Fisheries Research and Development Corporation

Southern Shark Tagging Project

Terence I. Walker, Lauren P. Brown and Natalie F. Bridge

November 1997

PO Box 114 Queenscliff VIC 3225 Australia

ISBN: 0 7306 6293 4

Table of Contents

93/066 Southern Shark Tagging Project

Principal Investigator:

Terence I. Walker
Marine and Freshwater Resources Institute
PO Box 114
Queenscliff VIC 3225

Telephone: 03 5258 0111
Fax: 03 5258 0270

Objectives:

(1) Determine annual rates of movement and mixing of gummy shark and school shark across southern Australia.

(2) Provide current estimates of natural mortality and fishing mortality of gummy shark and school shark.

(3) Address specific stock hypotheses and their implications for management of the fishery.

Non Technical Summary

A total of 6 years is required to meet these three objectives—3 years to design and implement the tagging of sharks and a further 3 years to allow sufficient time for tag recaptures. This report covers the 3-year period for the Southern Shark Tagging Project (FRDC 93/066). The second 3-year period of the project is being funded by FRDC through the ongoing Southern Shark Tag Database Project (FRDC 96/162).

Implementation of the Tagging Project was coordinated through the Shark Industry Research Liaison Committee which served as a project steering committee with industry, fishery manager and scientist representation.

Following an initial pilot tagging phase, Rototags and Jumbo tags, attached at the lower anterior region of the first dorsal fin, and nylon-headed dart tags, inserted into dorsal muscle tissue or cartilage at the base of the first dorsal fin, were chosen in preference to the Peterson fin tags used during 1947–56 and internal Nesbit tags used during 1947–56 and 1973–76. Peterson fin tags have been shown to be quickly shed and internal tags are difficult and time consuming to insert and can be discarded when sharks are headed and gutted without being seen by fishers. A model was developed to test for the effects of time at liberty, sex and length of shark, tag type and tag attachment position on tag shedding rates. Preliminary analysis of tag-recapture data available to the end of 1996 indicated shedding rates are higher for nylon-headed dart tags than for Rototags and Jumbo tags. Shedding rates of dart tags locked into the cartilage at the base of the first dorsal fin are lower than those inserted into muscle tissue. These analyses are in progress.

Dummy archival tags were successfully trialed in preparation for the Southern Shark Archival Tagging Project (FRDC 96/128). Block or torpedo shaped dummy tags were attached to the first dorsal fin or block dummy tags with wire streamers were inserted into the body cavity of 244 large school sharks and 1 large gummy shark.

An experimental design was developed where 500 school sharks and 800 gummy sharks of commercial size (>650 mm total length) (i.e. a total of 5200 sharks) were to be tagged and released in each of four zones on the shark fishing grounds of the continental shelf and slope of southern Australia. A scientific paper, which describes a new method developed for the experimental design, was published in an international journal (see appendices).

During 1990–96, 2505 school sharks and 6535 gummy sharks (i.e. 9040 for the two species combined) were tagged off southern Australia. The sharks were marked with rototags and dart tags as part of the Tagging Project (1994–96) and the Southern Shark Nursery Project (FRDC 93/061) conducted by CSIRO in collaboration with MAFRI (1990–96). Other data in the Tag Database includes sharks tagged with T-bar tags used by Tasmanian Department of Primary Industry and Fisheries during 1990–1992, Peterson fin tags used by CSIRO during 1947–56, internal Nesbit tags used by CSIRO during 1947–56 and by Fisheries Victoria during 1973–76. A large number of fisheries agencies collaborated and cooperated to implement the Tagging Project, most sharks tagged were caught by professional fishers, and both professional and recreational fishers undertook voluntary tagging. For age validation purposes, about one-third of the tagged sharks were injected with the antibiotic and vertebra-marking tissue-dye oxytetracycline.

A specially designed database (Southern Shark Tag Database) was developed to manage all available tag release–recapture data from the southern Australian shark fishery using Microsoft ACCESS. All data from earlier tag releases during 1947–56 and 1973–76, as well as for tag releases during 1990–96, as part of the present study, have been validated and consolidated within this Tag Database. The Tag Database is routinely updated with incoming tag recaptures and has facility for preparing data summaries and rapid data extraction for analysis.

A number of tasks undertaken as part of the Tagging Project will be continued as part of the Tag Database Project. These tasks include (a) liaison with industry to receive and provide feedback on tag recapture data and hold periodic tag lotteries, (b) routine verification and entry of incoming tag recapture data into the Tag Database, (c) production of ongoing data summaries and basic analysis of the data, and (d) provision of up-to-date data for the SharkFAG stock assessment process for estimating rates of movement and mortality.

The report provides a description and summary of all the tag release and recapture data available to the end of 1996 (i.e. for releases during 1947–56, 1973–76 and 1990–96). No inferences are made about movement, mortality or growth rates for the population of all tagged sharks or for the entire shark population.

Two computer display packages, one for displaying release and recapture information on recaptured tagged sharks and the other to display hypotheses of movement of sharks, were specially developed and are presented in the appendices.

Acronyms

AFMA	Australian Fisheries Management Authority
CSIRO	CSIRO Division of Marine Research
MAFRI	Marine and Freshwater Resources Institute
NSWFRI	New South Wales Fisheries Research Institute
SARDI	South Australia Research and Development Institute
SharkFAG	Southern Shark Fishery Assessment Group
TL	Total length of shark
TDPIF	Tasmanian Department of Primary Industry and Fisheries
WAMRL	Western Australian Marine Research Laboratories

Definitions

Zones and Regions

BS Zone	Bass Strait Zone defined as the area on the continental shelf and slope between Victoria and the north coast of Tasmania.
SA Zone	South Australia Zone defined as the area on the continental shelf and slope off South Australia east of longitude 132° East.
GAB Zone	Great Australian Bight Zone defined as the area on the continental shelf and slope off South Australia west of 132° East together with waters off Western Australia.
Tas Zone	Tasmania Zone defined as the area on the continental shelf and slope south of the north coast of Tasmania.

Eastern Region	BS and Tas Zones combined.
Western Region	SA and GAB Zones combined.

Terms

East vector	'Distance' moved by a recaptured tagged shark east from its position of release to its position of recapture.
North vector	'Distance' moved by a recaptured tagged shark north from its position of release to its position of recapture.
Direction	Direction moved from true North by a recaptured tagged shark from its position of release to its position of recapture.
Dispersion	Square of the 'distance' moved divided by 'time free'.
Displacement	Calculated distance (resultant vector) from 'east vector' and 'north vector' (in this report, the term applies only to the entire population and not to individual sharks).
Distance	Shortest distance between a tagged shark's positions of release and recapture.
Time free	Time period for a recaptured tagged shark from the date of release to its date of recapture.
Velocity	'Displacement' divided by 'time free' (in this report, the term applies only to the entire population and not to individual sharks).

Background

Scope of Report

To meet the three objectives of the project requires 6 years—3 years to design and implement the tagging of sharks and a further 3 years to allow sufficient time for tag recaptures. This report covers the first 3-year period funded by FRDC through the Southern Shark Tagging Project (FRDC 93/066). The second 3-year period of the ongoing project is being funded by FRDC through the Southern Shark Tag Database Project (FRDC 96/162).

This report for the Southern Shark Tagging Project (FRDC 93/066) consolidates material presented in the project milestone reports as well as presenting material not previously reported. Implementation of this project, along with several reports and scientific papers from the project, is the result of scientific collaboration between the Marine and Freshwater Resources Institute (MAFRI) and CSIRO Marine Research and of cooperation and support from the Australian Fisheries Management Authority (AFMA) and the State fisheries agencies in southern Australia (see Acknowledgements).

Implementation of the Tagging Project involved nine tasks: (1) establish a project steering committee with industry, fishery manager and scientist representation, (2) undertake pilot tagging to select appropriate tags, (3) develop an experimental design to determine the appropriate number of sharks to tag and release for estimating rates of movement between broad regions of southern Australia, within prescribed confidence limits, (4) undertake field tagging of sharks to implement the experimental design, (5) develop a database for managing all incoming and historic shark tag release and recapture data (referred to as the Southern Shark Tag Database), (6) liaise with industry to receive and provide feedback on tag recapture data and hold periodic tag lotteries, (7) routinely verify and enter incoming tag recapture data into the Tag Database, (8) produce ongoing data summaries and basic analyses of the data, and (9) provide up-to-date data for the SharkFAG stock assessment process for estimating rates of movement and mortality.

These nine stages of the project have been undertaken and are described in this report. Tasks 6–9 are ongoing as part of the 3-year FRDC Tag Database Project because several hundred tagged sharks will continue to be recaptured throughout the remainder of the 1990s. Although tagged sharks will continue to be recaptured into the next century, there will be sufficient data by June 1999 to undertake full analysis of the data. By that time there will be enough tagged sharks recaptured to provide estimates of movement, mortality and growth rates for the populations of gummy shark and school shark. Estimating these population parameters is Stage 10 of the process and is being undertaken by MAFRI and CSIRO through the SharkFAG process (see Further Development).

This report describes Stages 1–9 to the end of 1996. Cooperation between industry, research scientists and fishery managers for the successful implementation of the Tagging Project was facilitated through the Shark Industry Research Liaison Committee which served as the steering committee for the project. Development and implementation of the experimental design, development of the Tag Database and preliminary estimation of movement rates of only recaptured tagged sharks are discussed below under Methods and Results. Full details of the methods adopted for developing the experimental design are published in the *Canadian Journal of Marine and Freshwater Research* (Xiao 1996) but are reprinted as Appendix A of this report. Other outputs from the project include two computer display packages: one to display the start and finish positions of recaptured tagged sharks (Appendix B) and the other to display hypotheses of movement of sharks (Appendix C).

The report provides a description of all the tag release and recapture data available to the end of 1996. Besides the tag release–recapture data collected from tag releases during 1994–96 as part of the Tagging Project, available data for releases during 1990–93, 1973–76 and 1947–56 have been consolidated in the Tag Database. Tables and figures of these data from recaptured tagged sharks are presented for four major tagging zones of the fishery for each species and sex and for each of several length-classes of shark. Special emphasis is given to presenting data for the most recent tag-release period 1990–96, but several of the tables also cover data from the 1947–56 and 1973–76 tag-release periods. These presentations show movements of only the population of recaptured tagged sharks. No inferences are made about movement, mortality or growth rates for the population of all tagged sharks or for the entire shark population.

Previous Research

Biological data were collected on school shark (*Galeorhinus galeus*), by CSIRO during the 1940s and early 1950s and on gummy shark (*Mustelus antarcticus*) by Fisheries Victoria during the 1970s. In 1984 stock assessments had been inconclusive and the former Southern Shark Fishery Task Force and, subsequently its successor, the Southern Shark Fishery Management Advisory Committee, recommended further research. These recommendations led to funds being provided from various sources to MAFRI during the late-1980s to continue investigation of the southern shark resources with the aim of providing resource assessments to guide and assist management of the fishery. During the 1990s, MAFRI and CSIRO completed age-validation (Officer 1995; Walker *et al.* 1995; Officer *et al.* 1996), nursery (Stevens and West 1997), genetic (MacDonald 1988; Ward and Gardner 1997), modelling (Walker 1992; Walker 1994a; Walker 1994b; Walker 1995; Xiao 1995; Punt and Walker in press), and fishery monitoring projects. In addition, the Western Australian Marine Research Laboratories has undertaken general biological study of sharks (Simpfendorfer *et al.* 1996).

Stock Distribution and Structure

School shark and gummy shark are harvested on the continental shelf and continental slope of southern Australia. School sharks also occur well off the continental shelf over the abyssal plain and are known to undertake long movements across southern Australia (Olsen 1953, 1954; Stanley 1988) and occasionally between southern Australia and New Zealand (Coutin *et al.* 1992).

Ward and Gardiner (1997) confirmed that there is a single, widely distributed species of *Galeorhinus galeus* from genetic analysis of samples from Australia, New Zealand, South Africa, Argentina and the United Kingdom. They used both allozyme and mitochondrial DNA techniques. They found no evidence for more than a single stock of school shark in the south-eastern Australian waters. There were some genetic differences in New Zealand sharks, which thus appear to constitute a distinct stock from the south-eastern Australian stock. However, these differences were small, and not incompatible with low levels of exchange between the two areas.

Ward and Gardiner (1997) identified three genetic stocks of *Mustelus antarcticus*. All endemic to Australia, one stock ranged along the southern coast of Australia from Bunbury in the west to Eden in the east, a second was located off New South Wales in the region from Newcastle to Clarence River, and a third was located off Queensland near Townsville.

The populations of both species exhibit complex stock structuring. School sharks have distinct "pupping" grounds referred to as "nursery areas" and, although gummy sharks do not have these distinct areas, the newborn pups tend to inhabit shallow inshore areas. Fishers often describe "mating grounds" in particular areas and there is a tendency for large school sharks to occupy the western region of their range in waters off western South Australia and off Western Australia to about 100 miles west of the South Australia–Western Australia border. School sharks (Olsen 1954), and, to a lesser extent, gummy sharks (Walker 1983) undergo long movements to give birth during Spring.

Aggregating behaviour appears to be different between school sharks and gummy sharks. School sharks form large schools when migrating and are often found aggregated when feeding on schooling prey such as pilchards, jack mackerel, snoek and squid. Although gummy sharks often feed on aggregated prey or form moving schools, the species is generally more dispersed as it feeds on demersal crustaceans, cephalopods and fish distributed over wide areas.

These characteristics affect the way shark fishers search for sharks and have important implications for interpretation of their catch and effort data. Most fishers tend to set, haul, move and then reset the gillnets to catch the dispersed gummy sharks, often with a bycatch of young school sharks. A smaller group of fishers specialise in targeting school sharks. These fishers often take a series of small, with occasional zero catches, while searching for school sharks, but then, having located aggregations of school sharks, often take large catches. Prior to the widespread use of gillnets in the 1970s, most shark fishers specialised in targeting school sharks with longlines. Hence to better interpret catch per unit effort trends and to improve stock assessment, there is a need to better understand the movement and distribution patterns of school sharks and gummy sharks.

SharkFAG recognises that the spatially aggregated fishery models currently applied for stock assessment of these species ignore the complex structuring of these stocks. Consequently, SharkFAG is currently developing species-specific spatially structured models which incorporate rates of movement between the major regions of the fishery. SharkFAG also uses these data for estimating mortality rates.

Tagging and releasing school and gummy sharks during 1947–56 and 1973–76 (Olsen 1953, 1954; Stanley 1988; Walker 1983, 1989) enhanced our knowledge of their movement patterns, but there are three reasons why it is not possible to adequately estimate rates of movement from these earlier data. Firstly, most of the tagging was confined to the eastern region of the fishery; secondly, fishing effort did not adequately cover the fishery; and, thirdly, facility for fishers to report fishing effort was inadequate. The current FRDC funded Southern Shark Tagging Project was designed to provide data for estimating rates of movement between the major regions of the fishery. The project will also provide current estimates of mortality and growth rates, and a basis for testing various stock hypotheses relevant to the management of the fishery.

Need

The shark fishery of southern Australia is based on several species of temperate-water sharks inhabiting the continental shelf and slope. The annual catch, mostly gummy and school shark, in recent years has been about 5000 tonnes live weight, valued at more than $15.6 million to fishers in Victoria, Tasmania and South Australia (Walker *et al.* 1996). Most of the catch is consumed in Victoria.

Current assessments of the Southern Shark Fishery indicate that the stocks of gummy shark are sound, but current assessments of school shark indicate that the current mature biomass is 15–46% of the initial mature biomass and that current catches are substantially larger than the estimates of maximum sustainable yield.

Stock structures of shark populations are highly complex. The stock structure for school shark is particularly complex and several competing hypotheses have been advanced to explain long tag movements and to explain data indicative of differences in age and size composition and breeding condition between separate regions across southern Australia. The complex structure of school shark and gummy shark stocks accounts for much of the uncertainty produced by spatially aggregated models applied in recent years.

To reduce the uncertainty in the assessments, SharkFAG, as a matter of high priority, is developing spatially structured models to explore the dynamics of school sharks in seven integrated regions across southern Australia. Similar models will be applied to gummy shark when the school shark modelling is complete.

Rates of shark movement between the major regions of the fishery and current estimates of mortality and growth of sharks are essential to these models. Data from the Tagging Project and all previous tag release–recapture data have been consolidated into the Southern Shark Tag Database and are being managed to provide complete, accurate and up-to-date data.

Objectives

(1) Determine annual rates of movement and mixing of gummy shark and school shark across southern Australia.

(2) Provide current estimates of natural mortality and fishing mortality of gummy shark and school shark.

(3) Address specific stock hypotheses and their implications for management of the fishery.

Methods

Selection of Tags

Following an initial pilot tagging phase, Rototags and Jumbo tags, attached at the lower anterior region of the first dorsal fin, and nylon-headed dart tags, inserted into dorsal muscle tissue or cartilage at the base of the first dorsal fin, were chosen in preference to the Peterson fin tags used during 1947–56 and internal Nesbit tags used during 1947–56 and 1973–76. Peterson fin tags have been shown to be quickly shed and internal tags are difficult and time consuming to insert and can be discarded when sharks are headed and gutted without being seen by fishers. A model was developed to test for the effects of time at liberty, sex and length of shark, tag type and tag attachment position on tag shedding rates. Analysis of tag-recapture data available to the end of 1996 indicated shedding rates are higher for nylon-headed dart tags than for Rototags and Jumbo tags (Xiao *et al* 1998). Shedding rates of dart tags locked into the cartilage at the base of the first dorsal fin are lower than those inserted into muscle tissue.

Experimental Design for Tag Releases

Quantifying shark movements between broad zones across southern Australia from tag release–recapture data required two steps. The first required developing a procedure for estimating movement parameters in a prescribed model and estimating confidence intervals associated with those estimates. The second step required an experimental design to collect a sufficient volume of data for applying that procedure to provide reliable estimates of the movement parameters.

The statistical framework adopted for developing the estimation procedure and the experimental design involved extending a method developed by Hilborn (1990) using maximum likelihood estimators. This approach provided a basis for collecting sufficient data for estimating movement rates to a chosen accuracy and precision (Xiao 1996) (see Appendix 1).

An experimental design was developed where 500 school sharks and 800 gummy sharks of commercial size (>650 mm total length) were to be tagged and released in each of four zones on the continental shelf and slope of southern Australia (Xiao 1996). The four tagging zones (Figure 1) are Bass Strait (BS) (defined here as between Victoria and the north coast of Tasmania), Tasmania (Tas) (south of the north coast of Tasmania), South Australia (SA) (off South Australia east of longitude 132° East), and the Great Australian Bight (GAB) (off South Australia west of 132° East together with waters off Western Australia).

Development of Southern Shark Tag Database

Tag release–recapture data available from CSIRO for shark tag releases during 1947–56, from Fisheries Victoria for releases during 1973–76, and from several sources for releases during 1990–96 have been validated and consolidated in the Microsoft ACCESS Southern Shark Tag Database. The database is routinely updated with tag releases and recaptures and has facility for preparing data summaries and extracting data for analysis.

Shark Tag Release-Recapture Data for 1947–56 Releases

Sharks were captured for tagging in offshore waters with longlines on board *FRV Derwent Hunter*, whereas in shallow inshore areas hand lines were used. For external tagging, a numbered Petersen disc tag, 16 mm in diameter, 1 mm thick and constructed of either white plastic, grey plastic or clear celluloid, was attached with 0.84 mm silver wire to the first dorsal fin of each shark tagged. This method of tagging was adopted after a series of successful preliminary tests in the experimental pool. However, it was found later that most of these tags were lost within 2–3 years because they tore the fin tissues. Consequently, in 1949 a white plastic internal tag was adopted and from then on most sharks were double tagged. Two sizes of internal tag were used and both were slightly tapered and rounded at one end. The smaller tag was 35 mm long and 10 mm wide at the wider end and the larger tag was 40 mm long and 23 mm wide. The smaller tag was used for sharks of total length shorter than 750 mm and the larger tag was used for longer sharks (Olsen 1953, 1954; Stanley 1988; Walker 1989; Stevens and West 1997). Of the double-tagged sharks recaptured, none had lost its internal tag. The internal tag had been used on the small number of sharks tagged during 1942–45, but not extensively because it is not visible externally. When the internal tag was used alone, fishermen became aware of the tag only when gutting the shark, by which time the shark had usually been decapitated and its total length could not be measured. The internal tag was inserted into the coelomic cavity through an incision on the left flank parallel to the muscles in the lower half of the body immediately below the posterior half of the first dorsal fin where the body wall is relatively thin.

Shark Tag Release-Recapture Data for 1973–76 Releases

Sharks were captured for tagging on board FV *Moondara* and FRV *Sarda* by fishing at 150 sites on the continental shelf between Streaky Bay, South Australia; Gabo Island, Victoria; and Hobart, Tasmania. The sharks were captured in experimental gillnets and longlines during 1973–76 as part of a study conducted by Fisheries Victoria.

Sharks longer than about 700 mm were tagged with 50 mm long by 20 mm wide serially numbered, yellow plastic internal tags whereas smaller sharks were tagged with 33 mm long by 9 mm wide white plastic internal tags. One end of the tag was rounded and a red plastic streamer about 150 mm long and 2 mm thick was attached at the other end. Each tag was inserted into the coelomic cavity through an incision, a little shorter in length than the width of the tag, made in the tough skin covering the myosepta fold between the lateral and ventral musculature of the body wall. The tag was pushed firmly through the incision so that the curved end of the tag tore the connective tissue and the myosepta of the fold while minimising loss of blood and damage to the internal organs, most notably the liver, and musculature. The red plastic streamer was allowed to protrude through the body wall. A curved needle was used to close the incision with a single stitch of soluble, surgical catgut and to thread the free end of the streamer under the skin for 5–12 mm, depending on length of the shark, and back out again. The free end of the streamer was then tied to the protruding section of the streamer near the incision to prevent the streamer from slipping inside the shark. The streamer was intended to alert fishermen to the presence of an internal tag. Red plastic cord similar to the streamer was also threaded through two holes of 5 mm diameter punched near the base of the anterior margin of the anterior dorsal fin. The cord was tied with a reef knot on each side of the fin. Finally the incision and the holes were disinfected with a solution of absolute alcohol containing a trace of malachite green. Before being released, the sex, length, and condition of each shark, and the position and the date of its release were recorded (Walker 1983, 1989).

Shark Tag Release-Recapture Data for 1990–96 Releases

During 1990–96, in offshore waters, sharks for tagging were caught on board specialist shark vessels during normal commercial operations using either bottom-set monofilament gillnets or bottom-set longlines. Sharks hauled on board and judged to be in strong live condition were purchased live from the professional fishers at market price. In inshore waters, most sharks for tagging were caught as part of the Southern Shark Nursery Project (FRDC 93/061) using experimental bottom-set monofilament gillnets (2-, 3- and 4-inch mesh-size) and longlines.

Within minutes of capture, each shark was identified, sexed, measured, marked with one or two uniquely numbered tags, injected with a vertebra-marking tissue-dye (in about one-third of the cases) and given a condition index before being released into the sea. The sharks were marked with either Dalton Rototags (36 mm long and 9 mm wide) or Jumbo tags (45 mm long and 18 mm wide), attached at the lower anterior region of the first dorsal fin, or Hallprint nylon-headed dart tags (95 mm long and 2 mm diameter), inserted either into dorsal muscle tissue or cartilage at the base of the first dorsal fin. Rototags were attached to small sharks (600–1000 mm TL), and Jumbo tags were attached to larger sharks (>1000 mm TL). To evaluate tag retention rates, more than a 1100 sharks were double tagged with a dart tag and either a Rototag or Jumbo tag. T-bar tags were used by Tasmanian Department of Primary Industry and Fisheries. In addition to these conventional tags, a ‘block-shaped dummy archival tag’ (52 mm long, 29 mm wide and 12 mm deep) or ‘torpedo-shaped dummy archival tag’ (115 mm long and 27 mm diameter) was attached to the first dorsal fin of 175 large school sharks and 1 large gummy shark, and a ‘block-shaped dummy archival tag’ with wire streamer was inserted into the coelomic cavity of 69 large school sharks. The purpose of these dummy tags was to evaluate the likely success of recovering archival tags designed for the FRDC funded Southern Shark Archival Tagging Project (FRDC 96/128) being undertaken by CSIRO. For age validation purposes, about one-third of the tagged sharks were injected with the antibiotic and vertebra-marking tissue-dye oxytetracycline in the form of the injectable solution of oxytetracycline hydrochloride (Terramycin, Pfizer Agricare P/L, Victoria, Australia) (100 mg ml^{-1}) at a dose of 25 mg kg^{-1} of shark body weight.

Several procedures were adopted to encourage fishers to report details of recaptured tagged sharks. Each commercial fisher was issued a tag recapture package which included an outline of the tagging program, booklets of pre-paid postcard-like recapture forms with facility for recording species, sex, length, recapture date and recapture position of the tagged sharks, and tag number(s), and plastic bags for the collection of vertebrae samples. A freecall telephone number was installed to facilitate reporting of recaptured sharks, and postage-paid labmailers (biological sample containers designed for postage purposes) were issued to return tags and vertebrae samples (either the whole column or the first five vertebrae behind the head). Tag lotteries were held to promote and improve awareness of the tag study and to provide added incentive for fishers to return tags and vertebrae samples from recaptured sharks. Two lotteries have been held: the first at the annual Shark Conference during November 1994 and the second at a meeting of SharkFAG during November 1996. A combination of cash, books, T-shirts and industry sponsored prizes were awarded. The project was publicised widely, to encourage professional and recreational fishers to report tag recaptures, in AFMA newsletters; television, radio, and newspaper interviews; a special Victorian video; the Victorian Boatshow (1994 and 1997); and various publications (Anon 1994ab, 1996, 1997abc).

Results

Shark Tag Release-Recapture for 1947–56 Releases

Of the total number of 6502 school shark tagged and released by CSIRO, 2597 were double-tagged with an external Petersen disc tag and an internal tag, 3566 were tagged only with an external Petersen disc tag, and 337 were tagged only with an internal tag. Recapture and reporting of these sharks by fishermen are continuing. By the end of 1996, a total of 594 (9%) have been recaptured of which 75 had been externally tagged only, 53 had been internally tagged only and 466 had been double tagged. Of the 466 double-tagged sharks recaptured, 379 (81%) had lost the external tag at the time of recapture and only 87 were reported with both tags. The last recaptured school shark was reported in 1995 (Table 1).

