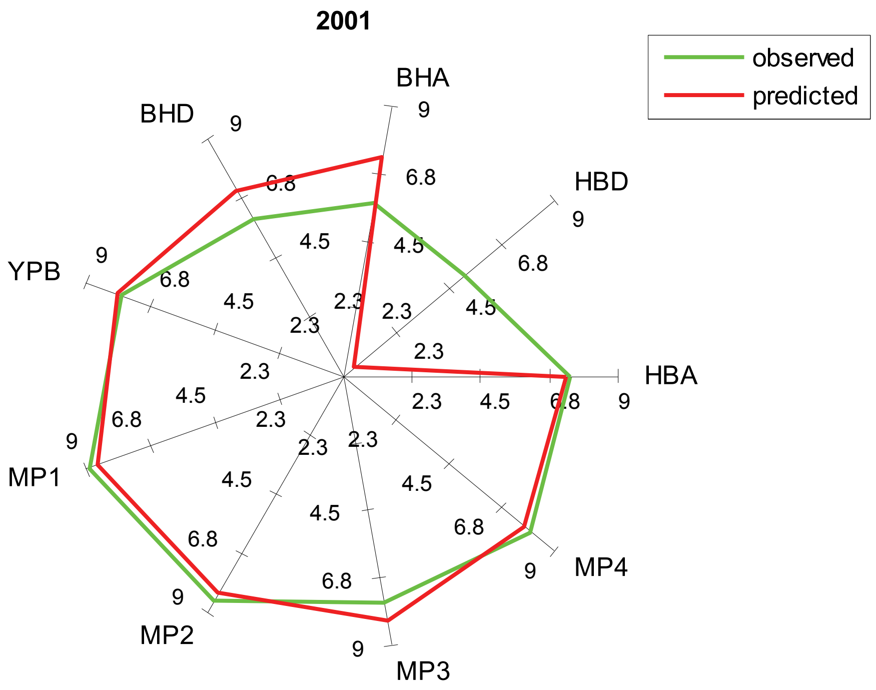

2004
observed
predicted
HBD
HBC
HBB
HBA
BHE
YPB
YPA
BHD
BHC
BHB
BHA
5.3
6.5
7.8
9

