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Final Report, FRDC Project 95/037: The biology and stock assessment of the tropical sardine, *Sardinella lemuru*, off the mid-west coast of Western Australia

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Objectives

Objectives 1-5 are as in the original proposal to FRDC. Objective 6 represents additional work.

1. Ascertain the correct taxonomic status of this species.

2. Describe the biology of *Sardinella lemuru*, especially its reproductive cycles (including spawning biology and fecundity); feeding ecology; age and growth.

3 Determine the catch-at-age distribution for this fishery.

4. Monitor the dynamics, locations and catch rates of the fleet.

5. Conduct ichthyoplankton surveys to provide data for the daily egg production method (DEPM) from which estimates of the spawning biomass will be calculated.

6. Conduct preliminary investigations into stock delineation.

Non-technical Summary

Exploratory fishing for the tropical sardine, *Sardinella lemuru*, offshore of Geraldton on the mid-west coast of Western Australia in the early 1990s, led to the establishment of a developmental purse seine fishery in this region. This fishery showed potential for substantial expansion, but as there was no information on *S. lemuru* in WA there was a need to undertake research during the developmental period. The biology and fishery for *S. lemuru* in WA were therefore investigated over a three year period between July 1995 and June 1998 with the aim of providing stock assessment advice.

The biology of *S. lemuru* (reproduction, age, growth and diet) was examined using samples obtained from the commercial fishing fleet. While most samples were collected during the project, others from 1990 to 1994 were also available. Preliminary investigation of stock structure was undertaken by analysis of certain chemical components of otoliths of *S. lemuru* from Fremantle, Geraldton and Carnarvon. Plankton surveys to collect eggs of *S. lemuru* were undertaken off Geraldton regularly between September 1995 and March 1996 to examine the distribution of spawning in the region of the fishery. A further plankton survey was undertaken in the region between Kalbarri and Dongara in February 1997 which, with concurrent sampling of adult fish, aimed to provide an estimate of spawning biomass of *S. lemuru* off the mid-west coast. Detailed data on catch, effort and fleet dynamics (e.g. effects of vessel size and weather) were collected from research logbooks.

Strong winds limited fishing to non-summer months and also necessitated the use of relatively large vessels, with nearly 50 per cent of potential fishing days lost due to rough sea conditions. Most fishing thus occurred between May and September. The lack of regular monthly samples in any one year impacted negatively on the collection of biological data.

Diet of *S. lemuru* is typical of sardines, consisting predominantly of zooplankton. Spawning occurs from December to March, with a peak in January to February. The duration of peak spawning was relatively short and also variable between years. Densities of planktonic eggs between September 1995 and March 1996 peaked for only two weeks in February.

Age of *S. lemuru* was difficult to determine. A combination of methods indicated a lifespan of six or seven years, with growth to an average length of 82 mm at one year, 122 mm at two years, and then to an average at age seven of 166 mm. Maturity occurs at about 140-150 mm. Three- and four-year-olds dominated the catch, with few younger and older fish present. The annual total mortality rate (i.e. both natural and fishing mortality) was relatively high, being greater than that for pilchards off the south coast of WA. Chemical analyses of otoliths indicated that smaller *S. lemuru* had been living in warmer water than the adults, which partially explains the scarcity of younger fish in the catch. The scarcity of older age classes was attributed to the relatively high total mortality.

Otolith chemistry provided no evidence for the existence of separate stocks of *S. lemuru* between Fremantle and Carnarvon. However, the results, along with those from plankton surveys, did suggest that the stock may be widespread, patchy and highly mobile. *Sardinella lemuru* eggs were typically found over the outer half of the continental shelf and were widely distributed along the shelf. No estimates of spawning biomass resulted from the concurrent sampling of eggs and adults, due primarily to insufficient samples of adults to estimate spawning parameters.

While there are recognised problems with estimating fishing effort, particularly for purse seine fisheries, three estimates of catch rates (kg/day, kg/litre of fuel, kg/hour searched) all indicated an increase from 1995 to 1996 and then a decrease in 1997. Assuming these changes reflect changes in abundance, the assemblage of *S. lemuru* in the Geraldton region declined in size markedly over a very short period. The reasons for this could not be determined within the three year duration of this project. Possible causes were fishing mortality, poor recruitment, migration, or a combination of some of these factors. Given the short history of the fishery, the evidence for a widespread/ patchy stock and the fact that the stock is close to the limit of its southern range, the decline was more likely due to migration and or poor recruitment rather than fishing mortality.

The small number of age classes, high natural mortality and lack of an estimate of stock size, along with the large interannual variations in recruitment strength expected of sardine stocks in general, provide a strong basis for conservative management of this fishery. Furthermore, if low abundance of *S. lemuru* in the mid-west's current purse seine grounds occurs periodically, for whatever reason, the fishery in the vicinity of Geraldton may not be commercially viable in some years. Therefore, any further large investment in the mid-west purse seine fishery would currently be unwise. If marked fluctuations in catch rates could positively be attributed to stock movement, any future investment has to consider the need for a mobile fleet which could fish in other areas and still land fish in good condition.

This project established a baseline of biological information for *S. lemuru* in WA, and represents the first intensive study of this species outside of Asia. This has immediate uses for FRDC project 98/203 on seabirds of the Abrolhos Islands. The biological, catch and effort data acquired during the project provide a basis for management of the fishery. The research indicates that the original concept that the fishery could expand greatly was over-optimistic and expansion of the Geraldton-based fleet is therefore unlikely to be economically realistic. Furthermore, the need for specialised purse seine vessels in order to viably operate in the mid-west coast sardine fishery has clearly been shown.

Monitoring of catches should continue so that a longer time series of biological information can be gathered. In particular, ongoing analysis of relative age composition should provide a cost effective method of assessing the status of the stock. Likewise, vessels will be encouraged to continue filling in logbooks so that deviations in catch rates or spatial extent of the fishery can be detected. This level of monitoring should meet future needs of management.

1.0 Introduction

1.1 Background

Interest in the usage and capture of baitfish stocks within Australia has increased substantially since the mid 1980s. The development of the market for pet food in the mid 1980s (SCP, 1988) combined with the more recent demand to feed caged southern bluefin tuna at Port Lincoln, South Australia, have expanded the markets for these species from their traditional base of supplying bait to recreational anglers and commercial pot and line fishermen. Consequently, a number of new baitfish fisheries have developed (e.g. Bremer Bay, Esperance, Port Lincoln) with considerable expansion occurring in fisheries that were already in existence (e.g. Albany, Fremantle). The total production of clupeids in Australia has, therefore, increased from less than 2,000 tonnes in 1980 to be greater than 10,000 tonnes by 1990 (Fletcher, 1991) with the total catch for 1994 exceeding 15,000 tonnes (Fletcher, 1994, Jones *pers comm*, MacDonald *pers comm*).

Until recently, nearly all fishing activities occurred in temperate regions with the species composition restricted, almost exclusively, to the pilchard *Sardinops sagax*. In Victoria, occasional catches of the anchovy, *Engraulis australis* have been made off Lakes Entrance and there is a relatively even mix between pilchards and anchovies in the purse seine catch of Port Philip Bay (Hobday, 1988; Fletcher, 1991). Anchovies are, however, largely absent from catches by the purse seine fleet in WA where the average annual production of this species is less than 50 tonnes.

The tropical sardine *Sardinella lemuru* has constituted a variable component of the purse seine catch in the Fremantle area of WA. The catches have fluctuated greatly, with over 1,000 tonnes taken in each of 1984 and 1985 but less than 20 tonnes was caught in 1993 (Fletcher, 1994). The market for *S. lemuru* has traditionally been as bait for the western rock lobster fishery, receiving a premium price (70-90 c/kg), in comparison with 28-35 c/kg that pilchards have received as rock lobster bait. This difference in price results from *S. lemuru* having a tougher body construction with scales that do not fall off (hence the local name, scaly mackerel).

Sardinella lemuru is a tropical species with Fremantle at the southern limit of its range (Whitehead 1985). The centre of distribution lies further north within the Indo-Chinese region where, apparently, annual catches exceed 100,000 tonnes (Whitehead, 1985, but see later). Within Australia, *S. lemuru* is distributed northwards from Fremantle up to the Pilbara region (Whitehead, 1985) but no information is available on the potential catches in this region. In 1989, a number of development purse seine fishing zones were instituted within WA to encourage a rational expansion of fishing outside of the established areas of Fremantle and Albany (Grill, 1987). The development zone north of the West Coast zone extends from Lancelin (31º10´S, 113º10´E) to Steep Point (26º08´S, 113º10´E) just south of Shark Bay (Figure 1.1). This Mid-west Coast zone is centred on the port of Geraldton (400 km north of Fremantle).

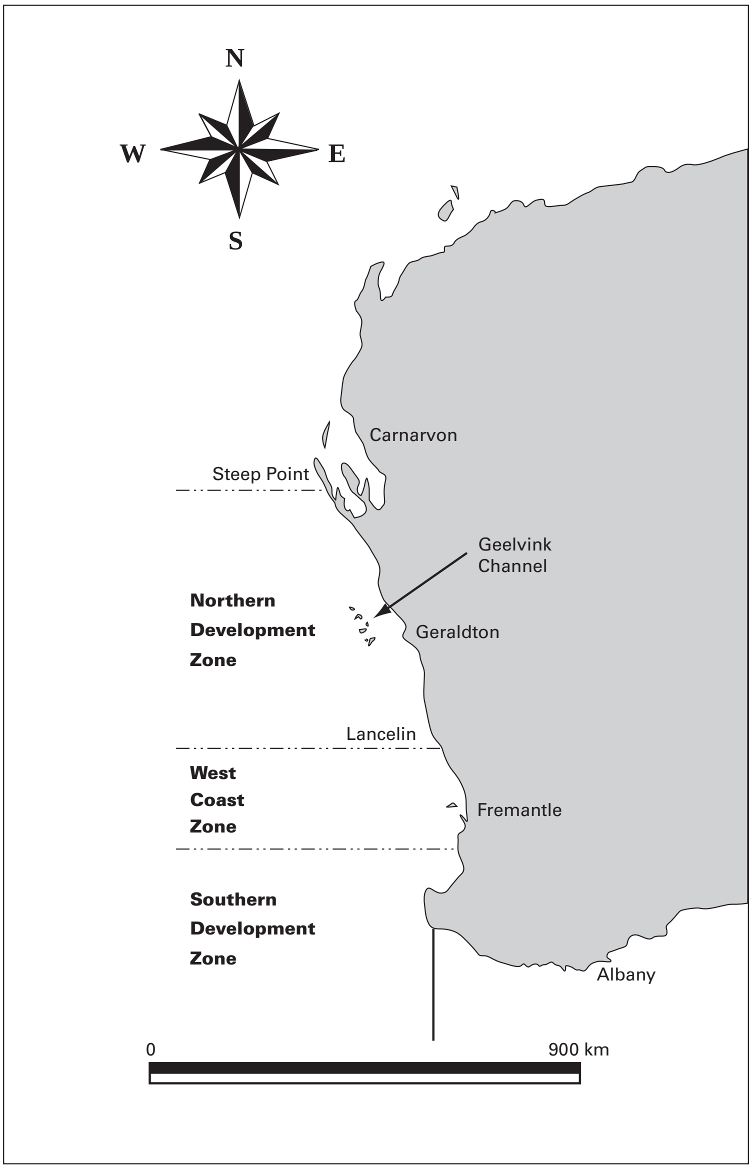


Figure 1.1 Part of the Western Australian coast showing the position of purse seine zones along the mid- and lower west coasts. Zones along the southern coast have not been shown.

The first attempt at purse seine fishing in this zone began at Geraldton in 1989, but whilst confirming that large numbers of *S. lemuru* were present in this region, the venture failed because of a lack of available onshore processing facilities. Subsequent ventures have also been restricted with the result that annual catches for the 1990-1992 period were each less than 200 tonnes. This small production was despite the vessels being comparatively large (20-30 m in length) with hold capacities between 20 and 80 tonnes, which is significantly larger than boats in the remainder of the WA purse seine fleet. There are currently no restrictions on vessel size within this Mid-west Coast zone because the area of fishing is about two hours steaming from port and the prevailing weather conditions in the Geraldton region are poor with consistently strong winds. Consequently, purse seine fishing in small boats would be dangerous. Furthermore, the relatively high water and air temperatures requires the fish rapidly be put into an ice slurry to maintain quality. Thus, all vessels which have fished in this region have used fish pumps and ice/brine tanks to handle the catch.

A major impediment to the development of this fishery has been the lack of blast-freezer space available at Geraldton. Whilst there were a large number of freezers in this region, these were almost constantly in use by either the rock lobster or scallop fisheries which, given the price differential, have first priority. As a consequence, two dedicated blast freezers to process *S. lemuru* were constructed during 1993 and 1994, following which, production by the fishery increased rapidly. The catch in 1993 was 600 tonnes with approximately 2,000 tonnes caught during 1994. In both these years, fishing did not occur in all months, with only one boat having fished in 1993 and at no time were all three licences being fished. The potential for effort to increase was, therefore, considered substantial. This combined with the experience gained by skippers during 1994 was considered likely to result in further increases in catch if there are no limits imposed.

There are additional considerations that need to be addressed, particularly if there is any possibility of the stock becoming heavily exploited. The majority of fishing occurs between the coast and the Abrolhos Islands. These islands are the breeding grounds for a large number of bird species (Hatcher *et al.*, 1988) and this area is also a marine nature reserve (Anon, 1993). Concerns have already been expressed that any exploitation of the baitfish in this region could have a deleterious affect on the breeding success of the birds. This issue is being addressed currently in FRDC project 98/203. Similar fears have also been expressed in relation to the impact on recreationally important fish species.

Given these problems, management arrangements for this fishery needed to be introduced as quickly as possible. Consequently there was an urgent requirement to determine the stock size and population dynamics of *S. lemuru* so that the appropriate level of exploitation could be determined. Interim management, in the form of a total allowable catch (TAC) set at 2,700 tonnes was introduced in 1995. Given the size of capital investment required for this fishery, the TAC was set with the aim of achieving a balance between conservationist fears and allowing sufficient room for the fishery to have a chance to become established. Catches in the early part of the fishery suggested that there was a potential for annual catches to expand to between 6,000 and 7,000 tonnes, equivalent to a production value of at least $4 million annually.

There is no published information available on the biology of *S. lemuru* within Australia except for data on the presence of *S. lemuru* larvae within the Swan River (Gaughan *et al.*, 1990). Some preliminary information on the reproductive cycle was obtained from opportunistic sampling, which suggested that the spawning season may be relatively short, being restricted to the January-March period.

Neither is there any published or unpublished information on the potential stock size of *S. lemuru* within Western Australian waters, nor on the level of separation between 'stocks' along the coast. Moreover, the relationship between *S. lemuru* in Australia and elsewhere in the world is also unclear. Whilst Whitehead (1985) classed this species as the main sardine species caught in Indonesia, many publications from this region identify their major sardine species as *Sardinella longiceps*. Thus, there has been uncertainty regarding the taxonomic status of this species.

Given the lack of data available and the urgency with which information on stock size is required, it was thought that the most efficient method of stock assessment for this species would be to apply the methods developed for the south coast pilchard stock (e.g. Fletcher, 1991, 1994, 1995; Fletcher *et al.*, 1992, 1994; Fletcher & Tregonning, 1992). This involves sampling the catch from the fleet to provide the basic biological parameters for adults of reproduction, feeding and growth. From these, the population dynamics of the stock, including the overall level of mortality, can be calculated. In addition, intensive and extensive ichthyoplankton sampling completed during the peak spawning period can be used to ascertain the aerial extent of the spawning stock, the intensity of spawning within this area and, combined with simultaneously measured adult reproductive parameters, allow estimates of stock abundance to be calculated using the daily egg production technique (Lasker, 1985).

1.2 Need

The Western Australian Purse Seine Management Advisory Committee has clearly identified that research on this stock should have the highest priority. This is a new fishery for a resource about which no data are available either locally, nationally or, possibly, internationally. The catch of the fishery, whilst having already increased substantially during the two years prior to the start of the project, was considered to have a high potential for further increases. Furthermore, since this species has been identified as a potentially important prey of nesting seabirds at the nearby Abrolhos islands, substantial declines in abundance of these sardines could have serious consequences for the breeding success of these unique seabird nesting colonies. It was therefore imperative that information on the biology and stock size of *S. lemuru* was collected quickly to determine the sustainable level of harvesting.

2.0 Methods

This part of the report follows the structure in the project proposal. Thus, the methods are separated into five sections, most of which have been divided into subsections. Descriptions for materials and methods for research additional to that originally planned, and also the subsequent results and discussion, are included within the main body of this report as appropriate, or as appendices.

2.1 Ascertain the correct taxonomic status of this species

The morphological features of scaly mackerel were closely examined with respect to the descriptions in Whitehead (1985) of the species *Sardinella lemuru* in comparison with the closely related species *Sardinella longiceps, S. aurita* and *Amblygaster sirm*. Some specimens from the Bali Strait 'lemuru' fishery (i.e. from Indonesia) were compared morphologically with the description in Whitehead (1985), but no genetic comparisons were made with fish from WA. Staff from the fish section of the WA Museum also provided assistance with the morphological comparisons.

2.2. Describe the biology of *Sardinella lemuru*, especially their reproductive cycles (including spawning biology and fecundity); feeding ecology; age and growth

2.2.1 Sample collection

Samples of *S. lemuru* were collected from commercial catches between January 1990 and July 1997. In some of those months where samples from commercial vessels were not available during the project (July 1995 to June 1998) samples were taken by one of two other methods. Mid-water trawling was conducted on board RV *Flinders* (see Research Trawling section of report [Appendix 1]). This technique proved effective, with between two and seven samples obtained during all but one of the surveys conducted, with the other survey seriously hampered by strong winds.

A gill net (mesh size of 36 mm) deployed from a vessel anchored overnight in the vicinity of the fishing grounds was also used to sample *S. lemuru*. A 3000 watt surface light was used to attract fish to the net. This method met with limited success, with only a single sample of *S. lemuru* obtained. Although the technique was good for catching sardines, with many round herring (*Etrumeus teres*) caught at anchorages near the Abrolhos Islands. However, *S. lemuru* occur infrequently near the islands. Because of frequent strong winds sampling vessels typically sheltered overnight in the lee of islands, and the single sample of *S. lemuru* was obtained on one of the three occasions when a vessel was able to anchor in the more exposed parts of Geelvink Channel.

Commercial purse seines were used to capture schools or portions of schools of *S. lemuru*, typically during the night, with total catches per night for a single vessel usually lying between five and 30 tonnes. Three vessels (licences) were permitted to operate in this fishery during the project, but only two did so. Due to various reasons, samples were normally obtained by only one, and less frequently two, vessels on any given night. The number samples collected in each month varied from zero to 23 (Figure 2.1). Although samples have been obtained from virtually every month that fishing has occurred since 1990, fishing usually took place for less than eight months of the year, and in some cases for only three or four months of the year (Figure 2.1).

Smaller catches constituted a single shot of the net, whereas larger catches often contain fish from up to three different shots. Samples of 25-50 fish were saved from the load of fish brought back by each vessel. An effort was made to obtain samples from each shot but this was only partly successful, largely due to the need for separate shots to be sampled at sea since fish from separate shots on any one night are mixed together in the holds prior to being transported to port. The large quantities of fish landed at any one time necessitated dividing the catch amongst the different holds of a vessel so that the weight was evenly distributed for the purpose of minimising vessel instability. Crew on the purse seine vessels were encouraged to take a sample from each shot as it was landed, but for various reasons often failed to do so.

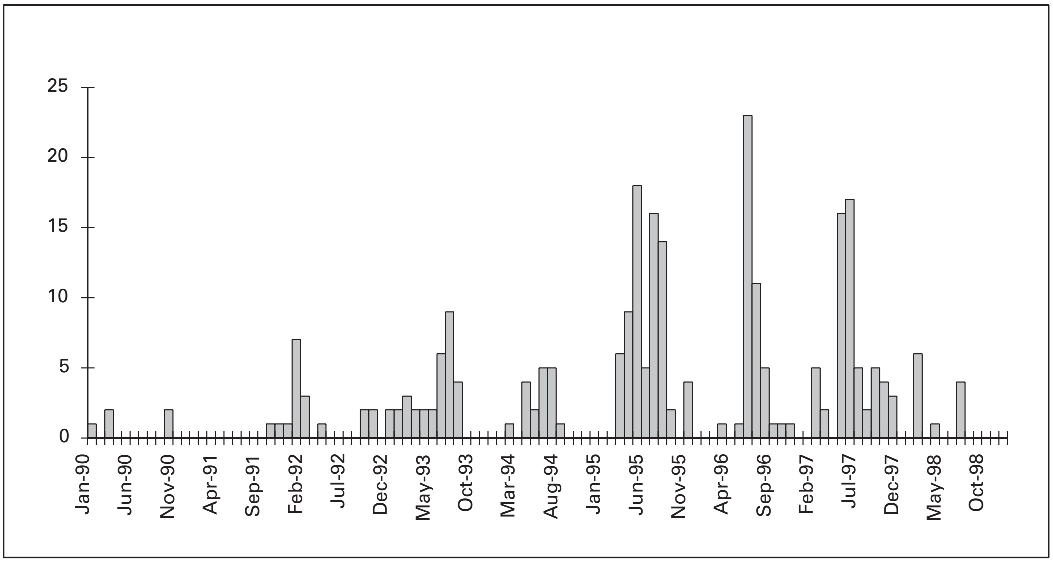


Figure 2.1 Numbers of samples of *Sardinella lemuru* collected in each month from 1990 to 1998.

2.2.2 Sample treatment

Each sample was frozen and returned to the laboratory. Fork length (FL) (±0.5 mm) and weight (±0.02 g) were measured for twenty to 50 fish from each sample. Biological data of fish collected (fork length, weight, visual estimate of sex and gonad stage, gonad weight, gut weight) were recorded. Other aspects of the biological sampling relating to reproduction, diets and ageing will be described separately in later sections.

2.2.3 Reproduction

Sex and gonad stage of all specimens was determined after dissection. A visual assessment of the developmental stage was made based on the macroscopic appearance of the gonads. Nine stages of gonad activity for female fish were recognised (Table 2.1). Fish for which no gonads could be found were classified as immature. In this context the term immature does not refer to gonads in the resting stage. Assessment of gonad stage for all *S. lemuru* sampled allowed size at sexual maturity to be determined.

Gonads from the first 10-20 individuals from each sample were weighed and gonadosomatic indices (GSI) calculated using the formula:

$$GSI = gonad\ weight * 100\ /\ (total\ weight - gonad\ weight)$$

Essentially all commercial fishing for *S. lemuru* during the project fell outside of the spawning season (Jan-Mar). The majority of gonads collected from the fleet between 1995 and 1997 were very small and often in poor condition. Therefore very few were kept. Thus, relatively few ovaries were preserved for estimation of fecundity or histological examination. Those ovaries saved were preserved in 10% buffered formalin (Hunter 1985).

Table 2.1 Descriptive criteria for macroscopic staging of *S. lemuru* ovaries.

Stage 1	**Immature or virgins** - Small, thread like structures, difficult to sex due to small size and lack of structure
Stage 2	**Inactive/Resting** - Gonads very small however still possible to determine sex. Gonad firm and red in colour.
Stage 3	**Active/Developing** - Gonad is about two thirds of body cavity in length; yellow-orange in colour. Oocytes still difficult to see with the naked eye.
Stage 4	**Ripe** - Ovaries now very large and occupy more then two thirds of body cavity. They are orange-red and individual oocytes visible.
Stage 5	**Running ripe/ Spawning** - Oocytes are hydrated and the ovary fills the entire body cavity. Eggs can be seen exiting the gonad under pressure using finger.
Stage 6	**Partially Spent** - Ovaries have massive haemorrhaging and are red. Still occupy about half to two thirds of cavity. Individual oocytes can still be seen.
Stage 7	**Recently Spent** - Ovaries are mid size but individual oocytes cannot be seen. Gonad is red with haemorrhaging throughout. Ovary is now very flaccid.
Stage 8	**Spent** - Ovary red with haemorrhaging. Very flaccid and only about half the length of the body cavity.
Stage 9	**Inactive** - Ovary small, less then half the length of the body cavity. Red and very flaccid.

Fecundity and oocyte size

Ovaries collected from January and February of 1992 and 1994 showed a high degree of spawning activity. Most gonads from these times were judged macroscopically to be at stages prior to spawning (stage 4) or immediate post spawn (stage 6). However, at this time no funds had been set aside for histological examination of these ovaries. Batch fecundity was estimated for 37 individuals from these two spawning seasons (1992 and 1994). However, a major impediment to the usefulness of the fecundity estimates obtained was that the females used ranged in weight from 80 to 120 grams, whereas the average size obtained during the study period was substantially smaller (40 g). The difficulty in obtaining samples through the spawning season after this time did not allow an assessment of batch fecundity to be made over the typical size range of females.

Ovaries macroscopically staged as being close to spawning (stage 4) were used for batch fecundity estimation since hydrated ovaries were rarely obtained. Each preserved ovary was blotted dry and weighed to the nearest 0.0001 g. Small sub-samples (~0.05 g) of the ovaries were then weighed to the same precision, placed on a slide with a drop of water and gently smeared across the slide with a scalpel blade to separate eggs into a single layer so that they could be measured and counted. The preparation was viewed at 40X magnification with a compound microscope. So that oocyte size distribution could be examined, diameters of 200 oocytes were measured using an eyepiece micrometer. Because female sardines typically release only a certain quantity of the oocytes present in the ovary at any one spawning event (Alheit, 1993), only the largest size class of oocytes were counted to estimate fecundity. For each subsample of ovary, all oocytes in the larger size class were counted. The counts from each subsample from were then averaged before batch fecundity was estimated using the following formula:

Batch fecundity = average oocyte count per gram in the sub-samples X weight of the ovary.

Relative fecundity (the number of eggs per gram of ovary-free body weight) was also calculated.

Histological studies

Of the samples collected during this project, only in February 1997 were ovaries obtained which were at a stage close to spawning. Therefore only these ovaries were subjected to histological examination. Ovaries were prepared for histological analysis using standard techniques, then stained using haematoxylin and eosin.

After spawning the remnant epithelial tissue which encapsulated each ovum, i.e. post ovulatory follicles (pofs), remains visible for a short period of perhaps 1-2 days. For some species of fish these structures can be aged, for example, as either day 0 (< 24 hours old) or day 1 (24-48 hours old) (Hunter & Macewicz 1985), which allows identification of the actual day of spawning. Knowledge of what proportion within a sample had spawned on a given day allows the spawning fraction to be estimated, a parameter necessary for the daily egg production method (DEPM) of estimating spawning biomass. Sections of ovary were thus examined under a compound microscope for the presence of pofs.

Also, to further assess oocyte size distribution, the diameters of 50 oocytes were measured on each of one to three ovaries at different developmental stages.

2.2.4 Diet

The gut contents samples of *S. lemuru* used in this study were collected over a four year period. Two different methods of preservation were used on those fish for which guts were examined. Firstly, samples of *S. lemuru* from the commercial catch were frozen and transported to Perth for biological processing. The stomachs of a number of these fish were removed and individually preserved in a five per cent formalin solution. Secondly, stomach contents samples of *S. lemuru* were collected during the various research cruises. Fish, or just their stomachs, were preserved fresh in a 10 per cent formalin solution.

Gut contents from 10 stomachs from each sampling occasion were examined. Both the pyloric and cardiac stomachs were cut open and the main bolus of contents removed and weighed. The contents were then placed into a 5 ml vial and any remaining contents were washed in with a five per cent formalin solution. The volume in each vial was then made up to 3 ml with the formalin solution. Once the gut contents were placed in the vials they were agitated to break up the bolus into an even mixture.

To assess the numbers and types of zooplankton present in the stomach contents of each fish a 1 ml subsample of the 3 ml volume in the vial was examined under a dissecting microscope. The zooplankton present in this portion were identified as far as possible and counted. These counts were multiplied by 3 to estimate the total numbers of each food item present. In some samples the numbers of zooplankton were very low or the samples did not readily break up during agitation. In these cases the whole sample was examined and the zooplankton present identified and counted. Additionally, the percentage of detritus in each sample was estimated at this stage.

To assess the numbers and types of phytoplankton present in the stomach contents of each fish a 0.1 ml subsample of the 3 ml volume in the vial was placed onto a slide with a cover slip and examined under a compound microscope. The phytoplankton present in this portion were identified as far as possible and counted. These counts were then multiplied by 30 to get the total numbers present. In some samples the number of phytoplankton was so large that further subsampling was required.

Additionally, some samples from 1996 were examined by Wasel Hosja of the Waters and Rivers Commission. These results were presented as volumes of diatoms, dinoflagellates and blue/green algae.

To calculate the relative proportions of zooplankton, phytoplankton and detritus in the diet of *S. lemuru* the approximate volume in the stomach contents was calculated for each fish. To calculate the volume of each phytoplankton group a number of measurements of specimens were taken to estimate its volume. From a number of these the average volume of a specimen from each group was calculated. These were determined to be 20,000, 50,000 and 1,000 cubic microns for diatoms, dinoflagellates and blue-green algae respectively. Similarly, the average volume of each zooplankton group was calculated using this method (Table 2.2) and these average specimen volumes were used to estimate the volume of each zooplankton type in the diet of *S. lemuru*.

Table 2.2 Estimated average specimen volumes (µL) of zooplankton organisms found in the diet of *S. lemuru*.

Zooplankton type	Average specimen volume
Eggs	2.5
Amphipoda	5.0
Cladocera	2.5
Calanoid copepods	5.0
Cyclopoid copepods	4.0
Harpaticoid copepods	2.0
Decapoda nauplii	2.5
Ostracoda	0.5
Bivalvia	0.5
Gastropoda	0.5
Tinntinnids	0.5
Salps	5.0

As detritus could only be measured as a percentage of each sample its approximate volume was estimated by equation

$$Vd = 100\,(Vz + Vp) / Pd$$

Where: Vd is the volume of detritus; Vz is the volume of zooplankton; Vp is the volume of phytoplankton; and Pd is the percentage of detritus.

The composition of the zooplankton and phytoplankton components in the diet of *S. lemuru* was compared for each of the 10 sampling occasions. The samples used in this study allowed both seasonal and diel variations in the diet to be considered.

2.2.5 Age and growth

2.2.5.1 *Overview*

The otoliths and scales of a random selection of each sample collected in 1995 were removed and prepared (approximately 100 individuals per month) according to the methods described in Fletcher (1991). These structures were examined for the presence and location of rings which may represent annuli. The validity of using these rings to age fish was investigated using the standard technique of marginal increment analysis. These ages estimated using 'annuli' were compared with those ascribed using otolith weight by the method used to age the south coast pilchards (Fletcher, 1991, 1995). It was hoped that the most appropriate structure (and the method of examination) for long term use would be determined during the first two years of the study to reduce the time to complete the processing of subsequent samples. The full methodology for estimate ages of *S. lemuru* is described below.

Assuming an appropriate estimate of age can be made for individuals, the growth rate and parameter estimates for each sex will be calculated using standard equations (e.g. Francis, 1990).

2.2.5.2 *Sample treatment*

The sagittal otoliths were removed from a subsample of 10 to 30 fish from each sample. In most cases both sagittae were obtained, but occasionally one of the two was not recovered or broke during removal. Otoliths were cleaned of all adhering tissue in water, air dried for at least 24 hours and weighed (± 0.000 002 grams, 0.002 milligrams) using an electronic balance. For each of the fish from which otoliths had been removed during 1995, three scales were removed from the dorso-lateral region of the left hand side of the body posterior of the head ('shoulder'). In some case, particularly for smaller individuals, there were no scales remaining at the time the samples were examined, due to total loss of scales during capture and handling. Scales were cleaned in water, dried and then mounted between microscope slides.

2.2.5.3 *Ageing methods*

Age was estimated for individual fish by counting of translucent zones on scales, whole otoliths and sectioned otoliths. In each case the 'best' estimates of age were used with fork length to estimate von Bertalanffy (vB) parameters (L_{inf}, k and t_0). vB parameters were estimated by minimising the sums of squares for the fitted model. The following constraints were applied: $t_0 \geq -5.0$, $k \geq 0.1$, $L_{inf} \geq 160$.

For each of the assessments of age, data were initially plotted so that extreme outliers could be identified. Such outliers typically resulted from errors in the databases. If reference to the original data did not permit a correction then such outliers were removed from the data.

2.2.5.4 *Scales*

All scales collected in 1995 were examined. The best of the three scales from each fish was chosen by the reader and the number of zones interpreted to be annuli were counted. Three readings of the scales were performed. The first reading was made by one reader and the second and third readings were made by a second, more experienced reader of scales.

2.2.5.5 *Whole otoliths*

Preliminary analysis indicated that there was a positive relationship between fork length and otolith weight, suggesting that the otolith kept growing as the fish grew. Therefore, early evidence suggested that otoliths could be used to estimate age.

Whole otoliths were examined for subsamples of fish from 1995, 1996 and 1997. A single otolith from each pair removed from fish was mounted on a black, plastic, microscope slide in casting resin and covered with a coverslip. Otoliths were viewed under a dissecting microscope using reflected light. The image was transmitted via camera to an desktop computer which employed an interactive program which enabled the reader to record (a) the number(s) of translucent zones, (b) the distance of each of these zones from the otolith core along the posterior axis, (c) the radius along the posterior axis and (d) whether the posterior edge of the otolith was opaque or translucent.

Initial examination of several otoliths indicated that translucent zones were going to be difficult to consistently identify. A small percentage of otoliths were read with the date of capture but not the size of fish known. However, the level of subjectivity needed to count rings observed on the otoliths was considered sufficient to warrant examining otoliths without knowing their details. Thus, the double blind method was employed for the majority of otoliths examined, with no details of the origin of each otolith known until after it had been read. To examine the readability of whole otoliths, which acts as a measure of the influence of subjectivity when identifying translucent zones, a second reading of the same otoliths was made by the same reader after an interval of two weeks.

Marginal increments (MI = width of outer ring as a proportion of width of the previous ring), the percentage of otoliths with opaque edges and the percentage of otoliths with new edges (MI < 20%) were each examined to assist with validating the annual periodicity of rings (e.g. Hyndes *et al.* 1992).

2.2.5.6 Sectioned otoliths

Several studies have found that otolith sections provide an image for estimating age superior to that obtained using whole otoliths.

For each month in which samples were obtained during 1995 whole otoliths, representing those remaining from the same fish for which otoliths were read whole, were sectioned transversely using a Beuhler low speed Isomet circular saw, following embedding in resin. Because samples were collected from the fishery in only several months each year during this study, otoliths obtained in various months from other years between 1990 and 1997 were also used. The sections were then ground down with a series of finer grades of abrasive paper until about 0.3 mm thick. The sections, which remained held within the blocking resin were then mounted on microscope slides. Rings were counted on these sections twice by one reader and then once by a second reader following the same methods used for whole otoliths, but with a combination of reflected and transmitted light for viewing under the microscope.

2.2.5.7 Micro-increment analysis

Larvae

Sagittal otoliths were removed from larvae collected in a plankton net in March 1995. The otoliths were mounted whole in clear finger-nail polish on a microscope slide. Micro-increments were counted at least twice under a compound microscope at a magnification of X1000. Otoliths were read with the size and time of capture of the fish unknown. Increments were counted from the core to the otolith edge, along a single transect if possible.

Juveniles and adults

An attempt was made to count the micro-increments on the sagittae of fifty fish between 120 and 180 mm. For each fish a sagitta was mounted convex side down on a microscope slide with thermo-plastic. The concave surface was then ground down using a series of sequentially finer abrasive paper. Micro-increments were counted at least twice under a compound microscope at a magnification of X1000. Otoliths were read with the size and time of capture of the fish unknown. Any otoliths on which increments could not be followed from the core to the posterior edge were not used further in this study. The radius to the posterior edge was also measured.

2.2.5.8 Otolith weight frequencies

Since otolith weight (OW) can be objectively measured and many can be processed in a relatively short period of time, this data set contains more measures than those for sectioned otoliths, scales and micro-increment analysis. To determine if OWs could be used to estimate age, the frequency distributions of OWs in each year and selected months were subjected to modal analysis with Battacharya's (1967) method using the module in the FISAT software package (Gayanilo *et al.*, 1996). Otolith-weight ages were also compared with ages obtained for whole and sectioned otolith methods. Modal analysis and the relationships between OW and age estimated using ring counts were then jointly examined in an effort to determine if it was feasible to assign ages using otolith weights.

2.2.5.9 Length frequencies

Age and growth were assessed from monthly length frequency data subjected to the ELEFAN module of the FISAT software package. Length frequency data for all samples collected and for the period 1995-1997 were analysed separately. The routines in ELEFAN estimated best fits of von Bertalanffy parameters and allowed a visual assessment of the associated von Bertalanffy growth plots.

2.2.5.10 Catch-at-age distribution for the fishery and estimates of total mortality

The data collected each month on the ages of individuals present in the catch will be combined with the relative magnitude of the catch to provide a suitably weighted, yearly catch-at-age distribution for the fishery. From this distribution, estimates of total mortality will be calculated. It was intended to use any changes in effort during the sampling period to separate total mortality into its two components, fishing and natural mortality. However, the changes and inconsistency in the fishery from year to year nullified this proposal since sufficiently comparable estimates of effort between years were not available.

2.2.5.11 Sampling juveniles

One of the key objectives of estimating age was to determine the age structure of the population. However, monitoring of the commercial catch for *Sardinella* did not record many individuals smaller than 100 mm FL. Although the mesh selectivity could be a reason for this, it is doubtful that the juvenile fish and the adult fish were schooling together to any large extent. For example, the south coast purse seine fisheries in WA regularly catch small numbers of juvenile pilchards around 80-90 mm FL, even though this size class is not effectively captured by commercial purse seine nets and avoided by fishers when possible. It was assumed that if juvenile *S. lemuru* less than 100 mm FL co-occurred with the adults, even if only periodically, then some would have been caught by the fleet, but this was not the case. Likewise, none were caught in the samples obtained using mid-water trawling, although the research mid-water trawl net was able to catch reasonable numbers of small fish less than 100 mm FL (e.g. sandy sprats in Cockburn Sound near Fremantle, slender sprats in Geelvink Channel).

The lack of juveniles from the commercial catch and the mid-water trawling program suggests that small *S. lemuru* do not occur in any reasonable quantities in the commercial fishing area. It was therefore hypothesized that juvenile *S. lemuru* may use the shallow inshore areas along the mainland and or lagoons around the Abrolhos Islands as nursery sites.

Although it was beyond the scope of this project to undertake comprehensive surveys to identify nursery areas of *S. lemuru*, a brief examination for potential nursery areas in nearshore waters of the mainland and at the Abrolhos islands was undertaken since there was a need to catch fish from a small size class so as to obtain some data points for the early part of the growth curve. These surveys are described in Appendix 1.

2.3 Stock delineation

In an effort to determine if there were separate stocks of *S. lemuru* along the lower and mid-west coast of WA the isotopic ratios of otolith carbonate were compared for samples of fish obtained from Fremantle, Geraldton and Carnarvon. While direct causes for differences in the isotopic ratio for carbon (i.e. $\delta^{13}C$)[†] between samples of otolith carbonate cannot be precisely ascribed, differences in the oxygen ratio ($\delta^{18}O$) has been shown to be closely linked to differences in water temperature in which the specimens lived (Edmonds & Fletcher 1997). Differences in ($\delta^{18}O$) can thus be examined with respect to a distinct environmental variable. Note that although $\delta^{13}C$ is not so easily linked to a distinct environmental variable, and is likely influenced by biological factors such as diet, significant differences in this ratio still indicate the presence of distinct groups of fish.

The analyses undertaken on *S. lemuru* during this study represented only an introductory examination of stock structure. The techniques used follow those described in Edmonds and Fletcher (1997).

2.4 Monitor the dynamics, locations and catch rates of the fleet.

Research logbooks were supplied to the skippers for completion on a shot-by-shot basis for the 1995 to 1997 seasons. Both skippers operating in the fishery at the time were consulted during, and thus contributed to, the development of the logbook. Measures of effort recorded in the logbooks were number of days fished, fuel-used, search-time-per-trip and number-of-blocks-searched. The latter measure of effort was found to be of no use because the areal extent of the preferred fishing grounds throughout the study period were considerably smaller than the block-size used in the logbook (i.e. 5 n mile X 5 n mile).

The effort information was used to estimate monthly and yearly catch rates in the fishery. This information will provide one of the baselines for any future assessments of the status of the stock.

In a further effort to assess relative changes in abundance, vessels also recorded the numbers of schools of *S. lemuru* detected during each trip.

To assess the spatial extent of the *S. lemuru* fishery the location of each catch was recorded. The logbook provided the option to identify the location as either a GPS co-ordinate (i.e. finescale) or by referring to individually numbered 5 n mile X 5 n mile blocks (i.e. broadscale) provided in the logbook.

[†] This is a standard notation for isotopic ratios.

In order to provide further understanding of the fishery, particularly as it was a developmental fishery, other ancillary information were recorded. These were incidence of zero-catches, reasons for "lost" fishing days, position of *S. lemuru* schools in the water column and the presence of predators in the fishing grounds.

2.5 Conduct ichthyoplankton surveys to provide data for the daily egg production method of estimating spawning biomass

2.5.1 Plankton sampling

Plankton surveys aimed at collecting eggs and larvae of *S. lemuru* in Geelvink Channel were conducted aboard the RV *Flinders* periodically between March 1994 and March 1995 (Table 2.3). In March 1994 a series of 42 samples were taken opportunistically while the vessel was in transit between Shark Bay and Dongara.

Table 2.3 Details of plankton surveys conducted during the project. The dates shown represents the midpoint for each survey. PV = patrol vessel, LFB = licensed fishing boat.

Survey vessel	Date	Region sampled	Number of stations sampled	Tow type: vertical (V) or horizontal (H)	Mesh size (microns)
RV *Flinders*	21/03/94	Shark Bay-Dongara	42	V	300
RV *Flinders*	23/03/95	Geraldton	53	V, H	300, 1000
RV *Flinders*	23/09/95	Geraldton	27	V	300
PV *McLaughlan*	29/11/95	Geraldton	34	V	300
PV *McLaughlan*	14/12/95	Geraldton	33	V	300
PV *McLaughlan*	11/01/96	Geraldton	40	V	300
RV *Flinders*	26/01/96	Geraldton	30	V	300
LFB *Phillip King*	14/02/96	Geraldton	46	V	300
LFB *Phillip King*	08/03/96	Geraldton	35	V	300
RV *Franklin*	27/03/96	Dampier-Fremantle	65	V, H	500, 1000
LFB *Calista* and LFB *Jet Flyte*	19/02/97	Kalbarri-Dongara	129	V	300

In March 1995 RV *Flinders* undertook a dedicated plankton survey in the waters between Geraldton and the Abrolhos Islands. The aim of this survey was to investigate the distribution of spawning by *S. lemuru* between the mainland and the Abrolhos Islands. Poor weather severely disrupted the planned program, which was to sample in a grid pattern at regular intervals throughout the region. When it became obvious that there would be insufficient time to complete even part of the grid of proposed stations, this trip then focused on collecting larvae with surface tows. The net used had a 1 m square mouth and was constructed of 1 mm mesh.

The final plankton survey aboard RV *Flinders*, in January 1996, searched for *S. lemuru* eggs in Geelvink Channel specifically with the purpose of obtaining live eggs to culture. When a high concentration of eggs were found these were quickly transferred to on-board aquaria and then identified as being those of *S. lemuru*. The vessel then moored in the lee of an island for two days while the development of eggs and then larvae was monitored.

In order to assess the temporal and spatial distribution of spawning within the region of the fishery, a grid of stations in Geelvink Channel was sampled at regular intervals between September 1995 and March 1996 (Table 2.3). Initial assessments of reproductive biology had indicated that the spawning season was from mid-summer to early autumn so this series of surveys was timed to track the seasonality of spawning. This program of sampling had an additional role of constituting a pilot survey for the DEPM survey to be conducted later. All samples were taken using 300 micron CALVET nets (set up as paired bongo nets) which were towed vertically from near the bottom to the surface. For all plankton surveys the volumes of water filtered by the nets were measured with flowmeters.

RV *Franklin* undertook a cruise from Dampier to Fremantle in late March 1996, with plankton samples taken at regular intervals across the continental shelf. Vertical tows were taken with a pair of 500 micron-mesh conical nets, and surface tows with the same net used for this purpose aboard RV *Flinders* (i.e. 1,000 micron-mesh net, 1 m square mouth).

2.5.2 The DEPM survey to estimate spawning biomass

The daily egg production method has been used to estimate the spawning biomass of sardines and anchovies in various regions around the world (Alheit 1993), including off the southern coast of WA (Fletcher *et al.*, 1996). This technique was attempted for *S. lemuru* in the Geraldton region.

The DEPM model is as follows:

$$\text{Spawning Biomass} = (A*P*W*k)/(S*F*R)$$

where: A = spawning area (km^2); P = daily egg production (numbers of eggs per 0.05 m^2 before losses due to mortality); W = average weight of spawning females (grams); k = conversion factor to bring the various units to a value in tonnes (k = 20); S = spawning fraction - the proportion of females that spawn per day; F = fecundity - number of eggs released by a female of average weight; and R = ratio of females.

This method of estimating biomass requires two distinct sampling surveys which need to be conducted simultaneously; one for the adults (from commercial catches) and another for the eggs (plankton sampling).

Adult sampling was conducted in the area of the fishery as described in Appendix 1. Estimates of the above parameters follow standard procedures which have been described elsewhere in this report.

During the DEPM survey in February 1997 a grid of plankton stations extended from inshore to the edge of the continental shelf and from Kalbarri in the north to Dongara in the south. Stations were sampled with 300 micron-mesh CAVET nets towed vertically from a depth of 70 m or close to the bottom in shallower water.

2.6 The environment in the region of the fishery

The environment, particularly wind, had such a dramatic influence on the collection of samples for this project, that a thorough description is included in this report. Furthermore, knowledge of environmental factors is necessary when studying the biology of a species.

The main commercial fishing grounds for *S. lemuru* extend offshore between the Houtman Abrolhos Islands and Geraldton on the mainland. In order to assess how weather impacts fishing effort, and consequently total catch, meteorological conditions in the region of the fishery were examined. Meteorological data were obtained from weather stations at North Island and Geraldton, the nearest facilities to the fishing grounds. North Island has an Automatic Weather Station (AWS), which was installed in 1990. This device records hourly air temperature, wind speeds (a.m. and p.m. averages) and wind directions. The weather station located in Geraldton is capable of recording more detailed atmospheric data.

The Leeuwin Current in the region of the fishery is also described. Pearce (1997) previously described environmental conditions in Geelvink Channel close to where the fishery operates.

3.0 Taxonomy

The FAO catalogue of clupeid species (Whitehead 1985) is the primary source of identification for sardines. The identity of the species of sardine caught at Geraldton and also at Fremantle, i.e. the scaly mackerel, most closely resembled *Sardinella lemuru* as described in Whitehead (1985). This identification was also reached by staff at the WA Museum.

The distribution of *S. lemuru* apparently extends northwards from WA into Indonesia and then beyond into coastal waters of southern Japan (Whitehead 1985). There has been some confusion regarding the identification of sardines caught in Indonesia, particularly in the important Bali Strait sardine fishery. For example, some references indicate that the major sardine species caught in the Bali Strait is *S. longiceps* (Ritterbush 1975; Pet *et al.* 1997a, b) while other works indicate that *S. lemuru* is the major species (Venema 1996; Merta 1995). The confusion with *S. longiceps* is not surprising since both species are taxonomically quite similar, but the FAO identification guide for clupeids (Whitehead 1985) states that *S. longiceps* does not occur in the region. Subsequently, some specimens recently collected from the Bali Strait proved to be *S. lemuru*. Therefore, in accordance with the FAO guide, the dominant sardine in the Bali Strait fishery is deemed to be the same species which is addressed in this report, i.e. *S. lemuru*. *Sardinella fimbriata* is another common, but far less abundant, component of the Bali Strait sardine catch, but is easily distinguished from *S. lemuru*.

Although there was a suggestion that the WA catch of scaly mackerel could be *Amblygaster sirm*, this was not the case. A specimen of *A. sirm* was examined and found to be easily distinguished from *S. lemuru*. During this study no *A. sirm* were recorded caught by the purse seine fleet in Geraldton.

Recent research in other parts of Indonesia has found sardine species which are difficult to identify using the FAO guide, so there are possibly clupeid species in the Indonesian archipelago which have not been formally described (H. van Oostenbrugge, P. Kailola, *pers. comm*).

4.0 Reproduction

4.1 Size at sexual maturity

All individuals less than 120 mm FL were immature (i.e. stage 1) (Figure 4.1). Fish began maturing at 120-130 mm FL and 50 per cent maturity (i.e. > stage 1) was attained at 140-150 mm FL.

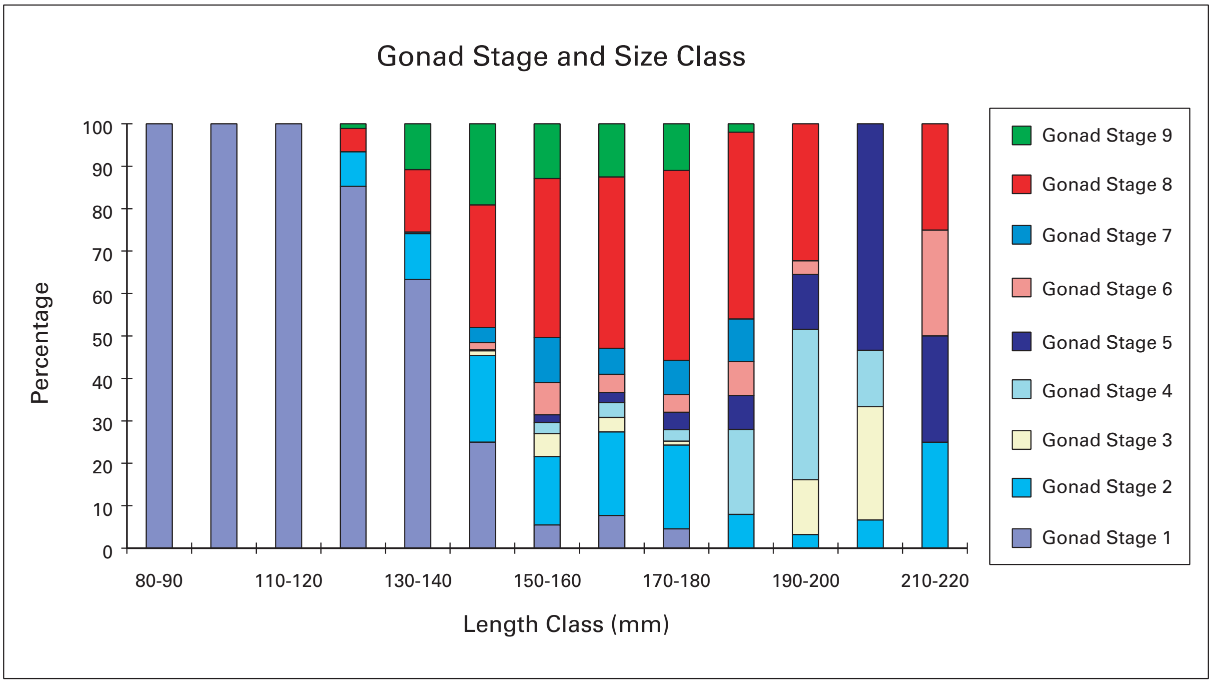


Figure 4.1 Relative proportion of gonad stages and maturity in each length class.

4.2 Gonadosomatic indices

The seasonality of the fishery combined with variations in the success of obtaining samples during certain months resulted in large differences between the sample sizes throughout the seasons (Figure 4.2). However, a pattern of high GSIs for several months over summer and very low GSIs (> 0.7) for the rest of the year was evident. During the 1991/92 summer there was clearly a peak spawning period for the month of January, GSI = 6.72, which followed a GSI of only 1.22 in the previous month (December). A very similar pattern of spawning activity was found in the following summer (1992/93) with GSI rising from 1.05 in December to 5.76 in January. However, unlike the previous spawning season, spawning activity remained high into February (5.37).

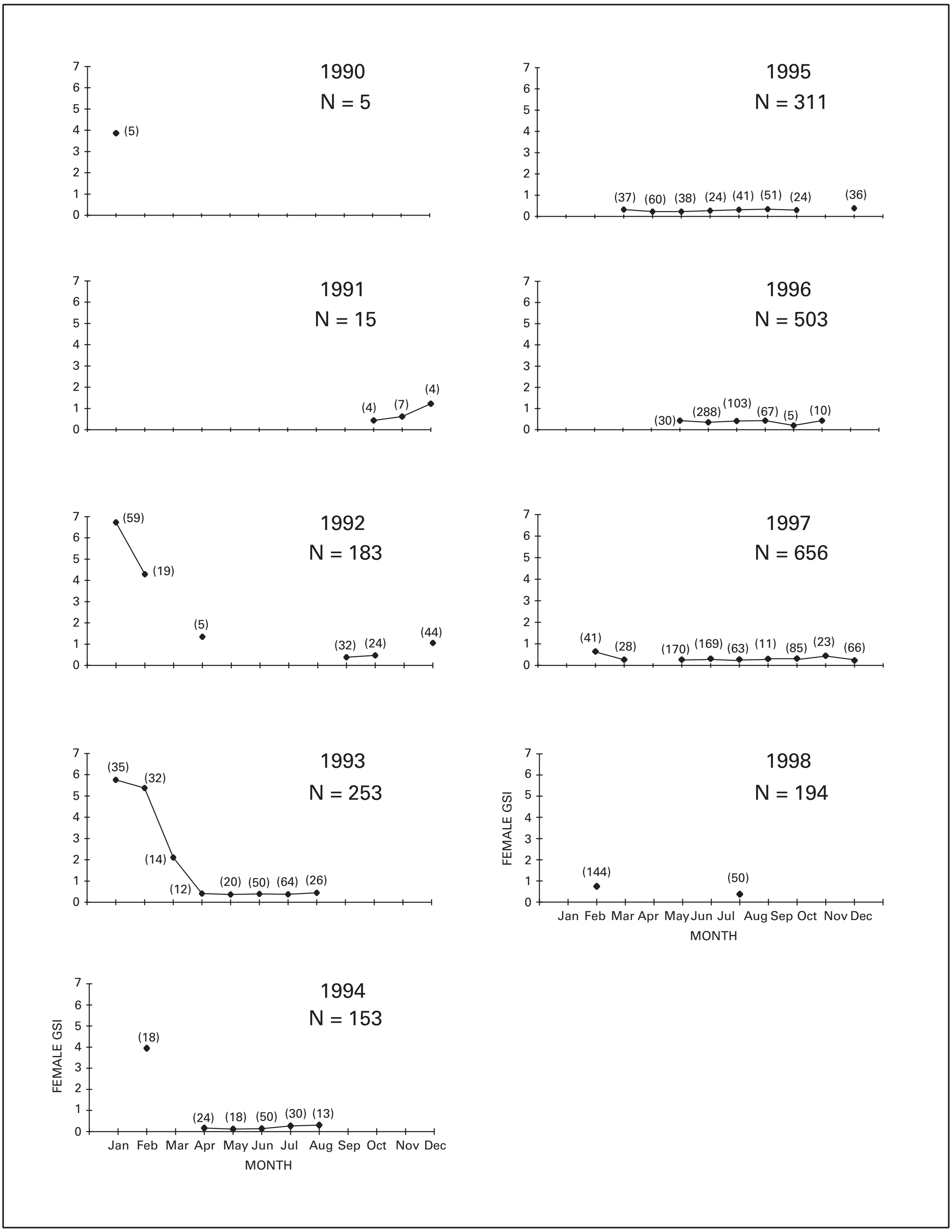


Figure 4.2 Mean monthly GSI from 1990 to 1998.

