DISCARDED CATCH IN A MULTI-SPECIES TRAWL FISHERY

by

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Declaration

The work contained in this thesis, except where otherwise acknowledged, is the result of my own investigations.

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Abstract

This thesis analyses by-catch and discarding for fish trawling off the coast of NSW. As observed in many trawl fisheries, discarding at sea of unmarketable components of the catch has been acknowledged as a long-established feature of the fishery off NSW. An observer survey, using approximately 24 fisher-days in each quarter (8 fisher-days per month), in each of the 3 regions (North, Ulladulla and Eden) during 1993-95 produced sufficiently precise estimates of amounts of discards.

Bias and precision were compared for stratified mean-per-unit (SMPU), combined ratio (Rc), combined regression (LRc), separate ratio (Rs) and separate regression (LRs) estimators for estimating 15 components of catch. Bootstrapping was used to assess the relative importance of bias compared to 'root-mean-square-error" (RMSE, a measure comprising both precision and bias). Rs and LRs estimators were biased and unsuitable. Precision of Rc and LRc estimates exceeded the precision of SMPU estimates for 2 species (tiger flathead and jackass morwong), when the weight of the retained catch of each species (IRQS) was used as an auxiliary variable. The SMPU estimator was as, or more precise, than Rc and LRc estimators for all other components of catch. An optimal strategy for estimating rates of catch from the observer survey was to use the SMPU estimator for all components of catch with the exception of 2 species (tiger flathead and jackass morwong), for which the combined ratio estimator (Rc, using IRQS) would provide greater precision.

Several factors affected random selection of fisher-days: (i) some fishers refused to participate in the survey; (ii) it was not possible to identify the population of fisher-days before sampling; (iii) fisher-days were not always sampled independently and (iv) an observer onboard a trawler may also have influenced fishing and discarding practices. So, estimates of the magnitudes and size-distributions of retained catches using observers were compared with independent, unbiased estimates (reported landings and size-distributions obtained from an auxiliary survey of catches landed at fishing co-operatives). Estimates of retained and discarded catches for the 3 year period 1993-95 were unaffected by significant bias.
Fin-fishes dominated the 365 taxa in discarded catches. Discarded catches were dominated by relatively few species and the discards were usually smaller than 30 cm and consistently

smaller than retained fish (with the exception of gemfish). Approximately 50 % of the mean annual catch was discarded. Approximately 30 % of the catch of SEF quota species and 34 % of the catch of non-quota commercial species was discarded. Mortality of discards was likely to be close to 100 %, because of the relatively long duration of tows, the rapid decompression experienced by fish brought to the surface, the relatively long sorting time on deck prior to being discarded and observations of physical damage, obvious mortality and predation by sea-birds and sharks following discarding. For many species, magnitudes and size-distributions of total catches were not well represented by data from retained (landed) catches.

Rates of discarding differed among regions, years and quarters and were species-dependent. Catches were greatest at Eden (where effort was greatest), intermediate at Ulladulla and smaller in the northern region. Total catch and discarded catches of all species combined were greatest during the 3rd quarter in each region and year. There were many interactions among combinations of Regions, Years and Quarters and a large proportion of variability that was unexplained by these factors. Size-distributions of discards varied among regions and years for redfish and mirror dory. High-grading practices differed between Ulladulla and Eden; the Ulladulla fleet retained smaller fish. Depth also affected discarding; fish were smaller and a greater proportion of catches were discarded in shallower waters.

The influences of managerial regulations and market forces on discarding were examined and discarding of the various species was attributed among several factors or interactions between these factors. Regulations concerning protected species, minimal legal lengths, trip-limits and the direct effects of TACs determined patterns of discarding for several species. Factors concerning markets and economics were the major determinants of patterns of discarding for most species. All non-commercial species (220 taxa) were discarded because of the lack of market for them. Very small fish, of commercial species, were consistently discarded because there was no market for them. Catches of many species were high-graded. Large redfish were discarded in greater quantities when market volumes were high and the price paid per kg was low.

The influence of exclusion or inclusion of data about discards on assessments of stocks was examined. Trends in CPUE during the period 1993-97, for 5 of the 6 SEF quota species examined, depended on whether or not discards were included in the calculation of CPUE.

The inclusion of estimates of discarded catches in a biomass dynamic model of the redfish stock significantly affected estimates of parameters of the model and the depletion of biomass. Positive relationships between the precision of estimates of discarded catches and the precision of estimates of model parameters and trends in biomass were also demonstrated. Age-distributions of retained versus total catches of redfish indicated that age-structured models that ignore discards would underestimate fishing mortality and stock sizes for many age-classes. Exploitable biomass and spawning biomass would be underestimated. Discarded components of catches should not be ignored during stock assessments.

Data about discarding are now routinely collected from the fishery and are included in fisheries models and assessments for several species. However, performance criteria based on CPUE (for several SEF quota species) must be modified to include discards. Options for reducing discards include development of more selective fishing gears and of markets for currently discarded fish.

Given the poor precision of estimates of rates of discarding from many observer surveys, a more widespread use of pilot surveys would be useful. Because surveys are expensive and discards variable, the performance of alternative estimators should be compared in order to maximise the precision and minimise the bias of estimates. Similarly, the methods used here to detect bias resulting from non-random sampling may prove useful elsewhere.

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Chapter 1

General introduction

1.1 Historical perspective

The capture and subsequent discard of fish is documented as far back as biblical times in the parable of the "drag-netters" (Matthew 13: 47-48):

> *"Again, the kingdom of heaven is like a net which was thrown into the sea and gathered fish of every kind; when it was full, men drew it ashore and sat down and sorted the good into vessels but threw away the bad."*

In Australia, the first documented evidence of discarding and associated problems is found in transcripts of a Royal Commission conducted by Sir William Macleay in 1879-80 (cited in Dannevig, 1904). Based on fishermen's evidence to the Royal Commission, Dannevig (1904) states:

> *"No regard whatsoever was given to the preservation of immature food-fish. Hauling nets were landed as most convenient, generally on the beach, and unmarketable fish were left to their fate on the shore. (In a few instances only, when the mud on the foreshore was particularly soft, a number of men would land their nets in the water for the sake of the appearance and quality of their catch.) Of the fish that became stranded behind the stalling-nets, a considerable portion was often too small for the market, and they perished in the mud."*

> *"The prawn net is no exception to this rule: but it remains to be ascertained whether its influence in this respect is in any way abnormal or extraordinary. Strong and unqualified assertions to this effect may frequently be heard, as also statements to the effect that 'bushels upon bushels' of young fish are being killed by the prawn nets, and that the latter 'have been the ruin of the local fisheries.' "*

Despite such early references to issues associated with by-catch and discarding, international interest in such issues was limited to relatively few studies and publications prior to the 1980s. The publication of the proceedings of a workshop concerned with the utilisation of by-catch from shrimp trawling (IDRC, 1982) and a review of discarding in commercial fisheries (Saila, 1983) marked the onset of an increasing awareness of by-catch and discarding. Saila's review, titled *"Importance and assessment of discards in commercial fisheries"*, was the first published review of by-catch and discarding and discussed available information about discards, the negative effects of discarding and recommendations for methods to estimate magnitudes, species- and size-compositions of discarded catches.

It has been during the last 2 decades that by-catch and discarding have become major fisheries management issues. Numerous research papers and several further reviews (Andrew & Pepperell, 1992; Alverson *et al.*, 1994; Kennelly, 1995; Hall, 1996; Crowder & Murawski, 1998) and conferences (SFA, 1992; Fowle & Bierce, 1992; Alaska Sea Grant College Program, 1995) have been devoted to topics concerning by-catch and discarding. These topics include: the description and classification of problems and issues; methods for estimating by-catch and discarded catches; identification of spatial and temporal, regulatory and economic factors influencing by-catch and discarding; effects of by-catch and discarding on fish populations and stock assessments within fisheries and for interacting fisheries; technological and regulatory means of reducing by-catch and discarding; and the development of research and management policies and strategies.

Alverson *et al.* (1994) provided a "provisional" estimate of 27 million t of fish discarded annually in the world's fisheries and estimated that economic losses associated with discarding and monitoring or preventing discarding were of the order of billions of dollars. Declines in fish stocks, the collapse of major fisheries and the failure of science and management to predict many of these events are also well documented (e.g. FAO, 1997; Garcia & Newton, 1997; Iudicello *et al.*, 1999). The extent to which discarding alone and not the fishing process as a whole is responsible for such events is unclear (Alverson *et al.*, 1994). It has been shown for some fisheries, however, that the component of fishing mortality attributable to the discarded component of catch is significant and that failure to account for this component of mortality may bias stock assessments and conclusions about the benefits of alternative harvest strategies (Pikitch, 1987, 1991; Lowe *et al.*, 1991; Alverson, 1994; Chen & Gordon, 1997; Erhardt & Legault, 1997; Chen *et al.*, 1998). Given declining fish stocks, competition for the ocean's fishery resources is increasing with a consequent increase in conflict among competitors and between recreational and commercial sectors in particular (e.g. Foldren, 1989; Alverson *et al.*, 1994; Alverson & Hughes 1996; Harnwell, 1996; Schott, 1999). There have also been increases in the conservation and environmental movements in recent years resulting in increased public awareness and political activity concerning fisheries-related issues including by-catch and discarding (Alverson & Hughes, 1996; Kaufmann *et al.*, 1999).

Against this background, the dramatic explosion of interest in issues concerning by-catch and discarding is hardly surprising. Indeed, the issue of discarded by-catch has often been referred to as "the issue of the 90's" for fisheries (e.g. Tillman, 1993).

1.2 By-catch, discards & unaccounted fishing mortality

The definitions of by-catch, discarded catch and associated terminology used in this thesis are based on those described by Saila (1983) and Alverson *et al.* (1994). Specifically, by-catch is *"that part of the gross catch which is captured incidentally to the species toward which there is directed effort"* (Saila, 1983). The targeted catch is the catch of species *"toward which there is directed effort"* (Saila, 1983) which is essentially the same as *"the catch of a species or species assemblage which is primarily sought in a fishery"* (Alverson *et al.*, 1994). The retained catch is *"that portion of catch kept by fishers"* (Alverson *et al.*, 1994) whereas the discarded catch is *"that part of the gross catch not used in any way but thrown back into the waters as whole fish or whole organisms (in the case of invertebrates, amphibians, reptiles or mammals)"* (Alverson *et al.*, 1994). Note that, in using this definition, the discarded catch does not include offal that may also be thrown overboard after fish (or other organisms) in the retained catch are processed (e.g. gilled, gutted or filleted) onboard. Using these definitions, (i) targeted catch and by-catch are mutually exclusive and (ii) retained and discarded catch are mutually exclusive. It is possible for targeted catch to be retained or discarded and for by-catch to be retained or discarded.

Operationally, the identification of retained and discarded components of catch is straightforward because the processes of keeping versus throwing fish overboard can be observed. In contrast, the identification of targeted catch versus by-catch is problematic, particularly so for a multi-species fishery. In such circumstances, the classification of catch as target catch or by-catch is complex and relatively imprecise because it constitutes a value judgement (Murawski, 1992; Alverson *et al.*, 1994). For example, a fisher might target a particular species on a particular tow in a trawl fishery but may also expect or hope that he/she will also catch several other species of value. Whether or not these other species are targeted in this particular tow is debatable. Extracting the information about target catch for a particular tow from fishers is also complex because of variations in the accuracy of information provided by fishers regarding their intentions and expectations. This is not an issue of particular importance to this thesis because the main topic of interest is retained versus discarded catch rather than targeted catch versus by-catch. Nevertheless, throughout this thesis, the terms by-catch and targeted catch are used conceptually when appropriate.

Issues associated with the fishing mortality resulting from discarded catch (estimating the mortality, understanding the factors that influence it, consequences for assessments of stocks and developing strategies to reduce the mortality; see Section 1.3) are more generally applicable to any source of mortality that is not accounted for by the retained catch. The term "unaccounted fishing mortality" has been used to include those components of fishing mortality that are not accounted for by landed catch (e.g. Alverson *et al.*, 1994; Chopin et al., 1996; Alverson & Hughes, 1996). Realistic estimates of fishing mortality, F, depend on realistic estimates of the unaccounted components of F, a formal representation of such unaccounted fishing mortalities being provided by Chopin *et al.* (1996):

$$F = [F_{CL} + F_{AL} + F_{RL}] + F_B + F_D + F_O + F_A + F_E + F_G + F_P + F_H$$

in which components of total fishing mortality are associated with: commercial, artisan and recreational fishery landings (F_{CL}, F_{AL} and F_{RL} respectively), illegal and mis-reported landings (F_B), discards (F_D), fish passively dropping off or out of fishing gears (F_O), fish avoiding fishing gear (F_A), mortality after escape from fishing gear (F_E), ghost fishing (F_G, i.e. when lost fishing gear continues to fish and cause mortality), predation after escape (F_P) and as a consequence of gear-induced changes to habitat (F_H).

Whilst some of these unaccounted fishing mortalities may be insignificant in many fisheries, the importance of components associated with escape or passive exit from fishing gears (F_O, F_E and F_P) has been demonstrated (Chopin & Arimoto, 1995). The component associated with illegal fishing (F_B) is considered to be most significant in many fisheries (e.g. Alverson & Hughes, 1996). Similarly, estimates of magnitudes of discards in many fisheries demonstrate that F_D is an important component of the total fishing mortality (e.g. Kulka & Waldron, 1983; Pikitch, 1987, 1991; Alverson *et al.*, 1994; Chen & Gordon, 1997; Chen *et al.*, 1998; Stratoudakis *et al.*, 1998). It is F_D, the unaccounted fishing mortality associated with discarding, that is the focus of this thesis.

1.3 Issues concerning discards

1.3.1 General categories of issues

There are numerous issues concerning discarded catch and their complexity has been discussed in several reviews of by-catch and discarding (Saila, 1983; Andrew & Pepperell, 1992; Alverson et al., 1994; Kennelly, 1995; Hall, 1996; Crowder & Murawski, 1998). These issues may be classified into 5 general categories concerning: (i) estimating the magnitude and composition of discarded catch; (ii) the fate of discards; (iii) identification of factors affecting discarding; (iv) assessing the consequences of discarding for populations, ecosystems and fishery management and (v) strategies for managing and reducing discarding.

1.3.2 *Estimating the magnitude and composition of discarded catch*

The basic requirement for consideration of any of the issues in categories (ii) - (v) above, is an understanding of the species-specific magnitudes, size- and/or age-distributions of retained and discarded catches (e.g. Saila, 1983; Alverson *et al.*, 1994; Kennelly, 1995). Observer surveys, in which scientific observers collect data onboard fishing vessels during normal commercial fishing are the favoured method for collecting such data (Saila, 1983; Alverson *et al.*, 1994; Kennelly, 1995). Observer programmes have been used for this purpose in many fisheries, particularly trawl fisheries (e.g. Jean, 1963; Jermyn & Robb, 1981; Howell & Langan, 1987, 1992; Liggins & Kennelly, 1996; Liggins *et al.*, 1996; Kennelly *et al.*, 1997, 1998; Stratoudakis *et al.*, 1999). Alternative methods for estimating discards rely on fishers providing estimates of discards in logbooks and/or collecting sub-samples of catch at sea and providing these data and samples to scientists on return to port (e.g. Jean, 1963; Evans *et al.*, 1994; and the "Hillis" method described in Saila, 1983). Such methods are not ideal, because they rely on the skill, honesty and memory of fishers (Alverson *et al.*, 1994; Kennelly, 1997).

Issues associated with estimating magnitudes and size-distributions of retained and discarded catches from observer surveys include those associated with survey design and execution, selection of suitable estimators and detection of bias in estimates (e.g. Cochran, 1977; Saila, 1983). In particular, Saila (1983) stressed the value of pilot surveys prior to observer surveys as a means of testing sampling methods and determining optimal sample size. There is, however, little evidence in the literature of the use of pilot surveys for optimising the design of observer surveys in fisheries. Similarly, there have been few reported studies of the comparative accuracy and precision of alternative estimators that can be used to scale observed rates of discarding to estimates of discards by whole fleets (Andrew & Pepperell, 1992; but see Tamsett *et al.,* 1999a). The estimators most commonly used are simple ratio and mean-per-unit estimators (Andrew & Pepperell, 1992; Alverson et al., 1994; Kennelly, 1995). Using the ratio estimator, the ratio of discarded catch to retained catch is multiplied by the known landed catch for the whole fleet, to estimate discarded catch for whole fleets (e.g. Keiser, 1977; Atkinson, 1984; Stratoudakis *et al.,* 1999). The mean-per-unit estimator uses the observed quantity of discards per unit of effort is to estimate total discards by multiplying by the known total effort (e.g. Gutherz & Pellegrin, 1988; Harris & Poiner, 1990; Fennessy, 1994; Liggins *et al.,*1996, Kennelly *et al.*, 1998). It is surprising that the regression estimator, the stratified mean-per-unit estimator and the forms of ratio and regression estimators appropriate to stratified survey designs (e.g. Cochran, 1977; Saila, 1983; Sukhatme *et al.*, 1984) have rarely been used in analyses of data from observer surveys (but see Liggins *et al.,*1996, Kennelly *et al.*, 1998; Stratoudakis *et al.*, 1999). Saila (1983) and Andrew and Pepperell (1992) have emphasised the importance of considering the advantages of alternative estimators for estimating discards by whole fleets from observer surveys.

Detection of bias in observer-based estimates of discards has also received scant attention in the literature. Estimates of discards may be biased by non-representative selection of sampling units or by changes in fishing practices onboard vessels when observers are present (Saila, 1983; Alverson *et al.*, 1994). Non-representative sampling errors may result in biased estimates from observer surveys because: (i) random selection of sampling units (e.g. trips) is difficult when the sample population cannot be enumerated until the period from which the sample is taken is complete and (ii) refusals by masters of vessels to allow an observer onboard will bias estimates unless rates of retained and discarded catch of respondents and non-respondents are the same. A third likely source of bias for observer surveys of discards results from changed fishing or discarding practices onboard vessels when observers are present. The only discussion of bias found in publications concerning the results of observer surveys was in Stratoudakis *et al.* (1998) who reported that their observations of illegal catches during observed fishing trips suggested the estimates from their survey were reliable.

1.3.3 The fate of discards

The consequence of the capture and discard of a given species of fish to stocks of that species depends on the mortality associated with the capture and subsequent discarding, in addition to the natural mortality and the size of the stock of that species (e.g. Kennelly, 1995). Biological, environmental and operational factors have been shown to influence survival of discards from trawl fisheries (see reviews by: Andrew & Pepperell, 1992; Alverson *et al.*, 1994; Kennelly, 1995). Species-specific differences in mortality following capture by trawling have been demonstrated for both prawn trawl fisheries (e.g. Wassenberg & Hill, 1989, 1990; Hill & Wassenberg, 1990) and fish trawl fisheries (Jean, 1963; NRC, 1990; Van Beek *et al.*, 1990). The size of fish, air temperature, depth of fishing, tow duration, catch size and sorting time (exposure time on deck) have all been shown to influence mortality (Jean, 1963; De Veen *et al.*, 1975; Neilson *et al.*, 1989; Wassenberg & Hill, 1989; Van Beek *et al.*, 1990). Despite these variabilities, it is often assumed that the survival of fish discarded in trawl fisheries is extremely small (Alverson *et al.*, 1994; Kennelly, 1995).