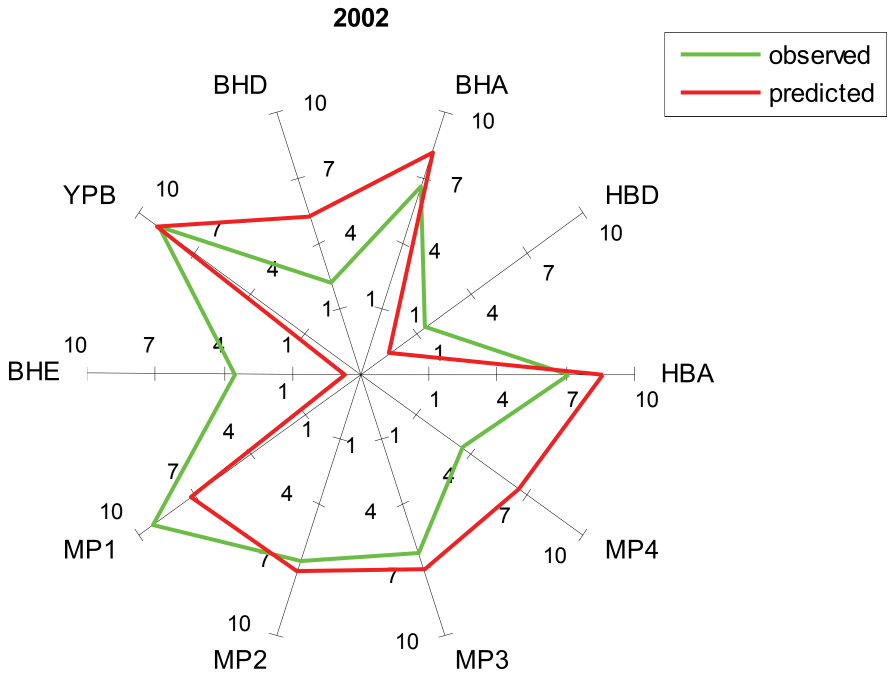

2005
observed
predicted
HBD
HBC
HBB
HBA
BHE
YPB
YPA
BHD
BHC
BHB
BHA
10
8.5
7
5.5

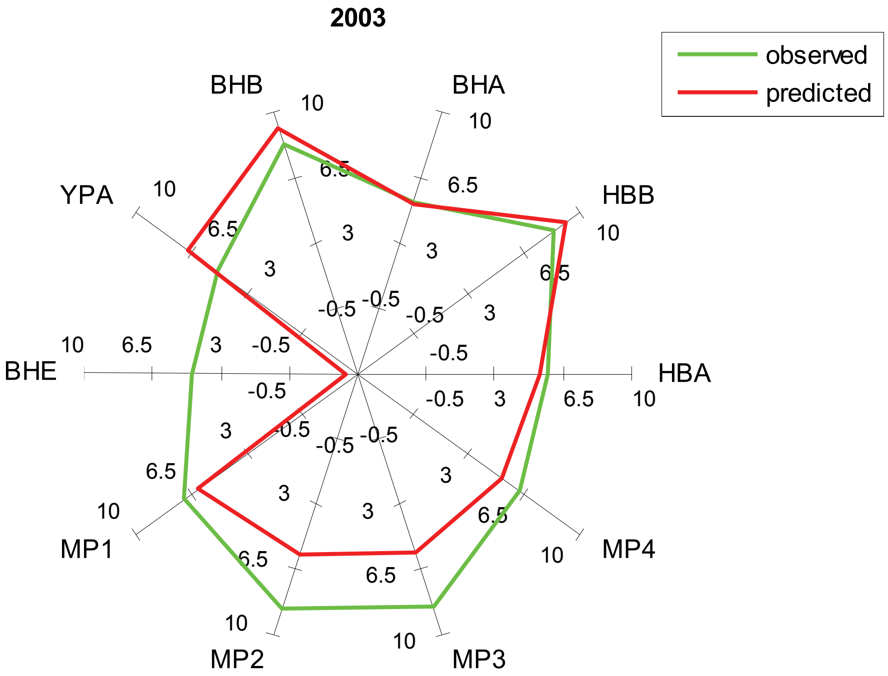

2006
observed
predicted
HBD
HBC
HBB
HBA
BHE
YPB
YPA
BHD
BHC
BHB
BHA
9
7.8
6.5
5.3

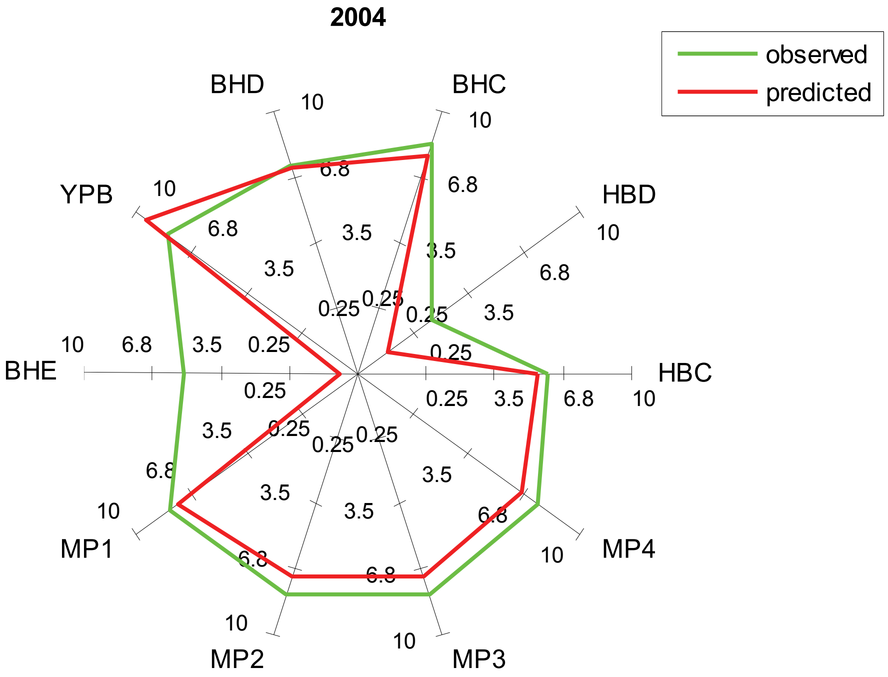
17.5.4 Goodness of Fit of predicted catch proportions compared to VMS-derived catches in Chapter 9