The CSIRO, concurrently with the work on school sharks, also tagged and released 587 gummy sharks (223 internally and 363 double-tagged) of which 60 (10%) were recaptured and reported by fishermen. Of the recaptured sharks, 32 had been internally tagged only and 28 had been double tagged. Of the 28 double-tagged sharks recaptured 21 (75%) had lost the external tag at the time of recapture and only 7 were reported with both tags. The last recaptured gummy shark was reported in 1969 (Table 1).

Shark Tag Release-Recapture for 1973–76 Releases

During 1973-76, Fisheries Victoria tagged and released 1525 gummy shark, 631 school shark, 294 common saw shark, 246 southern saw shark, and 299 elephant fish. By the end of May 1988, 380 gummy shark (24%), 116 school shark (18%), 25 common saw shark (10%), 9 southern saw shark (3%), and 12 elephant fish (4%) had been recaptured and reported by professional and recreational fishers (Table 1).

Shark Tag Release-Recapture for 1990–96 Releases

During 1990–96 a total of 2505 school shark and 6535 gummy shark were tagged off southern Australia. Other shark species tagged include 2 blue whaler, 46 bronze whaler, 75 dusky whaler, 515 elephant fish, 130 common saw shark, 205 southern saw shark, 79 whiskery shark, 2 grey nurse and 3 great white shark (Table 1). In addition to the sharks tagged with the conventional tags, a total of 244 school sharks and 1 gummy shark were released with dummy archival tags (Table 2). Of the sharks released, 1157 sharks (13%) were double tagged and 2791 sharks (31%) were injected with the vertebra-marking tissue-dye oxytetracycline. Over half of the tagged gummy shark and school shark (4920) were purchased at market price from commercial fishers.

A breakdown of the various projects, agencies and groups involved in tagging the sharks is provided in Table 3: (1) 26 cruises on board commercial vessels coordinated by MAFRI as part of the FRDC Southern Shark Tagging Project and opportunistic tagging undertaken by MAFRI during operations associated with other projects, (2) 6 cruises on board commercial vessels undertaken by the Western Australian Marine Research Laboratories as part of a separate FRDC funded shark tagging program, (3) opportunistic tagging undertaken by

New South Wales Fisheries Research Institute on board *FRV Kapala* during trawl surveys, (4) tagging of juvenile and adult sharks in Victorian inshore waters by MAFRI as part of the current FRDC funded Southern Shark Nursery Project, (5) tagging of juvenile and adult sharks in Tasmanian inshore waters by CSIRO as part of the current Southern Shark Nursery Project and an earlier nursery project conducted by CSIRO during 1990–92, (6) tagging of sharks in east Tasmanian waters as part of a study conducted by the Tasmanian Department of Primary Industry and Fisheries, (7) tagging of sharks in Victorian waters by recreational fishers participating in the VICTAG program coordinated by the Australian National Sportfishing Association and encouraged by MAFRI, and (8) tagging of sharks throughout the shark fishery by voluntary taggers (mainly commercial fishers) trained by MAFRI as part of the FRDC Tagging Project. A breakdown by zone of the sharks purchased during 32 cruises on board commercial shark gillnet and longline vessels is given in Table 4.

Length–Frequency Composition

Length–frequency distributions of released and recaptured tagged sharks for the 1990–96 release period are different between gummy shark and school shark (see Figures 2.1–2.4 for each of male and female gummy sharks, and male and female school sharks, respectively). These data are separated into sharks released inshore (mainly <30 m depth, including bays and inlets) and sharks released offshore (mainly >30 m depth) within each of the four tagging zones. In presenting the distributions for recaptured sharks, where recapture length was not reported or appeared improbable, lengths were calculated using von Bertalanffy growth parameters published for gummy shark (Moulton *et al* 1992) and school shark (Grant *et al* 1979).

The inshore and offshore length–frequency distributions also differed markedly. Most inshore releases were small sharks caught in experimental gillnets with small mesh-sizes as part of the nursery studies in Victoria and Tasmania whereas the larger sharks released offshore (62% of all releases) were caught in the larger mesh-sizes of commercial gear.

Offshore, the length–frequency distributions varied with zone. For gummy sharks released offshore, the modal length was greater in the Western Region (i.e. GAB and SA Zones) than in the Eastern Region (i.e. BS and Tas Zones) (1200 mm and 1000 mm, respectively, for sexes combined) but the spread of lengths was less in the GAB and SA Zones than in the BS and Tas Zones (Figures 2.1–2.2). For school sharks released offshore, the modal lengths were similar among the zones, but the spread of lengths was less in the Western Region (1000–1700 mm) than in the Eastern Region (400–1800 mm) (Figures 2.3–2.4). Small school sharks were present in the Eastern Region but absent in the GAB Zone. By combining the inshore and offshore school shark distributions for the BS and Tas Zones, an absence of mid-sized immature sharks (850–1000 mm TL) was observed. Olsen (1954) and Walker (1976) also noted a similar absence of immature sharks in the Eastern Region.

Geographical Range of Tag Recaptures

For the 1990–96 release period, gummy shark have been recaptured throughout most of its range, from Geraldton (28° South) on the west coast of Australia, through the whole of the south coast fishery to Wollongong (34° South) on the east coast. Gummy shark movements have been observed between Perth and Esperance around Cape Leeuin, throughout the entire GAB, within Bass Strait and southern Tasmanian waters, and between Bass Strait and the east coast of Australia.

School sharks have been recaptured throughout much of its range, with several sharks moving between the GAB and Tas Zones. There is, however, a notable absence of school shark recaptures west of 126° East and up the east coast of Australia into southern NSW. In the present study, no school sharks were released or recaptured west of longitude 126° East despite Olsen (1954) reporting school sharks west of Point Culver (125° East) to Cape Leeuin and north to the Abrolhos Islands (28° South). The northernmost recapture on the east coast for the 1990–96 tag period was 37.5° South, off southern NSW.

Of particular interest were the recaptures of two school sharks—a male and a female—in New Zealand waters (168° East) having crossed the Tasman Sea. These two recaptures are not totally unexpected as school shark are found in New Zealand waters and during the last 5 years 18 school sharks have migrated from New Zealand to Australia, with one moving as far west as 135° East. None of the school shark tag releases from 1947–56 and 1973–76 were recaptured off New Zealand. A lower fishing effort in New Zealand at the time probably accounts for this.

Tag Recapture Rates

By the end of 1996, 1219 gummy sharks and 301 school sharks had been recaptured. The tag recapture rate of gummy shark (18% of tag releases) is nearly one and half times that of school shark (12% of tag releases), whilst within each species, the rates of recapture between male and female sharks were similar. Percentages of tagged shark recaptured within each recapture zone from each release zone are presented separately for each of three release length-classes (650–949, 950–1099, ≥1100 mm for gummy shark and 650–949, 950–1399, ≥1400 mm for school shark) in Tables 5.3.1–5.3.2.

Gummy shark reported tag recaptures for commercial sized (≥650 mm total length) male and female sharks are 19% and 20% of releases, respectively (Table 5.3.1). Most recaptures occurred within their release zones with the inter-zone rate of recaptures being only 6% for males and 7% for females, and most of these were in a neighbouring zone. There are no recorded movements of male gummy shark between the GAB and BS Zones or between GAB and Tas Zones, and only one female moved between the GAB and BS Zones. Female gummy sharks exhibit slightly more inter-zone movements than males. The inter-zone movements do not appear to be size specific as movements have occurred for all three length-classes.

School shark reported tag recaptures for commercial sized male and female sharks are 12% and 13%, respectively (Table 5.3.2). Whilst the recapture rates were less than those for gummy shark, there was greater inter-zone movement. In contrast to gummy shark, movements were recorded between all zones for both male and female school shark; 45% of male and 63% of female recaptures were outside their release zone. These high rates of movement are likely to be a result of most female school sharks (>70%) being released in Tas and GAB Zones where fishing effort is lower than in BS and SA Zones. Similar to female gummy sharks, female school sharks exhibited greater inter-zone movement than the male sharks. Of the 389 commercial sized male school shark released in the Tas Zone, 3.6% of releases (i.e. 38 % of recaptures) were recaptured within the Tas Zone, whereas

5.9% of releases (62% of recaptures) were recaptured outside the Tas Zone in another zone (Table 5.3.2). In contrast, given a similar number of 389 commercial sized releases, only 2.8% of the female school shark releases (21% of recaptures) were recaptured within the Tas Zone, whereas 10.2% of the releases (21% of recaptures) were recaptured outside the Tas Zone. Of male and female sharks released in the Tas Zone, a higher proportion of female recaptures (42%) than male recaptures (27%) were caught in the more distant SA and GAB Zones. Not unexpectedly because of the higher fishing effort, BS and SA Zones have more than twice as many sharks recaptured as the Tas and GAB Zones.

The recapture rates for the three tag-release periods 1947–56 (Stanley 1988), 1973–76 (Walker 1983, 1989) and 1990–96 for gummy sharks are 10%, 24% and 18%, respectively, and for school sharks are 9%, 18% and 12%, respectively. These recapture rates are not directly comparable as they have not been standardized. Differences in tag type, changes in fishing gears from longlines to gillnets of varying mesh-size (with selectivity greatly affected by the length of shark), and expansion of the fishery into the Western Region all effect the probability of a tag recapture, and hence the recapture rate.

Recapture rates varied between the inshore and offshore tag releases. Recapture rates for inshore and offshore releases were similar for school shark (11% of tag releases) but were different for gummy shark (20% of offshore releases and 14% of inshore releases) (Figures 2.1–2.4). Nearly 10% of all recaptures were reported by recreational fishers, with most from inshore waters (<30m). Over 12% of the inshore released sharks were recaptured, with 25% of the recaptures (i.e. 107 recaptures) reported by recreational fishers. Almost all the inshore releases caught by recreational fishers were in either Victorian waters (54 recaptures) or Tasmanian waters (51 recaptures). Recreational fishers have reported less than 2% (18 recaptures) of all recaptures from sharks released offshore.

Distances Moved by Tagged Sharks

Recaptured tagged school sharks moved further than gummy sharks, and large sharks tended to move further than small sharks for both species. Small (<1000 mm TL) male and female sharks moved similar distances to each other but female sharks moved further than male sharks when larger for both species. These patterns are evident from Tables 6.1.1–6.4.2 tabulating several movement quantities by tag-release period, tag-release region, species, sex, and tag-release length-class of shark, where release region is either the Eastern Region (i.e. BS and Tas Zones) or Western Region (i.e. SA and GAB Zones) and tag-release period is either 1947–56, 1973–76 or 1990–96. For 1990–96 releases, the patterns are also evident in Figures 3.1–3.2 which present relative frequencies of movement of shark for each tag-release zone and each species–sex–recapture-length-class.

The tables show that the recaptured tagged school sharks moved a mean distance between release and recapture positions of about four times the mean distance moved by gummy sharks. For tagged sharks released in the Eastern Region during 1990–96, school sharks moved a mean distance of 415 km (SE=37 km, n=202) (Table 6.3.2) whereas gummy sharks moved a mean distance of 106 km (SE=7 km, n=711) (Table 6.3.1). Similarly, for tagged sharks released in the Western Region during 1990–96, school sharks moved a mean distance of 498 km (SE=45 km, n=91) (Table 6.4.2) whereas gummy sharks moved a mean distance of 83 km (SE=7 km, n=311) (Table 6.4.1). These distances are a little less for release periods 1947–56 (Tables 6.1.1 and 6.1.2) and 1973–76 (Tables 6.2.1 and 6.2.2) and can probably be explained by low levels of fishing effort in the Western Region of the fishery.

Times free by tagged sharks for release periods 1947–56, 1973–76, 1990–96 in the Eastern Region and 1990–96 in the Western Region are progressively shorter for gummy shark at 1644, 692, 302 and 200 days, respectively, and for school shark at 2254, 1216, 304 and 260 days, respectively.

Gummy sharks <650 mm TL moved a mean distance of 15 km in the Eastern Region and there are no data for gummy shark in the Western Region, and gummy sharks 650–949 mm TL moved 79 km in the Eastern Region and 128 km in the Western Region. In the Eastern Region, male gummy sharks 950–1099 mm TL and ≥1100 mm TL moved mean distances of 76 and 80 km, respectively, whereas females in these length-classes moved further at 148 and 228 km, respectively. Similarly in the Western Region, males moved mean distances of 37 and 111 km, respectively, whereas females in these length-classes moved 58 and 89 km, respectively.

School sharks <650 mm TL moved a mean distance of 22 km and those 650–949 mm TL moved 241 km in the Eastern Region. There are no data for these length-classes in the Western Region. Male school sharks 950–1399 mm TL and ≥1400 mm TL moved mean distances of 441 and 503 km, respectively, whereas females in these length-classes moved further at 606 and 909 km, respectively, in the Eastern Region. Similarly in the Western Region, males moved mean distances of 435 and 555 km, respectively, whereas females in these length-classes moved 464 and 680 km, respectively.

Gummy shark had at least 60% of the sharks in each of four length-classes recaptured <50 km from their release positions. Female gummy sharks (>20% of movements >250 km) exhibited slightly longer movements than male gummy sharks (>10% of movements >250 km) (Figure 3.1). No small gummy sharks (<650 mm TL) had movements >250 km, whilst >10% of large sharks (>1100 mm TL) had movements >250 km. This trend was particularly marked for large females (>1100 mm TL); i.e. >20% had movements >250 km and 10% had movements >500 km. Movement patterns were similar for the various zones with the exception of the SA Zone where >40% of recaptures had movements >500 km for large female (>1100 mm TL). There was a complete absence of recaptures of gummy shark <950 mm TL in the GAB Zone; however, this is consistent with the absence of sharks <800 mm TL tagged and released within this zone(Figures 2.1–2.2).

School shark, with the exception of the smallest length-class (<650 mm TL), had >50% of movements >250 km (Figure 3.2). For small-medium females (650–949mm TL), about 20% of movements were >500 km, whilst for large females (>1400 mm TL) > 65% of movements were >500 km. Nearly 20 school sharks were recaptured more than 1000 km from their release position.

Discussion and Conclusions

No attempt has been made to provide estimates of movement or mortality rates to address the three objectives of the project. These will be made over the next 1–2 years as further tagged sharks are recaptured and reported. Nevertheless there are several other conclusions that can be drawn from the tag recapture data reported to the end of 1996.

(1) Tag retention rates of Rototags and Jumbo tags are higher those of nylon-headed dart tags, and tag retention rates of dart tags locked into the cartilage at the base of the first dorsal fin are higher than of those inserted into muscle tissue.

(2) Tag recapture rates are higher for gummy sharks (19% for males and 20% for females) than for school sharks (12% for males and 13% for females).

(3) Most gummy shark recaptures occur within their release zones with the inter-zone recapture rate being only 6% for males and 7% for females, and most of these are in a neighbouring zone.

(4) There is little movement of gummy sharks between the GAB and BS Zones or between the GAB and Tas Zones; only one female moved between the GAB and BS Zones. Female gummy sharks exhibit slightly more inter-zone movements than males. The inter-zone movements do not appear to be size specific as movements have occurred for all three length-classes.

(5) School shark movements occur between all zones for both males and females; 45% of male and 63% of female recaptures were outside their release zone.

(6) Female school sharks exhibit greater inter-zone movement than the male sharks.

(7) Recaptured tagged school sharks move further than gummy sharks, and large sharks tended to move further than small sharks for both species. Small male and female sharks moved similar distances to each other but female sharks move further than male sharks when larger for both species.

(8) Mean distance between release and recapture positions for recaptured tagged school sharks (415 km) is about four times that for gummy sharks (106 km).

Benefits

Estimates of movement rates of school shark and gummy shark between the major regions of southern Australia and current estimates of mortality and growth will improve the predicative capability of stock assessment models used for the fishery. This will contribute to establishing the Southern Shark Fishery as one managed with high sustainable catches. This will ensure improved economic viability of industry for the catching and processing sector participants, and will ensure an ongoing supply of fresh shark meat so highly esteemed by some sections the Australian community.

The flow of benefits are allocated as 60% Commonwealth, 10% Victoria, 10% Tasmania, 10% South Australia and 10% Western Australia.

Intellectual Property

No intellectual property has arisen from the research that is likely to lead to significant commercial benefits, patents or licences. Intellectual property associated with information produced from the project will be shared equally by the Fisheries Research and Development Corporation and by the Victorian Department of Natural Resources and Environment. CSIRO Division of Marine Research, Tasmanian Department of Primary

Industry and Fisheries and the New Zealand National Institute of Water and Atmospheric Research Limited will continue to retain their intellectual property rights over the tag release-recapture data they contributed to the Southern Shark Tag Database.

Further Development

Data Collection

At the time of preparing this report, field tagging of the sharks was complete but it will be a further 2–3 years before sufficient tagged sharks are recaptured to provide sufficient data for estimating movement rates with the required precision. Several hundred additional tag returns are expected over this period. The data will be collected, managed, summarised and made available for analyses through the current Tag Database Project (FRDC 96/162).

Parameter Estimation

Meanwhile, appropriate models and parameter estimation procedures are being developed by MAFRI and CSIRO through the SharkFAG process for producing unbiased estimates of movement, mortality and growth rates from the tag release-recapture data used in conjunction with available catch and effort data and available gillnet selectivity parameters.

In general, data from tag and release of a sample of animals from a population and recapture of a proportion of these tagged animals have to be treated in complex models to make inferences about movement, mortality and growth rates for the population of all released tagged animals or for the entire population of animals. For school shark and gummy shark, determining these rates is particularly complex because of the highly length-selective characteristics of shark gillnets used widely in the fishery. Gillnets were phased into the fishery during the late 1960s and early 1970s to replace the less length-selective longlines with attached baited hooks. Today the different mesh-sizes used in the various regions of the fishery (predominantly 6-inch in Bass Strait and 7-inch, and more recently 6½-inch, in the other regions) affects the probability of recapture of any tagged shark; small mesh-sizes are most effective at catching small sharks and large mesh-sizes are most effective at catching large sharks.

Estimating parameters used to represent movement, mortality and growth rates requires considering the probability of recapture of each tagged shark released. Recapture depends on biological and fishery factors such as (a) how natural survival is affected by the initial tagging event and by the subsequent presence of the tag, (b) levels of fishing effort and the spatial distribution of this effort, and (c) the length-selectivity characteristics of the fishing gear. In addition, the probability of recapture in a particular region and instant of time is also affected by all three of (i) its position which depends on its movement rate, (ii) its length which depends on its length at release and subsequent growth rate; and (iii) its survival rate. Parameter estimates are also affected by the rates of sighting and reporting of tags by the fishers recapturing the sharks and by the rate of tag retention on the sharks over time. All this means that movement, mortality and growth rates cannot be estimated independently of each other.

Budget

Details of project grant and expenditure are presented in the following table.

Budget item	1993/94 $	1994/95 $	1995/96 $	1996/97 $
Project grant				
Salaries and oncosts	50955	64253	67464	0
Operating expenses	59000	73000	65000	0
Travelling expenses	16750	17650	18650	0
Capital items	0	0	0	0
Total	126705	154903	151114	0
Expenditure				
Salaries and oncosts	25,610	62,955	73,504	26,494
Operating expenses	40,086	71,083	89,418	15,517
Travelling expenses	4,759	9,698	7,666	5,933
Capital items	0	0	0	0
Total	70,455	143,735	170,588	47,944

Staff

Organisation, position, period on the project and percentage of time each year on the project are listed for each staff member.

Marine and Freshwater Resources Institute,			
Terry Walker	Principal Scientist	1 Jul 93–30 Jun 97	35%
Lauren Brown	Marine Scientist	1 Jan 94–30 Jun 97	100%
Natalie Bridge	Technical Officer	1 Jan 94–30 Jun 97	25%
Bruce Taylor	Systems Officer	1 Jul 95–30 Jun 97	10%
CSIRO Division of Marine Research			
John Stevens	Senior Research Scientist	1 Jul 95–31 Nov 95	15%
Yongshun Xiao	Senior Research Scientist	1 Jul 95–31 Nov 95	10%

Acknowledgments

The success of this project can be attributed to the active participation and cooperation of many people in national and state research and management agencies, and in commercial and recreational fishing bodies. We wish to thank all those many individual professional and recreational fishers, too numerous to mention, who tagged sharks, captured sharks for tagging, or returned tags and information from recaptured tagged sharks.

Special acknowledgement is due to many individuals. These include members of the large team of shark taggers: Treena Bath, Ian Duckworth, Russell Hudson, and Ken Smith from MAFRI; Joel Scott and Grant West from CSIRO; Melany Burke, David Johnson, Antonio Mosquiera and Trysh Stone from AFMA; Colin Simpfendorfer and Phil Unsworth from

WAMRL; and Ken Graham from NSWFRI. We would like to mention by name those professional shark fishers who provided tagging services more than once: Rob Wilson, Joe Pinzone, Dean Lade, Peter Risely, Wayne Hayhow, Lofty Atterton, Ian Rule, Damien Hursey, Maury Hyslop, Bill Palmer, Steve Brockwell, Allan Broadhurst, Ron White, Brian Tee, Leigh Chambers, Charlie Brown, Harry Ferrier, Malcolm McKenzie, Sean McKenzie, and Geoff Campbell. Also we acknowledge the cooperation of VICTAG program coordinator Don Fraser of the Australian National Sportsfishers Association and the generous donations by way for shark tagging lottery prizes provided by the Melbourne Wholesale Fish Market, C. H. Smith Marine Pty Ltd, Tuff Marine Pty Ltd, Mount Gambier Frozen Foods, Quinn Marine Pty Ltd and AFMA. Finally, important scientific input to the project was provided by Yongshun Xiao, John Stevens, Grant West and André Punt of CSIRO, Colin Simpfendorfer of WAMRL, and Bruce Taylor of MAFRI.

References

Anon (1994a). Shark! Shark tag team embarks on project. *Australian Fisheries* **53** (6), 8–12.

Anon (1994b). 1994 shark tagging lottery results. *Australian Fisheries* **53** (12), 11, 13.

Anon (1996). The world of research, second southern shark tagging lottery. *Profish*, 6–7. (Victorian Fisheries, department of Natural Resources and Environment: Melbourne.)

Anon (1997a). Shark hiked 1800 kilometres across Tasman. *Professional Fisherman*. 18 January 1997.

Anon (1997b). Steve collects a cool $1000 for a tag return. *Professional Fisherman*. 18 January 1997.

Anon (1997c).Shark treks intrigue scientists. *Outdoors* No 10, 3. (The Quarterly magazine of the Department of Natural Resources and Environment: Melbourne.)

Coutin, P., Bruce, B., and Paul, L. (1992). New Zealand sharks cross the Tasman Sea. *Australian Fisheries* **51** (3), 24–25.

Hilborn, R. Determination of fish movement patterns from tag recoveries using maximum likelihood estimators. *Canadian Journal of Fisheries and Aquatic Sciences* **47**, 635–643.

MacDonald, C. M. (1988). Genetic variation, breeding structure and taxonomic status of the gummy shark *Mustelus antarcticus* in southern Australian waters. *Australian Journal of Marine and Freshwater Research* **39**, 641–648.

Officer, R. A. (1995). Vertebral mineralisation patterns in gummy and school sharks and their utility in age determination. Ph.D. Thesis, University of Melbourne, Melbourne, Victoria. 299 pp.

Officer, R. A., Gason, A. S., Walker, T. I., and Clement, J. G. (1996). Sources of variation in counts of growth increment lines in vertebrae from gummy shark, *Mustelus* *antarcticus*, and school shark, *Galeorhinus galeus*: implications for growth determination. *Canadian Journal of Fisheries and Aquatic Sciences* **53**, 1765–1777.

Olsen, A. M. 1953. Tagging of school shark, *Galeorhinus australis* (Macleay) (Carcharhanidae) in south-eastern Australian waters. *Australian Journal of Marine and Freshwater Research* **4**, 95–104.

Olsen, A. M. 1954. The biology, migration, and growth rate of the school shark, *Galeorhinus australis* in south-eastern Australian waters. *Australian Journal of Marine and Freshwater Research* **5**, 353–410.

Punt, A. E., and Walker, T. I. (in press). Stock assessment and risk analysis for the school shark *Galeorhinus galeus* (Linnaeus) off southern Australia. *Marine and Freshwater Research* **49**

Stanley, C. A. (1988). Tagging experiments on school shark (*Galeorhinus australis*) and gummy shark (*Mustelus antarcticus*): recapture data for south-eastern Australian releases, 1942 to 1956. *CSIRO Marine Laboratories Report* No. **192**, 92pp.

Simpfendorfer, C., Lenanton, R., and Unsworth, P. (1996). Stock assessment of large coastal and demersal sharks. (Fisheries Department of Western Australia, Fisheries Research and Development Corporation Final Report, September 1996)

Stevens, J. D., and West, G. J. (1997). Investigation of school and gummy shark nursery areas in south eastern Australia. (July 1997.) (CSIRO Marine Research: Hobart.)

Walker, T. I. (1976). Effects of species, sex, length and locality on the mercury content of school shark *Galeorhinus australis* (Macleay) and gummy shark *Mustelus antarcticus* Guenther from south-eastern Australian waters. *Australian Journal of Marine and Freshwater Research* **27**, 603–616.

Walker, T. I. 1983. Investigations of the gummy shark, *Mustelus antarcticus* Gunther, from south-eastern Australian waters. Report to Fishing Industry Research Committee June 1983. In 'Proceedings of the Shark Assessment Workshop, South East Fisheries Committee Shark Research Group , Melbourne.' 7–10 March 1983. (Department of Primary Industry: Canberra) 94pp.

Walker, T. I. (1989). 'Methods of Tagging Adopted in the Southern Shark Fishery'. Workshop on 'Tagging - Solution or Problem?'. Sixteenth Annual Conference. 1989. Canberra.

Walker, T. I. (1992). A fishery simulation model for sharks applied to the gummy shark, *Mustelus antarcticus* Günther, from southern Australian waters. *Australian Journal of Marine and Freshwater Research* **43**, 195–212.

Walker, T. I. (1994a). Fishery model of gummy shark, *Mustelus antarcticus*, for Bass Strait. In 'Resource Technology '94 New Opportunities Best Practice'. 26–30 September 1994, University of Melbourne, Melbourne. (Ed. I. Bishop.) pp. 422–438. (The Centre for Geographic Information Systems & Modelling, The University of Melbourne: Melbourne.)

Walker, T. I. (1994b). Stock assessments of the gummy shark, *Mustelus antarcticus* Günther, in Bass Strait and off South Australia. In 'Population Dynamics for Fisheries Management'. 24–25 August 1993, Perth. (Ed. D. A. Hancock.) *Australian Society for Fish Biology Workshop Proceedings*. pp. 173–187. (Australian Government Printing Service: Canberra.)