Following this two-year period (91/92-92/93) very few *S. lemuru* were obtained during summer, with the result that the last sample which contained a reasonable number of fish with highly developed gonads, was in February 1994. The collection of samples of *S. lemuru* prior to the formal start of this project was thus very fortuitous since only a brief description of the reproductive biology would otherwise have been possible.

Because of substantial gaps in the data, we also examined monthly GSI data pooled from different years (Figure 4.3). The monthly mean GSI values for females was highest in January with a peak value of 6.23. The GSI dropped during the month of February but remained relatively high at 4.7. Mean GSI decreased further during March to 1.44. GSI for males was also highest in January with a peak of 7.53. As with the females, GSI decreased in February to 5.13 and then more rapidly in March to 1.3. Minimum GSI for females was 0.29 in April, and that for males was 0.164 in June.

This pattern indicates a single spawning season, during the months of December to March with a peak in January.

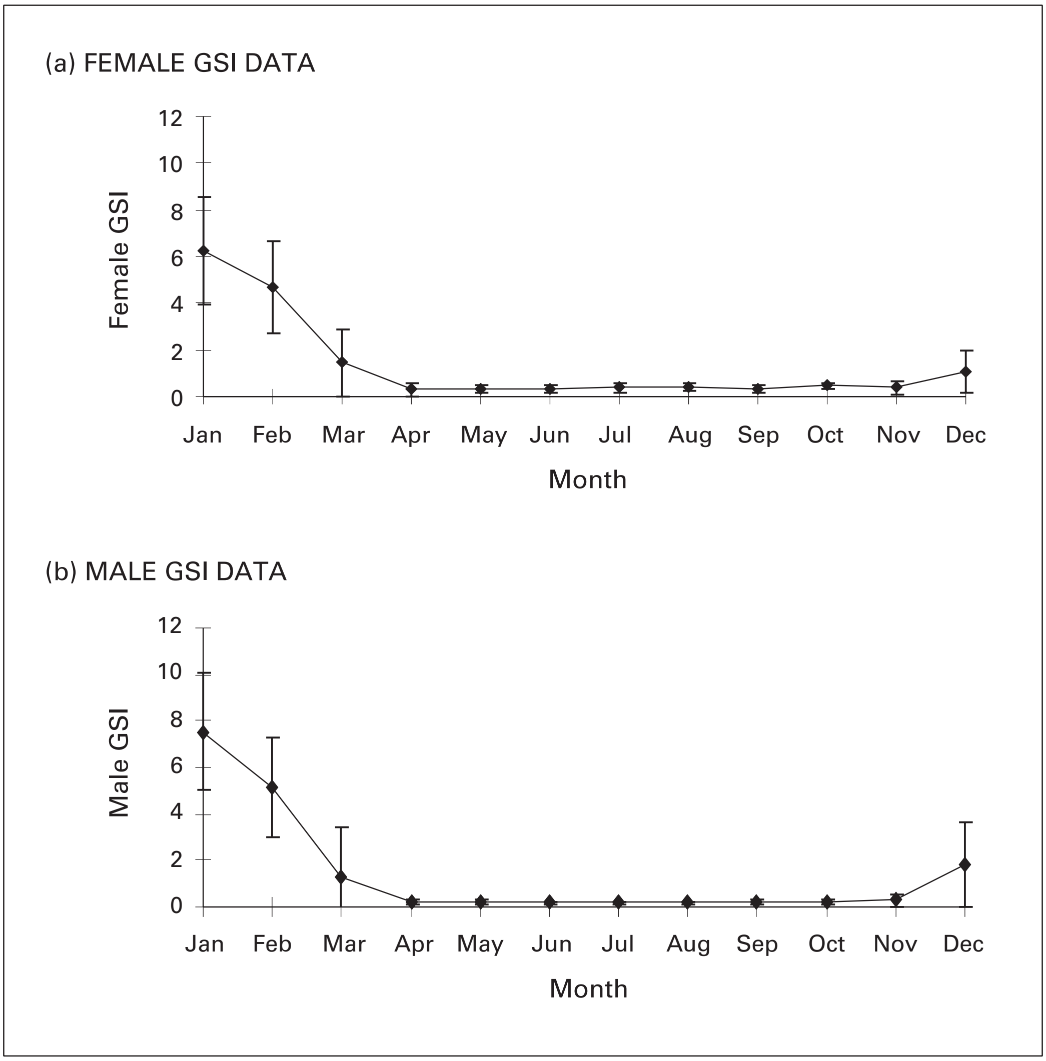


Figure 4.3 Monthly mean (± SD) GSI for (a) female and (b) male *S. lemuru* for all years combined.

4.3 Monthly changes in gonad stage

The highest proportions of individuals with gonads close to spawning condition occurred in the same months that GSI was highest (Figure 4.4). The macroscopic examination combined with the GSI monitoring for the winter months showed no evidence of spawning activity taking place outside the summer season, December-March.

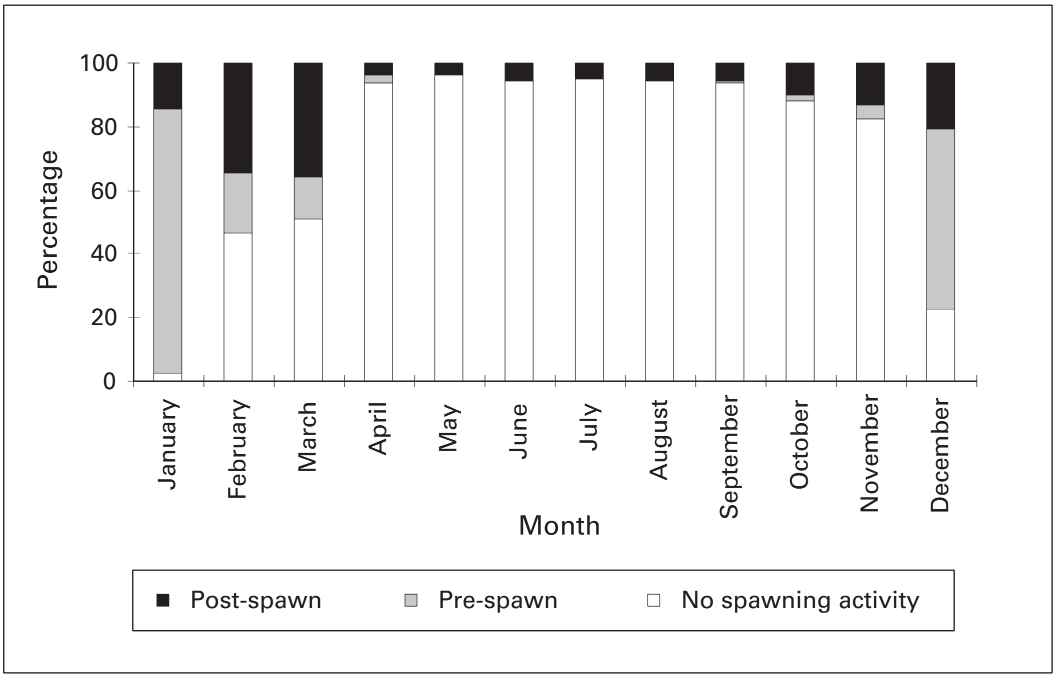


Figure 4.4 Relative proportion of gonad stages for mature individuals > 140 mm FL in each month. Gonad stages were grouped into pre-spawn (stages 3-5), post-spawn (stages 6-8) or no spawning activity (stages 9, 1-2).

4.4 Sex ratio

When the combined data for all years were examined there was not a large difference in the sex ratio for *S. lemuru* (Figure 4.5). The proportion of males to females remained generally constant throughout the sampling period, apart from minor fluctuations at times when sampling was particularly poor. For the total of all fish examined during this study, the ratio was very close to 1:1 (0.49 females : 0.51 males). When the size classes were examined separately, differences were found in the sex ratio. For the < 140 mm size class a ratio of 1.7:1 females to males was found. For the > 170 mm size class there was also a tendency for greater numbers of females to males with a ratio of 2:1. However, the majority of the individuals (86%) fell within the 140-170 mm size class, for which there were marginally fewer females than males (1:1.1).

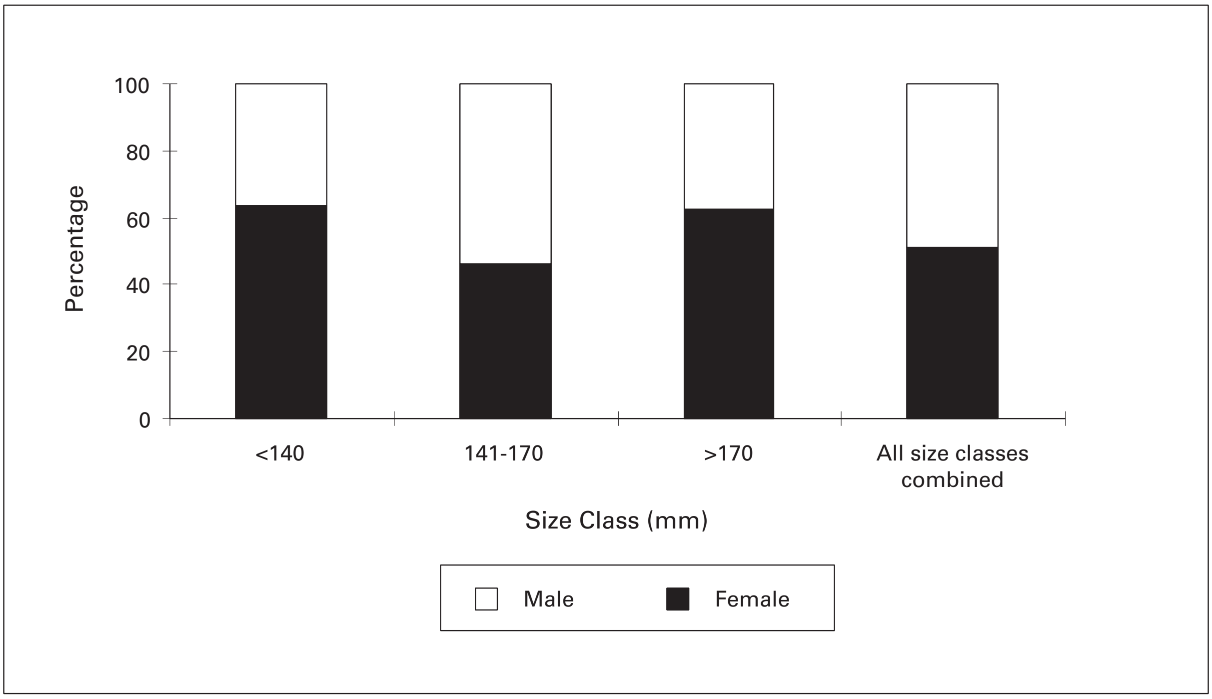


Figure 4.5 Proportions of male and female *Sardinella* for various size classes.

4.5 Histology

Developmental stages of ovaries were identified by examination of the structure of the oocytes in each slide (Figure 4.6, Table 4.1). Immature or virgin fish (stage 1) contained only primary cells of very small diameters. The oocytes present in resting/inactive ovaries (stage 2) were small and undeveloped. Wallace & Selmen (1981) described these gonads as being in the 'primary growth phase'. Developing ovaries (stage 3) had oocytes where yolk vesicles had begun to develop and the nucleus had begun to enlarge. Oocytes showing this stage of development continue to enlarge, with the yolk becoming granular and the nucleus begins to migrate towards the edge of the oocyte (stage 4).

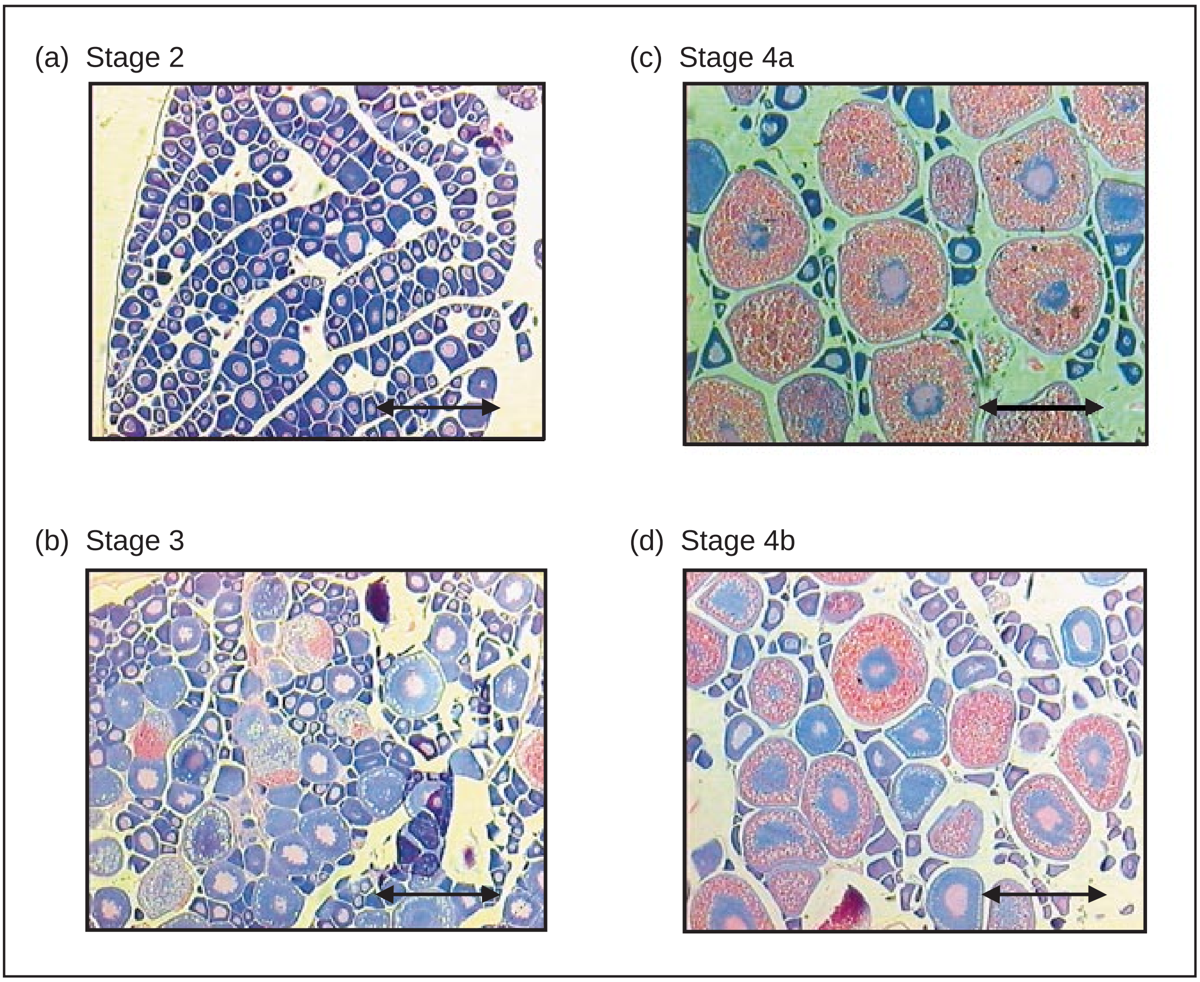


Figure 4.6 Histological sections of *S. lemuru* ovaries showing oocyte development. (a) stage 2, (b) stage 3, (c) stage 4a and (d) stage 4b. Scale bar is equal to 0.5 mm.

Table 4.1 Histological stages used to classify *S. lemuru* ovary sections.

Stage 1	Immature or virgin fish with primary oogonia within ovaries.
Stage 2	Resting/Inactive ovaries with small resting oogonia.
Stage 3	Developing ovaries with enlarging primary cells.
Stage 4a	Continued development with yolk becoming granular.
Stage 4b	Yolk now totally granular and nucleus migrates towards edge.
Stage 4c	Following migrating nucleus stage, primary hydration of oocyte commences.
Stage 5	Hydrated. Nuclear membrane dissolves and oocyte is fully hydrated prior to spawning.
Stage 6	Post ovulatory follicles can be observed in the ovary following spawning.

Successive development during stage 4 can be further divided into stages 4a, 4b and 4c. The final phase before spawning is hydration of the oocyte during which the nuclear membrane breaks down and the oocyte enlarges (stage 5).

To measure spawning fraction effectively from post ovulatory follicles (pofs), one must be able to estimate the age of the pofs on the basis of the rate of degeneration. The most accurate way to develop criteria for estimating the age of pofs is to spawn fish in the laboratory and sample at known times after spawning (Hunter & Macewicz 1985) so that degeneration of pofs can then be monitored in time series. However, it is possible to monitor the age of pofs by sampling fish at sea through the day and night (Alheit 1993). This was not accomplished for *S. lemuru* due to several factors. Firstly, *S. lemuru* predominantly school in tight aggregations at night and were very difficult to capture during the day. Consequently the commercial operators typically applied effort into catching them during the latter part of the afternoon and at night. Secondly, the limited fishing season made it very difficult to obtain samples during the spawning months. Lastly, the research vessel, which operates with a single crew, is not permitted to work a continuous 24-hour shift.

Post ovulatory follicles analysed from histology sections from the February 1997 biomass survey showed that only a few fish had recently spawned. Of the 172 ovaries analysed only seven had pofs, so the estimated spawning fraction was relatively low (4.1%). These results were consistent with the plankton survey which found that the peak spawning did not occur at the time of the survey, with few eggs being found (see Figure 9.2).

In comparison with the low spawning fraction obtained for *S. lemuru* in February 1997, the range for pilchards in WA is nine to 13 per cent at time of peak spawning (Fletcher *et al.*, 1996). Likewise, the low value for *S. lemuru* in this study is less than typical estimates of spawning fraction for various other clupeoids (Alheit 1993). Thus, the low value for *S. lemuru* off Geraldton was indicative of missing the peak spawning period. Furthermore, the estimate was suspect because it was based on only a small number of samples collected from a limited area.

For the purpose of organising DEPM surveys, prediction of the peak spawning month a year in advance, when we were required to reserve cruise time aboard the Fisheries research vessel, was problematical. Lack of commercial purse seining during the summer spawning season compounded the problem. Due to this paucity of samples, it was not possible to track GSIs in the months/weeks leading up to peak spawning, and, consequently, the peak spawning period was missed.

4.6 Oocyte size frequency distributions from the histological sections

The oocyte size frequency distributions for histological sections from different ovary stages generally supported the macroscopic staging. Thus, ovaries staged as two or three had single modes of oocytes with diameters of 0.03-0.11 mm (Figure 4.7). Stages from three to five had an increasingly large component of oocytes of greater diameter. By stage 4c, just prior to hydration, a second mode occurred at around 0.33-0.35 mm, and possibly a third mode at 0.43-0.45 mm. A similar trend was observed for fish staged as 4c/5.

The presence of these modes indicate that *S. lemuru* is likely a synchronous batch spawner and that enumeration of the largest size class of oocytes would provide a basis for estimating batch fecundity.

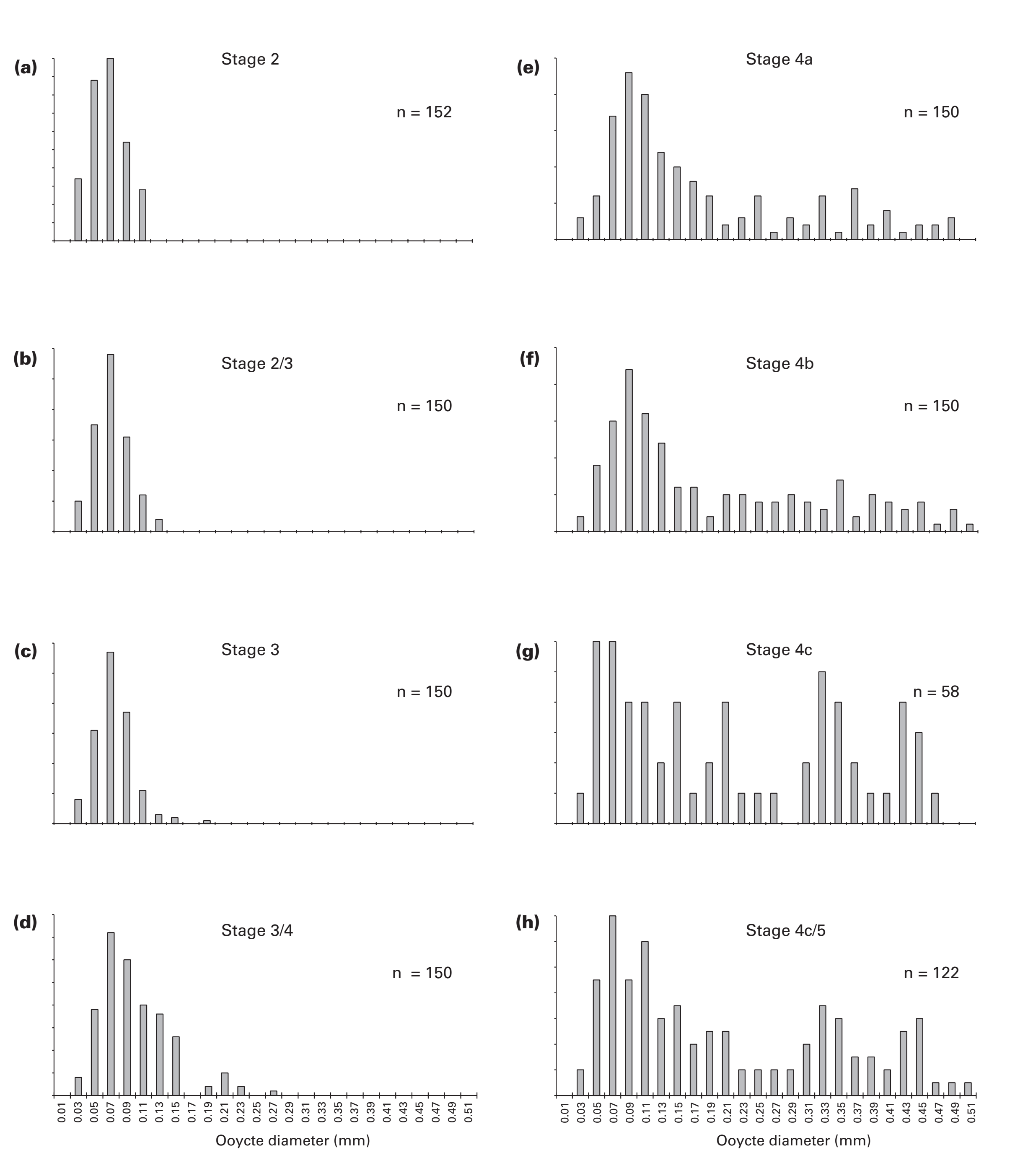


Figure 4.7 Size frequency distributions of oocyte diameters from ovaries at different stages. (a) stage 2 - resting/inactive; (b) stage 2/3 - resting/developing; (c) stage 3 - developing; (d) stage 3/4 - developing with yolk formation; (e) stage 4a - fully yolked; (f) stage 4b - migratory nucleus; (g) stage 4c - pre-hydration of oocyte; and (h) stage 4c/5 - hydration of oocyte and nuclear membrane begins to dissolve immediately prior to spawning.

4.7 Oocyte size frequency distributions for whole ovaries

All *S. lemuru* ovaries examined had a very high proportion of undeveloped primary oocytes with diameters between 75 and 125 microns (Figure 4.8). For ovaries with stages approaching spawning there were two modes of oocyte sizes, contrasting the three to four possible modes discernible for size frequency distribution obtained from sectioned ovaries. These ranged between 75 and 125 microns and the other mode between 525 and 600 microns (Figure 4.8). The smaller of these two modes constituted the undeveloped primary oocytes, while the larger represented the developed oocytes. This larger mode was assumed to constitute the next batch of oocytes to be spawned.

The presence of two modes of oocyte sizes does not provide as clear evidence for serial batch spawning as does the three modes discernible for size frequency distribution obtained from sectioned ovaries. Again, sample size was limited. Serial batch spawning is typical of many clupeoids, including most sardines and anchovies (Alheit 1993), and the evidence suggests this is also the case for *S. lemuru*.

(a) January

(b) February

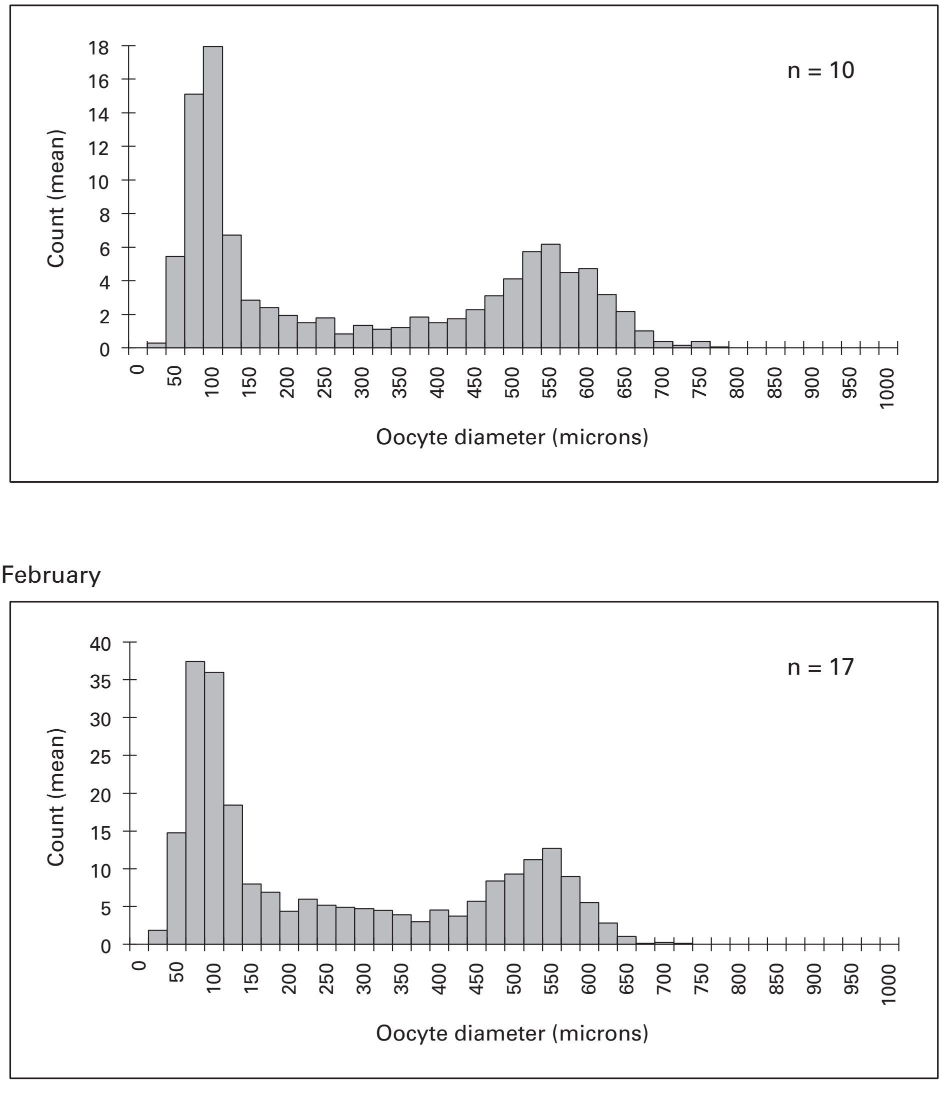


Figure 4.8 Mean oocyte diameters from ovaries collected in (a) January and (b) February. Data from different years have been pooled.

4.8 Fecundity

The larger of the two modes in the size frequency distribution of oocyte diameters (greater than 425 microns) was used to estimate batch fecundity. Oocytes in this size mode were counted under a compound microscope. Batch fecundity varied from 7,248 to 40,710, with a mean of 21,064 oocytes per female. The mean relative fecundity for *S. lemuru* was 436 eggs/g, similar to other clupeoid species (Alheit 1993).

4.9 Discussion

Sardinella lemuru reaches 50% sexual maturity at between 140 and 150 mm FL. This gives a ratio of length at maturity to maximum length of 0.66, which is quite similar to the value of 0.68 for the more temperate pilchards in southern WA (Fletcher 1990). In contrast, the ratio for *S. lemuru* is less than that for some other sub-tropical clupeids, which generally reach sexual maturity at younger ages than similar species from cooler waters.

The sex ratio for *S. lemuru* in WA coastal waters was close to unity. This is similar to some other species of *Sardinella* (e.g. Lazarus 1990) and was not unexpected.

Sardinella lemuru off the mid-west coast of WA spawn during summer with a peak in January/February. Because *S. lemuru* is essentially a tropical species, spawning may occur during this period so as to coincide with maximum water temperatures. However, the series of plankton samples taken from September 1995 to March 1996 (Figure 9.2) indicated that the peak spawning period was in February and may have been as short as two weeks. Thus, the month of peak spawning and duration of the spawning season can change markedly between years. Therefore, in any one year spawning may be 'early' or 'late' and of a long or short duration. Alternatively, during the monthly plankton surveys there may have been significant spawning occurring outside the region sampled, resulting in a biased indication of peak spawning period. Finally, considering that *S. lemuru* caught at Geraldton are relatively close to their southern limit, the water temperature in some years may be sufficiently low to partially inhibit spawning.

In *S. lemuru*, as in other fishes, there are almost certainly a series of physiological changes causing gonad activity to range from inactivity (stages 1 and 2), through the various stages of development to actual spawning (stage 5). Assuming that increases in water temperature provide the stimulus to these internal physiological changes in gonad activity, the apparent shift in period of peak spawning between years suggests interannual variability in the pattern of increases in water temperature during summer. Furthermore, such variability is expected due the interannual variations in the strength and position of the Leeuwin Current as it flows past the mid-west coast of WA (see section 10.8).

As the satellite images of the main commercial fishing area for *S. lemuru* show (Figure 10.3), sea surface temperatures are subject to large fluctuations. The movement of the Leeuwin Current south along the coast is reasonably predictable, but formation and intensity of eddies which bring warm pockets of water to inshore waters is less predictable. If a rise in water temperature occurs at the beginning of the spawning season, an early stimulus for gonad development could lead to an 'early' spawning. Early and late spawning may be important in relation to survival of eggs and larvae (Davies 1956) but there are very few data with which to hypothesise on the direction or magnitude of such potential influences. Interannual differences in temperature and vagaries of the Leeuwin Current most likely have some bearing on the reproductive activity and success of *S. lemuru* in the Geraldton region and, if so, the variation in these environmental factors may contribute to large interannual variations in recruitment strength.

Although the GSI data indicated a two to three month spawning season for *S. lemuru* off the mid-west coast, the lack of major spawning in two consecutive Februaries suggests that this duration may be an artefact of pooling data across years. Thus, although the duration of the reproductive period was two to three months, the peak period was quite short.

Further hypotheses regarding the potential influence of the Leeuwin Current and other environmental factors on reproductive success and recruitment are discussed in section 10.

5.0 Diets

The preserved gut contents samples from commercial catches in 1994 and 1995 were found to be unsuitable for processing. The stomach contents of these samples were very difficult to separate from the epithelium, as also encountered by Kagwade (1967). As a result the samples used in this study were limited to those from the research cruises.

5.1 Weight of stomach contents

A large number of the *S. lemuru* stomachs examined were empty or almost empty (Figure 5.1). Thus, the average weight of stomach contents for most of the samples was very low, often less than 0.05 g. In particular, all samples collected on 29/09/97 and 01/10/97 had very low average gut content weights.

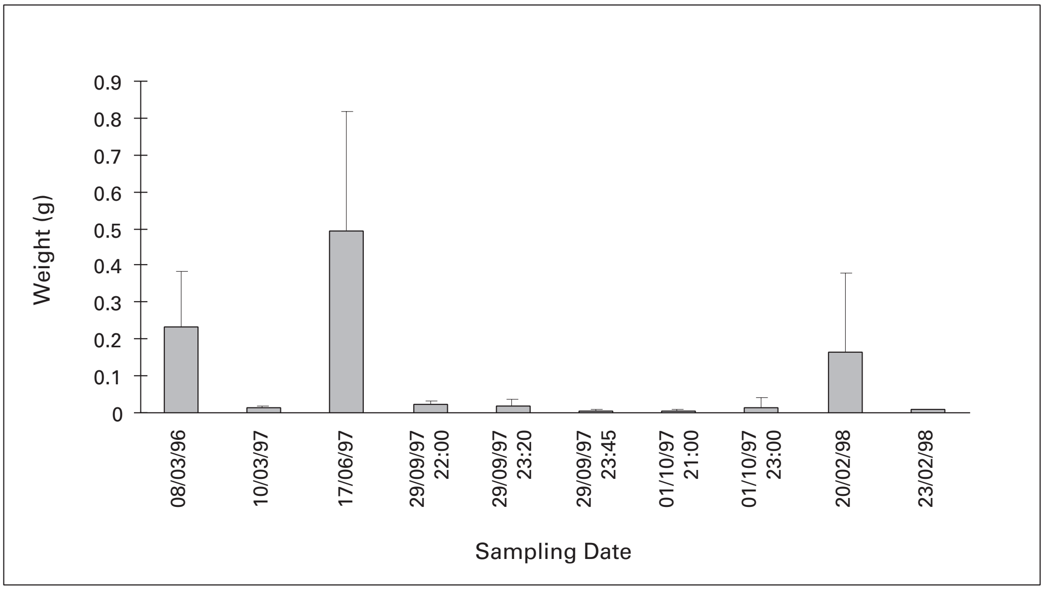


Figure 5.1 Average weight (+SD) of gut contents for each sample of *S. lemuru*.

5.2 Food groups

Due to the large differences in the average weight of stomach contents between samples, the results are described in terms of relative occurrence of different prey categories. On all but one of the sampling occasions, the diet of *S. lemuru* consisted predominantly of zooplankton and detritus (unidentifiable material) with relatively small quantities of phytoplankton (Figure 5.2).

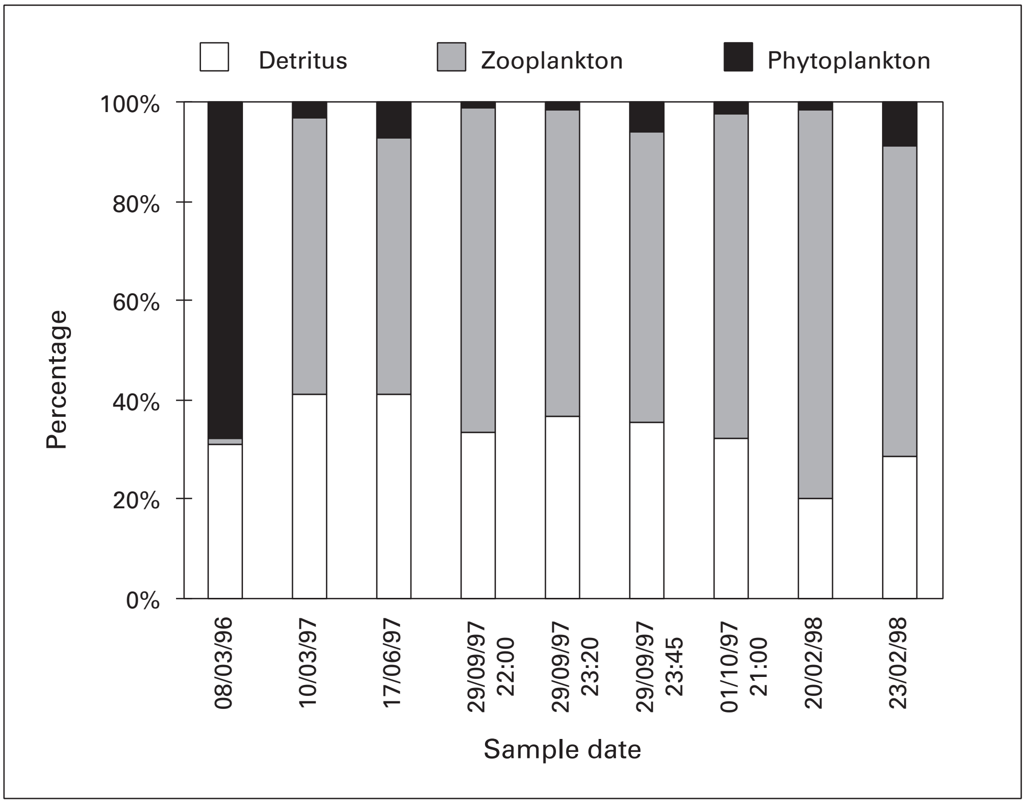


Figure 5.2 Relative occurrence of the major food categories for *S. lemuru*.

5.3 Phytoplankton

A large number of genera is consumed by *S. lemuru*. Each sample had both diatom and dinoflagellate genera present, while blue-green algae was found in the stomach contents on only a few of the sampling occasions, but occurred in all of the fish collected on the 08/03/96. Diatoms of the *Chaetoceros, Bacteriastrum, Coscinodiscus, Nitzschia,* and *Thalassiothrix* genera were consistently present in the diet while the dinoflagellate *Ceratium lineatum* was also usually represented by a few individuals in each stomach.

The stomach contents of the fish collected on the 08/03/96 had a noticeably higher proportion of phytoplankton than those of the other sampling occasions (Figure 5.2). In most cases the diets of these fish were dominated by diatoms, but in three of the fish the blue-green algae, *Trichodesmium*, was dominant (Figure 5.3). These differences were not found to be associated with the size of the fish.

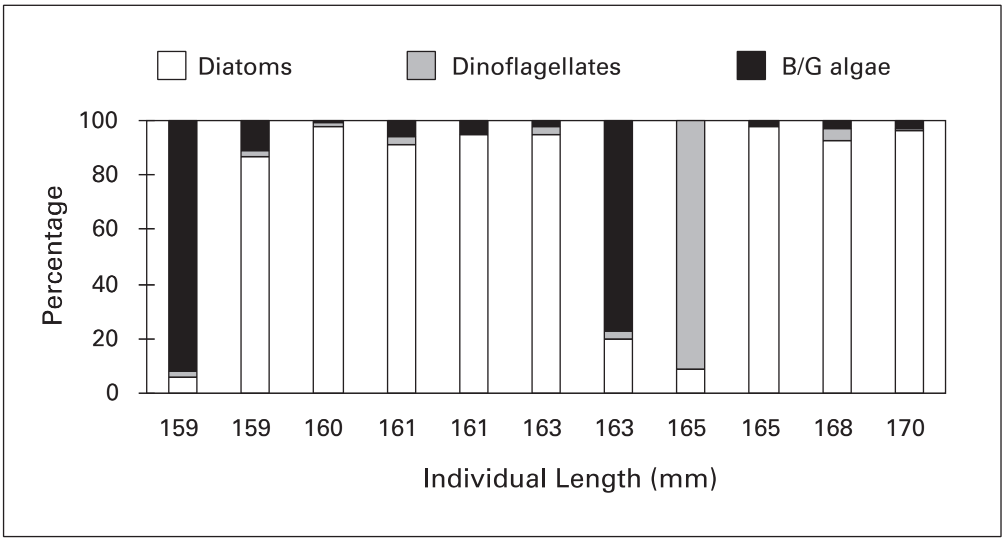


Figure 5.3 Occurrence of phytoplankton groups in the stomach contents of different sizes of *S. lemuru* collected on 08/03/96.

The three samples collected on the 29/09/97 showed a fluctuation in the average volume of each phytoplankton group in the stomach contents (Figure 5.4). The sample collected at 2120 hours had a noticeably lower volume of diatoms and dinoflagellates. This may be associated with the sampling of different schools during the night.

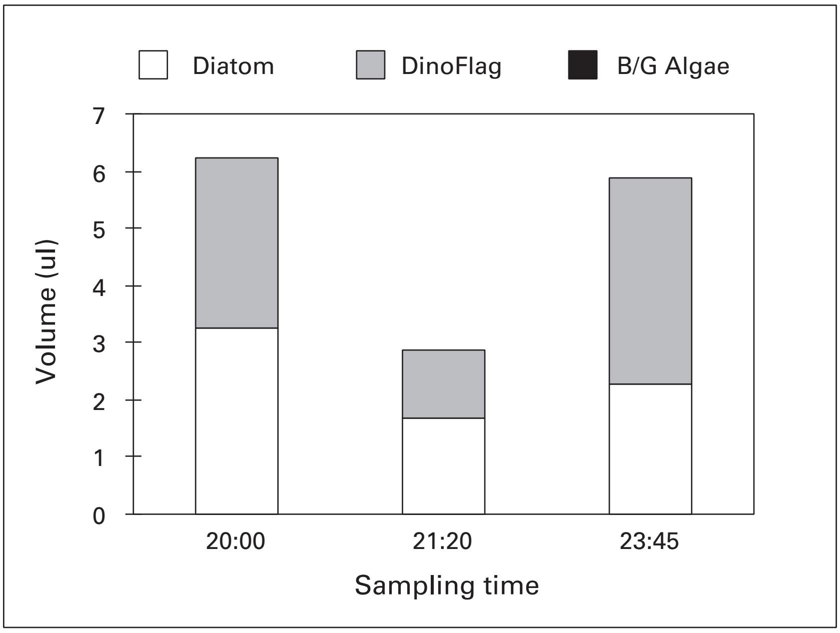


Figure 5.4 The average volume of each phytoplankton group found in the stomach contents of *S. lemuru* collected on 29/09/97. Note that the blue/green algae were inconsequential.

5.4 Zooplankton

The average numbers of different zooplankton types in the diet of *S. lemuru* collected on each sampling occasion is shown in Figure 5.5. Copepods, particularly calanoids, were present in the stomach of all *S. lemuru* in each sample. There were only a few other types of zooplankton that were regularly found in the stomach contents of *S. lemuru*. Of these other zooplankton, the salps (Tunicata) were of note as they occurred in high numbers in the stomachs of fish collected on 20/02/98, but then occurred in low numbers in fish collected on 23/02/98 and were found in no other samples.

In the three *S. lemuru* gut content samples collected on 29/09/97 the numbers of zooplankton decline progressively through the night (Figure 5.5). In contrast, the later of the two samples collected on 01/10/97 contained a higher number of each zooplankton type than the earlier sample.

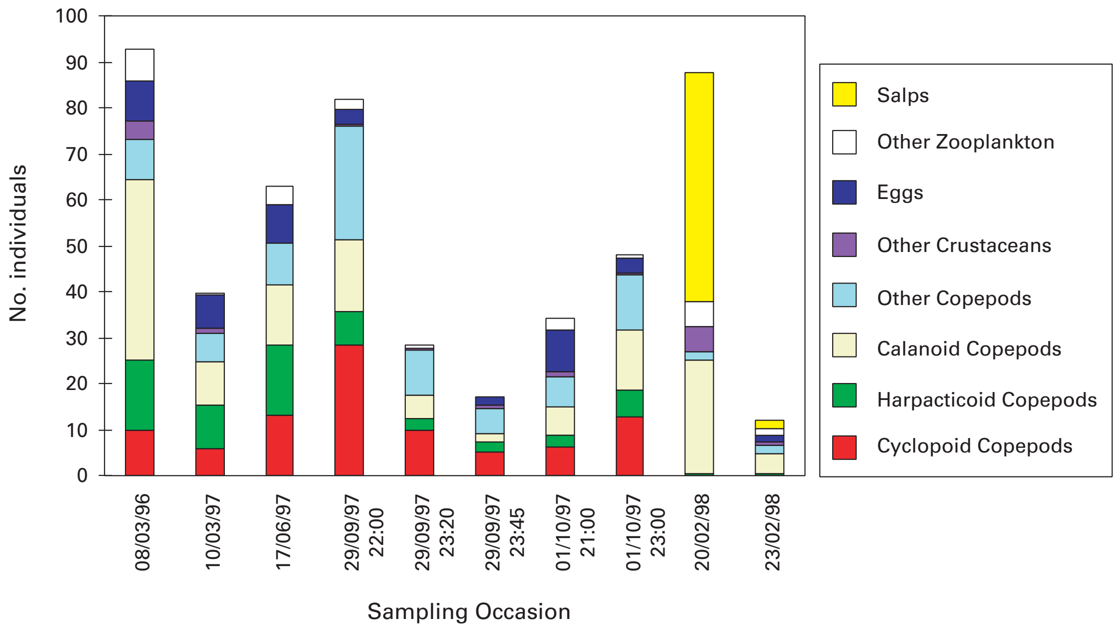


Figure 5.5 Average number of individuals for each zooplankton group found in the stomach contents of the *S. lemuru* samples.

5.5 Discussion

This study found that, for all but one of the sampling occasions, in waters off Geraldton the main planktonic group in the diet of *S. lemuru* was zooplankton and that unrecognisable detritus consistently made up at least 1/3 of the stomach contents. Thus, *S. lemuru* consumed a wide variety of planktonic organisms but copepods were their main dietary component. However, on one occasion phytoplankton were the major component of their diet and on another occasion salps were dominant, indicating that extreme shifts in diet can occur, at least periodically. There was also some evidence to suggest that their diet may vary spatially between schools. The presence of both zooplankton and phytoplankton in the diet of *S. lemuru* was not unexpected as most sardine species filter-feed, and thus have diets largely composed of plankton. As found for this species in the Bali Strait (Ritterbush 1975), copepods form a large component of the diet of *S. lemuru* off the mid-west of WA.

The presence of unrecognisable detritus or "marine snow" as an important component in the diet of *S. lemuru* has also been noted in other related species such as the Indian oil sardine *Sardinella longiceps* (Kumar and Balasubrahmanyan 1987). The importance of "marine snow", with its organic content and associated bacteria, has been noted in the diet of many pelagic species.

The large numbers of *Trichodesmium* in the stomachs of only three of the 10 fish collected on 08/03/97 could not be attributed to size of fish examined. Therefore, assuming the individual fish have little if any capabilities of selectively filtering certain plankton, the simplest explanation is that the fish with *Trichodesmium* had been feeding in a different location or different depth to the other *S. lemuru* in that sample. Alternatively, because this sample was a subset of 60 *S. lemuru* captured with a gill net that had been set overnight (i.e. about seven hours), the differences in diets may have also resulted from temporal changes in diet during the night.

While examining the stomach contents of *S. lemuru* the occurrence of an internal parasite was noted. This was identified to be a Turbellarian of the *Fecampia* genus. For most of the samples only three out of the 10 fish (i.e. 30%) contained the parasite and in numbers of less than 10 per individual (Figure 5.6). However, none of the fish collected on 17/06/97 were found to have the parasite and all of the fish collected on 20/02/98 were found to contain the parasite in numbers of up to 12 per individual. Thus, there was considerable variability in infection rate and parasite loading between sampling dates, even those only days apart, and also between samples collected only hours apart on the same night.

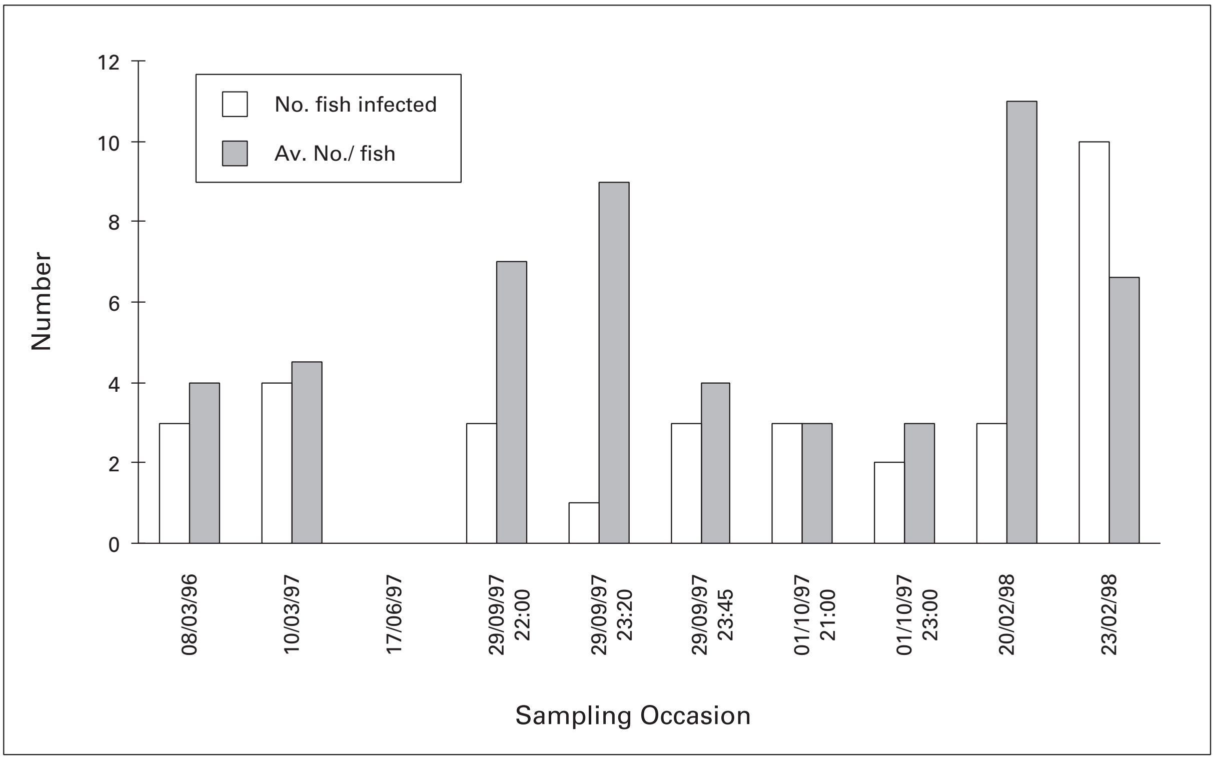


Figure 5.6 Numbers of infected fish and average parasite-loading in these fish.

6.0 Ageing

6.1 Sampling for juveniles

No juvenile *S. lemuru* (nor adults) were obtained in the brief sampling programs which targeted nearshore areas on the mainland between Cervantes and Lucky Bay (see Figure 1A page 124). Nor were any captured in the shallow waters near Rat Island, in the Middle Group of the Abrolhos Islands. Other studies which have sampled nearshore waters with beach seine along the mid-west coast of WA have also failed to capture *S. lemuru*. In particular, monthly sampling of five sites near Carnarvon, north of the Geraldton fishery, was conducted between 1995 and 1998 by students at Carnarvon High School but no *S. lemuru* were caught. Monthly sampling between 1995 and 1998 at Cervantes, south of the Geraldton fishery, which was conducted as part of a project on Australian herring (*Arripis georgianus*) and tailor (*Pomatomus saltatrix*), likewise did not record any *S. lemuru*.

Since both the commercial and research samples contained few juveniles, results of the following techniques for assessing age of *S. lemuru* therefore suffer from the common problem of having a poor representation of juvenile specimens.

6.2 Scales

Rings on scales of *S. lemuru* were difficult to consistently identify or interpret. Discrepancies between counts between different readers and for a single reader were reasonably large. While the same values (i.e. no difference between readings) accounted for most of the observations, there were large numbers of counts which differed by one (Figure 6.1) and, because tropical sardines such as *S. lemuru* are typically short-lived, this difference was considered to be significant. For both the same reader and for the different readers there was a tendency for counts to differ in the negative direction. This resulted from the second reader generally counting fewer rings in the third reading of the scales. There was 43.2 per cent agreement for the second and third readings by the same reader, but only 17.15 per cent agreement between two readers. The average percentage error (APE) (Beamish & Fournier 1981) measure also indicates a high rate of disagreement for counts of scale rings. For some scales the difference between readings was as high as four.

Table 6.1 Summary table of ageing techniques for S. lemuru.

Method	Period covered	n	Agreement (%) and APE for 1 reader	Agreement (%) and APE for 2 readers	vB parameters (L_{inf}, k, t_0)	vB parameters (with larvae) (L_{inf}, k, t_0)	Age	Total annual mortality
Scales	1995	361	43.2, 39.1	17.1, 49.4	-	-	1-5	
Whole otoliths	1995-97	1336	40.4, 19.7	-	173.4, 0.42, -1.78	164.1, 0.86, -0.06	1-7	1995: 1.26 1996: 0.68 1997: 1.05
Sectioned otoliths	1995, 1996	899	67.0, 10.3	32.8, 21.0	172.6, 0.97, -1.01	166.7, 0.60, 0.03	1-6	1995:1.48 1996:1.32
Lengths	1990-98	7040	-	-	179, 1.52 $R_n = 0.195$	178, 1.0 $R_n = 0.158$	0-3	1-2 yr: 3.02 2-4 yr: 1.59
Otolith weights	1995-97	4665	-	-	-	-	2-6	-

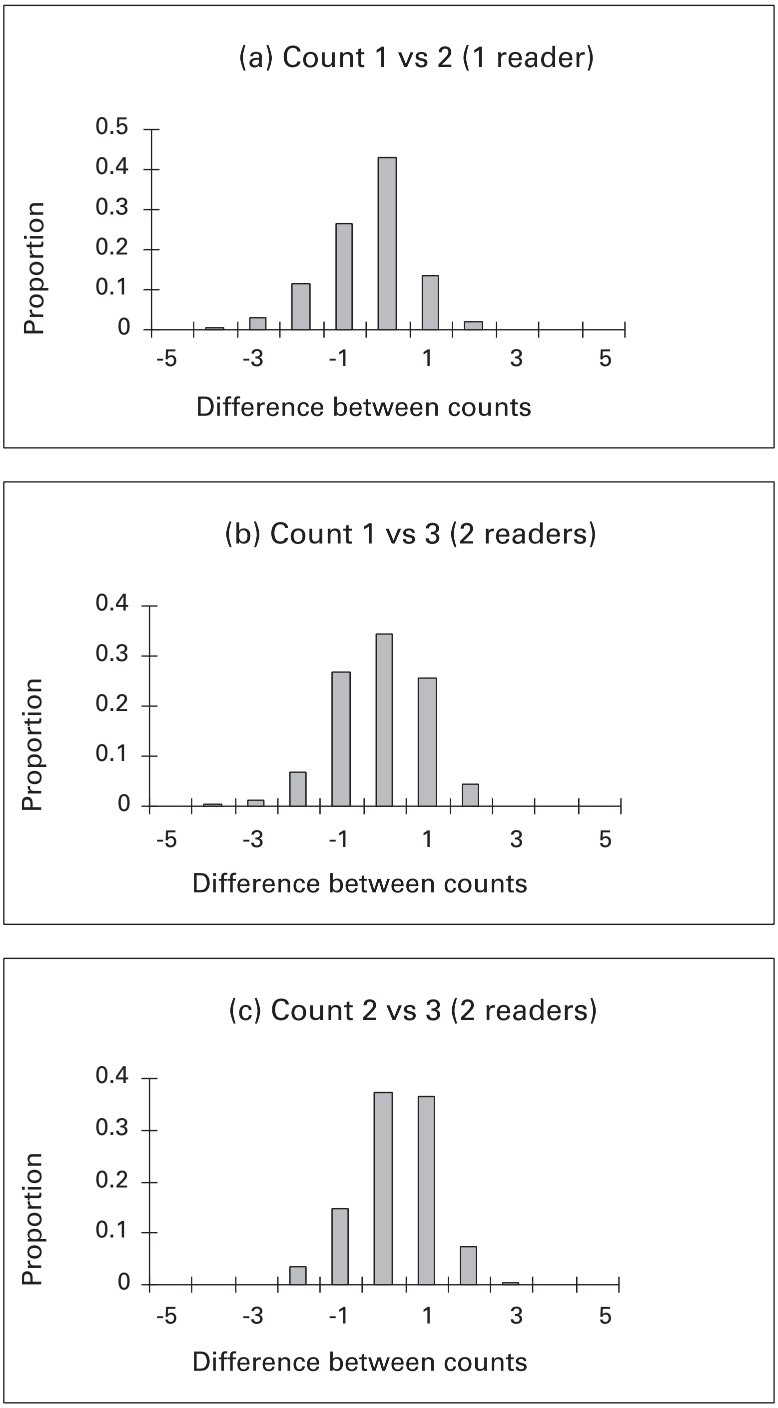


Figure 6.1 Discrepancies between three readings by two readers for counts of rings on the scales of *S. lemuru*.