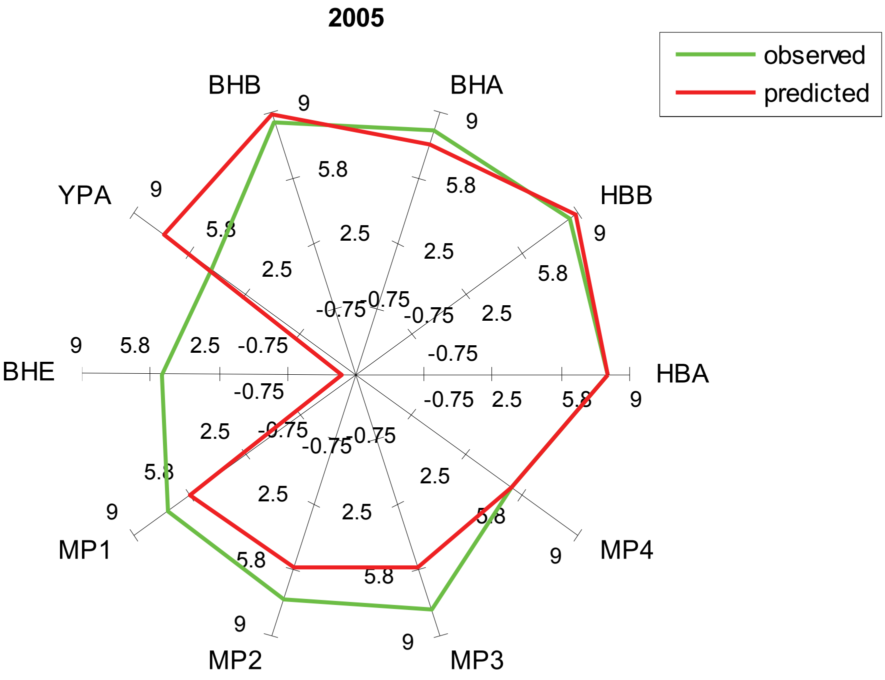
The following are spatial catch proportions in January of 2001 through 2006 – goodness of fit to VMS derived catches. These plots also use a log-scale approach where response = 10+log(proportion).