In contrast to the direct effect of mortality of discarded fish on stocks of the species discarded, discarding may also produce more indirect effects on ecosystems. Removal of fish (retained as well as discarded) may alter competitive or predator-prey relationships (e.g. Jennings & Kaiser, 1998; Hall, 1999). Moreover, the return of dead fish to the water may affect the diets and abundance of surface scavengers, pelagic or benthic feeders (e.g. Hudson & Furness, 1988; Wassenberg & Hill, 1987, 1990; Blaber & Wassenberg, 1989). The study of indirect effects of discarding on ecosystems is, however, very much in its infancy.

1.3.4 Identification of factors affecting discards

An understanding of the variability of discarding in space and time (e.g. regions, latitude, depth, seasons, years) would facilitate the assessment of alternative strategies for reducing discarding. Importantly, it is a pre-requisite to assessing the potential utility of spatial and temporal closures for reducing discarding (Alverson et al., 1994; Hall, 1996; Liggins *et al.*, 1996; Kennelly, 1997; Kennelly *et al.*, 1997). Moreover, identification of "hot spots" for discarding of key species may also be useful when selecting locations and times for experiments to evaluate the effectiveness of alternative gears (Kennelly, 1999).

Differences in the magnitudes and composition of discarded catches have been identified at a variety of spatial and temporal scales in many fisheries. For fish trawl fisheries, such differences have been identified among fisheries, among regions within fisheries, related to distance offshore, among depths, among seasons and years (French *et al.*, 1982; Jean, 1963; Jermyn & Robb, 1981; Howell & Langan, 1987; Alverson *et al.*, 1994; Kennelly *et al.*, 1997; Stratoudakis *et al.*, 1998; Tamsett & Janacek, 1999; Tamsett *et al.*, 1999a). Moreover, observer surveys stratified over multiple spatial and temporal scales have found a variety of interactions among such factors (e.g. Liggins & Kennelly, 1996; Kennelly *et al.*, 1998; Stratoudakis *et al.*, 1998).

Alverson *et al.* (1994) classified factors that affect discarding into 3 categories: "physical-biological interaction", "economic" and "legal". Under such a classification, physical-biological factors include the distribution, abundance, species- and size-composition of fish on fishing grounds, the behaviour of fish when encountering fishing gears and the selectivity of fishing gears (Alverson *et al.*, 1994; Kennelly, 1995; Crowder & Murawski, 1998; Broadhurst, 2000). These factors influence the magnitude, species- and size-composition of the catch landed on deck. A second phase determining discards then occurs when fishers make decisions about what is to be retained and discarded, based on economic and legal considerations (Alverson *et al.*, 1994; Crean & Symes, 1994). Legal or regulatory factors identified as affecting discarding include: minimal legal length regulations, prohibited species regulations, regulated trip limits and annual catch quotas. Economic factors include: lack of a market for particular species, sizes or damaged fish; high-grading resulting from interaction between market forces and quotas and high-grading resulting from interaction between market forces and limited capacity for storage of catch onboard vessels.

1.3.5 Assessing the consequences of discarding for populations and fishery management

Fundamental to stock assessment and fishery management is an understanding of fish population dynamics, the study of how and why a population changes (e.g. Gulland, 1988; Hilborn & Walters; 1992; Quinn & Deriso, 1999). The basic data requirements for various quantitative models of the dynamics of fish populations involve some combination of catch-per-unit-effort (CPUE), catch-at-age or catch-at-length data (Doubleday & Rivard, 1983; Gulland, 1988; Hilborn & Walters, 1992; Quinn & Deriso, 1999). Such data may be obtained from observations on commercial fisheries ("fishery-dependent" data) or from sources independent of the fishery ("fishery-independent" data). Commercial catch statistics are, by definition, fishery-dependent. Fishery-dependent catch and effort data are often used to provide an index of abundance for a population of fish. Fishery-dependent catch-at-age and catch-at-length statistics are commonly used to provide estimates of the relative abundance of different ages or length-classes of fish in the population or to estimate successive annual catches from individual cohorts of fish. Biases in commercial catch data may be avoided by obtaining data from fishery-independent sources, for example: visual surveys using underwater breathing apparatus or submersible craft; hydro-acoustic surveys; or research cruises using various fishing gears. Each type of survey has specific problems and benefits but the cost of collecting data using such methods is generally great. Consequently, fishery-dependent data currently provides and will continue to provide the basis for many fisheries assessments (Hilborn & Walters, 1992).

If discards, or any source of fishing mortality, are excluded from estimates of catch, CPUE, size- or age-distributions from fishery-dependent sources, the results of analyses based on such data are potentially biased (Hilborn & Walters, 1992; Alverson & Hughes, 1996; Crowder & Murawski, 1998; Alverson *et al.*, 1994). As a consequence, conclusions drawn from these models that form the basis of stock assessments and subsequent management actions may not be justified.

Analysis of how discarding affects fish populations, stock assessment, the subsequent management of fisheries and yields to commercial and recreational harvesters has been presented in relatively few publications. A review of the theoretical impact of including data about discarding on population dynamics models was provided by ICES (1986, cited in

Alverson *et al.*, 1994) which concluded that inclusion of data about discards could, in some cases, drastically alter perceptions of the status of exploitation of stocks and yields accruing from changes in regulations. This conclusion is supported by the few published studies that address these issues using real data (e.g. Pikitch, 1987, 1991; Lowe *et al.*, 1991; Alverson, 1994; Chen & Gordon, 1997; Erhardt & Legault, 1997; Chen *et al.*, 1998).

1.3.6 Strategies for managing and reducing discarding

The need to reduce discarding may be indicated by the demonstration of negative effects on populations or fisheries. Moreover, strategies to reduce discarding may be necessary to manage the perceptions of commercial fishers or recreational fishers in interacting fisheries, concerns of environmental and conservation groups or the general public (Alverson & Hughes, 1996; Kennelly, 1997; Crowder & Murawski, 1998). Images of large quantities of fish being shovelled over the side of a trawler or publicity concerning the by-catch and discard of "charismatic megafauna" such as dolphins, turtles and seals evoke strong reactions from the public. Regardless of whether such events have any impacts on populations or ecosystems, such reactions by the public to by-catch and discarding represent a major threat to the fishing industry.

Potential strategies for reducing discards may be categorised as those that: (i) reduce the capture of fish that are subsequently discarded or (ii) affect the decisions of fishers to discard fish following capture (Alverson *et al.*, 1994). Spatial and temporal closures to fishing and the development of fishing gears and practices that are more selective for the species or sizes of fish targeted by the fishery are examples of strategies in the first category (e.g. Isaksen *et al.*, 1992; Walsh *et al.*, 1992; Crean & Symes, 1994; Kennelly, 1995; Hall, 1996). Strategies that seek to increase the utilisation of components (e.g. Peterkin, 1982; IDRC, 1982) of catch that are currently discarded influence the decisions of fishers to discard fish following capture (the second category). Development of markets (for species or sizes of fish for which no market currently exists) or, more generally, any measures that increase the economic incentive for fishers to retain fish currently discarded are examples of strategies that influence the decisions of fishers to discard fish they have caught. Changes to minimal legal length regulations, trip-limits or annual catch quotas, provided that the benefits of these actions outweigh the costs, may also allow fishers to retain fish that must currently be discarded.

1.4 A logical framework for proceeding toward solutions

Several authors have documented processes by which the various issues described above (or a subset of these issues) may be addressed within a logical framework (e.g. Saila, 1983; Crean & Symes, 1994; Alverson *et al.*, 1994; Kennelly, 1997; Hall, 1996; Crowder & Murawski, 1998).

Saila (1983) provided a broad review of issues concerning discards and a detailed framework for the design and implementation of observer surveys and estimating magnitudes and size-composition of discarded catches. Kennelly (1997) proposed a framework for solving perceived by-catch problems that comprised multiple stages: (i) observer surveys to estimate quantities and variabilities of discards ; (ii) identification of alternative solutions (spatial/temporal closures, gear modification, etc.) for reducing by-catch and discards; (iii) testing of alternative solutions (e.g. evaluation of alternative gears); (iv) publicity of these results to fishers; and (v) publicity to the general public. This framework did not include a phase in which the effects of discarding are assessed. Key features of Kennelly's framework were an emphasis on consultation with fishers during all phases of the project and the emphasis on reduction of by-catch and discarding. Alverson *et al.* (1994), Crean & Symes (1994), Hall (1996) and Crowder & Murawski (1998) provided a general review of issues concerning discarded catch and structured these issues into categories similar to those described in Section 1.3 of this thesis.

These reviews and proposed frameworks imply, or explicitly recommend, a logical sequence of steps that provide strategies for solving the many issues associated with discarding. The 5 categories of issues presented in Section 1.3.1 (and discussed in Sections 1.3.2 - 1.3.6) and the order of these categories of issues represents a synthesis of the frameworks presented by the authors mentioned above.

1.5 Fish trawling off the coast of NSW

The fish trawl fishery off the coast of NSW is one of Australia's oldest commercial fisheries. Following exploratory fishing by the experimental trawler *Endeavour* between 1909 and 1914, the NSW government brought three steam trawlers out from England, to be based in Sydney. An additional four trawlers were constructed in the NSW government dockyard in 1920. All seven trawlers were sold to private industry in 1923 and Australia's first commercial fish trawl fishery was established off the coast of NSW (Fairbridge, 1951; Houston, 1954). The fishery was dominated by steam trawlers from 1915 to 1950, by Danish seiners from the early 1950s to the early 1970s and by modern otter-board trawlers since this time (Tilzey, 1994).

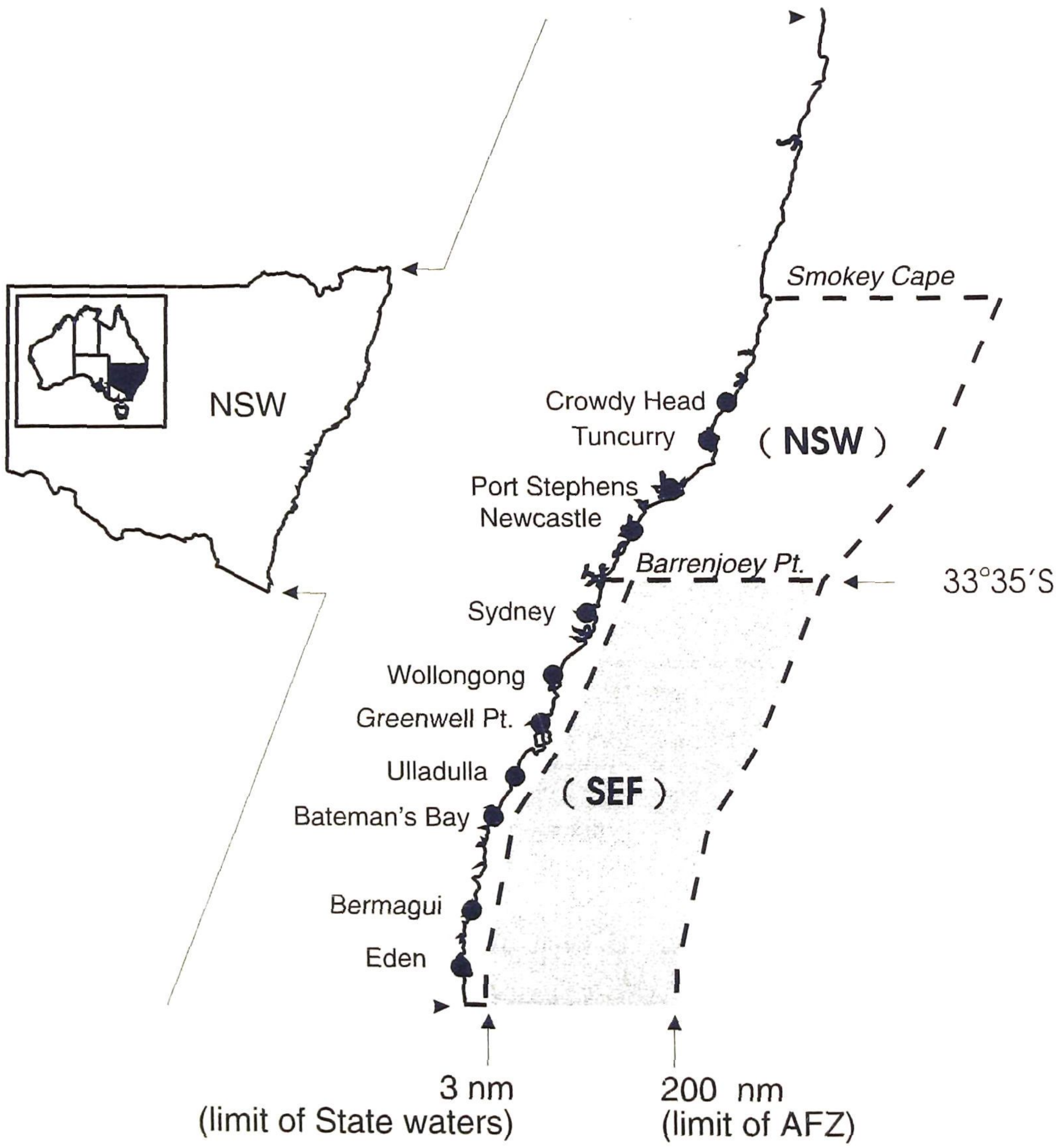
Early fishing was confined to the waters on the continental shelf (< 200 m depth) but expanded offshore onto the continental slope (> 200 m depth) during the 1970's. Tiger flathead (*Neoplatycephalus richardsoni*) was the main species targeted by trawlers prior to 1930 but declining catches led to increasing exploitation of jackass morwong (*Nemadactylus macropterus*) and redfish (*Centroberyx affinis*) from the late 1940s onwards (Fairbridge, 1951, 1952; Houston, 1955). The otter-trawl fleet expanded in the 1970s with the development of a fishery targeting the spawning run of gemfish (*Rexea solandri*) on the upper continental slope. By the early 1980s the NSW fleet had grown to 130 vessels (Tilzey, 1994).

Prior to 1985, the NSW government had jurisdiction over all fishing in coastal waters out to a distance of 3 nm and the Commonwealth government held jurisdiction for waters beyond this line. Following declaration of the Australian Fishing Zone (waters out to a distance of 200 nm offshore) in 1985, the jurisdiction and the management framework for the fishery changed dramatically (Tilzey, 1994). The South East Trawl Fishery (later to become the South East Fishery, SEF), managed by the Australian Fisheries Management Authority (AFMA) under Commonwealth jurisdiction, was established for waters south of Barrenjoey Point (Lat. 37°30'S), from a distance of 3 nm offshore to the 200 nm limit of the Australian Fishing Zone (Fig. 1.1). Fish trawling in waters to the north of Barrenjoey Point and in waters south of Barrenjoey Point within 3 nm of the coast have continued to be managed by NSW Fisheries under State jurisdiction (Fig. 1.1).

Figure 1.1

Jurisdiction for fish trawling off the NSW coast

(NSW) State jurisdiction
(SEF) South east trawl fishery (Commonwealth jurisdiction)



Prior to 1985, there was a limit on the number of trawlers greater than 32 m in length permitted to enter the fishery, but there were no regulations controlling the number of vessels less than this size. In 1985, management based on limited entry was introduced for the SEF and this was followed in 1986 by a boat replacement policy to prevent the expansion of effort through upgrading of boats. Despite these measures, fishing capacity and effort continued to increase (Tilzey, 1994). With the economic state of the fishery deteriorating and concerns about over-fishing of stocks of gemfish and redfish, a management system comprising "total allowable catch" (TAC) and "individual transferable quota" (ITQ) for each of 16 species was introduced in 1992 (ABARE, 1993; Tilzey, 1994).

There is currently a minimal mesh-size of 90 mm for trawls in this fishery and this has applied since the mid 1950s. Selectivity experiments by Houston (1955) indicated that a mesh-size of 3.25" (83 mm) in Danish seines would retain about 50 % of tiger flathead at the minimal legal size of 33 cm. Based on comparative studies of the selectivity of Danish seines and trawls done overseas, Houston (1955) also recommended a minimal mesh-size of 90 mm for trawls. Consequently, the 90 mm mesh-size that still is in regulation for trawls today was determined with no consideration of its selectivity for species other than flathead and very little scientific investigation.

By-catch and discarding were recognised as features of this fishery early in its history. Fairbridge (1952) notes:

> *"The relative values of the three species can be expressed as their fixed wholesale prices (1950), namely flathead 1/1 per lb; morwong 10d. per lb; nannygai* (redfish) *8d. per lb. Prior to the second world war the latter two species were largely discarded. With the decreasing availability of flathead, the fishing boats have had to make up their catches with the poorer priced species."*
>
> [Note that: "1/1" means 1 shilling and 1 penny; "10d" and "8d" mean 10 pence and 8 pence respectively; there were 12 pence to a shilling and 20 shillings to a pound]

It was not until the late 1980s and early 1990s, however, that the importance of discarding to the management of this fishery was formally recognised. A national working group was established by the Commonwealth Government in 1990 to consider the application and implementation of ESD (ecologically sustainable development) principles to the management of fisheries. Recommendations of this working group (Green, 1991) included:

> *"that fisheries management authorities, in collaboration with research agencies, collect and analyse the data necessary to measure the impact of fishing on non-target and by-catch species"*
>
> *"as data permits, fisheries management authorities set target species catch levels in accordance with the requirement that fishing does not exceed ecologically sustainable levels for both target and non-target species and where data on by-catch exists, harvesting levels in those fisheries be immediately reviewed."*

In the SEF, it was acknowledged that discarding of unmarketable species and unmarketable sizes and quantities of commercial species was a long-established practice (Tilzey, 1994). Moreover, it was a major concern that stock assessments based on data about the landed component of catch, ignoring discards, may be inaccurate. It was concluded in the early 90s that emphasis should be placed on quantifying the extent of discarding and incorporating this information into the stock assessment process (Tilzey, 1994). This was reflected in the *Strategic Research Plan for the SEF* (e.g. SETMAC, 1995) that specifically recognised the need for: collection of data about the magnitude, size- and age-composition of discarded catches; an understanding of the impacts of fishing on non-target species; inclusion of estimates of discarded catch in stock assessments and the investigation of management options for reducing by-catch and discarding.

It was against this background that NSW Fisheries completed a pilot survey of the discarded catch from fish trawling and subsequently received a 3-year research grant from the Fisheries Research and Development Corporation (FRDC) to examine issues associated with discarding by fish trawlers off the NSW coast. I ran this project for NSW Fisheries and the data from this project forms the basis of this thesis.

1.6 Objectives of this thesis

The scope of this thesis concerns many of the issues associated with discarding that were outlined in Section 1.3. The structure of this thesis is based on a synthesis of the various frameworks for addressing these issues (described in Section 1.4), and comprises a step-wise approach, in which chapters address particular issues or categories of issues (Fig. 1.2). This thesis builds to conclusions about strategies for managing discards including recommendations concerning ongoing monitoring, inclusion of data about discards in assessments of stocks and options for reducing discarding.

Chapters 2-4 concern issues associated with estimating the magnitude and composition of discarded catch (category "(i)" issues in Section 1.3.1). Chapter 2 examines the design and implementation of an observer survey to estimate the quantities and size-distributions of retained and discarded catches by fish trawlers off the coast of NSW. This is based on a pilot observer survey and analyses of sample sizes and precision. The methods used during the observer programme and the sampling coverage achieved are discussed. The objective of Chapter 3 is to compare a range of estimators and determine an optimal method for estimating annual discards and total catches, taking into account both bias and precision. Chapter 4 concerns the difficult problem of detecting bias in observer-based estimates of catch and presents a novel methodology for estimating this.