Walker, T. I. (1995). Stock assessment of the school shark, *Galeorhinus galeus* (Linnaeus), off southern Australia by applying a delay-difference model. Report to Southern Shark Fishery Assessment Group. 28 pp. (27 Feb–3 Mar 1995.) (Marine and Freshwater Resources Institute: Queenscliff.)

Walker, T. I., Officer, R. A., Clement, J. G., and Brown, L. P. (1995). Southern shark age validation: Part 1 - Project overview, vertebral structure and formation of growth-increment bands used for age determination. Final Report to Fisheries Research and Development Corporation (FRDC Project 91/037). Client Report. (May 1995.) (Victorian Fisheries Research Institute, Department of Conservation and Natural Resources: Queenscliff, Victoria.)

Walker, T. I., Stone, T., Battaglene, T., and McLoughlin, K. (1996). 'Fishery Assessment Report, the Southern Shark Fishery 1995'. 55 pp. (Australian Government Printing Service: Canberra).

Ward, R. D., and Gardner, M. G. (1997). Stock structure and species identification of school and gummy sharks in Australasian waters. Project FRRF 93/11 and FRDC 93/64. (February 1997.) (CSIRO Marine Research: Hobart.)

Xiao, Y. (1995). Stock Assessment of the School Shark *Galeorhinus galeus* (Linnaeus) off Southern Australia by Schaefer production model. Report to Southern Shark Fishery Assessment Group Workshop. 55pp. (27 February–3 March 1995.) (CSIRO Division of Fisheries: Hobart.)

Xiao, Y. (1996). A framework for evaluating experimental designs for estimating rates of movement from tag recoveries. *Canadian Journal of Fisheries and Aquatic Sciences* **53**, 1272–1280.

Table 1. Shark tag and recaptures for the release periods 1947–56, 1973–73 and 1990–96.

Common Name	Scientific Name	Tag-release period	Number of sharks		Percentage recaptured
			Released	Recaptured	
Major Commercial Sharks					
Gummy Shark	*Mustelus antarcticus*	1947–56	587	60	10
		1973–76	1525	380	24
		1990–96	6535	1219	18
School Shark	*Galeorhinus galeus*	1947–56	6502	594	9
		1973–76	631	116	18
		1990–96	2505	301	12
Common saw shark	*Pristiophorus cirratus*	1947–56			
		1973–76	246	25	10
		1990–96	130	5	3
Southern saw shark	*Pristiophorus nudipinnis*	1947–56			
		1973–76	294	9	3
		1990–96	205	12	5
Elephant fish	*Callorhinchus milii*	1947–56			
		1973–76	299	12	4
		1990–96	515	9	1
Other sharks					
Angel shark	*Squatina australis*	1990–96	4		
Southern Dogfish	*Centrophorus uyato*	1990–96	6		
Greeneye spurdog	*Squalus mitsukuri*	1990–96	10	1	10
Grey nurse shark	*Carcharias taurus*	1990–96	2		
Spurdog sp.	*Squalus sp.*	1990–96	4		
Blue whaler	*Prionace glauca*	1990–96	2		
Broadnose sevengill	*Notorynchus cepedianus*	1990–96	116	8	6
Bronze whaler	*Carcharhinus brachyurus*	1990–96	46	2	4
Stingray	*Dasyatid*	1990–96	4		
Draughtboard shark	*Cephaloscyllium sp.*	1990–96	16	1	6
Dusky whaler	*Carcharhins obscurus*	1990–96	75	7	9
Great white shark	*Carcharodon carcharias*	1990–96	3	1	33
Hammerhead	*Sphyrna zygaena*	1990–96	7		
Melbourne skate	*Raja whitleyu*	1990–96	15		
Piked spurdog	*Squalus megalops*	1990–96	617	9	1
Port Jackson shark	*Heterodontus portjacksoni*	1990–96	25	3	12
Shortfin Mako	*Isurus oxyrinchus*	1990–96	1		
Smooth stingray	*Dasyatis brevicaudata*	1990–96	681	38	5
Southern eagle ray	*Myliobatis australis*	1990–96	28		
Thornback skate	*Raja lemprieri*	1990–96	1		
Thresher sharks	*Alopias vulpinus*	1990–96	5		
Whiskery shark	*Furgaleus macki*	1990–96	79		
White-spotted spurdog	*Squalus acanthias*	1990–96	7		

Table 2. Gummy and school shark recaptures by tag type for the release period 1990–96.

Tag type	Number released	Number recaptured	% Returned	Number of tags present		
				Both	1st only	2nd only
Single tag						
Rototag	2412	488	20%			
Jumbo	2055	432	21%			
Mini	306	26	8%			
Dart (Muscle)	2253	235	10%			
Dart (Fin)[A]	453	37	8%			
Steel	97	10	10%			
T-Bar	110	10	9%			
Archival-Internal	67	9	13%			
Archival-Block	82	6	7%			
Archival-Torpedo	66	7	11%			
Sub-total	7901	1260	16%			
Double tagged (major combinations)						
Rototag-Dart(Muscle)	366	96	26%	50	43	3
Rototag-Dart(Fin)	35	6	17%	4	0	0
Jumbo-Dart(Muscle)	397	108	27%	58	49	1
Jumbo-Dart(Fin)	267	43	16%	38	3	2
Jumbo-Jumbo	35	9	26%	7	2	
Internal-Dart(Fin)	2	0				
Block-Dart(Muscle)	2	0				
Block-Dart(Fin)	4	0				
Torpedo-Dart (Fin)	20	4	20%	3	0	1
Sub-total	1128	266	24%			
Total	9029	1526	17%			

[A] Tag attachment site changed from muscle to fin as of 27th September 1995

Table 3. Gummy and school shark recaptures by source for the release period 1990–96

OTC, oxytetracycline; MAFRI, Marine and Freshwater Resources Institute; SSTP, Southern Shark Tagging Project; WAMRL, Western Australian Marine Research Laboratories; NSWFRI, New South Wales Fisheries Research Institute; SSNP, Southern Shark Nursery Project; CSIRO, CSIRO Division of Marine Research; TDPIF, Tasmanian Department of Primary Industry and Fisheries; ANSAVol, Australian National Sportfishing Association Victoria Inc; FisherVol, Voluntary tagging by professional fishers and several recreational fishers.

Source	Project	Period	Number of sharks tagged and released									
			Gummy			School			Total	OTC injected	Double tagged	Archival tag
			Male	Female	Unknown	Male	Female	Unknown				
MAFRI	SSTP	1993–96	1228	1638	4	822	771	3	4466	1417	946	244
WAMRL	SSTP	1993–95	144	396	0	8	73	0	621	249	39	0
NSWFRI	SSTP	1994	14	13	0	0	0	0	27	26	0	0
MAFRI	SSNP	1993–96	480	249	3	107	149	1	989	303	170	0
CSIRO	SSNP	1991–96	765	475	3	168	230	1	1642	796	0	1
TDPIF		1990–95	141	115	1	22	24	0	303	0	0	0
ANSAVol		1994–96	1	3	48	1	0	11	64	0	0	0
FisherVol		1994–96	398	406	10	49	63	2	928	0	2	0
Total			3171	3295	69	1177	1310	18	9040	2791	1157	245

Table 4. Major cruises on board commercial vessels in offshore waters during 1994–96

Lat, latitude; Long, longitude; Unk, unknown sex; OTC, oxytetracycline. LL, longline; S5, gillnet 5-inch mesh-size;. S6, gillnet 6-inch mesh-size; S6.5, gillnet 6.5-inch mesh-size; S7, gillnet75-inch mesh-size.

Zone	Cruise code	Date	Locality		No. of shots	Gear type	Number of sharks tagged									
							Gummy			School			Total	OTC	Double	Dummy
			Lat	Long			Male	Female	Unk	Male	Female	Unk		injected	tagged	tag
BS	2	Mar-94	40	148	11	S6	47	81	0	1	1	0	130	58	41	0
	3	Mar-94	10	147	13	LL	242	237	0	19	10	0	508	107	22	0
	5	May-94	40	143	9	S6	25	56	0	3	5	0	89	0	27	0
	7	Oct-94	39	145	12	S6	96	24	1	2	1	0	124	52	36	0
	8	Oct-94	40	143	5	LL	23	36	0	6	4	0	69	31	19	0
	9	Nov-94	39	146	4	LL	43	53	0	60	30	0	186	58	54	0
	10	Dec-94	39	146	2	LL	23	21	0	1	1	0	46	20	15	0
	12	Feb-95	39	147	13	S6	37	58	0	2	9	0	106	40	44	10
	15	Apr-95	36	150	3	LL	25	66	1	0	0	0	92	43	14	0
	16	May-95	36	150	3	LL	4	12	0	0	0	0	16	9	0	0
	23	Nov-95	38	142	3	LL	1	11	0	2	0	0	14	11	7	1
	24	Dec-96	38	145	5	LL	1	40	0	0	3	0	44	21	19	2
	26	Feb-96	39	146	7	S6	2	2	0	71	2	0	77	48	9	15
Total	13						569	697	2	167	66	0	1501	498	307	28
Tas	13	Feb-95	41	144	14	S6	24	29	0	60	100	0	213	94	45	34
	17	May-95	41	144	8	LL	18	16	1	193	129	3	360	64	53	107
	25	Jan-96	43	147	12	LL	33	30	0	111	72	0	246	99	58	28
Total	3						75	75	1	364	301	3	819	257	156	169
SA	4	Apr-94	37	139	18	S7	19	101	0	4	8	0	132	0	24	0
	6	Jun-94	35	135	28	S7	32	49	1	18	18	0	118	54	26	0
	14	Mar-95	36	138	31	S6.5	108	291	1	9	5	0	414	123	71	11
	18	Aug-95	34	135	16	S7	24	29	0	5	7	0	65	21	28	0
	19	Sep-95	37	139	11	LL	12	36	0	25	13	0	86	35	0	9
	21	Oct-95	33	133	29	S7	128	12	0	3	1	0	144	18	31	0
Total	6						323	518	2	64	52	0	959	251	180	20
GAB	1	Feb-94	32	131	37	S7	35	35	0	170	134	0	374	62	36	0
	11	Jan-95	32	130	34	S6.5, 7	11	89	0	26	43	0	169	91	60	0
	20	Oct-95	31	128	18	S7	10	139	0	7	42	0	198	113	48	0
	22	Oct-95	31	129	20	S5,6,6.5,7	157	16	0	19	130	0	322	99	114	26
	WA1	Jul-94	34	122	12	S7	55	73	0	0	0	0	128	0	34	0
	WA2	Mar-95	36	124	36	S7	46	40	0	0	0	0	86	45	0	0
	WA3	Mar-95	34	119	26	S7	2	117	0	0	0	0	119	59	0	0
	WA4	May-95	34	119	20	S7	12	50	0	0	0	0	62	27	0	0
	WA5	Aug-95	32	127	26	S7	19	58	11	0	0	0	88	76	0	0
	WA6	Oct-95	32	127	32	S7	3	21	0	9	62	0	95	39	0	0
Total	10						350	638	11	231	411	0	1641	611	292	26
All zones Total	32				518		1317	1928	16	826	830	3	4920	1617	935	243

Table 5.1.1. Gummy shark recaptures for the release period 1947–56 (≥650 mm TL).

Sex	Release length-class (mm)	Release zone	Number tagged	Percentage recaptured in each zone				
				BS	Tas	SA	GAB	All
Male	650–949	BS	33	9.1	0.0	0.0	0.0	9.1
		Tas	19	0.0	15.8	0.0	0.0	15.8
		SA	2	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	54	5.6	5.6	0.0	0.0	11.1
	950–1099	BS	76	2.6	1.3	0.0	0.0	3.9
		Tas	31	0.0	0.0	0.0	0.0	0.0
		SA	4	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	111	1.8	0.9	0.0	0.0	2.7
	≥1100	BS	123	13.8	3.3	0.0	0.0	17.1
		Tas	37	0.0	0.0	0.0	0.0	0.0
		SA	11	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	171	9.9	2.3	0.0	0.0	12.3
	Total	BS	232	9.5	2.2	0.0	0.0	11.6
		Tas	87	0.0	3.4	0.0	0.0	3.4
		SA	17	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	336	6.5	2.4	0.0	0.0	8.9
Female	650–949	BS	26	23.1	0.0	0.0	0.0	23.1
		Tas	16	0.0	0.0	0.0	0.0	0.0
		SA	2	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	44	13.6	0.0	0.0	0.0	13.6
	950–1099	BS	50	8.0	0.0	0.0	0.0	8.0
		Tas	5	0.0	0.0	0.0	0.0	0.0
		SA	6	0.0	0.0	16.7	0.0	16.7
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	61	6.6	0.0	1.6	0.0	8.2
	≥1100	BS	69	13.0	1.4	1.4	0.0	15.9
		Tas	7	0.0	0.0	0.0	0.0	0.0
		SA	34	2.9	0.0	8.8	0.0	11.8
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	110	9.1	0.9	3.6	0.0	13.6
	Total	BS	145	13.1	0.7	0.7	0.0	14.5
		Tas	28	0.0	0.0	0.0	0.0	0.0
		SA	42	2.4	0.0	9.5	0.0	11.9
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	215	9.3	0.5	2.3	0.0	12.1

Table 5.1.2. School shark recaptures for the release period 1947–56 (≥650 mm TL).

Sex	Release length-class (mm)	Release zone	Number tagged	Percentage recaptured in each zone				
				BS	Tas	SA	GAB	All
Male	650–949	BS	79	13.9	0.0	2.5	0.0	16.5
		Tas	59	3.4	8.5	0.0	0.0	11.9
		SA	2	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	140	9.3	3.6	1.4	0.0	14.3
	950–1399	BS	197	15.2	7.1	4.6	0.0	26.9
		Tas	24	4.2	4.2	0.0	0.0	8.3
		SA	30	3.3	0.0	33.3	3.3	40.0
		GAB	1	0.0	0.0	0.0	100.0	100.0
		All	252	12.7	6.0	7.5	0.8	27.0
	≥1400	BS	443	9.7	1.8	0.7	0.0	12.2
		Tas	96	4.2	7.3	0.0	0.0	11.5
		SA	111	3.6	0.0	20.7	0.0	24.3
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	650	7.8	2.3	4.0	0.0	14.2
	Total	BS	719	11.7	3.1	1.9	0.0	16.7
		Tas	179	3.9	7.3	0.0	0.0	11.2
		SA	143	3.5	0.0	23.1	0.7	27.3
		GAB	1	0.0	0.0	0.0	100.0	100.0
		All	1042	9.2	3.4	4.5	0.2	17.3
Female	650–949	BS	91	16.5	0.0	2.2	0.0	18.7
		Tas	51	5.9	3.9	0.0	0.0	9.8
		SA	4	0.0	0.0	50.0	0.0	50.0
		GAB	1	0.0	0.0	0.0	0.0	0.0
		All	147	12.2	1.4	2.7	0.0	16.3
	950–1399	BS	144	9.0	0.7	9.7	0.0	19.4
		Tas	3	0.0	0.0	0.0	0.0	0.0
		SA	31	12.9	9.7	12.9	0.0	35.5
		GAB	2	0.0	0.0	0.0	0.0	0.0
		All	180	9.4	2.2	10.0	0.0	21.7
	≥1400	BS	212	7.5	2.4	8.0	0.0	17.9
		Tas	29	3.4	3.4	3.4	0.0	10.3
		SA	31	16.1	0.0	19.4	0.0	35.5
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	272	8.1	2.2	8.8	0.0	19.1
	Total	BS	447	9.8	1.3	7.4	0.0	18.6
		Tas	83	4.8	3.6	1.2	0.0	9.6
		SA	66	13.6	4.5	18.2	0.0	36.4
		GAB	3	0.0	0.0	0.0	0.0	0.0
		All	599	9.5	2.0	7.7	0.0	19.2

Table 5.2.1. Gummy shark recaptures for the release period 1973–76 (≥650 mm TL).

Sex	Release length-class (mm)	Release zone	Number tagged	Percentage recaptured in each zone				
				BS	Tas	SA	GAB	All
Male	650–949	BS	272	16.2	0.4	0.0	0.0	16.5
		Tas	58	13.8	15.5	0.0	0.0	29.3
		SA	0	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	330	15.8	3.0	0.0	0.0	18.8
	950–1099	BS	276	27.9	0.7	0.0	0.0	28.6
		Tas	26	3.8	23.1	0.0	0.0	26.9
		SA	0	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	302	25.8	2.6	0.0	0.0	28.5
	≥1100	BS	158	31.6	1.3	0.0	0.0	32.9
		Tas	41	4.9	19.5	0.0	0.0	24.4
		SA	6	0.0	0.0	16.7	0.0	16.7
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	205	25.4	4.9	0.5	0.0	30.7
	Total	BS	706	24.2	0.7	0.0	0.0	24.9
		Tas	125	8.8	18.4	0.0	0.0	27.2
		SA	6	0.0	0.0	16.7	0.0	16.7
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	837	21.7	3.3	0.1	0.0	25.2
Female	650–949	BS	281	19.2	1.1	1.4	0.4	22.1
		Tas	25	12.0	20.0	4.0	0.0	36.0
		SA	0	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	306	18.6	2.6	1.6	0.3	23.2
	950–1099	BS	156	19.2	0.6	0.6	0.0	20.5
		Tas	5	0.0	40.0	0.0	0.0	40.0
		SA	0	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	161	18.6	1.9	0.6	0.0	21.1
	≥1100	BS	115	26.1	0.0	1.7	0.0	27.8
		Tas	7	14.3	0.0	0.0	0.0	14.3
		SA	9	0.0	0.0	22.2	0.0	22.2
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	131	23.7	0.0	3.1	0.0	26.7
	Total	BS	552	20.7	0.7	1.3	0.2	22.8
		Tas	37	10.8	18.9	2.7	0.0	32.4
		SA	9	0.0	0.0	22.2	0.0	22.2
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	598	19.7	1.8	1.7	0.2	23.4

Table 5.2.2. School shark recaptures for the release period 1973–76 (≥650 mm TL).

Sex	Release length-class (mm)	Release zone	Number tagged	Percentage recaptured in each zone				
				BS	Tas	SA	GAB	All
Male	650–949	BS	48	31.3	2.1	2.1	0.0	35.4
		Tas	23	21.7	4.3	0.0	0.0	26.1
		SA	3	0.0	0.0	33.3	0.0	33.3
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	74	27.0	2.7	2.7	0.0	32.4
	950–1399	BS	95	18.9	1.1	4.2	0.0	24.2
		Tas	0	0.0	0.0	0.0	0.0	0.0
		SA	14	0.0	0.0	21.4	7.1	28.6
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	109	16.5	0.9	6.4	0.9	24.8
	≥1400	BS	92	2.2	1.1	2.2	0.0	5.4
		Tas	1	0.0	0.0	0.0	0.0	0.0
		SA	2	0.0	50.0	0.0	0.0	50.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	95	2.1	2.1	2.1	0.0	6.3
	Total	BS	235	14.9	1.3	3.0	0.0	19.1
		Tas	24	20.8	4.2	0.0	0.0	25.0
		SA	19	0.0	5.3	21.1	5.3	31.6
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	278	14.4	1.8	4.0	0.4	20.5
Female	650–949	BS	37	16.2	2.7	2.7	0.0	21.6
		Tas	14	14.3	7.1	0.0	0.0	21.4
		SA	5	0.0	0.0	0.0	0.0	0.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	56	14.3	3.6	1.8	0.0	19.6
	950–1399	BS	71	16.9	2.8	2.8	0.0	22.5
		Tas	0	0.0	0.0	0.0	0.0	0.0
		SA	9	11.1	0.0	11.1	0.0	22.2
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	80	16.3	2.5	3.8	0.0	22.5
	≥1400	BS	24	0.0	8.3	12.5	4.2	25.0
		Tas	2	0.0	0.0	50.0	0.0	50.0
		SA	8	0.0	0.0	25.0	0.0	25.0
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	34	0.0	5.9	17.6	2.9	26.5
	Total	BS	132	13.6	3.8	4.5	0.8	22.7
		Tas	16	12.5	6.3	6.3	0.0	25.0
		SA	22	4.5	0.0	13.6	0.0	18.2
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	170	12.4	3.5	5.9	0.6	22.4

Table 5.3.1. Gummy shark recaptures for the release period 1990–96 (≥650 mm TL).

Sex	Release length-class (mm)	Release zone	Number tagged	Percentage recaptured in each zone				
				BS	Tas	SA	GAB	All
Male	650–949	BS	790	18.1	0.0	0.1	0.0	18.2
		Tas	526	1.0	12.0	0.4	0.0	13.3
		SA	26	0.0	0.0	26.9	0.0	26.9
		GAB	0	0.0	0.0	0.0	0.0	0.0
		All	1342	11.0	4.7	0.7	0.0	16.5
	950–1099	BS	310	22.3	0.0	0.0	0.0	22.3
		Tas	146	0.7	12.3	0.0	0.0	13.0
		SA	127	0.0	0.0	18.9	1.6	20.5
		GAB	98	0.0	0.0	1.0	9.2	10.2
		All	681	10.3	2.6	3.7	1.6	18.2
	≥1100	BS	200	27.5	0.0	0.0	0.0	27.5
		Tas	74	2.7	10.8	0.0	0.0	13.5
		SA	208	1.0	0.5	26.0	0.0	27.4
		GAB	230	0.0	0.0	0.4	17.0	17.4
		All	712	8.3	1.3	7.7	5.5	22.8
	Total	BS	1300	20.5	0.0	0.1	0.0	20.6
		Tas	746	1.1	11.9	0.3	0.0	13.3
		SA	361	0.6	0.3	23.5	0.6	24.9
		GAB	328	0.0	0.0	0.6	14.6	15.2
		All	2735	10.1	3.3	3.3	1.8	18.5
Female	650–949	BS	680	17.1	0.0	0.6	0.0	17.6
		Tas	361	3.3	8.6	1.9	0.0	13.9
		SA	77	1.3	0.0	14.3	0.0	15.6
		GAB	7	0.0	0.0	0.0	14.3	14.3
		All	1125	11.5	2.8	2.0	0.1	16.3
	950–1099	BS	283	27.2	0.4	2.5	0.0	30.0
		Tas	58	3.4	10.3	0.0	0.0	13.8
		SA	252	0.4	0.0	27.4	0.8	28.6
		GAB	143	0.0	0.0	0.7	28.0	28.7
		All	736	10.9	1.0	10.5	5.7	28.0
	≥1100	BS	265	15.1	0.8	2.3	0.0	18.1
		Tas	38	13.2	10.5	5.3	0.0	28.9
		SA	224	0.4	0.0	15.6	0.4	16.5
		GAB	502	0.2	0.0	1.0	16.3	17.5
		All	1029	4.6	0.6	4.7	8.1	17.9
	Total	BS	1228	19.0	0.2	1.4	0.0	20.6
		Tas	457	4.2	9.0	2.0	0.0	15.1
		SA	553	0.5	0.0	20.8	0.5	21.9
		GAB	652	0.2	0.0	0.9	18.9	19.9
		All	2890	8.9	1.5	5.1	4.4	19.8

Table 5.3.2. School shark recaptures for the release period 1990–96 (≥650 mm TL).

Sex	Release length-class (mm)	Release zone	Number tagged	Percentage recaptured in each zone				
				BS	Tas	SA	GAB	All
Male	650–949	BS	33	15.2	0.0	3.0	0.0	18.2
		Tas	86	5.8	5.8	7.0	1.2	19.8
		SA	1	0.0	0.0	0.0	0.0	0.0
		GAB	1	0.0	0.0	0.0	0.0	0.0
		All	121	8.3	4.1	5.8	0.8	19.0
	950–1399	BS	104	10.6	1.0	2.9	0.0	14.4
		Tas	224	2.2	3.6	0.9	0.0	6.7
		SA	153	2.0	0.7	8.5	0.7	11.8
		GAB	120	1.7	0.8	10.8	5.8	19.2
		All	601	3.5	1.8	5.2	1.3	11.8
	≥1400	BS	130	8.5	0.0	1.5	0.8	10.8
		Tas	79	3.8	1.3	0.0	1.3	6.3
		SA	17	0.0	0.0	11.8	0.0	11.8
		GAB	13	0.0	0.0	7.7	7.7	15.4
		All	239	5.9	0.4	2.1	1.3	9.6
	Total	BS	267	10.1	0.4	2.2	0.4	13.1
		Tas	389	3.3	3.6	2.1	0.5	9.5
		SA	171	1.8	0.6	8.8	0.6	11.7
		GAB	134	1.5	0.7	10.4	6.0	18.7
		All	961	4.7	1.8	4.5	1.2	12.2
Female	650–949	BS	40	20.0	2.5	0.0	0.0	22.5
		Tas	110	10.0	4.5	2.7	1.8	19.1
		SA	8	0.0	0.0	25.0	0.0	25.0
		GAB	1	0.0	0.0	0.0	0.0	0.0
		All	159	11.9	3.8	3.1	1.3	20.1
	950–1399	BS	50	20.0	0.0	8.0	0.0	28.0
		Tas	192	3.1	2.6	3.6	1.6	10.9
		SA	115	2.6	0.0	2.6	1.7	7.0
		GAB	203	0.0	0.5	8.4	3.9	12.8
		All	560	3.4	1.1	5.5	2.3	12.3
	≥1400	BS	35	5.7	2.9	2.9	5.7	17.1
		Tas	87	1.1	1.1	6.9	1.1	10.3
		SA	32	0.0	3.1	0.0	9.4	12.5
		GAB	132	0.8	0.0	5.3	3.8	9.8
		All	286	1.4	1.0	4.9	3.8	11.2
	Total	BS	125	16.0	1.6	4.0	1.6	23.2
		Tas	389	4.6	2.8	4.1	1.5	13.1
		SA	155	1.9	0.6	3.2	3.2	9.0
		GAB	336	0.3	0.3	7.1	3.9	11.6
		All	1005	4.2	1.5	5.0	2.6	13.2

Table 6.1.1. Gummy shark movement of recaptured 1947–56 releases in southern Australia.

See glossary for definition of terms.