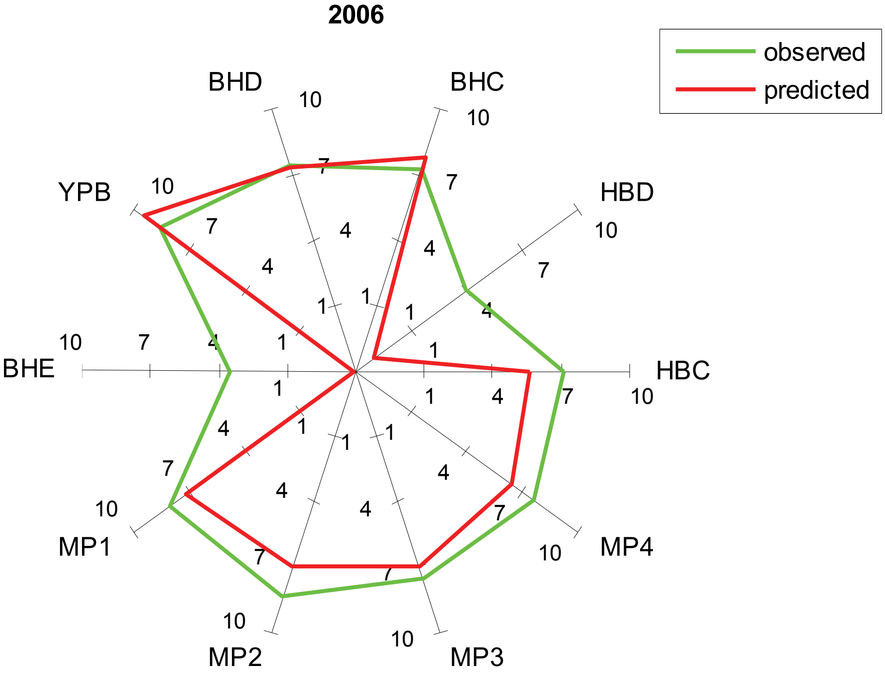





2003
observed
predicted
BHB
BHA
HBB
HBA
MP4
MP3
MP2
MP1
BHE
YPA
10
6.5
3
-0.5

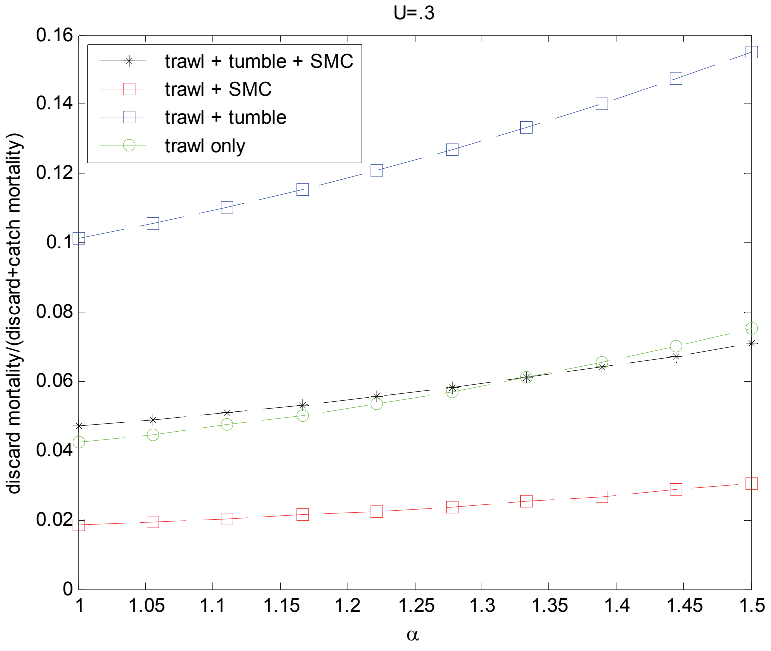

2004
observed
predicted
BHD
BHC
HBD
HBC
MP4
MP3
MP2
MP1
BHE
YPB
10
6.8
3.5
0.25

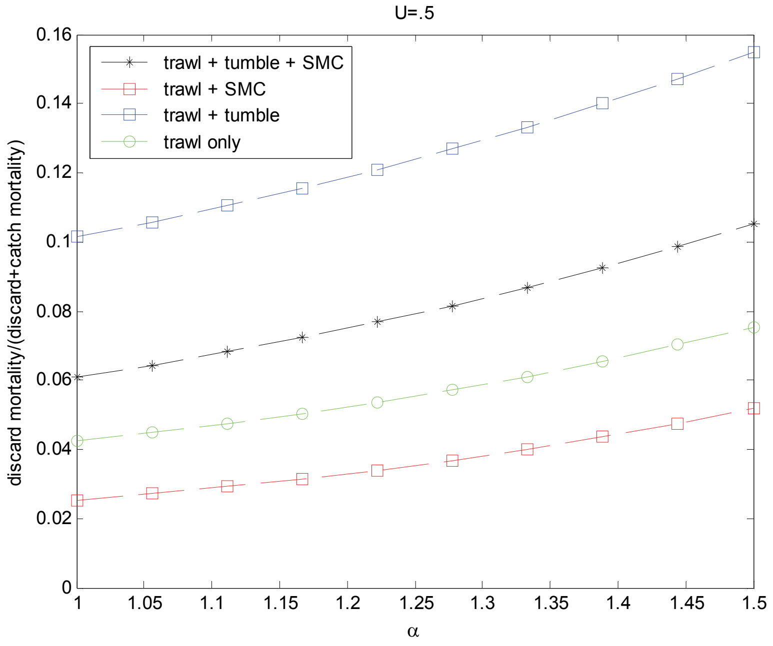


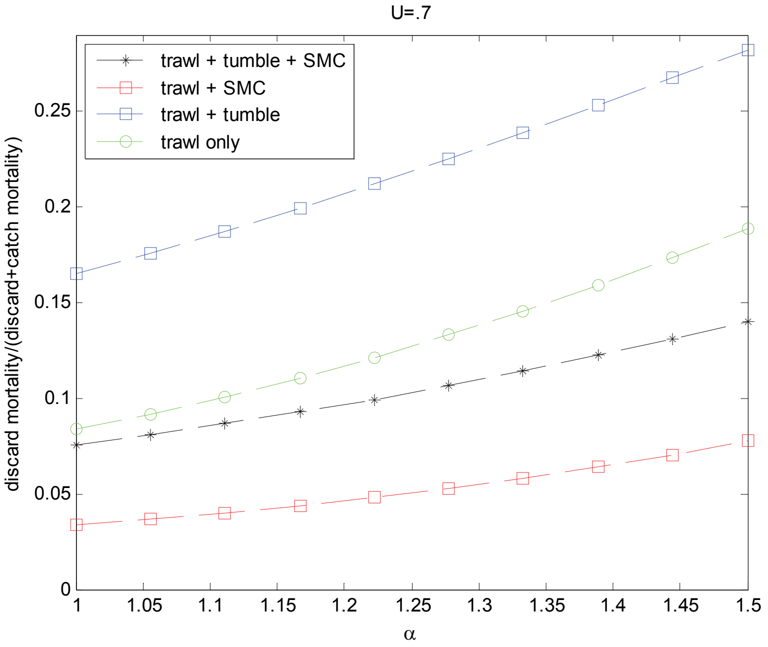


17.5.5 Discard Mortality

Proportion of total mortality attributable to tumbling over three harvest rates scenarios (U), two selectivity curve scenarios (SMCs or no SMCs), and a range of 'spatial aggregation' scenarios (α). See Section 9.2.3 on page 60 and Section 9.3.1 on page 80 for details.


U=.3
discard mortality/(discard+catch mortality)
α
trawl + tumble + SMC
trawl + SMC
trawl + tumble
trawl only
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
1.5


U=.5
discard mortality/(discard+catch mortality)
α
trawl + tumble + SMC
trawl + SMC
trawl + tumble
trawl only
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
1.5