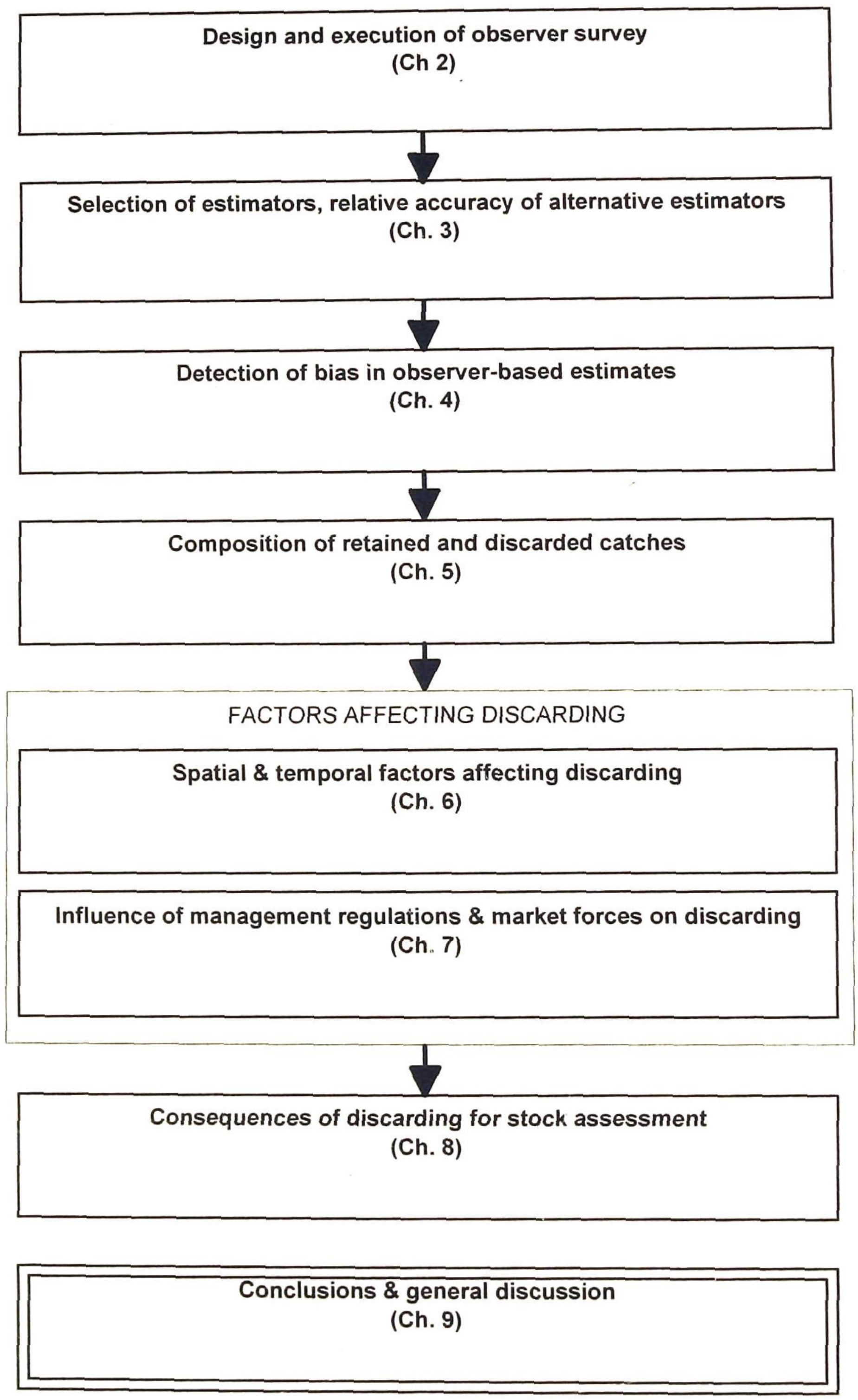
Using data from the observer survey (Chapter 2) and appropriate estimators (Chapter 3), the magnitude and species composition of discarded catch from fish trawling off the NSW coast during 1993-95 is presented in Chapter 5. The fate of these discards (category "(ii)" issues in 1.3.1) is also discussed in this chapter. Whilst no experiments were done to estimate mortality, conclusions about the mortality resulting from capture and discard in this fishery were based on observations made during the observer survey and conclusions from other studies.

Chapters 6 and 7 identify factors that influence discarding (category "(iii)" issues in 1.3.1). Hypotheses concerning variation in: mean rates of discarding across regions, years and quarters (seasons), size-distributions of discards and discarding practices among regions and years; and the mean sizes of fish and proportions of catch discarded with depth are presented and tested in Chapter 6. In Chapter 7, the influence of management regulations (minimal sizes, trip limits and TACs) and market/economic forces on discarding are examined.

Chapter 8 examines the consequences of discarding for stock assessments and fisheries management (category "(iv)" issues in Section 1.3.1). The effect of including data about

Figure 1.2

Structure of thesis



discards on trends in CPUE is examined because analysis of CPUE trends is currently the basis for stock assessment and performance indicators for the majority of SEF quota species. A biomass dynamic model is used to examine how the inclusion of estimates of discards of redfish affects parameter estimates and conclusions about the current status of the redfish stock. Size-distributions of redfish are converted to age-distributions and the consequences of observed age-distributions of discarded redfish for age-based assessment methodologies are considered.

Finally, based on the results and conclusions from Chapters 1-8, future strategies for managing and reducing discards in the fish trawl fishery off NSW, and in fisheries generally, are discussed in Chapter 9 (category "(v)" issues in 1.3.1).

Chapter 2
Design and execution of an observer survey

2.1 Introduction

Observer surveys, in which scientific observers on fishing vessels collect data during normal commercial fishing, have been used to estimate quantities and size/age distributions of discarded catches in a variety of fisheries. This has particularly been the case in demersal trawl fisheries, where by-catch and discards are often perceived as problems (e.g. Jean, 1963; Jermyn & Robb, 1981; Howell & Langan, 1987; Gutherz & Pellegrin, 1988; Poiner *et al.*, 1990; Fennessy, 1994; Liggins & Kennelly, 1996; Kennelly *et al.*, 1997, 1998; Stratoudakis *et al.*, 1998, 1999; Tamsett & Janacek, 1999; and reviews by Andrew & Pepperell, 1992; Alverson *et al.*, 1994; Kennelly, 1995).

Several less reliable methods for estimating discards have also been used. Fishers have recorded estimates of discards in logbooks (e.g. Jean, 1963) or taken sub-samples of catches at sea for researchers in port (e.g. Evans *et al.*, 1994; and the "Hillis" method, described in Saila, 1983;) or have been interviewed about discarding practices (e.g. Jermyn & Hall, 1978, cited in Jermyn & Robb, 1981; Evans *et al.*, 1994). Such methods all depend on the skill and honesty or memory of fishers. Indeed, it has been argued that it is often in fishers' best interests not to provide such information (Kennelly, 1997). Some studies have used research or chartered vessels to provide data about magnitudes and composition of by-catches (e.g. Keiser, 1977; Gray *et al.*, 1990; Harris & Poiner, 1990; Ramm *et al.*, 1990; Evans *et al.*, 1994). Estimates of magnitudes and size-compositions of by-catches and discards from such surveys may not, however, represent accurately those of the commercial fleets because of differences in fishing gears and operating procedures. Except for fisheries in which the sizes of vessels prevent carriage of an additional observer, the observer-based survey is the favoured method for estimating discards (Saila, 1983; Alverson *et al.*, 1994; Kennelly, 1997).

The design and implementation of any survey must take account of the specific objectives of the survey, definition of the survey population, construction of the sampling frame (i.e. the list of sampling units), the data to be collected, priorities if time or resources are limiting, the required precision for estimates and benefits of alternative sampling plans and methods (see also Cochran, 1977; Saila, 1983). Pilot surveys are particularly useful for providing data about variabilities of the quantities being estimated and facilitate calculation of appropriate sample sizes to achieve specified levels of precision (e.g. Cochran, 1977; Saila, 1983; Doubleday & Rivard, 1983; Andrew & Mapstone, 1987; Underwood, 1997). Pilot surveys followed by analyses of cost-benefit have been used to determine optimal sample sizes (within the logistic constraints of time and money) in a variety of applications concerning fisheries (e.g. Saila *et al.*, 1976; Schwiegert & Sibert, 1983; Kennelly *et al.*, 1993; Tamsett *et al.*, 1999a, 1999b). Despite recognition of the importance of such methods to the design of observer surveys of discarding (Saila, 1983), documented evidence of the application of such methods to observer surveys is scarce (but see Jermyn & Robb, 1981, regarding a pilot survey concerning estimation of discards from a logbook programme; Tamsett *et al.*, 1999a). There is, however, evidence of making on-going modifications to designs of observer surveys based on variances of estimates of discards calculated during preceding periods of the survey (e.g. Jermyn & Robb, 1981; Baird & Stevenson, 1983; Kulka & Waldron, 1983; Tamsett & Janacek, 1999). In addition to providing data about variabilities of rates of discarding, pilot surveys also provide a means of testing proposed methodologies and identifying unforeseen practical problems (Saila, 1983; Tamsett *et al.*, 1999a).

In this thesis, an observer survey of catches by fish trawlers in NSW provided the basis for estimating quantities and size-distributions of retained and discarded catches. This chapter: (i) describes a pilot observer survey and subsequent analyses of sample size and precision; (ii) explains the rationale for the design of the observer survey; (iii) describes the methods used in the survey and (iv) reports on the implementation and achieved sampling coverage.

2.2 Methods

2.2.1 Determination of size of sample using data from a pilot survey

A pilot survey of the magnitudes and size-distributions of retained and discarded catches by fish trawlers operating out of Ulladulla and Eden was completed during July and August, 1992. The objectives of this survey were: (i) to discuss the forthcoming full-scale survey and to establish some rapport with owners and skippers; (ii) to assess the logistics of collection of data and sub-sampling of catches on trawlers; and (iii) to collect data on the quantities of retained and discarded catches that could be used to estimate the precision (in terms of SE / mean ratios) that could be expected for various levels of sampling effort (in terms of number of fisher-days per region) in the forthcoming survey. Nine fisher-days were observed at Ulladulla during July 1992 and 10 fisher-days were observed at Eden between July 16 and August 16, 1992. The data derived from each of these trips included weights and counts of all species retained and weights, counts and length-distributions of sub-samples of the discarded catch.

For the most abundant species in the retained and discarded catches at Ulladulla and Eden, means and standard deviations of catch rates per fisher-day were calculated and used to estimate the precision (SE / Mean) of catch per fisher-day across a range of sample sizes (2 - 10 fisher-days per month). Assuming, for the purposes of this exercise, that the variabilities of catch-rates estimated during the pilot survey (within the July-August period) approximated the variabilities of catch-rates across a quarter (3-month period) and a year, the expected precision of estimates of mean catch per fisher-day were also calculated for sample sizes 6 - 30 and 24 - 120 (the quarterly and annual sample sizes that would result from monthly sample sizes in the range 2 - 10, respectively; Figs. 2.1.a and 2.1.b).

Given the financial resources available for this project and the need to survey 3 regions along the NSW coast for 3 years, 8 fisher-days per region was the maximal possible size of sample. This analysis was done to confirm that the precisions of estimates of catch-rate likely to result from this sampling regime were acceptable. If not, consideration would have had to be given to increasing the size of samples at the expense of the number of regions or the number of years surveyed. This analysis also provided a means of informing interested parties (funding agencies, fishery managers and other scientists) of the expected precision of estimates prior to the expenditure of large amounts of money on surveys. This analysis indicated that a sample of 8 fisher-days per month would result in precisions (SE / Mean) as in Table 2.1. These data indicate it could be expected that the precision of estimates of total discards per annum per region would be approximately 17 % and for discards of the main species of interest, within the range 13 - 31 %. These precisions were considered acceptable for annual estimates, recognising that the precision of estimates calculated: (i) across the 3 year survey for a region would be improved by $1/\sqrt{3}$; (ii) across the 3 regions in a year, by approximately $1/\sqrt{3}$; and (iii) across the 3 years and 3 regions by approximately $1/\sqrt{9}$.

2.2.2 Design of the observer survey

To provide the necessary data for tests of hypotheses and to maximise the precision of estimates of catch-rates and total catches within the financial constraints of the project, the following design for the observer survey of retained and discarded catches of fish trawlers in NSW was chosen.

The target sample size was 24 fisher-days for each quarter (Jan.-Mar, Apr.-Jun, Jul.-Sep, Oct-Dec.) in each of 3 years (1993, 1994, 1995) in each of 3 regions (North, Ulladulla, Eden).

Figure 2.1.a

Effect of size of sample on the precision of monthly, quarterly and annual estimates of retained and discarded catch per fisher-day, for the Ulladulla fleet.

Estimates of SE/Mean for samples of 2 - 10 fisher-days per month (A), corresponding to 6 - 30 fisher-days per quarter (B) and 24 - 120 fisher-days per year (C).

Retained catch (kg per fisher-day) **Discarded catch (kg per fisher-day)**

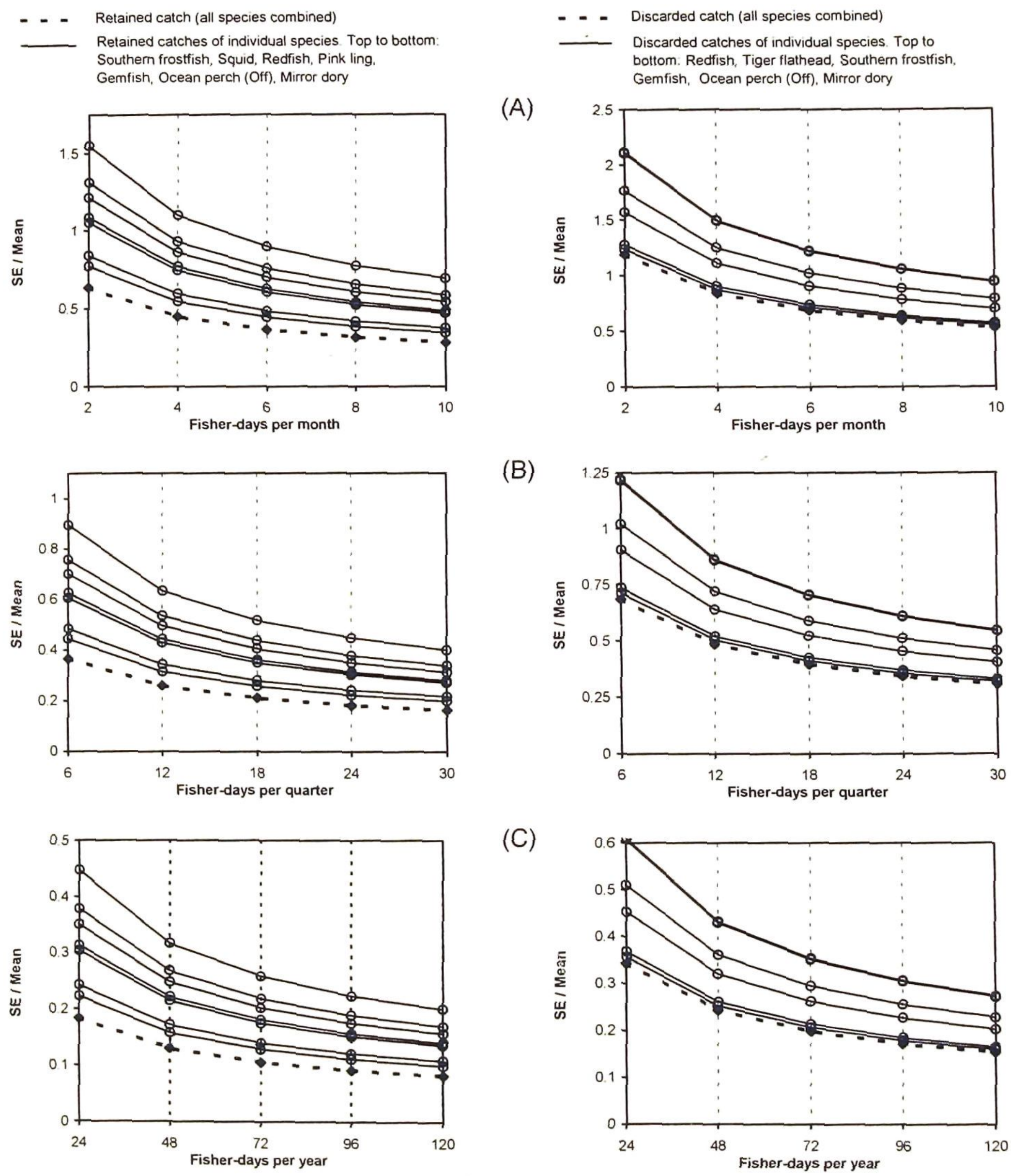


Figure 2.1.b

Effect of size of sample on the precision of monthly, quarterly and annual estimates of retained and dicarded catch per fisher-day, for the Eden fleet.

Estimates of SE/Mean for samples of 2 - 10 fisher-days per month (A), corresponding to 6 - 30 fisher-days per quarter (B) and 24 - 120 fisher-days per year (C).