Ageing of *S. lemuru* using scales suggested that the commercial catch consisted of fish aged between one and five years, with full recruitment at two years of age and the catch largely comprising two- and three-year-olds (Figure 6.2).

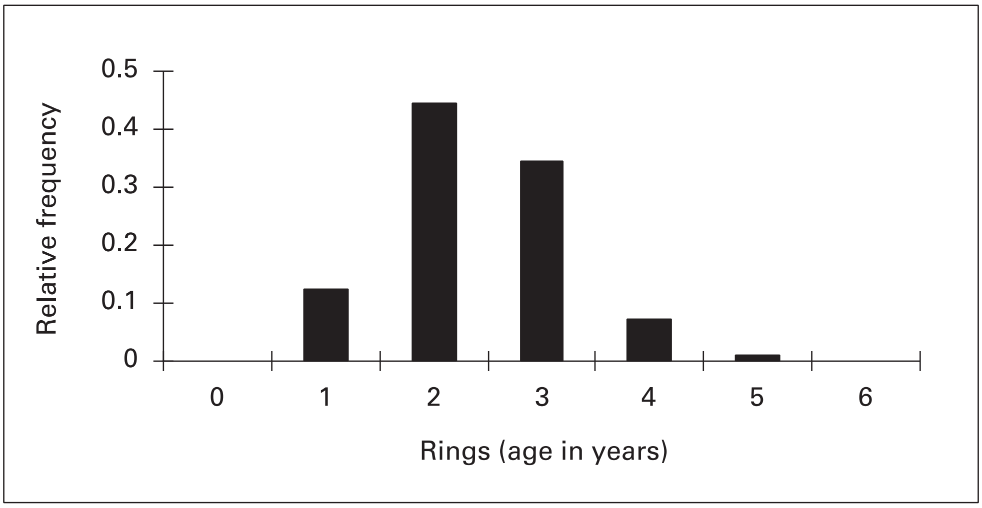
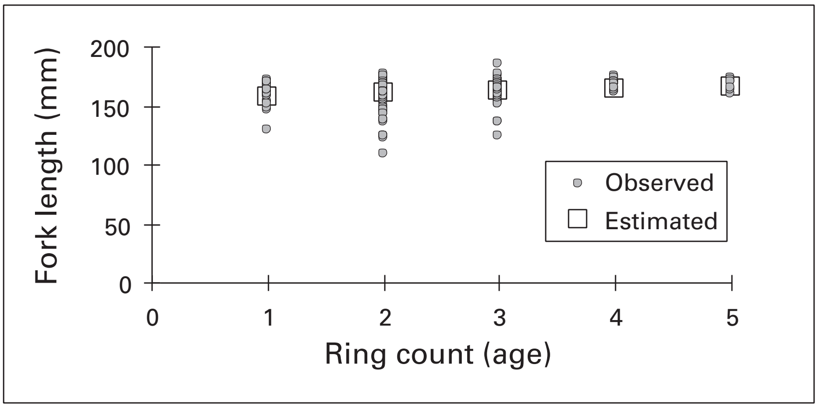


Figure 6.2 Age structure of *S. lemuru* off Geraldton indicated by the scale rings.

A very poor fit was obtained for the data using a von Bertalanffy growth function (Figure 6.3a, t_0 = -5.0, i.e. the lower constraint). This curve employed much of the data obtained, including scales for which consecutive counts differed, since the use of those ring-counts with zero discrepancies provided insufficient data (Figure 6.3b).

However, inclusion of this data still failed to provide much contrast in the relationship between length and estimated age, with the length for each age from one to five years varying little. Thus, counts of scale rings suggested that fish of each ring class were around 160 mm FL (Figure 6.3a), which was probably due, in part, to the more substantial scale-loss incurred by smaller fish. These results indicated that scales were of limited use for ageing *S. lemuru* and this technique was not investigated further.

(a)



(b)

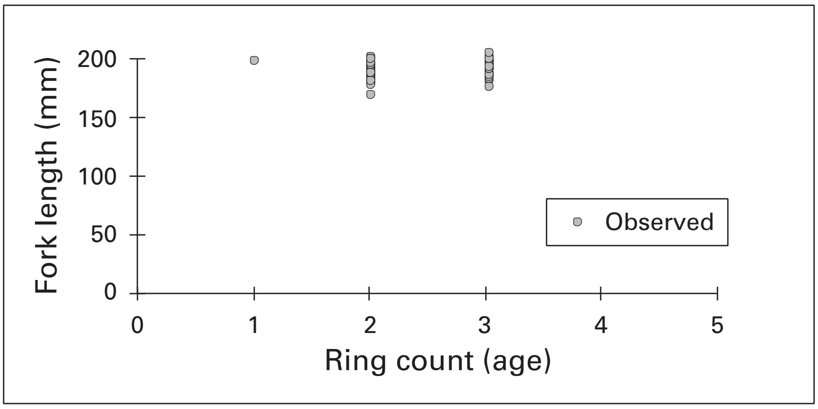


Figure 6.3 (a) von Bertalanffy curve for *S. lemuru* based on counts of rings on scales which included discrepancies between successive counts. (b) Length versus age, with age estimated using only counts for which there were zero discrepancies.

6.3 Whole otoliths - translucent zones

Whole otoliths were examined from 2267 *S. lemuru* individuals from the Geraldton region. Translucent zones on whole otoliths were difficult to interpret consistently (see Figure 6.4). Repeatability of readings for otoliths was relatively poor with the overall level of agreement between the two counts only 40.4 per cent (Table 6.1). However, the APE of 19.7 per cent was substantially better than that for scales. Most unequal counts differed by only one or two, but some counts differed by up to five in either the positive and negative directions (Figure 6.5), indicating a high level of subjectivity in assessing increments on whole sagittae of *S. lemuru*. As was initially attempted with count-data from scales, due to the likelihood that *S. lemuru* is a short-lived species, ring counts of whole-otolith (and sectioned otoliths, see below) which differed were not considered in subsequent analyses unless otherwise indicated.

Although readings of sectioned otoliths resulted in a higher rate of agreement (see below), an assessment of the total time (i.e. processing and reading) taken to achieve an age estimate with zero discrepancies between successive counts was much shorter with whole otoliths. Thus, zero-discrepancy counts could be achieved for eight whole otoliths in an hour, whereas for sectioned otoliths this was only three, primarily due to the substantially longer preparation time for the latter. Therefore, more whole otoliths than sectioned otoliths were examined during this study.

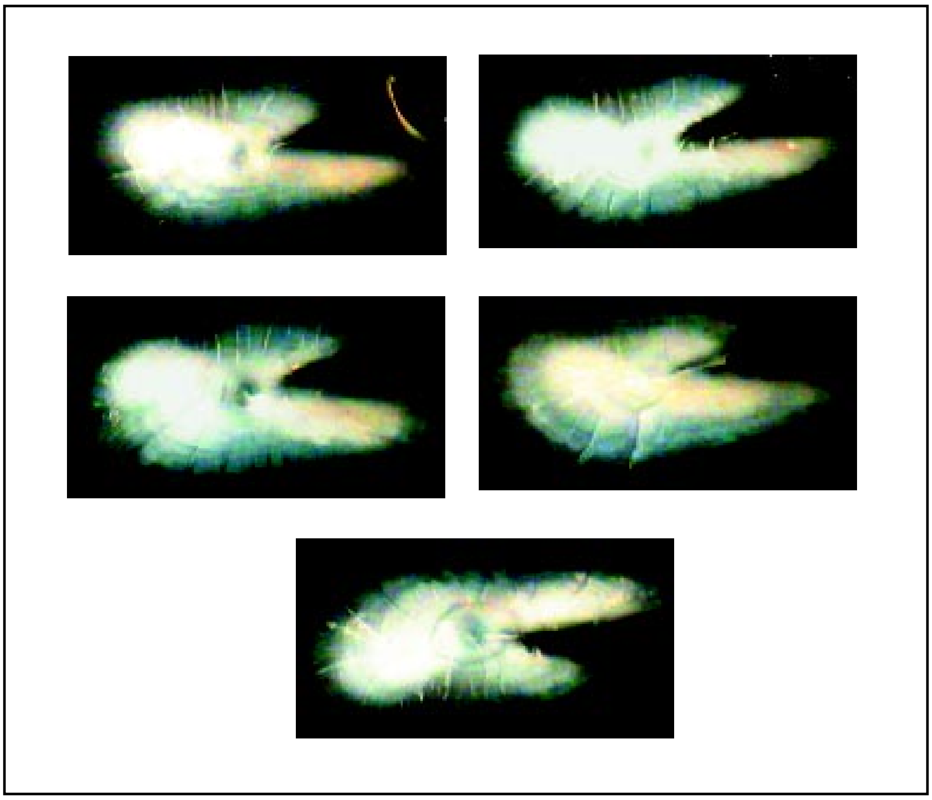


Figure 6.4 Photomicrographs of a random selection of whole otoliths of *S. lemuru*, mounted on black slides. These are shown here to indicate the poor contrast of translucent zones.

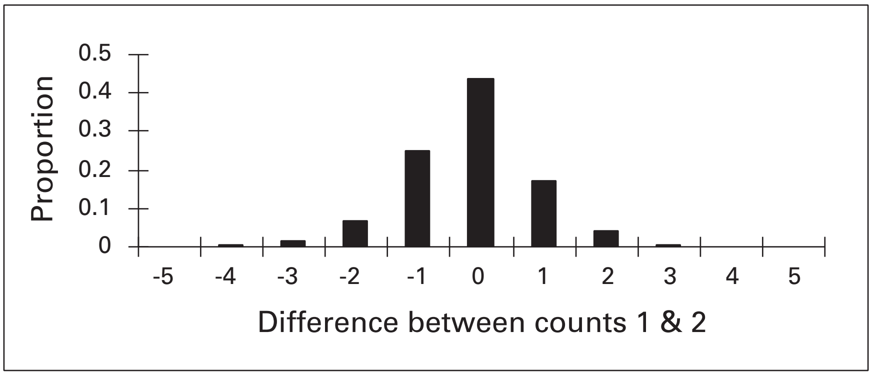


Figure 6.5 Discrepancies between readings for whole *S. lemuru* otoliths.

6.3.1 Marginal increments (MI)

Attempts to use the data available from the otolith readings to validate an annual periodicity of ring formation produced contradictory results. The problem of identifying translucent zones on whole otoliths was highlighted by the occurrence of MI values which exceeded 100 per cent, even when using only those otoliths for which there was no discrepancy between counts. Furthermore, there was an extremely poor relationship between estimates of MI from successive readings of whole otoliths by the same reader (Figure 6.6).

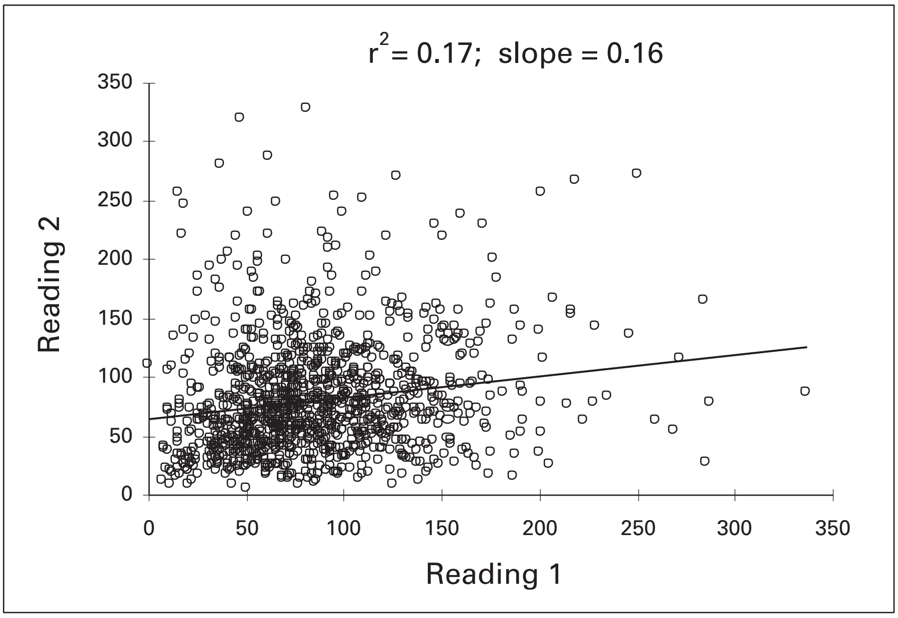


Figure 6.6 Relationship between marginal increment for consecutive readings of the same otoliths.

Only 24.8 per cent of the coefficients of variation (CVs) for successive estimates of MI fell below the 10 per cent level, with 47.3 per cent falling within the 20 per cent level. Mean monthly MIs from data corresponding to these two CV levels are shown in Figure 6.7. Mean monthly MIs provided little evidence of an annual periodicity in the formation of translucent zones on the sagittae of *S. lemuru*. Given the extremely poor relationship between estimates of MI from successive counts of otolith rings, this was not surprising. Due to the difficulty of identifying translucent zones there was no value investigating monthly proportions of otoliths with new edges (e.g. where MI < 10%).

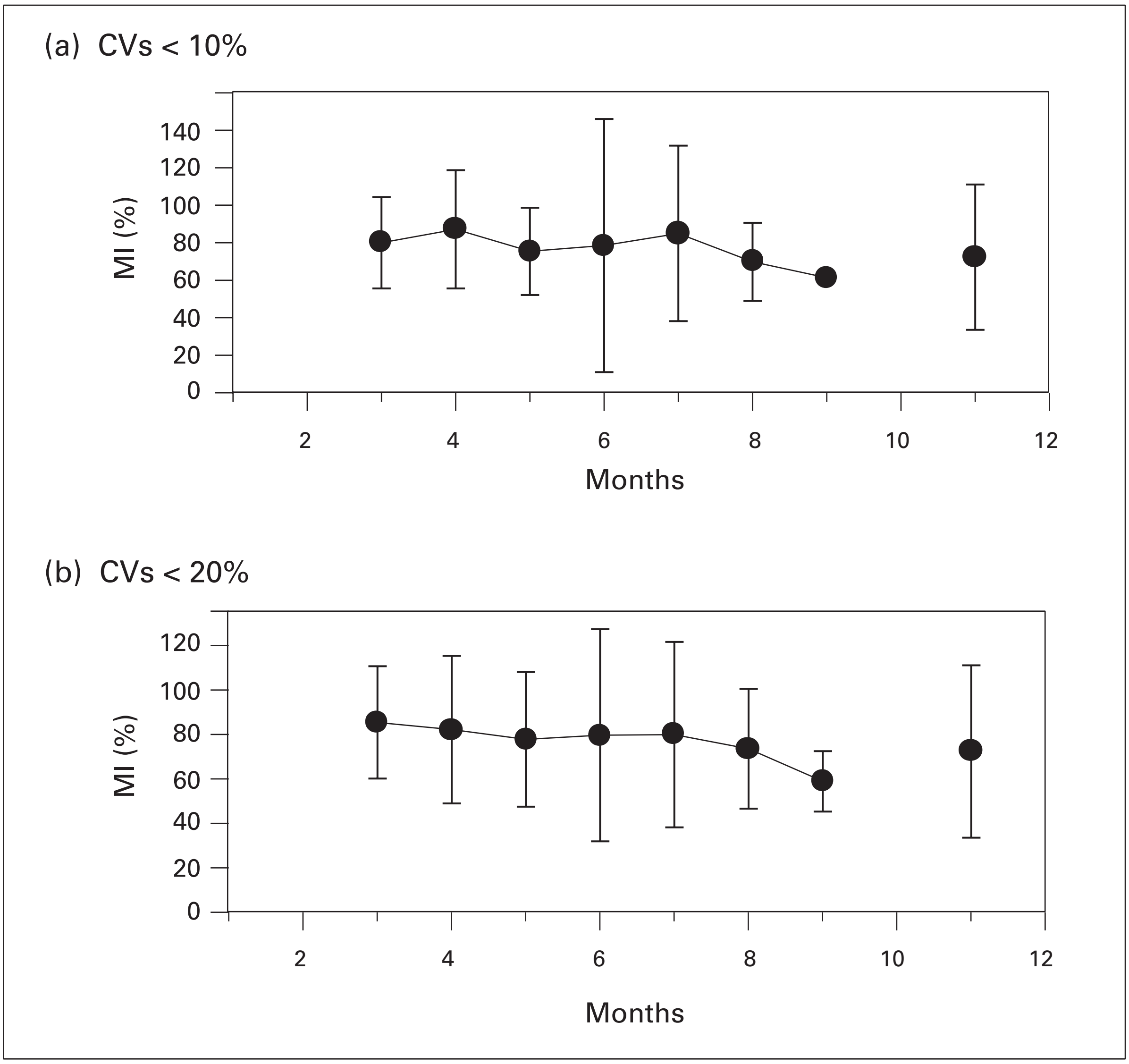


Figure 6.7 Mean monthly marginal increments (±SD) of those otoliths for which the CVs between consecutive counts were (a) less than 10% and (b) less than 20%.

6.3.2 Opaque edges (OE)

In an attempt to determine if new rings (opaque area) formed on sagittae at a particular time of year, otoliths were allocated to classes having either an opaque or a translucent edge. However, this method of checking for annual periodicity in ring formation also proved to be difficult, with very poor repeatability between successive assessments of the otoliths (Figure 6.8). These results were therefore not analysed further.

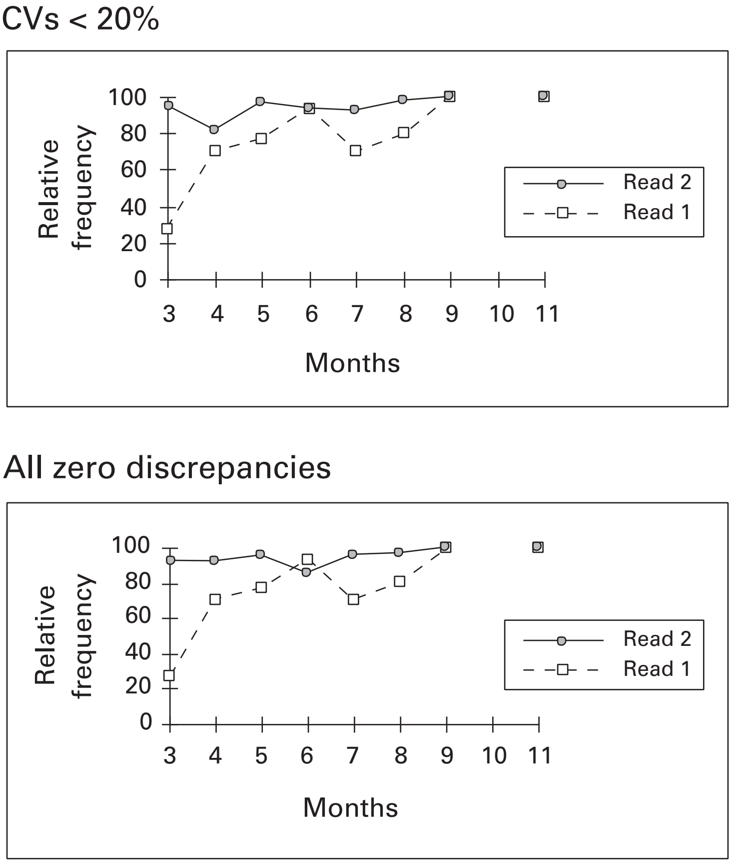


Figure 6.8 Relative frequency of otoliths with opaque margins for two readings of whole otoliths. (a) Those otoliths for which the CVs of successive assessments of marginal increment were less than 20 per cent. (b) All otoliths for which there was no discrepancy between counts.

6.3.3 Age determination using translucent zones on whole otoliths

Based on GSIs and data from plankton surveys, a birthdate of January was chosen for *S. lemuru*. Winter was chosen as the period of slower growth, when water temperatures are at their annual minima. Thus, time of formation of the first translucent zone was chosen to be July. Because it was unlikely that the otolith of a fast growing 0+ sardine would develop a visible translucent zone during its first winter (i.e. at an age of six months), *S. lemuru* off Geraldton would be 18 months old at the formation time of their first translucent zone. Thus, those classified with having one ring may be up to 30 months old (e.g. Jan 95-Jan 96-Jul 97, with the only visible translucent zone being that which formed in Jul 97). These criteria were used to estimate age (in months) of individual fish.

Sardinella lemuru in the Bali Strait have been estimated to reach 12.2 cm FL and 16.8 cm FL at ages 1 and 2 respectively. In Bali Strait temperature (25.5-30.4°C, Ritterbush 1975) is typically several degrees warmer than the waters off Geraldton (19.2-22.9°C, Pearce 1997) and there are also significantly higher nutrient levels for the former via much greater river runoff and regular upwelling. Because higher temperature and higher levels of nutrients would be expected to manifest themselves as faster growth, it is very likely that *S. lemuru* from the Geraldton region would have a lower growth rate than those from Bali Strait. Thus, size at a given age would also be less than for *S. lemuru* from Bali Strait. Therefore, it was assumed that the 120-130 mm size class (size at recruitment from length frequency analysis) of *S. lemuru* from Geelvink Channel were two years old rather than one year old.

Both fork length and otolith weight (two objective measures) increased for each successive age interval (Figure 6.9a and b), indicating that the ageing method was reasonable (Jones & Wells 1998). Similar relationships were obtained for otolith weight and estimated age when males and females were examined separately (Figure 6.10a and c). However the relationship between length and estimated age was less convincing for each sex, producing counterintuitive results (Figure 6.10b and d).

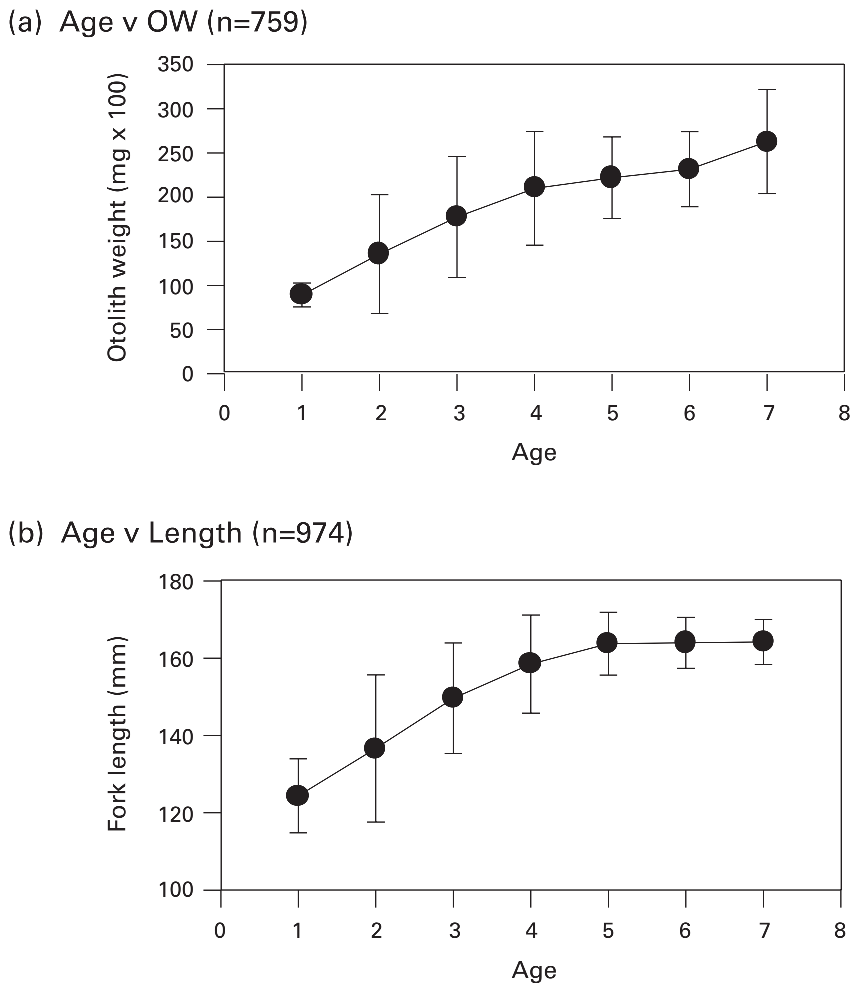


Figure 6.9 Relationship between mean age (±SD) estimated using whole otoliths and (a) otolith weight and (b) fork length.

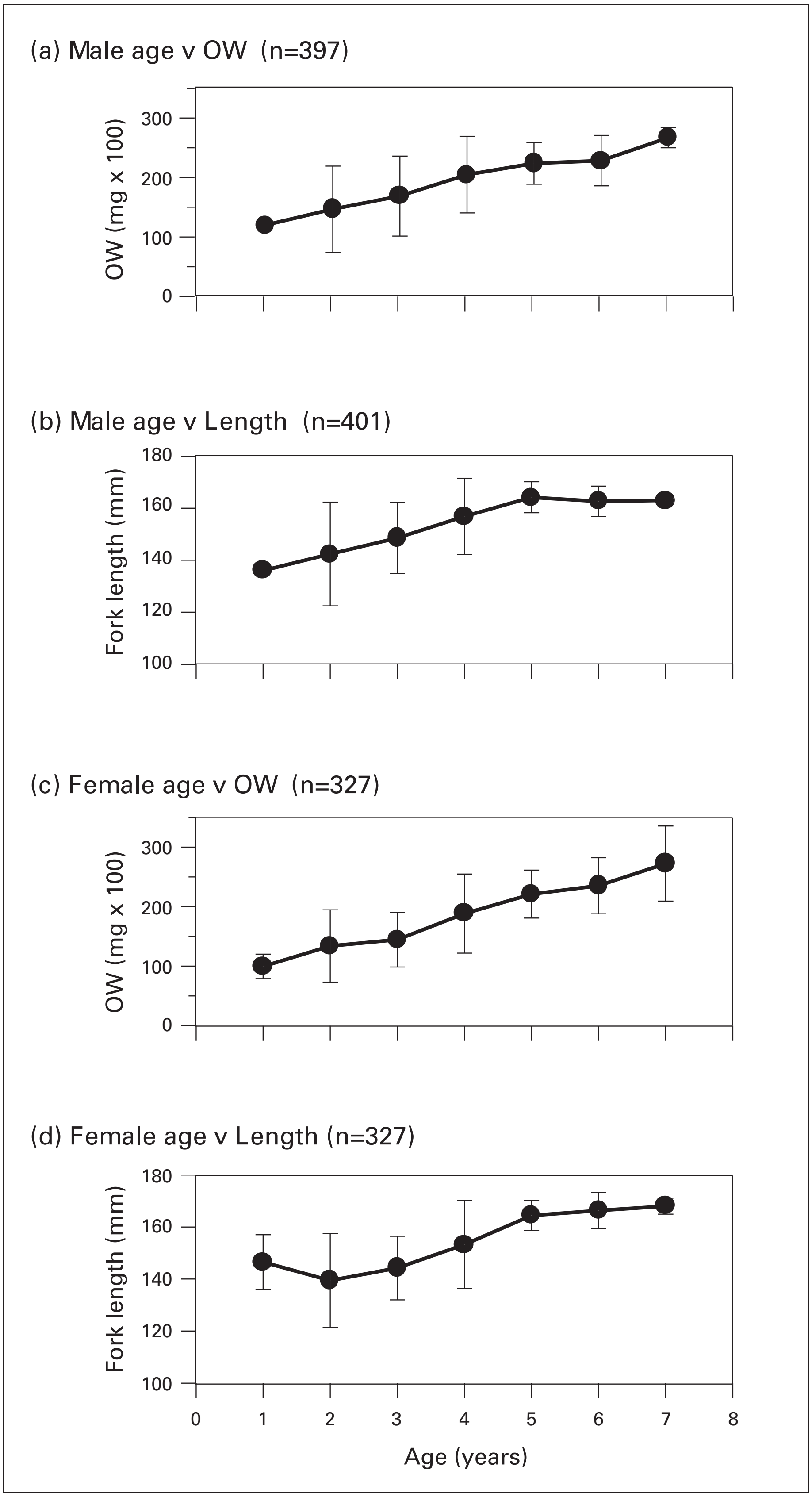


Figure 6.10 Relationship between age estimated using whole otoliths and mean (±SD) otolith weight (OW) and mean (±SD) fork length for males and females.

Counts of translucent zones on otoliths suggested that the *S. lemuru* live to six or seven years and that the commercial catch was dominated by fish estimated to be between three and five years old (Figure 6.11), which is two years older than estimated from scales.

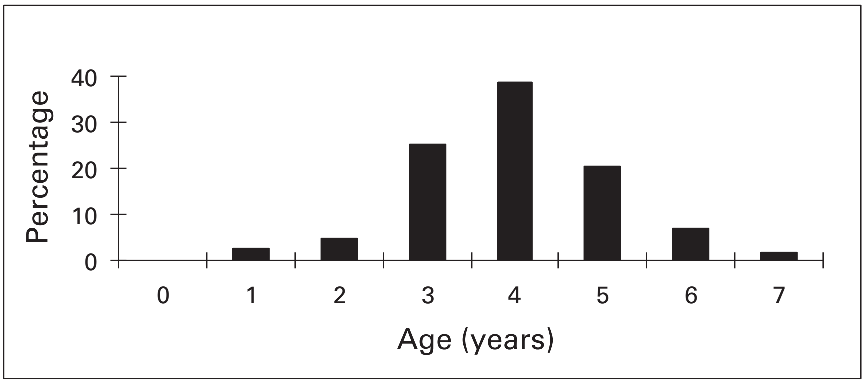
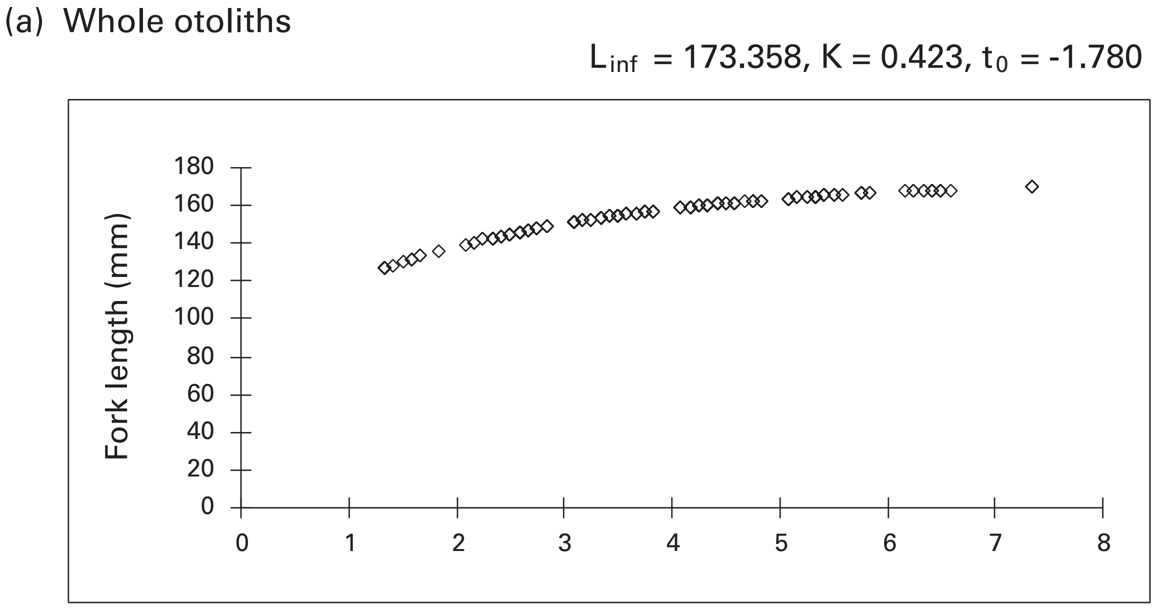


Figure 6.11 Combined age structure (relative frequency) for 1995 to 1997 based on whole otoliths.

However, t_0 with the fitted vBGF curve (Figure 6.12a**)** was excessively large (-1.78) for a species with a maximum age of only six or seven years. Also, the apparent growth rate had not reached the asymptote by age eight, which would be highly unusual for a sardine. This poor aspect of the vBGF fit was probably partly due to absence of fish less than 120 mm FL in the samples. Age-length data for larval *S. lemuru* caught in the Geraldton region (see Micro-increments section below) were used to supplement the gap at the lower end of the growth curve.

The addition of the data for larval fish resulted in a more acceptable growth curve, with t_0 equal to -0.06 years (Figure 6.12b). However, the inclusion of this data also caused L_{inf} to decrease from 173.4 mm FL to 164.1 mm FL (Table 6.1).



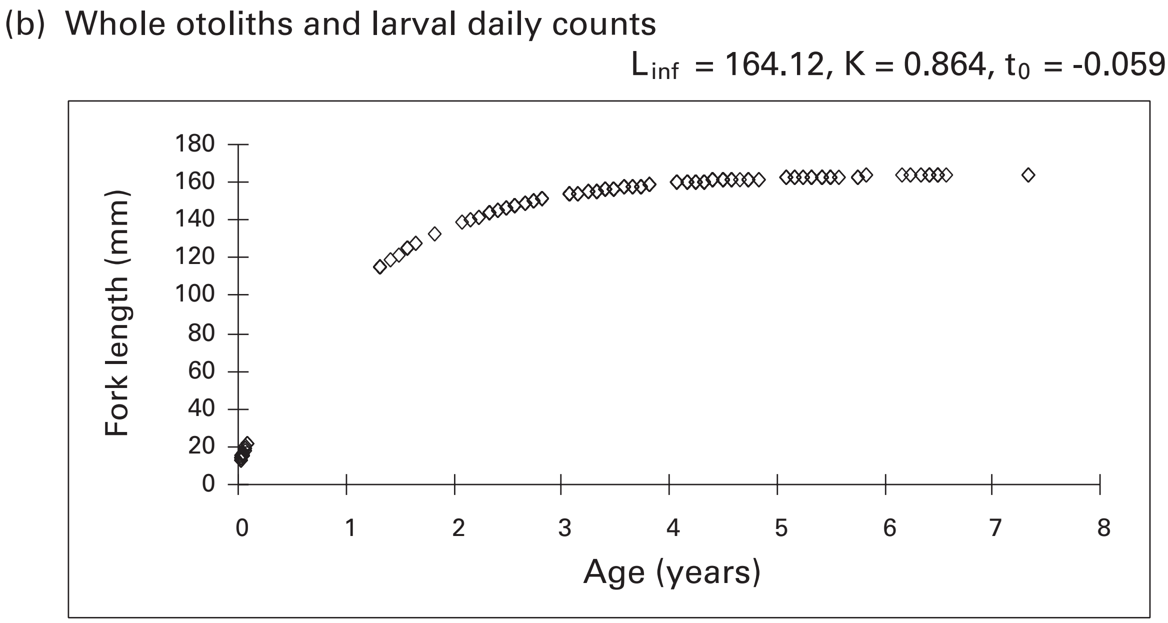


Figure 6.12 von Bertalanffy growth curves for *S. lemuru* aged using the whole otolith method (a) with and (b) without data for larval fish.

Relative age structures of catches for 1995-1997 are shown in Figure 6.13. Annual catch-at-age curves (Figs 6.14) were produced using numbers of fish in each age class, estimated using monthly proportions of each age class, average weight of an individual fish in each month and the total catch in each month. In 1995, the catch predominantly consisted of three- and four-year-olds. Recruitment was represented by two- and three-year-olds, with full recruitment by age four. The 1996 catch predominantly consisted of four- and five-year-olds, with much fewer two- and three-year-olds. This could initially be interpreted as a recruitment failure. However, yet another pattern was observed in 1997, with very few two-year-olds but large numbers of three-year-olds. Thus, as in 1995, the 1997 catch consisted mainly of three- and four-year-olds.

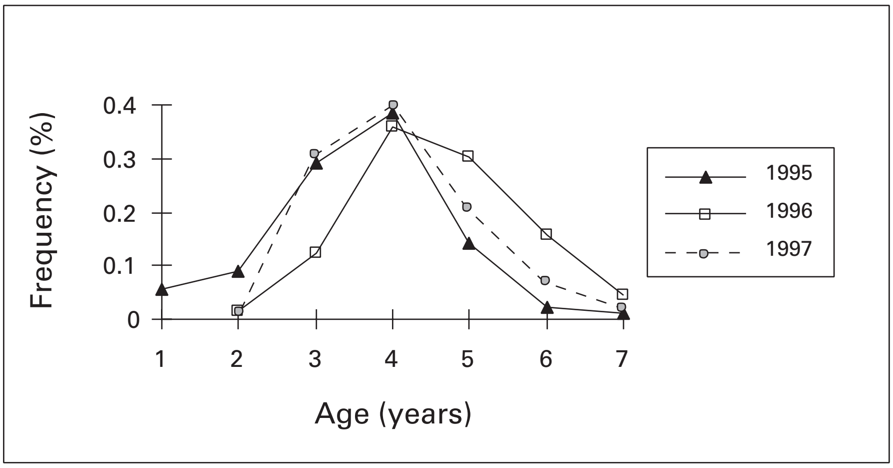


Figure 6.13 Relative age structure for each year (1995-1997) based on whole otoliths.

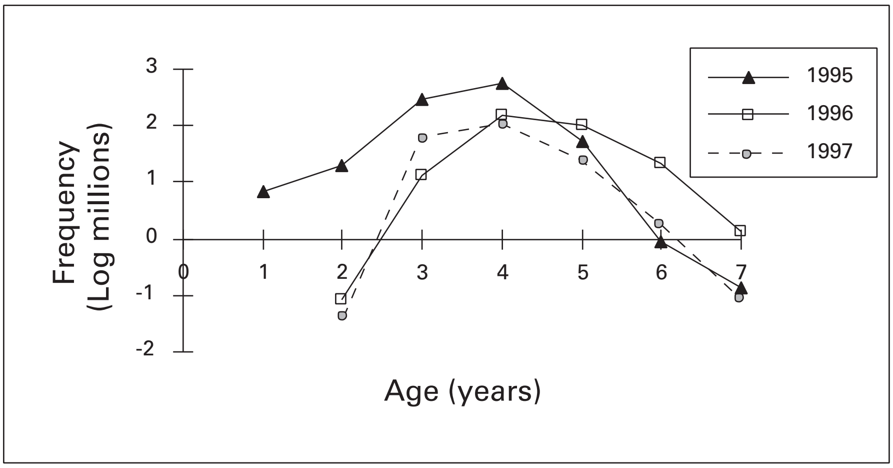


Figure 6.14 Annual catch-at-age curves each year (1995-1997) based on whole otoliths.

Total annual mortalities for 1995, 1996 and 1997 were estimated from the regressions of fully recruited age classes (ages 4-7) against abundance (log millions). Total annual mortality varied from 0.68 to 1.26 for the years studied (Table 6.1).

6.4 Sectioned otoliths

Translucent zones on sectioned otoliths were easier to identify (Figure 6.15) than those on whole otoliths. The level of agreement between different readings of translucent zones from sectioned otoliths by a single person was 67 per cent, with an APE of 10.3 (Figure 6.16, Table 6.1). However, when both readers were considered the agreement dropped to 32.8 per cent and the APE increased to 21.0 per cent. Double-blind readings of sectioned otoliths indicated that the consistent interpretation of translucent zones was difficult, as was the case with whole otoliths. Note that this was despite having guidelines and photographs of sectioned otoliths on hand specifically with the purpose of maintaining a level of consistency between different readers. Therefore, use of the second reader was not continued. As for whole otoliths, the levels of uncertainty in counting translucent zones on the sectioned otoliths of *S. lemuru*, and the strong likelihood that this species was short-lived, dictated that only those counts with zero discrepancy between readings were used to estimate age.

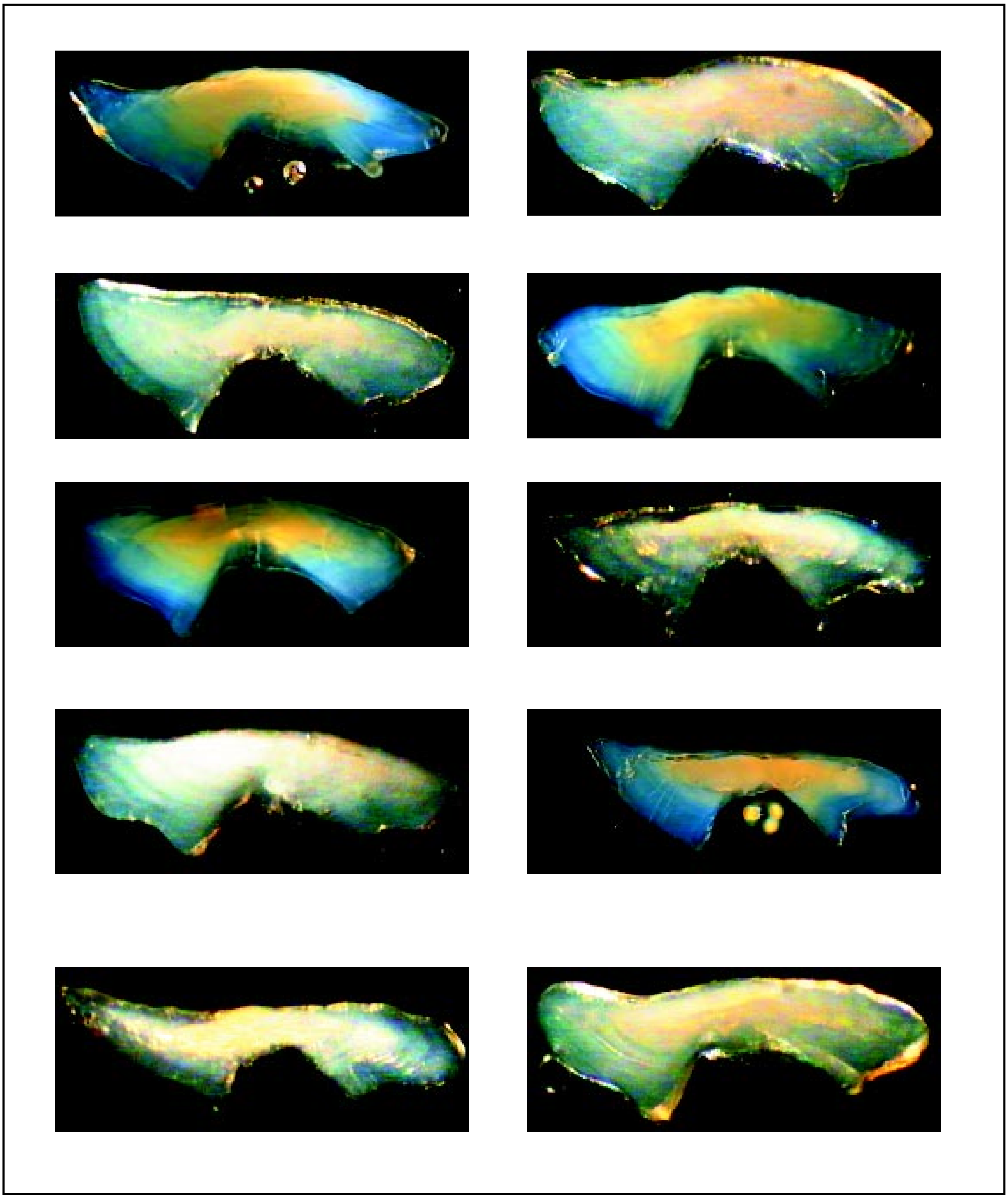


Figure 6.15 Photomicrographs of a random selection of sectioned *S. lemuru* otoliths.

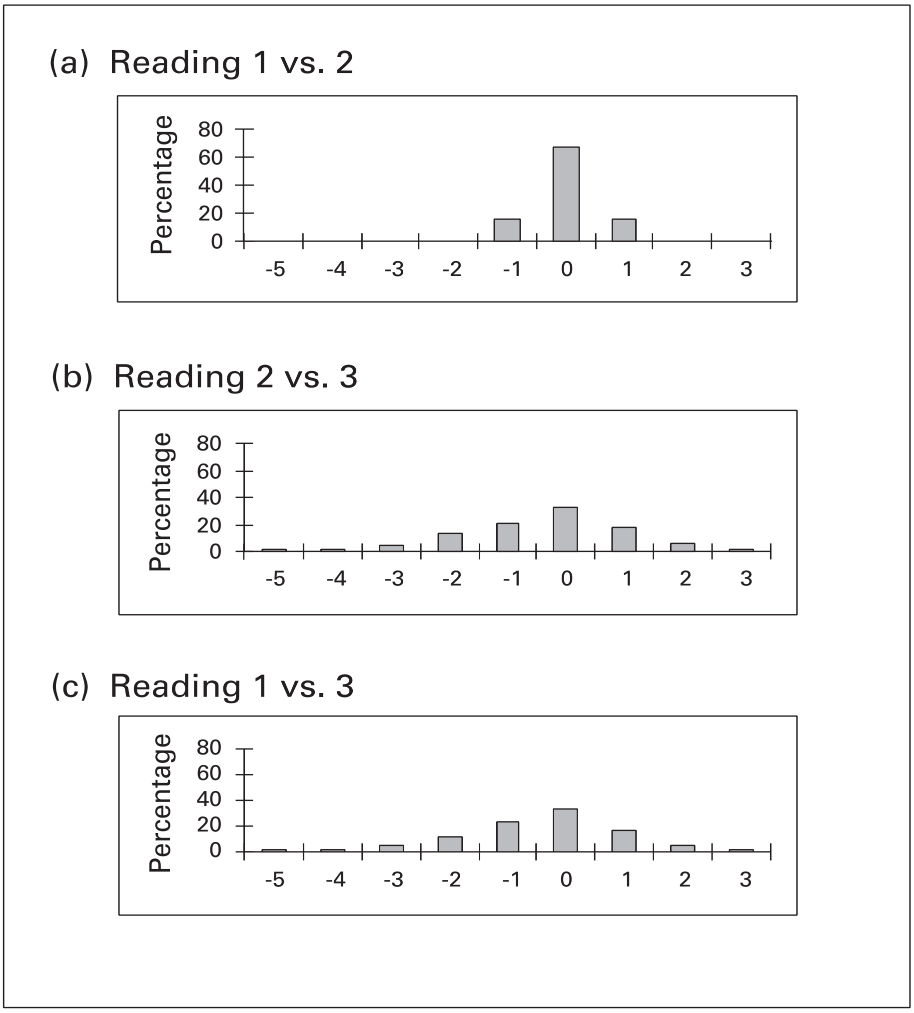
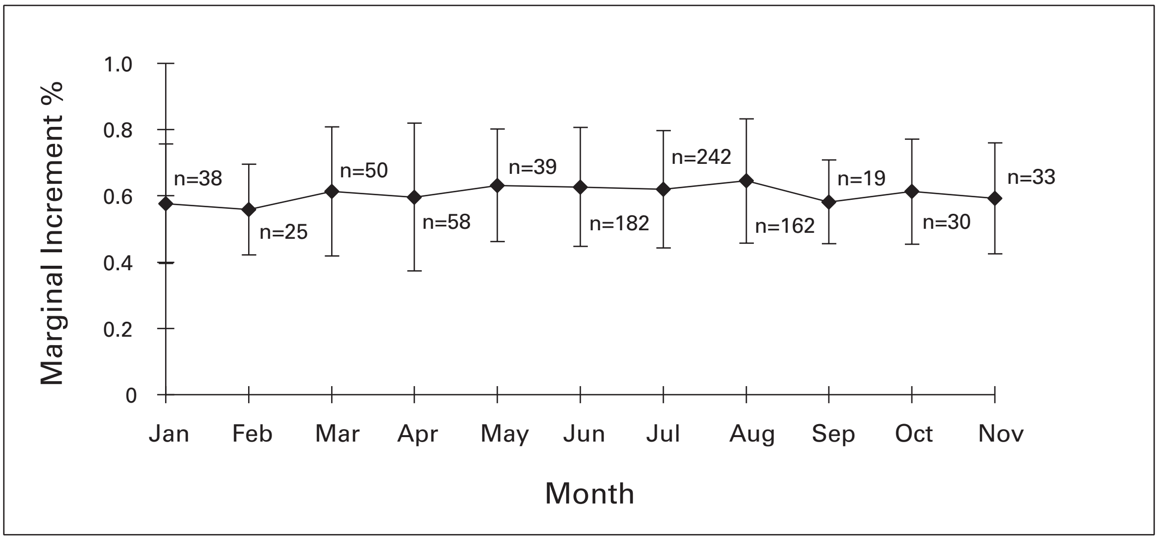


Figure 6.16 Discrepancies between three readings of sectioned otoliths.

Marginal increment analysis was attempted using sectioned otoliths. The 1995 data was supplemented with data from *S. lemuru* collected in the early 1990s so that values could be obtained for the "missing" months, particularly the summer months of January and February. However, as with whole otoliths, there was insufficient contrast in MI between months and excessive variation between successive readings for this method to indicate an annual periodicity in the formation of translucent zones (Figure 6.17a). Likewise, edge condition (opaque or clear) provided no evidence for annual periodicity of translucent zones (Figure 6.17b).

(a)



(b)

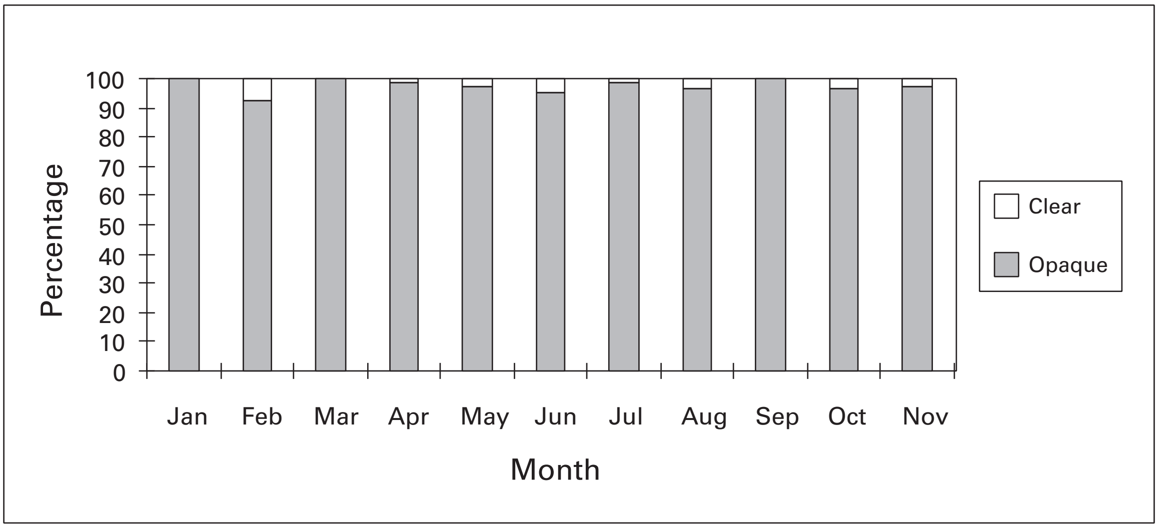


Figure 6.17 (a) Monthly marginal increments for sectioned otoliths (±SD).
(b) Monthly frequency of sectioned otoliths with opaque and clear edges.

Age (in months) was estimated using the same criteria as for whole otoliths (i.e. January spawning, with new translucent zone forming in July). As with whole otoliths, there were positive relationships between estimated age and both mean otolith weight and mean length (Figure 6.18a and b). The decrease in mean length between the ages of five and six years probably reflects both ageing errors in older fish and the small sample size of sectioned otoliths. Due to the latter, males and females were not examined separately.