Recapture length-class (mm)	Sex	Sample size	Mean ± standard error								
			Release length (mm)	Time free (days)	Dispersion (km^2/day)	Distance (km)	Direction ^{0}N	North vector (km)	East vector (km)	Displacement (km)	Velocity (m/day)
< 650	Male	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Female	2	555 ± 55	251 ± 149	0 ± 0	3 ± 3	202	-3 ± 3	-1 ± 1	3	12
	Total	2	555 ± 55	251 ± 149	0 ± 0	3 ± 3	202	-3 ± 3	-1 ± 1	3	12
650–949	Male	3	807 ± 62	206 ± 171	16 ± 16	24 ± 14	193	-23 ± 14	-5 ± 3	24	117
	Female	1	840 ± 0	431 ± 0	0 ± 0	0 ± 0	1000	0 ± 0	0 ± 0	0	0
	Total	4	815 ± 44	262 ± 134	12 ± 12	18 ± 12	193	-18 ± 11	-4 ± 2	18	69
950–1099	Male	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Female	1	1040 ± 0	37 ± 0	1771 ± 0	256 ± 0	2	256 ± 0	8 ± 0	256	6919
	Total	1	1040 ± 0	37 ± 0	1771 ± 0	256 ± 0	2	256 ± 0	8 ± 0	256	6919
≥1100	Male	24	1122 ± 30	1890 ± 205	7 ± 2	64 ± 16	122	-6 ± 15	10 ± 14	11	6
	Female	24	1197 ± 47	1812 ± 305	341 ± 176	196 ± 55	303	52 ± 36	-80 ± 55	95	52
	Total	48	1160 ± 28	1851 ± 182	174 ± 90	130 ± 30	303	23 ± 20	-35 ± 29	42	23
Total	Male	27	1087 ± 33	1703 ± 210	8 ± 3	59 ± 14	135	-8 ± 13	8 ± 12	11	6
	Female	28	1133 ± 53	1587 ± 281	356 ± 160	177 ± 49	308	53 ± 32	-68 ± 48	87	55
	Total	55	1110 ± 31	1644 ± 175	185 ± 84	119 ± 27	307	23 ± 18	-31 ± 25	39	24

Table 6.1.2. School shark movement of recaptured 1947–56 releases in southern Australia.

See glossary for definition of terms.

Recapture length-class (mm)	Sex	Sample size	Mean ± standard error								
			Release length (mm)	Time free (days)	Dispersion (km^2/day)	Distance (km)	Direction ^{0}N	North vector (km)	East vector (km)	Displacement (km)	Velocity (m/day)
< 650	Male	62	522 ± 10	84 ± 11	9 ± 2	16 ± 2	108	-3 ± 1	9 ± 2	10	119
	Female	68	517 ± 9	80 ± 8	10 ± 2	16 ± 2	110	-4 ± 1	10 ± 2	11	138
	Total	130	519 ± 7	82 ± 7	10 ± 1	16 ± 1	109	-3 ± 1	10 ± 2	10	122
650–949	Male	25	626 ± 10	321 ± 59	154 ± 98	121 ± 52	296	38 ± 34	-77 ± 43	86	268
	Female	44	611 ± 13	271 ± 36	177 ± 101	127 ± 36	59	32 ± 35	53 ± 19	62	228
	Total	69	616 ± 9	289 ± 31	169 ± 73	125 ± 29	10	34 ± 25	6 ± 21	35	121
950–1399	Male	47	670 ± 38	1768 ± 108	202 ± 35	484 ± 47	303	213 ± 36	-325 ± 52	389	220
	Female	41	695 ± 38	1585 ± 132	368 ± 113	520 ± 53	324	231 ± 51	-170 ± 71	287	181
	Total	88	682 ± 27	1683 ± 85	279 ± 56	500 ± 35	311	221 ± 30	-253 ± 44	336	200
≥1400	Male	168	1332 ± 19	4206 ± 249	88 ± 20	264 ± 18	63	7 ± 18	14 ± 21	16	4
	Female	97	1290 ± 32	3698 ± 250	284 ± 63	595 ± 44	316	178 ± 44	-173 ± 55	248	67
	Total	265	1316 ± 17	4020 ± 183	160 ± 27	385 ± 22	322	70 ± 20	-54 ± 25	88	22
Total	Male	302	1004 ± 24	2659 ± 174	95 ± 15	236 ± 16	310	40 ± 13	-47 ± 16	62	23
	Female	250	863 ± 26	1764 ± 143	205 ± 36	343 ± 26	323	111 ± 21	-83 ± 25	139	79
	Total	552	940 ± 18	2254 ± 116	145 ± 19	284 ± 15	319	72 ± 12	-63 ± 14	96	43

Table 6.2.1. Gummy shark movement of recaptured 1973–76 releases in southern Australia.

See glossary for definition of terms.

Recapture length-class (mm)	Sex	Sample size	Mean ± standard error								
			Release length (mm)	Time free (days)	Dispersion (km^2/day)	Distance (km)	Direction ^{0}N	North vector (km)	East vector (km)	Displacement (km)	Velocity (m/day)
< 650	Male	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Female	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Total	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
650–949	Male	14	767 ± 25	440 ± 95	136 ± 90	114 ± 26	1	32 ± 33	1 ± 23	32	73
	Female	16	790 ± 22	456 ± 76	22 ± 10	59 ± 21	355	32 ± 20	-3 ± 13	32	70
	Total	30	779 ± 16	448 ± 59	75 ± 43	85 ± 17	358	32 ± 19	-1 ± 13	32	71
950–1099	Male	72	932 ± 12	514 ± 49	67 ± 28	63 ± 10	45	12 ± 9	12 ± 8	17	33
	Female	48	900 ± 12	509 ± 45	38 ± 15	72 ± 16	108	-5 ± 11	15 ± 15	16	31
	Total	120	919 ± 9	512 ± 34	55 ± 18	67 ± 9	69	5 ± 7	13 ± 8	14	27
≥1100	Male	127	1085 ± 12	800 ± 65	30 ± 8	64 ± 10	355	23 ± 8	-2 ± 8	23	29
	Female	77	1077 ± 21	890 ± 100	173 ± 64	161 ± 34	314	85 ± 19	-89 ± 31	123	138
	Total	204	1082 ± 11	834 ± 55	84 ± 25	100 ± 15	323	46 ± 9	-35 ± 13	58	70
Total	Male	213	1012 ± 11	679 ± 44	49 ± 12	67 ± 7	8	20 ± 6	3 ± 6	20	29
	Female	141	984 ± 15	711 ± 59	110 ± 36	119 ± 20	318	48 ± 12	-44 ± 18	65	91
	Total	354	1001 ± 9	692 ± 35	74 ± 16	88 ± 9	333	31 ± 6	-16 ± 8	35	51

Table 6.2.2. School shark movement of recaptured 1973–76 releases in southern Australia.

See glossary for definition of terms.

Recapture length-class (mm)	Sex	Sample size	Mean ± standard error								
			Release length (mm)	Time free (days)	Dispersion (km^2/day)	Distance (km)	Direction ^{0}N	North vector (km)	East vector (km)	Displacement (km)	Velocity (m/day)
< 650	Male	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Female	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Total	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
650–949	Male	8	655 ± 46	597 ± 96	40 ± 19	122 ± 44	76	8 ± 42	30 ± 46	31	52
	Female	5	659 ± 48	604 ± 38	141 ± 74	243 ± 88	16	177 ± 110	51 ± 44	184	305
	Total	13	656 ± 32	600 ± 59	79 ± 32	168 ± 45	28	73 ± 53	38 ± 32	82	137
950–1399	Male	41	960 ± 36	754 ± 103	117 ± 30	202 ± 32	331	49 ± 28	-27 ± 34	56	74
	Female	22	946 ± 49	802 ± 121	273 ± 125	280 ± 73	327	60 ± 56	-38 ± 76	71	89
	Total	63	955 ± 29	771 ± 79	172 ± 48	229 ± 33	330	53 ± 27	-31 ± 34	61	79
≥1400	Male	14	1255 ± 66	2754 ± 379	285 ± 132	606 ± 111	274	18 ± 112	-245 ± 154	246	89
	Female	16	1338 ± 58	2125 ± 423	951 ± 463	579 ± 128	293	157 ± 91	-371 ± 142	403	190
	Total	30	1299 ± 44	2418 ± 288	640 ± 258	592 ± 84	286	92 ± 71	-312 ± 103	326	135
Total	Male	63	987 ± 36	1179 ± 151	145 ± 36	281 ± 39	298	37 ± 31	-68 ± 42	77	65
	Female	43	1059 ± 49	1271 ± 195	510 ± 188	387 ± 64	306	110 ± 46	-152 ± 70	187	147
	Total	106	1016 ± 29	1216 ± 119	293 ± 81	324 ± 35	303	66 ± 26	-102 ± 38	122	100

Table 6.3.1. Gummy shark movement of recaptured 1990–96 releases in the Eastern Region.

See glossary for definition of terms.

Recapture length-class (mm)	Sex	Sample size	Mean ± standard error								
			Release length (mm)	Time free (days)	Dispersion (km^2/day)	Distance (km)	Direction ^{0}N	North vector (km)	East vector (km)	Displacement (km)	Velocity (m/day)
< 650	Male	8	536 ± 29	101 ± 47	9 ± 7	14 ± 9	256	-2 ± 7	-7 ± 7	7	69
	Female	9	493 ± 18	186 ± 67	6 ± 4	15 ± 5	261	-1 ± 4	-4 ± 6	4	22
	Total	17	513 ± 17	146 ± 42	7 ± 4	15 ± 5	258	-1 ± 4	-6 ± 5	6	41
650–949	Male	167	786 ± 7	264 ± 19	56 ± 12	53 ± 6	344	18 ± 6	-5 ± 5	19	72
	Female	124	798 ± 8	239 ± 19	183 ± 48	114 ± 18	316	42 ± 14	-41 ± 14	59	247
	Total	291	791 ± 5	253 ± 14	109 ± 22	79 ± 9	324	28 ± 7	-20 ± 7	35	138
950–1099	Male	110	943 ± 8	316 ± 32	91 ± 24	76 ± 13	309	19 ± 12	-23 ± 9	30	95
	Female	119	940 ± 9	324 ± 31	245 ± 77	148 ± 22	311	66 ± 16	-76 ± 19	101	312
	Total	229	941 ± 6	320 ± 23	172 ± 42	113 ± 13	310	43 ± 10	-51 ± 11	67	209
≥1100	Male	90	1136 ± 11	355 ± 36	112 ± 37	80 ± 14	347	14 ± 10	-3 ± 13	14	39
	Female	84	1171 ± 20	399 ± 42	641 ± 284	228 ± 30	309	90 ± 24	-111 ± 26	143	359
	Total	174	1153 ± 11	376 ± 28	367 ± 140	151 ± 17	312	50 ± 13	-55 ± 15	75	200
Total	Male	375	911 ± 9	297 ± 16	79 ± 13	65 ± 6	329	17 ± 5	-10 ± 5	20	67
	Female	336	933 ± 11	308 ± 17	316 ± 79	152 ± 13	311	61 ± 10	-70 ± 11	93	302
	Total	711	921 ± 7	302 ± 12	190 ± 38	106 ± 7	315	38 ± 5	-38 ± 6	54	179

Table 6.3.2. School shark movement of recaptured 1990–96 releases in the Eastern Region.

See glossary for definition of terms.

Recapture length-class (mm)	Sex	Sample size	Mean ± standard error								
			Release length (mm)	Time free (days)	Dispersion (km^2/day)	Distance (km)	Direction ^{0}N	North vector (km)	East vector (km)	Displacement (km)	Velocity (m/day)
< 650	Male	15	421 ± 21	49 ± 15	1 ± 1	3 ± 1	217	-1 ± 1	-1 ± 1	1	21
	Female	20	425 ± 18	73 ± 29	29 ± 17	36 ± 18	132	-20 ± 12	23 ± 14	30	414
	Total	35	424 ± 14	62 ± 18	17 ± 10	22 ± 10	134	-12 ± 7	13 ± 8	17	273
650–949	Male	17	689 ± 25	344 ± 67	384 ± 236	278 ± 98	314	138 ± 74	-144 ± 82	199	579
	Female	23	683 ± 18	324 ± 40	287 ± 105	214 ± 44	333	98 ± 49	-50 ± 32	110	340
	Total	40	686 ± 15	332 ± 36	328 ± 115	241 ± 48	322	115 ± 42	-90 ± 40	146	439
950–1399	Male	37	1115 ± 39	375 ± 61	774 ± 167	441 ± 90	315	251 ± 65	-251 ± 79	355	946
	Female	48	1065 ± 34	413 ± 56	2155 ± 531	606 ± 81	314	324 ± 60	-331 ± 81	463	1122
	Total	85	1086 ± 26	396 ± 41	1554 ± 316	534 ± 61	315	293 ± 44	-296 ± 57	416	1049
≥1400	Male	25	1448 ± 12	300 ± 34	2081 ± 696	503 ± 111	326	267 ± 71	-181 ± 118	322	1074
	Female	17	1462 ± 15	281 ± 41	4379 ± 1071	909 ± 160	306	516 ± 111	-700 ± 140	869	3091
	Total	42	1453 ± 9	292 ± 26	3011 ± 617	667 ± 96	313	367 ± 64	-391 ± 98	536	1834
Total	Male	94	1016 ± 41	297 ± 30	927 ± 213	358 ± 52	318	195 ± 35	-173 ± 47	260	874
	Female	108	928 ± 36	310 ± 30	1714 ± 321	464 ± 53	313	242 ± 37	-264 ± 48	358	1155
	Total	202	969 ± 27	304 ± 21	1348 ± 199	415 ± 37	315	220 ± 26	-221 ± 34	312	1026

Table 6.4.1. Gummy shark movement of recaptured 1990–96 releases in the Western Region.

See glossary for definition of terms.

Recapture length-class (mm)	Sex	Sample size	Mean ± standard error								
			Release length (mm)	Time free (days)	Dispersion (km^2/day)	Distance (km)	Direction ^{0}N	North vector (km)	East vector (km)	Displacement (km)	Velocity (m/day)
< 650	Male	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Female	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Total	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
650–949	Male	3	867 ± 34	212 ± 108	37 ± 25	42 ± 27	226	-24 ± 26	-24 ± 17	34	161
	Female	5	890 ± 18	182 ± 55	257 ± 172	163 ± 68	119	-59 ± 27	109 ± 83	124	681
	Total	8	881 ± 16	193 ± 49	175 ± 111	118 ± 47	128	-46 ± 19	59 ± 55	75	388
950–1099	Male	27	1021 ± 10	154 ± 27	101 ± 68	37 ± 15	268	0 ± 11	-6 ± 13	6	39
	Female	84	1007 ± 5	149 ± 15	182 ± 88	58 ± 15	90	0 ± 9	18 ± 13	18	121
	Total	111	1011 ± 4	150 ± 13	163 ± 69	53 ± 12	90	0 ± 8	12 ± 10	12	80
≥1100	Male	81	1171 ± 7	199 ± 21	242 ± 86	111 ± 22	132	-15 ± 13	16 ± 22	22	111
	Female	111	1170 ± 10	250 ± 18	171 ± 65	89 ± 19	114	-15 ± 10	34 ± 18	37	148
	Total	192	1171 ± 6	229 ± 14	201 ± 52	98 ± 14	119	-15 ± 8	26 ± 14	30	131
Total	Male	111	1126 ± 9	188 ± 17	204 ± 65	91 ± 17	139	-11 ± 10	10 ± 16	15	80
	Female	200	1095 ± 8	206 ± 12	178 ± 52	78 ± 12	109	-10 ± 7	29 ± 12	30	146
	Total	311	1106 ± 6	200 ± 10	187 ± 41	83 ± 10	115	-10 ± 6	22 ± 9	24	120

Table 6.4.2. School shark movement of recaptured 1990–96 releases in the Western Region.

See glossary for definition of terms.

Recapture length-class (mm)	Sex	Sample size	Mean ± standard error								
			Release length (mm)	Time free (days)	Dispersion (km^2/day)	Distance (km)	Direction ^{0}N	North vector (km)	East vector (km)	Displacement (km)	Velocity (m/day)
< 650	Male	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Female	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Total	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
650–949	Male	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Female	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
	Total	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0	0 ± 0	0 ± 0	0	0
950–1399	Male	37	1184 ± 15	267 ± 38	1735 ± 498	435 ± 66	125	-201 ± 47	290 ± 64	353	1321
	Female	31	1164 ± 25	256 ± 38	1795 ± 649	464 ± 67	123	-175 ± 50	274 ± 76	325	1267
	Total	68	1175 ± 14	262 ± 27	1762 ± 398	448 ± 47	124	-189 ± 34	283 ± 49	340	1296
≥1400	Male	6	1416 ± 29	367 ± 111	1171 ± 474	555 ± 202	119	-209 ± 175	378 ± 190	432	1177
	Female	17	1472 ± 15	212 ± 36	3632 ± 1022	680 ± 130	125	-289 ± 104	416 ± 142	506	2387
	Total	23	1457 ± 14	252 ± 41	2990 ± 792	647 ± 108	123	-268 ± 88	406 ± 114	487	1929
Total	Male	43	1217 ± 18	281 ± 36	1656 ± 433	451 ± 63	124	-202 ± 46	302 ± 61	363	1291
	Female	48	1273 ± 27	241 ± 28	2446 ± 562	540 ± 64	124	-215 ± 49	324 ± 70	389	1616
	Total	91	1246 ± 17	260 ± 22	2073 ± 361	498 ± 45	124	-209 ± 34	314 ± 47	377	1451

Figures

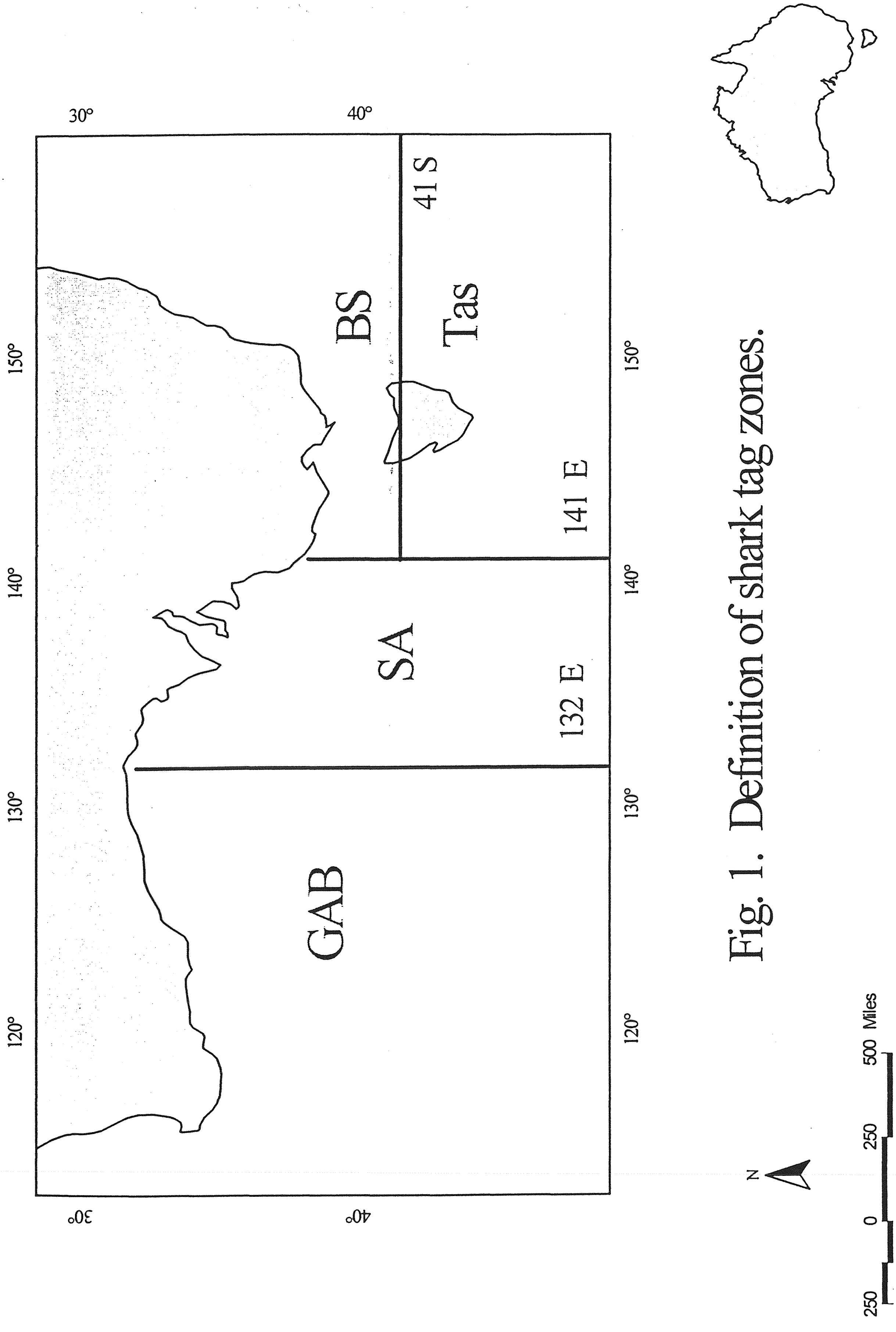


Fig. 1. Definition of shark tag zones.

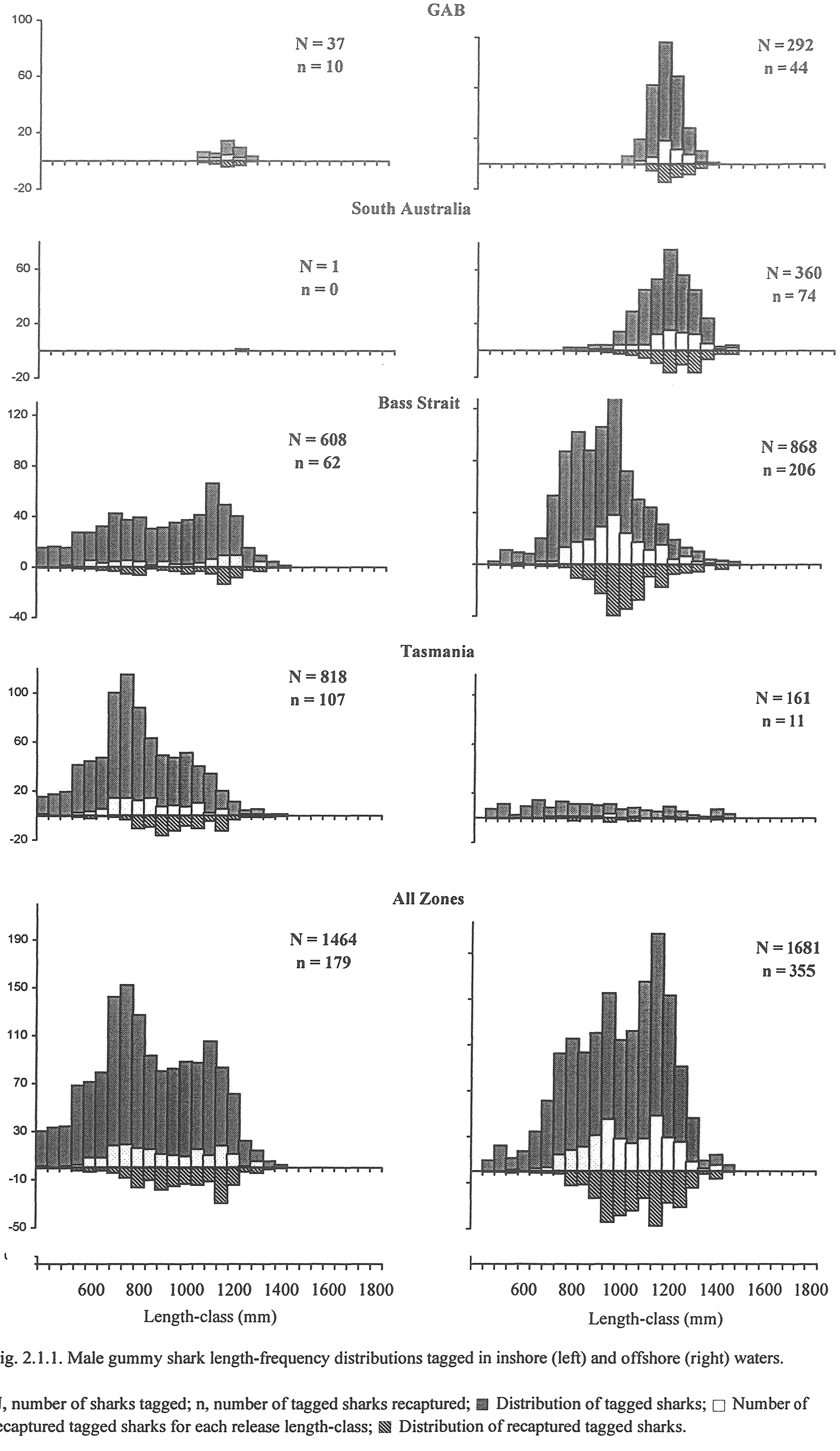


Fig. 2.1.1. Male gummy shark length-frequency distributions tagged in inshore (left) and offshore (right) waters.

N, number of sharks tagged; n, number of tagged sharks recaptured; ▩ Distribution of tagged sharks; ☐ Number of recaptured tagged sharks for each release length-class; ▨ Distribution of recaptured tagged sharks.