17.5.6 *LTMP Survey catch rates according to closure duration*

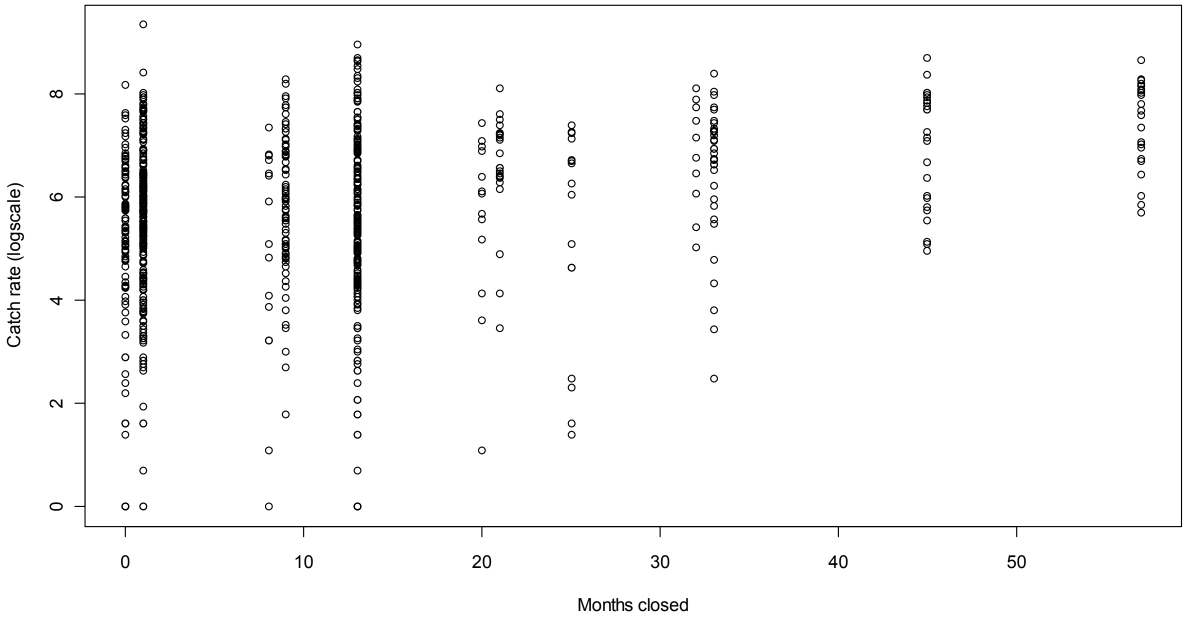
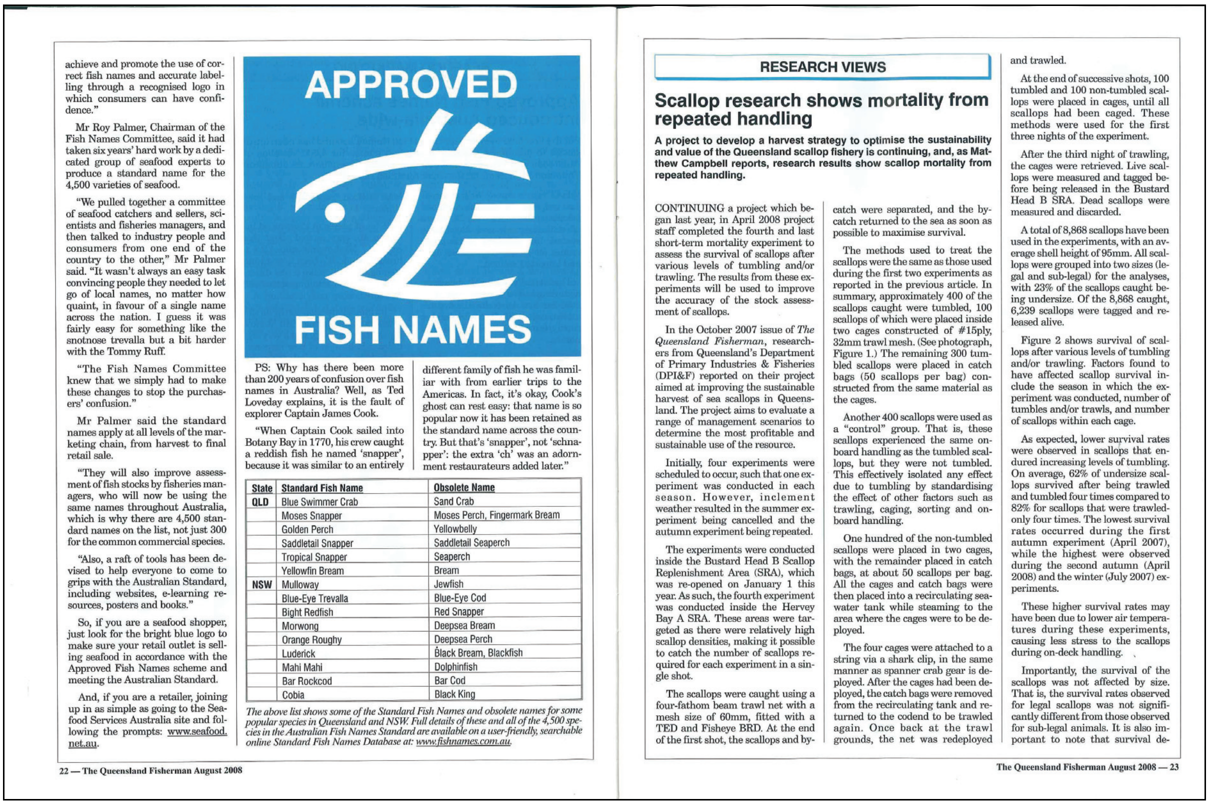


Figure 17-22: LTMP Recruitment Survey catch rates as a function of closure duration.