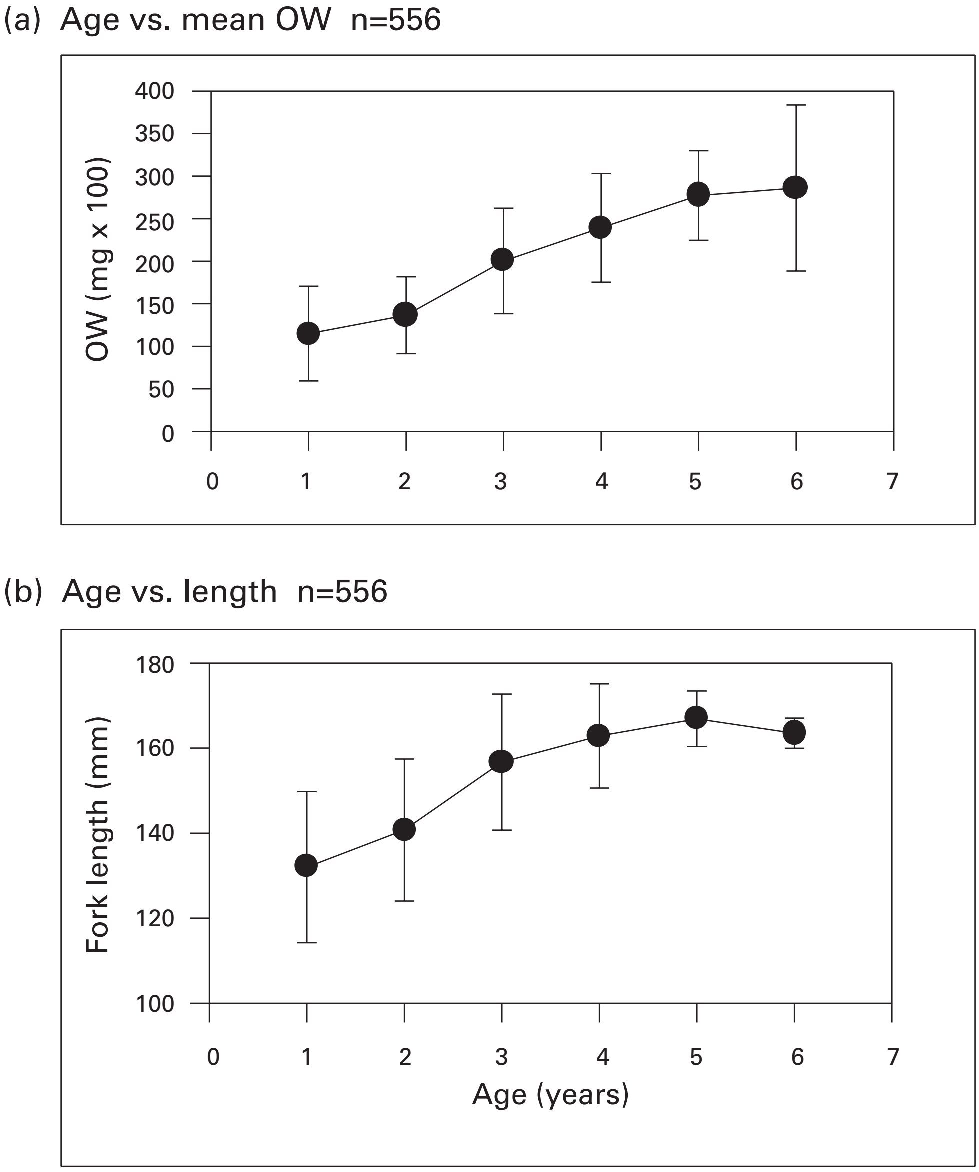


Figure 6.18 Relationships between age estimated using the sectioned otolith method and (a) mean otolith weight (±SD) and (b) mean length (±SD).

Estimated age ranged from one to six years using sectioned otoliths, with full recruitment to the fishery at three years and the catch largely comprising three- and four-year-olds (Figure 6.19). L_{inf} was estimated to be 172.6 mm FL, with k = 0.97 and t_0 = -1.006 years. When the data for larval fish were included L_{inf} decreased to 166.7 mm FL, k declined to 0.60 and t_0 moved much closer to zero (Figure 6.20, Table 6.1).

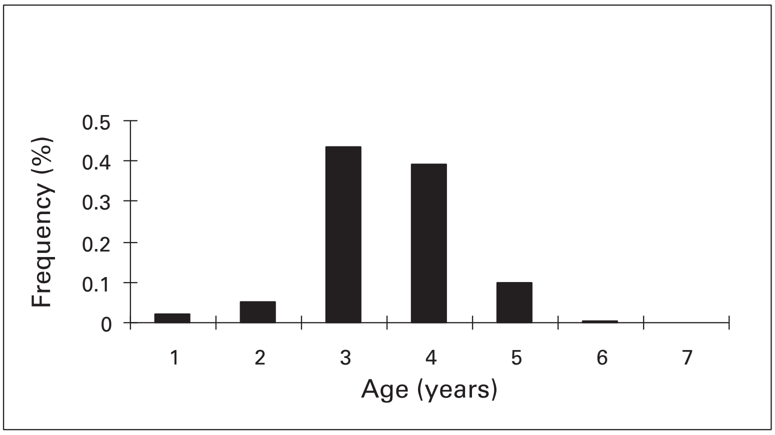
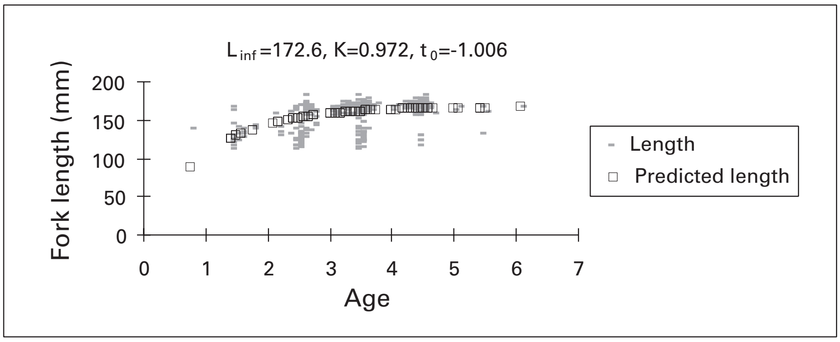


Figure 6.19 Relative age structure based on sectioned otoliths for *S. lemuru* caught off Geraldton.

(a) Sectioned otoliths



(b) Sectioned otoliths and larval data

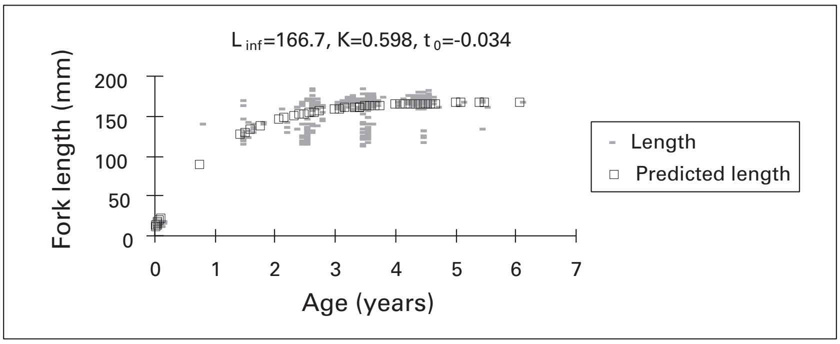


Figure 6.20 von Bertalanffy growth curves for *S. lemuru* aged using the sectioned otolith method (a) with and (b) without data for larval fish.

Relative proportions of age classes were essentially similar between 1995 and 1996, but with two key differences (Figure 6.21). Firstly, whereas the 1995 and 1996 catches both consisted predominantly of three- and four-year-olds, full recruitment occurred at age four in 1995 but at age three in 1996. Secondly, annual catch-at-age curves (Figure 6.22) indicate a substantial decrease in the abundance of two-year-olds in the 1996 catch.

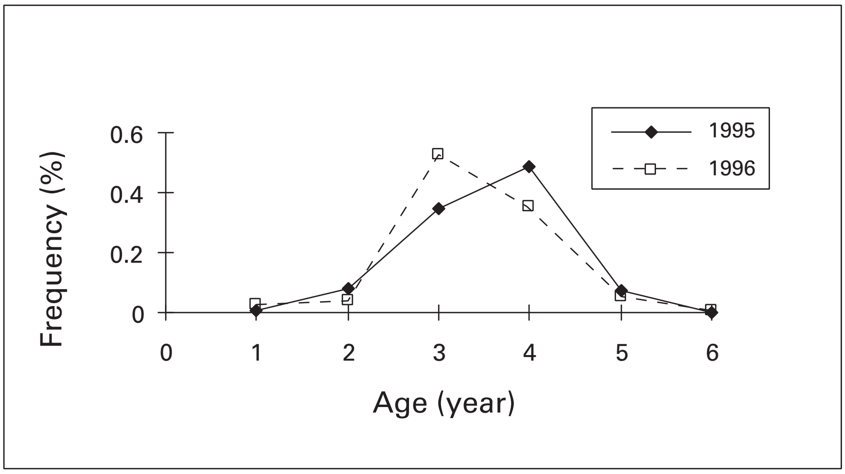


Figure 6.21 Relative age structure for 1995 and 1996 based on sectioned otoliths.

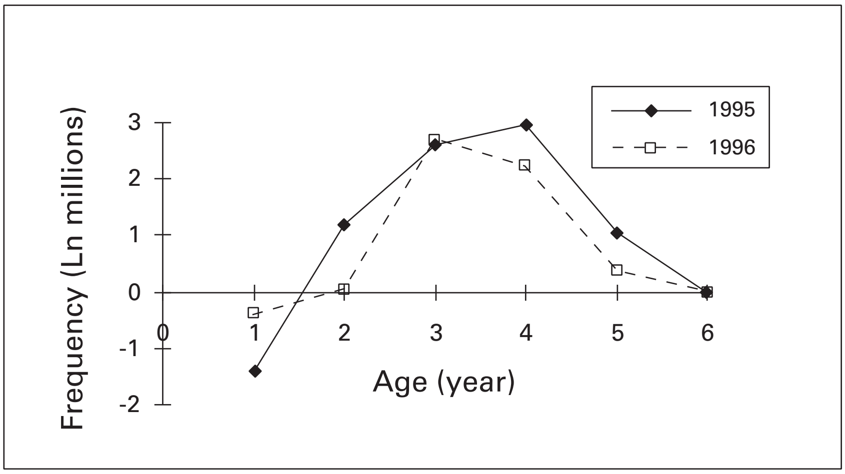


Figure 6.22 Annual catch-at-age curves for 1995 and 1996 based on sectioned otoliths

6.5 Otolith micro-increments

Micro-increments could be seen on otoliths from both larval and juvenile *S. lemuru* (Figure 6.23).

The relationship between number of micro-increments and length for juvenile and adult *S. lemuru* was very poor (Figure 6.24), with the counts obtained for the larger fish being much less than expected. Thus, the maximum count was only 322 days (145 mm FL). The counts obtained for *S. lemuru* in this study can confidently be disregarded and appear to seriously underestimate age. Dayaratne and Gjosaeter (1985) underestimated age of the related *Sardinella longiceps* from Sri

Lanka because using a light microscope enforces a restriction on resolution to increments wider than approximately 1 micron (Neilson 1992). Large errors in counts of micro-increments less than 1 micron are thus associated with the use of light microscopy.

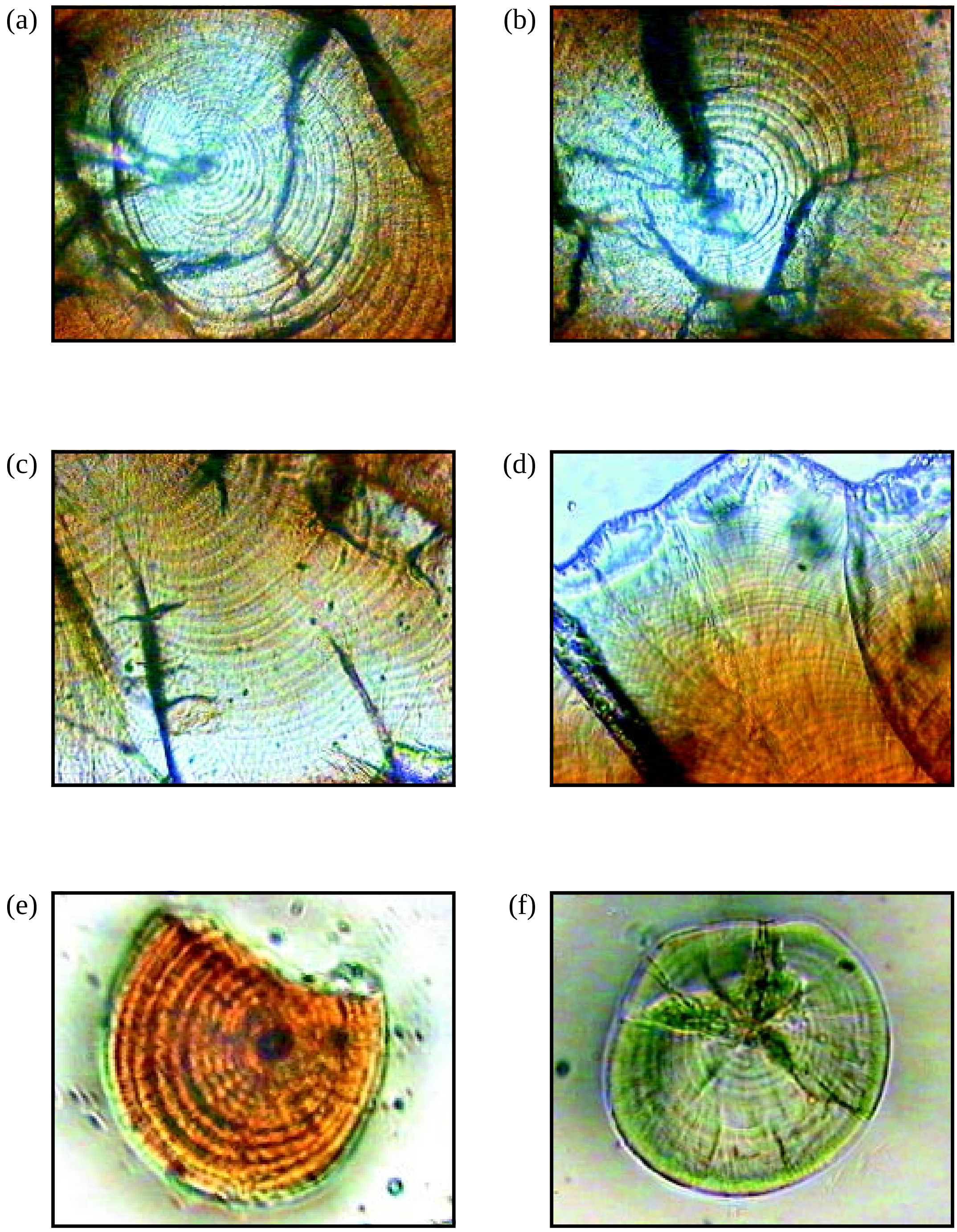


Figure 6.23 Micro-increments on the sagittae of *S. lemuru*.
(a) and (b): the core region of juveniles (400X magnification);
(c) and (d): a portion of the outer edge of juveniles (400X magnification);
(e) and (f): whole otoliths from larval specimens (400X magnification).

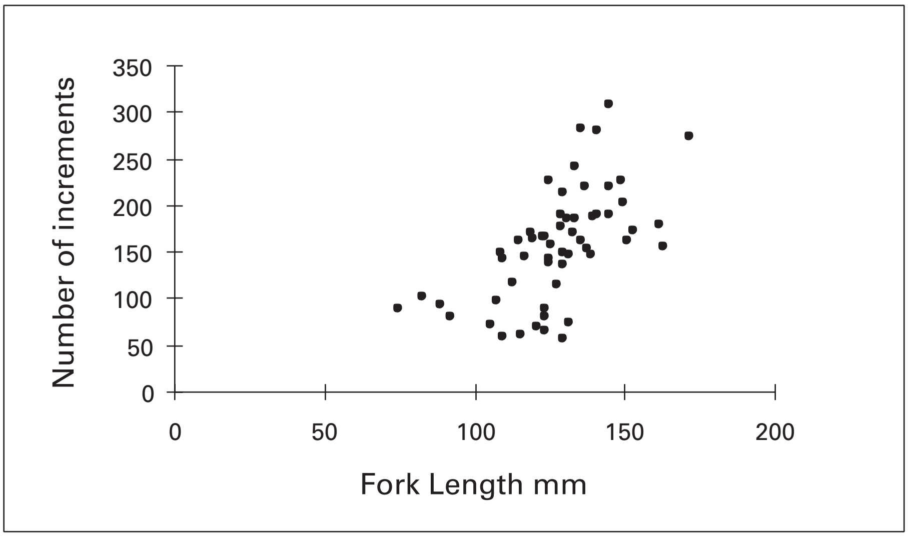


Figure 6.24 Counts of micro-increments on otoliths of juvenile and adult *S. lemuru.*

Counts for larval otoliths where consecutive readings differed by more than 5% were discarded. *Sardinella lemuru* larvae in the length range of 9.6 to 20.3 mm SL were estimated to be 11-39 days old. The counts for larval otoliths (Figure 6.25), which are inherently less difficult to read due to their smaller size and relatively fast growth, also suggest that the counts for juveniles and adults grossly underestimated age. As is typical of studies not focused on larval growth dynamics, the periodicity of increments on larval otoliths was not validated. However, the estimated ages of larvae collected in March, indicate a hatching times which fall within the summer spawning period. Furthermore, the widths of the increments counted on the larval otoliths (Figure 6.26) are in the same range as those recorded for other larval clupeids (e.g.Thorrold and Williams 1989; Folkvord *et al.* 1997; Ohshimo *et al.* 1997).

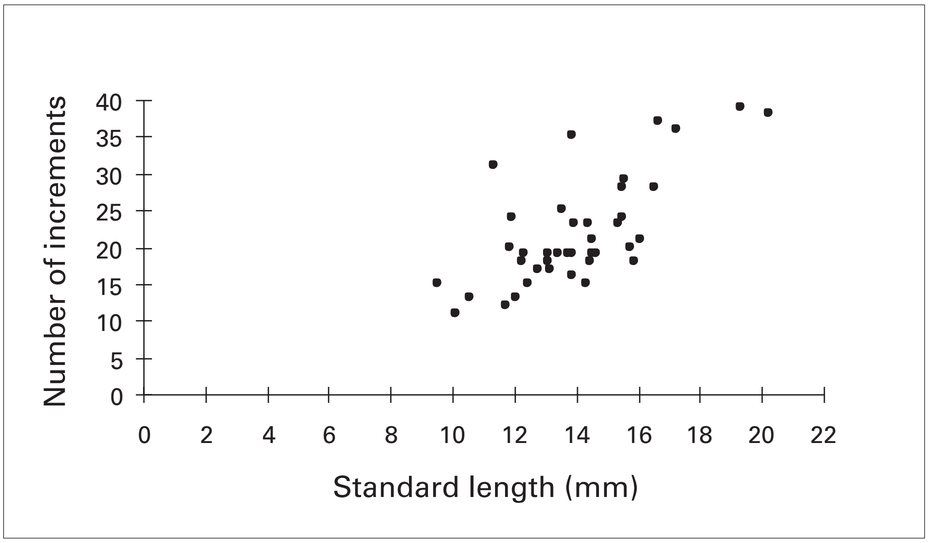


Figure 6.25 Counts of primary increments for larval *S. lemuru* caught in the Geraldton region.

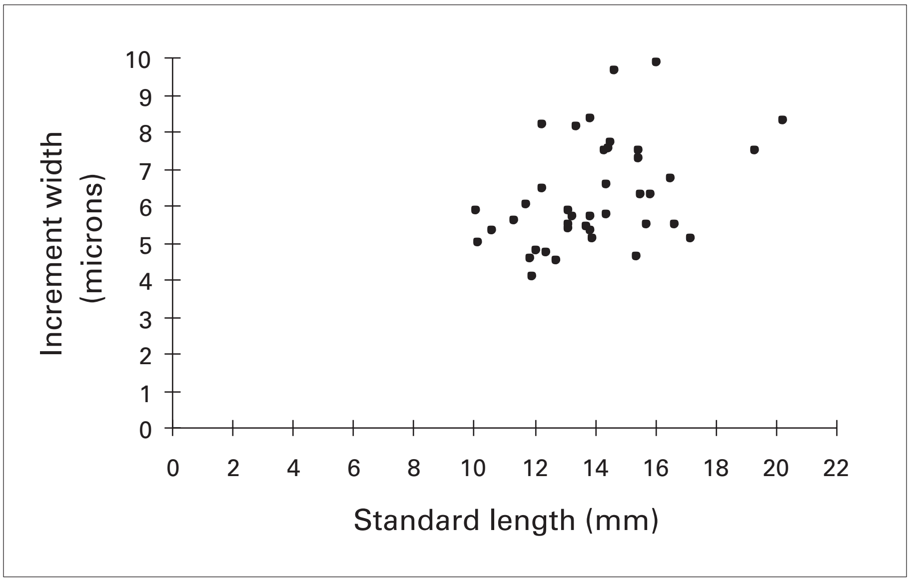


Figure 6.26 Mean width of micro-increments on larval *S. lemuru* otoliths.

6.6 Otolith weight

Otolith weight clearly increased with fish size (Figure 6.27), indicating that this measure is potentially useful for ageing *S. lemuru*. Likewise, otolith weight increased for successive age classes as determined from examination of whole and sectioned otoliths (Figures 6.9a and 6.18a).

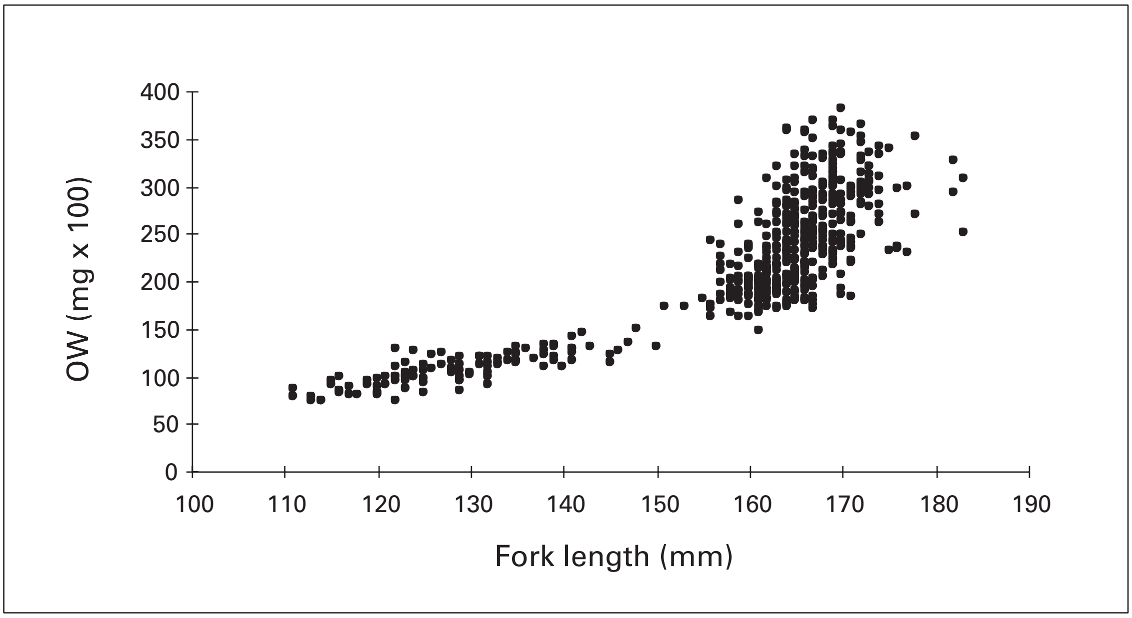


Figure 6.27 Relationship between fork length and otolith weight for *S. lemuru* from Geraldton.

Monthly otolith weight frequency

Monthly otolith weight frequency histograms were constructed for each year from 1991 to 1998 (Figure 6.28). Multiple (two or more) modes were discernible in some months, but mostly only for those whose sample size exceeded 100. Since the previous data suggested that *S. lemuru* live to more than two years, only those months which appeared to have multiple modes were subsequently analysed. While the number of modes which could be reasonably fitted to the observed distributions varied between two and five for those months where sample size exceeded 100 (Figure 6.28), clear separation of multiple modes occurred irregularly (e.g. May 1995, August 1995). For each month with a reasonable sample size and obvious multiple modes, objective identification of these modes was performed with Bhattacharya's (1967) method (using FiSAT). For each analysis, and for the annual data below, various combinations of modes were tried, with the experience gained on each run being used to improve subsequent fits, thereby reducing the statistical difference between the observed and predicted data. Only in May 1995 was the predicted series of modes not significantly different to the observed data (Figure 6.28, Table 6.2). In this case, six modes were identified, with the first four appearing to be quite well separated.

Table 6.2 Modes for those months and years for which the observed monthly or annual distributions of otolith weight frequencies were not significantly different ($p < 0.05$) from the predicted.

Data set	Modes (mg x 1000)					
May 1995	91	186	238	290	338	367	
1993	121	190	241	283	320	354	
1995	95	134	188	216	250	298	335
1996	98	204	301	360			

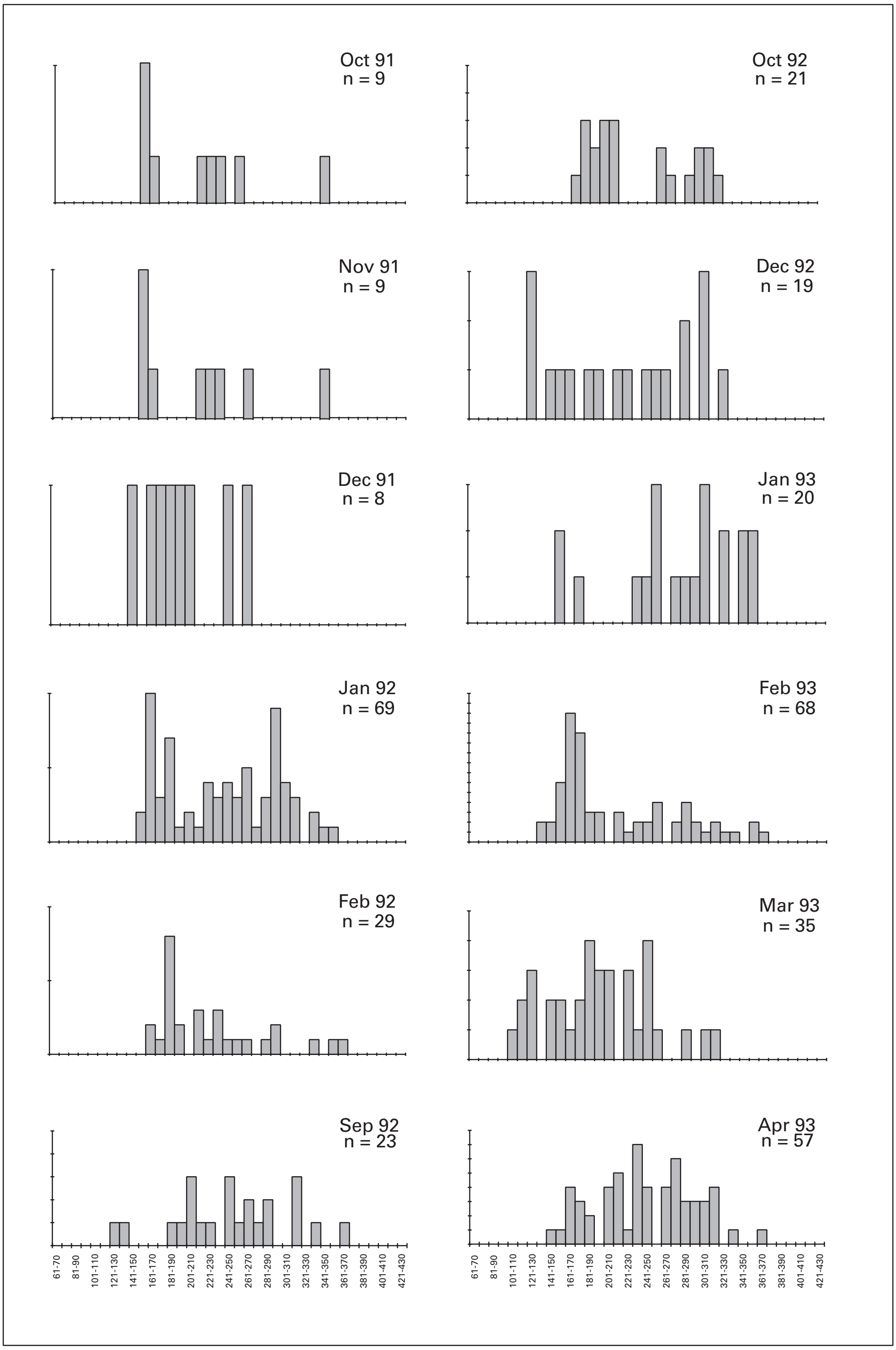


Figure 6.28 (and following 3 pages) Monthly otolith weight frequencies for *S. lemuru* from the Geraldton region 1991-1998.

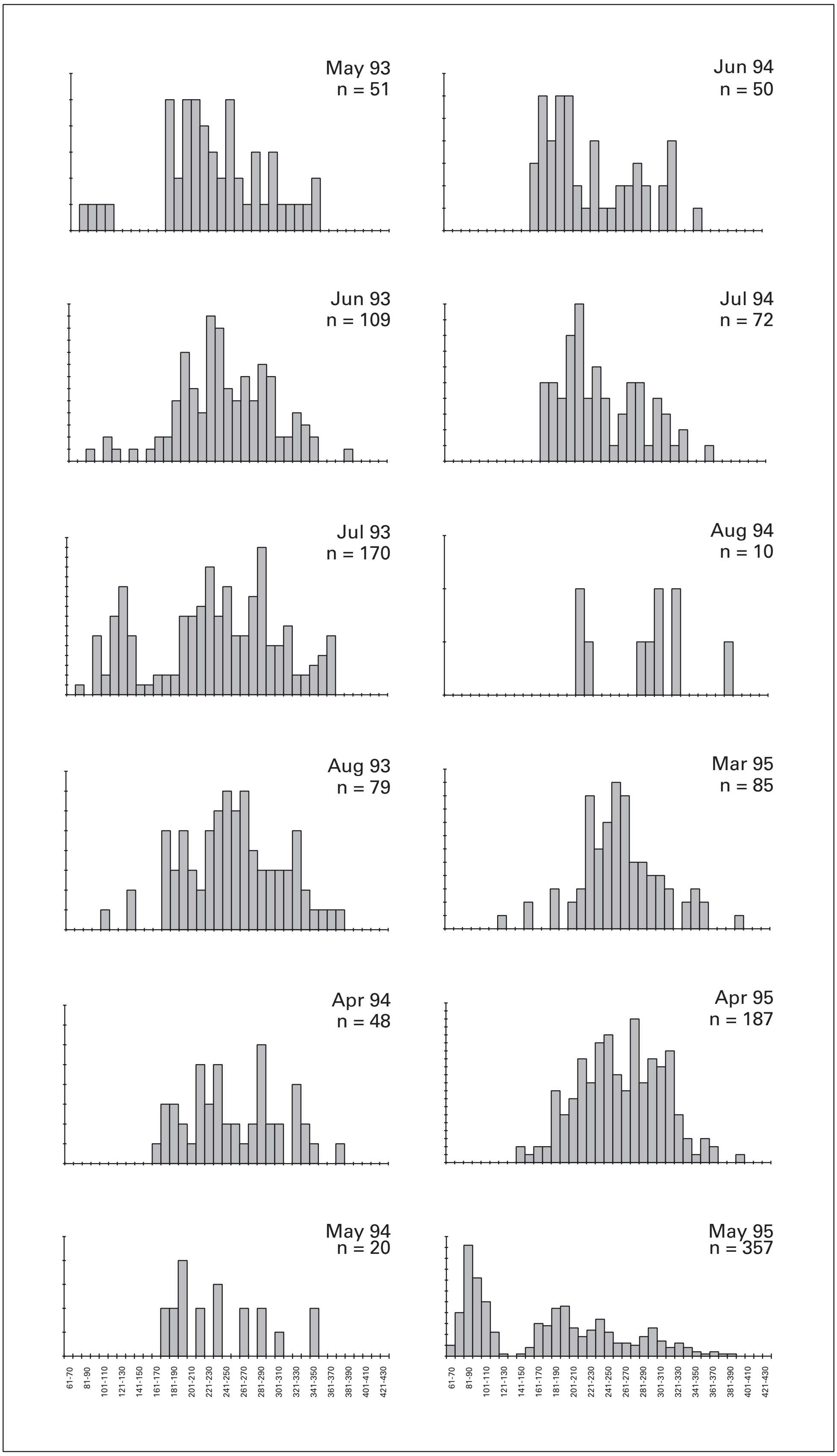


Figure 6.28 (cont'd).

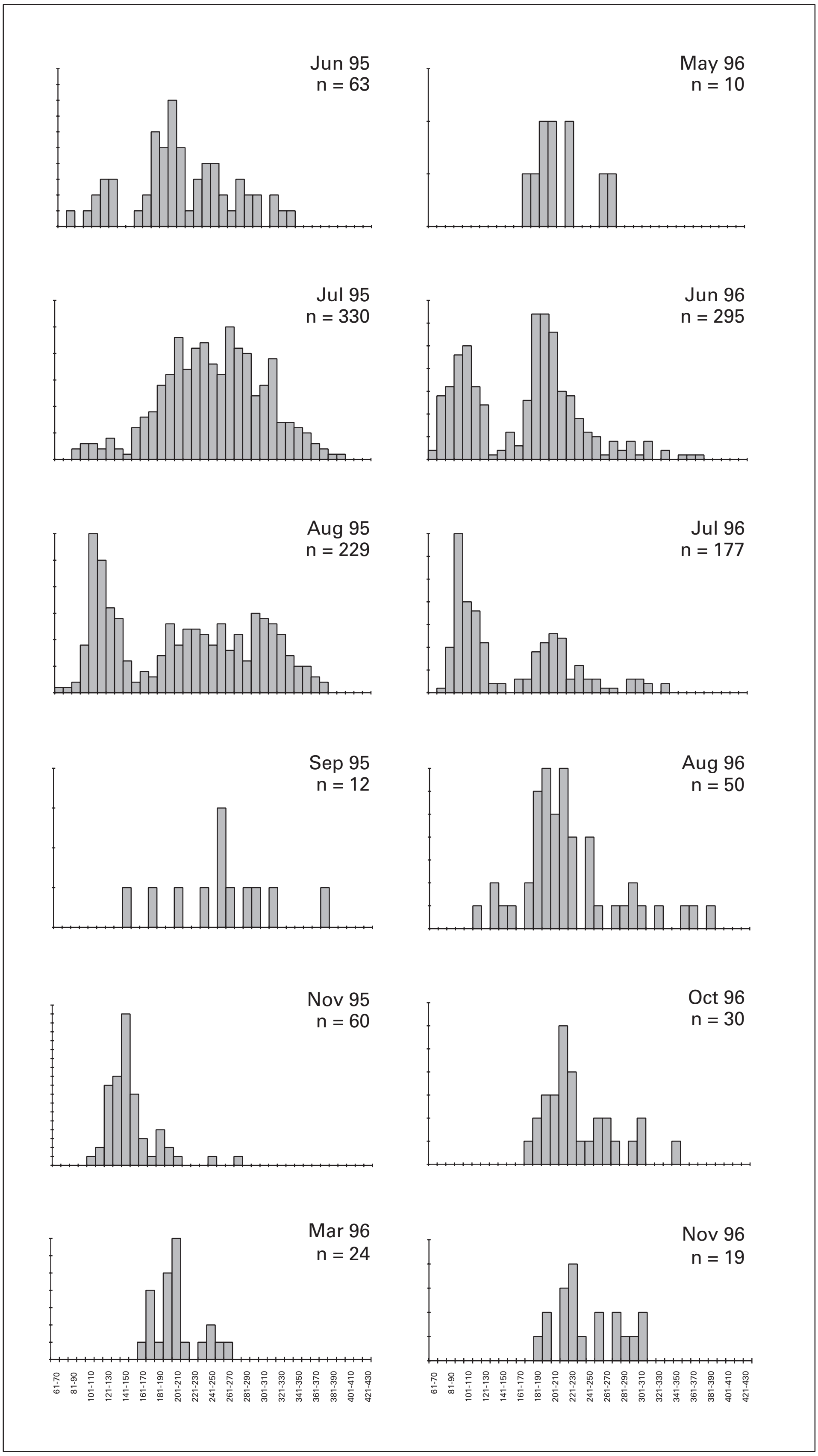


Figure 6.28 (cont'd).

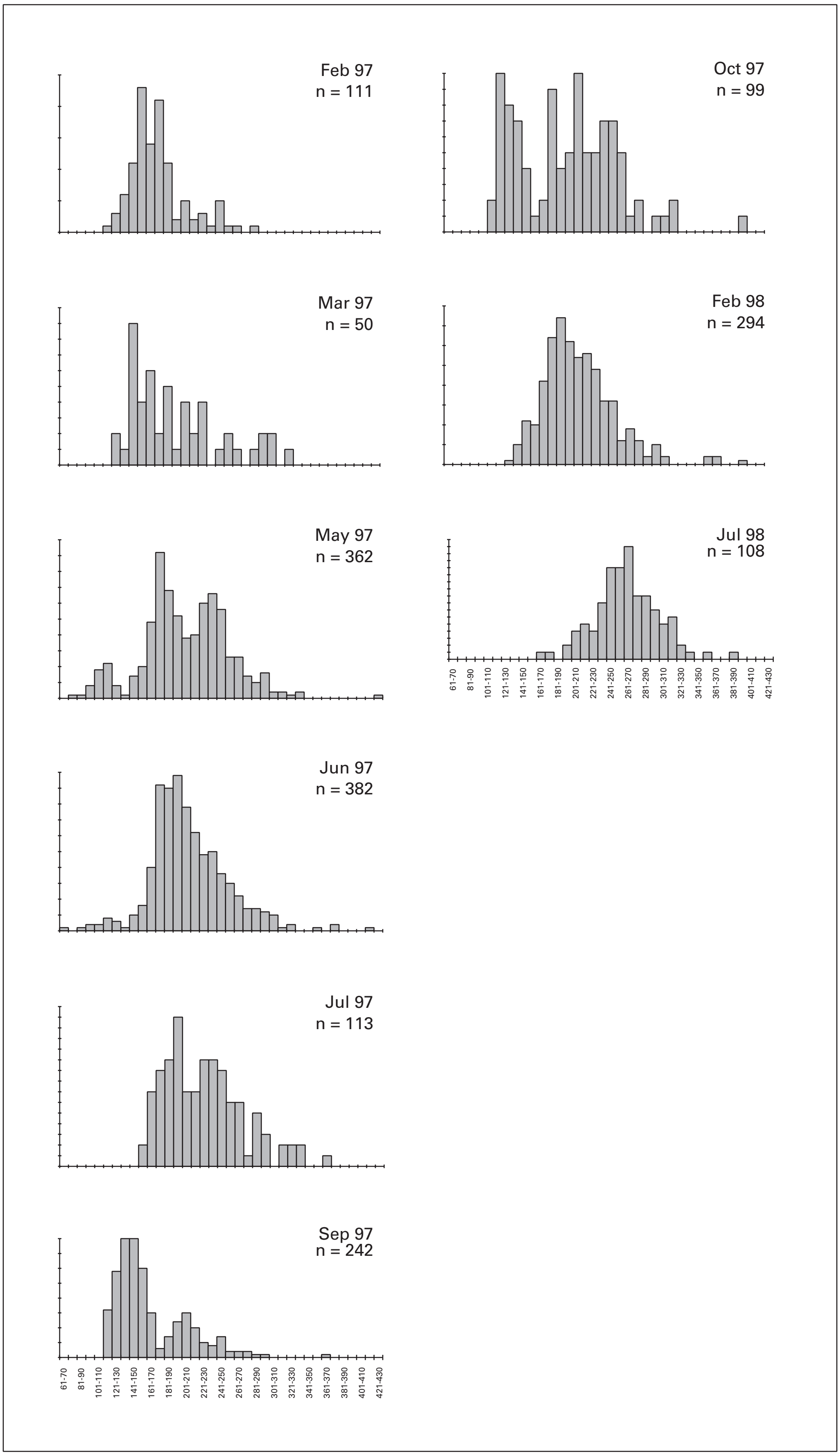


Figure 6.28 (cont'd).

Annual otolith weight frequency

Annual otolith weight frequency histograms were also constructed for each year from 1993 to 1997 to determine if modes were apparent for samples taken over an entire year,. Although at least two modes were present for each year from 1993 to 1996, the plots for all years were quite different (Figure 6.29). This may be attributed to both natural variation in the stock and the irregularity in fishing periods between years. For each of 1993, 1995 and 1996, Bhattacharya's (1967) method identified series of modes for which the fits were not significantly different to the observed data (Figure 6.29, Table 6.2). While the modes identified were obvious on the plots for 1993 and 1996, the 1995 plot was much less convincing. Furthermore, seven modes were found for the 1995 data, and considering our previous contention that the recruiting fish are two years old, this result would suggest a maximum age of eight years. This exceeds both the previous results for this study and the typical maximum ages of tropical/sub-tropical sardines.

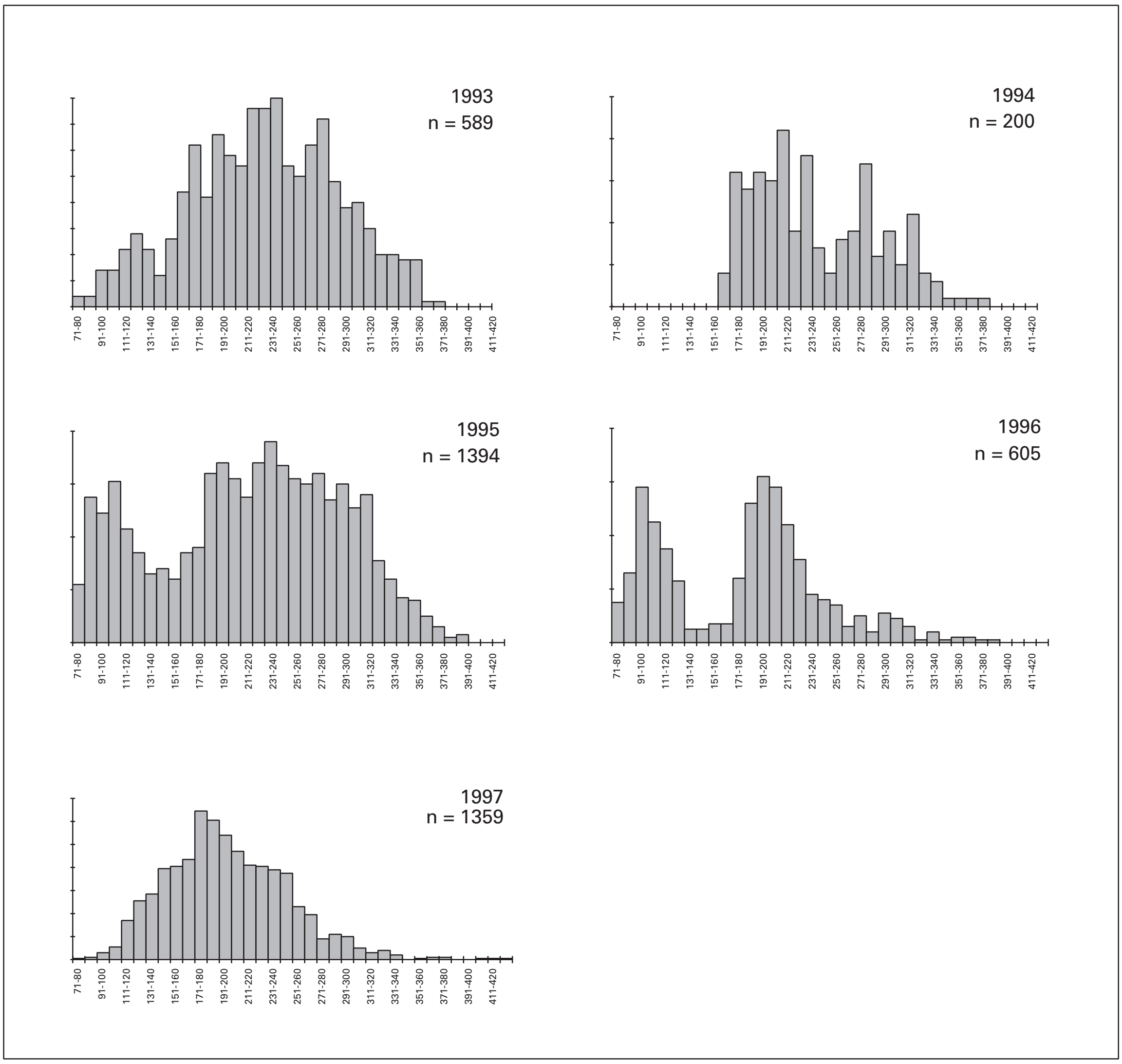


Figure 6.29 Annual otolith weight frequencies for *S. lemuru* caught at Geraldton between 1993 and 1997.

To further examine the validity of the modes chosen, the difference between each consecutive mode within individual data sets, were plotted (Figure 6.30). Assuming the growth rate of otoliths decreases as fish growth decreases with ageing, for the modes to be valid representations of year classes the difference in OW between consecutively higher modes must decrease, or at least remain level. This was clearly not the case for 1995. The other data sets generally showed the expected decline in the "gap" between consecutively larger modes; the means for these other data sets have been included on Figure 6.30 to show the average trend. These results do not provide evidence that the modes reflect age classes, but given the problem of having samples from only several months within any given year, neither do they discount this hypothesis.

The use of otolith weights as a tool for assigning ages requires several forms of verification (Pawson 1990; Fletcher 1991b), which has not been achieved for *S. lemuru*. Therefore, it is not currently possible to estimate age of individual *S. lemuru* using otolith weight. However, because otolith weight obviously increases as fish age (i.e. as they increase in size) and is relatively quick to measure, continuing to assess otolith weight may allow the annual average otolith weight to be used as an objective proxy for assessing interannual changes in age composition of the commercial catch.

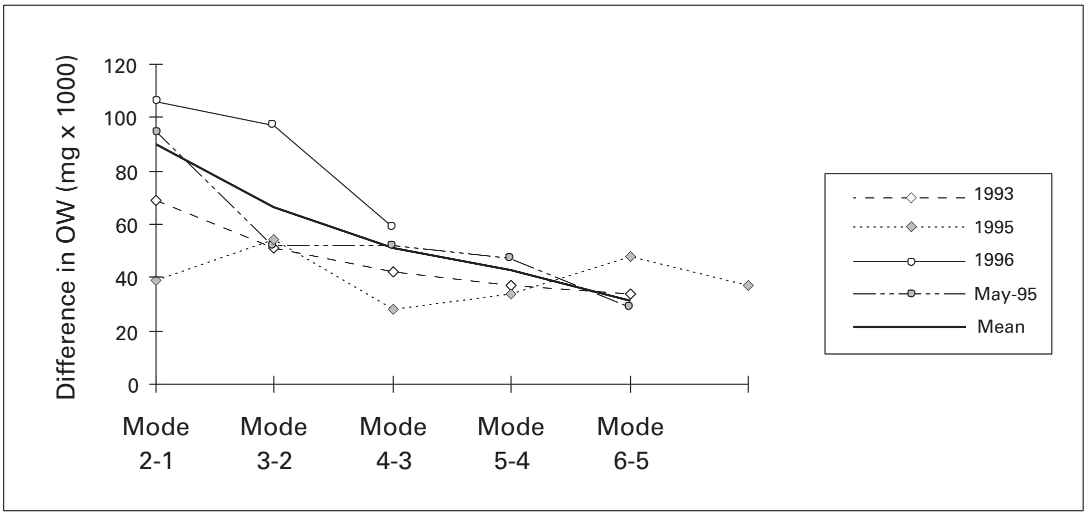


Figure 6.30 Differences between consecutive modes for otolith weight distributions. The mean does not include the 1995 annual data.

6.7 Length frequency analysis

Plots of the monthly length frequencies generally showed two distinct modes (Figure 6.31). The mode 120-130 mm FL corresponds to the traditional notion of a recruiting age class, with the mode at 160-170 mm FL constituting the bulk of the catches. The recruiting class contains those fish deemed to be two years rather than one year old. Thus, based on the ages estimated using whole and sectioned otoliths, the second mode very likely consists of several age classes. The lack of evidence for multiple modes within the size range greater than the 120-130 mm (i.e. the recruiting size) for *S. lemuru* was not unexpected. A similar pattern occurs for commercial catches of *Sardinops sagax* in southern WA (Fletcher 1995). Likewise, as found with *S. sagax* (Fletcher 1995; Fletcher and Blight 1997), evidence for several age classes over 120-130 mm was provided both by counting translucent zones on otoliths and by modal analysis of otolith weight in *S. lemuru*.

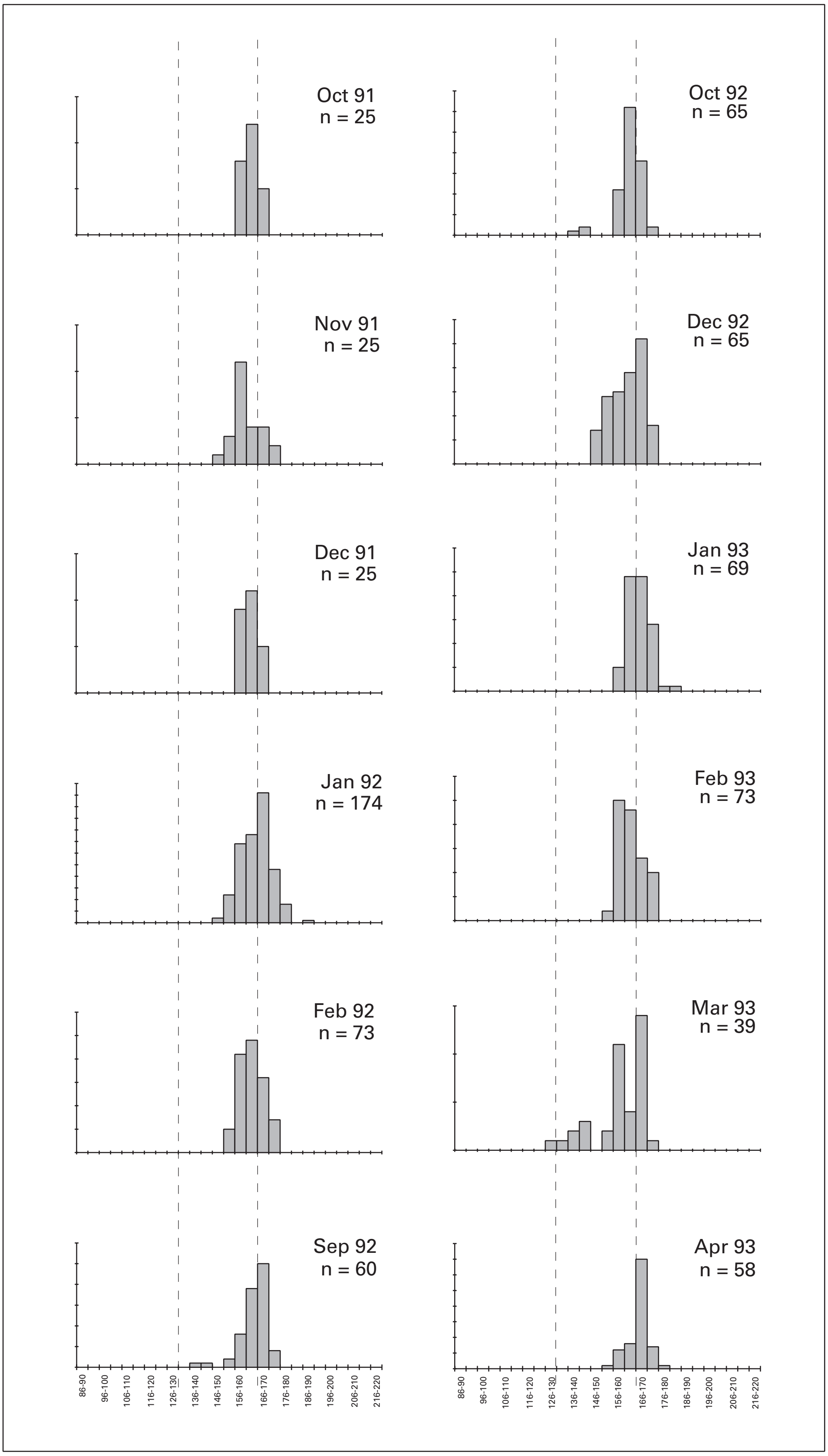


Figure 6.31 Monthly length frequency distributions for *S. lemuru* caught in the Geraldton region. Dashed lines have been included to assist in the interpretation of the figure.

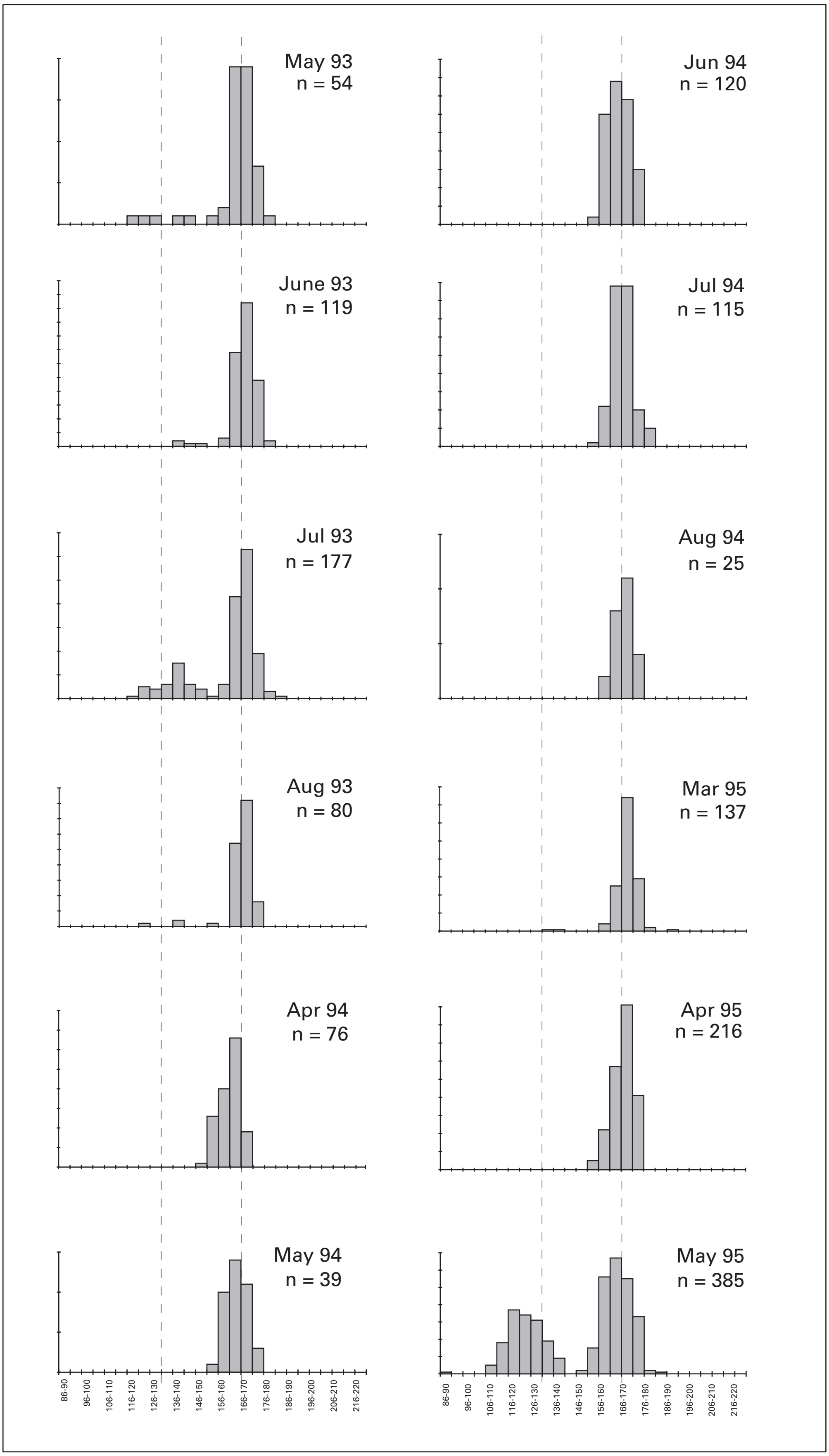


Figure 6.31 (cont'd).