Retained catch (kg per fisher-day) | **Discarded catch (kg per fisher-day)**

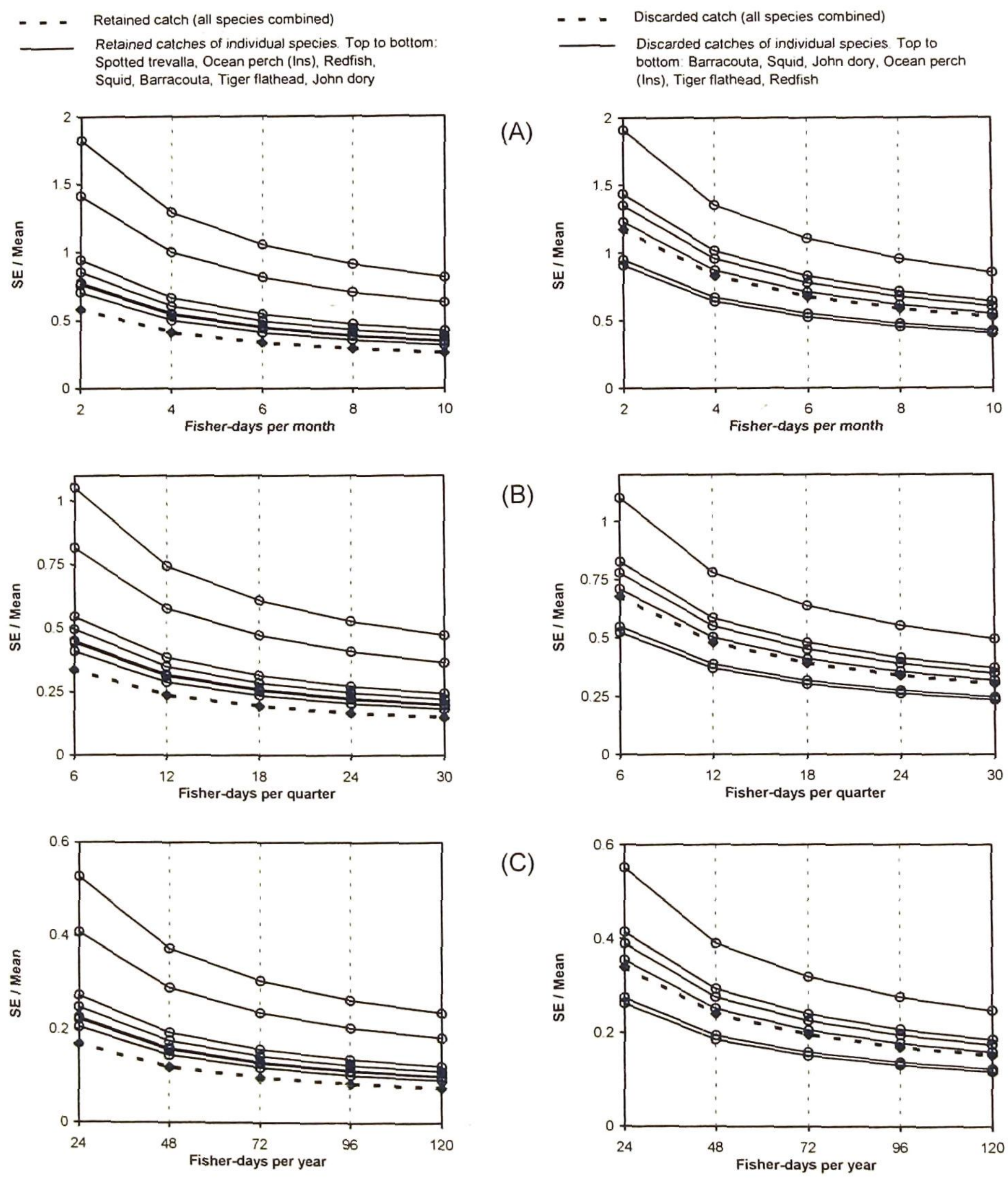


Table 2.1

(SE/mean)

Precision of estimates of monthly, quarterly and annual mean catch per fisher-day, based on samples of 8 fisher-days per month

	Month (n = 8)	Quarter (n = 24)	Year (n = 96)
Retained catch (all spp.)			
Ulladulla	0.32	0.18	0.09
Eden	0.29	0.17	0.08
Retained catches of main species			
Ulladulla	0.39 - 0.98	0.22 - 0.57	0.11 - 0.28
Eden	0.35 - 0.91	0.20 - 0.53	0.10 - 0.26
Discarded catch (all spp.)			
Ulladulla	0.59	0.34	0.17
Eden	0.59	0.34	0.17
Discarded catches of main species			
Ulladulla	0.62 - 1.05	0.36 - 0.61	0.18 - 0.31
Eden	0.45 - 0.95	0.27 - 0.55	0.13 - 0.28

Size-distributions of retained commercial species were sampled if time was available after all other observations had been completed. This task was given the lowest priority because size-distributions of retained commercial species were available from an on-shore sampling program of fish landed. Observers usually had time to sample size-distributions of the retained catch of one or two commercial species each tow. Quota species were given the highest priority and observers selected the species most abundant in the catch. Approximately 100 of each species were measured. If the retained catch of a species was graded, then approximately 100 fish from each grade were measured.

The 3 regions were selected to cover the geographic range of the fishery in NSW. The Eden and Ulladulla fleets were selected because they were the largest fleets on the NSW coast south of Sydney. The 3rd region, "North", comprised the fleets of Newcastle and Tuncurry. It was originally intended that "North" also include the Port Stephens fleet but the owners and skippers of trawlers at Port Stephens did not wish to participate.

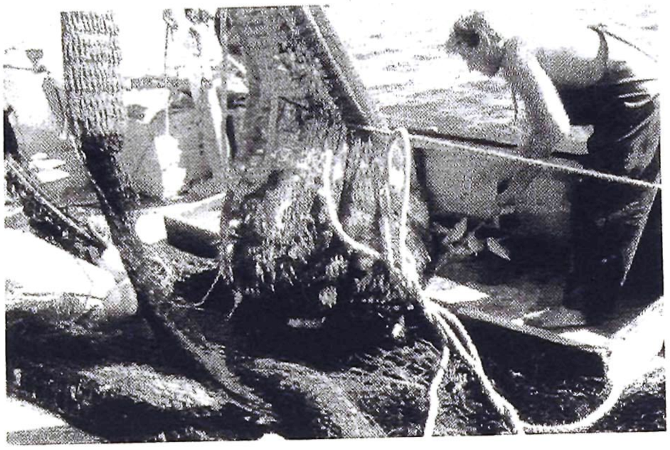
Fishing trips out of Eden, that were intended to last more than 3 days were excluded from the population of trips surveyed because fishing during these trips generally took place far to the south of the study area. Fishing trips targeting royal red prawns (*Haliporoides sibogae*) were also excluded from the sampled population because the objective of the survey was to estimate catches from fish trawling.

Within each region/year/quarter, fisher-days were selected at random for inclusion in the survey. At Eden, where the majority of fishing trips lasted 1 day, but some were of 2 or 3 days, fishing trips were selected randomly until the targeted number of fisher-days had been observed. Fisher-days on multi-day trips at Eden were treated as being independent (see Section 2.3 Results & Discussion and Chapter 4 in which evidence is provided that this non-independence did not result in significant bias for estimated rates of catch).

For each tow during each fisher-day sampled, observers recorded weights and numbers of the retained and discarded catches of each commercial species and size-distributions of sub-samples for each commercial species present in the discards (Plates 2.1 - 2.9). Size-distributions of retained catches were recorded opportunistically as time permitted (these data were of lower priority than size-distributions of discarded commercial species). Operational data (location, depth, time, duration of tow) and a list of non-commercial species present in the catch were also recorded.

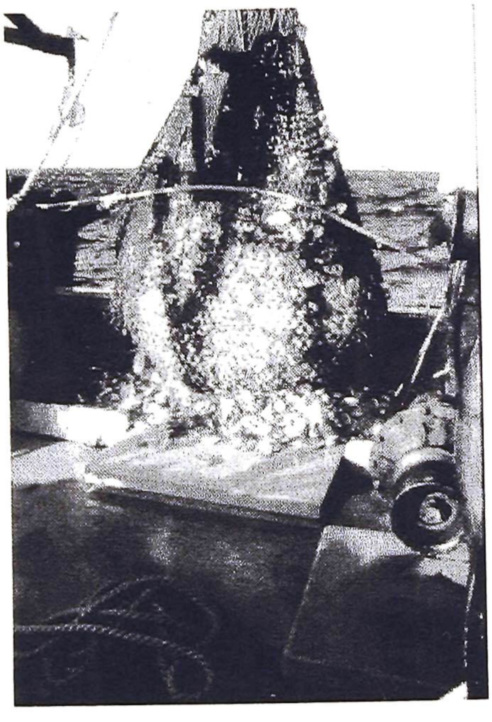
Retained weights of each species were estimated by weighing each box of fish or a sub-sample of boxes and counting the total number of boxes. On occasions when fishers graded species into separate size-classes for marketing, the average weight of fish was estimated from a sub-sample of each grade of each species (usually a 30 - 40 kg box of fish) and used to estimate the total number of each species of each grade and, consequently, the total number of each species retained.

The total weight of discards and weights of discards of individual commercial species were estimated using one of two methods. If the catch was relatively small, total weight of discards was estimated from the catch remaining on deck after the crew had sorted out the fish to be retained. Abundances and size-distributions of commercial species were estimated from a



< Plate 2.1

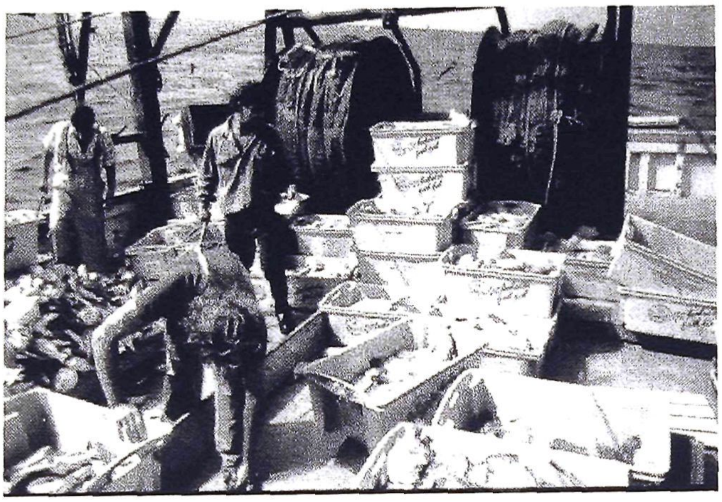
A small catch of silver trevally about to be released from the cod-end into the fish pound; Tuncurry.



< Plate 2.2

A catch of redfish being released from the cod-end into the pound; Ulladulla.

Plate 2.3 >
A mixed catch in the pound, awaiting sorting; Ulladulla.

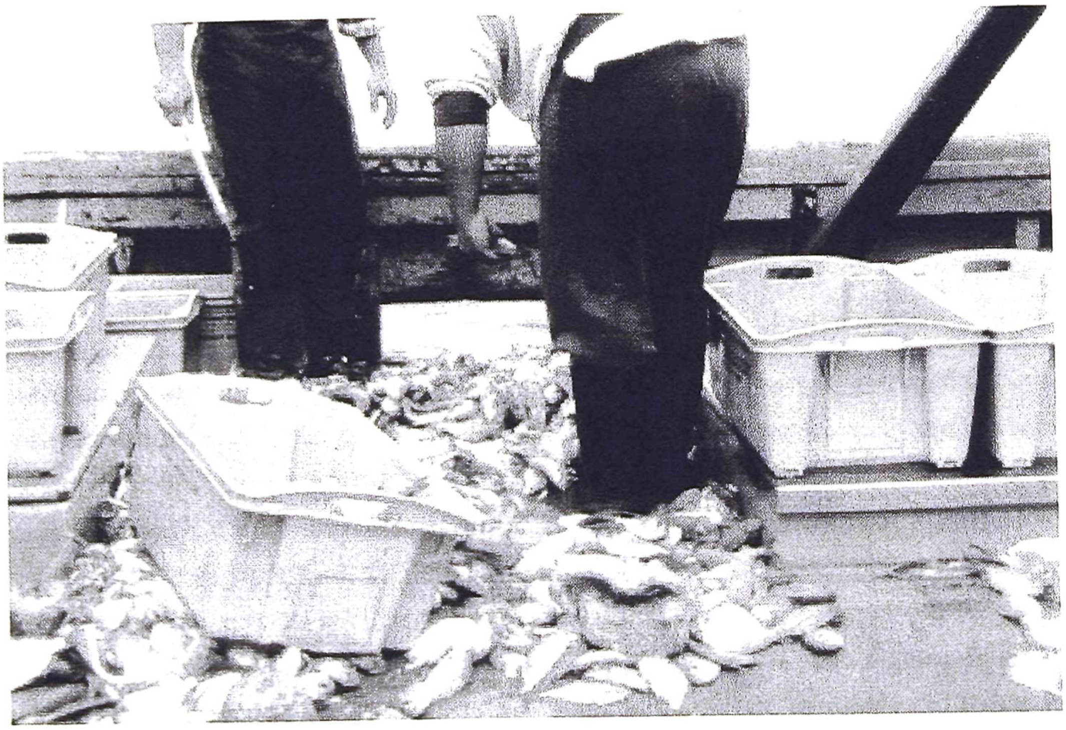


< Plate 2.4
Fish to be retained have been selected and graded by the crew into separate boxes; fish to be discarded remain in the pound (left side of photograph); Ulladulla.

Plate 2.5 >
Observer weighing part of the catch; in this instance, a sub-sample of the fish to be discarded; Tuncurry.

< Plate 2.6
Observer measuring sizes of fish on a measuring board; in this instance, under-size snapper to be discarded; Tuncurry.

< Plate 2.7
Observer recording identification of non-commercial species in the discards; Tuncurry.



^ **Plate 2.8**
Crew discarding fish through one of the skuppers; Ulladulla.

sub-sample of discards (usually a 30-40 kg box) and an estimate of the sampling fraction. If the catch was relatively large, the crew discarded fish as the catch was sorted. In these circumstances, the weight of total catch was estimated by estimating the volume of catch on the deck (volumetrically, in terms of the estimated number of fish boxes) and the weight of catch that could fit into a fish box (or several fish boxes, usually 30 - 40 kg each). An estimate of total discards could then be calculated by subtracting the estimated total weight of retained catch from the estimated weight of total catch. Abundances and size-distributions of commercial species were estimated from a sub-sample of discards (those fish remaining in the 30-40 kg box or boxes after fish that were retained had been removed) and an estimate of the sampling fraction.

2.2.3 Storage of data and verification

All data collected from the observer survey were entered into a relational database using the "Advanced Revelation" database management system. The accuracy of data in the database was verified by checking printouts of data from the database against the original data sheets. To ensure reliability of this time-consuming task, artificial errors were inserted into the printouts from the database so that the quality of the checking procedure (performed by multiple technicians) could be measured.

2.3 Results & Discussion

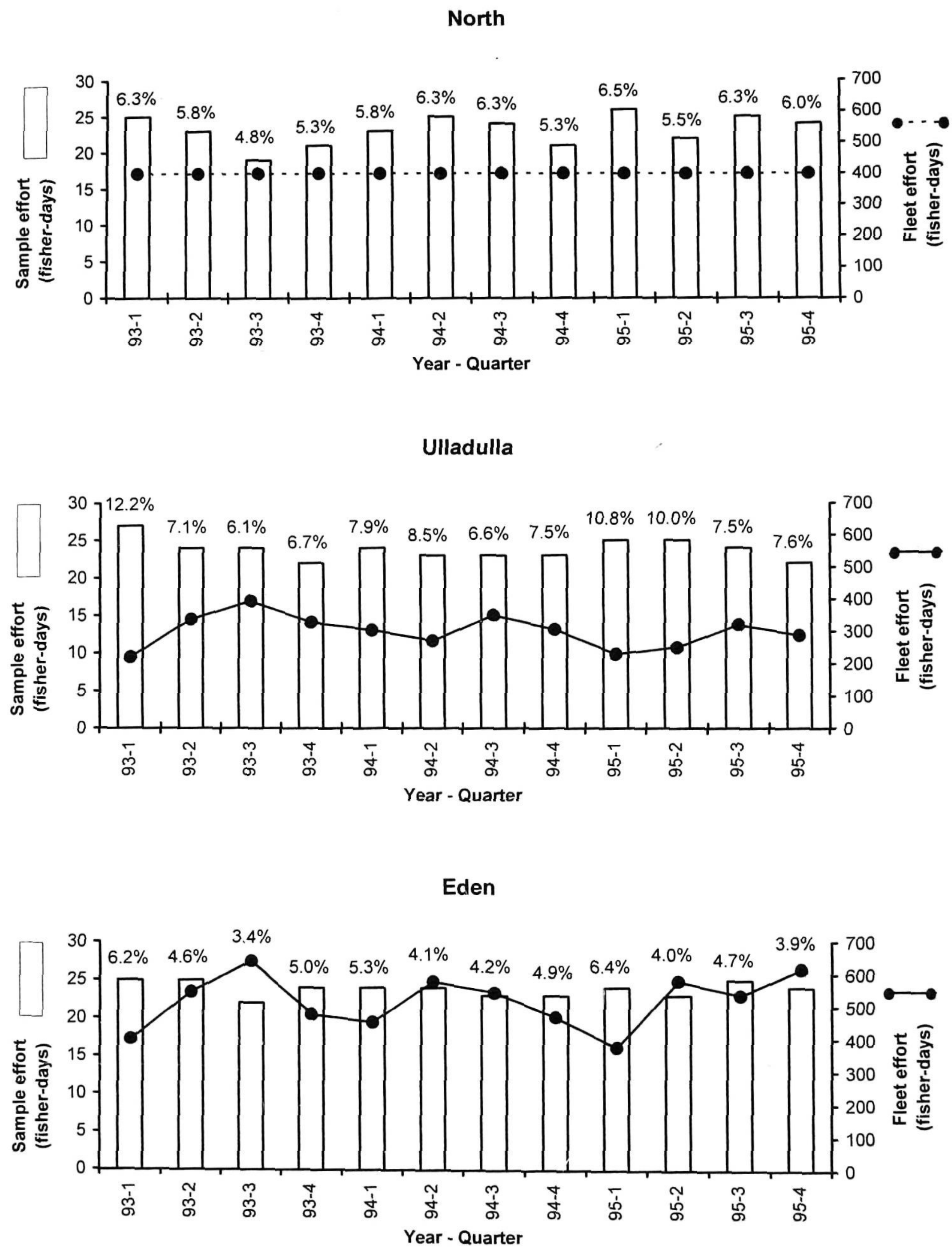
The number of fisher-days sampled during each quarter, in each year, averaged 23.2 (range 19 - 26) for North, 23.8 (range 22 - 27) for Ulladulla and 23.8 (range 22 - 25) for Eden (Fig. 2.2), slightly less than the target sample size of 24 fisher-days per quarter. Despite concerns expressed by fishers at various times during 1993-95 and refusals by some fishers to allow scientific observers onboard, the desired size of sample was achieved in most quarters in each year in each region (see Fig. 2.2).

The sources and assumptions associated with the calculation of the number of fisher-days completed by fleets and resulting sampling fractions (see Fig. 2.2) are discussed fully in Chapter 5. However, it is important to note that: (i) the estimates for Ulladulla and Eden are considered reliable because all fishers in the SEF are required to report the duration of each fishing trip (dates of departure and return to port) to the AFMA (on "SEF-2", "Quota monitoring system" returns); but (ii) due to limitations of the data collected on NSW fishers'

Figure 2.2

Quarterly sampling effort, fishing effort and sampling fraction (%), by region

Fishing effort data for Ulladulla and Eden derived from Commonwealth "SEF-2" data
Fishing effort for North based on assumption of 400 fisher-days per quarter



monthly returns during these years, an approximation of 400 fisher-days per quarter (i.e. 1600 fisher-days per year) was estimated for trawlers in region North (see Section 5.2.2 for the rationale for this estimate). These data are presented here so that the sampling fractions can be presented.

During the 3 years surveyed, 88, 93 and 97 fisher-days were observed in region North. These represented sampling fractions of 5.5 %, 5.8 % and 6.1 %, respectively, of the estimated total number of fisher-days completed by the Newcastle/Tuncurry fleets. Quarterly sampling fractions ranged between 4.8 % and 6.5 % in the northern region. At Ulladulla, 97, 93 and 96 fisher-days were observed, with sampling fractions of 7.5 %, 7.5 % and 8.8 %, respectively. Quarterly sampling fractions ranged between 6.6 % and 12.2 % for Ulladulla. At Eden, 96, 94 and 96 fisher-days were surveyed during the 3 years, with sampling fractions of 4.6 %, 4.6 % and 4.5 %, respectively. The range of quarterly sampling fractions here was 3.4 % to 6.4 %.

Despite the "success" of achieving the desired sizes of samples and sampling fractions in the 3-12 % range, the "randomness" of the selection of fisher-days sampled was, to some degree, affected by: (i) refusals by some fishers at times to participate in the survey; (ii) the fact that the population from which fisher-days were sampled was not actually enumerated until after sampling was complete in each quarter and (iii) non-independence of fisher-days surveyed on multi-day trips at Eden. The consequences of these factors for the accuracy of estimates of catch-rates are evaluated in Chapter 4 with other potential sources of bias.

Chapter 3

Selection of estimators: relative accuracy of mean-per-unit, ratio and regression estimators.

3.1 Introduction

The method most commonly used to estimate discards (or by-catches) by whole fleets from observed rates of discarding (or by-catch) uses a ratio estimator. The observed ratio of discarded catch to retained catch is scaled to total discards over some time period using the known total landed catch as the multiplier (e.g. Hoag, 1971, cited in Richards *et al.*, 1995; Keiser, 1977; Atkinson, 1984; Stratoudakis *et al.,* 1999). Estimates of discards (or by-catches) by whole fleets have also been calculated using a simple mean-per-unit estimator, in which the observed quantity of discards per unit of effort is used to estimate total by-catch by multiplying by the known total effort (e.g. Gutherz & Pellegrin, 1988; Harris & Poiner, 1990; Fennessy, 1994; Liggins & Kennelly, 1996; Kennelly *et al.*, 1998).