17.6 THE QUEENSLAND FISHERMAN ARTICLE REGARDING DISCARD SURVIVAL

The following article, published in the industry magazine The Queensland Fisherman, informed fishers about the survival of discarded sub-legal scallops. The article was designed to give fishers some detail regarding the methods used and the results gained during the survival experiments conducted within the Bustard Head B SRA.



achieve and promote the use of correct fish names and accurate labelling through a recognised logo in which consumers can have confidence."

Mr Roy Palmer, Chairman of the Fish Names Committee, said it had taken six years' hard work by a dedicated group of seafood experts to produce a standard name for the 4,500 varieties of seafood.

"We pulled together a committee of seafood catchers and sellers, scientists and fisheries managers, and then talked to industry people and consumers from one end of the country to the other," Mr Palmer said. "It wasn't always an easy task convincing people they needed to let go of local names, no matter how quaint, in favour of a single name across the nation. I guess it was fairly easy for something like the snotnose trevalla but a bit harder with the Tommy Ruff.

"The Fish Names Committee knew that we simply had to make these changes to stop the purchasers' confusion."

Mr Palmer said the standard names apply at all levels of the marketing chain, from harvest to final retail sale.

"They will also improve assessment of fish stocks by fisheries managers, who will now be using the same names throughout Australia, which is why there are 4,500 standard names on the list, not just 300 for the common commercial species.

"Also, a raft of tools has been devised to help everyone to come to grips with the Australian Standard, including websites, e-learning resources, posters and books."

So, if you are a seafood shopper, just look for the bright blue logo to make sure your retail outlet is selling seafood in accordance with the Approved Fish Names scheme and meeting the Australian Standard.

And, if you are a retailer, joining up in as simple as going to the Seafood Services Australia site and following the prompts: www.seafood.net.au.

APPROVED
FISH NAMES

PS: Why has there been more than 200 years of confusion over fish names in Australia? Well, as Ted Loveday explains, it is the fault of explorer Captain James Cook.

"When Captain Cook sailed into Botany Bay in 1770, his crew caught a reddish fish he named 'snapper', because it was similar to an entirely different family of fish he was familiar with from earlier trips to the Americas. In fact, it's okay, Cook's ghost can rest easy: that name is so popular now it has been retained as the standard name across the country. But that's 'snapper', not 'schnapper': the extra 'ch' was an adornment restaurateurs added later."

State	Standard Fish Name	Obsolete Name
QLD	Blue Swimmer Crab	Sand Crab
	Moses Snapper	Moses Perch, Fingermark Bream
	Golden Perch	Yellowbelly
	Saddletail Snapper	Saddletail Seaperch
	Tropical Snapper	Seaperch
	Yellowfin Bream	Bream
NSW	Mulloway	Jewfish
	Blue-Eye Trevalla	Blue-Eye Cod
	Bight Redfish	Red Snapper
	Morwong	Deepsea Bream
	Orange Roughy	Deepsea Perch
	Luderick	Black Bream, Blackfish
	Mahi Mahi	Dolphinfish
	Bar Rockcod	Bar Cod
	Cobia	Black King

The above list shows some of the Standard Fish Names and obsolete names for some popular species in Queensland and NSW. Full details of these and all of the 4,500 species in the Australian Fish Names Standard are available on a user-friendly, searchable online Standard Fish Names Database at: www.fishnames.com.au.

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RESEARCH VIEWS

Scallop research shows mortality from repeated handling

A project to develop a harvest strategy to optimise the sustainability and value of the Queensland scallop fishery is continuing, and, as Matthew Campbell reports, research results show scallop mortality from repeated handling.

CONTINUING a project which began last year, in April 2008 project staff completed the fourth and last short-term mortality experiment to assess the survival of scallops after various levels of tumbling and/or trawling. The results from these experiments will be used to improve the accuracy of the stock assessment of scallops.

In the October 2007 issue of *The Queensland Fisherman*, researchers from Queensland's Department of Primary Industries & Fisheries (DPI&F) reported on their project aimed at improving the sustainable harvest of sea scallops in Queensland. The project aims to evaluate a range of management scenarios to determine the most profitable and sustainable use of the resource.

Initially, four experiments were scheduled to occur, such that one experiment was conducted in each season. However, inclement weather resulted in the summer experiment being cancelled and the autumn experiment being repeated.

The experiments were conducted inside the Bustard Head B Scallop Replenishment Area (SRA), which was re-opened on January 1 this year. As such, the fourth experiment was conducted inside the Hervey Bay A SRA. These areas were targeted as there were relatively high scallop densities, making it possible to catch the number of scallops required for each experiment in a single shot.