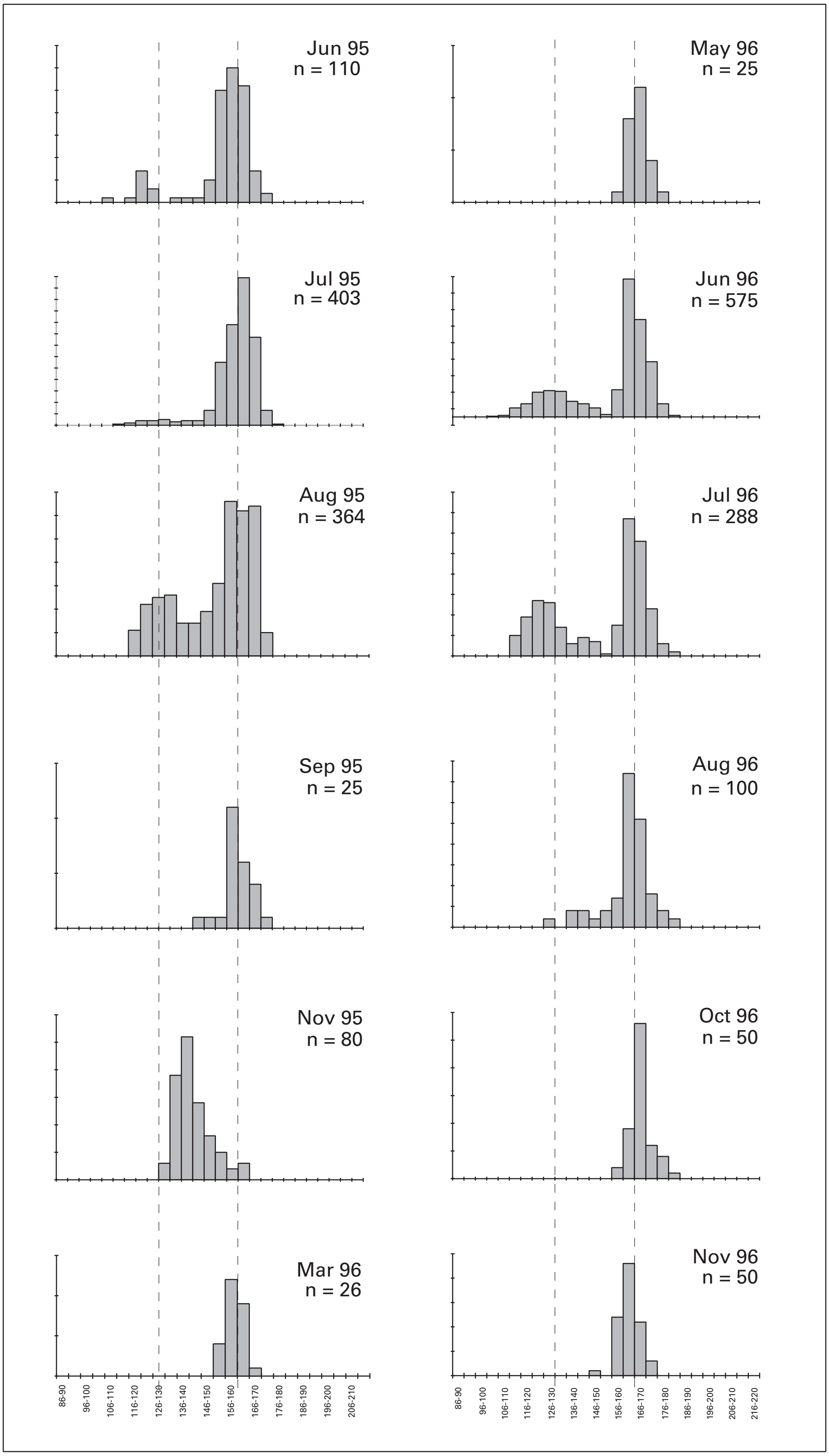


Figure 6.31 (cont'd).

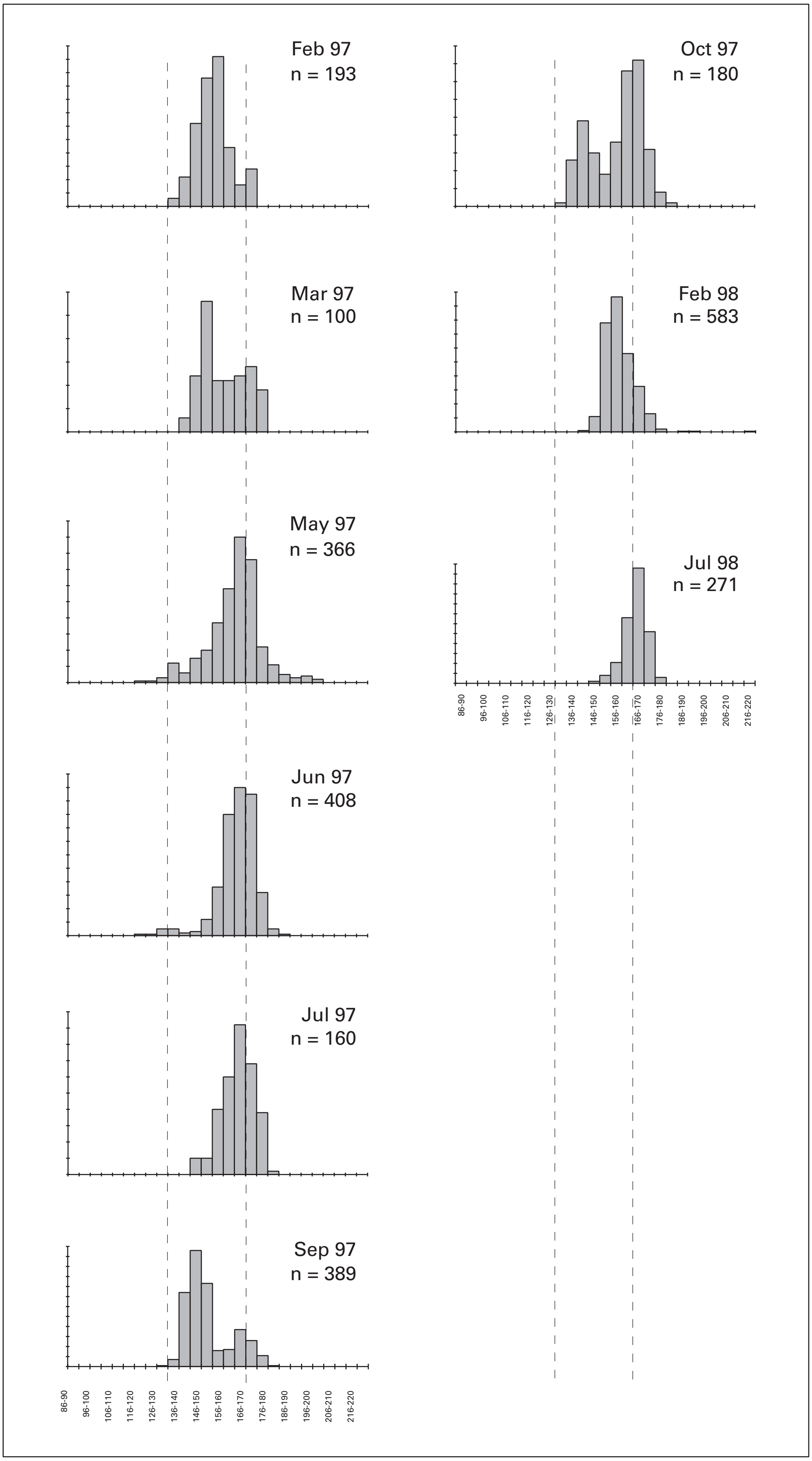


Figure 6.31 (cont'd).

Analysis of the monthly length frequency data with the ELEFAN module of the FiSAT program did not provide a good fit (R_n = 0.195) to the von Bertalanffy model (Table 6.1). Estimated L_{inf} was 179 mm FL, which is considerably larger than estimates obtained using otolith methods. Likewise, the k of 1.52 was much higher than those obtained using otoliths. Total mortality (Z) was estimated to be 3.02. The high k and Z indicate faster growth and shorter life span than suggested by the otolith methods. ELEFAN essentially recognised only two age classes, with full recruitment apparently at less than two years of age and a maximum age of less than three years. Comparative growth data for *S. lemuru* in the much more productive Bali Strait clearly indicate that lengths of 130 mm in the first year and 160 mm in the second year for *S. lemuru* in WA waters are extremely unlikely (Table 6.3).

Employing knowledge of the spawning season of *S. lemuru* off Geraldton, a count of 50 for the 25 mm size was added to each February (i.e. pseudo-information) and the analysis performed again, with the constraint that the curve must originate at the larval size class. The fit for this data was also poor (R_n= 0.158). While L_{inf} was similar to that obtained with the original length frequency data, both k and Z decreased to levels closer to those obtained using the otoliths (Table 6.1).

6.8 Discussion of age and growth results with comparisons to *S. lemuru* from Bali Strait

6.8.1 Age determination and growth parameters

The estimates of age for *S. lemuru* should be regarded only as approximates, due to lack of validation of an annual periodicity in ring formation on the sagittal otoliths. Further monitoring of commercial catches may allow some of the "gaps" in the data, used both to validate age and determine number of year classes, to be addressed.

For the data sets both with and without larval lengths and ages, L_{inf} for whole and sectioned otoliths did not differ greatly (Table 6.1). However, there were considerable differences in k, which ranged from 0.42 to 0.97. As estimates of t_0 were substantially better when larval data were included in the vB models, the results for vB parameters L_{inf} and k obtained from data sets which included the data for larval *S. lemuru* were used in the comparisons with age and growth data for *S. lemuru* from Indonesia (Bali Strait and Madura Strait).

Estimates of age, and thus growth and mortality, derived from examination of whole and sectioned otoliths for *S. lemuru* from Geraldton, were conditioned on the assumption that this species grows at a slower rate in WA waters than in the more productive, and warmer, Bali Strait. Length-at-age estimates for *S. lemuru* from Geraldton, calculated using vB parameters derived from the otolith and length frequency methods which included information on larvae, are thus less than those derived for this species in the Bali Strait (Table 6.3).

Although the age and growth estimates for *S. lemuru* that originated from the whole- and sectioned-otolith methods of estimating ages were similar, they contrasted those derived from length frequency data. Thus, for Geraldton fish aged using length frequency data, length-at-age, L_{inf} and k values were higher. The estimates for Geraldton *S. lemuru* derived using length frequency data were more similar to those obtained for *S. lemuru* in Bali Strait using the same type of data.

Tied in with the above argument for slower growth is the general premise that faster growth within teleosts equates to a shorter life-span. Thus, the otolith methods estimated maximum age of *S. lemuru* from Geelvink Channel as six or seven years, whereas that for Bali Strait is only three or four years (e.g. Pet *et al.* 1997a; Merta 1995). However, the original length frequency analyses (i.e. no larval age classes used) suggested only two age classes, which is unlikely given the ages of *S. lemuru* from Bali.

Even though forcing the length-frequency-generated growth curves to start at a pseudo-cohort of larvae in each February resulted in the von Bertalanffy model predicting more age classes and a slower growth rate than when this constraint was not applied, length-at-age, k and total mortality (Z) were still much higher than estimated using whole and sectioned otoliths.

Table 6.3 Estimated length-at-age, L_{inf}, k and total mortality (Z) for *S. lemuru* from Geelvink Channel and Indonesia (Bali and Madura straits). Note that because most overseas studies have measured total length (TL) a conversion has been applied so that length estimates are given as fork length (FL), as measured in the present study.

Region/Method	Year	Length-at-age							L_{inf}	k	Z	Ref.
		1	2	3	4	5	6	7				
INDONESIA												
Length frequency	69-72	9.4	15.1	18.5	20.6							1
" "	73-74	13.2	18.3	20.3	21.4				18.1	0.950	1.4	2
" "		12.8	17.1	19.0	19.9						3.23	3
" "	77-78	13.5	18.4	20.2							2.9	4
" "	1979	16.7	21.4	22.7							6.6	5
" "	1980	14.2	19.5	21.4							4.4	5
" "		15.4	19.9	21.6					22.7	0.961	4.82	6
" "	1991	11.5	16.5	19.0							3.1	7
" "	1977										2.74	8
" "	1978										2.76	8
" "	1979										1.43	8
" "	1980										2.89	8
Average TL		13.3	18.2	20.3	21.0				20.4	0.956	3.14 (1.50)	
Average FL		12.2	16.8	18.7	19.4							
GERALDTON												
Whole otoliths	95-97	9.1	13.3	15.1	15.9	16.2	16.3	16.4	16.4	0.864		
	1995										1.26	
	1996										0.68	
	1997										1.05	
Sectioned otoliths	95-96	7.3	11.5	13.8	15.1	15.8	16.2	16.3	16.7	0.598		
	1995										1.48	
	1996										1.32	
Average (from otolith methods)		8.2	12.2	14.4	15.5	16.0	16.2	16.3	16.6	0.731	1.16 (0.31)	
Length frequencies		11.2	15.4	16.9	17.5				17.3	1.000	1.48	

1 Dwiponggo (1974)
2 Ritterbush (1975)
3 Gumilar (1985) (in Merta 1995)
4 Naamin (1987)
5 Dwiponggo *et al.* (1986)
6 Merta (1992)
7 Pet *et al.* (1997a)
8 Sujastani and Nurhakim (1982)

6.8.2 Mortality

Estimates of total annual mortality derived from the whole and sectioned otolith methods were similar in 1995, but differed by a factor of two in 1996, indicating that further work is needed on the ageing of *S. lemuru*.

The mean of all otolith based estimates of Z was 1.16 (SD = 0.31). This is less than the range of Z values (1.4-6.6, n = 10, average = 3.14) estimated for *S. lemuru* in Indonesia (Table 6.3). Higher total mortality for *S. lemuru* in Indonesia would be expected due to the apparent shorter life-span, faster growth and, in particular, the longer history of exploitation[1]. The taxonomically similar *S. longiceps*, which lives in warmer and more productive conditions than found off Geraldton, has been studied extensively in India and has estimated Zs of 1.3-4.2 (Biradar & Gjøsaeter 1989). The estimates for Bali Strait *S. lemuru* and also for *S. longiceps* from India were based on length frequency analyses and direct assessments of ages were not performed. Interestingly, estimates of Z based on length frequency analysis for *S. lemuru* in WA (i.e. Z = 1.48) were also higher than those for age estimates based on otoliths.

In contrast to the above tropical sardines, *Sardinops sagax* in southern WA live for 8-9 years and total annual mortality is typically < 1 (Fletcher 1995). Since *S. sagax* and *S. lemuru* are very similar in appearance and size, it follows that lower natural mortality will be expected in regions with lower water temperatures but similar levels of primary productivity, and this is likely to be driving the substantial differences in Z in the above examples. Thus, *S. lemuru* in WA probably have a higher natural mortality rate than *S. sagax* from southern WA, but less than *S. lemuru* from Indonesia. As estimates of natural mortality (M) for *S. lemuru* from Bali Strait have ranged from 0.8 to 2.17 (Merta 1995) and that for *S. sagax* is 0.43 (Fletcher 1995), M for *S. lemuru* off Geraldton most likely lies between 0.43 and the average total annual mortality estimated in this study as 1.16. The estimated M derived from Pauly's (1980) empirical relationship, along with the correction factor of 0.6 for clupeoids (Pauly 1982), was 0.93, which falls within the expected range. Assuming this is a reasonable representation of M (noting that there is no direct evidence for this), fishing mortality, F (i.e. F = Z – M), thus equals 0.23. Patterson (1992) suggested that sustainability of clupeoid stocks was more likely if F/M was kept below 2/3 (i.e. 0.67). In the case of *S. lemuru* at Geraldton, F/M = 0.25, which suggests that current catch levels (i.e. 500-2000 tonnes per annum) are sustainable. However, because the causes for the decrease in catch rates in 1997 (section 8.0) are not clear, work on the age and growth of *S. lemuru* in WA will need to continue as further monitoring of commercial catches takes place. Another possibility to be addressed is the potential existence of size-dependent spatial separation within the mid-west assemblage, which could have resulted in an under-representation of older *S. lemuru* in the samples, thereby overestimating total mortality.

6.8.3 Recruitment

The catch-at-age curves generated using both otolith methods indicate that the catch largely consists of two to three age classes, similar to the Bali Strait *S. lemuru* fishery (Merta 1995). Recruitment to the fishery occurs at two to three years of age, with full recruitment at three to four years. Length-at-age for three-year-olds, based on otoliths, equates to size at recruitment of 12-14 cm which encompasses the recruiting size class evident in the length frequency plots. Such recruitment events typically occurred in only one or two months of any given year, always within the period from March to August, and most frequently in the three-month period from May to July.

[1] Annual catch of *S. lemuru* in Bali Strait has reached 50 000 tonnes.

Within the *S. lemuru* stock there is most likely a strong relationship between abundance of consecutive age classes in consecutive years even though it does not manifest within consecutive annual catch curves. This may indicate that the presence of one- and two-year-old, and to a lesser extent, three-year-old *S. lemuru* in the commercial fishing grounds is sporadic or their vulnerability to capture varies widely between years. In either case, it indicates that the abundance of these age groups in the commercial catch is of little use as an indicator of recruitment strength. Three-year-olds may be used to estimate relative rates of annual recruitment, but because this age group forms a substantial portion of the catch in some years, it will not be possible to use such rates to predict catch levels for the subsequent year(s).

6.9 Conclusions

Sardines typically experience large interannual fluctuations in recruitment strength and are also relatively short-lived. These factors, along with associated biological and environmental factors, can lead to large changes in stock size over short periods. While there is uncertainty over the age structure, and thus mortality estimates, of the commercial catch of *S. lemuru* off Geraldton, the evidence strongly suggests that this species is short-lived. Along with the likelihood of substantial interannual recruitment variability, the purse seine fishery at Geraldton needs to be managed conservatively.

7.0 Stock delineation

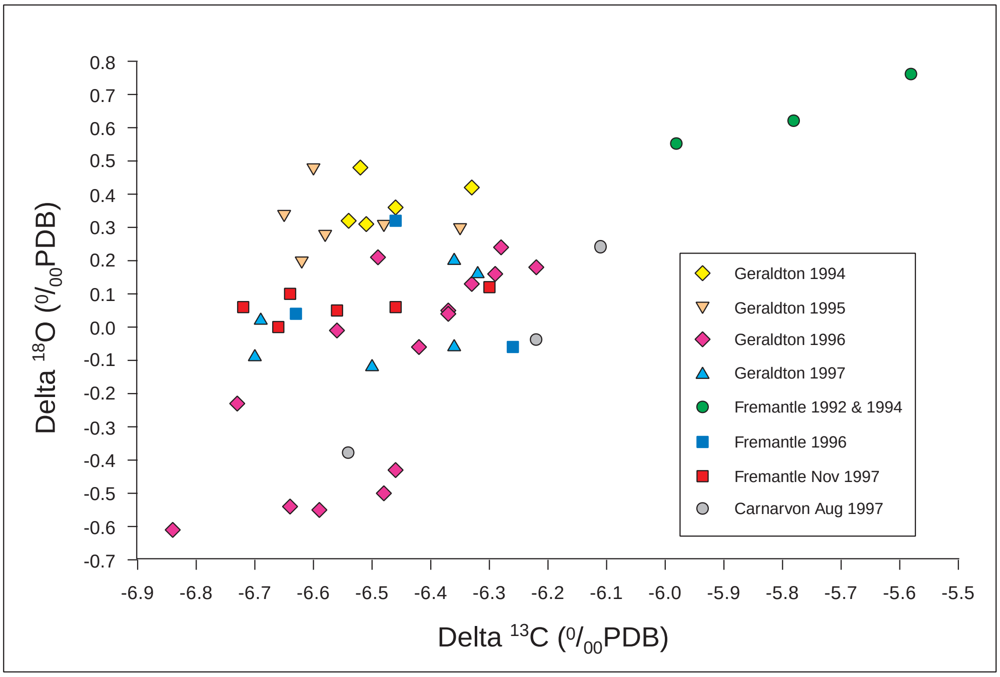
Ratios of stable isotopes for oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) were determined for 58 samples, most of which came from Geraldton (Figure 7.1a). Plots of the $\delta^{13}C$ against $\delta^{18}O$ for each sample indicated considerable overlap between regions, except for those samples from Fremantle in 1992 and 1994. These latter samples had both the highest $\delta^{18}O$ and $\delta^{13}C$.

The groupings for the more substantial numbers of samples from Geraldton shifted up and down the $\delta^{18}O$ axis from year to year, with those from Fremantle in 1996 and 1997 overlapping the Geraldton groups (Figure 7.1b). The Carnarvon sample (August 1997 only) separated off from the main body of Geraldton and Fremantle samples along the $\delta^{13}C$ axis.

The 1996 Geraldton and Carnarvon groups both included otoliths from small (< 145 mm FL) *S. lemuru*, which were analysed separately. For each group the points for the smaller otoliths are those with the lower $\delta^{13}C$ and $\delta^{18}O$ values. The two larger size classes from the single sample from Carnarvon had much higher $\delta^{18}O$, a trend also obvious when the Geraldton samples from the months of June and July of 1996 were plotted separately (Figure 7.2). The otoliths in the Fremantle 1992 and 1994 samples were also large and this was probably a major influence on the magnitude of the $\delta^{18}O$ and $\delta^{13}C$ values recorded. This level of difference between size classes indicated that size had to be considered as a factor in subsequent analyses.

Because there are differences in the mean water temperature at each of the locations, if there were separate stocks of *S. lemuru*, then a difference in $\delta^{18}O$ would be expected. A plot of mean sea surface temperature (SST) (Reynold's data) against mean $\delta^{18}O$ for each region shows the expected relationship of lower $\delta^{18}O$ with the northward increases in SST (Figure 7.3a). The same trend was obvious with data for similar sized otoliths from *S. lemuru* caught within a four-month period in 1997 (Figure 7.3b). In the latter case, the difference in $\delta^{18}O$ between the two most distant locations was 0.43, whereas for the overall location-means this difference was only 0.29. Thus, for similar sized fish in a substantially narrower time period the difference was greater. The smaller difference over the longer period probably resulted from smearing of temperature signatures between years as well as the disparities in sizes of fish sampled. However, despite that, these data suggest a degree of consistency in separation between *S. lemuru* along the WA coast, the same type of plot for Geraldton from the years 1994 to 1997 (Figure 7.3c) indicates that the difference between minimum and maximum values (0.51) far exceeded that between regional means. This indicated that no conclusions on stock structure could be drawn from the isotopic analyses.

(a)



(b)

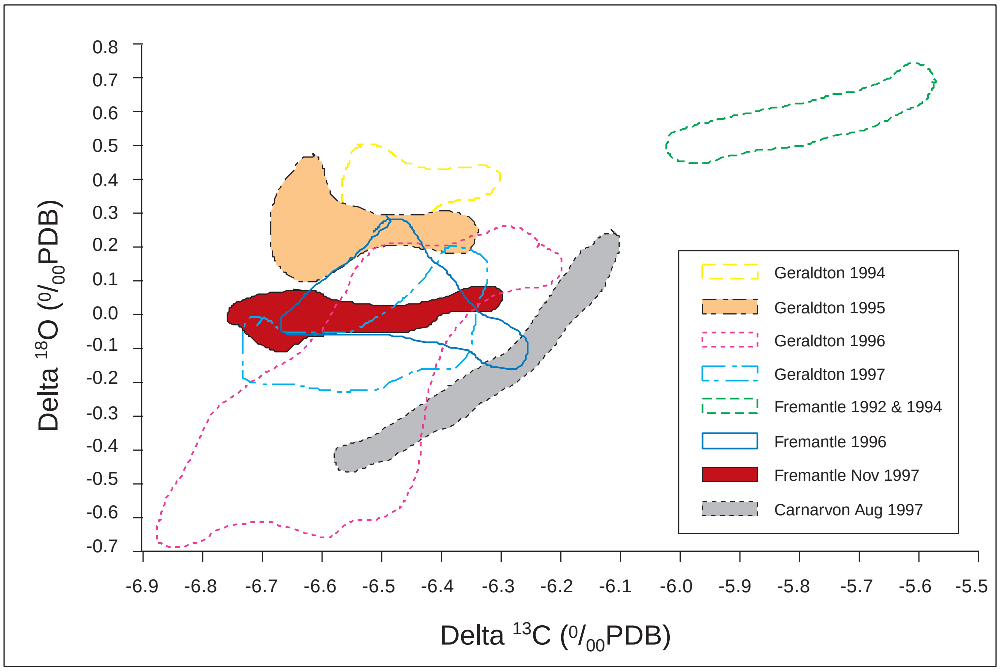


Figure 7.1 (a) Isotopic ratios of oxygen and carbon for otoliths samples of *S. lemuru* from Geraldton, Fremantle and Carnarvon. (b) Outlines of groupings from graph (a) for different regions and years.

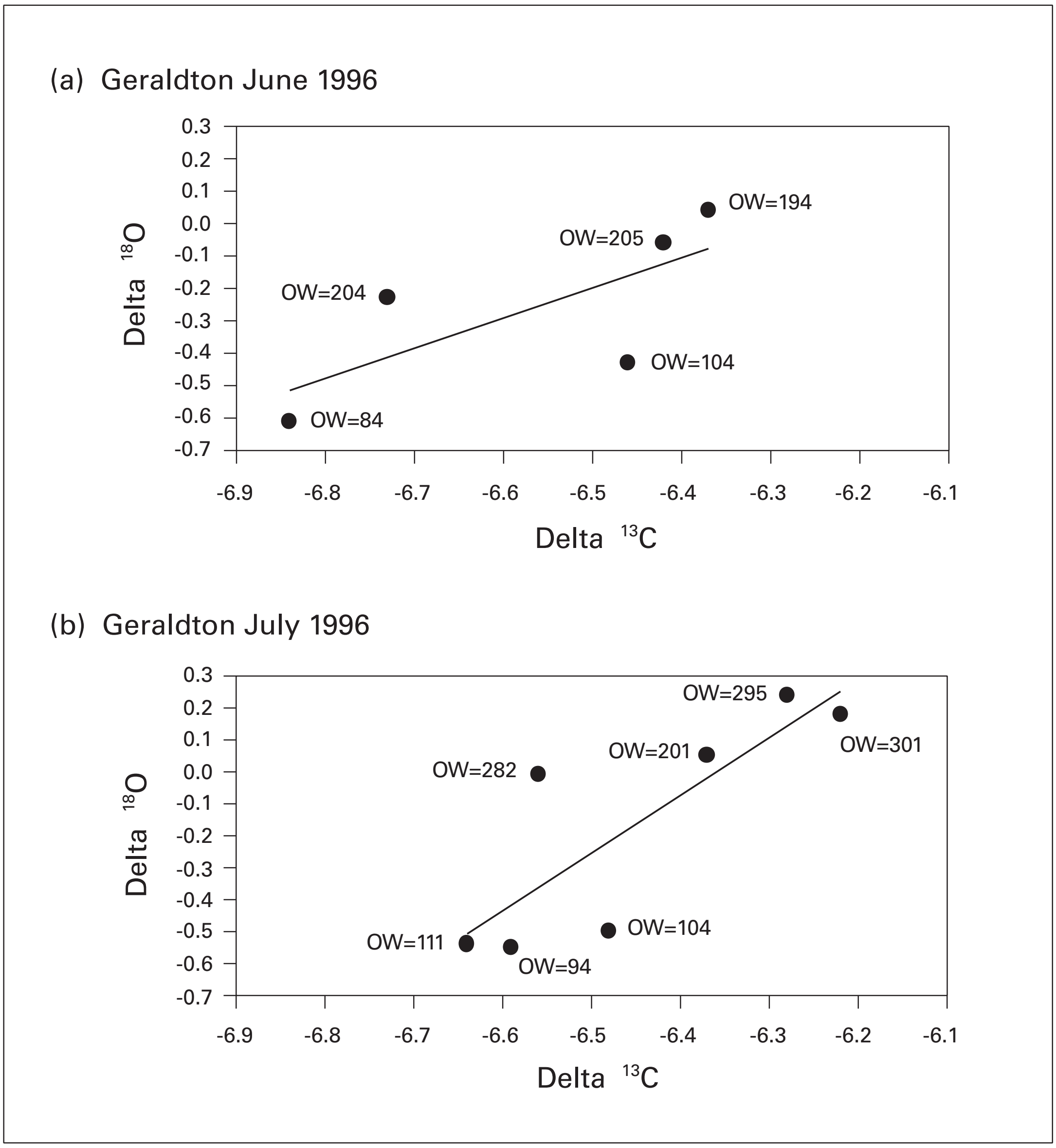


Figure 7.2 The relationship between otolith size and the isotopic ratios of oxygen and carbon for *S. lemuru* from the Geraldton area during (a) June and (b) July of 1996.

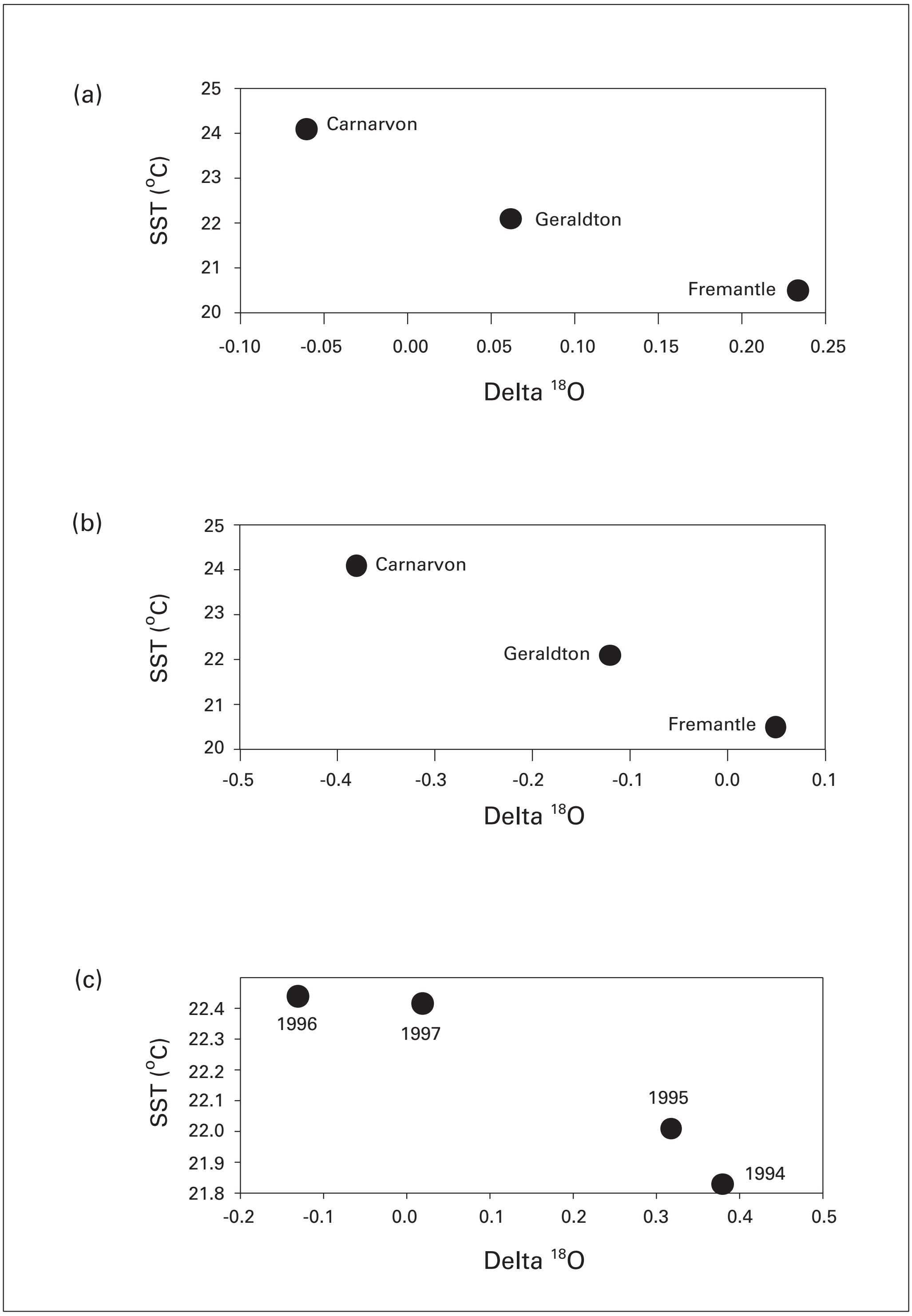


Figure 7.3 Relationship between SST and mean isotopic ratios of oxygen for:
(a) all samples of *S. lemuru* otoliths from Geraldton, Fremantle and Carnarvon;
(b) for similar sized *S. lemuru* otoliths obtained within a four month period in 1997 at the same regions; and
(c) samples of *S. lemuru* from Geraldton between 1994 and 1997.

ANCOVA was used to objectively compare isotopic ratios between locations while accounting for both otolith size and date of capture. When these co-variates were accounted for, the difference between location was only marginally significant for $\delta^{18}O$ ($0.1 < P > 0.05$) and not significant for $\delta^{13}C$ (Table 7.1). This result is consistent with the observations on plotted data, indicating evidence for some level of separation between populations of *S. lemuru* along the WA coast from Fremantle to Carnarvon, but lack of consistency in this separation. Thus, substantial variation between years within locations, as indicated by the significant location*year affect, provides no evidence of stock separation, and also confounds the possibility of the data providing evidence for a single stock. The highly significant differences in both $\delta^{18}O$ and $\delta^{13}C$ with otolith weight were also expected.

Table 7.1(a) ANCOVA results for $\delta^{18}O$ of otolith carbonate.

Source	df	Type III SS	MS	F-value	Level of significance
Otolith weight	2	1.392017	1.392017	122.3351	**0.000000**
Location	1	0.590557	0.295279	7.8047	0.056523
Year	5	0.769833	0.153967	4.1485	0.119927
Location*Year	3	0.127209	0.042403	3.7265	**0.018980**
Error	39	0.443770	0.011379		
Total	50	4.444729			

Table 7.1(b) ANCOVA results for $\delta^{13}C$ of otolith carbonate.

Source	df	Type III SS	MS	F-value	Level of significance
Otolith weight	2	.0253068	0.253068	12.99692	**0.000874**
Location	1	0.328339	0.164170	1.59935	0.330794
Year	5	0.382730	.076546	0.76252	0.629124
Location*Year	3	0.351046	0.117015	6.00960	**0.001815**
Error	39	0.759385	0.019471		
Total	50	2.659204			

Replicate samples from each location, taken at the same time over several years, would be required before this method could be expected to provide a more definitive description of stock structure of *S. lemuru* in WA. The $\delta^{18}O$ data provide some evidence that *S. lemuru* caught at different locations have indeed lived most of their lives in waters of different temperatures, but this could be interpreted, for example, as resulting from a widespread stock. If differences between location were stable over time (Edmonds and Fletcher 1997) then this would provide evidence for delineation between locations.

The interesting results from these analyses were the substantial differences between large and small *S. lemuru*. The large differences in $\delta^{18}O$ for the single Carnarvon sample, and in the Geraldton 1996 group, strongly suggest that smaller size classes of *S. lemuru* have been living in warmer water (i.e. lower $\delta^{18}O$ values) than the larger size classes. Because the smaller sizes can be regarded as recent recruits, these results indicate that recruits have come from a different (i.e. warmer) location than the main adult stock being fished.

For each of the Fremantle, Geraldton and Carnarvon regions of coast, warmer average water temperature occurs both offshore and to the north of the inshore areas from where samples were obtained. Either represents possible nursery areas for pre-recruit *S. lemuru*. This hypothesis is further examined later in context of the Geraldton *S. lemuru* fishery.

8.0 Monitor the dynamics, locations and catch rates of the fleet

8.1 Vessel dimensions

This developmental fishery was fished by three vessels. Two of these were relatively large, purpose-built, purse seine vessels of approximately 24 m in length and will be referred to as the 24 m vessels. The third vessel was smaller, being about 19 m in length. One of the 24 m vessels and the 19 m vessel, which actively participated in the fishery during the period of this project, are briefly described below. Descriptions are included because the types of vessels used had a large influence on their relative success in the fishery.

8.1.1 24 m vessel

The 24 m vessel which participated in the fishery during the project (length = 24.4 m, beam = 3.5-4 m, gross tonnage = 147 t) was of steel construction and built in 1968 specifically as a purse seiner to work in the North Sea. A single diesel engine produces 237 kilowatts of power with a maximum speed of 9-10 knots. The 24 m vessel has a brine tank capacity of 24 tonnes and an icebox capacity of 25 tonnes. Electronics included sonar, colour echo sounder and satellite navigation. The purse seine net used was 512 m in length with a 101 m drop and a mesh size of 19 mm. The net was hauled by a power block system.

8.1.2 19 m vessel

The 19 m vessel was also constructed of steel but was built as a trawler and later modified to work as a purse seiner. This vessel was fitted with a 300 hp D-rated engine, and also carried sonar and sounder. The purse seine net used on the 19 m vessel was 600 m in length with a drop of 110 m and a mesh size of 19 mm. The net was hauled by a power block system.

8.2 Catch and effort

8.2.1 19 m vessel

This fishery commenced with the 19 m vessel in November 1989. Monthly catches of less than 500 kg were made then and in February 1990 (Figure 8.1). Larger catches of between 16,000 and 24,000 kg were subsequently made between June and September 1990, after which no fishing occurred with this vessel until September 1991. Fishing then occurred regularly for the following four months up until January 1992, with catches for this period varying between 7,200 and 17,600 kg per month. Between February 1992 and February 1994 there was little effort by the 19 m vessel in this fishery, with relatively small catches being recorded in three months only.

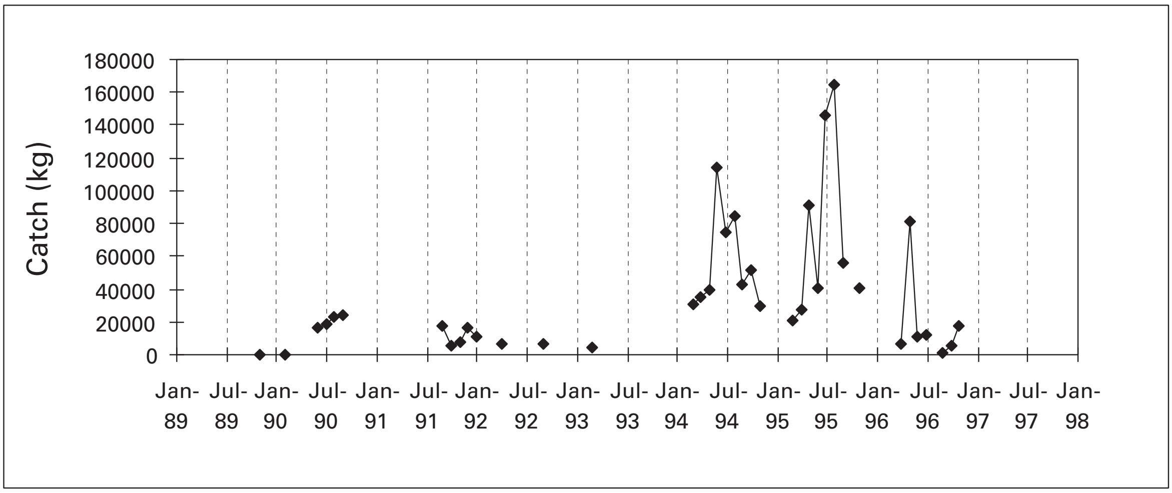


Figure 8.1 Monthly catches of the 19 m vessel.

During 1994, 1995 and 1996 the 19 m vessel fished in nine, eight and seven months respectively. Catches of *S. lemuru* were more consistent and more substantial than in previous years. This was in part due to the hiring of a skipper with considerable previous experience in purse seining for small pelagic fish. Furthermore, onshore processing facilities linked to this vessel had been developed so that larger quantities of *S. lemuru* could be landed. Onshore staff also meant that the skipper of the vessel could concentrate on catching fish. These changes represented a substantial investment in this developmental fishery.

Between 1994 and 1997 catches and catch rates by the 19 m vessel were highest during May to August (Figure 8.2). However, whereas monthly catch rate usually exceeded 5,000 kg/day in 1994 and 1995, during 1996 catch rate was mostly less than 5,000 kg/day and in two months was less than 500 kg/day. Furthermore, the 19 m vessel suffered various mechanical problems during 1996 and did not fish in August, one of the main catching months. These patterns were reflected in the annual catches and catch rates for this vessel (Figure 8.3). Annual catch rate peaked in 1994 at about 10,000 kg day and declined sharply in the next two seasons to a level of only 2,300 kg/day in 1996.

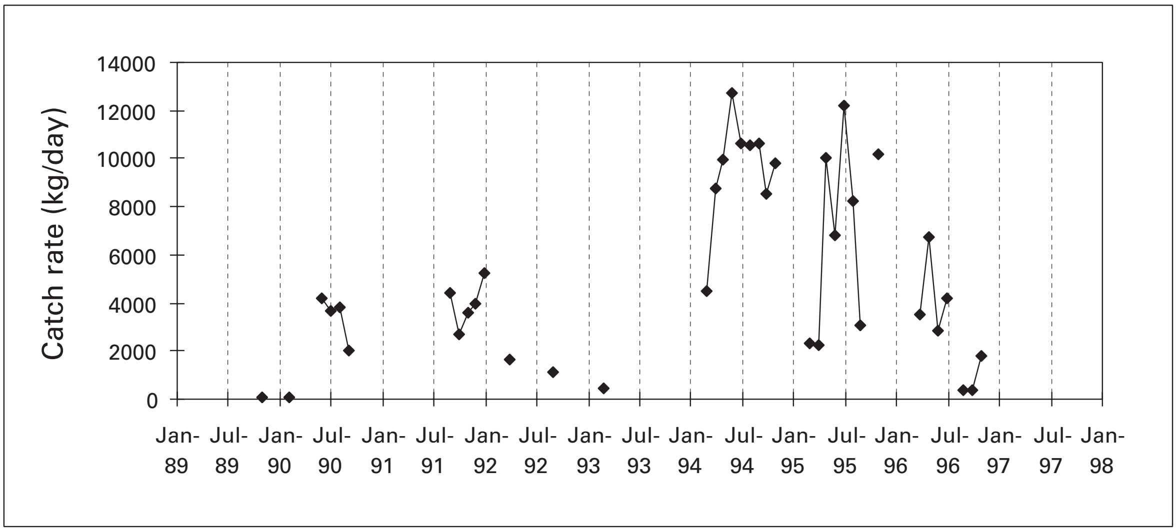


Figure 8.2 Monthly catch rate (kg/day) of the 19 m vessel.

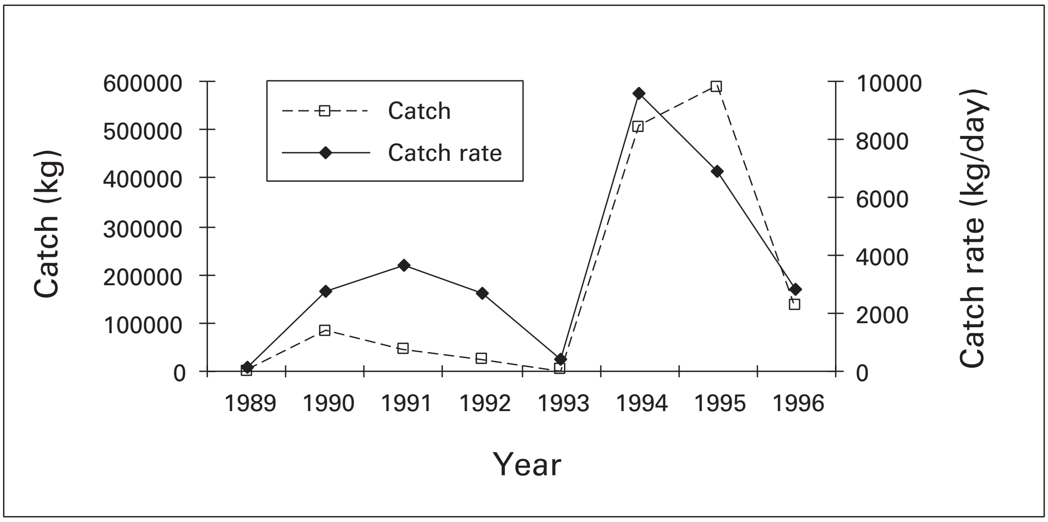


Figure 8.3 Annual catch and catch rate of the 19 m vessel.

Due to poor economic returns, driven partly by the inability to capture the particular size of *S. lemuru* required for the licensee's intended market, this vessel has not participated in this developmental purse seine fishery since the 1996 season and at this point appears unlikely to do so, having effectively left the fishery, along with disposing of the processing facilities.

This operator was trying to develop high value product for a particular market but was thwarted both by a paucity of sufficiently large *S. lemuru* over the three year period of relatively intensive fishing and by mechanical problems with the vessel. Whereas a large size class of fish was regularly caught early on in the fishery, catches in later years not only contained fewer of these larger fish but, when present, they were typically mixed in with smaller size classes and could not be effectively sorted in an economically suitable time frame. Considerable effort was made to install a fish sorter onto the vessel, but this met with only limited success. Besides these difficulties, the size and, more particularly, the design of the vessel appeared to be unsuitable for purse seining in the waters offshore of Geraldton, with the limiting factor being poor sea conditions generated by frequent strong winds.

8.2.2 24 m vessel

Whereas the 19 m vessel had intended to market a high quality and relatively high value product, the 24 m vessel sought bulk quantities for the pet food industry and therefore was not vulnerable to interannual variations in fish size.

Monthly catches for 24 m vessels varied from zero in August 1993 to 500,000 kg in August 1996 (Figure 8.4). Relatively small catches were recorded over the summer period of late 1991 and early 1992. Catches were similarly small in the following summer (1992/93) but then increased from less than 70,000 kg per month over summer and autumn, up to 237,000 and 187,000 kg in June and July 1993, respectively. Catch rates were less than 10,000 kg/day in the summers of 1991/92 and 1992/93, then reached 15,800 and 18,700 kg/day in June and July 1993, respectively (Figure 8.5). In September 1993 a single day's fishing produced a notable catch of 23,680 kg. For a variety of reasons not related to the fishery, this particular vessel has not subsequently fished for *S. lemuru* in the Geraldton region.

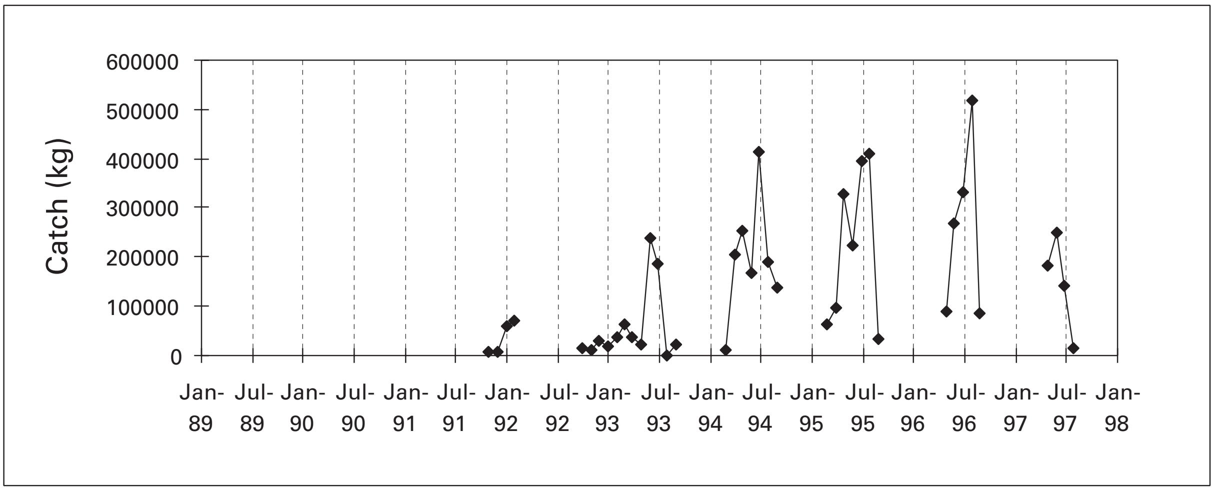


Figure 8.4 Monthly catches of the 24 m vessel.

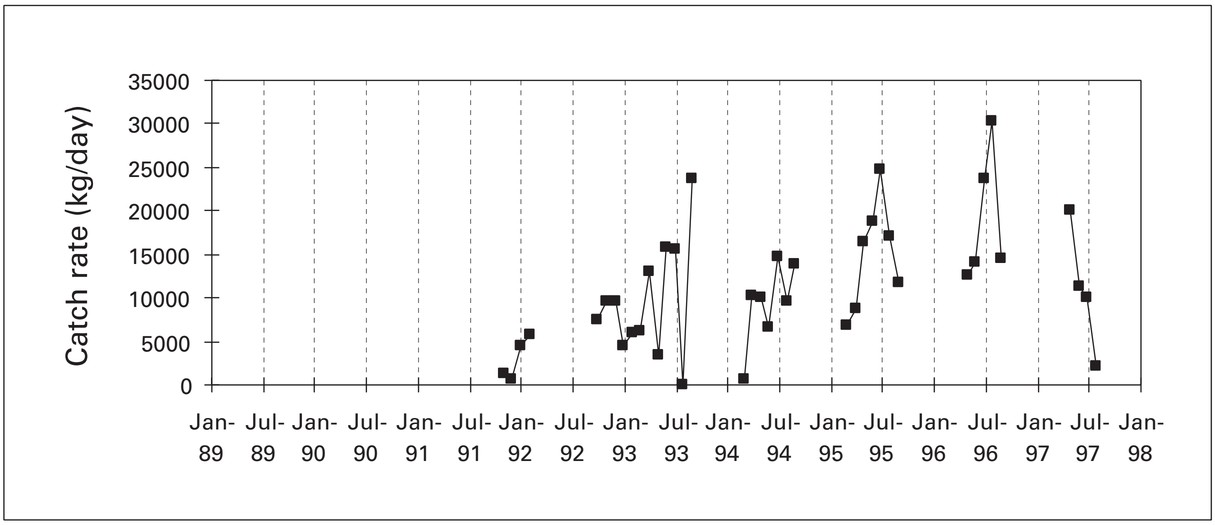


Figure 8.5 Monthly catch rates of the 24 m vessel.

The second 24 m vessel, which can be essentially be viewed as a replacement for the first 24 m vessel but with different ownership and a "new" skipper, began fishing for *S. lemuru* in March 1994. The new skipper had extensive experience in the fishing industry, including recent and ongoing participation in the Tasmanian jack mackerel fishery. Due to commitments elsewhere (i.e. Tasmania), this vessel was not able to fish all year round in the Geraldton region, and in both 1994 and 1995 fished from March to September, a period of seven months. Experience gained in these first two years led to a shortened season for this vessel in 1996, with only five months being fished between May and September. However, this then led to a decrease in the annual catch (but see below) from a peak of 1.55 x 10^6 kg in 1995 to 1.29 x 10^6 kg in 1996 (Figure 8.6). In 1997 the fishing season was again shortened to a four month period between May and August, with the annual catch declining by over 50 per cent to only 0.57 x 10^6 kg.

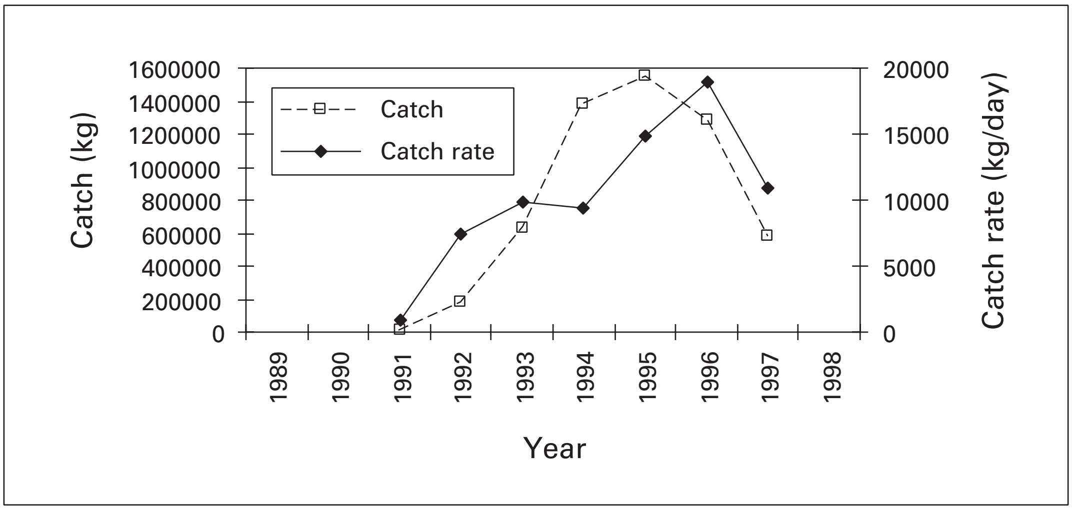


Figure 8.6 Annual catch and catch rate of the 24 m vessel.

The progressive shortening of the fishing season for this 24 m vessel was partly linked to fishing conditions and the ability of the onshore facilities to process the catch. Onshore processing facilities were further improved in 1996 so that larger individual catches could be adequately dealt with in a reasonable time frame. This meant that more fish could be landed on a given day thereby permitting a shorter season and leading to a later start to the season in 1997.

The decision to fish a shorter season was driven by economics, so that after catching the desired amount of *S. lemuru* in a shorter period the vessel was able to pursue other activities. Note that the minimum "desired amount" was that which would be sufficient for the enterprise to make a profit in any given year. However, despite this plan, a large decrease in catch rate from 1996 to 1997 resulted in the much lower annual catch (Figure 8.6) and may have been indicative of decreased abundance of *S. lemuru* in that region of the fishery. Thus, the shortened season in 1997 may have been partly due to unexpectedly lower catch rates.

Monthly catch rates in 1997 were considerably less than in 1995 and 1996 (Figure 8.5). Annual catch rates had peaked in 1996 at nearly 20,000 kg/day and then declined markedly in 1997 to a level lower than that for 1995 (Figure 8.6). The decline in catch rate by the 24 m vessel in 1997 followed a similar marked decline for the 19 m vessel in 1996. This decline may have been indicative of a decrease in abundance, with the larger and apparently more efficient vessel (see below) requiring a larger decrease in abundance before catch rates were adversely affected.

An apparent lack of large schools of *S. lemuru*, noted by pilots of small aircraft flying between Geraldton and the Abrolhos Islands, in conjunction with personal matters, resulted in no fishing being conducted by the 24 m vessel in the Geraldton region during 1998. While the observations by pilots did not involve any specific recordings of school numbers, the *S. lemuru* schools have traditionally been observed from the air and therefore a lack of sightings in late 1997 and early 1998 did provide anecdotal evidence for a decrease in abundance, or numbers of large schools, of *S. lemuru* in Geelvink Channel.