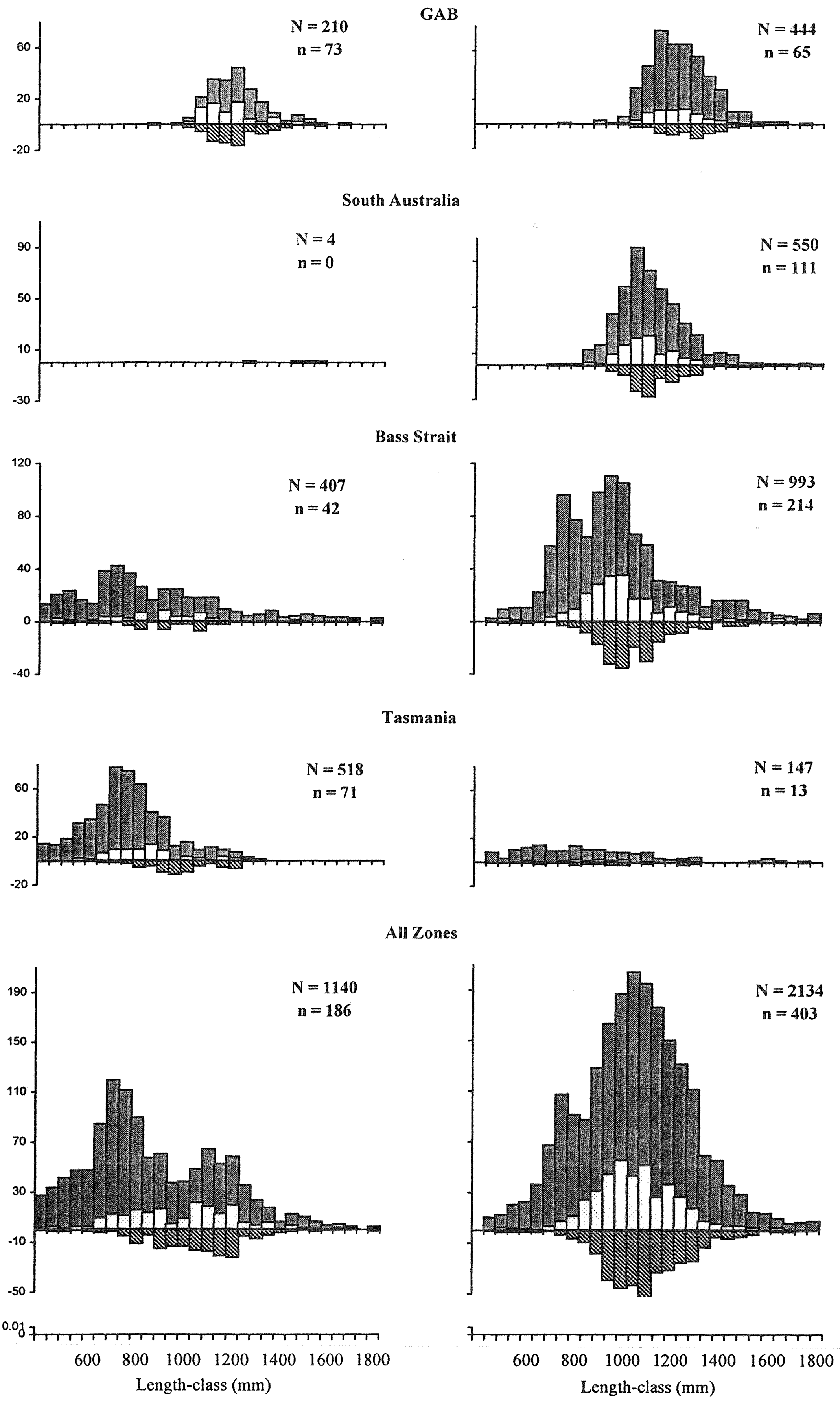


Fig. 2.1.2. Female gummy shark length-frequency distributions tagged in inshore (left) and offshore (right) waters.

N, number of sharks tagged; n, number of tagged sharks recaptured;■ Distribution of tagged sharks;□ Number of recaptured tagged sharks for each release length-class;▨ Distribution of recaptured tagged sharks.

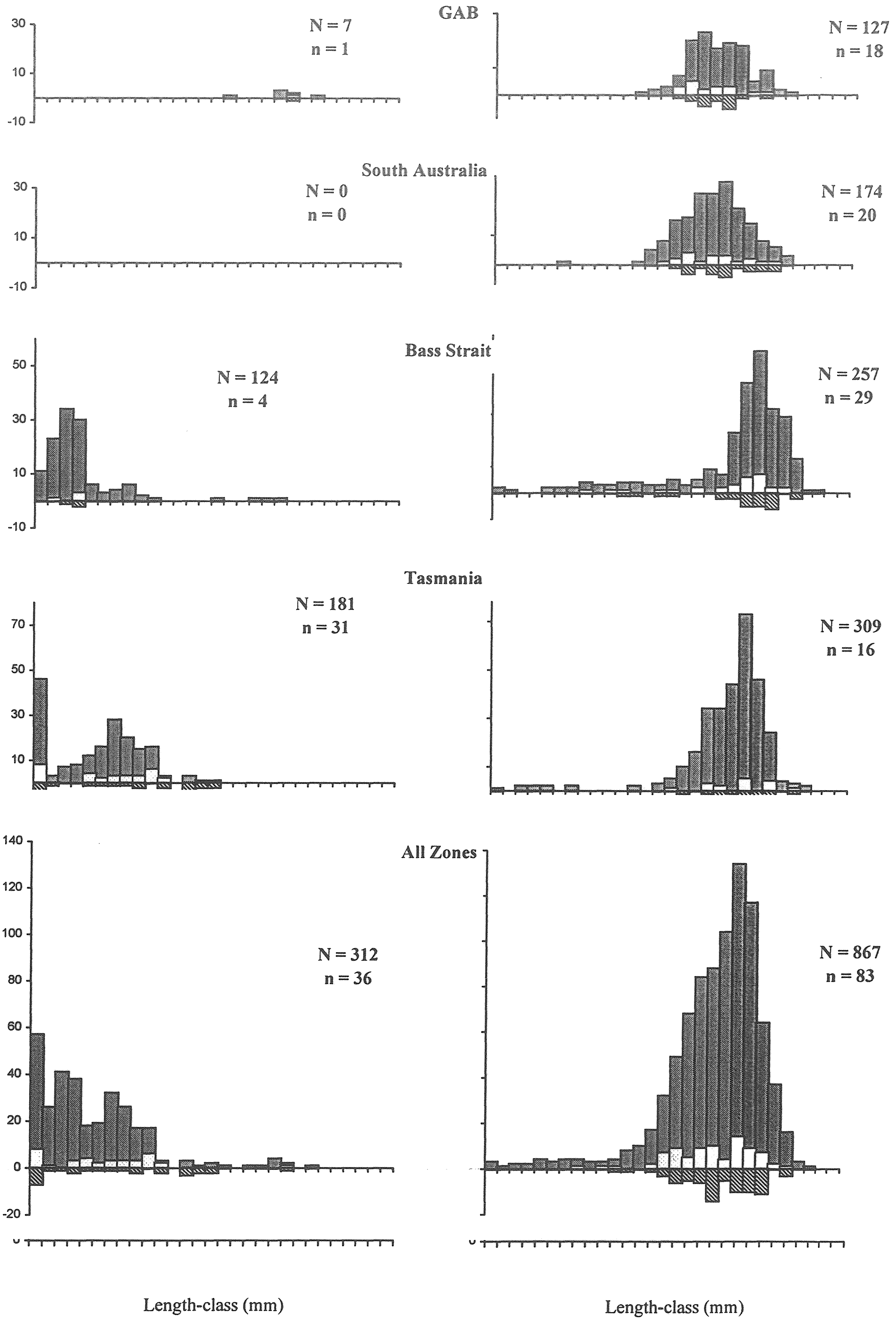


Fig. 2.2.1. Male school shark length-frequency distributions tagged in inshore (left) and offshore (right) waters.

N, number of sharks tagged; n, number of tagged sharks recaptured; ■ Distribution of tagged sharks; □ Number of recaptured tagged sharks for each release length-class; ▧ Distribution of recaptured tagged sharks.

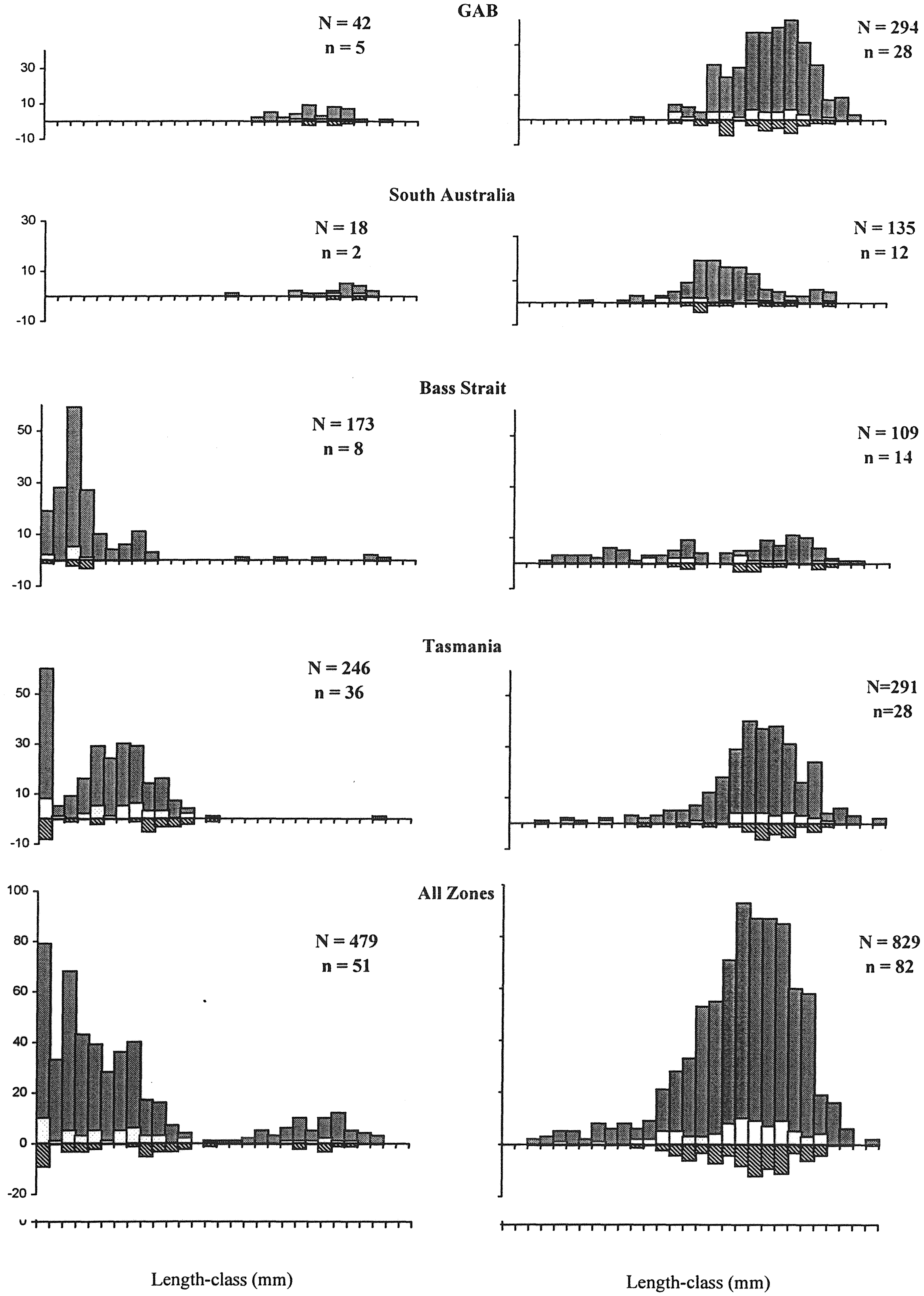


Fig. 2.2.2. Female school shark length-frequency distributions tagged in inshore (left) and offshore (right) waters.

N, number of sharks tagged; n, number of tagged sharks recaptured; ▩ Distribution of tagged sharks; □ Number of recaptured tagged sharks for each release length-class; ▨ Distribution of recaptured tagged sharks.

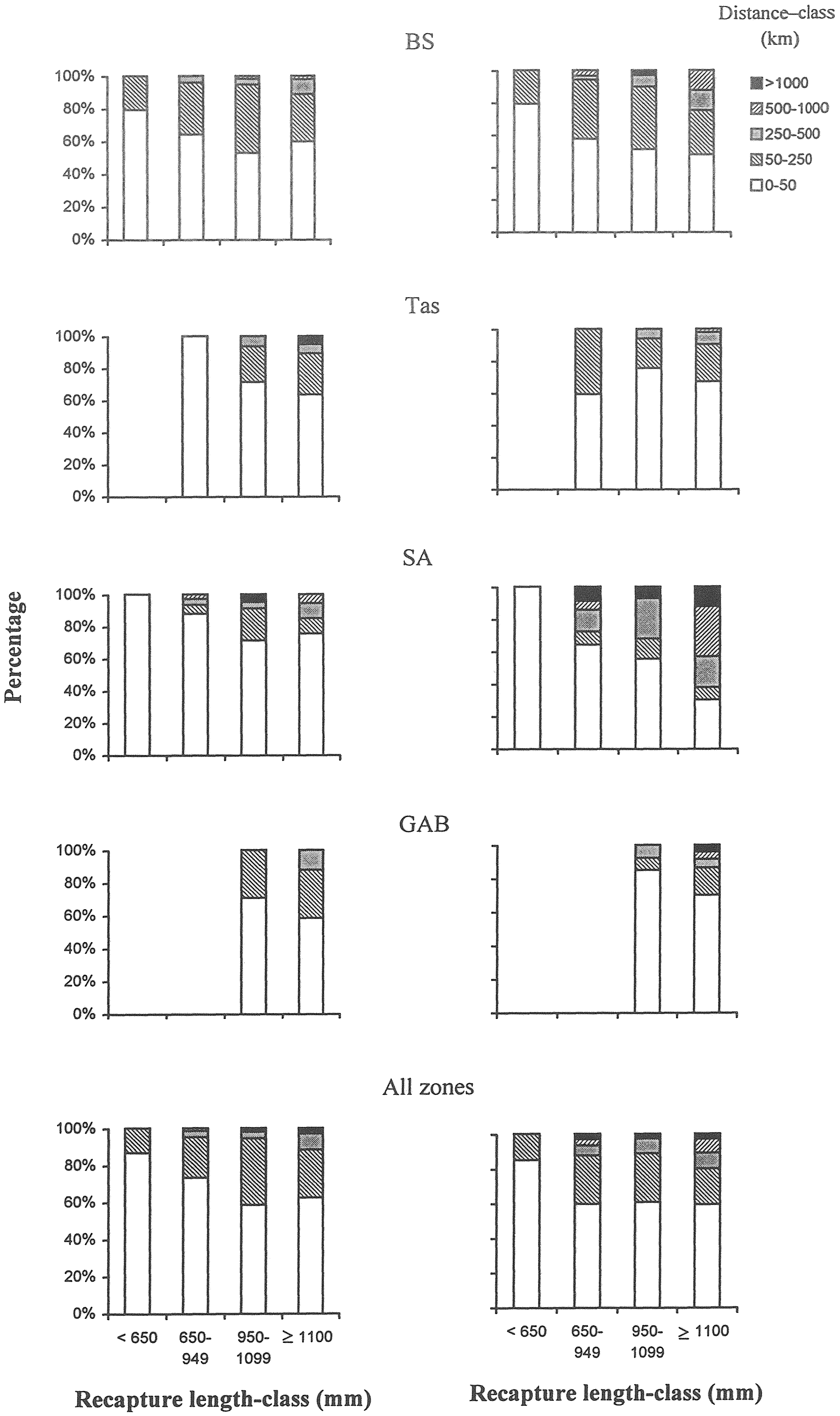


Fig. 3.1. Percentage of recaptured male (left) and female (right) gummy sharks within each distance-class.

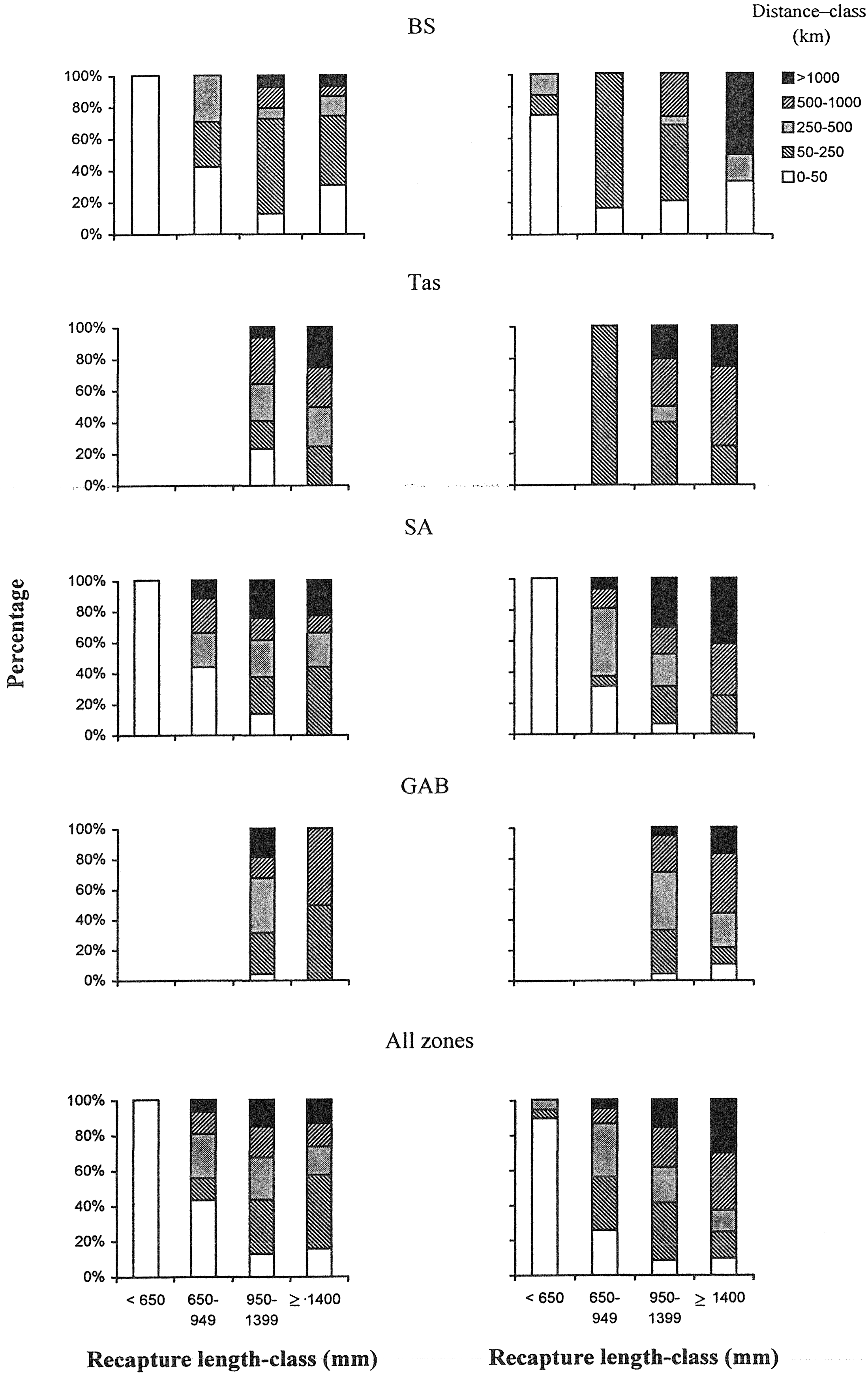


Fig. 3.2. Percentage of recaptured male (left) and female (right) school sharks within each distance-class.

Appendix A. Experimental Design for Tag Releases

A framework for evaluating experimental designs for estimating rates of fish movement from tag recoveries

Yongshun Xiao

Abstract: Reliable estimates of fish movement rates from tag recoveries require an experimental design for collecting sufficient data and a procedure for estimating quantities of interest from the data. Although many such procedures have been developed, suitable experimental designs have not been. In this paper, I present a framework for calculating the accuracy and precision of estimates of movement rates for different experimental designs combined with an estimator, thereby providing a basis for collecting sufficient data to estimate movement rates to a chosen accuracy and precision. The framework is used to evaluate a set of experimental designs for a tagging program for school shark, *Galeorhinus galeus*, when Hilborn's (R. Hilborn. 1990. Can. J. Fish. Aquat. Sci. 47: 635–643) maximum likelihood method is used to estimate movement rates. In this application, the minimum, mean, maximum, and three common norms of both relative bias and relative standard error of estimates of all movement rates were each regressed on the total number of fish released as a power function. From these regression equations, one can calculate the number of releases to achieve a certain level of precision and accuracy in estimates of movement rates or vice versa. Extensions of Hilborn's (1990) model and other statistical movement models can be examined similarly.

Résumé : Il faut un plan d'expérience pour recueillir suffisamment de données et une méthode pour déduire les résultats chiffrés qu'on cherche à extraire de ces données si l'on veut obtenir des estimations fiables des taux de déplacement de poissons à partir de la recapture de sujets marqués. Il existe un grand nombre de méthodes pour cela, mais pas de plans d'expérience bien adaptés à cette tâche. Dans cet article, l'auteur présente un cadre pour le calcul de l'exactitude et de la précision des estimations des taux de déplacement des poissons en fonction de différents plans d'expérience combinés à l'utilisation d'un estimateur, ce qui constitue une base pour la cueillette d'une quantité suffisante de données pour estimer les taux de déplacement avec l'exactitude et la précision choisies. Ce cadre est appliqué à l'estimation d'un ensemble de plans d'expérience à utiliser dans le cadre d'un programme de marquage de chiens de mer (*Galeorhinus galeus*) lorsque la méthode de la probabilité maximale de Hilborn (R. Hilborn. 1990. J. can. sci. halieut. aquat. 47: 635–643) est employée pour estimer les taux de déplacement. Dans cette application, on effectue une régression de fonction de puissance entre le nombre total de poissons libérés et le minimum, la moyenne, le maximum et trois normalisations courantes des estimations de biais relatif et d'écart-type relatif de tous les taux de déplacement des poissons. À partir de ces équations de régression, on peut calculer le nombre de lâchers requis pour obtenir un niveau cherché de précision et d'exactitude dans les estimations des taux de déplacement, et l'inverse. On peut, de la même manière, examiner des extensions du modèle de Hilborn (1990) et d'autres modèles statistiques de déplacements.

Introduction

Many fish move long distances to complete their life cycles; understanding these movements is essential to studies of their population dynamics. Estimates of rates of fish movement between spatial strata from tag recoveries rely on (*i*) an experimental design for collecting sufficient data and (*ii*) a procedure for estimating quantities of interest from the data. Many such procedures are available. The simplest is to draw arrows from the sites of release to the sites of recapture and to calculate proportions of recaptures to total releases as a function of time for all sites (e.g., Schaefer et al. 1961). This analysis can, however, be substantially biased, because it does not allow for spatiotemporal variations in fishing effort, which also affects the number of recaptures. Several statistical methods for estimating movement rates from tag recoveries have also been developed (e.g., Ishii 1979; Cormack 1981; Sibert 1984; Hilborn 1990; Schwarz et al. 1993; Schweigert and Schwarz 1993; Anganuzzi et al. 1994).

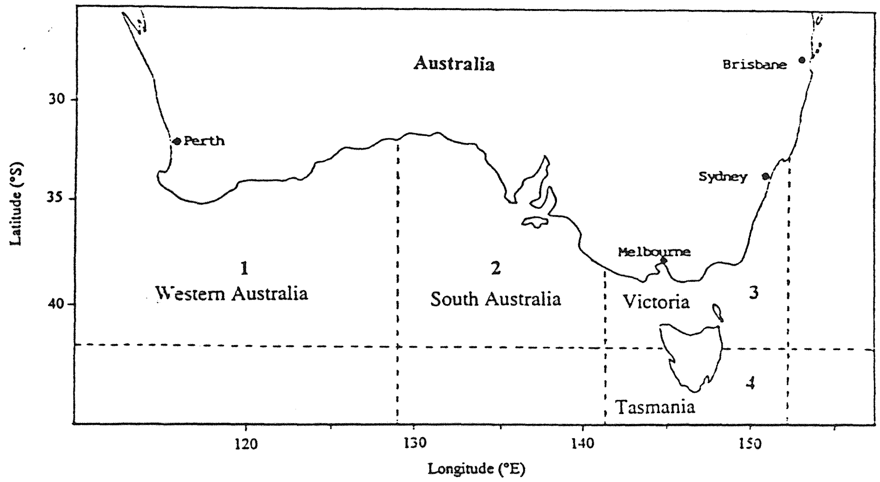
By contrast, the problem of selecting an experimental design, such as allocation of the number of fish releases by area and time, remains unsolved. This lack of systematic designs can have major implications for previous and, if not addressed, future estimates of movement rates. Obviously, if fewer recaptures than are needed to estimate movement rates reliably are made from a tagging experiment, then both the accuracy (measured, say, by relative bias) and the precision (measured, say, by relative standard error) of the resulting estimates are compromised, and the experiment can be considered a failure. In this case, caution must be exercised, in ensuing applications, about poor accuracy and precision in existing estimates of parameters. On the other hand, if more than the required number of recaptures is made, more resources than necessary have been consumed for unnecessarily accurate and precise estimates; such resources might have otherwise been used for wiser purposes. Thus, an experiment must be designed to avoid

Received March 17, 1995. Accepted December 15, 1995.
J12826

Y. Xiao. CSIRO Division of Fisheries, GPO Box 1538, Hobart, Tasmania 7001, Australia. e-mail: xiao@ml.csiro.au

Can. J. Fish. Aquat. Sci. 53: 1272–1280 (1996).

Fig. 1. Management areas in the Australian southern shark fishery. Area 1, Western Australia; area 2, South Australia; area 3, Victoria; area 4, Tasmania.



either too few or too many recaptures. In other words, the design must determine how many fish should be released, when and where, to achieve a chosen level of precision and accuracy in estimates of movement rates.

School shark, *Galeorhinus galeus* (Linnaeus) (Last and Stevens 1994), is a major species in the Australian southern shark fishery. The fishery extends from Western Australia in the west through South Australia to Bass Strait and Tasmania in the east (Fig. 1) and has an annual landed value of SA 15.6 million (Walker et al. 1994). Tagging programs were undertaken to study its growth and natural mortality (Grant et al. 1979) and local movements in Victoria and off southern Tasmania (T.I. Walker, Victorian Fisheries Research Institute, P.O. Box 114, Queenscliff, Victoria 3225, Australia, unpublished data). Both studies suggest that school shark are highly migratory, but they provide little information about the sharks' movement rates beyond these areas, where most sharks were tagged and released. Also, fishing effort was poorly documented at the time of Grant et al.'s (1979) tagging program (1940s and 1950s) and the data are inadequate for quantifying movement rates. Finally, predominant use of gill nets with large mesh sizes (8 in.; 1 in. = 25.4 mm) off the southern coast of Western Australia and off South Australia at the time of T.I. Walker's tagging program (1970s) led to a low level of fishing effort and a small number of recaptures.

The implications of fish movements for stock assessment and management are poorly understood. It seems, however, that assuming that the fish are not moving while they are leads to a loss in potential yields (e.g., Tuck and Possingham 1994), whereas assuming that they are moving while they are not can result in a depletion of the most accessible stocks (Hilborn and Walters 1992). The lack of quantitative information on the movement rates of school shark has precluded a quantitative analysis of the implications of an often-made assumption that its regional stocks do not mix. A large-scale tagging program is essential for quantifying its movement rates so that they can be incorporated in management decisions. Such a program was initiated recently by the Victorian Fisheries Research Institute (VFRI) in collaboration with the CSIRO Division of Fisheries.