The precision of such estimates in the literature is highly variable, with many studies reporting poor precision. Many studies provided no information about variances of estimates (Andrew & Pepperell, 1992; Alverson *et al.,* 1994) nor about any biases associated with the estimators used. Moreover, the rationale for adopting a particular estimator was rarely presented. In a review of the literature concerning the by-catch of shrimp-trawl fisheries, Andrew and Pepperell (1992) found no direct comparisons of the reliability of ratio and mean-per-unit methods. Moreover, there has been no reported use of the estimator based on the linear regression of amounts of discards on the amount of retained catch. If the relationship between discards and retained catch is approximately linear, but does not go through the origin, a linear regression estimator will achieve greater precision than an estimator based on the ratio of discarded catch to retained catch. These observations are surprising since the theory of mean-per-unit, ratio and linear regression estimators in simple random samples has been described in frequently-cited references: Saila (1983) and Cochran (1977). It is also surprising that the stratified mean-per-unit estimator and the forms of ratio and regression estimators appropriate to stratified designs (Cochran, 1977; Sukhatme *et al.,* 1984) have rarely been used in analyses of observer data (but see Liggins & Kennelly, 1996; Liggins *et al.,* 1996; Stratoudakis *et al.*, 1999). Note that there are two general forms of ratio and linear regression estimators applicable to stratified surveys. Using the "separate" ratio or regression estimator, separate ratio or regression estimates are made for each stratum and these are added to provide the total across strata. Alternatively, the "combined" ratio or regression estimators involve the calculation of a combined ratio or regression relationship across all strata.

Accuracy refers to how closely an observation, or a statistic derived from a number of observations, is to the true value of the population parameter. Precision refers to the consistency of a number of values or estimates sampled from a population. Bias refers to the difference between the expected value of a statistic and the true value of the population parameter (e.g. Cochran, 1977; Kotz & Johnson, 1982; Efron & Tibshirani, 1993). The definition of accuracy used here incorporates components of bias and precision. It is necessary to consider these components of accuracy separately because, in the presence of bias, a precise estimate cannot be accurate. The precision and bias of mean-per-unit, ratio and regression-based estimates of catch in simple random sampling and in stratified survey designs depend on the type of estimator in association with the design of sampling, size of sample, survey data at hand, availability and reliability of auxiliary catch and effort data for whole fleets and the strength of the relationship between observed discards and auxiliary data (e.g. observed retained catches) (Cochran, 1977; Saila, 1983). This study concerns the accuracy of various types of estimator in relation to these influences. In addition, bias and accuracy are influenced by factors associated with the efficiency of completing the survey (e.g. randomness of selecting samples, biases in measurement) (Cochran, 1977; Saila, 1983). Biases resulting from these latter factors are considered in Chapter 4.

The objective of this chapter was to compare a range of estimators and to determine an optimal method (in terms of bias and precision) for estimating annual discards and total catches from the data collected from the observer survey of this fishery. Bias and precision of stratified mean-per-unit, combined ratio, combined regression, separate ratio and separate regression estimators were examined for estimating mean catch per fisher-day and annual catches of 15 components of catch chosen to represent the various types of catch taken in this fishery.

3.2 Materials and methods

3.2.1 Components of catch

Comparisons of bias and precision of various estimators were made for calculating mean catches per fisher-day, annually (1993, 1994), for each region (Ulladulla, Eden), for 15 components of catch.

Estimates were made for 5 partitions of total catch, each comprising multiple species: (i) discards of all species; (ii) discarded non-commercial species; (iii) discarded quota species; (iv) discarded non-quota commercial species; and (v) the retained catch of non-quota commercial species. The weight of all retained (landed) quota species ("ARQS"), was used as the auxiliary variable for the combined ratio and combined regression estimators.

Estimates of the total catches (retained and discarded catches combined) were made for 5 non-quota commercial species: (i) rubberlip morwong (*Nemadactylus douglasi*); (ii) piked dogfish (*Squalus megalops*); (iii) angel shark (*Squatina spp.*); (iv) barracouta (*Thyrsites atun*); and (v) arrow squid (*Nototodarus gouldi*).

Discarded catches were estimated for 5 quota species: (i) redfish; (ii) tiger flathead; (iii) mirror dory (*Zenopsis nebulosis*); (iv) jackass morwong; and (v) john dory (*Zeus faber*). In addition to using ARQS, ratio and regression estimates were made for these species using the retained weight of the individual species in question ("IRQS") as the auxiliary variable.

The non-quota commercial species and quota species included in the study were selected as being broadly representative of all species caught in the fishery. The selection includes species taken as targeted catch and as by-catch; of high and low market value; caught seasonally and year-round; with and without minimal size limits and for which rates of discarding range from low to high.

3.2.2 Estimators

Stratified mean-per-unit, combined ratio, separate ratio, combined regression and separate regression estimators (e.g. Cochran, 1977; Sukhatme *et al.*, 1984) were applied to data from the observer survey and auxiliary data as follows:

Stratified mean-per-unit estimator

With a simple random sample of fisher-days taken in each quarter of each year, the estimated mean catch (discards, retained or total catch) per fisher-day (for a region), $\bar{y}$, was calculated using the stratified mean-per-unit ("SMPU") estimator as:

$$\bar{y}_{SMPU} = \sum_{q=1}^{4} W_q \cdot \bar{y}_q \qquad \text{(Eq. 3.1)}$$

in which $W_q = N_q / N$ is the relative size of the stratum, $\overline{y}_q$ is the mean discarded catch (or retained or total catch) in quarter q of the year. N_q is the number of fisher-days completed by the fleet in quarter q of the year and N the number of fisher-days completed by the fleet in the year. The SMPU estimator is unbiased (e.g. Cochran, 1977).

Combined and separate ratio estimators

A ratio estimator may be applied to a stratified survey by calculating a single "combined" ratio across strata or by calculating a "separate" ratio and estimate of mean discards (or total catch) within each stratum and then taking a weighted mean across strata. The combined ratio estimator uses the ratio of the SMPU estimate of catch (discards, retained or total), to the SMPU estimate of an auxiliary variable (ARQS or IRQS), $\hat{R}_c = \dfrac{\overline{y}_{SMPU}}{\overline{x}_{SMPU}}$, to estimate mean catch per fisher day, $\overline{y}_{Rc}$,as follows:

$$\overline{y}_{Rc} = \hat{R}_c . \overline{X} \qquad \text{(Eq. 3.2)}$$

in which $\overline{X}$ is the mean landed catch (ARQS or IRQS).

The separate ratio estimator uses the ratio of the estimate of catch (discards, retained or total) to the estimate of an auxiliary variable (ARQS or IRQS) in each stratum, $\hat{R}_q$, to estimate mean catch per fisher day, $\overline{y}_{Rs}$, as:

$$\overline{y}_{Rs} = \sum_{q=1}^{4} W_q . \hat{R}_q . \overline{X} \quad \text{with} \quad \hat{R}_q = \frac{\overline{y}_q}{\overline{x}_q} \qquad \text{(Eq.3.3)}$$

Unlike the SMPU estimator, ratio estimates are biased of order 1/n. If the sample size is small in each of multiple strata, and there are many strata, bias in $\overline{y}_{Rs}$ may not be negligible (Cochran, 1977).

Combined and separate regression estimators

As for the stratified ratio estimators, "combined" and "separate" forms of the linear regression estimator may be used. The combined regression estimator (LRc) calculates mean catch per fisher-day, $\bar{y}_{LRc}$, as:

$$\bar{y}_{LRc} = \bar{y}_{SMPU} + \hat{B}_c(\bar{X} - \bar{x}_{SMPU}) \quad \text{(Eq. 3.4)}$$

in which $\hat{B}_c$ is the estimate of the combined regression coefficient and is calculated as a weighted mean of stratum regression coefficients as follows:

$$\hat{B}_c = \frac{s(\bar{y}_{SMPU}, \bar{x}_{SMPU})}{s^2(\bar{x}_{SMPU})} = \frac{\sum_{q=1}^{4} \frac{W_q^2 \cdot (1-f_q)}{n_q} \cdot s(y_q, x_q)}{\sum_{q=1}^{4} \frac{W_q^2 \cdot (1-f_q)}{n_q} \cdot s^2(x_q)} \quad \text{(Eq. 3.5)}$$

in which n_q is the sample size, f_q is the sampling fraction, $s(y_q,x_q)$ is the covariance of catch (y) and the auxiliary variable (x) and $s^2(x_q)$ is the variance of the auxiliary variable in quarter q.

The separate regression estimator (LRs) calculates mean catch per fisher-day, $\bar{y}_{LRs}$, as:

$$\bar{y}_{LRs} = \sum_{q=1}^{4} W_q \cdot \left[\bar{y}_q + \hat{B}_q\left(\bar{X}_q - \bar{x}_q\right)\right] \quad \text{(Eq. 3.6)}$$

in which $\hat{B}_q$ is the estimate of the regression coefficient in stratum q and calculated as:

$$\hat{B}_q = \frac{s(\bar{y}_q, \bar{x}_q)}{s^2(\bar{x}_q)} \quad \text{(Eq. 3.7)}$$

Like the ratio estimators, LRc and LRs are biased of order 1/n and bias may be significant for LRs when applied to small samples from multiple strata (Cochran, 1977).

3.2.3 Comparisons of bias of estimators

The root mean square error (RMSE) of an estimator $\hat{\theta}$ for θ, $\sqrt{E\left[(\hat{\theta}-\theta)^2\right]}$ is a measure of accuracy that takes into account both precision and bias and is equal to: $\sqrt{se(\hat{\theta})^2 + bias(\hat{\theta},\theta)^2}$. If bias equals 0 then RMSE equals SE. Consequently the ratio of RMSE to SE provides a useful measure of the importance of estimator bias relative to the SE (e.g. Cochran, 1977; Kotz & Johnson, 1982; Efron & Tibshirani, 1993).

A bootstrap re-sampling method was used to calculate estimates of standard error, bias and RMSE for each of the 5 estimators used to estimate catch per fisher-day for each of the 15 components of catch, for each year (1993 and 1994) and region (Ulladulla and Eden). The bootstrap methods used in this study are based on the general methods described in Efron and Tibshirani (1993). Several algorithms have been described for the application of bootstrap methods to stratified survey designs (Rao & Wu, 1988; Sitter, 1992; Davison & Hinkley, 1997; Smith, 1997). The simplest approach is referred to as the "naïve bootstrap" and this is the method used here. The algorithm is as follows:

(i) within stratum q take a simple random sample of size n_q, sampling with replacement. Repeat for each of the strata (4 quarters in this study).

(ii) calculate the stratified mean using this re-sampled set of data and the appropriate formula (for SMPU, Rc, Rs, LRc or LRs)

(iii) repeat steps (i) and (ii) a total of B times to get B bootstrap estimates (B = 1000 in this study) of the stratified mean.

It is assumed that the empirical distribution of the B estimates approximates the distribution from which the sample is taken. The bootstrap estimate of SE of the statistic is calculated as the standard deviation of the B bootstrap estimates. Bias is estimated as the difference between the mean of all bootstrap estimates and the estimate based on the original sample. This approach is referred to as the "naïve" approach because it produces estimates of SE and bias that are not consistent with the classical estimators of variance. Bootstrap estimates of variance and bias in a single stratum are underestimated by the factor $\frac{n-1}{n}$ and SE is underestimated by $\sqrt{\frac{n-1}{n}}$ (Efron & Tibshirani, 1993; Rao & Wu, 1988). In a stratified sampling design, variance and bias will be underestimated by a factor between $\frac{n_{\min}-1}{n_{\min}}$ and $\frac{n_{\max}-1}{n_{\max}}$ where n_{min} and n_{max} represent the minimum and maximum value of n across the strata (Rao & Wu, 1988). This can be effectively ignored in the application of the naïve bootstrap in the current instance because sample sizes (numbers of fisher-days per quarter at Ulladulla and Eden) range between 21 and 27. Consequently, at worst, variance will be underestimated by about 5 %, standard errors by 2 % and bias by 5 %. Neither does the naïve bootstrap account for sampling fraction (Davison & Hinkley, 1997). The naïve bootstrap will overestimate SE unless $f = n/N$ is very small in all strata. The SE of a stratified mean will be overestimated by between $\frac{1}{1-f_{\min}}$ and $\frac{1}{1-f_{\max}}$. Again, this is not a significant problem in the current application because sampling fractions (per quarter at Ulladulla and Eden) range between 6 % and 12 % for Ulladulla and between 3 and 6 % for Eden.

This bootstrap method (using B = 1000 bootstrap estimates) was used to estimate the SE and bias for each estimator (SMPU, Rc, Rs, LRc, LRs), applied to each of the 15 components of catch, for each of the 2 regions (Ulladulla and Eden), for each of the 2 years (1993,1994). Because the accuracy of the bootstrap estimate of bias is particularly sensitive to the number of bootstrap replications, B, and it is possible to calculate an approximate confidence limit for this estimate, the 95 % confidence limit for the estimate of bias was also calculated (Efron & Tibshirani, 1993) using:

$$\textit{Probability that} \quad |\widehat{bias}_B - \widehat{bias}_\infty| < 2.\frac{\widehat{se}_B}{\sqrt{B}} \cong 0.95 \qquad \text{(Eq. 3.8)}$$

Ratios of RMSE / SE (+ 95 % confidence limit) were calculated from the bootstrap estimates of SE and bias. For the purposes of this study, RMSE / SE < 1.05 is deemed to indicate inconsequential bias.

3.2.4 Comparisons of precision of estimators

Relative precision of SMPU, Rc and LRc estimates were examined for each component of catch, in each year, in each region. Rs and LRs estimators were not considered in these comparisons because the significant biases demonstrated by these estimators disqualifies their routine use in this project (see Results, Section 3.3.1).

Variances of SMPU, Rc and LRc estimates of catch were calculated as follow:

$$s^2(\bar{y}_{SMPU}) = \sum_{q=1}^{4} \frac{W_q^2.(1-f_q)}{n_q} . \frac{\sum_{i=1}^{n_q} (y_{qi} - \bar{y}_q)^2}{(n_q - 1)} \quad \text{(Eq. 3.9)}$$

in which y_{qi} is the discarded catch (or retained or total catch) taken on the i^{th} fisher-day in quarter q of the year.

$$s^2(\bar{y}_{Rc}) = \sum_{q=1}^{4} \frac{W_q^2.(1-f_q)}{n_q} . \frac{\sum_{i=1}^{n_q} (y_{qi} - \hat{R}_c.x_{qi})^2}{(n_q - 1)} \quad \text{(Eq. 3.10)}$$

in which x_{qi} is the auxiliary variable (ARQS or IRQS) taken on the i^{th} fisher-day in quarter q.

$$s^2(\bar{y}_{LRc}) = \sum_{q=1}^{4} \frac{W_q^2.(1-f_q)}{n_q} . \frac{\sum_{i} [(y_{qi} - \bar{y}_q) - \hat{B}_c.(x_{qi} - \bar{x}_q)]^2}{(n_q - 2)}$$

(Eq. 3.11)

Note that the variance formulae for Rc and LRc (Eq. 3.10 and 3.11) are approximate and valid only for large samples (Cochran, 1977).

A coefficient of variation, CV, was defined as:

$$CV_{est} = \frac{s(\bar{y}_{est})}{\bar{y}_{SMPU}} .100 \quad \text{(Eq. 3.12)}$$

in which the numerator is the standard error of the estimate ($s(\bar{y}_{SMPU})$, $s(\bar{y}_{Rc})$ or

$s(\bar{y}_{LRc})$) and the denominator is, for all estimators, the SMPU estimate of mean catch. The calculation of $s^2(\bar{y})$ for each estimator (see equations 3.10 and 3.11) is independent of the calculation of $\bar{y}$, so the relative magnitude of $s(\bar{y}_{est})$ indicates the relative precision of each estimator. Estimates of $\bar{y}$ by each estimator will differ unless the estimated mean catch-rate of the auxiliary variable, $\bar{x}$, is identical to the mean catch-rate calculated from the reported landings, $\bar{X}$ (see equations 3.2 and 3.4). Consequently, the measure of precision specified above (Equation 14) allows comparison of the precision of estimators without confounding by any variation in estimates of $\bar{y}$.

The increase or decrease in precision of ratio and regression estimates, relative to SMPU estimates, was calculated as:

$$\frac{CV_{est} - CV_{SMPU}}{CV_{SMPU}} \cdot 100 \qquad \text{(Eq. 3.13)}$$

In comparing the precision, *CV*, of Rc and LRc estimators with the SMPU estimator, an increase in precision of 10 % was defined as a "useful" increase, an increase of 5 % as a "minimal" increase and an increase of less than 5 % was considered inconsequential.

3.2.5 Precision of estimates of mean catch across regions and years

Mean catches (and associated variances) calculated for each year, in each region, were used to calculate mean catches (i) during the period 1993-94 for each region; (ii) for Ulladulla and Eden combined, in each year and (iii) for both years and both regions combined. Using an SMPU estimator, estimates of mean catch, $\bar{y}_h$, and variance, $s^2(\bar{y}_h)$, in each year for each region were combined to estimate mean catch, $\bar{y}$, and associated variance, $s^2(\bar{y})$, over *k* strata (regions or years), as follows:

$$\bar{y} = \sum_{h=1}^{k} W_h \cdot \bar{y}_h \qquad \text{(Eq. 3.14)}$$

$$s^2(\bar{y}) = \sum_{h=1}^{k} W_h{}^2 \cdot s^2(\bar{y}_h) \qquad \text{(Eq. 3.15)}$$

in which W_h is the proportion of fishing effort in stratum h. For estimates of mean catch across both years for each region and across both regions for each year, $k = 2$. For estimates of mean catch across both regions and both years, $k = 4$. For all components of catch, except discarded tiger flathead and jackass morwong, SMPU estimates of catch during each year at each location were used. For tiger flathead and jackass morwong, Rc estimates of discards during each year, in each region were used (the rationale for this is explained in the Discussion). Coefficients of variation (CV = SE x 100 / mean) were calculated for each estimate of mean catch.

3.3 Results

3.3.1 Comparisons of bias of estimators

Bootstrapped estimates of RMSE / SE (+ 95 % C.L.) were significantly less than 1.05 for combined ratio and regression estimators using ARQS as auxiliary variable for each of the 15 components of catch, for each combination of port and year (Fig. 3.1). Separate ratio and regression estimators using ARQS showed greater biases. Estimates of RMSE / SE for the separate ratio estimator using ARQS were not significantly less than 1.05 for discards of tiger flathead at Eden in 1993, discards of all species combined at Eden in 1993, discards of non-commercial species at Eden in 1994, retained catches of non-quota commercial species at Ulladulla and at Eden in 1993 and the total catch of barracouta at Eden in 1993 (Fig. 3.1). Estimates of RMSE / SE using the separate regression estimator using ARQS were not significantly less than 1.05 for discards of non-commercial species at Eden in 1993 and for the total catch of angel shark at Ulladulla in 1994 (Fig. 3.1).