As an aid to the mid-water trawling for *S. lemuru* in February 1998, a flight was chartered specifically to look for *S. lemuru* in Geelvink Channel but also failed to find any schools. Neither were any schools located by the RV *Flinders* one week either side of the flight. However, RV *Flinders* did locate and catch reasonable numbers of *S. lemuru* two weeks later, indicating either that some fish had moved back into the search area or dense schools formed in the search area towards the end of the survey period.

Catches and catch rates were much larger for the 24 m vessel than the 19 m vessel. The large differences in catches between these vessels were evident in 1995 when both were fully operational. For each month between March and September during the 1995 fishing season, catches on the 24 m vessel were between 270 and 550 per cent larger than those taken from the 19 m vessel. The 24 m vessel recorded an annual catch of 1,552 tonnes compared with an annual catch of 326.2 tonnes recorded from the 19 m vessel. Noting that both vessels had similar sized nets, experienced skippers and were fishing the same grounds, the large differences in catch rate reflected the greater fishing power (efficiency) of the larger, purpose built purse seine vessel. Thus, although both vessels were at times hampered by the poor sea conditions, this was more of a problem for the smaller vessel.

Besides the influence of vessel type, smaller catches by the 19 m vessel were also related to a much lower blast-freezer and cold store capacity at the associated factory. For a large volume, relatively low value product, freezing and storage represent a major cost and therefore represent a central consideration for a developing fishery which targets sardines.

8.3 Other estimates of catch rate from 1995-1997

Catch rates based on another three estimates of effort obtained from the logbooks are compared. Besides "days fished" as used above, the three other estimates of effort were fuel used, searching time (hours) and number of blocks searched. Other potential estimates of abundance included in the logbook were number of schools observed and incidence of zero catch. These results were mostly restricted to those obtained from the 24 m vessel since this was the only vessel to fish during most of the project period and hence gave a longer time series of data (i.e. three years as opposed to two).

8.3.1 Fuel used

CPUE based of the amount of fuel used (i.e. kg/L) showed a steady decline from 1995 to 1997. This did not the match the pattern for catch rate based on kg/day, for which 1996 had the highest catch rate, although both methods were similar in that 1997 had the lowest catch rate (Figure 8.7). A concern with this data was the magnitude of the 1995 estimate (310 kg/L), which was much larger than expected. A closer examination of the data revealed a distinct discrepancy in the expected linear relationship between fuel used and days fished (Figure 8.8), with the 1995 fuel value appearing to be grossly underestimated. Further review found substantial differences in records of fuel use from the logbook data and that derived from the compulsory catch and effort reporting system. The revised relationship between days fished and fuel used was clearly linear (Figure 8.9) and, therefore, fuel values from the compulsory reporting system were considered substantially more reliable. Catch rates based on fuel data from the compulsory reporting system rose from 27.7 kg/L in 1995 to a maximum during the study period of 37.9 kg/L in 1996, before declining to 23.8 kg/L in 1997 (Figure 8.10). This pattern matched that for catch rates which used days fished as a measured of effort.

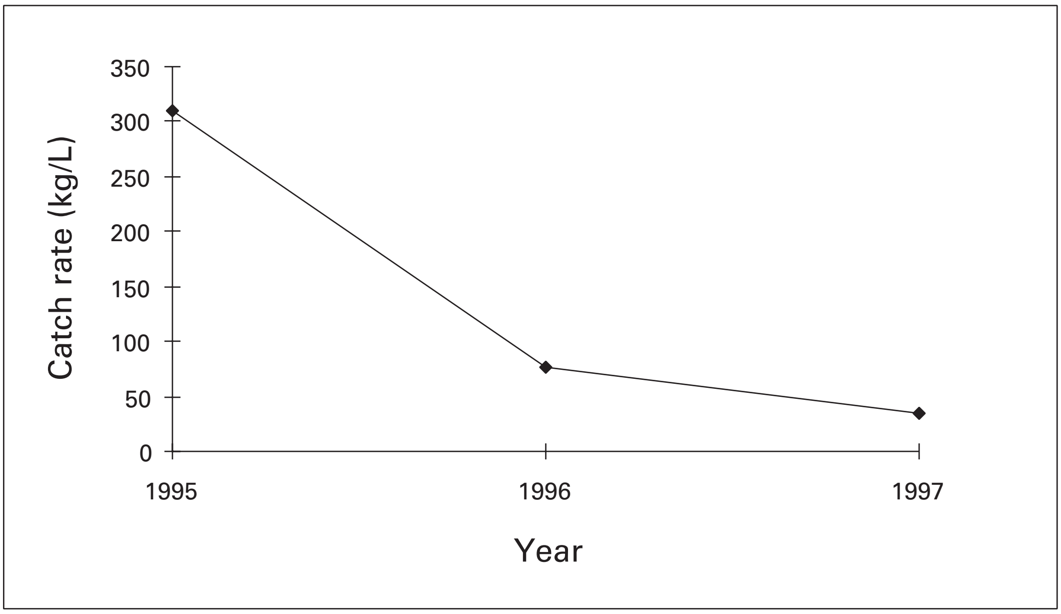


Figure 8.7 Catch rate (kg/L) of the 24 m vessel during the 1995-1997 fishing seasons.

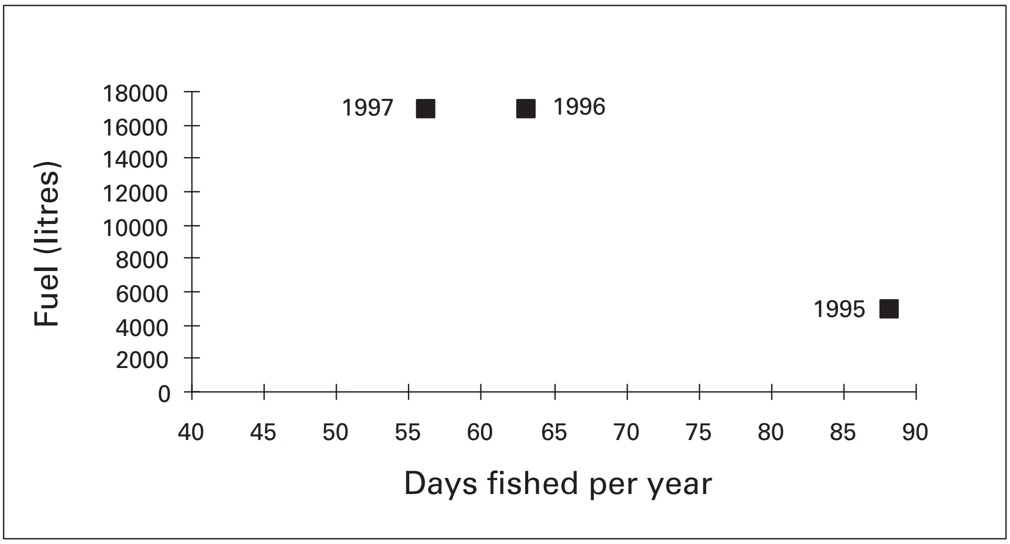


Figure 8.8 Relationship between fuel used and days fished for the 24 m vessel annually from 1995 to 1997.

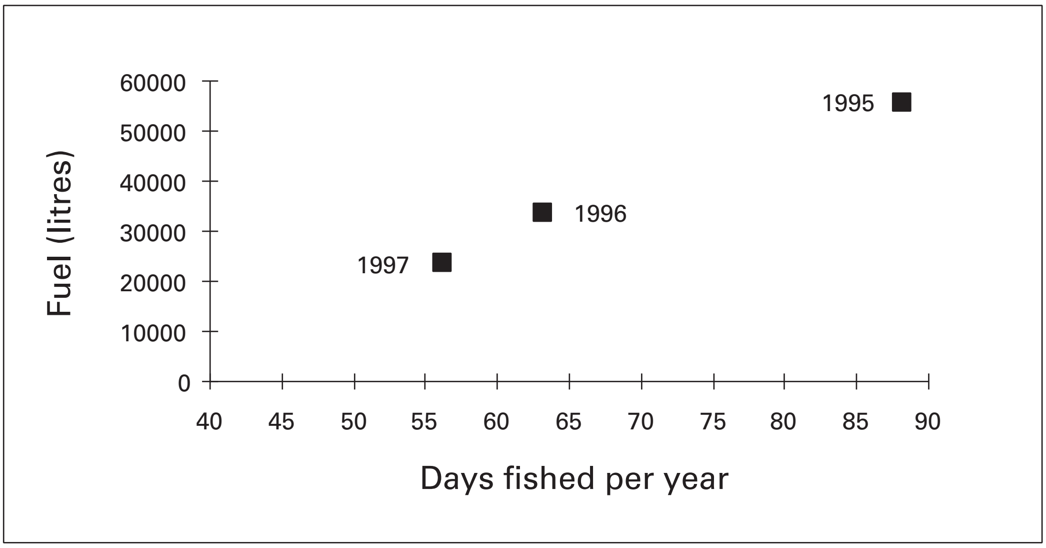


Figure 8.9 Relationship between fuel used and days fished for the 24 m vessel annually from 1995 to 1997, using the fuel data from Fisheries WA's compulsory catch and effort reporting system.

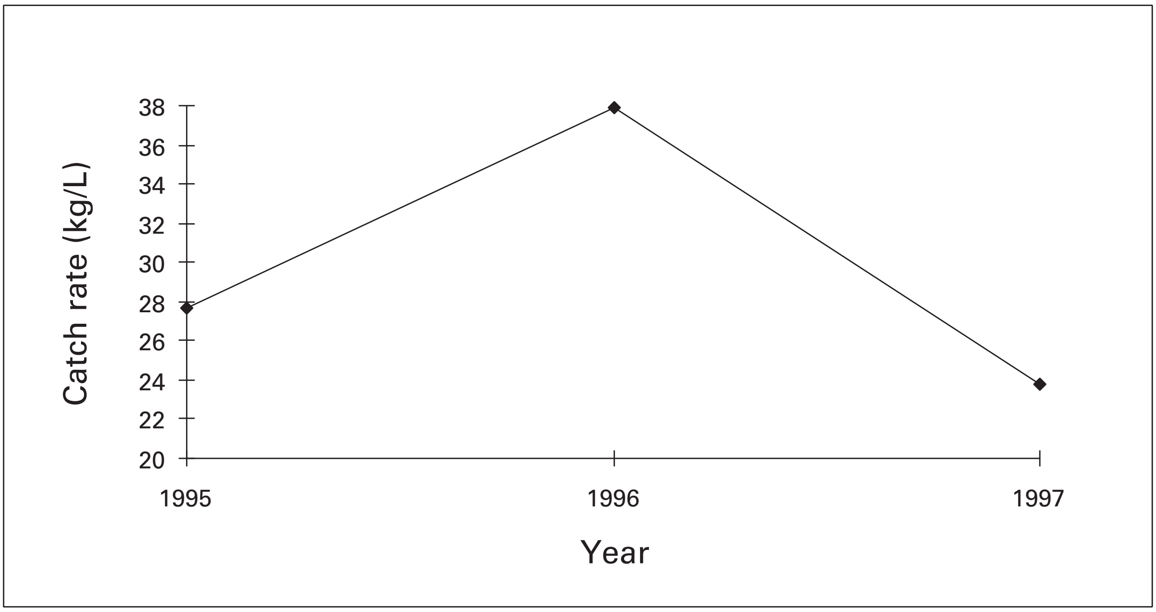


Figure 8.10 Catch rate (kg/L) of the 24 m vessel during the 1995-1997 fishing seasons, using fuel data from Fisheries WA's compulsory catch and effort reporting system.

8.3.2 Search times

Search time was recorded in hours for each trip and represented the time from arrival at the fishing grounds until a school of *S. lemuru* worthy of shooting the net around was located. Because *S. lemuru* were rarely caught in the inner/eastern side of Geelvink Channel, the time taken to steam through this area to the central or western part of the channel was not included as searching time. This was explained to the skippers during the development of the logbook.

The mean search times per fishing trip for 1995 were considerably higher than those in the following years (Figure 8.11). The decrease in search time resulted from an increase in experience at locating fish and familiarisation with the fishing grounds.

In 1995 the mean monthly search times for the 24 m vessel were relatively stable at 12 and 14 hours per trip for most of the season, but increased to 20 hours in September. During 1996, search time had decreased dramatically to less than four hours per trip in each month during the fishing season and there was little variability in search time between months. In 1997 mean search times progressively increased from only 1.8 hours in May to six hours per trip in August.

The increase in search time in late winter/early spring of 1995 and 1997 was reflected by decreases in the mean monthly catch rate (Figure 8.12) and was possibly due to *S. lemuru* leaving the area and thus becoming harder to find. That is, a seasonal change in availability. A similar substantial reduction in catch rate during September 1996, however, was not accompanied by a large increase in search time, suggesting reduced vulnerability of *S. lemuru* at this time, possibly linked to a decrease in the size of schools encountered to a level below what was considered to be economically worthwhile.

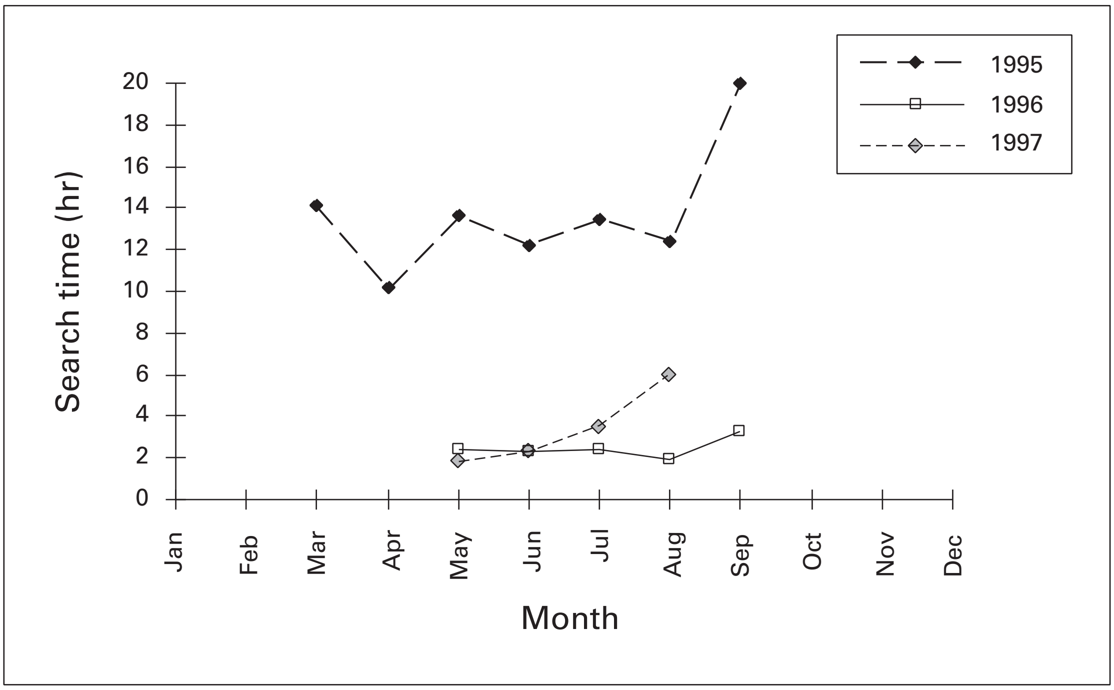


Figure 8.11 Mean monthly search time (hours) per trip for the 24 m vessel from 1995 to 1997.

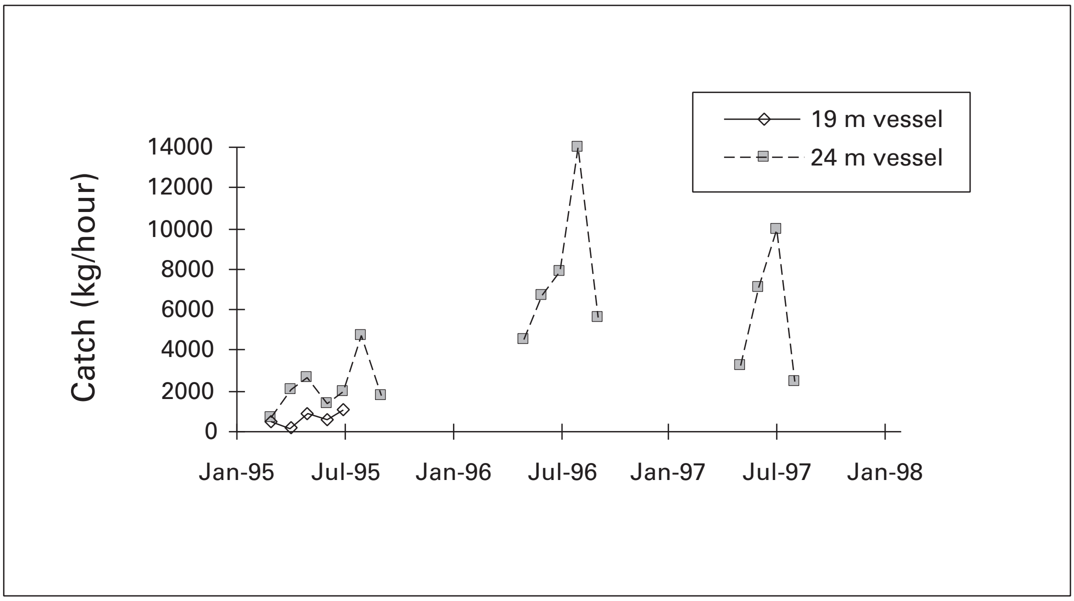


Figure 8.12 Mean monthly catch rate (kg/hour searched) for *S. lemuru* from 1995 to 1997.

In 1995 the 24 m vessel recorded a maximum monthly catch per hour of 4,724 kg in August. By 1996 the catch per hour of searching had increased beyond that for the same months from the previous year. Catch rates of 6,674 kg/hr and 7,840 kg/hr were recorded in June and July, followed by the 1996 peak of 13,975 kg/hr in August. Catch rate declined in September to 5,647 kg/hr.

During 1997, catch per hour of search in May was 1,300 kg/hr lower than in May 1996, while that for June had increased by the small amount of 468 kg/hr. In July 1997 there was a 2,160 kg/hr increase over July 1996, but during August 1997 the catch per hour of search fell dramatically by 11,400 kg/hr to 2,500 kg/hr. This large decrease in August 1997 was reflected by the annual catch per hour, which decreased from 8,574 kg in 1996 to 5,279 kg in 1997 (Figure 8.13). Despite the decreases, the overall mean search time was similar for both years (2.56 and 2.27 hours).

Catch per hour was thus markedly higher in the two years after 1995, particularly for the peak catching months (Figure 8.12). The same pattern was also evident when the annual means for this same data set were examined (Figure 8.13). However, as with catch per day, the annual catch per hour decreased in 1997 from the peak in 1996. Thus, the two estimates of catch rate based on a temporal measure of effort, showed evidence for a decrease in abundance of *S. lemuru* schools at the fishing grounds in Geelvink Channel. Therefore, the same trend of a marked decrease in catch per litre of fuel from 1996 to 1997, provides further evidence for a decrease in abundance of *S. lemuru*.

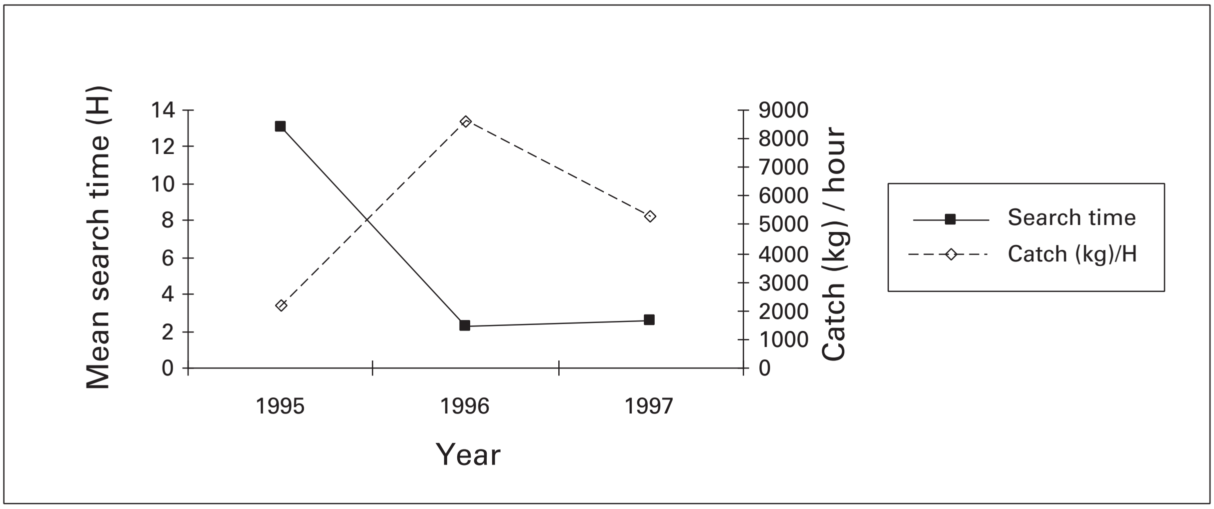


Figure 8.13 Mean annual search time per fishing trip and catch rate (kg/hour) for the 24 m vessel from 1995 to 1997.

8.3.4 Number of schools observed

June and July were the two most successful fishing months in any year, however, there were fluctuations in the mean number of schools observed per hour of searching (schools/hour) during these two months between the three years of the study (Figure 8.14).

In 1995 there was very little variation in the values for June and July, with 0.570 and 0.574 schools/hour respectively. In 1996, the values for June and July were twice those of 1995, at 1.23 and 1.07 schools/hour respectively. Then in May and September of 1996 the values were both about 0.46 schools/hour. In 1997, the value for May increased to 2.2 schools/hour, then decreased slightly in June and July to 1.7 and 1.6 schools/hour, before dropping further to 0.16 schools/hour in August.

The irregularity of the schools/hour between months within a year showed the cyclical nature of the fishery. During the peak months, the gradual increase in schools/hour may have reflected increased abundance or availability (e.g. formation of bigger schools) at these times and was consistent with the catch rates. However, the interannual differences were not consistent with catch rates. In 1997, the decreases in kg/day and kg/hour suggest fewer schools were present in the fishing grounds than in 1996. Counts of the number of schools per hour appears to be of little use as an indicator of abundance. It is possible that the sightings of more schools per hour in 1996 and then in 1997 resulted from increased knowledge of the behaviour of *S. lemuru* in Geelvink Channel.

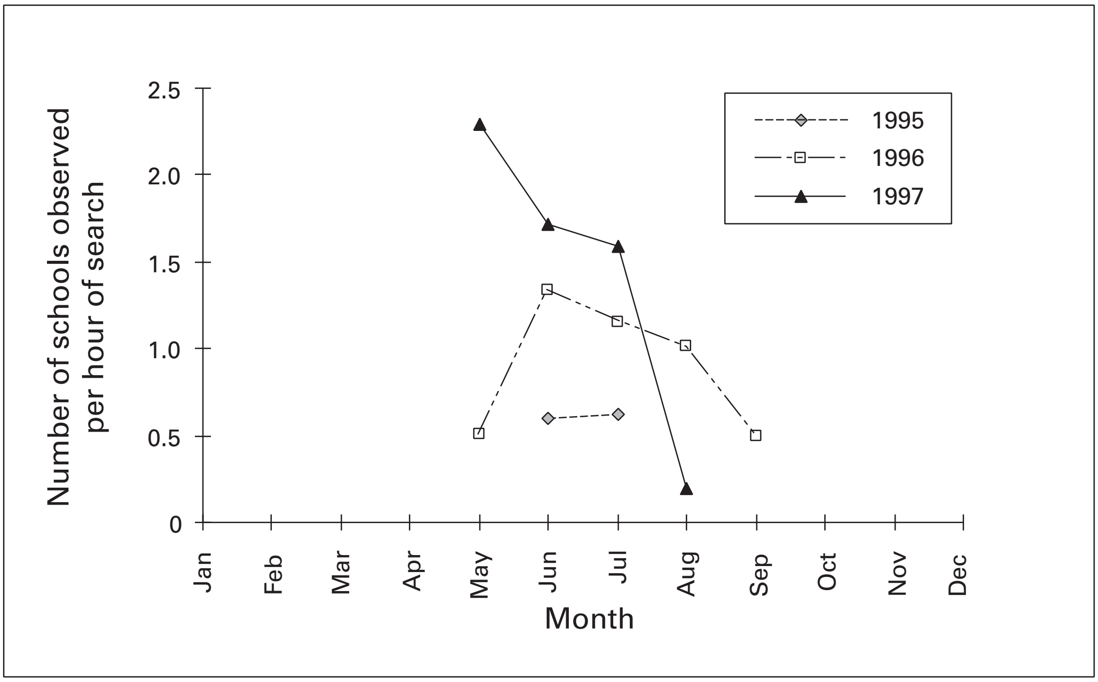


Figure 8.14 Mean number of *S. lemuru* schools encountered per hour of searching for each month from 1995 to 1997.

8.4 Commercial fishing area

Most purse-seine fishing effort and catch of *S. lemuru* in the mid-west coast purse seine fishery, occurred in the central regions of Geelvink Channel, east of the Abrolhos Islands (Figure 8.15). Local fishers who work near the Abrolhos contend that schools of *S. lemuru* very rarely occur close to the islands. The catch data support this observation with only a few schools caught close to the islands (< 2 km).

Areas inshore of this region, towards Geraldton, were probably also 'searched', at least in a cursory fashion, during passage out to the main fishing grounds. However, although sporadic catches were made within a few miles of the coast both north and south of Geraldton, aggregations of *S. lemuru* were apparently not as consistent in this inshore region.

The offshore extent of the fishing grounds was largely limited by a marked increase in the number of potential snags (i.e. rough bottom, potentially hazardous to netting) to the west. Indeed, even within the main fishing grounds the fleet recorded dozens of uncharted snags, noting that some areas of relatively flat substrate may still contain sufficient hard structure to snag a net.

The location of the main fishing grounds was also limited to within a few hours steaming from port. Even with an ice slurry, the catch needed to be returned to port within several hours of capture or could suffer serious deterioration, particularly as a further several hours were typically required to unload the catch. The area to the south of the fishing grounds was avoided due to significantly greater exposure to ocean swells.

Large numbers of catches were recorded from relatively few of the 5 n mile x 5 n mile (82.5 km^2) blocks designated in the logbook, which, in simplest terms, indicated that *S. lemuru* were very catchable (available and or vulnerable) in particular areas. This may have been due to localised areas of high abundance (for whatever reason) combined with suitable substrate for setting a purse seine net.

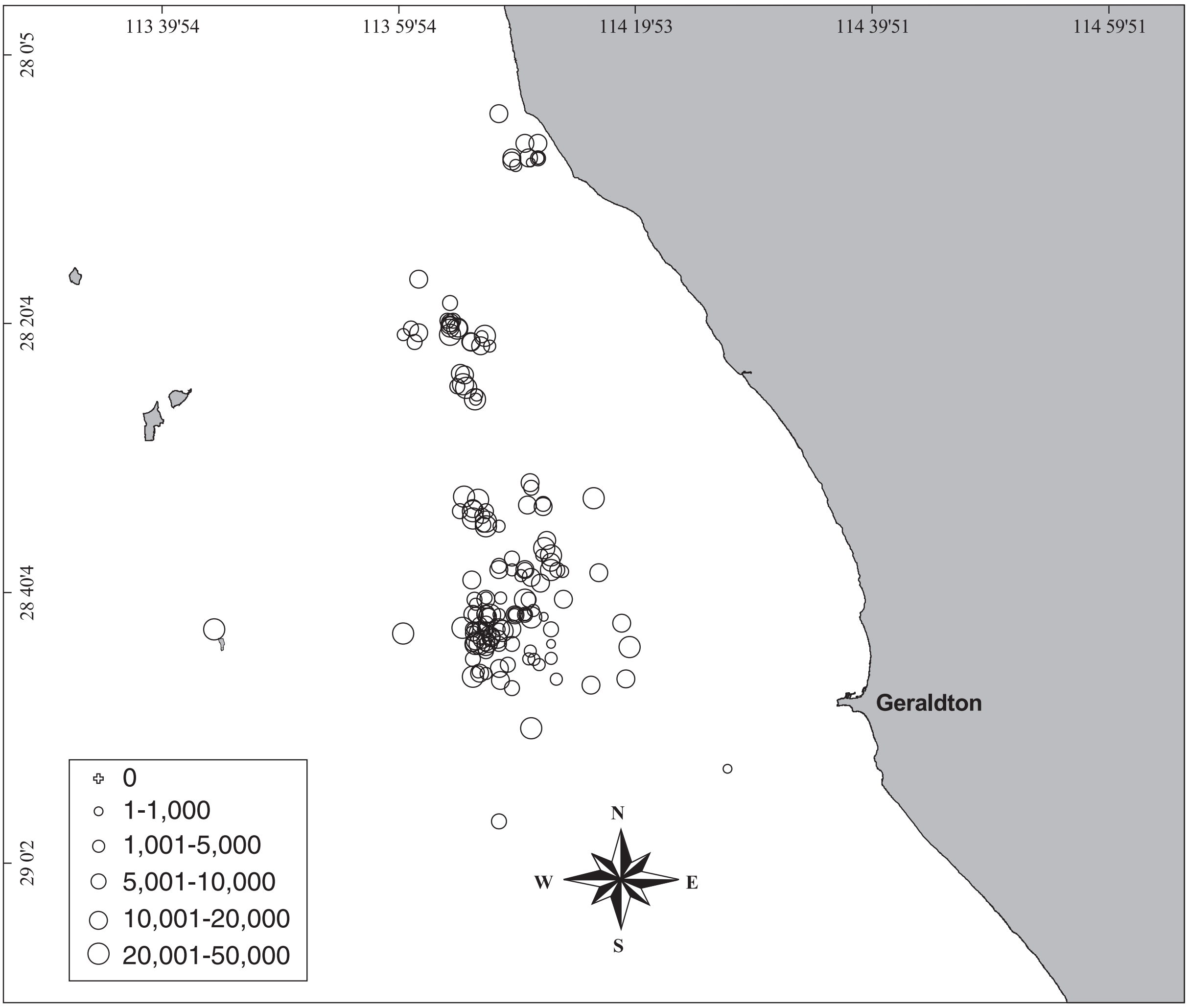


Figure 8.15 Locations of captures of *S. lemuru* in the mid-west coast purse seine fishery. Catch units are in kilograms.

8.5 Incidence of zero catches

There were 37 days (12% of total) through the 1995-1997 fishing seasons when no schools were found (Figure 8.16). Zero catches were sporadic and occurred more often outside the peak fishing months of June and July.

Another factor which affected fishing success was whether or not the fish formed sufficiently large and dense schools. For example, a large school was not worth targeting if it was sparsely spread over a relatively large area. The skipper used his experience to estimate the size of a school based on the sonar image and decide whether or not to shoot the net. Only larger schools (greater than 10 tonnes) were typically targeted. However, if there were only a few schools around during a particular time of year, then smaller schools would be targeted.

The typical pattern observed by fishermen was that the *S. lemuru* began to aggregate in the late afternoon/early evening and remained in relatively dense schools for several hours before dissipating after midnight. However, there were occasions when *S. lemuru* remained scattered throughout the water column and did not school-up at all during the night. There was no obvious seasonality to this behaviour (Figure 8.16). *Sardinella lemuru* remained scattered and could not be purse-seined, which resulted in zero-catches on 7.2 per cent of fishing trips.

The position of a school in the water column was noted prior to capture, based on the sonar and sounder readings. Position of a school was designated as surface (0-10 m depth), mid-water (10 m depth to 10 m from bottom) and bottom (within 10 m of the bottom). From a total of 145 observations of school position, six were at the surface, 91 at mid-water and 48 at the bottom. This indicates that not only were deeper schools targeted, but that they were targeted regularly. So, although fish located "hard against the bottom" did not represent good targets, often being spread as a relatively thin layer (e.g. a few metres or less) over a relatively wide area, schools in the lower water column represented a viable target and contributed substantially to the total catch. Between 1995 and 1997 there were few occasions (2.9% of trips) when the net could not be shot because schools were only found close to the bottom and in an area where attempting a shot may have resulted in a damaged net.

The final factor relating to zero catches was the presence of predators in or near the school. On most occasions the school targeted was monitored for several minutes with the sonar as the boat was positioned (e.g. with respect to wind direction) prior to deploying the net. On many occasions the school was noted to be under attack by large predators such as sharks and dolphins. These predators can scatter large schools apart or cause a school to be very 'flighty' and unpredictable in their direction of travel. Schools under attack from predators will also change their depth in the water column very quickly. The combination of scattering and or rapid changes in position can at times make it very difficult to target schools of *S. lemuru*. The presence of predators resulted in zero catches for 7.2 per cent of the fishing trips from 1995 and 1997. The only months when predators were observed amongst aggregations of *S. lemuru* were June and July, the peak catching months. During one trip, a school of 8-9 tonnes of *S. lemuru* was captured. Once the fish had been pursed-up and bunted close to the boat, several species of shark, including bronze whalers, hammerheads and tigers, were observed attacking the net. Dolphins could also be seen feeding on fish that escaped from the net. At any one time, between 15 and 20 large predators could be seen around the net feeding on *S. lemuru* which escaped. It appears that the higher concentrations of *S. lemuru* during June and July which generate high catch rates for the commercial fishermen, also attract large concentrations of predators.

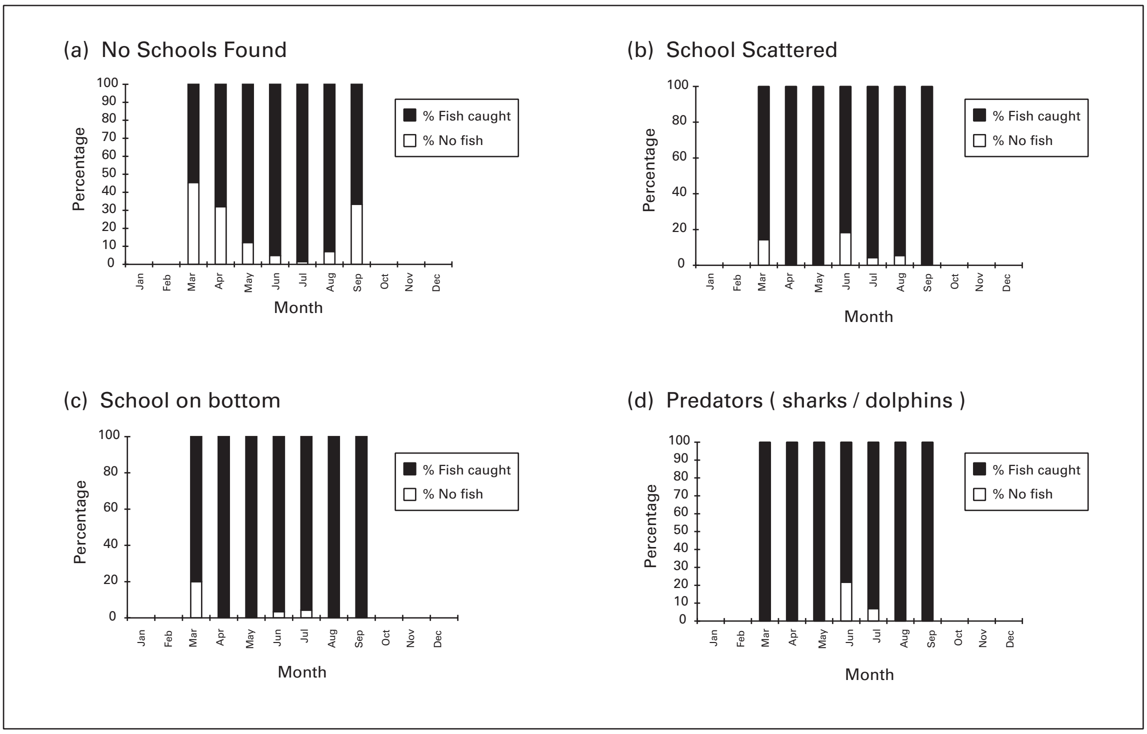


Figure 8.16 Percentage of fishing days in each month when no fish were captured, during the combined 1995-1997 fishing seasons. (a) no schools found, (b) schools scattered, (c) school on bottom and (d) predators (dolphins/sharks).

8.6 Days not fished

Both vessels lost a high number of days during the fishing season due to bad weather, repairs and inability of factories to accept more fish (Tables 8.1 and 8.2). During the 1995 season, the 24 m vessel lost 52 per cent of potential fishing days and the 19 m vessel lost 65 per cent. The number of lost fishing days for the 24 m vessel decreased in 1996 to 43 per cent of the season, then rose again in 1997 to 47 per cent.

Bad weather

Strong winds were a major cause of lost fishing time, accounting for 21 and 24.5 per cent of lost fishing days for the 24 m and 19 m vessels, respectively, in 1995. While the influence of poor weather on effort for both vessels appeared similar in 1995, an important factor not directly apparent from the logbook data was that when fishing was attempted in moderate wind conditions, the smaller vessel was much less efficient than the 24 m vessel. In particular, the larger vessel had considerably more freeboard, and could purse the net more easily, since purse seine vessels typically lie beam-on to the wind while hauling the net. Larger quantities of fish were therefore a safer option on the larger vessel. Furthermore, a large vessel allowed better advantage to be taken of the relatively infrequent calm days.

Thus, the 19 m vessel appeared to be unsuitable for the purse seine fishery operating off Geraldton. Linked to this was the low value of the product, problems with the size structure of the catch for the smaller vessel and the need to catch large quantities for the operation to be viable.

Repairs

The 19 m vessel lost 6.8 per cent potential fishing days due to repairs, whereas the 24 m vessel lost less than 1 per cent of fishing days. Although running repairs are always necessary, days lost to repairs are costly, particularly if they coincide with a period of good weather. Data for the 19 m vessel have not been presented for 1996, but it is important to note that a significant amount of time was lost due to major repairs on the vessel. Furthermore, time was also spent installing an onboard fish-sorter designed to separate out the more marketable, larger fish. This modification to the vessel subsequently met with limited success due to the lack of suitably large fish in the catches.

Table 8.1 Lost fishing days during the 1995 fishing season due to vessel repairs, rough weather and limits on processing capacity (i.e. full factory).

24 m vessel		19 m vessel	
Month	**Lost Fishing Days**	**Month**	**Lost Fishing Days**
Jan-95		Jan-95	
Feb-95		Feb-95	
Mar-95	21	Mar-95	16
Apr-95	21	Apr-95	18
May-95	12	May-95	19
Jun-95	19	Jun-95	23
Jul-95	13	Jul-95	19
Aug-95	8	Aug-95	
Sep-95		Sep-95	
Oct-95		Oct-95	
Nov-95		Nov-95	
Dec-95		Dec-95	

Table 8.2 Number of fishing days lost for the 24 m vessel in 1996 and 1997.

1996		1997	
Month	**Lost Fishing Days**	**Month**	**Lost Fishing Days**
Jan-96		Jan-97	
Feb-96		Feb-97	
Mar-96		Mar-97	
Apr-96		Apr-97	
May-96	3	May-97	10
Jun-96	17	Jun-97	8
Jul-96	11	Jul-97	17
Aug-96	14	Aug-97	6
Sep-96	1	Sep-97	
Oct-96		Oct-97	
Nov-96		Nov-97	
Dec-96		Dec-97	

Factory capacity

The standard practice employed by the Geraldton purse seine fleet for maintaining product quality, was to transport the product in an ice slurry, incorporating a chemical preservative, to onshore facilities which would then freeze the fish as quickly as possible. The processing abilities of the factories associated with each vessel were markedly different. This resulted in almost three times more days lost to "full" factories for the 19 m vessel over the 24 m vessel (20 days compared with 7). Although storage freezer space was fairly compatible, the limit in blast freezer space accounted for the higher number of lost days for the 19 m vessel. The fact that this occured at times when catches were best, indicated that peak monthly catches for this fishery could have been substantially higher.

Due to the limited fishing season, this probably impacted seriously on profit during 1995 and indicates the establishment of suitably large processing facilities is an important consideration for a developing fishery which targets high volume species. This is particularly crucial in warmer climates where product deterioration can occur quickly. However, establishment of high-volume freezer facilities is costly and represents a substantial investment. The establishment of large freezers can be economically risky in a developmental fishery because catches may not be as high as expected or a potential market(s) may not eventuate. Alternatively, lack of investment in processing facilities may result in the "sustainable" yield never being realised.

8.7 Discussion

8.7.1 Catch rates

The apparent decline in abundance of *S. lemuru* in Geelvink Channel, as indicated by three methods of estimating catch rate, is difficult to interpret due to the extremely short time series of data. Large decreases in stock size of clupeoids are typically attributed to environmental variations, heavy fishing pressure, or a combination of these (e.g. Sharp and Csirke 1983). These possibilities will be examined as more monitoring takes place. For example, although the history of exploitation of *S. lemuru* in the Geraldton region has been short (i.e. only a few years), the possibility of localised depletion having already occurred cannot be ignored. Alternatively, some members of the *Sardinella* genus are known to undertake seasonal migrations in response to environmental and biological conditions, with associated seasonal changes in catch rates (Mendelssohn and Cury 1989).

The decline in catch rates in the Geraldton region happened in the same extended period that *S. lemuru* became prevalent in the Fremantle region. Furthermore, *S. lemuru*, albeit an individual, was recorded in a catch of pilchards off Cape Naturaliste, 160 km south of Fremantle, for the first time in this same period. There is thus some evidence that a southward migration over an extended period (i.e. a shift or extension in distribution), rather than a strictly seasonal migration, occurred. This apparent shift occurs when water temperatures are relatively high in the Fremantle region, close to the southern extent of *S. lemuru's* range.

Interestingly, in contrast to the Geraldton fishery, commercial quantities of *S. lemuru* frequently occur close inshore at Fremantle (i.e. within a few kilometres of port). The protected embayment of Cockburn Sound may provide particularly good feeding conditions for *S. lemuru*, with annual catches having reached 900-1100 tonnes in 1984-1986. Interannual variability in the magnitude and duration of 'high' water temperatures along the lower west coast of WA, may thus be responsible for the sporadic occurrence and varying persistence of relatively large quantities of *S. lemuru* in the Fremantle region. Assuming these fish do in fact move into this southern area from further north, these events should accompany decreased abundance of *S. lemuru* in the Geraldton region.

While the causes for the decrease in catch rates in 1997 may not be fully understood, the important point for the fishery is whether or not catch rates will improve when fishing continues. This awaits further monitoring of the fishery, particularly with respect to the timing and duration of any improvements in future catch rates.

8.7.2 Development of the Geraldton purse seine fishery

The relatively few calm days necessitate that large catches be made whenever possible, therefore, purse seining in the Geraldton region, which aims at supplying a high volume market, requires a relatively large vessel. However, associated with the limited history of the fishery was uncertainty over whether or not large catches would continue. This dictated that it would be unwise to invest towards further substantial and rapid expansion of processing facilities, including freezing capacity, to levels that could accommodate substantially larger catches over even shorter periods.

The more successful operation in the mid-west coast developmental fishery was able to utilise existing freezer space and contracted, rather than purchased, a vessel. This practice meant that investments were more or less on a year-to-year basis rather than for the long term. For a fishery which targets sardines, which typically undergo large fluctuations in stock size over relatively short periods, this was a safer business option. In 1998 when, for various reasons, little or no profit was made from the target species, the business was able to continue essentially because it did not have an overly large capital investment, and hence repayment commitments, relying on the purse seine fishery. Given the apparent decline in catch rate from 1996 to 1997, and the lack of any fishing activity in 1998, this decision has been justified.

In at least the short term, factory capacity will likely continue to limit the catching ability of a large vessel in those calm periods at the peak of the catching season.

As strong wind is the primary cause of lost fishing days and as further large investments in freezers are unlikely for this fishery, it is likely that around 50 per cent of potential fishing days in a typical season can be expected to be lost. Furthermore, the obvious impact on effort-levels for even a relatively large, purpose-built purse seiner, suggests a higher proportion of days would by lost by smaller purse seine vessels working in Geelvink Channel.

Both licensees who participated in the developmental fishery had other business interests and hence were not totally financially reliant upon the *S. lemuru* resource. Although both invested heavily in the fishery, being a developmental fishery there has not been a problem with over-capitalization forcing unsustainable management, a problem seen in many of the world's large fisheries. The instigation of a three-year developmental period for this fishery and the limitation during this period to three licenses has, in retrospect, assisted in keeping investment at a reasonable level.

9.0 Conduct ichthyoplankton surveys to provide data for the daily egg production method from which estimates of the spawning biomass will be calculated

9.1 Plankton sampling

In the March 1994 survey (Shark Bay to Dongara) *S. lemuru* eggs were caught only in Geelvink Channel (Figure 9.1), indicating that spawning adults were located in this region of the mid-west coast at that time.

The series of monthly surveys between September 1995 and March 1996 confirmed that stocks of *S. lemuru* in the Geraldton region have a short spawning season which occurs in mid- to late summer. No *S. lemuru* eggs or larvae were obtained in Geelvink Channel between September and December 1995 (Figures 9.2a and b; 9.3a). Both were first recorded in early January 1996, with concentrations peaking in mid-February, at which time the spawning area (indicated by the number of positive stations) had increased (Figures 9.3b and c). By early March concentrations were again low and in late March 1996 only a single egg was found in the samples collected aboard RV *Franklin* (Figure 9.4).

While the monthly series of samples clearly indicated that spawning peaked in mid-February, the stations sampled were inadequate to cover the spawning area of *S. lemuru*. Thus, in the peak spawning month of February the largest concentrations of eggs occurred in an extensive "patch" at the northern limit of sampling, with smaller concentrations extending to the southern limit of sampling (Figure 9.2c).

In early March, when numbers of eggs were less, the highest concentrations occurred at the southern limit of sampling (Figure 9.2d), indicating the possibility of more extensive spawning south of the sampling area. If so, this confounds the concept of a very short period of peak spawning. That is, spawning may be more temporally extensive than suggested but this is possibly being masked by spatial shifts in the areas of peak spawning beyond the areas sampled. Not only do areas of spawning shift over relatively short periods, but may do so regularly and in an unpredictable manner.

As the 1994 survey from Shark Bay to Dongara only found *S. lemuru* eggs in the region between the Abrolhos Islands and the mainland (Figure 9.3), it was considered possible that spawning may not have extended too far beyond the sampling area covered between September 1995 and March 1996. Thus, it was not clear whether or not the apparent shifts in area of peak spawning were largely confined to the mid-west coast region, north and south of Geraldton, or whether they extended further along the coast. Unfortunately, the samples collected during the cruise aboard RV *Franklin* between Exmouth and Fremantle could not support either hypothesis since this cruise missed the spawning period.

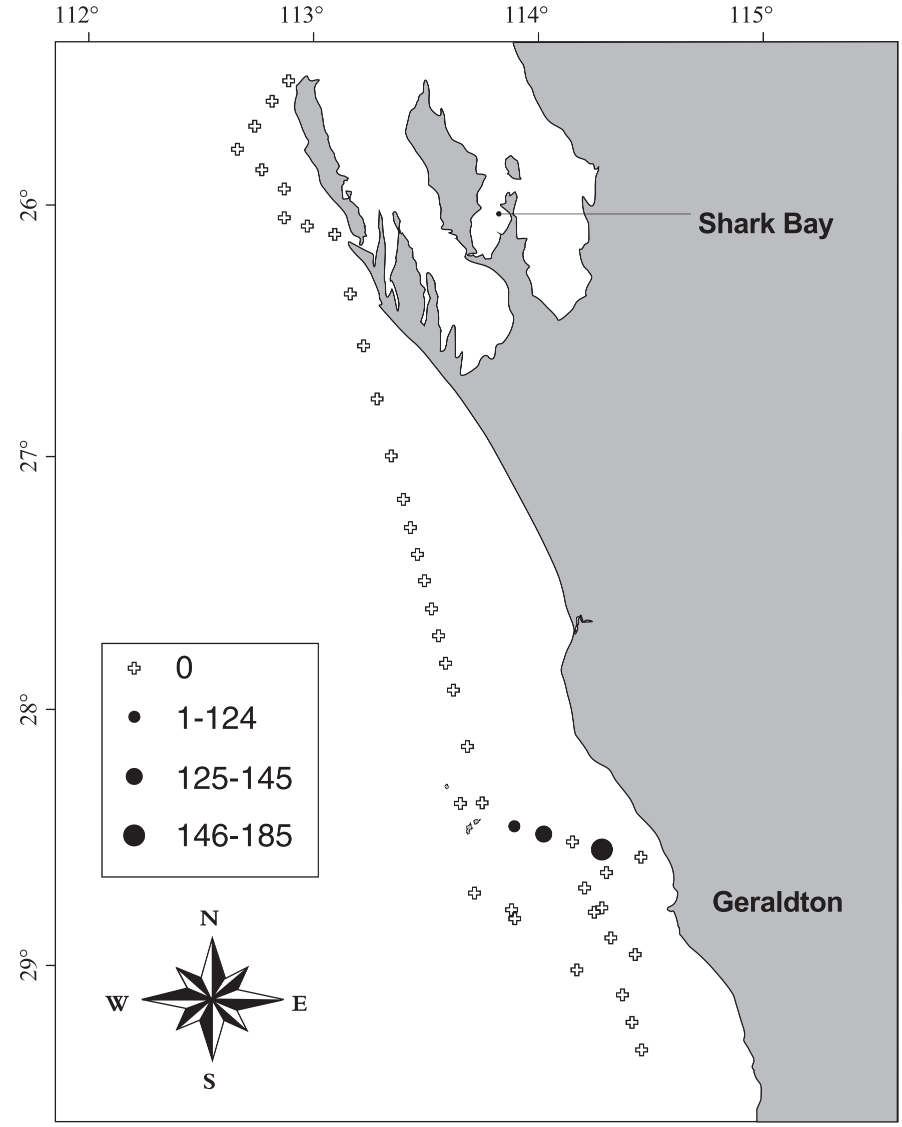
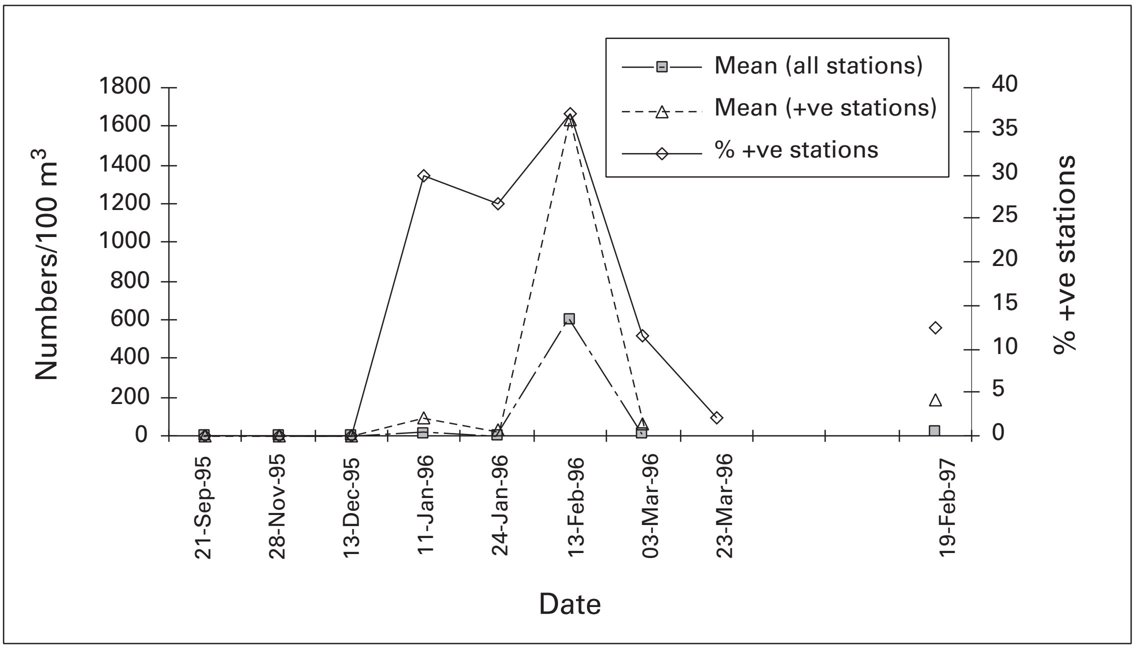


Figure 9.1 Concentrations of *S. lemuru* eggs (number/100 m^3) expressed using a relative scale for the plankton survey conducted between Shark Bay and Dongara in March 1994. Spawning area is 490 km^2.

(a) Eggs



(b) Larvae

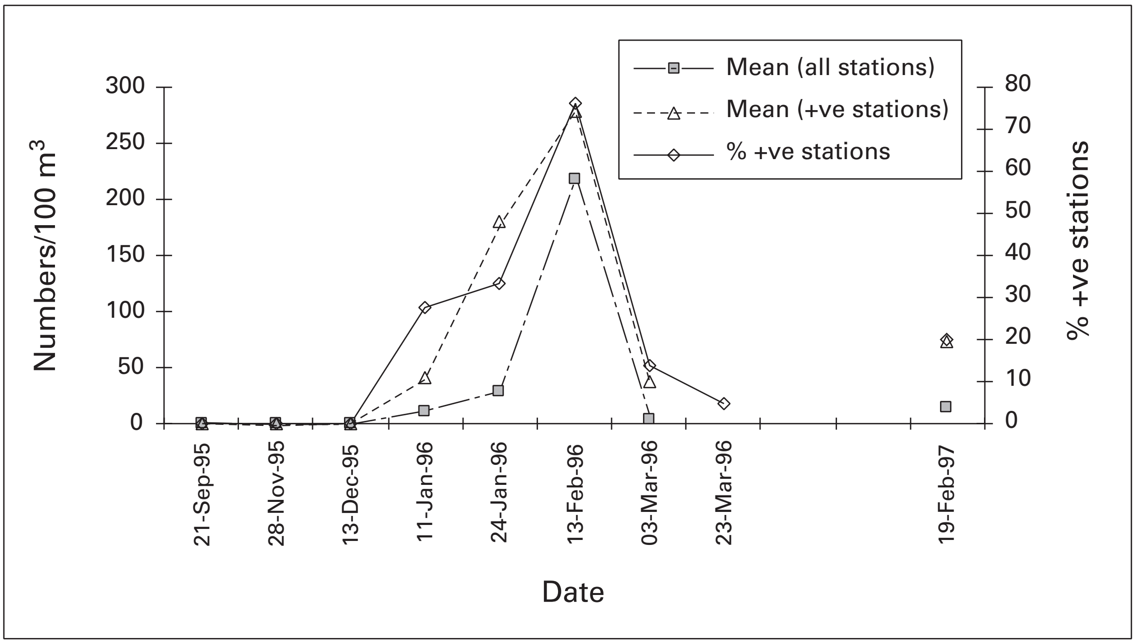
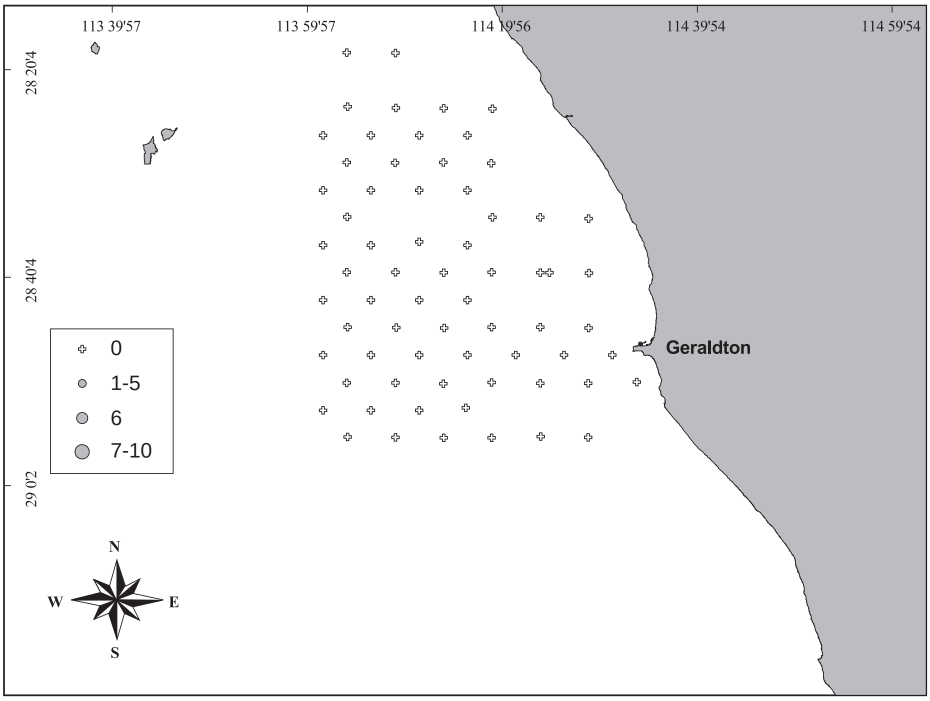


Figure 9.2 Monthly relative occurrence (% positive stations) and mean monthly concentration (number/100 m^3) both with and without negative stations (i.e. zero counts) of *S. lemuru* (a) eggs and (b) larvae.