The scallops were caught using a four-fathom beam trawl net with a mesh size of 60mm, fitted with a TED and Fisheye BRD. At the end of the first shot, the scallops and by-catch were separated, and the by-catch returned to the sea as soon as possible to maximise survival.

The methods used to treat the scallops were the same as those used during the first two experiments as reported in the previous article. In summary, approximately 400 of the scallops caught were tumbled, 100 scallops of which were placed inside two cages constructed of #15ply, 32mm trawl mesh. (See photograph, Figure 1.) The remaining 300 tumbled scallops were placed in catch bags (50 scallops per bag) constructed from the same material as the cages.

Another 400 scallops were used as a "control" group. That is, these scallops experienced the same onboard handling as the tumbled scallops, but they were not tumbled. This effectively isolated any effect due to tumbling by standardising the effect of other factors such as trawling, caging, sorting and onboard handling.

One hundred of the non-tumbled scallops were placed in two cages, with the remainder placed in catch bags, at about 50 scallops per bag. All the cages and catch bags were then placed into a recirculating seawater tank while steaming to the area where the cages were to be deployed.

The four cages were attached to a string via a shark clip, in the same manner as spanner crab gear is deployed. After the cages had been deployed, the catch bags were removed from the recirculating tank and returned to the codend to be trawled again. Once back at the trawl grounds, the net was redeployed and trawled.

At the end of successive shots, 100 tumbled and 100 non-tumbled scallops were placed in cages, until all scallops had been caged. These methods were used for the first three nights of the experiment.

After the third night of trawling, the cages were retrieved. Live scallops were measured and tagged before being released in the Bustard Head B SRA. Dead scallops were measured and discarded.

A total of 8,868 scallops have been used in the experiments, with an average shell height of 95mm. All scallops were grouped into two sizes (legal and sub-legal) for the analyses, with 23% of the scallops caught being undersize. Of the 8,868 caught, 6,239 scallops were tagged and released alive.

Figure 2 shows survival of scallops after various levels of tumbling and/or trawling. Factors found to have affected scallop survival include the season in which the experiment was conducted, number of tumbles and/or trawls, and number of scallops within each cage.

As expected, lower survival rates were observed in scallops that endured increasing levels of tumbling. On average, 62% of undersize scallops survived after being trawled and tumbled four times compared to 82% for scallops that were trawled-only four times. The lowest survival rates occurred during the first autumn experiment (April 2007), while the highest were observed during the second autumn (April 2008) and the winter (July 2007) experiments.

These higher survival rates may have been due to lower air temperatures during these experiments, causing less stress to the scallops during on-deck handling.

Importantly, the survival of the scallops was not affected by size. That is, the survival rates observed for legal scallops was not significantly different from those observed for sub-legal animals. It is also important to note that survival de-

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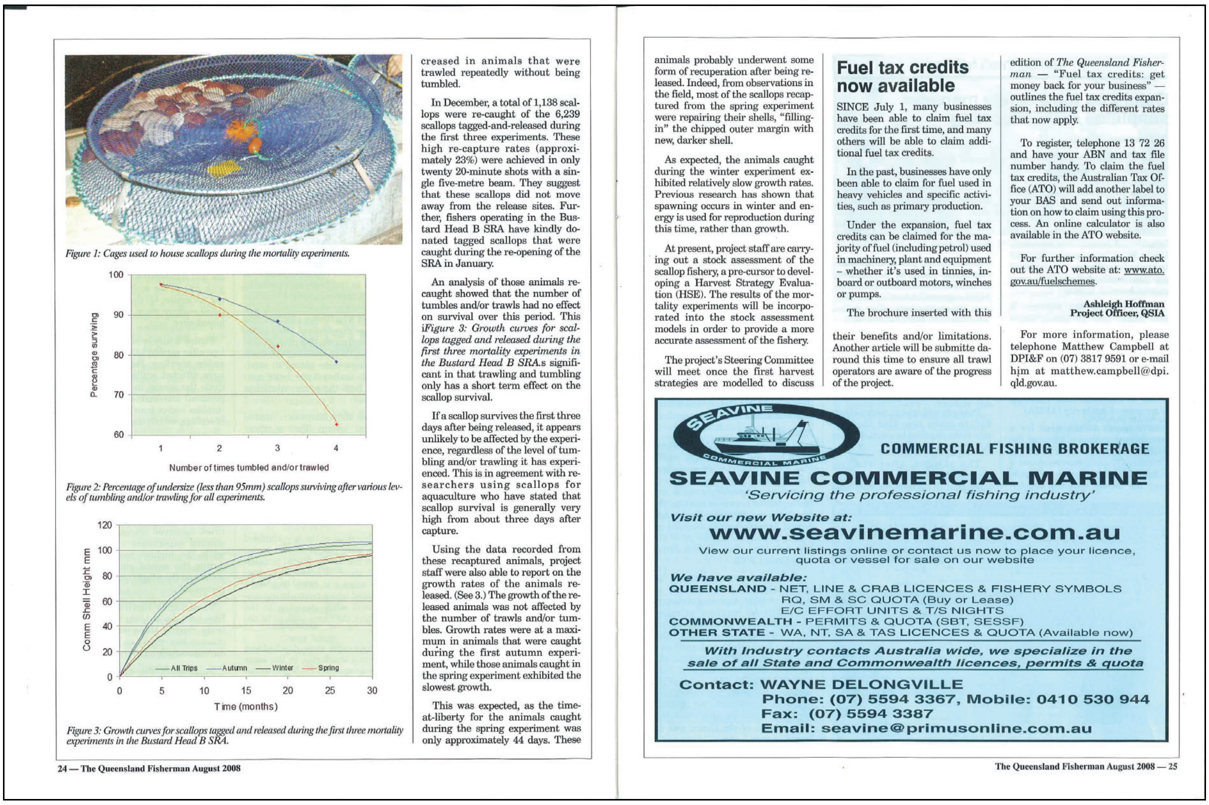