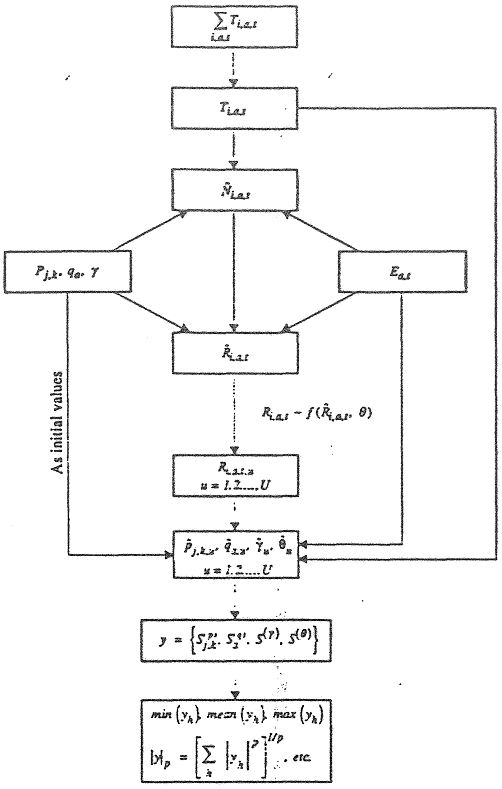
In this report, I present a framework for calculating the accuracy and precision of estimates of fish movement rates that can be expected from different experimental designs combined with an appropriate estimation procedure, thereby providing a basis for collecting sufficient data to achieve a chosen accuracy and precision in estimates of movement rates. The framework is used to evaluate a set of experimental designs for the tagging program for school shark, when Hilborn's (1990) maximum likelihood method is used to estimate movement rates. This estimation procedure is chosen because it is simple and widely applicable. Extensions of Hilborn's (1990) model and other statistical models can be examined similarly.

Framework

In this framework (Fig. 2), different experimental designs for determining rates of fish movement from tag recoveries can theoretically be developed by varying the number and patterns of fish released by area and time, controlling the levels of fishing effort, and varying the values of model parameters including movement rates. In reality, it is unusual to control fishing effort for this purpose because of the difficulties in doing so (Hilborn and Walters 1992).

The variant of the framework described below assumes constant, but can readily be expanded to handle time-varying, values of natural and fishing mortalities, tag shedding rate, and movement rates. For consistency, Hilborn's (1990) notation will be used below with minimal modifications. Let $T_{i,a,t}$ = number of tags released from tag group i in area a at time t, $\hat{N}_{i,a,t}$ = expected number of tagged fish in tag group i in area a at time t, $R_{i,a,t}$ = number of tags recovered from tag group i in area a at time t, $\hat{R}_{i,a,t}$ = expected number of tags recovered from tag group i in area a at time t, $p_{j,k}$ = probability of movement from area j to k, $E_{a,t}$ = fishing effort in area a at time t, q_a = catchability coefficient in area a, M = constant instantaneous

Fig. 2. Flow chart of simulation.



natural mortality rate, and λ = constant instantaneous tag shedding rate. Other notations will be introduced as they arise.

The tag group must be defined properly to get the desired results. Generally, a tag group is a group of fish tagged in a spatiotemporal stratum but this could be extended to include size groups, sex, or whatever criteria thought to be important in movement, survival, and probability of recapture. At the least, fish released in each area must be treated as a tag group. The framework involves 13 steps.

(1) Specify a population dynamics and movement model, an observation model, and a procedure for parameter estimation. In the example below, I will use Hilborn's (1990) models and procedure.

(2) Select a set of input fish movement rates $p_{j,k}$, catchability coefficients q_a, and other parameters γ in the estimation procedure.

(3) Select projected levels of future fishing effort $E_{a,t}$.

(4) Specify the total number of fish releases $x = \sum_{i,a,t} T_{i,a,t}$ and a procedure for allocating releases to spatiotemporal strata, $T_{i,a,t}$.

(5) Calculate the expected number of tags recovered from tag group i in area a at time t, $\hat{N}_{i,a,t}$, from $T_{i,a,t}$, $p_{j,k}$, q_a, γ, and $E_{a,t}$ using the population dynamics and movement model.

(6) Calculate the expected number of tags recovered from tag group i in area a at time t, $\hat{R}_{i,a,t}$, from $\hat{N}_{i,a,t}$, q_a, and $E_{a,t}$ using the observation model.

(7) Specify a statistical distribution for the recapture process $R_{i,a,t} \sim f(\hat{R}_{i,a,t}, \theta)$ with a mean of $\hat{R}_{i,a,t}$ and a vector of parameters (other than those in population dynamics and movement model and observation model) θ, and simulate a sufficiently large number U of data sets of recaptures $R_{i,a,t,u}$, with $u = 1, 2, \ldots, U$.

(8) Estimate, for the uth set of simulated data, movement rates $p_{j,k,u}$, catchability coefficients $q_{a,u}$, γ_u, and θ_u from $R_{i,a,t,u}$, $T_{i,a,t}$, and $E_{a,t}$, with $u = 1, 2, \ldots, U$ and with the input values of $p_{j,k}$, q_a, γ, and θ as the initial values of parameters.

(9) Calculate statistics (e.g., relative bias and relative standard error) that summarize the estimates of movement rates $S^{(p)}_{j,k}$, catchability coefficient $S^{(q)}_a$, $S^{(\gamma)}$, and $S^{(\theta)}$. In the example below, I will calculate the relative bias of estimates of movement rates

$$B^{(p)}_{j,k} = 1 - \frac{1}{p_{j,k}U} \sum_u \hat{p}_{j,k,u}$$

and relative standard error of estimates of movement rates

$$RSD^{(p)}_{j,k} = \frac{1}{p_{j,k}} \left(\frac{1}{U} \sum_u \left(\hat{p}_{j,k,u} - \frac{1}{U} \sum_u \hat{p}_{j,k,u} \right)^2 \right)^{1/2}.$$

(10) Form vector $y = \{S^{(p)}_{j,k}, S^{(q)}_a, S^{(\gamma)}, S^{(\theta)}\}$ and calculate the minimum, mean, and maximum of all elements of vector y, i.e., $\min_h (y_h)$, $\mathrm{mean}_h (y_h)$, and $\max_h (y_h)$, and various norms of vector y, i.e.,

$$|y|_p = \left[\sum_h |y_h|^p \right]^{1/p}.$$

(11) Repeat above steps for different values of $\sum_{i,a,t} T_{i,a,t}$, $T_{i,a,t}$, $p_{j,k}$, q_a, γ, θ, and $E_{a,t}$ to get corresponding minimum, mean and maximum of all elements, and various vector norms, of vector y.

(12) Determine the empirical relationships of minimum, mean, and maximum of all elements, and various norms, of vector y, with $\sum_{i,a,t} T_{i,a,t}$, $T_{i,a,t}$, $p_{j,k}$, q_a, γ, θ, and $E_{a,t}$. In this study, I regress each of them, S, on the total number of releases x using the power function $S = ax^{-b}$, where a and b are regression parameters to be estimated.

(13) Evaluate those empirical relationships and decide, for a tagging experiment, appropriate values of $\sum_{i,a,t} T_{i,a,t}$, $T_{i,a,t}$, $p_{j,k}$, q_a, γ, θ, and $E_{a,t}$ to achieve a chosen level of accuracy and precision in terms of minimum, mean, and maximum of all elements, and various norms, of vector y.

Design of a tagging experiment for school shark: an application

Of a few statistical models, I choose to illustrate my framework using Hilborn's (1990) model and maximum likelihood estimator because of their simplicity and wide applicability. His population dynamics and movement model is rewritten as

Table 1. Summary of inputs to the model.

	j/a	1	2	3	4
$a_{j,a}(p_{j,a})$	1	0.50 (0.985777)	0.10 (0.001110)	0.20 (0.005564)	0.20 (0.007549)
	2	0.10 (0.002990)	0.70 (0.992280)	0.10 (0.002052)	0.10 (0.002677)
	3	0.05 (0.001235)	0.10 (0.002276)	0.80 (0.995374)	0.05 (0.001115)
	4	0.10 (0.002990)	0.30 (0.009688)	0.10 (0.002052)	0.50 (0.985270)
q_a	—	2.43×10^{-9}	1.31×10^{-9}	2.78×10^{-9}	3.21×10^{-9}
M	—	0.193×10^{-2}	0.193×10^{-2}	0.193×10^{-2}	0.193×10^{-2}
λ	—	0.914×10^{-3}	0.914×10^{-3}	0.914×10^{-3}	0.914×10^{-3}
$E_{a,t}$	—	64 986	217 002	150 397	29 200
$T_{i,a,0}$	—	140	0	0	0
$T_{i,a,1}$	—	0	140	0	0
$T_{i,a,2}$	—	0	0	140	0
$T_{i,a,3}$	—	0	0	0	140
$T_{i,a,4}$	—	140	0	0	0
...	—	...	...	...	...

Note: (1) conversion of annual movement rates $a_{j,a}$ to weekly movement rates $p_{j,a}$ by taking the 7/365.25th = 28.1461th power of square matrix $\{a_{j,a}\}$ using Mathematica (Wolfram 1991), with 1 = Western Australia, 2 = South Australia, 3 = Victoria, 4 = Tasmania; (2) catchability coefficient q_a ((m·hook lifts·week^{-1})$^{-1}$); (3) instantaneous natural mortality M (week^{-1}); (4) instantaneous tag shedding rate λ (week^{-1}); (5) fishing effort $E_{a,t}$ (m·hook lifts·week^{-1}); (6) number and pattern of fish releases $T_{i,a,t}$ (individuals) that are continued until the total number of releases is reached. Subscripts: $a, i, j, k = 1, 2, \ldots, n = 4$; $t = 1, 2, \ldots, \max(t) = 157$ weeks: $u = 1, 2, \ldots, U = 500$ trials. —, not applicable. Fish released in each area are considered a tag group. The release protocol is repeated for a total number of release of 560 to 10 640 by 560.

$$\hat{N}_{i,a,t+1} = \sum_{j=1}^{n} \hat{N}_{i,j,t}\,(1 - q_j E_{j,t})\, e^{-(M+\lambda)}\, p_{j,a} + T_{i,a,t},$$

and his observation model as

$$\hat{R}_{i,a,t} = \hat{N}_{i,a,t}\, q_a E_{a,t},$$

with $\hat{N}_{i,a,0} = 0$ and a maximum of $n(n + 1)$ parameters (assuming that both M and λ are known constants), of which n^2 are movement rates and n catchability coefficients. The number of movement parameters is reduced to $n(n - 1)$ under the constraint $\sum_{k} p_{j,k} = 1$. Note that $T_{i,a,t}$ in his population dynamics and movement model must be multiplied by a term to correct for its associated mortality over the period $[t, t + 1]$, unless releases are made at the very end of each period. In this application, then, $\gamma = \{M, \lambda\}$ and $\theta = 0$. Gear selectivity, initial tag loss, underreporting of fish recaptures, and emigration can also be incorporated into this model, but are ignored below because of a lack of quantitative information. These models can be implemented for any time intervals (e.g., day, week, month, or year) after conversion of movement rates (see Table 1 for a proper conversion). Since recaptures are recorded as date of recapture, one may as well be as prepared to convert annual movement rates and fishing effort to daily movement rates and effort as to convert daily to annual recaptures. In this work, t is measured in weeks. Also, for most tagging programs, it should be reasonable to expect sufficient tag recoveries within not too long a period (e.g., 3–6 years). For this application, I set $\max(t) = 157$ weeks, and considered fish released in each area as a tag group.

To estimate various model parameters, I assume that $R_{i,a,t}$ follows a Poisson distribution with a mean (and also variance) of $\hat{R}_{i,a,t}$, i.e., $R_{i,a,t} \sim \text{Poisson}(\hat{R}_{i,a,t})$, and simulate a sufficiently large number ($U = 500$) of data sets of recaptures $R_{i,a,t,u}$, with $u = 1, 2, \ldots, U$. For the uth simulated data set, the Poisson distribution for fish from tag group i in area a at time t can be written as

$$L(R_{i,a,t,u} | \hat{R}_{i,a,t}) = \frac{e^{-\hat{R}_{i,a,t}}\, \hat{R}_{i,a,t}^{R_{i,a,t,u}}}{R_{i,a,t,u}!},$$

and the total likelihood function as

$$\prod_{i,a,t} \frac{e^{-\hat{R}_{i,a,t}}\, \hat{R}_{i,a,t}^{R_{i,a,t,u}}}{R_{i,a,t,u}!}$$

(Hilborn 1990). Model parameters can then be estimated by minimizing

$$\sum_{i,a,t} [\hat{R}_{i,a,t} - R_{i,a,t,u} \log(\hat{R}_{i,a,t})].$$

A summary of inputs to the model is given in Table 1. $T_{i,a,t}$ is determined mainly by the availability of fish to be tagged and by logistics, although it is desirable and sometimes essential to examine a variety of release patterns. Releases should at least cover all of the spatiotemporal strata concerned to provide contrast in the data. In the case of school shark, I examined only one release pattern. Initial trials from a pilot tagging program during 1994 by staff from the VFRI indicated that personnel available for that tagging program could go to the field weekly. Because it is a small team, as in most tagging programs, various spatial strata would have to be visited consecutively. Existing data suggested that for tagging purposes, school shark would be equally available in all spatial strata and at all times; approximately 140 sharks can be tagged during a weekly trip to a single area, and releases are assumed to be made at the very end of each period. In this application, I assume, therefore, that the four areas are visited consecutively; each area is visited in turn for a week to tag 140 sharks. This tag and release protocol is maintained until the total number of releases specified is reached. Finally, I repeat steps 4–10 of the general framework by varying the total number of releases from 560 to 10 640 by 560, while holding constant $p_{j,k}$, q_a,

γ, θ, and $E_{a,t}$, all for Hilborn's (1990) population dynamics and movement model, observation model, and estimation procedure.

It is difficult to determine $E_{a,t}$ reliably, although fishing effort in the near future should be adequately approximated by averaging the fishing effort over the past few (say 4) years. In the case of school shark, I estimated fishing effort for 1990–1993 from the VFRI's data (T.I. Walker, personal communication). Since several types of gear (gill nets of various mesh sizes, and hooks) are used in the fishery, all effort for South Australia, Victoria, and Tasmania was converted to m·hook lifts·week^{-1} through a regression of catch on fishing effort and types of gear (see below). Note that this method for standardizing catch and effort uses catches as the dependent variable, and effort and all other factors that contribute to catch variations as independent variables. Thus, provided that catches are given in the same unit, it suits effort even of entirely different kinds. The effort for Western Australia (C. Simpfendorfer, Western Australia Marine Research Laboratories, P.O. Box 20, North Beach, Western Australia 6020, Australia, personal communication) also used several types of gear. It was calculated from information from the VFRI, as associated catch data were not available at the time of standardization. In this application, fishing effort $E_{a,t}$ in the future is assumed to be constant over time for a particular area: 64 986, 217 002, 150 397, and 29 200 m·hook lifts·week^{-1} for Western Australia, South Australia, Victoria, and Tasmania, respectively.

For this application, I had planned to estimate $p_{j,k}$ from three sets of tagging data: one from Grant et al. (1979), one from a pilot tagging program as part of this experimental design, and the third from a tagging study by the VFRI. As mentioned earlier, the first source of data was limited in release site to the coasts of Tasmania, Victoria, and South Australia. When fitted into Hilborn's (1990) model and estimation procedure under various hypothetical patterns of fishing effort (as a result of a lack of detailed data on fishing effort), these data gave unrealistic estimates of $p_{j,k}$ and q_a, which were therefore not used below. The pilot tagging program has, as of February 1995, resulted in about 200 recaptures mainly from the sites of release, which are insufficient for estimating annual movement rates even roughly. The VFRI's data, which were collected mainly from Victoria and Tasmania, are still being analysed to determine local movement rates. Data from all three sources and analysis of the length frequency distribution of school shark (T.I. Walker, personal communication) indicate, however, that the annual movement rates in Table 1 are possible for South Australia, Victoria, and Tasmania. Since there were no releases, relatively little fishing effort in, and almost no recaptures from, Western Australia, $p_{1,k}$s and $p_{j,1}$s cannot be determined but are assumed to take the values in Table 1. These annual movement rates were converted by appropriate matrix manipulations (see Table 1 for details) to weekly movement rates, which were then used as input movement rates.

For school shark, q_as can be estimated in many ways. Previous estimation attempts by multiple linear regression did not meet with much success, probably because some process error estimators, which may behave badly (Punt 1989), had been used in almost all cases. For this application, they were estimated from the VFRI's catch and effort data (T.I. Walker, unpublished data) through an observational error estimator conditional on catch, by minimizing

$$\sum_{a,t,j} (\log(C_{a,t,j}) - \log(q_{a,j} B_t E_{a,t,j}))^2,$$

where $C_{a,t,j}$ is observed catch in area a at time t for gear type j, $q_{a,j}$ is catchability coefficient for area a and gear type j, $E_{a,t,j}$ is observed fishing effort in area a at time t for gear type j, and B_t is fish biomass at time t as calculated from the Schaefer (1954) production model, $B_{t+1} = B_t + rB_t(1 - B_t/K) - \sum_{a,t,j} C_{a,t,j}$, with rate of population natural increase r and environmental carrying capacity K. $q_{a,j}$, r, K, and B_0 are parameters to be estimated. Thus, fish in all areas are assumed to be in a unit stock and errors in $C_{a,t,j}$ are assumed to be independent, identical lognormal variates. The standardized (in reference to gear type 1, i.e., hooks) total fishing effort, as used above, is calculated as

$$E_{a,t} = \frac{1}{q_{a,1}} \sum_j q_{a,j} E_{a,t,j}.$$

Let $q_{a,1} = q_a$. The estimates of catchability coefficient thus obtained are $q_1 = 2.43 \times 10^{-9}$, $q_2 = 1.31 \times 10^{-9}$, $q_3 = 2.78 \times 10^{-9}$, and $q_4 = 3.21 \times 10^{-9}$ (m·hook lifts·week^{-1})$^{-1}$. These catchability coefficients correspond to weekly exploitation rates of 0.016, 0.028, 0.042, and 0.009%, respectively, or annual exploitation rates of 0.821, 1.483, 2.182, and 0.489%.

The instantaneous natural mortality of school shark M is 0.193×10^{-2}·week^{-1} (Grant et al. 1979), and the instantaneous tag shedding rate is assumed to be the same ($\lambda = 0.914 \times 10^{-3}$·week^{-1}) as that of a similarly sized and shaped species of shark *Carcharhinus tilstoni* (G. West, CSIRO Division of Fisheries, GPO Box 1538, Hobart, Tasmania 7001, Australia, personal communication).

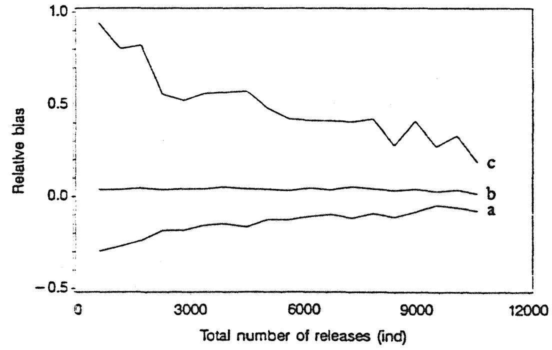
There are many criteria for determining the number of fish releases by area and time, other than relative bias and relative standard error of, and various norms derived from, estimates of all parameters. Two of these are time averages of relative biases of $\hat{N}_{i,a,t}$, which is the expected number of tagged fish in area a at time t, and $\hat{R}_{i,a,t}$, which is the expected number of tags recovered in area a at time t. Also, since the purpose of determining movement rates is usually to improve fisheries management, apart from increasing our knowledge, various summary statistics might be given by such management variables as quotas. Finally, one can examine the absolute bias and absolute standard error of estimates of each parameter and then devise a common criterion for an experimental design. As required, in this application, I used relative bias and relative standard error of estimates of all parameters as measures of their accuracy and precision.

The model parameters are estimated by Nelder and Mead's (1965) simplex method. Only the movement parameters were estimated; catchability coefficients, instantaneous natural mortality, and instantaneous tag shedding rate were fixed and hence not estimated, to save computer time. Regression analyses of the minimum, mean, and maximum of all elements of vector y, i.e., $\min_h(y_h)$, $\operatorname{mean}_h(y_h)$, and $\max_h(y_h)$, and various norms of vector y, i.e.,

$$|y|_p = \left(\sum_h |y_h|^p\right)^{1/p},$$

as functions of the number of releases were made, using non-

Fig. 3. Minimum (a), mean (b), and maximum (c) relative bias of estimates of all parameters as functions of the total number of fish releases. ind, individuals.



linear least squares method assuming identically, independently, and normally distributed errors in the dependent variables. Estimates of each parameter were also related, as a first approximation, to its input values and fishing effort in an area through a stepwise regression analysis to examine the interactions between fishing effort and values of input movement rates.

Results

For a max(t) of 157 weeks (i.e., 3 years), the minimum, mean, and maximum relative bias of estimates of all parameters increased, decreased, and decreased towards zero, respectively, with increased number of fish released, each following a power function of the form $S = ax^{-b}$, with a and b being regression parameters estimated by the nonlinear least squares method under the assumption that errors in S follow an independent, identical normal distribution (Fig. 3, Table 2). Three common norms, i.e., absolute norm $|y|_1 = \sum_h |y_h|$, Euclidean norm $|y|_2 = (\sum_h |y_h|^2)^{1/2}$ and maximum norm $|y|_\infty = \max_h |y_h|$, of the relative bias of estimates of all parameters also decreased towards zero as the number of fish released increased, each following a power function (Fig. 4, Table 2). Note that in this case the maximum norm is equivalent to the above maximum relative bias.

Similarly, minimum, mean, and maximum relative standard error of estimates of all parameters all decreased with an increased number of fish released (Fig. 5, Table 2). Absolute, Euclidean, and maximum norms of relative standard error all decreased with an increased number of fish released, again each following a power function (Fig. 6, Table 2). Again, the maximum norm is also equivalent to the above maximum relative standard error.

The relative bias and relative standard error of the estimate of each parameter $\hat{p}_{j,k}$ were related, separately, to input movement rate $p_{j,k}$ and fishing effort $E_{a,t}$ (million m·hook lifts·week^{-1}) through a stepwise multiple linear regression, with the full model of the form $Y = \beta_0 + \beta_1 p_{j,k} + \beta_2 E_{a,t}$, where βs are parameters to be estimated, under the assumption that errors in Y are normally distributed with a mean of $\hat{Y}$ and a (constant) variance of σ^2. For relative bias, the regression analysis yielded $\hat{\beta}_0 = 0.0761$, SE($\hat{\beta}_0$) = 0.0173, $t = 4.393$, $P = 0.0001$; $\hat{\beta}_1 = -0.0521$, SE($\hat{\beta}_1$) = 0.0208, $t = -2.501$, $P = 0.0129$; $\hat{\beta}_2 = -0.2210$, SE($\hat{\beta}_2$) = 0.1209; $t = -1.828$, $P = 0.0685$; $F_{[2,301]} = 4.798$, $P = 0.0089$, $R^2 = 0.0309$, $n = 304$. Although the linear regression model is formally significant (because of the large number of degrees of freedom, 304), from the practical viewpoint, inclusion of both variables is inconsequential ($R^2 = 0.0309$).

For the relative standard error, the stepwise multiple linear regression gave an R^2 value of 0.4465 for $p_{j,k}$ alone, of 0.0041 for $E_{a,t}$ alone, and of 0.4505 for $p_{j,k}$ and $E_{a,t}$ jointly. Thus, the model with $p_{j,k}$ only is appropriate: $\hat{\beta}_0 = 0.8109$, SE($\hat{\beta}_0$) = 0.0260, $t = 31.225$, $P = 0.0001$; $\hat{\beta}_1 = -0.8213$, SE($\hat{\beta}_1$) = 0.0526, $t = -15.607$, $P = 0.0001$; $F_{[1,302]} = 243.590$, $P = 0.0001$, $R^2 = 0.4465$, $n = 304$. Then, the relative standard error of the estimate of each parameter decreased with input movement rate but was not related statistically significantly to fishing effort. In other words, if the movement rate is small, then that parameter is difficult to estimate.

Discussion

The framework developed above for evaluating different experimental designs, combined with an appropriate estimation procedure, provides a systematic basis for selecting the total number of fish released to estimate their movement rates and other model parameters of interest to a chosen accuracy and precision. For example, one can now readily calculate the number of releases for school shark to achieve a chosen level of accuracy and precision. Since the minimum, mean, and maximum of all elements, and various norms, of vector y is a power function of the number of releases, of the form $S = ax^{-b}$, there is not an objective criterion for choosing a particular total number of releases that will give a level of accuracy and precision in estimates of various parameters. Thus, one has to decide the value of S first, and then calculate $x = (a/S)^{1/b}$ by substituting appropriate estimates of a and b in Table 2. For a maximum relative standard error of 1.6079, $x = (12.2741/1.6079)^{1/0.2386} = 5000$, which corresponds to a maximum relative bias of $10.7145 \times 5000^{-0.3718} = 0.4516$.

This work also provides information on the performance of Hilborn's (1990) model and estimation procedure. Generally, the degree of relative bias of an estimator depends on the input values of model parameters, the structures of the population dynamics and movement model and the observational model, max(t), error structures of the recapture process, and the definition of a tag group. For this application, the first two possibilities can be excluded because the data used were simulated from specific models. My limited trials suggest that the performance of Hilborn's model and estimation procedure improves as max(t) increases. As shown above, his model and estimation procedure are robust for Poisson-distributed recaptures, whose variance equals their mean. Finally, definition of a tag group will greatly affect the bias: those that reduce data contrast increase relative bias and vice versa. More studies are needed to understand this problem. The mean relative bias was only about 0.0376 (SD = 0.0084) over the range of fish releases tested (560 – 10 640 individuals). Thus, Hilborn's (1990) model and estimation procedure are unbiased, at least for the

Table 2. Minimum, mean, maximum, and three common norms of relative bias (RB) and relative standard error (RSD) of estimates of all parameters as a power function of the number of fish releases of the form $S = a\left(\sum_{i,a,t} T_{i,a,t}\right)^{-b}$, where parameters a and b are estimated by the nonlinear least squares method under the assumption that errors in S are normally distributed with a mean of $\hat{S}$ and a (constant) variance of σ^2.