Using ARQS as auxiliary variable, estimates of RMSE / SE (+ 95 % C.L.) were significantly less than 1.05 for discards of each of the 5 quota species, for each region and each year with a single exception (redfish at Eden in 1993). Similarly, there was inconsequential bias demonstrated for the LRc estimator using IRQS except for discards of tiger flathead at Ulladulla in 1994. Separate ratio and regression estimators using IRQS as auxiliary variable

Figure 3.1, page 1

Bootstrap estimates of RMSE / SE (+ 95% confidence limit) for estimates of catch-rate per fisher day, for 15 components of catch, using Rc, Rs, LRc andLRs estimators, using IRQS and ARQS as *auxiliary variables*, for Ulladulla and Eden, 1993 and 1994.

For each component of catch and estimator, the 4 bars represent RMSE / SE for Ulladulla in 1993, 1994, Eden in 1993 and 1994 respectively. The dashed line indicates RMSE / SE = 1.05.

QUOTA SPECIES

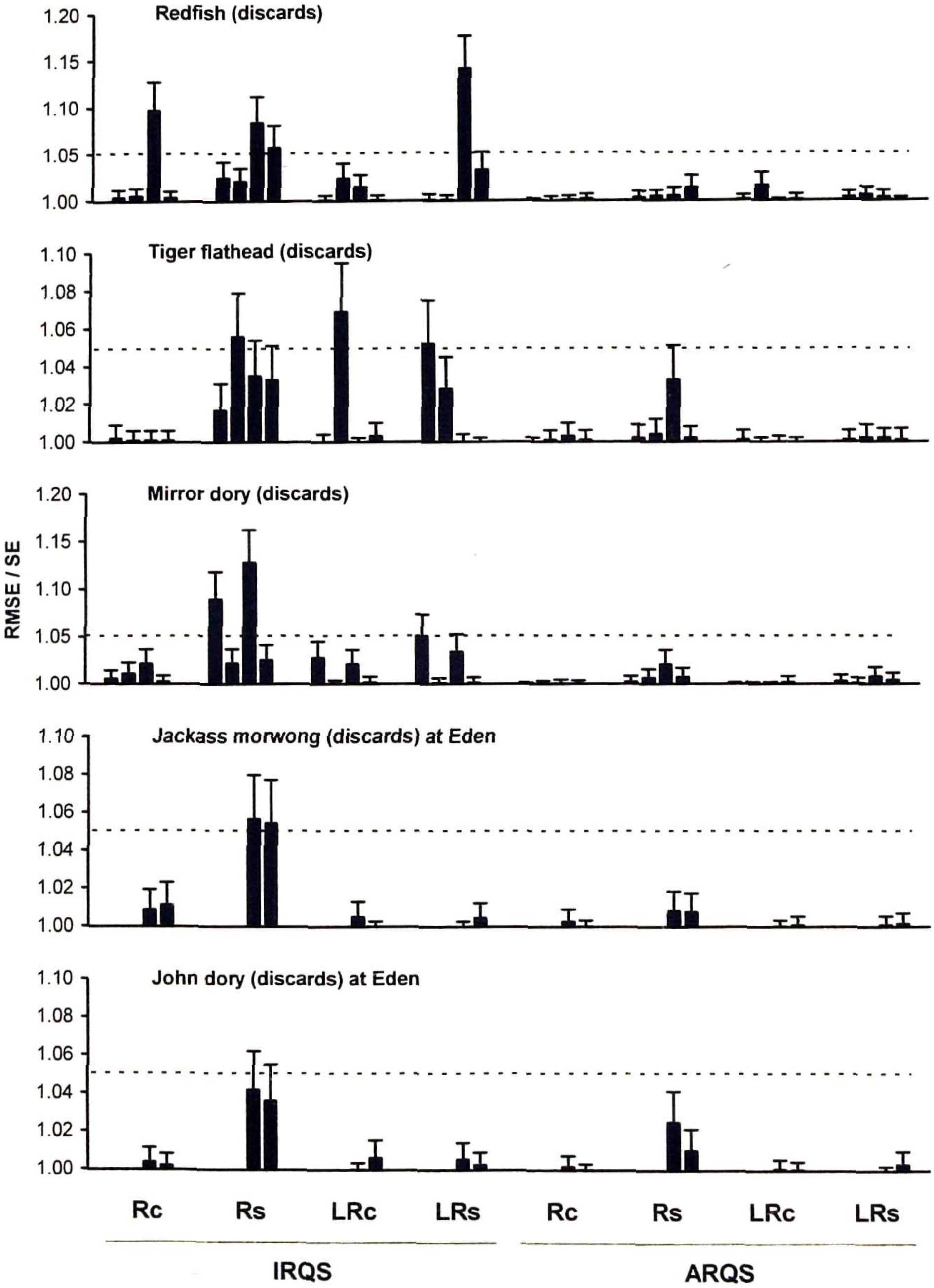
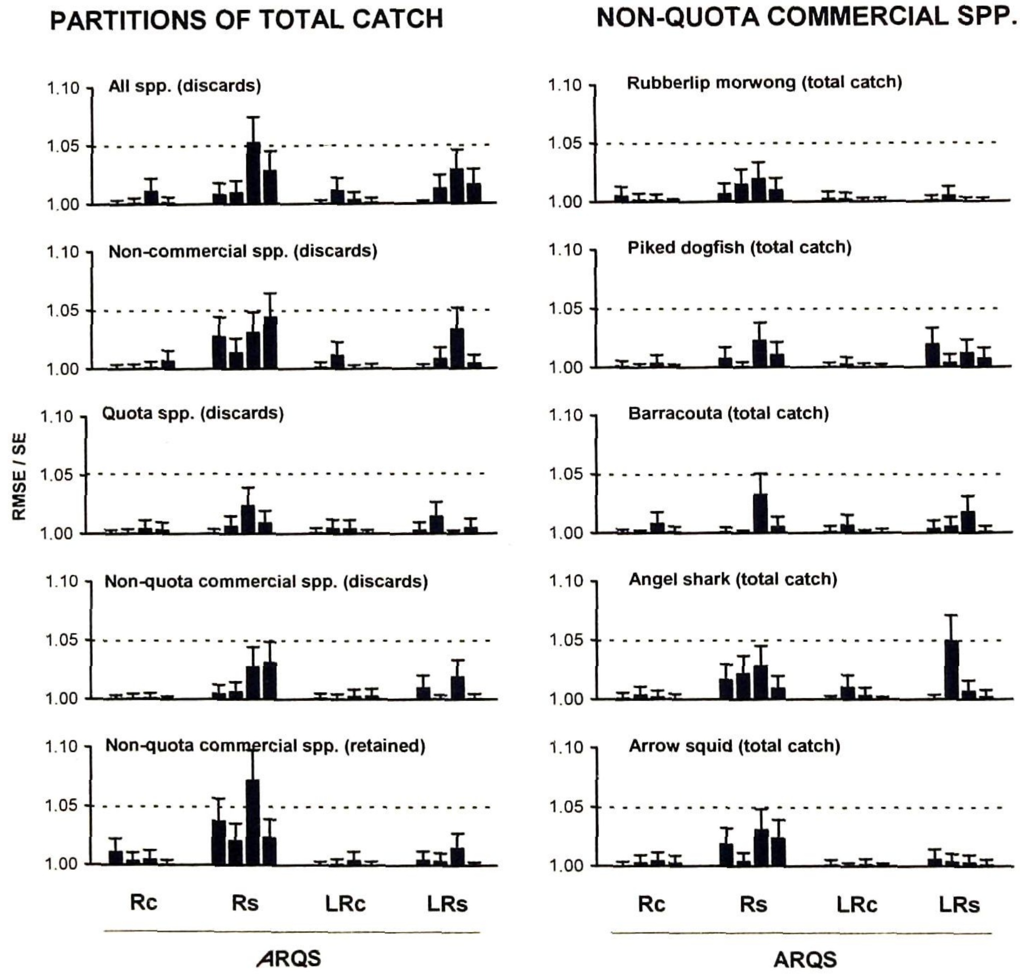


Figure 3.1, page 2

Bootstrap estimates of RMSE / SE (+ 95% confidence limit) for estimates of catch-rate per fisher day, for 15 components of catch, using Rc, Rs, LRc andLRs estimators, using IRQS and ARQS as auxiliary variables, for Ulladulla and Eden, 1993 and 1994.

For each component of catch and estimator, the 4 bars represent RMSE / SE for Ulladulla in 1993, 1994, Eden in 1993 and 1994 respectively. The dashed line indicates RMSE / SE = 1.05.



demonstrated significant bias on multiple occasions. For Rs, RMSE / SE (+95 % C.L.) was not significantly less than 1.05 for 11 of the 16 combinations of species/region/year examined. Similarly, for LRs, RMSE / SE (+95 % C.L.) was not significantly less than 1.05 for 5 of the 16 cases of species/region/year examined (Fig. 3.1).

Generally, separate ratio and regression estimators showed greater bias than the combined estimators. The combined ratio and regression estimators showed no significant bias when using ARQS as auxiliary variable and no significant bias for 15/16 estimates of discards of quota species using Rc and for 15/16 estimates using LRc.

3.3.2 Comparisons of precision of estimators

The Rc estimator, using ARQS as the auxiliary variable, achieved no useful gain (i.e. < 10 %) in precision, compared to the SMPU estimator, for any of the 15 components of catch, in either year at Ulladulla or Eden (Table 3.1). In 24 of 56 instances, precision of the Rc estimate was decreased by 10 % or more, relative to the SMPU estimate. Using IRQS as the auxiliary variable, Rc achieved a decrease or no useful gain in precision for 10/15 instances examined. Rc did, however, provide a useful gain in precision in 3 out of 4 instances for tiger flathead. This gain was substantial for Ulladulla in 1994, the ratio estimator producing a gain in precision of 46 % (14 % precision compared to 26 % precision using the SMPU estimator). For Eden, improvements in precision were 11 % and 13 % in 1993 and 1994, respectively. Rc also produced minimal gains in precision of estimates of discarded jackass morwong (7 % and 9 % gains for Eden in 1993 and 1994, respectively).

The LRc estimator using ARQS achieved no useful improvement or reduction in precision relative to the SMPU estimator. Using IRQS as the auxiliary variable, there was a gain in precision of 50 % for tiger flathead at Ulladulla in 1994, a minimal gain of 7 % for Eden in 1994 and a gain of 10 % for Eden in 1993. An 11 % gain in precision was made for jackass morwong at Eden in 1993. For tiger flathead discards across the 2 years and 2 regions, mean CV of each of the ratio and regression estimates was 24 %, compared to 29 % for SMPU estimates, an average increase of 17 %. Averaging the precisions calculated for jackass morwong (by the Eden fleet), mean precision of ratio and regression estimates was 29 % compared to 32 % for the SMPU estimates, an average increase of 8 %.

Relative to SMPU estimates, combined ratio and combined regression estimators produced the greatest gain in precision for estimates of tiger flathead discarded by Ulladulla trawlers in 1993. This case provides a useful illustration of the circumstances under which combined ratio and combined regression estimators result in increased precision. The relationship between discarded and retained tiger flathead catches during each quarter was approximately linear, in all cases intersecting the *y*-axis close to the origin (Fig. 3.2.a). For both estimators, the gradients of relations among quarters were similar and, consequently, either the combined ratio or combined regression relations provided a better fit to the combined data than the line of no relationship (Fig. 3.2b). As the regression line of best fit intersects the y axis close to the origin, the scatter of data points around the combined ratio line of best fit (y = 0.114x) and the combined regression line of best fit (y = 0.153x - 4.397) is similar (Fig. 3.2.b). Consequently, estimates from each relationship are of similar precision.

The derivation of SMPU, Rc and LRc estimates of mean discards per fisher-day is shown graphically in Fig. 3.2.c. Note that if the mean catch-rate of retained tiger flathead estimated from the observer survey (which was 113.3 kg per fisher-day), were equal to the mean landed catch reported by fishers (146.3 kg per fisher-day), all estimators would generate the same estimate of mean discards.

3.3.3 Precision of estimates of mean catch across regions and years

The precision of mean catches estimated for each year, in each region, varied among the components of catch examined, but was generally poor for estimates of discards of quota species (Table 3.2). Coefficients of variation ranged between 11 % (tiger flathead, Ulladulla, 1994) and 63 % (mirror dory, Eden, 1994) but were generally within the range 20 % - 40 %. Precision of estimates of catches across combinations of regions, years, or both, was, however, much improved (Table 3.2). With the exception of mirror dory, coefficients of variation of mean discarded catches of quota species during the period 1993-94 for Ulladulla and Eden combined, ranged between 17 % and 20 %. At the same spatial and temporal scale, coefficients of variation for estimates of partitions of catch and total catches of non-quota commercial species ranged between 6 % and 14 %.

Table 3.1

Precision of stratified mean-per-unit, combined ratio and combined regression estimates of annual catch-rates (per fisher-day).

SMPU: stratified mean-per-unit Rc: combined ratio estimate LRc: combined regression estimate
ARQS: weight of all retained quota species used as auxilliary variate IRQS: retained weight of the given species used as auxilliary variate

Precision of SMPU estimate is calculated as (se x 100% / mean). Precision of Rc and LRc estimates are relative to SMPU as follows:
o: gain/loss of precision less than 5% <: loss of precision exceeds 5% (x) : gain in precision exceeds 5%, precision is "x"%
<<: loss of precision exceeds 10% **[x]** : gain in precision exceeds 10%, precision is "x"%

Region, Year:	**Ulladulla, 1993**					**Ulladulla, 1994**					**Eden, 1993**					**Eden, 1994**				
Estimator:	**SMPU**	**Rc**	**LRc**	**Rc**	**LRc**	**SMPU**	**Rc**	**LRc**	**Rc**	**LRc**	**SMPU**	**Rc**	**LRc**	**Rc**	**LRc**	**SMPU**	**Rc**	**LRc**	**Rc**	**LRc**
Auxilliary variable:		**ARQS**	**ARQS**	**IRQS**	**IRQS**		**ARQS**	**ARQS**	**IRQS**	**IRQS**		**ARQS**	**ARQS**	**IRQS**	**IRQS**		**ARQS**	**ARQS**	**IRQS**	**IRQS**
Partitions of catch																				
Discards, All spp.	19	<<	o			25	o	o			12	<<	o			9	<	(8)		
Discards, Non-commercial spp.	10	<<	o			19	o	o			13	<<	o			10	<	o		
Discards, Quota spp.	42	o	o			35	o	o			26	<<	o			15	o	o		
Discards, Non-quota commercial spp.	24	o	o			44	o	o			22	o	o			12	o	o		
Retained, Non-quota commercial spp.	8	<<	o			11	<<	o			8	<<	o			13	<<	o		
Non-quota species, Total catch																				
Blue morwong	21	<<	o			23	<<	o			24	<<	o			22	<<	o		
Piked dogfish	20	<	o			33	o	o			21	<	o			19	o	o		
Angel shark	17	<<	o			13	<<	o			22	<<	o			18	o	o		
Barracouta	21	<<	o			23	<<	o			16	<<	o			25	o	o		
Arrow squid	14	<	o			21	o	o			17	<<	o			13	o	o		
Quota species, Discards																				
Redfish, Discarded	32	o	o	<<	o	39	o	o	(37)	o	38	<<	o	<<	o	19	<	o	<<	(18)
Tiger flathead, Discarded	37	<	o	o	o	26	o	o	**[14]**	**[13]**	23	<<	o	**[20]**	(21)	29	<	o	**[25]**	(26)
Mirror dory, Discarded	31	o	o	<<	o	48	o	o	<<	o	25	<	o	<<	o	63	(59)	o	<<	o
Jackass morwong, Discarded											36	<<	o	(34)	**[32]**	28	o	o	(25)	o
John dory, Discarded											20	<<	o	o	o	31	o	o	<	o

Figure 3.2.

Relation between observed discards and retained catches of tiger flathead (kg per fisher-day) at Ulladulla in 1994: (a) by quarter; (b) in year; (c) calculation of annual estimates of discards.

Aspect ratios of all graphs are identical, so that slopes of lines on different graphs can be directly compared. The "dashed" line indicates the mean-per-unit estimate of discards, the "solid" line indicates the ratio relationship and the "dotted" line indicates the linear regression relationship between retained and discarded catch-rates in each quarter in panel (a). These lines represent the SMPU estimate and Rc and LRc relationships in panels (b) and (c).

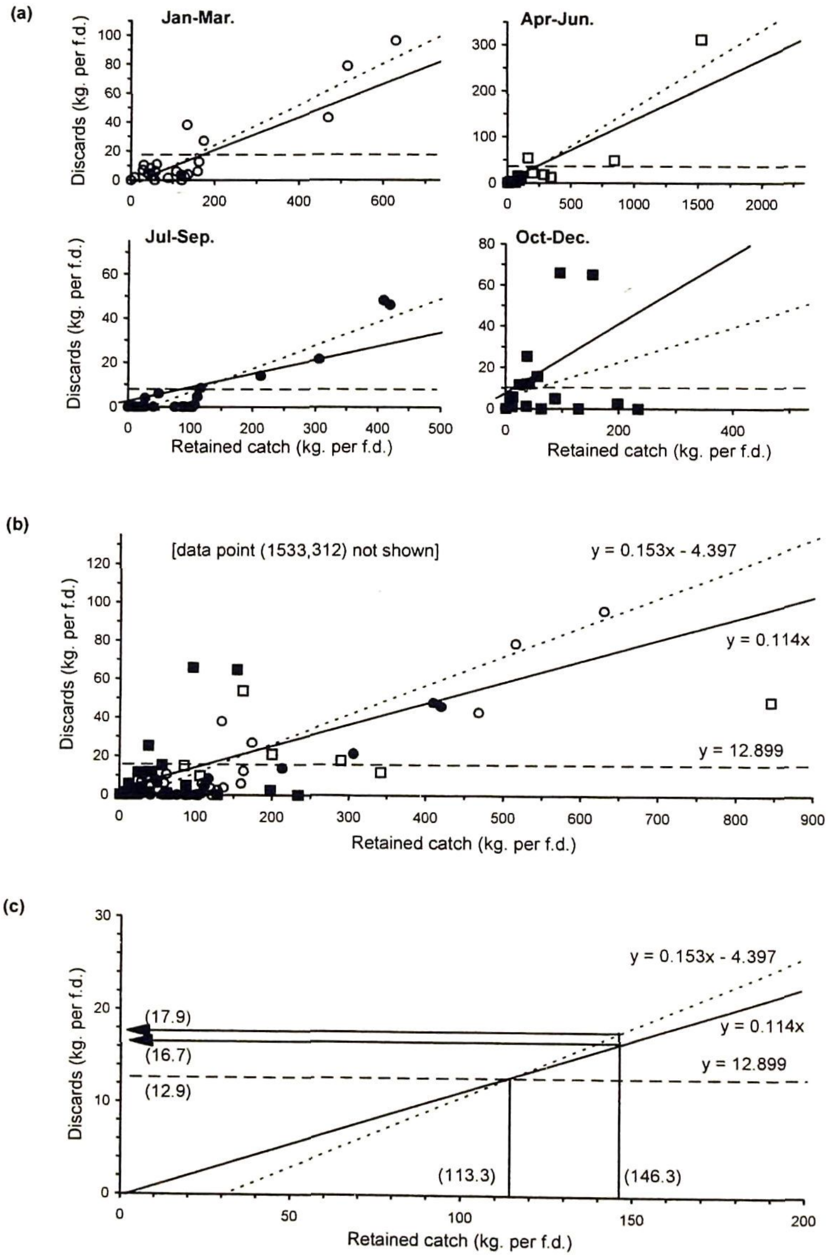


Table 3.2

Precision (% CV) of estimates of catch for combinations of regions and years.