(a) September–December 1995.



(b) January 1996. Spawning area is 708 km^2

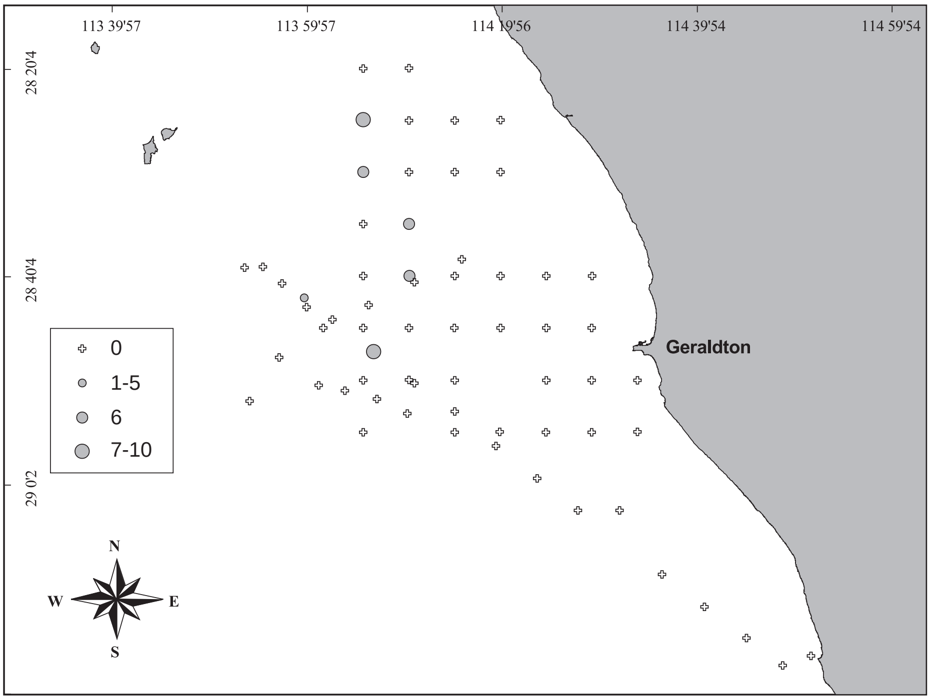
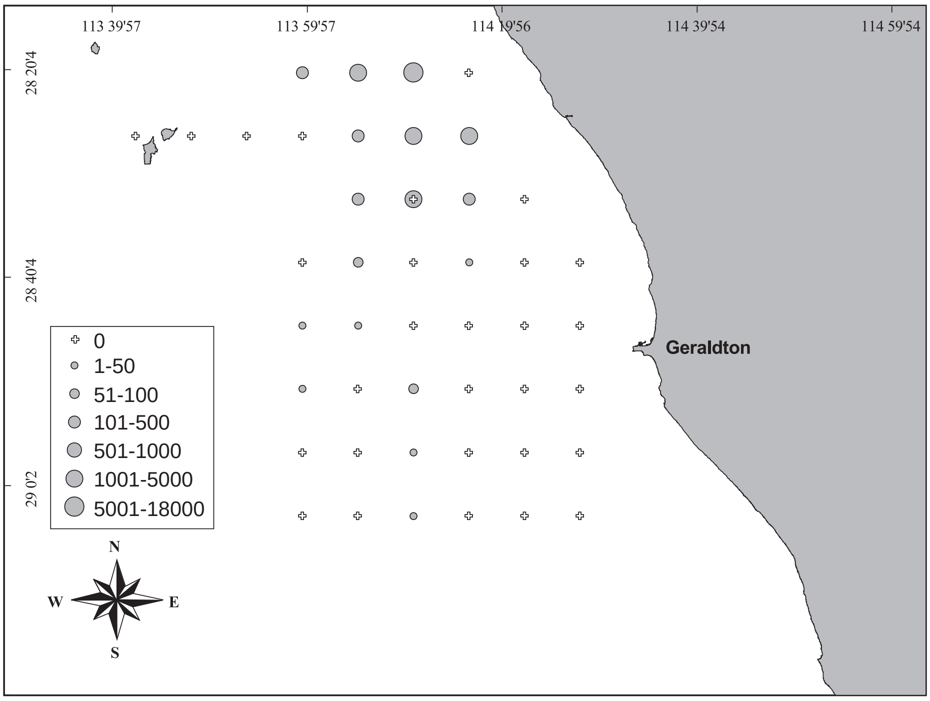


Figure 9.3 Concentrations of *S. lemuru* eggs (number/100 m^3) expressed using a relative scale for plankton surveys conducted in (a) September, November and December 1995, (b) January 1996, (c) February 1996 and (d) March 1996.

(c) February 1996. Spawning area is 1,865 km².



(d) March 1996. Spawning area is 454 km²

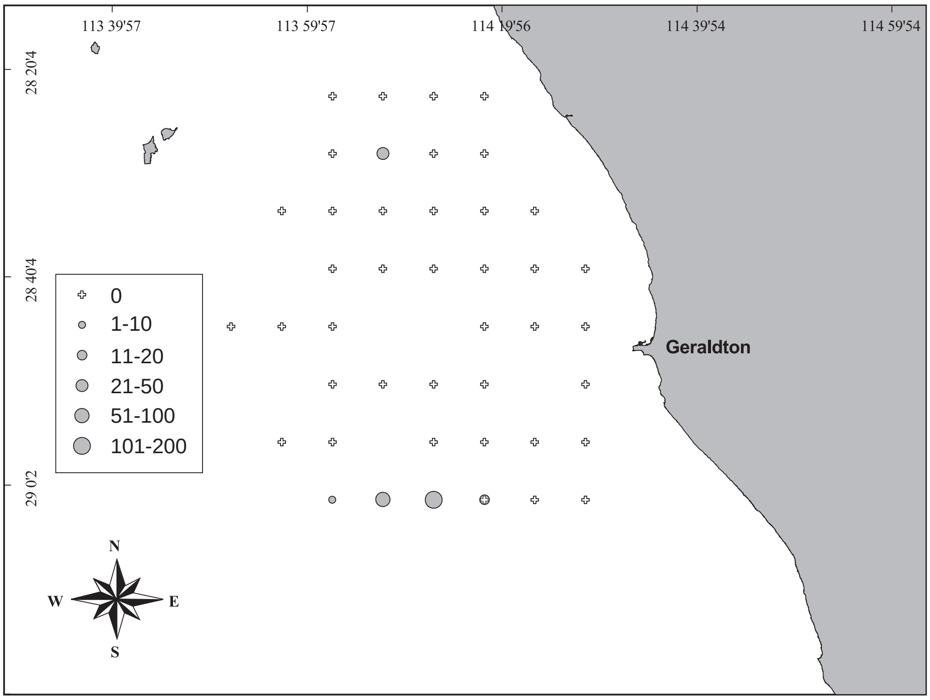


Figure 9.3 (cont'd).

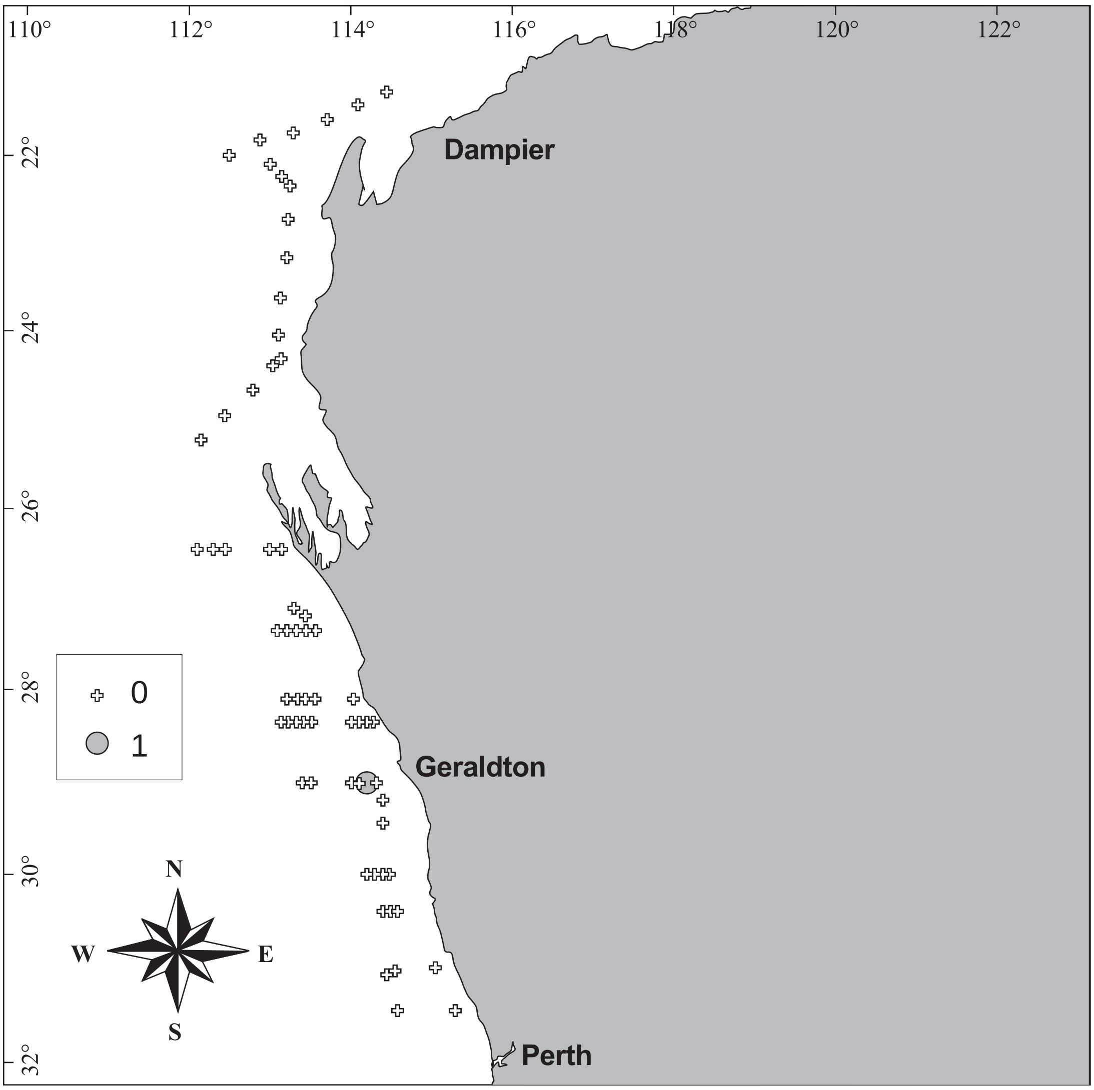


Figure 9.4 Locations of plankton sampling conducted between Dampier and Fremantle in late March 1996. Note that only a single *S. lemuru* egg was captured.

9.2 Culturing of *S. lemuru* eggs

The eggs identified as being those of *S. lemuru* and cultured onboard RV *Flinders* were captured at 1400 hours. At this time most were at a stage of development equivalent to that of stage 6 for the pilchard, *S. sagax* (White and Fletcher 1998). Based on the developmental rates of pilchard eggs in the cooler waters off southern WA, coupled with the fact that sardines typically spawn at night, it was assumed these eggs had been spawned the previous night. Assuming spawning at mid-night, the eggs were thus around 14 hours old at time of capture.

Development of these eggs was monitored closely until around the following mid-night at which time many had hatched, with most hatching complete two hours later. Therefore, this indicates that *S. lemuru* eggs develop and subsequently hatch into larvae in approximately 24 hours, plus or minus a few hours.

9.3 Plankton sampling for the February 1997 DEPM survey

While the need to sample to the north and south of the commercial fishing area during the DEPM survey was recognised prior to the start of this project, and was justified by the results of the initial sampling, the large variation in time of peak spawning proved to be problematical.

Plankton sampling for the 1997 DEPM survey indicated that spawning of *S. lemuru* was more widespread than anticipated. The usefulness of the survey design was compromised by the fact that the entire spawning area for the stock could not be estimated because relatively large concentrations of eggs occurred at the northern, southern and offshore boundaries of the sampling area (Figure 9.5). However, by far the largest continuous patch of eggs occurred east of the Abrolhos Islands, in a similar location to the region of highest egg concentrations found in February 1996, which indicated a certain level of continuity in the spawning region for *S. lemuru* offshore of Geraldton.

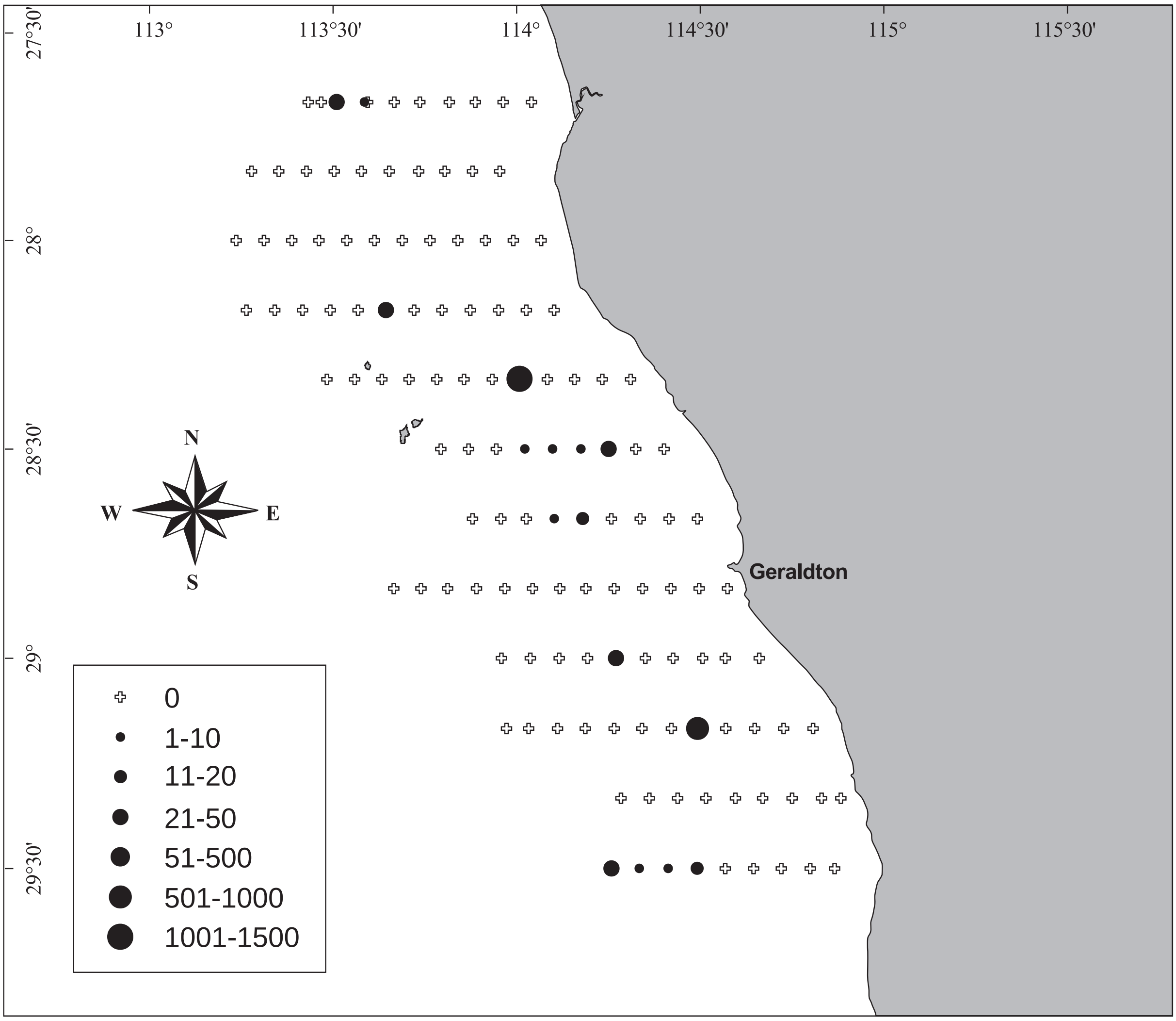


Figure 9.5 Concentrations of *S. lemuru* eggs (number/100 m^3) expressed using a relative scale for the plankton survey conducted between Kalbarri and Dongara in February 1997. Spawning area is 2,308 km^2.

The distribution of *S. lemuru* eggs suggested that the stock is widespread along the mid-west coast of WA, predominantly across the outer half of the continental shelf, with a large aggregation perhaps located in Geelvink Channel. While there had been anecdotal evidence for large schools of small pelagic fish to the north of the Abrolhos Islands, further discussions with licensees subsequent to the survey, indicated that large concentrations also occurred to the south. However, it was also pointed out that it was not known if these baitfish were *S. lemuru*.

Although there was a reasonable spatial distribution of *S. lemuru* eggs in the February 1997 survey, the numbers collected were not large. Furthermore, due to the relatively short development time, the range of developmental stages obtained was also small, with most eggs being more advanced than stage 6. This, in turn, resulted in insufficient data to estimate egg production with any degree of accuracy. Thus, whereas a CV for an estimate of egg production would hopefully be less than 0.4 (e.g. Fletcher *et al.* 1996), that obtained for the February 1997 egg data was 2.6, which was unacceptably high.

As the CVs associated with the DEPM parameters of egg production and spawning fraction are typically greater than those for the other parameters, large confidence intervals around either (or both) will result in a large range around the best estimate of spawning biomass.

9.4 Discussion

9.4.1 Application of the daily egg production method to estimate spawning biomass

The two significant problems with sampling adult *S. lemuru* during the 1997 and 1998 DEPM surveys were (1) the small number of samples obtained and (2) the samples obtained indicated that the peak spawning period had been missed.

A pre-requisite for any DEPM survey is that it must be conducted close to the time of peak spawning. The main problem encountered with predicting spawning times for the DEPM survey was the difficulty in obtaining samples of *S. lemuru* prior to the spawning months, which would have allowed changes in GSI to be closely monitored. Commercial vessels were not operating at these times and the availability of Fisheries WA's RV *Flinders* was limited. As the RV *Flinders* had to be booked up to a year in advance and was not available to sample *S. lemuru* in the months leading up to peak spawning, historical GSI values had to be used to predict the time of peak spawning. However, during the DEPM survey in February 1997, the mean GSI for females was 0.72 and in February 1998 was only 0.75. These low GSI values, estimated in February of 1997 and 1998, represented a huge reduction in mean GSI compared with GSI values for Februaries of earlier years, when it was considerably higher (~ 4.7). These low GSI values also indicated that there was comparatively little spawning activity when the surveys were attempted. This confirmed the general lack of spawning activity observed in freshly caught *S. lemuru* aboard RV *Flinders*, and justified not conducting the plankton survey in 1998. Thus, for two consecutive years the peak spawning period was not identified.

The purpose of the mid-water trawling aboard RV *Flinders* was to catch *S. lemuru* so that the adult parameters could be estimated. However, the number of samples obtained in February 1997 (n = 7) and 1998 (n = 6) was insufficient in each case to obtain reliable estimates of adult parameters, with the recognised minimum number of samples for this type of survey being 35 (Alheit 1993). Note that besides the limited numbers of samples obtained, the area sampled in each year was also limited and thus it is possible that the peak spawning area was missed, although there is no evidence for this.

Finally, estimates of fecundity were only available for *S. lemuru* collected prior to the project (1990-1994) and these were for fish which weighed between 85 and 128 g, considerably higher than the average weight of females collected during the study period (i.e. ~40 g). Because of this large size difference and since fecundity of sardines can vary between years, no estimate of fecundity was available for the DEPM method.

This lack of success with the adult sampling essentially nullified any possibility of obtaining even an approximation of the spawning biomass. Thus, while a reasonable estimation of average weight could be obtained from the adults caught during the survey, and sex ratio could be determined from the longer term data for this species, the imprecision expected with an estimate of spawning fraction from a sample of only seven and the lack of fecundity data meant that the estimate of spawning biomass would have very large confidence intervals.

In summary, a combination of the very small sample size of adults, the fact that the peak spawning period (or area) was missed, and insufficient egg data from which to obtain an estimate of egg production, meant that it was not worth pursuing an estimate of spawning biomass using the DEPM technique.

9.4.2 Spatial extent of spawning

The spawning area for various surveys was estimated from the distribution of positive stations (i.e. ≥ 1 egg). Polygons were drawn around groups of positive stations, or isolated positive stations, with the extent of each polygon being defined by the distance between transects and between stations along transects. In those cases where a negative station was embedded, or partially embedded, within a group of positive station then this was also considered to represent part of the spawning area.

Spawning area at those times when spawning was not at its seasonal peak was generally around 400-700 km^2 (Figures 9.1, 9.2b and d) In February 1996 when spawning activity was more substantial, the spawning area was 1,865 km^2 (Figure 9.2c), representing 2-3 times the area recorded in the previous and following months.

During the more extensive survey of February 1997 the spawning area was 2308 km^2 (Figure 9.5). While this represents the best estimate of spawning area for *S. lemuru* along the mid-west coast, it is obvious that the 1,865 km^2 estimated for February 1996 resulted from a considerably smaller sampling area. Thus, the February 1997 estimate may under-represent spawning area since the peak spawning period was missed.

The estimates of spawning area and the patterns of egg distribution, do not provide evidence of a large and extensive stock, but rather of a dispersed stock with relatively large distances between what are possibly quite small aggregations.

10.0 Environmental conditions - influence on the biology of *S. lemuru* and the developmental fishery

Note that much of the material on environmental conditions presented in this section has been taken from the comprehensive review paper "The Leeuwin Current and the Houtman Abrolhos Islands" (Pearce 1997).

10.1 Wind

Seasonal variation in the climate of the Abrolhos Islands is largely a result of the meridional shift in the axis of the subtropical high-pressure belt (Scott 1983). During summer, the high-pressure ridge lies well to the south and the local winds are dominantly southerly. During autumn and winter, the ridge migrates northwards and as a result of the shifting high pressure cells the winds are highly variable (Pearce 1997). The ridge returns southwards during spring and the southerly winds return.

The mean annual 1500 hours wind speed is 23.61 km/hr (6.6 m/s) at Geraldton, very similar to the 24.44 km/hr recorded at North Island. However the mean 09:00 wind speed for the year at Geraldton is 18.4 km/hr (5.1 m/s) compared with 24.49 km/hr (6.8 m/s) at North Island. This indicates the winds at the islands are more persistent than on the mainland. Although there was some variation in wind speed and direction at Geraldton, the winds at the islands blow predominantly from the south with little variation in strength or direction. It is also evident that there is much greater variability in wind direction on the mainland coast than at the islands (Figure 10.1). The greatest variability in wind direction at the islands occurs during the winter months.

On the mainland, the morning wind direction during the hotter summer months is predominantly easterly (NE, E or SE). However, by 1500 hours the wind is nearly always from the south, with diurnal heating and cooling of the land resulting in a distinctive sea breeze pattern on the mainland coast.

The winds at the islands also show a diurnal pattern, however it is not as pronounced as that on the mainland coast. The data also show that the afternoon winds at the islands during the summer months are strong (often > 30 km/hr) and from the south.

(a)

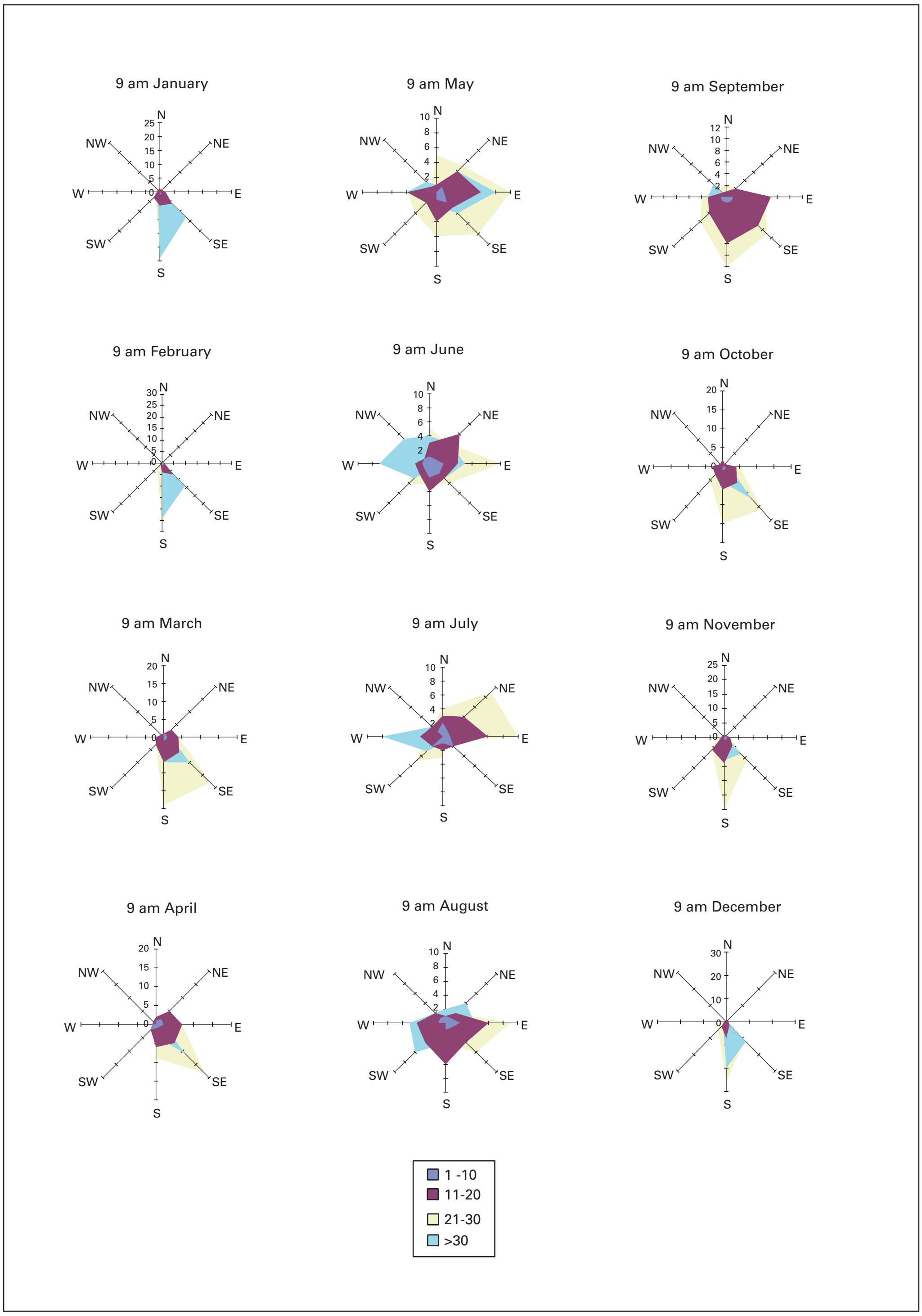


Figure 10.1 Monthly mean wind speeds recorded for (a) 9 am North Island, (b) 3 pm North Island, (c) 9 am Geraldton and (d) 3 pm Geraldton. Data are displayed as wind-strength intervals (km/hr) with the percentage of observations falling within compass direction shown.

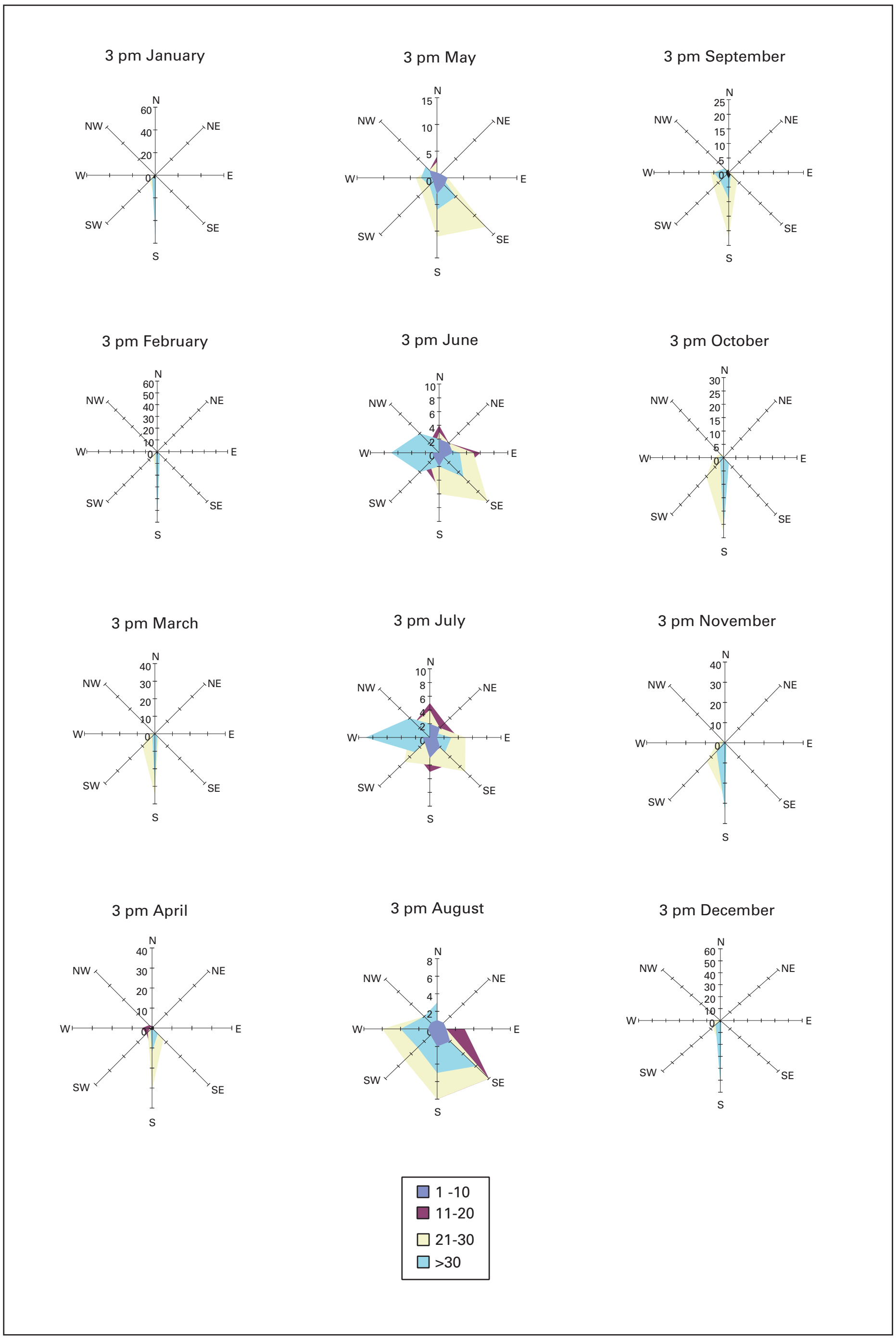


Figure 10.1 (b) 3 pm North Island.

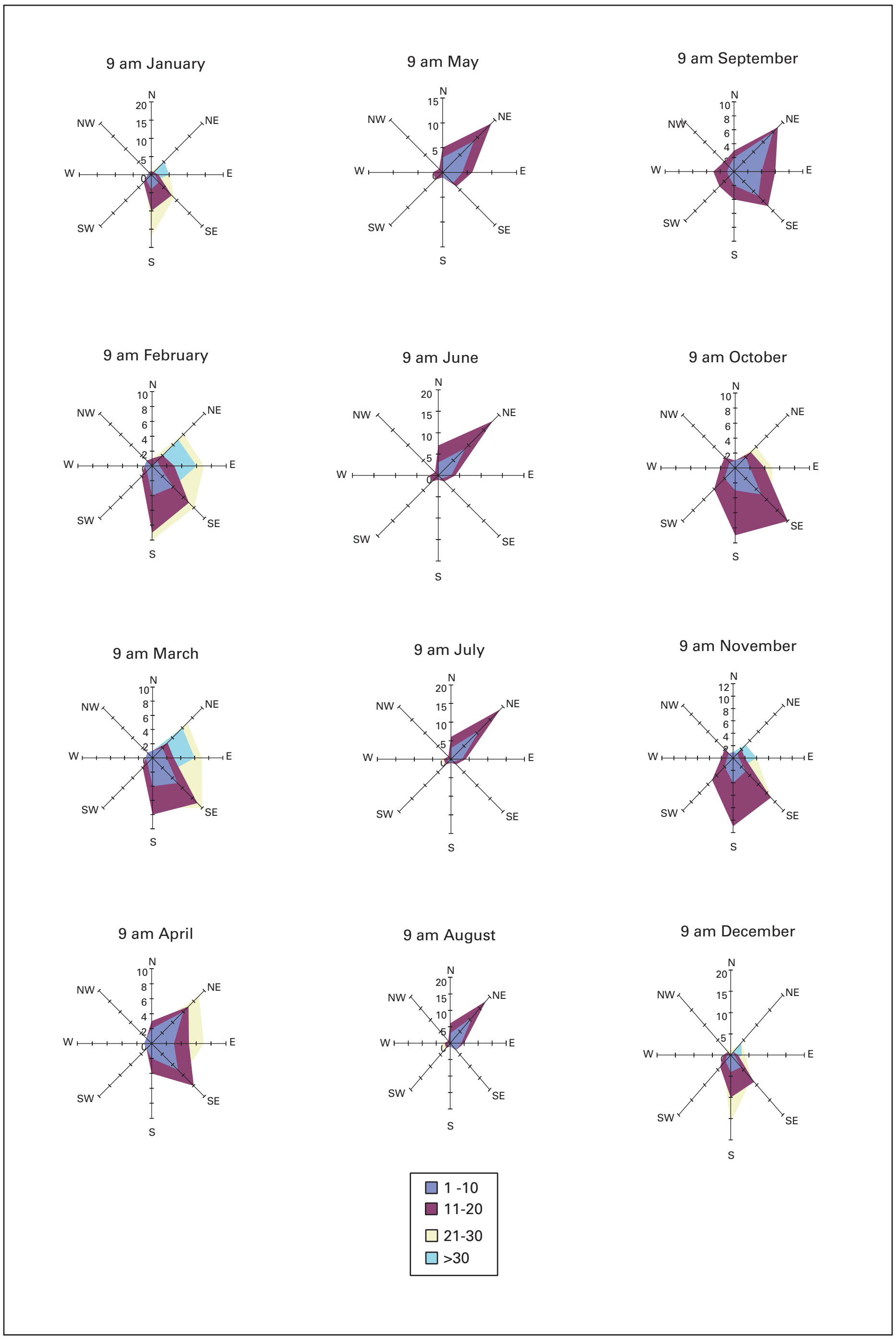


Figure 10.1 (c) 9 am Geraldton.

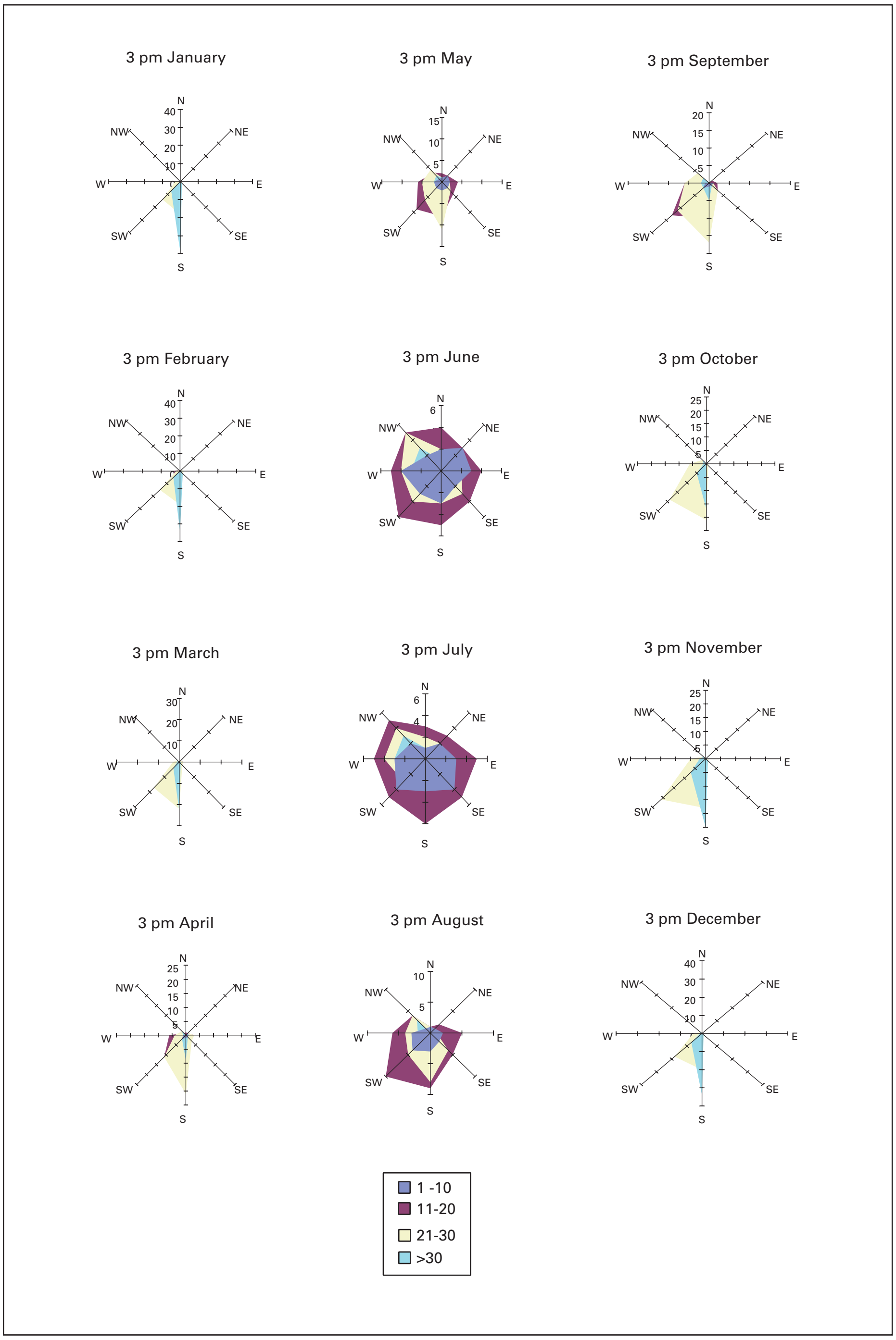


Figure 10.1 (d) 3 pm Geraldton.

Interestingly, the 09:00 wind direction on the mainland is predominantly north-east, which is markedly different from that at the islands during the winter months. However, at the islands there is much greater variability in direction and winds are significantly stronger. During the winter months on the mainland coast, the strong winds are normally associated with frontal systems and wind direction is west to north-west. At the islands the variation in direction for strong winds ranges from east clockwise to north-west.

In conclusion, the winds at the islands are more persistent and stronger than those encountered on the mainland coast (Tabel 10.1). The afternoon winds, in particular, are consistently from the south for much of the year and it is in the late afternoon/evening when most of the fishing effort is applied in the *S. lemuru* fishery. It is these dominant, strong southerly winds that persist throughout most of the year that results in many lost fishing days (section 3.5).

The southerly winds during summer results in a net northwards drift of water in Geelvink Channel which flows at about 10 cm/s (Cresswell *et al.* 1989).

Table 10.1 Monthly mean 0900 hours and 1500 hours wind speeds (km/hr) recorded at a) Geraldton and b) North Island. Monthly data recorded in Geraldton from 1941 and North Island from 1990.

a) Geraldton

Month	Mean 09:00 Wind Speed (km/hr)				Mean 15:00 Wind Speed (km/hr)			
	Mean	Median	Highest	Lowest	Mean	Median	Highest	Lowest
January	21.5	21.1	30	12	30.5	29.7	40	23
February	21.4	21.2	32	13	29.0	28.6	38	21
March	20.0	19.9	28	12	26.8	26.5	35	18
April	17.7	17.4	32	8	22.7	22.8	29	16
May	16.8	16.9	25	11	19.0	18.6	25	13
June	17.1	17.2	22	12	16.8	16.4	26	10
July	16.5	16.5	21	11	16.4	16.7	23	10
August	15.2	15.1	20	9	17.3	17.5	22	5
September	15.3	15.2	21	10	21.0	21.3	27	15
October	18.5	18.5	26	13	25.7	25.8	36	19
November	20.2	19.9	27	14	28.2	28.5	37	17
December	20.6	20.4	29	13	29.9	29.5	42	22

b) North Island

Month	Mean 09:00 Wind Speed (km/hr)				Mean 15:00 Wind Speed (km/hr)			
	Mean	Median	Highest	Lowest	Mean	Median	Highest	Lowest
January	26.5	27.3	28	22	31.6	31.9	33	29
February	27.4	27.5	31	24	32.3	31.9	36	29
March	23.0	22.3	27	21	27.3	26.7	31	25
April	21.7	21.7	25	19	22.6	23.2	25	19
May	24.0	23.1	27	22	22.1	22.5	24	19
June	25.4	25.4	28	23	24.1	24.8	27	20
July	23.8	25.9	28	11	22.7	22.7	28	19
August	24.7	24.5	30	22	23.1	22.4	30	17
September	22.9	21.9	26	21	23.7	23.3	26	22
October	24.3	24.4	27	21	27.2	27.2	29	25
November	23.6	23.6	26	21	28.5	28.6	30	27
December	26.6	26.1	31	23	31.8	31.2	35	29

10.2 Temperature

Water temperatures in Geelvink Channel, several kilometres off Geraldton, typically range from 19°C in late winter (August/September) up to about 23°C in summer (Pearce 1997). A larger annual range, with lower minima and higher maxima, occurs in the nearshore waters, while at the Abrolhos Islands the annual range is less (Pearce 1997).

10.3 Rainfall

The rainfall patterns in the Geraldton region follow those of a typical Mediterranean climate. Most rain falls in winter and the summer months are usually dry with infrequent rain resulting from tropical low pressure systems (Table 10.2). June is the wettest month with an average of 108.1 mm and December the driest with an average of only 5 mm.

Table 10.2 Mean monthly rainfall statistics for Geraldton (recorded from 1941).

Rainfall Averages - Geraldton	Month											
	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Mean rainfall (mm)	6.4	12.7	14.4	25	70.5	108.1	93.7	66.7	31.4	19.7	10.4	5
Median (decile 5) rainfall (mm)	0.8	2.8	6.1	17.4	60.5	91.5	93.7	62.4	31.7	16.6	5.5	2
Decile 9 rainfall (mm)	22.1	41.5	37.8	60.8	142.4	215.2	155	109.5	53.1	38	37.2	22
Decile 1 rainfall (mm)	0	0	0.2	3.1	16.6	43.7	36.2	30.8	10.6	4.6	0.4	0
Mean number of rain days	1.8	2.3	2.9	6.1	10	14	14.7	12.6	9.6	7	4.1	2
Highest monthly rainfall (mm)	63.6	131.4	88.7	100.3	282.2	286.4	243.3	155.4	80.8	109.1	47.4	58
Lowest monthly rainfall (mm)	0	0	0	0.5	2.8	24.8	24	10.8	6	0.3	0	0
Highest recorded daily rain (mm)	36.3	79.6	88.4	47.8	62.2	109.2	71.9	59	38.6	71.1	25.8	51

10.4 River run-off and nutrient inputs

The majority of nutrients and sediments washed from the land into coastal waters worldwide are transported by rivers. On a more localised scale, submarine discharges of groundwater into a marine system may also be significant.

The Geraldton region has four main rivers that flow into the Indian Ocean; the Greenough, Irwin, Chapman and Bowes. The large amount of rainfall during the winter months may also result in the discharge of terrestrial sediment material into the ocean. It is during the winter months that flood events are associated with intense frontal systems. Flow rates during the rest of the year are comparatively low, however, infrequent tropical depressions during summer may result in localised flooding.

Concentrations of suspended sediments and dissolved materials in river waters vary greatly in response to varying flow rates. Flood events may increase primary production in coastal areas, however, the degree to which this occurs is not known. The main commercial fishing grounds for *S. lemuru* are situated well offshore so it is unlikely that any discharge of material during the winter months would impact directly on the species. There is no evidence to suggest that *S. lemuru* migrate inshore during the winter months to take advantage of any possible increase in nutrient levels.

10.5 Sea conditions

Although there is no published wave data for the islands, the mean wave height in the open ocean to the west of the islands is over 2 m for most of the year. However, inside the islands nearer to the mainland coast wave height decreases to a mean of 1.2 m (Pearce 1997). The mean wave period in the Geelvink Channel was nine seconds. Analysis of expected maximum individual wave heights showed that 50 per cent are likely to exceed 3 m and 10 per cent more than 4 m (Pearce 1997). The calmest times during the year occur in the months of March/April and October/November. The islands do offer some protection from the swell when fishing in the Geelvink Channel but strong southerly winds also generate quite large seas (> 2 m) which can make fishing and research operations difficult.

10.6 Tides

Although the tidal range at Geraldton (typically < 0.6 m) is not as pronounced as further north, tidal currents most likely still play an important role in biological processes occurring in the main commercial fishing grounds. Tidally induced mixing can be a major contributor to the nutrient dynamics of shallow, marine ecosystems. In these systems, bottom friction acts in a manner analogous to wind stress on the surface to mix the water column and inhibit stratification (Furnas 1995). This mixing ensures that nutrients are regularly resuspended from the benthos and rapidly distributed through the euphotic zone (i.e. the entire water column in Geelvink Channel), and thus has the capability to influence primary productivity of plankton communities.

Although not mentioned in the review by Pearce (1997), strong tidal fronts are apparently a common feature of some parts of Geelvink Channel and were targeted by commercial purse seiners while searching for *S. lemuru*. Such tidal fronts would be expected to occur regularly and probably represent areas of increased plankton concentrations, which attract schools of *S. lemuru*. Indeed, tidal fronts are also favoured search areas for south coast pilchard fishermen, who identify "tide-lines" by the associated accumulations of debris near the surface. In Geelvink Channel, where purse seining most often occurred at night, tide lines could be detected by the sonar and echo sounder.

10.7 Upwelling

A clear difference between the mid-west coast of WA and overseas locations, where sardines support commercial fisheries, is the very low nutrient levels of the former. Thus, whereas large sardine fisheries usually occur in areas of significant upwelling and or large inputs of nutrient from rivers, the mid-west of WA is extremely arid and the adjacent seas have no regular or consistent upwelling of colder, nutrient-rich water (Pearce 1997). In general terms, Australian marine waters are nutrient poor. The generally poor nutrient levels result in stock sizes of clupeoids, which are strongly linked to productivity, to be very low by world standards and particularly low when compared with stock sizes inhabiting eastern boundary upwelling systems.

However, "cold events" have occasionally been recorded at the CSIRO tide-gauge site near Rat Island, suggesting that localised up-welling may occur sporadically along the outer continental shelf (Pearce 1997). There may also be upwelling onto the continental slope of 'mid-depth' water, which is not detected as changes in sea surface temperature (SST) by satellite imagery because of insufficient thermal contrast.

10.8 Leeuwin Current

The Leeuwin Current is the dominant current off Western Australia (Caputi *et al.* 1996). It has been responsible for the distribution of tropical marine life further south than would otherwise be expected. This large current can best be described as a band of warm, tropical, low salinity water about 50 km wide and 200 m deep that flows south, generally along the shelf break, from North West Cape to Cape Leeuwin (Figure 10.2). From here it travels eastwards and flows into the Great Australian Bight.

The Leeuwin Current originates from the flow of water from the Pacific Ocean through the Indonesian archipelago, which results in higher sea levels off the north-west coast than the south-west coast of WA. The higher level is held back during summer by the prevailing southerly winds along the west coast. However, during autumn the onset of monsoon winds in the north further increases the flow and consequently the sea level. At the same time the dominant southerly winds on the west coast of Australia ease allowing the flow of warm tropical water down the coast and into the Southern Ocean. During the summer months there is a weaker northward flowing current between the Abrolhos Islands and the mainland coast (Pearce 1997).

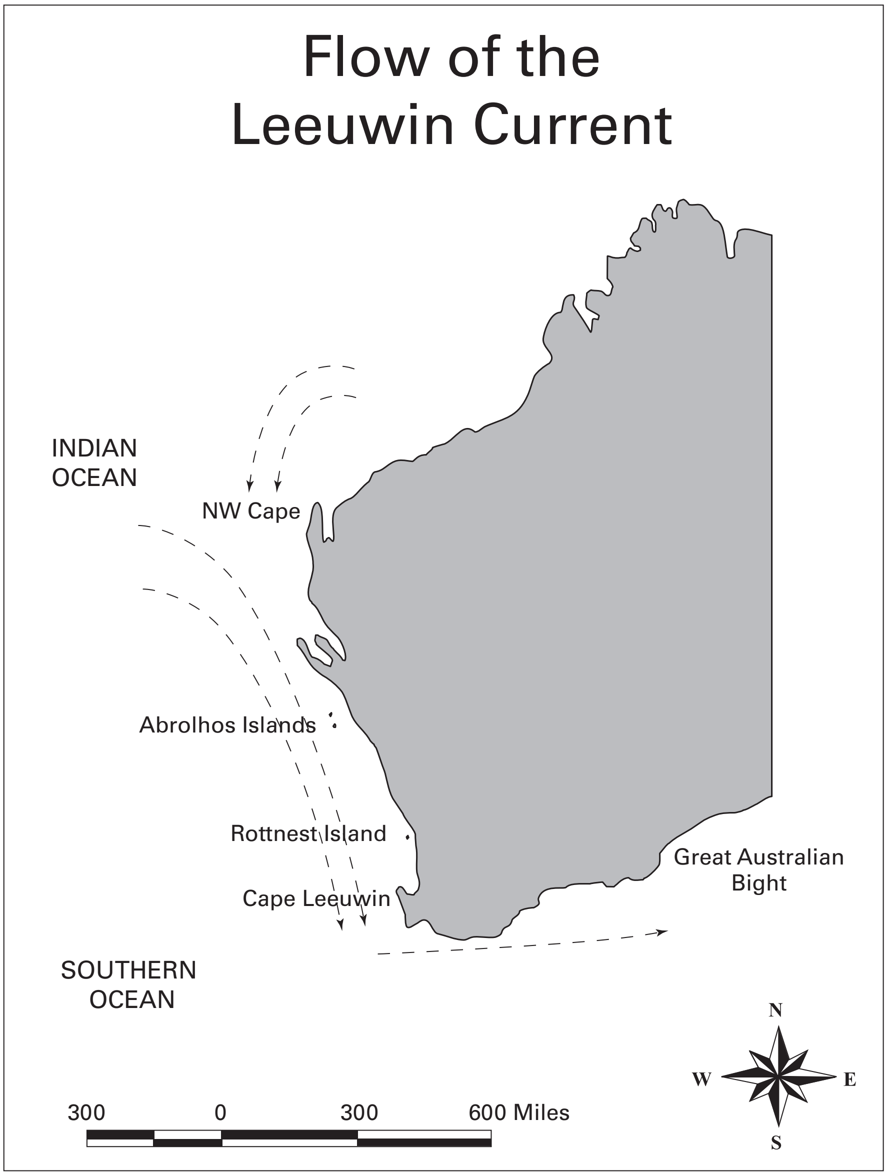


Figure 10.2 North to south movement of water by the Leeuwin Current, off Western Australia.

In January 1995 (Figure 10.3a) there was virtually no Leeuwin Current visible along the coast. However, by February 1995 (Figure 10.3b) there was an influx of warm water down the coast just off the continental shelf and SST had increased.

The flow of the current was more pronounced during January 1996 (Figure 10.3c). Warm water can be seen flowing south past Shark Bay, with eddy formation visible well offshore. In February 1996 (Figure 10.3d) the warm band of tropical water is still evident west of Shark Bay. Warm water has evidently moved on to the continental shelf. SST around the Abrolhos region increased marginally in February 1996

The flow of the current in January 1997 (Figure 10.3e) was again fairly strong with warm water reaching down the coast to Cape Naturaliste. A large tongue of warm water can be seen running adjacent to the continental slope with, with a band of slightly cooler water inshore of the Abrolhos Islands. In February 1997 (Figure 10.3f), the body of warmer water seen in January along the shelf edge can now be seen dispersed over a wide area due to weakening of the stream and mixing with shelf waters.