	Summary statistic	a	b	R^2
RB	Minimum	–5.3967 (1.4202)	0.4394 (0.0340)	0.9708
	Mean	0.0710 (0.0357)	0.0758 (0.0604)	0.9587
	Maximum	10.7145 (2.8164)	0.3718 (0.0334)	0.9786
	$\|y\|_1$	24.7859 (5.4263)	0.3581 (0.0278)	0.9835
	$\|y\|_2$	9.3622 (2.4009)	0.3294 (0.0323)	0.9800
	$\|y\|_\infty$	10.7145 (2.8164)	0.3718 (0.0334)	0.9786
RSD	Minimum	0.0031 (0.0004)	0.0662 (0.0145)	0.9975
	Mean	3.0288 (0.1405)	0.1930 (0.0057)	0.9995
	Maximum	12.2741 (0.9127)	0.2386 (0.0092)	0.9987
	$\|y\|_1$	48.4611 (2.2473)	0.1930 (0.0057)	0.9995
	$\|y\|_2$	15.6667 (0.8317)	0.1921 (0.0065)	0.9994
	$\|y\|_\infty$	12.2741 (0.9127)	0.2386 (0.0092)	0.9987

Note: Values in parentheses are asymptotic standard error. Absolute norm $|y|_1 = \sum_h |y_h|$; Euclidean norm $|y|_2 = \left(\sum_h |y_h|^2\right)^{1/2}$; maximum norm $|y|_\infty = \max_h |y_h|$; $560 \le \sum_{i,a,t} T_{i,a,t} \le 10\,640$; $n = 19$ in all cases. All regressions were significant at $P < 0.0001$.

Fig. 4. Maximum (a), absolute (b), and Euclidean (c) norm of relative bias of estimates of all parameters as functions of the total number of fish releases. ind, individuals.

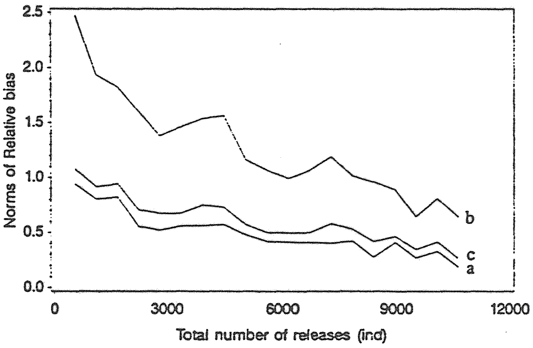


Fig. 6. Maximum (a), absolute (b), and Euclidean (c) norm of relative standard error of estimates of all parameters as functions of the total number of fish releases. ind, individuals.

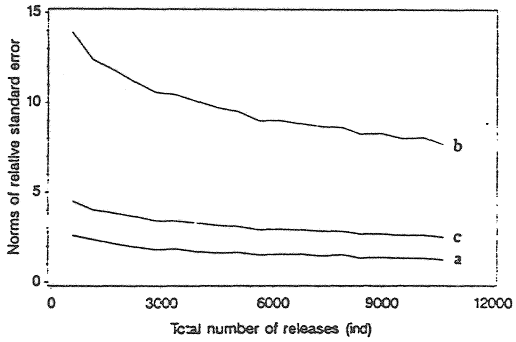
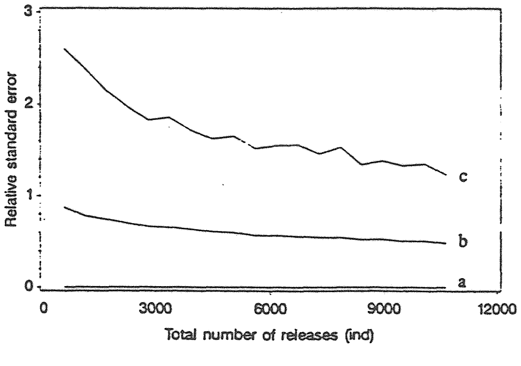


Fig. 5. Minimum (a), mean (b), and maximum (c) relative standard error of estimates of all parameters as functions of the total number of fish releases. ind, individuals.



above application. They are not very precise, however, because the minimum, mean, maximum, and three common norms of relative standard error of estimates of all parameters all do not tend to zero reasonably quickly with an increase in the number of fish releases (Figs. 5 and 6, Table 2). For example, the mean relative standard error varied from about 87% at a release of 560 fish to about 48% at a release of 10 640 fish.

In applying the results from that application and in discussing the merits and problems of Hilborn's (1990) model and estimation procedure, one must realize that the present study has examined only one set of input movement rates, catchability coefficients, and other parameters. Major departures from this set may result in quantitative changes in the conclusions, but qualitative conclusions, such as a decrease in relative standard error with an increase in the number of fish released, should not change. Ideally, one should examine a reasonable range of movement rates and catchability coefficients to determine the sensitivity of those conclusions to their changes. Finally, I have assumed values of catchability coefficients, instantaneous natural mortality rate, instantaneous tag shedding rate, and fishing effort to be known without error, and population dynamics, movement, and observation models to be correct. The results from that application may be overly optimistic.

The value of this work also lies in its insight into experimental designs of tagging experiments for estimating fish movement rates. Hilborn (1990) hypothesized that the best experimental design needs tagging and release to be done in each area, and fishing effort data to be available by time for each area. As shown above, the estimate of each parameter was related to its input value, such that the smaller a movement rate, the more difficult it was to estimate. Thus, to achieve the same or similar relative bias for each movement rate, more fish should be released in areas with low rates of inward and outward movement. Although the above application considered one release pattern only, regression equations may be established between the relative bias and relative standard error of estimates of each parameter Y and its input movement rate $p_{j,k}$, fishing effort $E_{a,t}$, and fish release $T_{i,a,t}$ of the form, say, $\hat{Y} = \beta_0 + \beta_1 p_{j,k} + \beta_2 E_{a,t} + \beta_3 T_{i,a,t}$, where βs are again parameters to be estimated, under the assumption that errors in Y are identically, independently, and normally distributed with a mean of $\hat{Y}$ and a (constant) variance of σ^2. One may then allocate the total number of fish releases and, if practical, regulate levels of fishing effort to achieve a given level of accuracy and precision of estimates of movement rates. Thus, Hilborn's (1990) hypothesis can be refined as follows: a good experimental design not only needs tagging and release to be done in each area, and fishing effort data to be available by time for each area, but also is a function of the values of input fish movement rates and possibly input fishing effort.

The application can be extended in several ways. Although simple and deterministic patterns of fish release and distribution of fishing effort have been assumed in it, complex patterns can be readily tested with my framework. Thus, one can try a range of values of $p_{j,k}$, $T_{i,a,t}$, $E_{a,t}$, q_a, and γ, but this would usually require a prohibitively large number of trials. Let n be the number of parameters in the model and m the number of values to be evaluated for each parameter, then there are m^n trials to run, for each release pattern. If $n = 16$, then one has $\geq 2^{16} = 65\,536$ trials to do, for a range of values of each parameter (i.e., $m \geq 2$). If one trial needs 1 min to complete, then one would require 45.5 days to evaluate all trials.

A computationally less intensive alternative is to limit the number of trials by assuming a joint distribution for all model parameters. Thus, fishing effort can be treated as a random variable with its errors following certain statistical distributions (e.g., $E_{a,t} \sim \Gamma(\bar{E}_{a,t}, \sigma^2_{E_{a,t}})$); movement rates can be assigned appropriate statistical distributions, say, $p_{j,k} \sim \Gamma(\bar{p}_{j,k}, \sigma^2_{p_{j,k}})$. Even this would require a substantial amount of computer time. The computation for that application takes about 12 days of central processor unit time to complete on an IBM PC (with a 66-MHz Pentium processor and Lahey FORTRAN 90), when Nelder and Mead's (1965) simplex method is used as a maximizer in the general framework. Therefore, before attempting a simulation, one should assess one's computing capacity.

One can also examine the effects of absence of fishing in one or more areas on, say, the relative bias and relative standard error of parameter estimates. Such effects are clearly important for design of a tagging experiment: if absence of fishing in one area would grossly bias estimated parameters in others, then there is little hope of unbiased estimates from real fisheries, where fishing may be absent in some areas; if it does not have any appreciable effects, one would expect that estimates of parameters are not biased by an absence of fishing in one or more areas. A related problem is to examine the effects of emigration. Failure to consider the whole fish population in a tagging study may affect the reliability of estimates of movement rates, if these estimates are biased by this process. Intuitively, the fewer data one has about a whole picture, the more prone one is to chance events. It might well be that the more areas considered, the less the bias. If so, certain estimates of movement rates would be biased. To avoid such bias, a tagging program should cover as wide an area as possible, should not be undertaken lightly, and must be based on sufficient information about fish distribution. Therefore, the effects of fish emigration should be examined.

Finally, experimental designs to estimate size- or sex-dependent movement rates can be realized by following my framework. One can obtain a separate set of estimates of movement rates for each sex or size group, from which differences in movement rates between sexes and sizes can be examined. One can also estimate each movement rate as an explicit function of fish size or sex. The second approach is preferred for three reasons. First, division into, say, fish larvae, juveniles, and adults involves arbitrary decisions. Within each group, there may also be considerable size variations. Treatment of a movement rate as an explicit function of fish size gives an objective decision, where size is seen as a continuous variable. Second, it is statistically desirable, because size- and (or) sex-dependent movement rates are estimated in a single framework, with movement rates as functions of size and (or) sex. If well determined, they allow predictions to be made for all sizes within the size range studied. Third, it does not require as many data as the first approach. Obviously, the requirement for more releases and hence recaptures is relatively large for estimating size- and (or) sex-mediated movement rates. If reliable estimation of movement rates for males requires a release of 1000 fish, then a release of roughly 2000 is required for both males and females if their movement rates are different from those of males. Thus, twice as many fish must be released to estimate movement rates by sex. The same argument applies to fish sizes. To be able to detect size-related differences, one has to recognize at least two size groups and to estimate two sets of movement rates; again, one needs at least twice as many releases as for one size group only. As the number of size groups increases, the increase in the requirement for the number of releases follows arithmetic progression, if the first approach is adopted. However, use of the second approach will usually substantially reduce the number of releases if many size groups are involved. This is because a couple of parameters may well describe some of those differences.

Acknowledgments

I thank Prof. Ray Hilborn of the Fisheries Research Institute, University of Washington, and Drs. You-Gan Wang of CSIRO IPP&P Biometrics Unit, Andre E. Punt, Anthony D.M. Smith, John D. Stevens, and Vivienne Mawson of CSIRO Division of

Fisheries for their valuable comments on the manuscript. I also thank two anonymous referees for their very constructive comments on the work. Special thanks go to my colleague Mr. Terence I. Walker of the Victorian Fisheries Research Institute for his valuable comments and discussions. The minimization routine was kindly provided by Dr. Douglas E. Shaw of CSIRO Division of Mathematics and Statistics; Mr. Bruce Taylor of the Victorian Fisheries Research Institute and Dr. Colin Simpfendorfer of Western Australia Marine Research Laboratories kindly provided southern shark catch and effort data; Mrs. Toni Cracknell, CSIRO Division of Fisheries, produced Fig. 2; Ms. Melanie Burke, Australian Fisheries Management Authority, produced Fig. 1. Finally, I thank Drs. John D. Stevens and Anthony D. M. Smith for supervising this project. This work was funded by the Australian Fisheries Management Authority.

References

Anganuzzi, A., Hilborn, R., and Skalski, J.R. 1994. Estimation of size selectivity and movement rates from mark–recovery data. Can. J. Fish. Aquat. Sci. 51: 734–742.

Cormack, R.M. 1981. Loglinear models for capture-recapture experiments in open populations. *In* The mathematical theory of the dynamics of biological populations. *Edited by* R.W. Hiorns and D. Cooke. Academic Press, London. pp. 217–235.

Grant, C.J., Sandland, R.L., and Olsen, A.M. 1979. Estimation of growth, mortality and yield per recruit of the Australian school shark, *Galeorhinus australis* (Macleay), from tag recoveries. Aust. J. Mar. Freshwater Res. 30: 625–637.

Hilborn, R. 1990. Determination of fish movement patterns from tag recoveries using maximum likelihood estimators. Can. J. Fish. Aquat. Sci. 47: 635–643.

Hilborn, R., and Walters, C.J. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York.

Ishii, T. 1979. Attempt to estimate migration of fish population with survival parameters from tagging experiment data by the simulation method. Invest. Pesq. 43: 301–317.

Last, P.R., and Stevens, J.D. 1994. Sharks and rays of Australia. Commonwealth Scientific and Industrial Research Organisation, Australia.

Nelder, J.A., and Mead, R. 1965. A simplex method for function minimization. Comput. J. 7: 308–313.

Punt, A.E. 1989. Bias and variance of catch-effort based model estimation procedures used in the management of the ICSEAF hake stocks: a preliminary comparative investigation. *In* Selected papers of the International Commission for Southeast Atlantic Fisheries. Vol. 1. pp. 39–54.

Schaefer, M.B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *In* Bulletin of the Inter-American Tropical Tuna Commission. Vol. 1. pp. 27–56.

Schaefer, M.B., Chatwin, B.M., and Broadhead, G.C. 1961. Tagging and recovery of tropical tunas, 1955–1959. Bulletin of the Inter-American Tropical Tuna Commission. Vol. 17. pp. 447–506.

Schwarz, C.J., Schweigert, J.F., and Arnason, A.N. 1993. Estimating migration rates using tag-recovery data. Biometrics, 49: 177–193.

Schweigert, J.F., and Schwarz, C.J. 1993. Estimating migration rates for Pacific herring (*Clupea pallasi*) using tag-recovery data. Can. J. Fish. Aquat. Sci. 50: 1530–1540.

Sibert, J.R. 1984. A two-fishery tag attrition model for the analysis of mortality, recruitment, and fishery interaction. Technical report No. 13. Tuna and Billfish Assessment Programme, South Pacific Commission, Noumea, New Caledonia.

Tuck, G.N., and Possingham, H.P. 1994. Optimal harvesting strategies for a metapopulation. Bull. Math. Biol. 56: 107–127.

Walker, T., Stone, T., Battaglene, T., and McLoughlin, K. 1994. Fishery assessment report: the southern shark fishery 1994. Victorian Institute of Marine Science, Victoria, Australia.

Wolfram, S. 1991. Mathematica: a system for doing mathematics by computer. 2nd ed. Addison-Wesley Publishing Company, Inc., Reading, Mass.

Appendix B. Tag Display Package SHARKTAG

Computer Software Tool for Displaying Tag Release–Recapture Data from the Australian Southern Shark Fishery.

Bruce Taylor

Marine and Freshwater Resources Institute
P.O. Box 114, Queenscliff, Victoria 3225 Australia

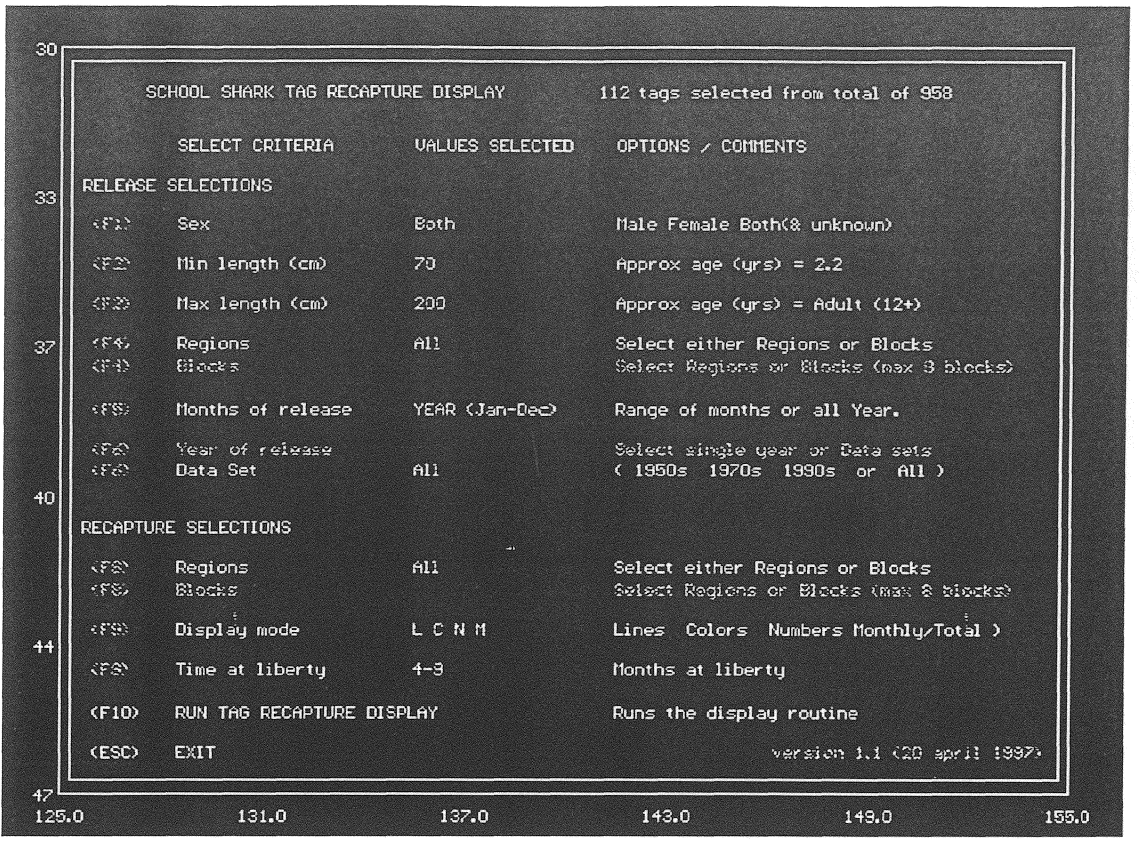
A computer software package SHARKTAG is used for displaying selected subsets of shark tag release–recapture data available in the Southern Shark Tag Database for the period 1947–96. The package is used for selecting subsets of data from files produced from the Tag Database and then displaying release and recapture fishing blocks, time at liberty and distance travelled.

The tag release-recapture data for display can be selected by:

sex
a range of length on release (minimum and maximum lengths)
region(s) or block(s) of release
month(s) of release
year(s) or period of release
region(s) or block(s) of release
region(s) or block(s) of recapture
a range of time at liberty (first and last months)

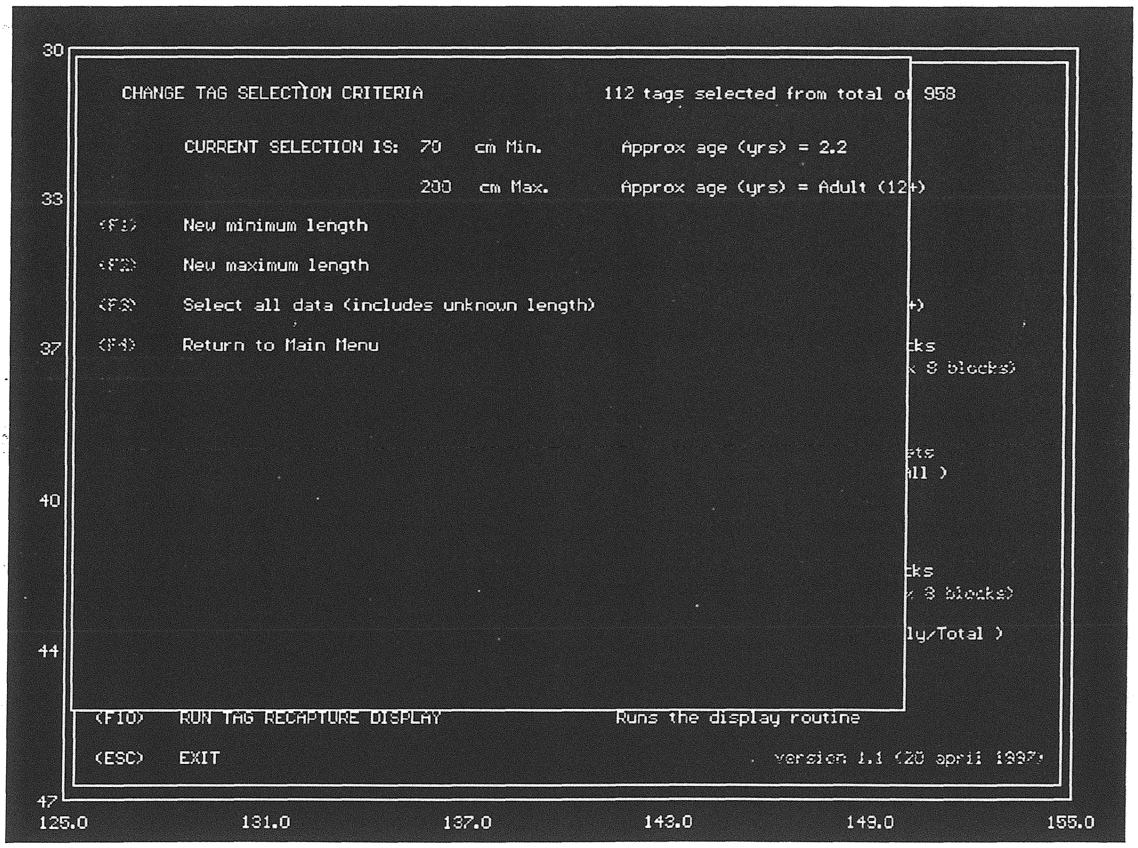
The selected options are clearly documented on the screen (Figure B1) as are the values of the selection criteria. These options can be readily changed interactively (Figure B2).

Coloured tag lines join the tag-release cell and the tag-recapture cell and can be shown growing by month to give an impression of relative movement. In addition, the number of recaptured tagged sharks in each cell can be displayed by colour code or number. These can be displayed by month (Figure B3) or as the final result (Figures B4 and B5).



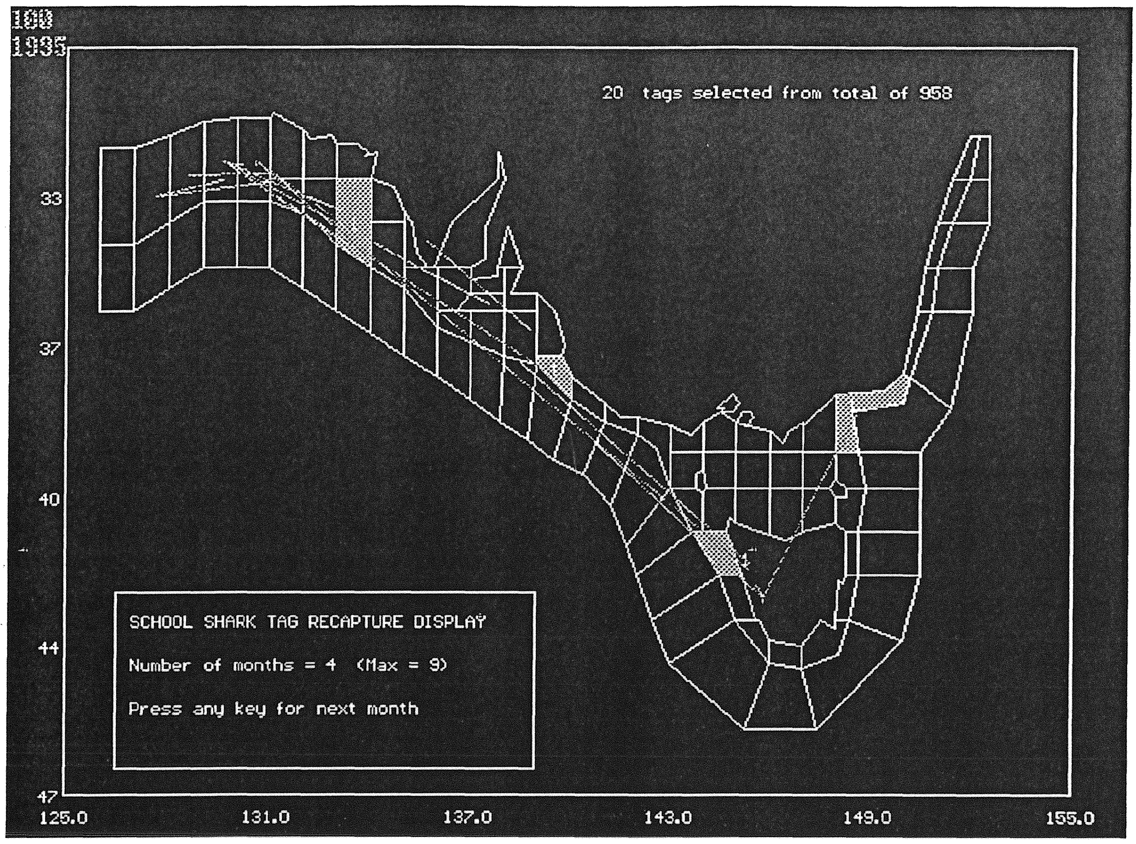
```
     SCHOOL SHARK TAG RECAPTURE DISPLAY          112 tags selected from total of 958

          SELECT CRITERIA          VALUES SELECTED     OPTIONS / COMMENTS
RELEASE SELECTIONS

 <F1>     Sex                      Both                Male Female Both(& unknown)

 <F2>     Min length (cm)          70                  Approx age (yrs) = 2.2

 <F2>     Max length (cm)          200                 Approx age (yrs) = Adult (12+)

 <F4>     Regions                  All                 Select either Regions or Blocks
 <F4>     Blocks                                       Select Regions or Blocks (max 8 blocks)

 <F5>     Months of release        YEAR (Jan-Dec)      Range of months or all Year.

 <F6>     Year of release                              Select single year or Data sets
 <F6>     Data Set                 All                 ( 1950s  1970s  1990s  or  All )

RECAPTURE SELECTIONS

 <F8>     Regions                  All                 Select either Regions or Blocks
 <F8>     Blocks                                       Select Regions or Blocks (max 8 blocks)

 <F9>     Display mode             L C N M             Lines  Colors  Numbers Monthly/Total )

 <F9>     Time at liberty          4-9                 Months at liberty

 <F10>    RUN TAG RECAPTURE DISPLAY                    Runs the display routine

 <ESC>    EXIT                                                 version 1.1 (20 april 1997)
```

Figure B1. Main menu and selection options



```
   CHANGE TAG SELECTION CRITERIA                 112 tags selected from total of 958

          CURRENT SELECTION IS:  70   cm Min.      Approx age (yrs) = 2.2

                                 200  cm Max.      Approx age (yrs) = Adult (12+)

 <F1>     New minimum length

 <F2>     New maximum length

 <F3>     Select all data (includes unknown length)                              +)

 <F4>     Return to Main Menu                                                    ks
                                                                                 8 blocks)

                                                                                 ts
                                                                                 ll )

                                                                                 ks
                                                                                 8 blocks)

                                                                                 ly/Total )

 <F10>    RUN TAG RECAPTURE DISPLAY                    Runs the display routine

 <ESC>    EXIT                                                 version 1.1 (20 april 1997)
```