CVs for Tiger flathead and Jackass morwong for individual regions in individual years are based on Rc estimates
CVs for all other species and partitions of catch are based on SMPU estimates
n/a indicates insignificant catch or discards for this species in this region

	Ulladulla		Eden		Both years		Both regions		Both regions
	1993	1994	1993	1994	Ulladulla	Eden	1993	1994	Both years
Partitions of catch									
Discards, All spp.	19	25	12	9	16	7	10	9	7
Discards, Non-commercial spp.	10	19	13	10	11	8	11	9	7
Discards, Quota spp.	42	35	26	15	27	17	22	16	14
Discards, Non-quota commercial spp.	24	44	22	12	36	12	22	11	12
Retained, Non-quota commercial spp.	8	11	8	13	7	7	7	10	6
Non-quota species, Total catch									
Blue morwong	21	23	24	22	15	17	18	19	13
Piked dogfish	20	34	21	19	23	14	18	16	12
Angel shark	17	13	22	18	11	14	14	11	9
Barracouta	21	23	17	25	15	15	16	24	14
Arrow squid	14	22	17	13	13	12	15	11	11
Quota species, Discards									
Redfish	32	39	38	19	30	25	33	20	20
Tiger flathead	37	11	24	35	19	21	20	27	17
Mirror dory	31	48	25	63	39	55	23	59	51
Jackass morwong	n/a	n/a	24	31	n/a	19	24	31	19
John dory	n/a	n/a	20	31	n/a	18	20	31	18

3.4 Discussion

Estimators based on separate ratios and regressions showed greater bias than the estimators from combined ratios and regressions (Fig. 3.1). Moreover, the magnitudes of biases estimated for the separate estimators were not inconsequential. Consequently, in terms of bias, the separate estimators (Rs and LRs) were considered unsuitable for use in this project. Combined ratio and regression estimators generally had inconsequential bias and were therefore candidates for routine use (as was the unbiased SMPU estimator).

There were, however, differences in the relative precision of SMPU, Rc and LRc estimators (Table 3.1). Precision of Rc and LRc estimates (using IRQS as auxiliary variable) of discarded tiger flathead and jackass morwong exceeded the precision of SMPU estimates. For each species, weights of discards were correlated with weights of retained catches. The Rc and LRc estimators were no more precise than the SMPU estimator for all other components of catch and, in many instances, the Rc estimator was less precise.

These conclusions suggest two alternative strategies for the routine estimation of catches from the observer survey. One option is the use of the combined linear regression estimator in all circumstances, using IRQS as auxiliary variable in preference to ARQS when possible (i.e. for quota species). In contrast to the combined ratio estimator, precision of combined regression estimates was never worse than that of the SMPU estimator (Table 3.1). Nor could it be, given that the formula for the variance of the LRc estimator differs from the corresponding formula for the SMPU estimator by the factor:

$$(1 - \hat{\rho}_c^2) \quad \text{in which} \quad \hat{\rho}_c = \frac{s(\bar{y}_{SMPU}, \bar{x}_{SMPU})}{s(\bar{y}_{SMPU}) . s(\bar{x}_{SMPU})}$$

in which $\hat{\rho}_c$ is the estimate of the population correlation coefficient (Cochran, 1977). In the few instances that the Rc estimator produced minimal or useful gains in precision over the SMPU estimator, the LRc produced similar gains.

The second approach (and the one chosen for use in this project) involves the routine use of the SMPU estimator except for discards of tiger flathead and jackass morwong, for which the ratio estimator (using IRQS) is superior. No gain in precision was achieved for the other components of catch using the ratio estimator (and IRQS). Complexity of calculation and exposure to inaccuracies of estimated variances using ratio and regression estimators (see below) would be minimised using this approach. Total catches of quota species (for which the weights of landings are known) can then be calculated as the sum of the reported weights of landings and estimated discards. Consequently, the standard error (and confidence interval) of estimated total catch will be equal to that of estimated discards. For all other species, retained, discarded and total catches must be estimated from observer data, using reported effort data to scale quarterly estimates to annual estimates of mean catch. For all components of catch, annual catches can be calculated as the product of mean catches (per fisher-day) and annual effort (number of fisher-days).

It is interesting to note that a minimal legal length is regulated for tiger flathead and for jackass morwong, but for no other quota species. Tiger flathead and jackass morwong are the only species for which there was a relationship between the weight of retained and discarded catches in more than a single instance (see Table 3.1). For each of these species, particularly tiger flathead, legal-sized and undersized fish were caught together and the minimal legal length was the main factor that determined whether fish were retained or discarded (see Chapter 7). In such circumstances, some relationship between retained catches and discards is expected. Moreover, variation in the relative weights of legal and undersized components of catch determines the strength of the relationship and therefore the gain in precision of ratio and regression estimators over the stratified mean-per-unit estimator.

The sampling estimate of the variance associated with ratio and regression estimators is an approximation, valid only in large samples (Cochran, 1977; Sukhatme *et al.*, 1984). Furthermore, confidence intervals calculated for estimates of catch, using any estimator (including SMPU), must be considered approximate. In general, frequency distributions of retained and discarded catches and of ratios were positively skewed. In these circumstances, it is likely that: (i) the probability exceeds 5 % that the population mean will be outside the calculated 95 % confidence interval; (ii) the probability is smaller than 2.5 % that the population mean will be below the lower confidence bound of the estimate; and (iii) the probability exceeds 2.5 % that the population mean will be greater than the upper confidence bound of the estimate (Cochran, 1977). Consequently, underestimates will occur more frequently than overestimates. A conservative bound may be placed on the actual probability of calculated 95 % confidence intervals using the Chebyshev inequality (Mood *et al.*, 1974) which states that at least 75 % of observations for any probability distribution will be within 2 standard deviations of their mean (e.g. as used by Crone 1995, for estimates of landings).

It may also be beneficial to reconsider strategies for estimation with increased understanding of factors affecting discarding and by-catch. Factors other than retained catches may be identified that will correlate with discarded catches (or other components of catch). Ratio or regression estimators using these variables, or multivariate ratio or regression estimators (e.g.

Sukhatme *et al.*, 1984), or combinations of different estimators may offer increased precision in such circumstances.

Increasing emphasis is being placed on the estimation and consequences of by-catch and discards in fisheries in Australia and throughout the world (Alverson *et al.*, 1994; Kennelly, 1995). If the discarded component of catch were included in models of fishery dynamics, conclusions drawn from such models may be drastically altered (e.g. Saila, 1983; ICES, 1986, cited in Alverson *et al.*, 1994; Pikitch, 1987 and 1991; Alverson *et al.*, 1994; Erhardt & Legault, 1997; Chen & Gordon, 1997). Recognition of the sampling error associated with estimates of catch is vital for the effective use of models of fishery dynamics and the confidence that can be placed on conclusions drawn from them (e.g. Pelletier & Gros 1991; McAllister & Peterman, 1992; Pope & Gray, 1983; Hilborn & Walters, 1992; Quinn & Deriso, 1999). If it is important to acknowledge the confidence associated with an estimate of total catch, then it is clearly desirable to maximise the precision of estimates of the weight, abundance or sizes of discards. While there is a trend toward increased statistical rigour in the design and implementation of surveys of landings (e.g. Sen, 1986; Crone, 1995), the relative merits of various techniques used to make estimates in the analyses of catch data from observer surveys have received little attention (Andrew & Pepperell, 1992). To maximise the precision of estimates of discarded catch (or by-catch) and total catch, the relative reliability of alternative estimators should be evaluated. This study has demonstrated the benefits of such an approach and has been used to select a strategy for routine use in this project.

Chapter 4

Detection of bias in observer-based estimates of retained and discarded catches

Appendix A.4.1 contains a copy of the paper "Detection of bias in observer-based estimates of retained and discarded catches from a multi-species trawl fishery" (G. W. Liggins, M. J. Bradley and S. J. Kennelly) published in Fisheries Research 32, 1997. A brief synopsis of the contents of this paper are provided here.

Observer-based estimates of quantities, size- and age-distributions of by-catches and discarded catches may be biased by non-representative selection of sampling units (fisher-days or trips) or by changes in fishing practices onboard trawlers when observers are present. Non-sampling errors may arise from many sources but several are of particular concern in observer surveys of fisheries (Kulka & Waldron, 1983; Saila, 1983; Alverson *et al.*, 1994). Non-random selection of sampling units (e.g. observed fisher-days or trips) from the sampled population may result in bias. Random selection of sampling units is difficult when the sample population cannot be enumerated (i.e. the sampling frame cannot be identified) until the period from which the sample is taken is complete. Refusals by masters of vessels to allow an observer onboard will also bias estimates, unless the retained and discarded catches of respondents and non-respondents are similar. Another problem for observer-based surveys is the influence that the process of observation may have on the process being observed. Bias could occur if fishers perceive that their interests may be enhanced by changing their normal practices when an observer is present (e.g. by discarding more or less; by fishing in an area or in a way such that discards will be maximised or minimised).

In this study, observer-based estimates of magnitudes and size-distributions of retained catches were compared with independent, unbiased estimates available for a subset of species (species managed by catch quotas) caught in the fishery. Observer-based estimates of magnitudes of retained catches (with 95 % confidence limits) of quota species were compared with reported landings. Size-distributions (and mean sizes and variances of mean sizes of samples) derived from the observer survey were compared with estimates from an auxiliary survey of catches landed at fishing co-operatives. Conclusions about bias in estimates of other components of catch (especially discards) are based on the premise that bias is unlikely to affect these estimates without also affecting estimates of retained catches of quota species.

The conclusion of this study was that estimates of catch, based on the 3 year period 1993-95, were unaffected by any significant bias. Observer-based estimates of magnitudes of retained catches did not differ significantly from reported landings for 6 out of 7 species and the combined catch of quota species (CQS) for the Ulladulla fleet, 11 out of 11 species and CQS for the Eden fleet and 10 out of 11 species and CQS for the 2 fleets combined. There was, however, some evidence of bias in estimates of catch for each fleet in 1 of the 3 years. Observer-based size-distributions were not significantly biased.

Chapter 5
Composition of retained and discarded catches

5.1 Introduction

Although mortalities of discards are very variable and depend on biological, environmental and operational factors, it is apparent that a large proportion of fish discarded at sea do not survive (Nielson *et al.*, 1989; Andrew & Pepperell, 1992; Alverson *et al.*, 1994; Richards *et al.*, 1995). In many countries, including Australia, an issue of primary concern is the direct mortality of discards of commercially and recreationally important species (Fennessy, 1994; Kennelly, 1995; Alverson & Hughes, 1996; Crowder & Murawski, 1998) because this may affect: (i) stocks of fish targeted by the fishery concerned and/or (ii) other commercial or recreational fisheries. Because fish discarded at sea represent real losses from populations, stock assessments that ignore the discarded component of catch may be erroneous (e.g. Pikitch, 1987, 1991; Hilborn & Walters 1992; Alverson *et al.* 1994; Ehrhardt & Legault, 1997; Chen & Gordon, 1997). In addition, the capture and discard of fish and other organisms may have more complex effects on the structure of communities, including influences on species interactions and their consequent cascading effect through the trophic web (e.g. Sainsbury 1987, 1988, 1991; Botsford *et al.*, 1997; Crowder & Murawski, 1998; Jennings & Kaiser, 1998; Hall, 1999; Estes & Peterson, 2000). In addition to potential impacts on stocks and ecosystems, discarding is also of concern to the fishing industry because: (i) the negative publicity associated with discarding poses a threat to ongoing public support for the industry (e.g. Foldren, 1989; Harnwell, 1996) and (ii) the capture and subsequent discard of large quantities of fish carries with it costs in terms of wear and tear on fishing gear and sorting time for crews (Alverson *et al.*, 1994).

An evaluation of the composition (species, quantities, size-distributions) of discarded catches is fundamental to any assessment of the effects of discarding on stocks and ecosystems and the subsequent need to reduce discards (Saila, 1983; Alverson *et al.*, 1994; Kennelly *et al.*, 1997). Moreover, such information provides a basis for determining options for reducing discards by (i) reducing capture of fish subsequently discarded (e.g. spatial or temporal closures, development of more selective gears) or (ii) by identifying opportunities for utilising components of discarded catch.

Alverson *et al.* (1994) provided a "provisional" estimate of global discards of 27 million tonnes (range 17.9-39.5 million tonnes). In this analysis, shrimp trawl fisheries generated more discards and greater proportions of catch were discarded than for any other type of fishery. In contrast, low rates of discarding generally occurred for pelagic trawling and particular types of purse-seine and drift-net fisheries. Long-lining and benthic fish trawling were generally associated with intermediate rates of discarding. Whilst this "intermediate" classification for fish trawling may be a valid generalisation, available information demonstrates there is considerable variation among fish trawl fisheries and among species within fish trawl fisheries in: the proportion of catch discarded; magnitude of discarded catches; and size-composition of retained and discarded catches.

The proportion of catch discarded in the fish trawl fisheries reviewed by Alverson *et al.* (1994) range from very low rates of discarding (e.g. 1 % in the Northwest Atlantic hake trawl, 4 % in the Northeast Pacific whiting trawl fishery) to comparatively high rates of discarding (e.g. 72 % in the Bering Sea rock sole and 69 % in the British Columbia cod trawl fishery). An estimated 48 % of the combined catch of all species was discarded by fish trawlers in the Atlantic ocean off the north-eastern United States (Kennelly *et al.,* 1997). This study also provided estimates of the proportion of catch discarded for 30 individual species and these ranged from a few percent to nearly 100 %, demonstrating great variation amongst rates of discarding within a fishery. Such variation in species-specific rates of discarding was also shown for the trawl fishery in the Gulf of St. Lawrence Canada, between 1956 and 1961, in which annual estimates of the proportion of catch of cod and plaice discarded were less than 20 % compared to discards of hake and redfish that were between 95 and 100 % (Jean, 1963). Variation in species-specific rates of discarding for primary target species has also been documented for North Sea trawl fisheries targeting cod, haddock and whiting (Jermyn & Robb, 1981; Stratoudakis *et al.*, 1998, 1999; Tamsett & Janacek, 1999) and the trawl fishery targeting flatfish species in the Gulf of Maine (Howell & Langan, 1987).

Just as the proportion of catch discarded varies among fisheries and among species within fisheries, there is great variation in the quantities of catch discarded at these scales. Tens and hundreds of thousands of tons of fish have been discarded annually in several fish trawl fisheries for which data exist. For example, fish trawl fisheries in the Bering Sea discarded approximately 204,491 t of fish during 1992 including discards of an estimated 75,734 t of pollock and 11,265 t of cod. Quantities of fish discarded varied among the 8 target fisheries examined (e.g. 2 t discards from the fishery targeting sablefish compared to 40,651 t discarded from the sub-fishery targeting pollock; Alverson *et al.,* 1994). Estimates of annual discards by Scottish fish trawlers in the North sea, during 1988-1993, ranged between 20,000 - 53,000 t for haddock, 20,000-29,000 t for whiting and 2500 - 13,000 t for cod (approximated from graph in Stratoudakis *et al.*, 1999).

Despite the great diversity in the quantities and composition of discards from trawl fisheries, several generalisations can be made. Andrew and Pepperell (1992) reviewed studies of by-catch and discarding from shrimp trawling and noted that: (i) fin-fishes commonly dominate by-catches and discards; (ii) a relatively small number of species dominates by-catches and discards; and (iii) sizes of fish in by-catches and discarded catches are generally small. A fourth generalisation can also be made with respect to fish trawling. If some of the catch of a target species is discarded, sizes of discarded fish are generally smaller than sizes of retained fish (e.g. Jean, 1963; Jermyn & Robb, 1981; Howell & Langan, 1987; Alverson *et al.*, 1994; Stratoudakis *et al.*, 1998).

Such generalisations and the estimated rates of discarding for fish trawl fisheries discussed above are based on information from the northern hemisphere. Little information is available describing the composition of discards in New Zealand and Australian fish trawl fisheries. Although discarding is illegal in the New Zealand fish trawl fisheries, evidence for discarding comes from anecdotal reports of high-grading and the observation that vessels carrying observers report greater quantities of non-target quota species than vessels in the same area without observers (Annala, 1996). A recent review of by-catch in Australian demersal trawl fisheries (Kennelly, 1995) discussed multiple studies concerning by-catch and discards from prawn trawling, but noted the lack of available information about the composition of discards from fish trawling.

This chapter provides a description of the composition of retained and discarded catches by fish trawlers operating on the NSW coast during the period 1993-95. Mean rates of catch (per fisher-day and per annum) and size-distributions of retained and discarded components of catch, for individual species and various partitions of catch, are estimated for the period 1993-95. This analysis is based on data from the observer survey (Chapter 2) and the methods of estimation were selected following comparisons of the relative performance of alternative estimators (Chapter 3) and an evaluation of the significance of bias (Chapter 4).

5.2 Materials and methods

5.2.1 Components of catch

Estimates of quantities of catch (at various spatial and temporal scales of interest) were made for 8 components of the total catch of all species. Each component comprises multiple species:

- Total catch of all species
  - Retained catch of all species
    - Retained catch of SEF quota species
    - Retained catch of non-quota commercial species
  - Discarded catch of all species
    - Discarded catch of SEF quota species
    - Discarded catch of non-quota commercial species
    - Discarded catch of non-commercial species

Estimates of quantities and size-distributions of catch were also calculated for all individual commercial species (SEF quota species and non-quota commercial species).

5.2.2 Sources of data

Data from the observer survey (described in Chapter 2) and auxiliary data about landed catch and effort provided the basis for estimating quantities and size-distributions of retained, discarded and total catches.

All fishers in the SEF are required to report landed catches of quota species and the duration of each fishing trip (dates of departure and return to port) to the AFMA (on "SEF-2 Quota monitoring system" returns). Only those fishing trips that conformed to the criteria for the sampled population of the observer survey were included in calculations of fishing effort and landed catch (i.e. trips of less than 3 days duration and trips not targeting royal red prawns). The number of fisher-days and total landings of each SEF quota species were calculated for the Ulladulla and Eden-based fleets, in each quarter of each year.

Quarterly fishing effort (in units of fisher-days), for the ports of Ulladulla and Eden, was calculated as follows: (i) trips for which the reported dates of departure and return to port were identical each contributed 1 fisher-day of effort; (ii) trips for which the dates of departure and return to port differed by d days contributed an estimated $d+0.5$ fisher-days. Annual weights of landed catches of each quota species were calculated from the data reported by fishers making landings into Ulladulla and Eden. Landed weights that were reported for "processed" fish (gutted, or headed and gutted) were converted to "whole" weights using approximate conversion factors (1.1 for pink ling, 1.25 for gemfish, 1.5 for blue grenadier).

Limitations of the data collected on NSW fishers' monthly returns meant that, in general, it was not possible to obtain reliable data for landed catches, taken by fish trawlers, for the

North region (Newcastle and Tuncurry). For example, Newcastle and Tuncurry fishers reported an effort of 2,426 fisher-days in 1993. This figure is not considered reliable and it almost certainly overestimates true effort. During the 3 years of observer work at Newcastle and Tuncurry observers consistently worked on 8 trawlers and occasionally on several others that trawled for fish part-time. Assuming that an average of 8 trawlers worked for an average of 17 fisher-days each month, fishing effort would be approximately 400 days per quarter. All observer-based estimates of retained and discarded catches by fish trawlers in region "North" are based on the assumption that the fleet completes 400 fisher-days per quarter, a total of 1600 fisher-days per year. The consequences of making this assumption are considered in the Discussion (Section 5.4).

5.2.3 Estimating magnitudes of retained and discarded catches

Based on a comparison of the relative precision and accuracy of alternative estimators (described in Chapter 3) and available landings and effort data for different regions, the methods used to estimate mean catch per fisher-day (and associated variances), calculated annually for each region, for various components of catch, are summarised in Table 5.1.