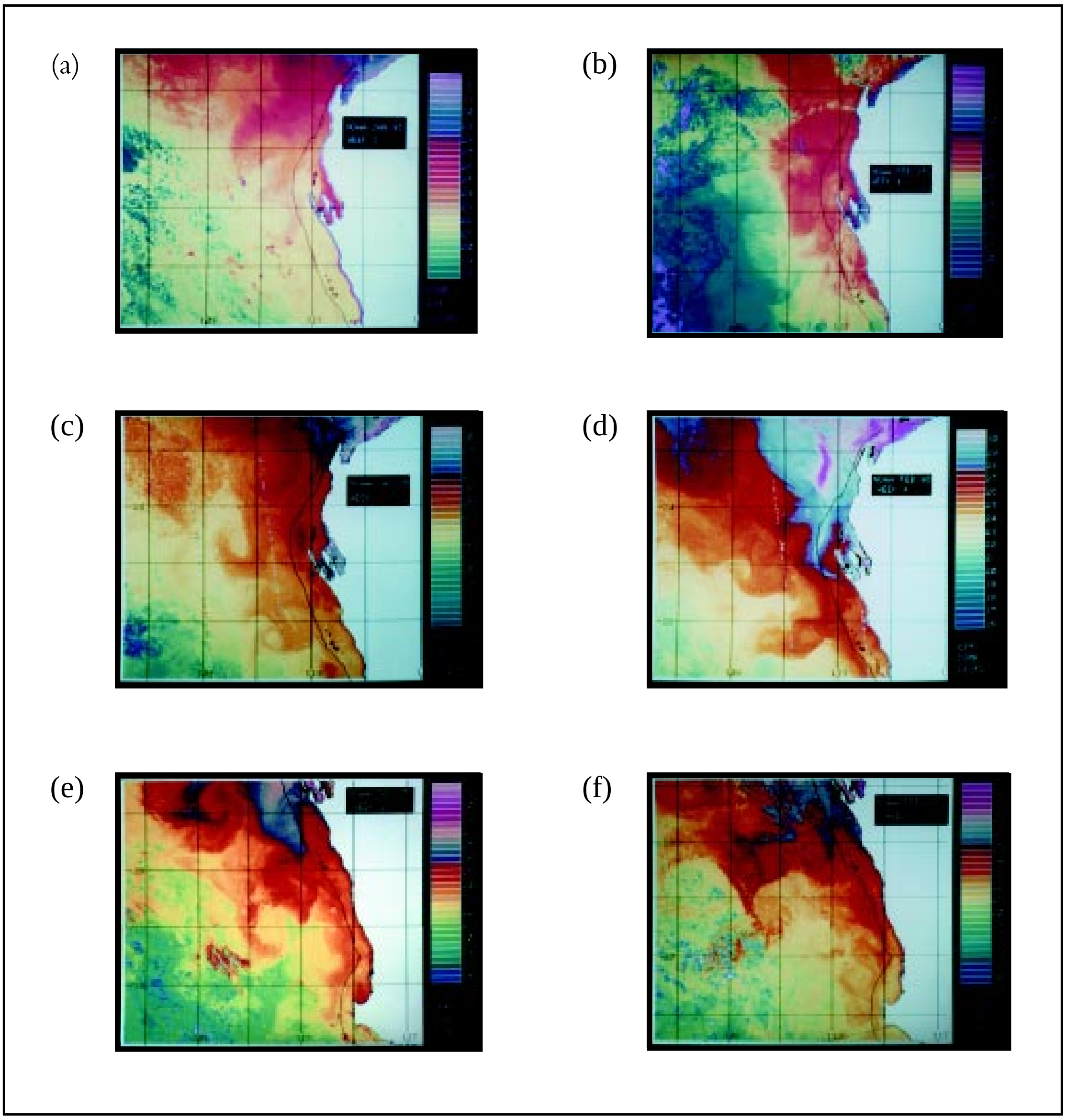


Figure 10.3 Satellite images of SST showing variation between years in flow rates down the west coast in (a) Jan 95, (b) Feb 95, (c) Jan 96, (d) Feb 96, (e) Jan 97 and (f) Feb 97 (peak spawning months).

10.9 Severe storms and cyclones

Intense low pressure systems, whether they be cyclones or gales, are irregular seasonal events off the mid-west coast of WA. Severe tropical storms which occasionally move down the west coast can have pronounced effects on continental shelf and coastal marine systems. The high winds and associated waves generated in these events result in intense mixing of surface waters with the lower layers of the water column. This mixing often brings nutrient enriched water to the surface along the storm track (Furnas 1995). As tropical storms move onto the continental shelf, mixing reaches the bottom and is sufficiently powerful to re-suspend sediments over wide areas. Dissolved and particulate nutrients are re-suspended into the water column which can result in localized phytoplankton blooms. In conjunction with nutrients in floodwater near the coast, regional primary productivity can increase 5 to 10 fold within a matter of days following a major storm (Furnas 1989). Although *S. lemuru* would presumably take advantage of such sporadic increases in plankton biomass, such storm events are irregular and are unlikely to influence spawning strategy.

There are no data relating to chlorophyll-*a* abundance within the fishing area for *S. lemuru*. Pearce (1997) found that nitrates, silicates and phosphates in the surface layers were generally low across the shelf and down to about 200 m, which confirms the low nutrient status of Western Australian shelf waters and the lack of nutrient input via upwelling.

10.10 Influence of environmental factors on spawning strategy and recruitment

10.10.1 Hypothesised effects

Sardinella lemuru, like other sardine species, most likely undergoes large interannual variations in recruitment abundance. Variations in relative recruitment success for many pelagic species have been linked to changes in the prevailing environmental conditions (e.g. Cury and Roy 1989). The dominant environmental factors for *S. lemuru* in Geelvink Channel are probably wind, temperature and the Leeuwin Current. As seasonal changes in temperature and wind patterns are very consistent, these factors are likely to be linked to spawning strategy. In contrast, the Leeuwin Current and the extent that it both impinges onto the continental shelf off the mid-west coast of WA and forms eddies offshore of the same region, can vary substantially between years. This variable environmental factor is discussed as a possible mechanism affecting interannual recruitment variability. Potential influences of wind and Leeuwin Current are discussed following the hypotheses outlined in Table 10.4.

Table 10.4 Hypotheses on the influence of wind and the Leeuwin Current during the summer spawning season on *S. lemuru* recruitment.

Environmental factor	Direct effect	Hypothesised result	Effect on recruitment
Wind	Increased mixing	Increased productivity	+
	Increased turbulence	Increased encounter rate with food or no stable aggregations of food	+ or -
	Net northward current	Larvae moved north and remain in warm water	+ or -
	Offshore (NE) drift of surface, shelf waters; offshore transport of eggs & larvae	Larvae placed in offshore frontal boundary systems or larvae "lost"	+ or -
Leeuwin Current	Flow into Geelvink Channel	Increased productivity via (1) mixing in Geelvink Channel, (2) development of frontal boundary systems	+
	Transport of larvae south	Nursery grounds to the south	?

10.10.2 Wind

Clupeoids associated with upwelling regions spawn in areas and at times where turbulence and offshore transport are low, but winds are sufficiently strong to generate upwelling (Bakun 1996). Successful spawning (in terms of subsequent recruitment) by some tropical and temperate clupeoids in upwelling regions has been linked to winds blowing within an optimum range of speeds (i.e. the "Lasker window", Bakun 1996). Winds below the optimum will be reflected by low levels of upwelling and hence low nutrient levels, whereas winds above the optimum cause increased turbulence which can disrupt plankton aggregations. In both cases, the negative effects of wind-strength outside of the optimum range of 5-6 m/s (Cury and Roy 1989) can be on either or both the adults and their offspring. Thus, it is believed that these conditions aid in the survival rates of the larval fish and by increasing reproductive output, via improved feeding conditions, for adults.

However Freon *et al.* (1997) found that for *Sardinella aurita* off Venezuela, spawning predominantly occurred not only in areas of low turbulence but also in areas that were exposed to trade winds and offshore transport. Thus, sardine populations in non-upwelling regions may develop spawning strategies to take best advantage of local conditions. Because of the variability in oceanographic conditions between such non-upwelling regions, different aspects of the environmental and biological conditions may be more important for successful spawning than others.

This may explain the apparent divergence of *S. lemuru* off Geraldton from previously described spawning strategies for sardines. The reproductive strategy exhibited by *S. lemuru* is different from that of sardines in upwelling regions. *Sardinella lemuru* spawn off Geraldton during the summer months (December-February). At that time the winds are at their strongest (mean wind speed of 8 m/s) and are also extremely predictable with very little interannual variation in strength or direction. *Sardinella lemuru* may use the predicability of these winds (prevailing southerly) to aid the survival of their larvae, although this is not likely to be linked to the retention of larvae in the spawning area since the southerly winds probably generate a north-west (i.e. offshore) movement of surface waters (A. Pearce, *pers. comm.*).

If increased survival of larvae during the spawning season is not linked to retention, then the alternative theory is that offshore transport places larvae in areas suitable for early growth and survival. Freon *et al.* (1997) found that *S. aurita* off Venezuela also spawn at a time when offshore transport of larvae is most likely. They proposed that, within the context of this other sardine's spawning strategy, optimising food availability for juveniles had precedence over larval retention. Such a possibility for *S. lemuru* off the mid-west coast of WA led to the hypothesis that localised regions of high productivity associated with frontal systems generated by the Leeuwin Current may be important in the survival of larval *S. lemuru* (see below).

Potential effects of the net northward movement of water in Geelvink Channel during summer are discussed below.

10.10.3 Leeuwin Current

10.10.3.1 Potential effects on primary productivity

The meeting of water masses with different hydrographic characteristics results in marked gradients in physical, chemical and biological variables across frontal boundary zones. These boundaries tend to be spatially complex and are characterised by eddies (swirling flows of water), streamers (extended, river like flows) and intrusions (tongues of water), all of which can be seen using satellite imagery (Figure 10.3).

The waters of the Leeuwin Current move much faster than the adjacent "slope water" mass nearer to the mainland coast. Frontal eddies develop at the interface in response to the frictional torque of the differential velocities of the adjacent water masses (e.g. Bakun 1996).

Although the main body of the Leeuwin Current is typically located offshore of the Abrolhos Islands, eddies or intrusions can break away from the main current, moving large amounts of warm water eastward up onto the continental shelf, around the islands and toward the mainland coast. These onshore intrusions can change over short time scales, which may lead to increased levels of mixing throughout the water column in the relatively shallow (50 m) waters inshore of the Abrolhos Islands. This may then result in localized increases in nutrients within the water column, despite that the warm pockets of tropical water coming onto the shelf are generally oligotrophic. If this process does occur, fluctuations in the Leeuwin Current and its offshoots may result in highly variable spatial patterns of nutrient and plankton densities between years.

More persistent intrusions may also result in distinct frontal boundaries. Frontal boundaries associated with well defined intrusions of Leeuwin Current water moving onto the shelf are likely to result in the formation of areas of higher productivity (e.g. Bakun 1996). These areas may provide sufficiently concentrated food for larval *S. lemuru*.

Frontal boundaries are also associated with the large scale eddies (Figure 10.3) which may detach from the Leeuwin Current off the mid-west coast of WA. Theory indicates that the dynamics of eddies will result in areas where particles (i.e. in this case plankton) accumulate (Bakun 1996). As a result of these eddy formations, high concentrations of plankton can develop at frontal zones, thereby giving rise to areas of intensified trophic activity. Furthermore, where meanders of coastal currents detach from the coast, localized zones of upwelling can form in the pocket of the loop (Tranter *et al.* 1986). Eddies off the mid-west coast of WA tend to persist for weeks (Pearce 1997), so areas of high productivity within eddy pockets would likewise be expected to persist for such periods. Such conditions may provide suitable feeding conditions for larval or juvenile *S. lemuru* offshore of the Abrolhos Islands.

Assuming that summer spawning in Geelvink Channel does indeed result in substantial offshore transport of *S. lemuru* eggs and early larvae, eddies produced by the Leeuwin Current may provide suitably enriched environments to assist in early feeding success. In which case, the offshore advection does not necessarily result in terminal loss of spawning products from the stock.

The most intense frontal boundaries observed in Figure 10.3 occur far offshore of the shelf edge, however, boundaries may occur closer to shore. These closer to shore bourndaries are more difficult to detect using satellite imagery since local inshore waters are warmer than oceanic waters at this time of year and so produce less thermal contrast. Thus, the Leeuwin Current may generate more extensive frontal boundaries close to the region of the fishery than indicated, and these may also result in localised areas of high productivity.

While the general form of the Leeuwin Current is reasonably consistent in the longer term, the strength and position of the current, with respect to the continental shelf, typically varies between years and is linked to El Niño/La Niña events. Thus, if reproductive success of *S. lemuru* in the Geraldton region has particular, although indirect, reliance on flow of the Leeuwin Current onto the shelf, then both recruitment and stock size can be expected to undergo regular large fluctuations over relatively short periods. Likewise, this hypothesised effect is further exacerbated if offshore eddies also influence survival of advected larvae and the resultant juveniles.

10.10.3.2 Transport of eggs and larvae

In recent years there has been an increasing interest in the Leeuwin Current and its role in biological/fisheries processes. The current may provide a transport system for pelagic larvae of several finfish and crustacean species. Hutchins (1991) hypothesised that the seasonal recruitment of juvenile tropical fish at Rottnest Island, off Fremantle, is a result of the south-ward transport in the Leeuwin Current from breeding populations to the north.

Along the south coast of WA, the Leeuwin Current is responsible for the eastward advection of pilchard eggs and larvae from offshore areas near Albany further east towards Bremer Bay, with transported distance of spawning products positively correlated to current strength (Fletcher *et al.* 1994). However, this is much less likely to occur with *S. lemuru* since the Leeuwin Current is typically weakest at the time of peak spawning (i.e. mid-summer). Indeed, spawning in Geelvink Channel places eggs and early larvae in a region which has a net northwards movement of water during summer and therefore the long term average transport of spawning products, if any, is more likely to be to the north. This hypothesis is supported by the oxygen-isotope data which indicated that juveniles had lived in warmer water than adults (section 7), which in turn suggests a southward flow of eggs and larvae is unlikely.

Because the net northward movement of water in Geelvink Channel during summer results from the very predictable and consistent southerly winds during this time of the year, it is most likely a more persistent feature than intrusions of Leeuwin Current water. Ignoring for the moment the possibility that relatively low (i.e. sub-tropical cf. tropical) temperatures may limit reproductive activity (section 4.9), spawning in summer may be a strategy to aid northward transport of eggs and larvae. Furthermore, shoreward movement of water induced by intrusions of Leeuwin Current water, which could be seen as a mechanism to aid in retention of larvae, is also weakest during summer, and thus retention of larvae in the region of the fishery does not appear to be part of the spawning strategy.

11.0 Project summary

11.1 Benefits

This project established an understanding of the biology of *S. lemuru* in WA and of the mid-west coast purse seine fishery. This information has, and will, be used in management decisions aimed at ensuring sustainability of the *S. lemuru* stock off the mid-west coast of WA. This in turn has flow-on benefits to recreational fishing and conservationist groups which may be concerned about effects of overfishing on predators of sardines in the Geraldton region. The data also have immediate uses for FRDC project 98/203 on birds of the Abrolhos Islands.

Knowledge of some of the difficulties encountered during the developmental period (e.g. influence of weather, vessel suitability, processing capacity, marked decline in catch rate) will benefit current and future industry members in the mid-west purse seine fishery and in other new fisheries which target high-volume, relatively low-value, species.

The anticipated benefits to the rock lobster and aquaculture (i.e. tuna farms) industries did not eventuate and these industries will therefore continue to have a heavy reliance on imported baitfish.

11.2 Further developments

Further research on the biology of *S. lemuru* and the mid-west coast purse seine industry will be undertaken through continued sampling of catches. In particular, further verification of age is warranted. Also, as samples of the commercial catch are obtained, investigations will continue into whether or not otolith weight can be used as a basis for analysing relative age composition. Likewise, vessels will be encouraged to continue filling in logbooks so that deviations in catch rates or spatial extent of the fishery can be detected. Given the current magnitude and value of the catch, this level of monitoring should meet future needs of management. If a perception developed that a substantial increase in annual catch is warranted, a further DEPM survey should be undertaken, but only if adult samples can be guaranteed to be available, and indeed obtained (i.e. from industry), prior to and during the period of peak spawning.

11.3 Conclusions

Given the current understanding of sardine taxonomy, the species studied in this project was confirmed to be *Sardinella lemuru*, a tropical species which, along the lower west coast of WA, is at the southern limit of its range.

The limited fishing season, typically from May to September, hampered efforts to describe the biology of *S. lemuru* and to estimate spawning biomass using the daily egg production method. The description of reproductive biology relied heavily upon samples collected between 1990 and 1995. Spawning season is from December to March with a peak in January to February. No adequate assessment of fecundity was possible during the project, although preliminary estimates indicate that fecundity may be approximated by that from similar species. Hypotheses concerning possible links between spawning strategy of *S. lemuru* off the mid-west coast and the dominant environmental factors (Leeuwin Current, wind) were discussed in the context of the potential influences on recruitment strength.

Sardinella lemuru are filter feeders, with diets composed predominantly of zooplankton.

Insufficient samples from all months of the year also affected the ability to validate the age of *S. lemuru* using otoliths. However, this was less critical than the difficulty in identifying suspected annuli, which subsequently resulted in a poor level of confidence in our ability to estimate age. Therefore, analyses of growth and age were conditioned on the assumption that *S. lemuru* in WA grow slower than in the warmer and more productive waters of Bali Strait. Maximum age was six or seven years, with an L_{inf} of 166 mm.

Notwithstanding the uncertainty in estimating age, the annual catch-at-age distributions indicated that the commercial catch predominantly consisted of only two or three age classes. Three- and four-year-olds dominated the catch, with few younger and older fish present. This observation may indicate that the stock could be characterised by occasional periods of strong recruitment, typical of small pelagic fish. Alternatively, an age-dependent spatial separation may have contributed to the low numbers of older fish by making them less vulnerable to fishing, although there is no evidence for this. Analysis of the annual catch-at-age distributions indicated a high rate of total annual mortality ($Z = 1.16$), which may include a component of lower vulnerability of older fish.

Data from research logbooks and compulsory monthly returns allowed a detailed description of dynamics, locations and catch rates of the fleet. Although the cause(s) for the decrease in catch rate in 1997, i.e. an apparent decline in abundance of *S. lemuru* in the vicinity of the fishing grounds, was not determined, the possibility of marked changes in catch rate from one season to the next have been demonstrated for this fishery. The research indicates that the original concept that the fishery could expand greatly was overoptimistic and expansion of the fleet is therefore not warranted. Furthermore, the need for specialised, rather than modified, purse seine vessels in order to operate viably in the mid-west coast sardine fishery has clearly been shown.

Sardinella lemuru eggs were typically found over the outer half of the continental shelf and were widely distributed along the shelf. The estimates of spawning area, along with the closely associated patterns of egg distribution, do not provide evidence of a large and extensive stock, but rather of a dispersed stock with relatively large distances between what are possibly quite small aggregations. A combination of the very small sample size of adults, the fact that the peak spawning period (or area) could not be identified in advance, and insufficient egg data from which to obtain an estimate of egg production, negated attempts to provide worthwhile estimates of spawning biomass using the daily egg production method.

Analysis of isotopic ratios of oxygen and carbon from otoliths did not provide any clear evidence for the presence of distinct stocks of *S. lemuru* between Fremantle and Carnarvon. The $\delta^{18}O$ data did, however, indicate that *S. lemuru* caught at different locations had lived most of their lives in waters of different temperatures. The otolith-isotope and plankton data together suggest that the stock may be widespread, patchy and highly mobile. This data is compatible with the hypothesis of a stock shifting and or dispersing along the coast in response to environmental changes.

11.4 Recommendations

1. The small number of age classes, high natural mortality and lack of an estimate of stock size, along with the large interannual variations in recruitment strength expected of sardine stocks in general, and the associated large changes in stock size over relatively short periods, provide a strong basis for conservative management of this fishery.

2. Due to lack of any evidence for a large stock in the current fishing area, there is currently no basis for expecting the TAC to increase above the current level of 2,700 tonnes in the future. Furthermore, because there is no estimate of stock size, catch levels in the short term should not be permitted to exceed those of the previous highest annual catches (2,000 t).

3. Monitoring of the commercial catch, to obtain data on age structure, catch and effort, should continue. A longer time series of data will assist in determining if and when exploitation levels need to be revised.

4. The apparent low abundance of *S. lemuru* in the mid-west's current purse seine grounds observed in 1997 may continue to occur periodically, and thus the fishery may not be commercially viable in some years. Therefore, any further large investment in the mid-west purse seine fishery should not be encouraged.

These recommendations have already been presented to industry and managers at a meeting of the WA Purse Seine Management Advisory Committee.

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14.0 Appendices

Appendix 1: Sampling for juvenile *Sardinella lemuru*

The background to this appendix is provided in section 2.2.5.11.

Materials and methods

Mainland

In July 1997 beach seine nets were used to sample several beaches between Cervantes and Lucky Bay (Figure 1A, Table 1A). At each site, three shots were made using a 67 m beach seine net. A 120 m beach seine was also shot once if there was no reef present close to the beach. The composition of the catch was recorded.

Abrolhos Islands

The Houtman Abrolhos Islands are a network of limestone and coral islands located about 60 miles from the mainland coast (Figure 1A). The islands constitute an area of high productivity within the relatively nutrient poor marine waters which surround.

The occurrence of coral and limestone in the shallows made it impractical to attempt beach seining in this region. Thus, attempts were made to catch small *S. lemuru* using other methods. Sampling was carried out in the months of September and November 1997 and June 1998 on Rat Island in the middle group of the Abrolhos Islands. This site was chosen for several reasons, including accessibility by boat and aircraft, and the existence of jetties to use as sampling platforms.

Sardinella lemuru are known to congregate towards light during the night, and have been successfully targeted with light-fishing in the Bali Strait (Ritterbush 1975; Venema 1996). The sampling technique aimed at congregating any light-respondent baitfish in the area to a point near a jetty where they could be netted. A 3000 watt lamp powered by a 240 volt generator was mounted onto a jetty and angled at 60 degrees to the water's surface. Two locations were sampled on Rat Island and the choice of which was used at any one time depended on the prevailing wind direction. Calm conditions were preferred so that surface ripples would not decrease light penetration into the water. Depth profiles were recorded at each site (Figure 1B). Both sites were cleared of any obstructions (e.g. steel pipes, tyres) on the bottom before sampling commenced. Pollard (crushed wheat) was mixed with sea water and vegetable oil and was used as an additional attractant at the sampling sites.

A conical lift net, with a 1.3 m mouth-diameter and 5 mm mesh was used to capture fish attracted to the lights. It had a drop of 2.5 m and was hauled by rope running through a pulley attached to a 3 m steel rod extended out from a jetty. The major advantage of using this technique is that it required little time and effort to set and retrieve the net. The light was concentrated above the lift net and when fish were aggregated in reasonable numbers the net was hauled vertically out of the water. The fish were then removed from the net and identified.

In conjunction with the lift net method, a 55 m gill net with a mesh size of 4 cm was used to target predatory fish which may have been feeding on baitfish. One end of the net was tied to the jetty a few metres from the deck lamp and the rest of the net was extended away from the jetty using a dingy. The gill net was left in the water for approximately five hours before it was checked. Captured fish were identified and their stomachs kept for subsequent examination of contents.

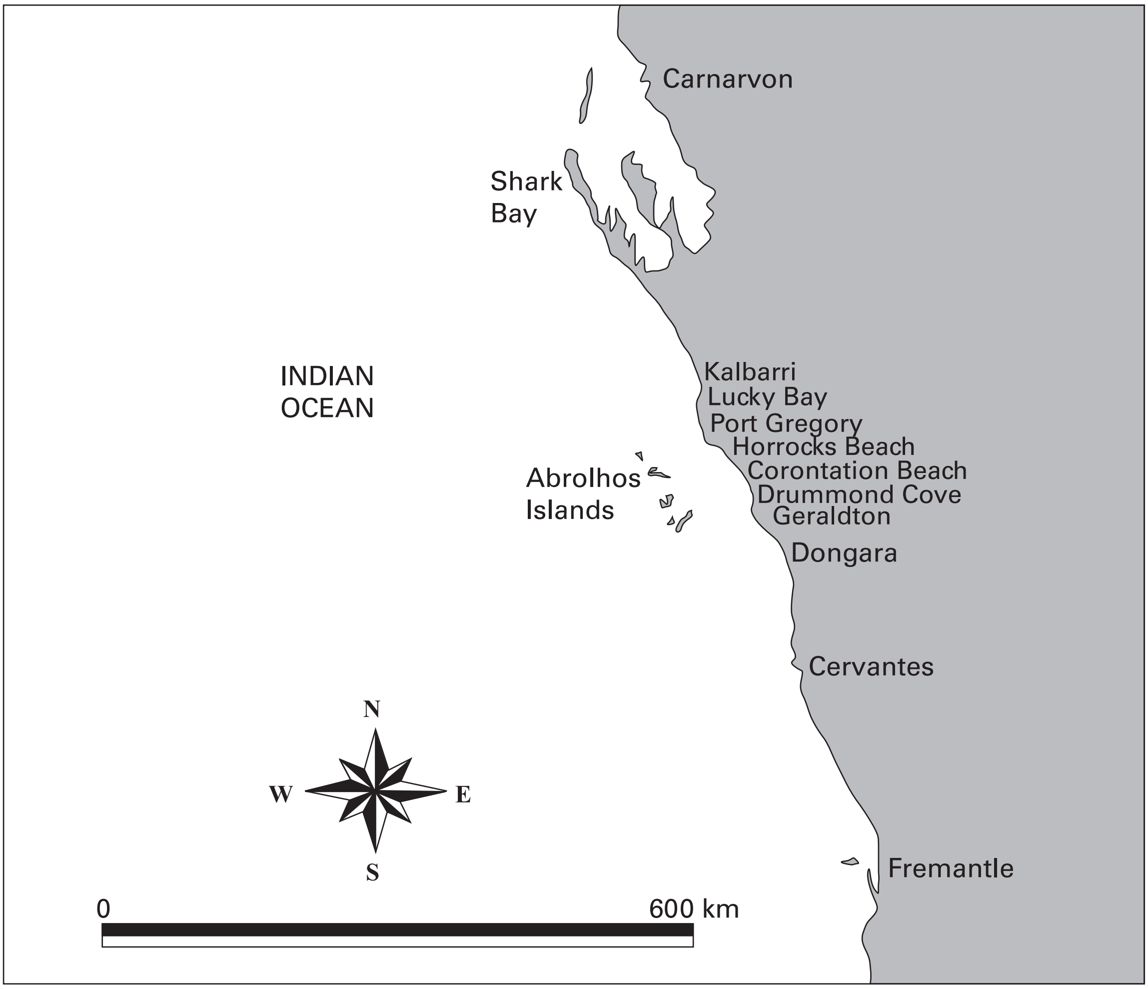

Figure 1A Beach seining sites along the mid-west coast of Western Australia.

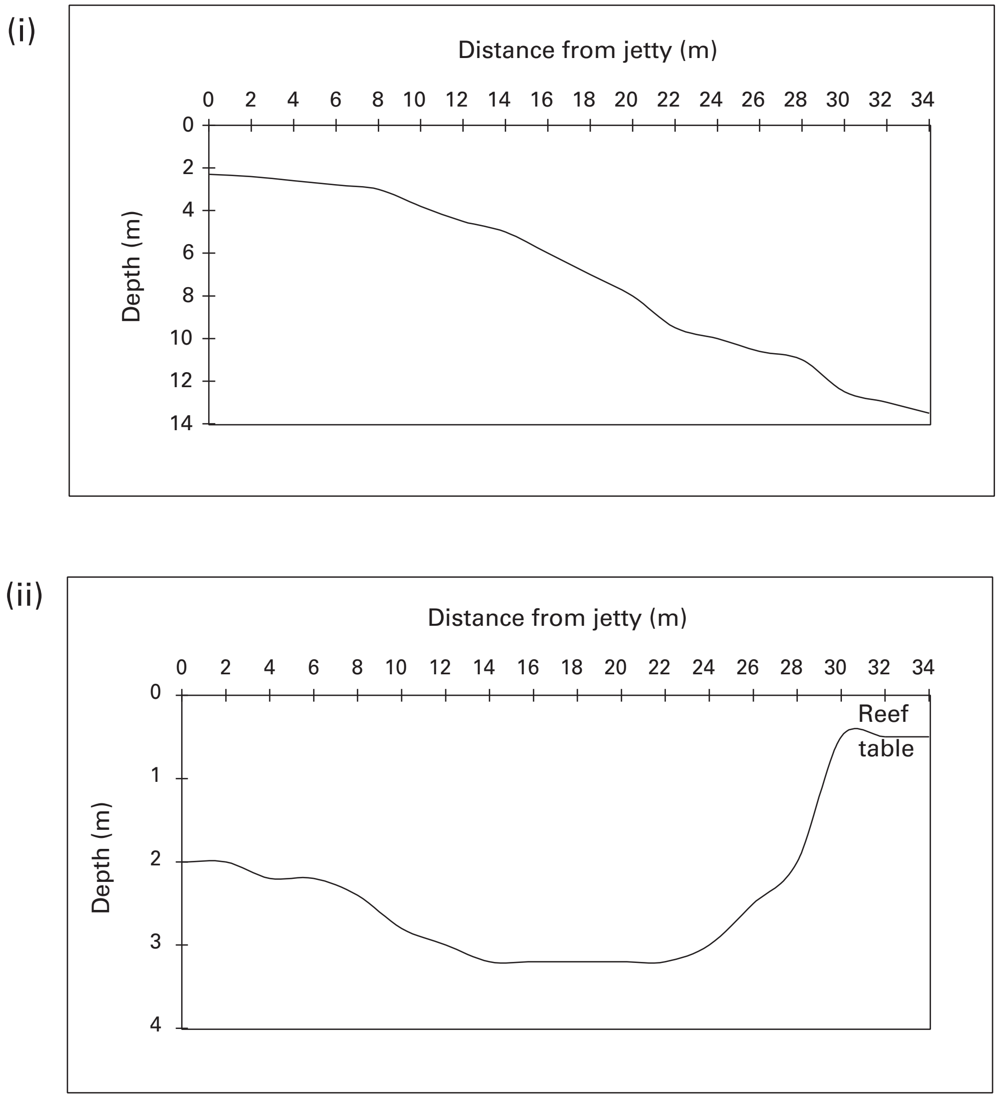

Figure 1B Depth profiles for (i) Site 1 and (ii) Site 2 on Rat Island.

Table 1A The sampling schedule for each successive shot at each location.

Date	Location	Time	Net	Shot #	Temp (°C)	Salinity (ppt)
26/07/97	Dongara Boat Harbour	12:05	67 m	1	18.5	35.1
	Dongara Boat Harbour	12:35	67 m	2	18.5	35.1
	Dongara Boat Harbour	13:05	67 m	3	18.5	35.1
27/07/97	Pages' Beach	8:00	67 m	4	18.1	35.4
	Pages' Beach	8:35	67 m	5	18.1	35.4
	Pages' Beach	8:55	67 m	6	18.1	35.4
27/07/97	Harbour beach	10:45	67 m	7	18.0	35.0
	Harbour beach	11:25	67 m	8	18.0	35.0
	Harbour beach	11:50	67 m	9	18.0	35.0
27/07/97	Point Moore	15:35	67 m	10	19.8	35.5
	Point Moore	15:55	67 m	11	19.8	35.5
	Point Moore	16:25	67 m	12	19.8	35.5
28/07/97	Drummond Cove	8:15	67 m	13	18.4	35.5
	Drummond Cove	8:40	67 m	14	18.4	35.5
	Drummond Cove	9:15	67 m	15	18.4	35.5
28/07/97	Coronation Beach	11:15	67 m	16	20.1	35.3
	Coronation Beach	11:45	67 m	17	20.1	35.3
	Coronation Beach	12:15	67 m	18	20.1	35.3
29/07/97	Horrocks Beach	8:00	67 m	19	19.7	35.1
	Horrocks Beach	8:25	67 m	20	19.7	35.1
	Horrocks Beach	8:55	67 m	21	19.7	35.1
	Horrocks Beach	13:15	67 m	22	20.3	35.1
	Horrocks Beach	13:45	67 m	23	20.3	35.1
	Horrocks Beach	14:25	120 m	24	20.3	35.1
30/07/97	Port Gregory	10:15	120 m	25	18.1	35.5
	Port Gregory	11:25	120 m	26	18.1	35.5
	Port Gregory	14:00	120 m	27	18.6	35.5
	Port Gregory	14:55	120 m	28	18.6	35.5
31/07/97	Lucky Bay	10:15	67 m	29	19.2	35.5
	Lucky Bay	10:45	67 m	30	19.2	35.5
	Lucky Bay	11:15	67 m	31	19.2	35.5
31/07/97	Cervantes Town Beach	15:30	67 m	32	18.7	35.2
	Cervantes Town Beach	15:55	67 m	33	18.7	35.2
	Cervantes Town Beach	16:25	67 m	34	18.7	35.2

Results

Mainland

The survey did not capture juvenile *S. lemuru* at any of the locations sampled. The most abundant species caught during the sampling were *Sillago schomburgkii*, *Aldrichetta forsteri*, *Pranesus ogilby* and *Sillago vittata* (Table 1B). *Sillago schomburgkii* ranged in size between 120 and 280 mm and *S. vittata* ranged from 100 to 150 mm. *Aldrichetta forsteri* ranged in size from 15 to 230 mm. *Mugil cephalus* ranged in size from 10 to 380 mm.

Abrolhos Islands

No *S. lemuru* were caught in the lagoon waters around Rat Island, although the presence of two sprat species with lengths around 9 cm TL indicated that similarly small *S. lemuru* were unlikely to be avoiding the net. The dominant species was the slender sprat (*Spratelloides gracilis*) and was captured on four of the nine nights sampled. Blue sprat (*S. robustus*) was caught on two of the nine sampling nights. Ogilby's hardyhead (*Pranesus ogilby*) was observed on all sampling nights and was caught on eight of the sampling nights. It was captured in both the lift net and the gill net.

Both sprat species occurred in gut samples taken from Australian herring (*Arripis georgianus*) and striped seapike (*Sphyraena obtusata*), which were captured in the gill net. It is likely that if small *S. lemuru* were present in the area they would have also ocurred in the guts of these predators.

Arripis georgianus were seen feeding on *S. gracilis* on several sampling nights at Site 1 and, although they would not stay in the light for long, they were seen patrolling the edge of the light. *Sphyraena obtusata* were caught in reasonable numbers at Site 1 during November 1997, with over 50 individuals retained in the gill net. The guts of the majority of these contained *S. gracilis*.

Sphyraena obtusata were never observed in the direct light although it is assumed they were feeding on the perimeter of the light boundary. Other species observed but not captured included tailor (*Pomatomus saltatrix*) and long-finned garfish (*Euleptorhamphus longirostris*).

Table 1B Numbers of each species caught for each shot of the seine net.

shot #	Sillago schomburgkii	Sillago vittata	Sillago maculata	Aldrichetta forsteri	Mugil cephalus	Elops machnata	Arripis georgianus	Pomatamus saltatrix	Rhabdosargus sarba	Platycephalus endrachtensis	Hemiramphus robustus	Pranesus ogilbyi	Cnidoglanis macrocephalus	Kyphosus sydneyanus	Gerres subfasciatus	Openeichthys vlamingii
1	19		7	4												
2						1										
3	50			50					6							
4				100	10					1						
5	2			26									1			
6	3			13												
7	1				2							30				
8	6											50				
9	4			20								46				
10											7					
11	20			31								152				
12	7	13		25												
13	2			7								52				
14	1	3		4								~200				
15	6	2		1												
16	7			22								32				
17	2			31							5	48				
18	3	9									1	26				
19																
20	6			2												
21	7	1										~80				
22	3															
23				6												
24	28	3		7												
25	31	11		10										2	3	
26	4			1										1	15	1
27	1			2												
28	16			25								45				
29			2	7	1											
30																3
31		1														
32	3			1	10											
33					7											
34	2			2			1	2								

Appendix 2: Experimental mid-water pelagic trawling for *Sardinella lemuru*

Introduction

The main aim of the mid-water trawling was to obtain samples of adults during the summer breeding period (e.g. February 1996) when commercial vessels were not operating, to provide estimates of parameters to be used in the daily egg production method (DEPM) of estimating spawning biomass. Additional surveys were also undertaken to fill large gaps in the periodicity of sample collection (e.g. late September 1997).

Survey equipment

Vessel dimensions

The RV *Flinders* is a 20.5 m trawler which was modified to perform mid-water trawling. It is constructed of steel and powered by a 235 hp Gardner engine.

Searching equipment

A Furuno colour video sounder was used during the surveys and this instrument was interfaced with an acoustic sonar and was designed to monitor bottom topography and to gauge school density and size.

A dualscan sonar, with two transducer scanpods, was also used during most surveys and this particular model has a function which allows the echo sounder to be displayed simultaneously on the same screen with the sonar image. This conveniently allowed the skipper to monitor one screen instead of having to observe two independent screens. This model of sonar also has a sidescope and octoscope function. These modes allow the user to accurately determine the vertical height, position and density of fish school targets on both sides of the vessel.

The tracking functions of the digital sonar allowed targets ahead of the vessel to be monitored before the net was lowered to the correct depth. It was also noticed that changes in school formation, in response for instance to predatory attacks, could be observed on the sonar's monitor, which allowed further adjustments to net depth.

Net description

The pelagic trawl net was relatively small, 47.9 m in length, so that it could be towed as quickly as possible and had a cod-end with a maximum catch rating of 1-2 tonnes. Schools of *S. lemuru* in the Geraldton region often exceed 10 tonnes in size. Therefore it was important that the sonar was used effectively to avoid chances of accidentally towing the net through the middle of a dense school, an event which would probably damage the net, result in lost sea time, and kill unnecessary numbers of fish.

The net was a standard mid-water trawl design with 3.2 m meshes in the opening (herding panels), tapering down from 162 cm to 20 cm mesh in the middle panels with a rear mesh size of 5 cm. The cod end was constructed from 12 mm mesh and was 2.5 m long. While fishing at a towing speed of 3 knots, the horizontal mouth opening of the trawl was 24.3 m.

The double foil pelagic trawl doors were 1.4 m^2 each and weighed 161 kg (Figure 2A). The doors were based on the cambered German Suberkrub design, that provides a hydrodynamically efficient door, with a high aspect ratio of 2:1, which greatly improves the lift to drag ratio. These doors are suitable only for mid-water trawling and are extremely sensitive to adjustments of backstrops or towing points.

Figure 2A Pelagic trawl doors used with the mid-water trawl net.

Net deployment

The mid-water trawl hauls were aimed at selected aggregations of fish as highlighted on the sonar and sounder. All fishing occurred at night when the *S. lemuru* are known to aggregate. Night trawling was also necessary to reduce avoidance of the net by *S. lemuru* as the RV *Flinders* was designed for benthic trawling and hence is relatively slow when undertaking pelagic trawling. Many of the schools encountered were against the bottom which presented difficulty when deploying the net as it is only designed to be used mid-water and may be damaged if it hits the bottom. The average depth fished ranged between 35 and 40 m and schools of *S. lemuru* were encountered sporadically during the surveys.

When a school was located on sonar the position was recorded and the immediate area was surveyed for other schools. The vessel was then slowed from its maximum speed of 8 knots and the size of the school was estimated from the display on the sounder. The school's depth in the water column was also assessed. If the school was large enough and well placed in the water column, the trawl gear was released and the boards lowered to the depth of the school. A minimum of three crew was required to set and retrieve the net.

Haul duration was variable and was generally kept to the minimum considered necessary to assure adequate samples of *S. lemuru* were retained. The skipper would typically make three runs over the school, winching up the trawl doors between each successive pass. At the end of the third pass, the towing speed was reduced to 1-2 knots as the net was pulled in. The boards were then raised and the cod-end winched in over the stern via the use of a "lazy line". Retrieval (until the cod-end was aboard) usually took around 15 to 20 minutes.

Survey area

The area covered during the surveys extended from 28° 20´ S to 29° 00´ S, and mostly in the western side of the Geelvink Channel between the Abrolhos Islands and the mainland. Figure 2B shows the track lines from independent cruises between February 1997 and June 1998. Figure 2C illustrates the area, which coincide with the main commercial fishing grounds, where catches of *S. lemuru* were made. There were, however, some isolated schools of *S. lemuru* encountered around the islands. Fishing only occurred close to the islands (< 5 km) when conditions in the Geelvink Channel were too rough. However, the majority of schools observed close to the islands (i.e. within 3 km) were most likely either *S. robustus* or *E. teres*, with small numbers of these typically dominating catches made close to the islands. Numerous commercial fisherman who work in the Abrolhos region were also of the opinion that the small, dense schools of fish found close to the islands consisted mainly of *S. robustus* and *E. teres*. Furthermore, when tracked on sonar these schools would suddenly change direction as the vessel approached with the trawl gear in the water, a behavioural pattern uncommon for *S. lemuru* in open water. In addition, the schools of *S. lemuru* were generally much larger and located closer to the bottom.

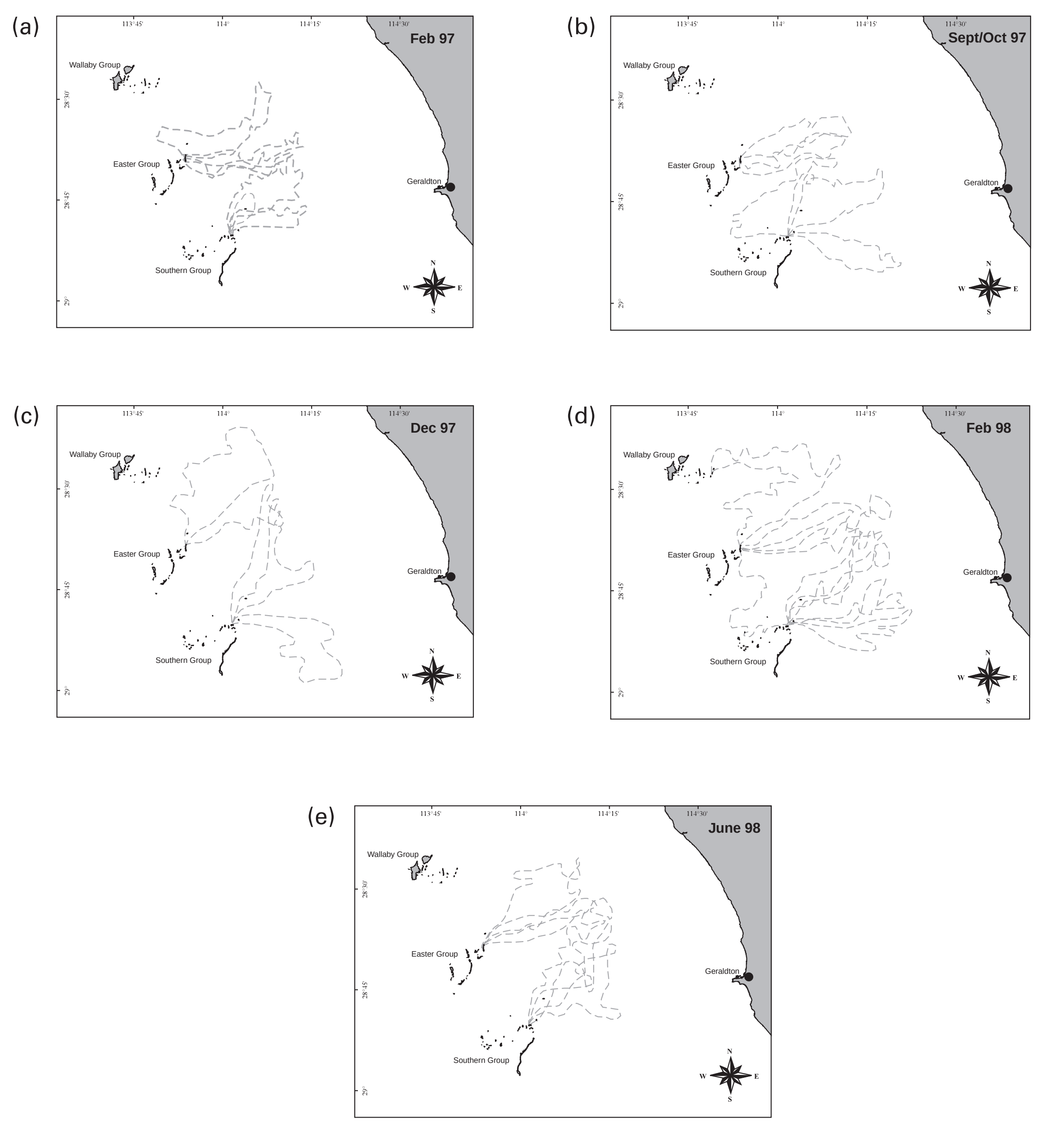

Figure 2B Track lines from research cruises between February 1997 and June 1998 aboard RV *Flinder*s (continued below).

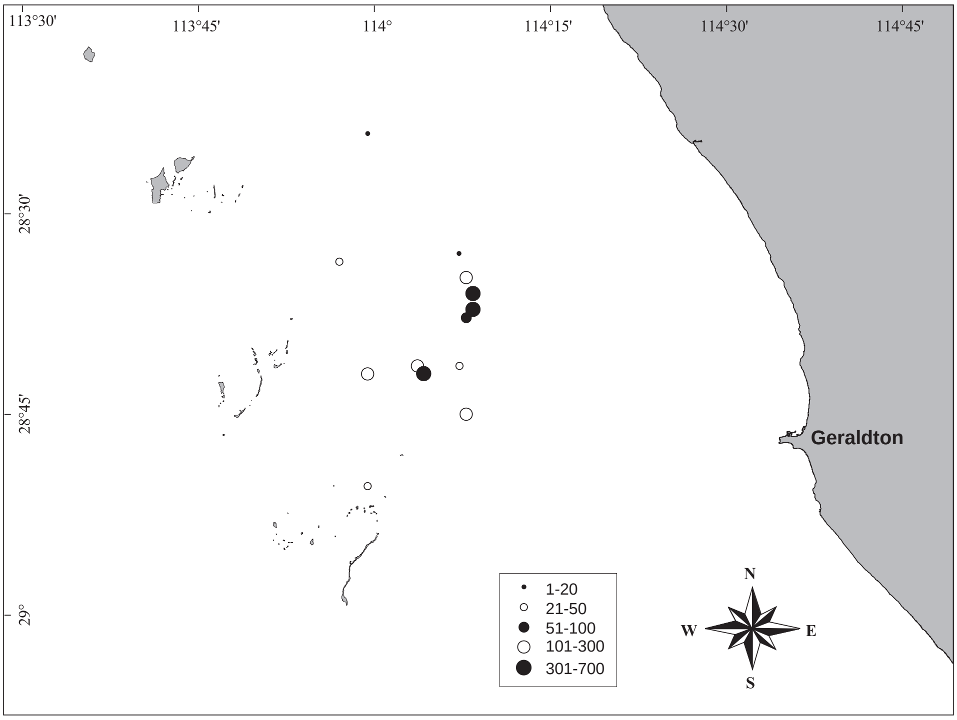

Figure 2C Positions of catches of *Sardinella lemuru* made with the mid-water trawl.

Catch results

Catches consisted of mainly of *S. lemuru* (Figure 2D), however, other species were also captured during the surveys (Table 2A). Due to various factors certain trawl shots resulted in zero captures of *S. lemuru*.

Other species caught during the sampling included maray (*E. teres*), yellowtail scad (*T. novaezelandiae*), tailor (*P. saltatrix*), skipjack trevally (*P. dentex*), blue mackerel (*S. australasicus*), blue sprat (*S. robustus*), slender sprat (*S. gracilis*), Australian anchovy (*E. australis*), striped seapike (*S. obtusata*), flying fish (*Cypselurus* spp.), blue-spotted goatfish (*O. vlamingii*) and three species of shark (*Sphyrna lewini, Carcharhinus brachyurus* and *Loxodon macrorhinus*).

From each successive shot a sample of *S. lemuru* (~100 individuals) was retained and these fish were frozen and taken back to the laboratory for further biological analysis. On occasions when fewer then 100 individuals were captured, all fish were retained. During the spawning months, the gonad condition of the females were assessed macroscopically immediately after capture. The percentage of females near spawning condition (ie. ovary stages 4-7) was determined. This information was required because plankton sampling which coincided with the adult sampling was only to be initiated if a reasonable number of adults were close to spawning condition. Gonads were removed from a random sub-sample of females and stored in 10 per cent formalin for fecundity and histological analysis. Representative gut samples were also extracted and placed in 10 per cent formalin to determine dietary components. Whole fish were also placed in formalin for further analysis of gonad condition and gut composition.

This form of fishing could only be successfully conducted when wind speeds were less then 25 kn. The main reason for this is that efficient trawl speed could not be maintained while steaming into the wind. It was also dangerous for the crew to be operating the trawl gear in strong winds.

Strong, southerly winds typically resulted in the loss of about one third of the scheduled sampling period for each trip. Strong winds were particularly chronic on the first mid-water trawl survey in January 1996 when no *S. lemuru* were caught.

Figure 2D An example of a clean catch of *S. lemuru* taken with the mid-water trawl net aboard RV *Flinders*.

Table 2A Numbers of each species caught during each trawl shot in 1997 and 1998.

Date	Time Net Shot	Scaly mackerel *Sardinella lemuru*	Blue mackerel *Scomber australasicus*	Blue sprat *Spratelloides robustus*	Scalloped hammerhead shark *Shyrna lewini*	Bronze whaler shark *Carcharninus brachyuru*
11/02/97	23:50	270	1	0	0	0
12/02/97	1:50	10	0	0	0	0
13/02/97	2:46	15	0	2	0	0
14/02/97	1:30	220	2	0	0	0
15/02/97	21:20	31	0	0	0	0
16/02/97	23:15	20	0	0	0	0
20/02/97	19:17	38	0	0	0	0
9/03/97	22:45	500	1	0	0	0
10/03/97	1:00	300	2	0	0	0
10/03/97	21:30	2	1	0	0	0
29/09/97	19:45	500	1	0	0	0
29/09/97	21:20	700	0	0	1	0
29/09/97	23:30	50	0	0	0	0
30/09/97	1:20	100	0	0	0	0
1/10/97	20:15	200	0	0	0	1
1/10/97	23:00	500	1	0	0	0
12/12/97	1:30	1	0	0	0	0
13/12/97	0:10	0	3	0	0	0
19/02/98	22:15	250	0	0	0	0
20/02/98	0:30	150	0	0	0	0
21/02/98	1:20	100	0	0	0	0
21/02/98	21:30	2500	0	0	0	0
22/02/98	21:00	1500	0	0	0	0
23/02/98	20:50	150	0	0	0	0
3/07/98	19:30	0	0	0	0	0
5/07/98	20:19	1	0	0	0	0
5/07/98	23:20	0	0	0	0	0
6/07/98	20:30	17	0	0	0	0
6/07/98	23:30	750	0	0	0	0
8/07/98	10:20	2500	0	0	0	0
9/07/98	19:30	11	0	0	0	0
9/07/98	21:20	0	0	0	0	0

Table 2A (cont'd)

Date	Time Net Shot	Flying fish *Cypselurus* spp.	Yellowtail scad *Trachurus*	Striped seapike *Sphyraena novaezelandiae*	Tailor *Pomatomus saltatrix obtusata*	Maray *Etrumeus teres*
11/02/97	23:50	1	0	2	0	10
12/02/97	1:50	0	2	0	0	0
13/02/97	2:46	0	0	1	0	0
14/02/97	1:30	2	0	0	0	1
15/02/97	21:20	0	0	0	0	0
16/02/97	23:15	0	0	0	0	0
20/02/97	19:17	0	0	0	0	0
9/03/97	22:45	0	1	3	0	1
10/03/97	1:00	1	2	5	0	0
10/03/97	21:30	0	0	10	0	5
29/09/97	19:45	1	2	3	1	0
29/09/97	21:20	0	1	0	0	1
29/09/97	23:30	0	0	1	0	0
30/09/97	1:20	1	0	2	0	0
1/10/97	20:15	0	2	2	0	0
1/10/97	23:00	1	1	1	0	0
12/12/97	1:30	0	2	0	0	0
13/12/97	0:10	0	0	0	0	7
19/02/98	22:15	1	2	0	0	0
20/02/98	0:30	2	1	0	1	1
21/02/98	1:20	0	0	1	2	0
21/02/98	21:30	1	0	2	0	2
22/02/98	21:00	1	1	0	5	0
23/02/98	20:50	0	0	0	2	0
3/07/98	19:30	0	6	0	0	17
5/07/98	20:19	0	0	0	0	12
5/07/98	23:20	0	0	0	0	0
6/07/98	20:30	1	0	0	0	0
6/07/98	23:30	0	2	0	0	3
8/07/98	10:20	0	7	0	0	6
9/07/98	19:30	1	0	0	0	0
9/07/98	21:20	0	0	0	0	0

Table 2A (cont'd)

Date	Time Net Shot	Silver trevally *Pseudocaranx dentex*	Blue-spotted goatfish *Openeichthys vlamingii*	Slit eye shark *Loxodon macrorhinus*	Australian anchovy *Engraulis australis*	Silver sprat *Spratelloides gracilis*
11/02/97	23:50	0	0	0	1	0
12/02/97	1:50	0	0	0	0	0
13/02/97	2:46	0	0	0	0	0
14/02/97	1:30	0	0	0	0	0
15/02/97	21:20	0	0	0	0	0
16/02/97	23:15	0	0	1	0	0
20/02/97	19:17	0	0	0	0	0
9/03/97	22:45	0	1	0	0	1
10/03/97	1:00	0	0	0	0	0
10/03/97	21:30	0	2	0	0	2
29/09/97	19:45	0	0	0	0	0
29/09/97	21:20	2	0	0	0	0
29/09/97	23:30	1	0	0	0	0
30/09/97	1:20	0	0	0	0	0
1/10/97	20:15	0	0	0	0	0
1/10/97	23:00	0	0	0	0	0
12/12/97	1:30	0	0	0	0	0
13/12/97	0:10	0	0	0	0	0
19/02/98	22:15	0	0	0	0	0
20/02/98	0:30	0	0	0	0	0
21/02/98	1:20	0	0	0	0	0
21/02/98	21:30	0	0	0	0	0
22/02/98	21:00	0	0	0	0	0
23/02/98	20:50	0	0	0	0	0
3/07/98	19:30	0	0	0	0	0
5/07/98	20:19	0	0	0	120	0
5/07/98	23:20	0	0	0	461	0
6/07/98	20:30	0	0	0	0	0
6/07/98	23:30	0	0	0	0	0
8/07/98	10:20	0	0	0	0	0
9/07/98	19:30	0	0	0	0	0
9/07/98	21:20	0	0	0	1600	0

Appendix 3: Intellectual property and valuable information

No saleable items were developed during this project.

Appendix 4: Staff

Staff that were employed on the project using FRDC funds were:
Mr J. Chidlow, Dr D. Gaughan, Mr R. Mitchell, Mr. R. Tregonning.

Staff who assisted on the project using non-FRDC funds were:
Mr G. Baudains, Mr T. Berden, Mr S. Blight, Mr I. Dunk, Dr W. Fletcher, Mr K. Gosden, Mr D. Harris, Mr K. Hillier, Mr A. Longstaff, Mr R. Mijat, Ms J. Murdoch, Mr W. Shaw, Mr T. Sheperd, Mr B. Webber, Mr K. White.