Figure B2. Change menu for length at release



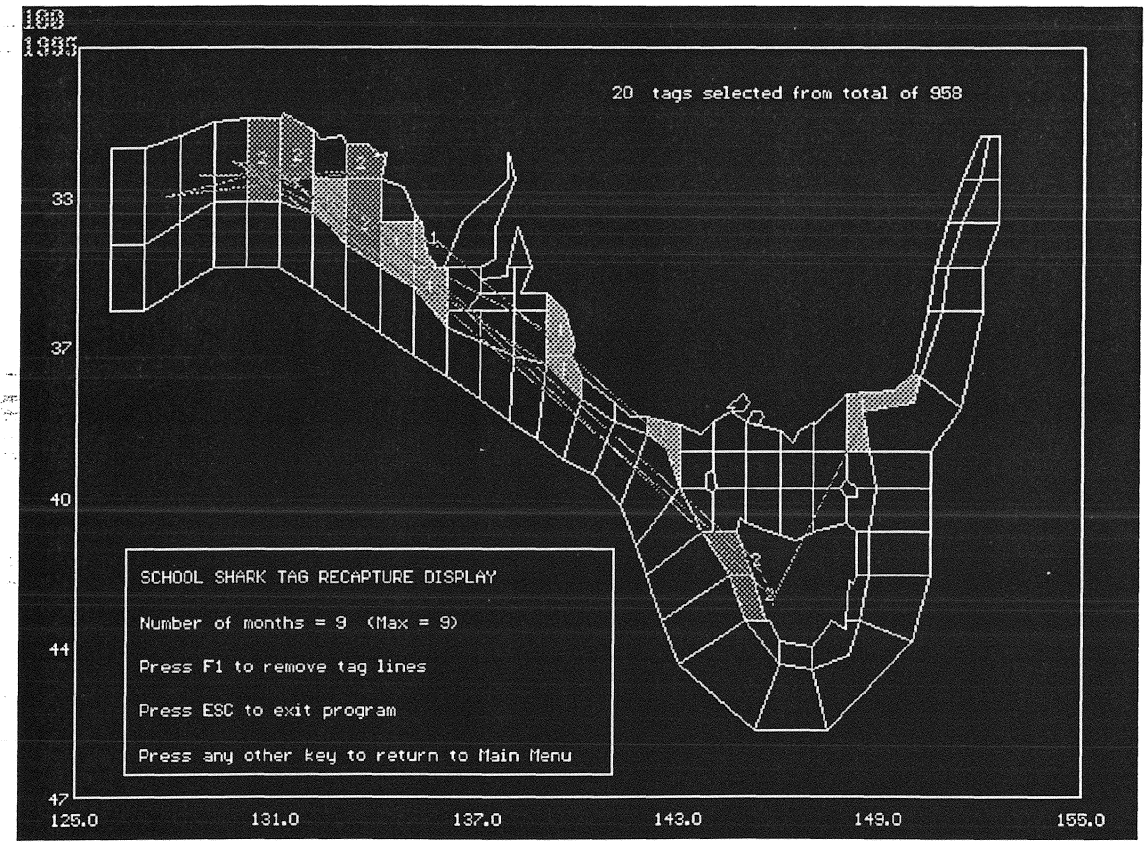
20 tags selected from total of 958

SCHOOL SHARK TAG RECAPTURE DISPLAY

Number of months = 4 (Max = 9)

Press any key for next month

Figure B3. Display screen showing early recaptures



20 tags selected from total of 958

SCHOOL SHARK TAG RECAPTURE DISPLAY

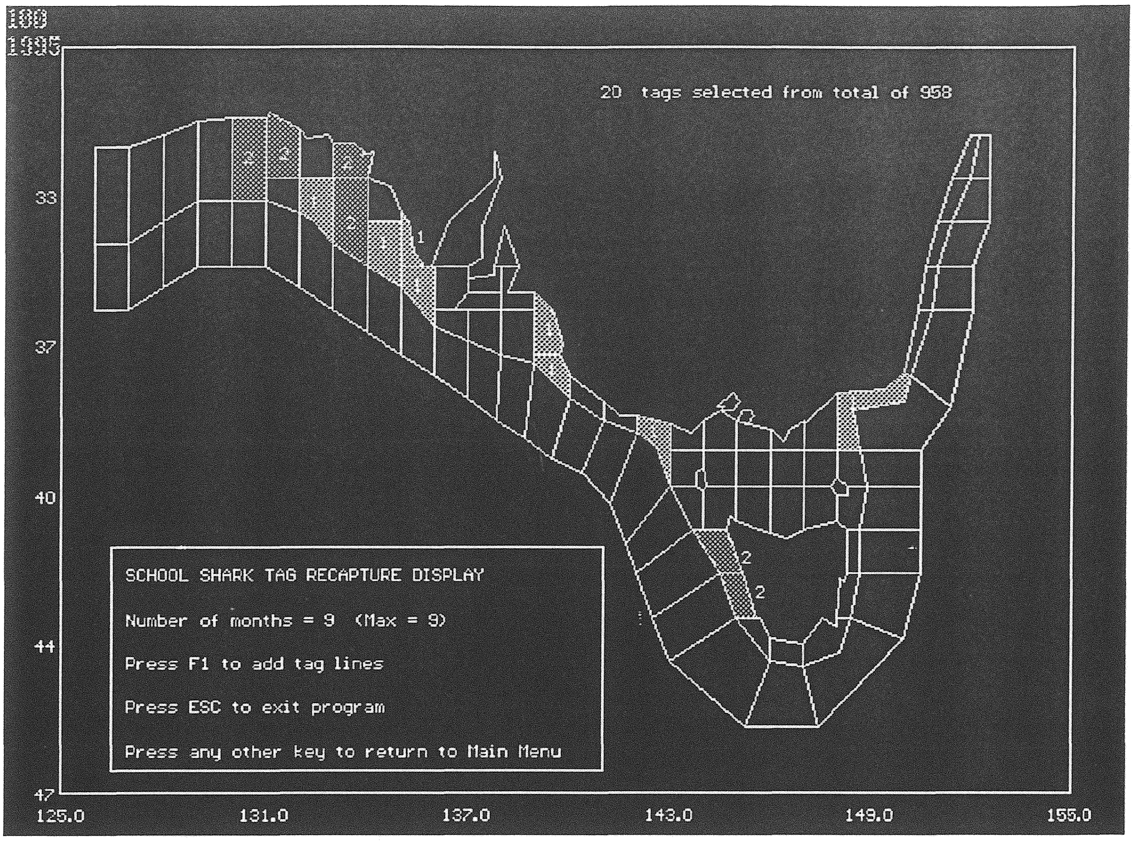
Number of months = 9 (Max = 9)

Press F1 to remove tag lines

Press ESC to exit program

Press any other key to return to Main Menu

Figure B4. Display screen showing tag release-recapture patterns



20 tags selected from total of 958

SCHOOL SHARK TAG RECAPTURE DISPLAY

Number of months = 9 (Max = 9)

Press F1 to add tag lines

Press ESC to exit program

Press any other key to return to Main Menu

Figure B5. Display screen showing recapture patterns only

Appendix C. Movement Modelling Shell SSMOVE

Movement Modelling Shell for School Shark (*Galeorhinus galeus*) in the Australian Southern Shark Fishery:
A users guide to SSMOVE (Version 1)

Bruce Taylor

Marine and Freshwater Resources Institute
P.O. Box 114, Queenscliff, Victoria 3225 Australia

Introduction

SSMOVE is a computer program for displaying changing distribution patterns of a shark population for any assumed movement parameters within the basic framework of a movement model. The user can represent alternative hypotheses of movement and explore the implications of varying the movement parameters. These in turn can be used for determining alternative movement rates for spatially disaggregated stock assessment models. These rates will be eventually compared with broad level rates estimated from analysis of the tagging data.

The underlying model

The movement parameters driving the model are the relative numbers of sharks remaining in each fishing block or moving in each direction to an adjoining block each day. Overall movement of a population is achieved by setting movement greater in one direction than in the opposite direction.

Version 1 of the computer program is currently set up to display two basic movement patterns—one for juveniles and the other for adults. The juvenile model investigates the movement of juvenile school shark from east to west. It assumes that 0–2 year old sharks remain near the nursery grounds of Bass Strait and eastern Tasmania. The 3–9 year olds move westward, slowly at first and, then more rapidly, to western South Australia. The model allows two different movement rates to be considered jointly (a 'slow' rate and a 'fast' rate)

The adult model has two 'adult' areas—one in western SA (west of Port Lincoln) and the other in Bass Strait. The proportion of the population in each area can be altered. The breeding adults move from western South Australia east to Bass Strait during spring and then move back to western South Australia during autumn.

Running the program

The program and data files are supplied on floppy disk. The files ssmove.exe, au_cell1.dat and au_cell2.dat are needed to run the program. The documentation (without the figures) is in ssmove.doc in Word6 format. SSMOVE was developed on a 486DX-33 computer where its speed is acceptable. It runs faster on a Pentium-75. It may run slowly on earlier computers.

SSMOVE runs directly under DOS. To install SSMOVE on a hard disk from a floppy disk, type **a:setup**. It can also be run from the floppy disk. Type **ssmove** to begin the program.

From the first menu (Figure C1), either a model can be run or another menu chosen. The juvenile models run a year at a time and then pause until any key is pressed before running the following year. The model can be exited at this stage by pressing the Esc key. The adult model runs for one year. The adult migration display is every 6 days while all other models display every month where there are 30 'days' in each month.

When the models are run, the colour scale is shown in the lower box, while the movement parameters for the slower group (juveniles) or circulating group (adults) are shown in the upper box. The behaviour of the model is altered by changing the movement values using the Change Movement Values menu (Figure C2).

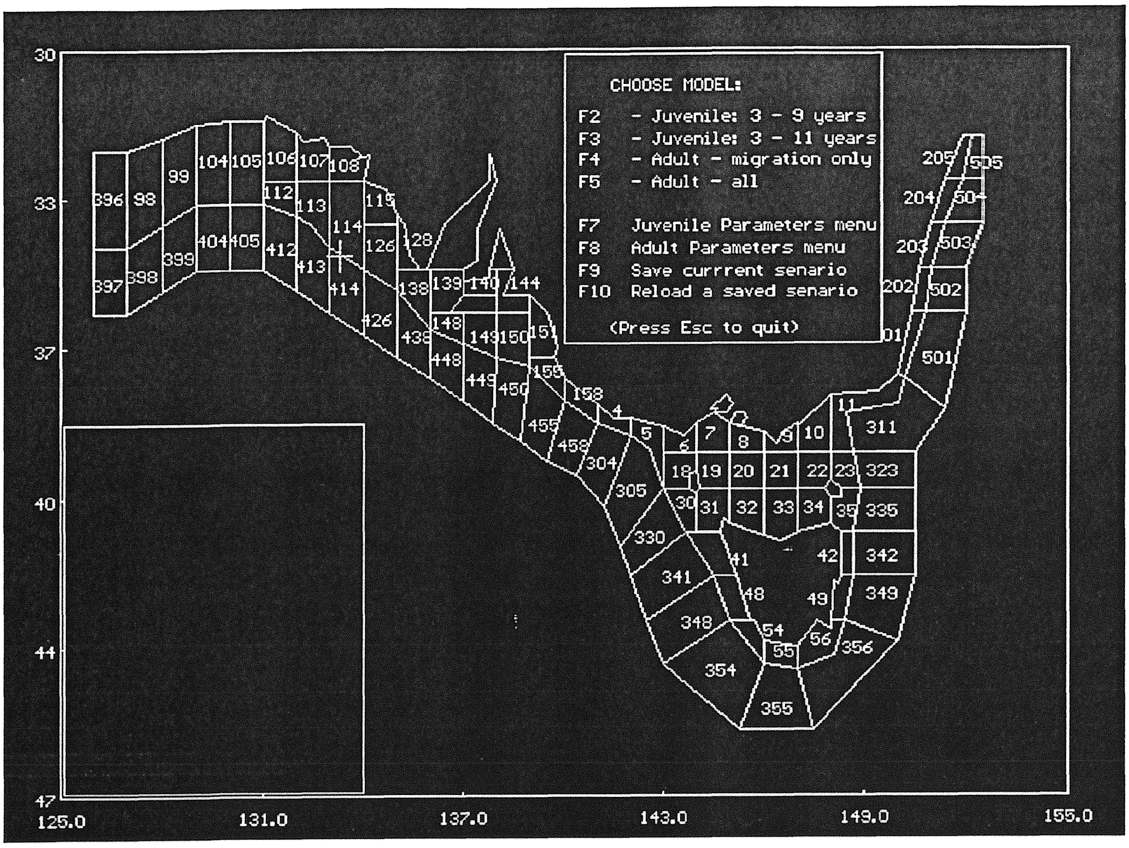
User defined parameters

The Change Movement Values menus (Figures C3 and C4) display the current movement values for the juvenile or adult models and allow them to be changed, saved or recalled. The values displayed in yellow can be changed. The initial values are also displayed as a reference point.

Enhancements

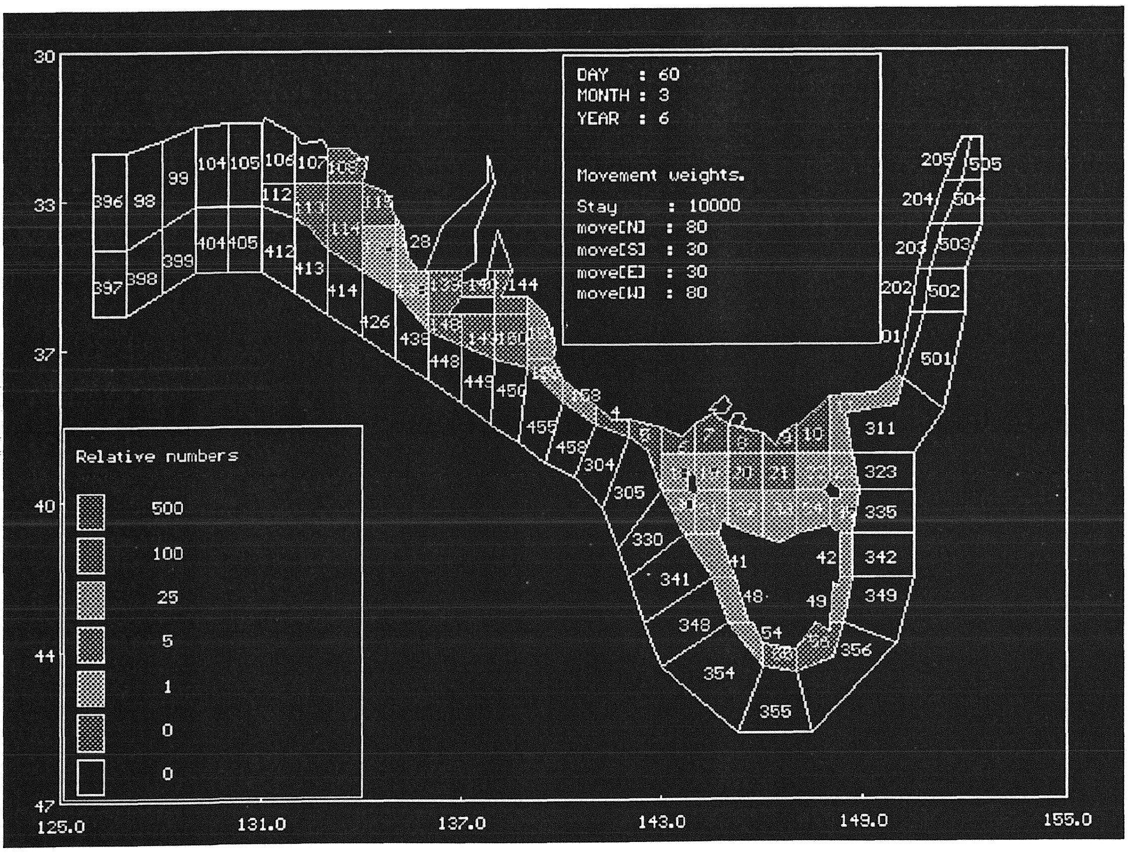
Some of the possible extensions that can be added are outlined below. This list needs to be amended then sorted into priorities for implementation.

Output of movement rates from a given cell after a month (Version 1a).
Off continental shelf (cryptic) population added.
Juveniles remaining in Bass Strait, just as some adults remain.
NSW population added.
Output or display of movement probabilities from a given cell after a several months.
Ability to redefine the initial distribution at 3 years of age.
Include provision for habitat effects which need to be defined.
Display regional population (on a subscreen).
Total numbers of all age-classes on a single display.
Subscreen for numbers by age when total number of all ages is on main screen.



```
CHOOSE MODEL:

F2    - Juvenile: 3 - 9 years
F3    - Juvenile: 3 - 11 years
F4    - Adult - migration only
F5    - Adult - all

F7    Juvenile Parameters menu
F8    Adult Parameters menu
F9    Save currrent senario
F10   Reload a saved senario

    (Press Esc to quit)
```

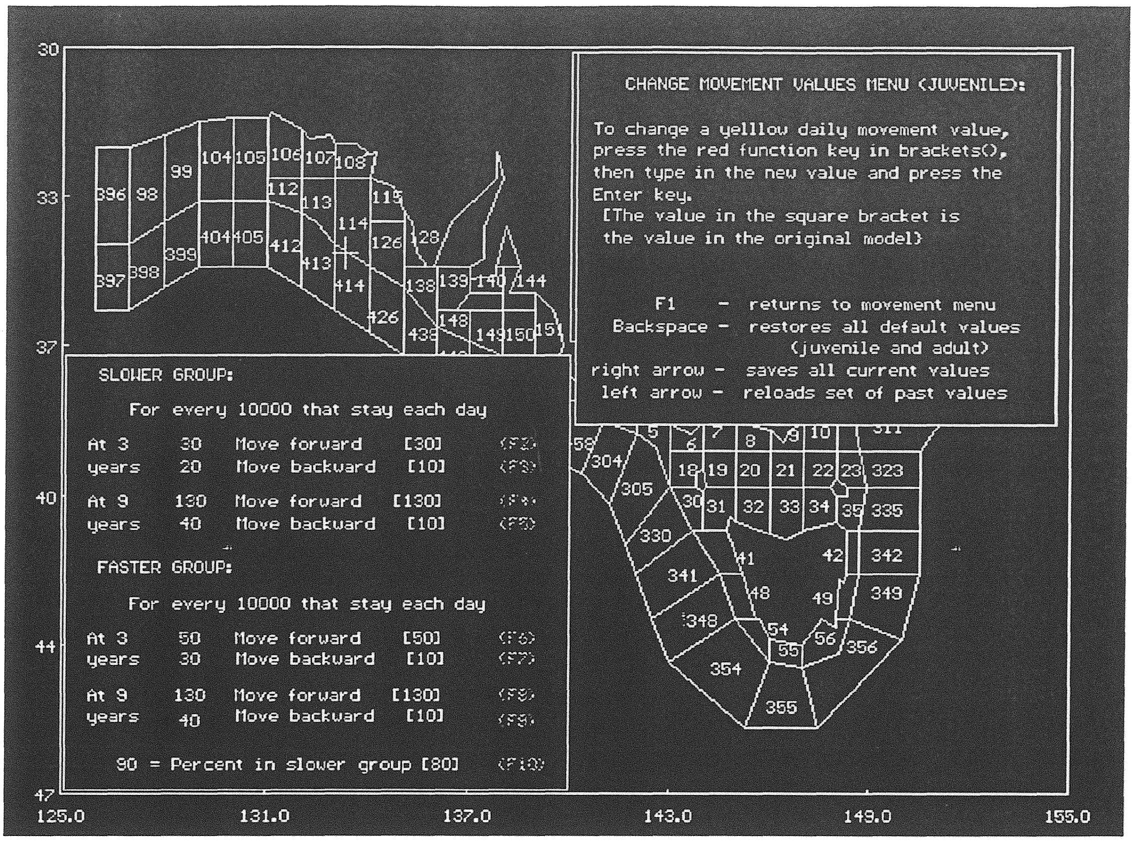
Figure C1. Initial menu



```
DAY   : 60
MONTH : 3
YEAR  : 6

Movement weights.

Stay      : 10000
move[N]   : 80
move[S]   : 30
move[E]   : 30
move[W]   : 80
```

```
Relative numbers

▨   500
▨   100
▨   25
▨   5
▨   1
▨   0
☐   0
```

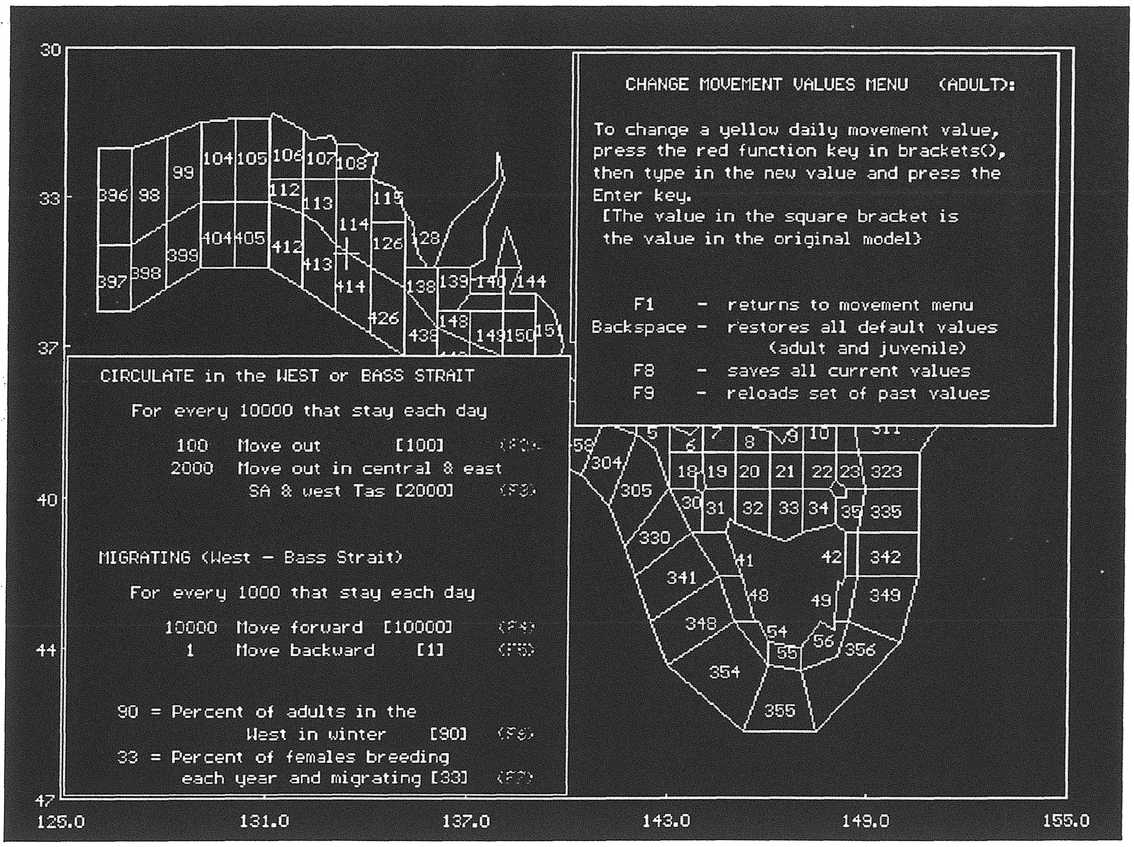
Figure C2. Juvenile model running



```
CHANGE MOVEMENT VALUES MENU (JUVENILE):

To change a yelllow daily movement value,
press the red function key in brackets(),
then type in the new value and press the
Enter key.
[The value in the square bracket is
 the value in the original model}

       F1     -  returns to movement menu
  Backspace  -  restores all default values
                    (juvenile and adult)
right arrow  -  saves all current values
 left arrow  -  reloads set of past values
```

```
SLOWER GROUP:

    For every 10000 that stay each day

At 3     30   Move forward    [30]      (F2)
years    20   Move backward   [10]      (F3)

At 9    130   Move forward   [130]      (F4)
years    40   Move backward   [10]      (F5)

FASTER GROUP:

    For every 10000 that stay each day

At 3     50   Move forward    [50]      (F6)
years    30   Move backward   [10]      (F7)

At 9    130   Move forward   [130]      (F8)
years    40   Move backward   [10]      (F9)

   90 = Percent in slower group [80]    (F10)
```

Figure C3. Menu for changing juvenile parameters



```
CHANGE MOVEMENT VALUES MENU   (ADULT):

To change a yellow daily movement value,
press the red function key in brackets(),
then type in the new value and press the
Enter key.
 [The value in the square bracket is
  the value in the original model}

       F1     -  returns to movement menu
 Backspace  -  restores all default values
                   (adult and juvenile)
       F8     -  saves all current values
       F9     -  reloads set of past values
```

```
CIRCULATE in the WEST or BASS STRAIT

   For every 10000 that stay each day

        100   Move out         [100]      (F2)
       2000   Move out in central & east
                SA & west Tas [2000]      (F3)


MIGRATING (West - Bass Strait)

   For every 1000 that stay each day

      10000   Move forward  [10000]       (F4)
          1   Move backward     [1]       (F5)


  90 = Percent of adults in the
                West in winter     [90]   (F6)
  33 = Percent of females breeding
          each year and migrating [33]    (F7)
```

Figure C4. Menu for changing adult parameters

Initial parameters

Juveniles

These values are linearly interpolated for ages from 4 to 8 years (e.g. at age 6 years, the value is midway between the 3 and 9 years values)

'Slower' group
For every 10000 sharks remaining in a block each day,
at 3 years, 30 move forward in each direction (north or west)
at 9 years, 130 move forward (north or west)
at 3 years, 20 move backward (south or east)
at 9 years, 130 move backward (south or east)

'Faster' group
For every 10000 sharks remaining in a block each day,
at 3 years, 50 move forward in each direction (north or west)
at 9 years, 130 move forward (north or west)
at 3 years, 30 move backward (south or east)
at 9 years, 130 move backward (south or east)

Adults

Circulating in western SA or in Bass Strait
For every 10000 sharks remaining in a block each day,
100 move out in each direction

Circulating in eastern central SA, eastern SA or western Tas
For every 10000 sharks remaining in a block each day,
2000 move out in each direction

The adults in western SA during winter are 80 per cent of the total.

Adult Migration

Migrating between western SA and Bass Strait
For every 1000 sharks remaining in a block each day,
10000 move forward
1 moves backward

The percentage of females breeding each year (and migrating) is 33 per cent.

Migration dates are fixed in Version 1 but will be changeable in Version 2.

16 August	Beginning of migration eastward
1 October	Peak of migration eastward
1 November	End of migration eastward
1 March	Beginning of migration westward
16 April	Peak of migration westward
30 May	End of migration westward