Figure 1: Cages used to house scallops during the mortality experiments.

Figure 2: Percentage of undersize (less than 95mm) scallops surviving after various levels of tumbling and/or trawling for all experiments.

Figure 3: Growth curves for scallops tagged and released during the first three mortality experiments in the Bustard Head B SRA.

creased in animals that were trawled repeatedly without being tumbled.

In December, a total of 1,138 scallops were re-caught of the 6,239 scallops tagged-and-released during the first three experiments. These high re-capture rates (approximately 23%) were achieved in only twenty 20-minute shots with a single five-metre beam. They suggest that these scallops did not move away from the release sites. Further, fishers operating in the Bustard Head B SRA have kindly donated tagged scallops that were caught during the re-opening of the SRA in January.

An analysis of those animals recaught showed that the number of tumbles and/or trawls had no effect on survival over this period. This i*Figure 3: Growth curves for scallops tagged and released during the first three mortality experiments in the Bustard Head B SRA.*s significant in that trawling and tumbling only has a short term effect on the scallop survival.

If a scallop survives the first three days after being released, it appears unlikely to be affected by the experience, regardless of the level of tumbling and/or trawling it has experienced. This is in agreement with researchers using scallops for aquaculture who have stated that scallop survival is generally very high from about three days after capture.

Using the data recorded from these recaptured animals, project staff were also able to report on the growth rates of the animals released. (See 3.) The growth of the released animals was not affected by the number of trawls and/or tumbles. Growth rates were at a maximum in animals that were caught during the first autumn experiment, while those animals caught in the spring experiment exhibited the slowest growth.

This was expected, as the time-at-liberty for the animals caught during the spring experiment was only approximately 44 days. These animals probably underwent some form of recuperation after being released. Indeed, from observations in the field, most of the scallops recaptured from the spring experiment were repairing their shells, "filling-in" the chipped outer margin with new, darker shell.

As expected, the animals caught during the winter experiment exhibited relatively slow growth rates. Previous research has shown that spawning occurs in winter and energy is used for reproduction during this time, rather than growth.

At present, project staff are carrying out a stock assessment of the scallop fishery, a pre-cursor to developing a Harvest Strategy Evaluation (HSE). The results of the mortality experiments will be incorporated into the stock assessment models in order to provide a more accurate assessment of the fishery.

The project's Steering Committee will meet once the first harvest strategies are modelled to discuss their benefits and/or limitations. Another article will be submitte daround this time to ensure all trawl operators are aware of the progress of the project.

For more information, please telephone Matthew Campbell at DPI&F on (07) 3817 9591 or e-mail him at matthew.campbell@dpi.qld.gov.au.

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Fuel tax credits now available

SINCE July 1, many businesses have been able to claim fuel tax credits for the first time, and many others will be able to claim additional fuel tax credits.

In the past, businesses have only been able to claim for fuel used in heavy vehicles and specific activities, such as primary production.

Under the expansion, fuel tax credits can be claimed for the majority of fuel (including petrol) used in machinery, plant and equipment – whether it's used in tinnies, inboard or outboard motors, winches or pumps.

The brochure inserted with this edition of *The Queensland Fisherman* — "Fuel tax credits: get money back for your business" — outlines the fuel tax credits expansion, including the different rates that now apply.

To register, telephone 13 72 26 and have your ABN and tax file number handy. To claim the fuel tax credits, the Australian Tax Office (ATO) will add another label to your BAS and send out information on how to claim using this process. An online calculator is also available in the ATO website.

For further information check out the ATO website at: www.ato.gov.au/fuelschemes.

Ashleigh Hoffman
Project Officer, QSIA

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