Estimates of mean catch per fisher-day in stratum h, $\bar{y}_h$ and associated variance, $s^2(\bar{y}_h)$ for each of the 3 regions in each of the 3 years (9 strata), were used to calculate estimates of mean catch per fisher day across these strata as follows:

$$\bar{y} = \sum_{h=1}^{9} W_h \cdot \bar{y}_h$$

$$s^2(\bar{y}) = \sum_{h=1}^{9} W_h^2 \cdot s^2(\bar{y}_h)$$

in which W_h is the proportion of fishing effort contributed to the total by stratum h .

Estimates of mean catch per fisher-day (across the 3 regions and 3 years combined) were multiplied by the mean annual effort (4,880 fisher-days) to provide estimates of mean annual catch by the combined fleets of the 3 regions.

Table 5.1

Methods used to estimate annual rates of catch for various components of catch and region

SMPU / OS / assume : SMPU estimator using catch data from the observer survey and assumed effort data

SMPU / OS / SEF2-E : SMPU estimator using catch data from the observer survey and effort data from SEF2 database

Rc / OS / SEF2-L : Rc estimator using catch data from the observer survey and auxiliary landings data from SEF2 database

SEF2-L : catch directly from SEF2 landings data

X + Y : catch calculated as catch X plus catch Y

	North	Ulladulla	Eden
Retained catches of individual species			
SEF quota spp.	*SMPU / OS / assume*	***SEF2-L***	***SEF2-L***
non-quota spp.	*SMPU / OS / assume*	*SMPU / OS / SEF2-E*	*SMPU / OS / SEF2-E*
Discarded catches of individual species			
SEF quota spp. *(excluding Tiger flathead & Jackass morwong)*	*SMPU / OS / assume*	*SMPU / OS / SEF2-E*	*SMPU / OS / SEF2-E*
Tiger flathead, Jackass morwong	*SMPU / OS / assume*	***Rc / OS / SEF2-L***	***Rc / OS / SEF2-L***
non-quota spp.	*SMPU / OS / assume*	*SMPU / OS / SEF2-E*	*SMPU / OS / SEF2-E*
Partitions of catch			
1. Retained catch of SEF quota spp.	*SMPU / OS / assume*	***SEF2-L***	***SEF2-L***
2. Retained catch of non-quota commercial spp.	*SMPU / OS / assume*	*SMPU / OS / SEF2-E*	*SMPU / OS / SEF2-E*
3. Retained catch of all spp. combined	*SMPU / OS / assume*	***1 + 2***	***1 + 2***
4. Discarded catch of SEF quota spp.	*SMPU / OS / assume*	*SMPU / OS / SEF2-E*	*SMPU / OS / SEF2-E*
5. Discarded catch of non-quota commercial spp.	*SMPU / OS / assume*	*SMPU / OS / SEF2-E*	*SMPU / OS / SEF2-E*
6. Discarded catch of non-commercial spp.	*SMPU / OS / assume*	*SMPU / OS / SEF2-E*	*SMPU / OS / SEF2-E*
7. Discarded catch of all spp. combined	*SMPU / OS / assume*	*SMPU / OS / SEF2-E*	*SMPU / OS / SEF2-E*
8. Total catch of all species combined	*SMPU / OS / assume*	***3 + 7***	***3 + 7***

5.2.4 Estimating size-distributions of retained and discarded catches

Quarterly size-distributions of retained and discarded catches for each commercial species, in each region, were calculated from data derived from the observer survey (see Chapter 2) and the survey of size-distributions of landed catches at fishing co-operatives (see Chapter 4). Size-frequency distributions (relative frequencies) obtained from each observed tow and each observed landing were weighted by the relative catch (number of fish) in the tow or landing from which they were sampled.

Size distributions for retained and discarded catches by the combined fleets of the 3 regions across the 3 years of the survey were calculated by combining the quarterly size-distributions (relative frequencies) after weighting by the relative catches (estimated number of fish caught) taken by fleets in each region, in each quarter.

5.3 Results

5.3.1 Species composition

A total of 365 taxa (species or higher taxonomic groups) were identified during the observer survey and 145 of these were defined as "commercial" species (see Appendix A.5.1 which contains a complete taxonomic listing of family, scientific and common names of species/taxa identified in catches during the observer survey).

Of the 309 fin-fish species identified, 121 were classified as "commercial" (i.e. species often retained in this fishery or in other commercial fisheries). Thirty-four crustacean taxa were identified, of which 17 were classed as "commercial". Of the 12 mollusc taxa identified, 7 were "commercial". Four echinoderm, 3 cnidarian, 1 annelid, 1 mammal and 1 reptile taxa were also identified.

5.3.2 Major components of catch

The mean annual catch of all species combined for the combined fleets of the 3 regions over the period 1993-95 was 12,336 +/- 316 t, corresponding to a mean catch per fisher-day of 2,528 +/- 65 kg. Approximately 50 % of this catch, 6,223 +/- 302 t (1,275 +/- 62 kg per fisher-day) was discarded (Table 5.2 & Fig. 5.1).

The estimated catch of SEF quota species was 6,004 +/- 191 t (1,230 +/- 39 kg per fisher-day), representing approximately 49 % of the catch of all species. Approximately 30 % of the catch of SEF quota species, 1,815 +/- 190 t (372 +/- 39 kg per fisher-day), was discarded. Non-quota commercial species represented 24 % of the overall catch (2,933 +/- 124 t annually, 601 +/- 25 kg per fisher-day) and approximately 34 % of this catch was discarded (1,009 +/- 89 t annually, 207 +/- 18 kg per fisher-day). The entire catch of non-commercial species (3,399 +/- 167 t annually, 697 +/- 34 kg per fisher-day), representing 28 % of the catch of all species, was discarded (Table 5.2 & Fig. 5.1).

The retained catch of all species comprised SEF quota species (68 %) and non-quota commercial species (32 %). Whilst non-commercial species represent 55 % of the discarded catch of all species, commercial species were discarded in substantial quantities (29 % SEF quota species and 16 % non-quota commercial species).

5.3.3 Individual taxa

Figure 5.2 provides a summary of rates of retained and discarded catch per fisher-day and the proportion of catch discarded for 40 commercial species (or taxa). These 40 species comprise the 34 species caught in greatest quantity and 6 additional species (eastern blue-spot flathead, *Platycephalus caeruleopunctatus*; tarwhine, *Rhabdosargus sarba*; red spot whiting, *Sillago flindersi*; snapper, *Pagrus auratus*; and tailor, *Pomatomus saltatrix*) that are targeted in other commercial and recreational fisheries in NSW. Table 5.3 lists estimates of mean annual catches (total, retained and discarded components) for all commercial species with a mean annual catch in excess of 1 tonne (80 species).

Of the 145 commercial taxa identified in this study, the 10 species caught in greatest quantity represented approximately 66 % of the weight of the total catch of commercial species. The next 10 most abundant species represented a further 19 % and the remaining 125 species represented the remaining 15 %. The catch of redfish (2,303 +/- 174 t per annum, 472 +/- 36 kg per fisher-day) was the greatest, representing 26 % of the total catch of commercial species.

Catches of spotted trevalla (*Seriolella puctata*; 9 % of the total commercial catch), tiger flathead (8 %), barracouta (5 %), silver trevally (*Pseudocaranx dentex*; 4 %), pink ling (*Genypterus blacodes*; 4 %), southern frostfish (*Lepidopus caudatus*; 4 %), piked dogfish (4 %), blue warehou (*Seriolella brama*; 3 %) and arrow squid (3 %) ranged from 788 +/- 11 t

Table 5.2

Retained and discarded catches, 3 regions combined, 1993-95

	Mean annual catch (tonnes, +/- 1 se)			Mean catch per fisher-day (kg, +/- 1 se)			% retained or discarded
All spp. combined							
Retained	6,113	+/-	89	1,253	+/-	18	*50 %*
Discarded	6,223		302	1,275		62	*50 %*
	12,336		316	2528		65	
SEF quota spp.							
Retained	4,189		20	858		4	*70 %*
Discarded	1815		190	372		39	*30 %*
	6,004		191	1230		39	
Non-quota commercial spp.							
Retained	1,924		86	394		18	*66 %*
Discarded	1,009		89	207		18	*34 %*
	2,933		124	601		25	
Non-commercial spp.							
Discarded	3,399		167	697		34	*100 %*

Figure 5.1

Retained and discarded components of catch, 3 regions combined, 1993-95

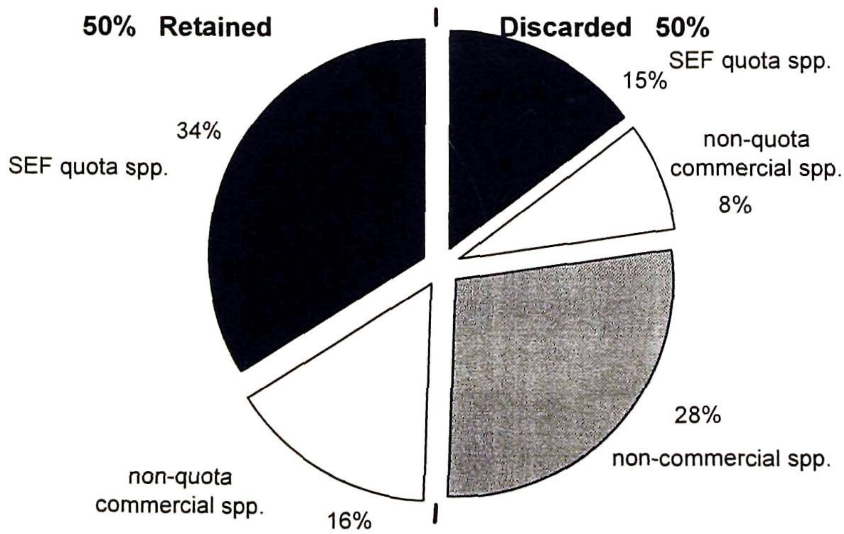


Figure 5.2, page 1

Estimates of mean catch-rates (per fisher-day, +/- 1 SE) for retained and discarded catches, for the combined fleets of North, Ulladulla and Eden, during 1993-95, 40 species (or species groups)

% of catch discarded shown above each graph, species ordered by decreasing total catch
(black bars: retained catch, white bars: discarded catch)

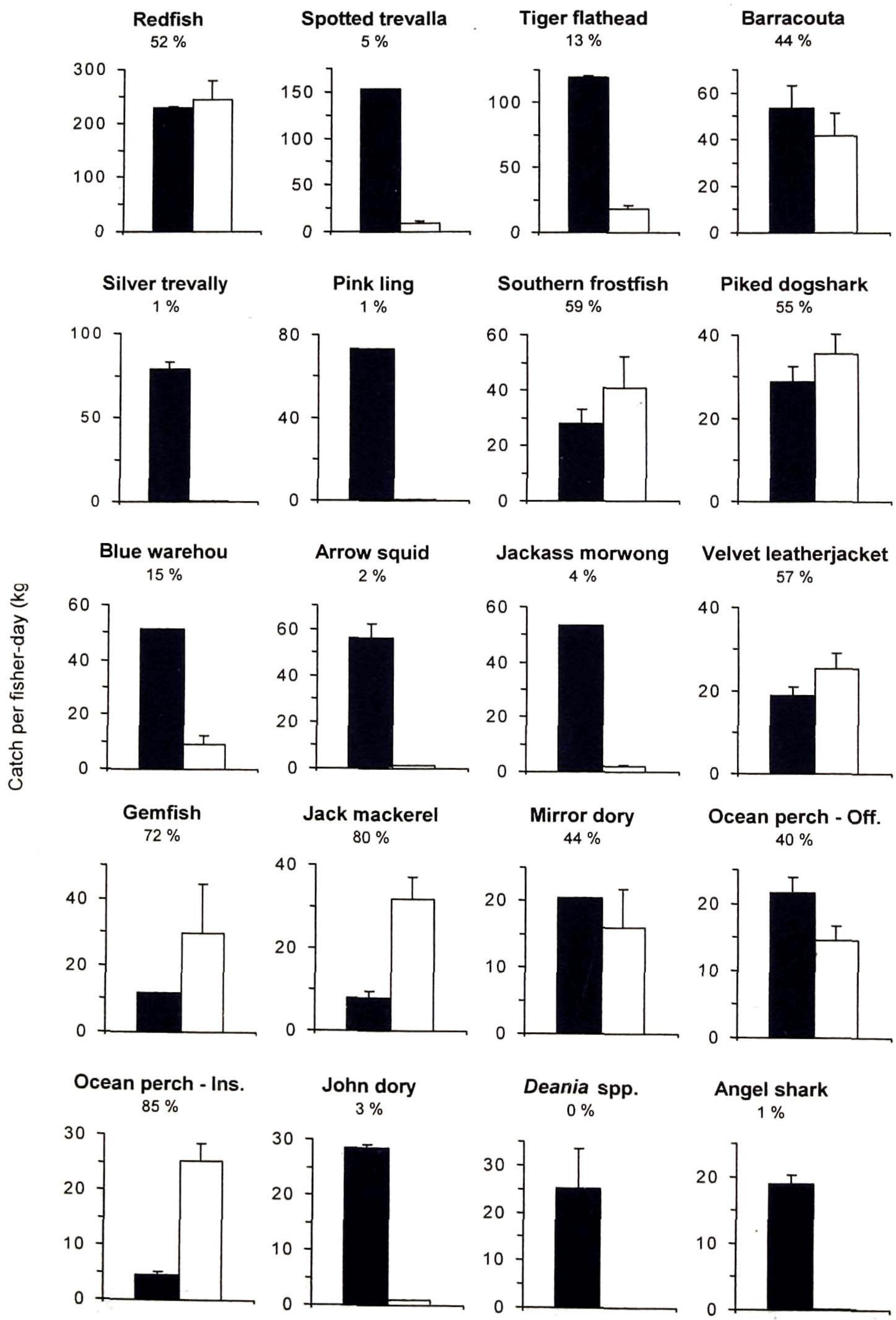


Figure 5.2, page 2

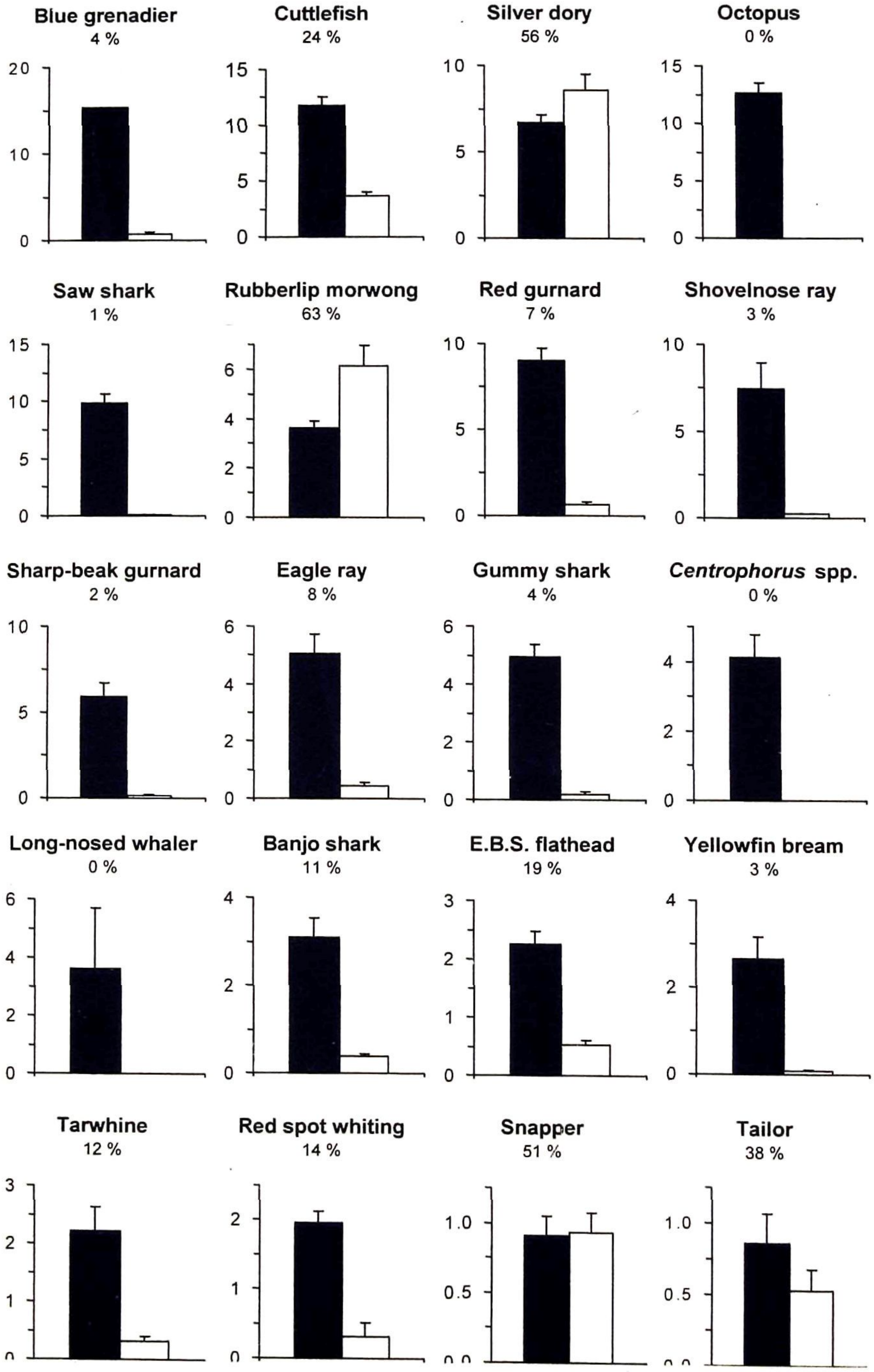


Table 5.3

Estimates of annual retained, discarded and total catches (estimates +/- 1 se) of commercial species 3 regions combined, 1993-95

	Total catch (t)		Retained catch (t)		Discarded catch (t)		% Discards	Relative magnitude of catch		
								Total	Retained	Discarded
Redfish	2,303	+/- 174	1,116	+/- 5	1,187	+/- 173	52	1	1	1
Spotted trevalla	788	11	745	0	43	11	5	2	2	13
Tiger flathead	671	12	582	4	89	11	13	3	3	9
Barracouta	463	70	261	47	202	47	44	4	7	2
Silver trevally	388	19	386	19	2	1	1	5	4	28
Pink ling	359	0	357	0	2	0	1	6	5	30
Southern frostfish	333	69	135	26	198	56	59	7	12	3
Piked dogfish	313	31	140	18	174	23	55	8	10	4
Blue warehou	294	14	249	0	45	14	15	9	9	12
Arrow squid	280	30	274	30	6	1	2	10	6	20
Jackass morwong	270	2	260	0	10	2	4	11	8	17
Velvet leatherjacket	216	22	92	9	124	18	57	12	17	7
Gemfish	203	71	58	0	146	71	72	13	20	6
Jack mackerel	195	28	39	7	156	25	80	14	24	5
Mirror dory	177	28	99	0	78	28	44	15	15	10
Offshore ocean perch	176	17	105	11	71	11	40	16	14	11
Inshore ocean perch	145	17	22	3	123	16	85	17	30	8
John dory	143	3	138	3	5	1	3	18	11	21
Deania spp. dogfish	123	40	123	40	0	0	0	19	13	52
Angel shark	93	7	93	7	0	0	1	20	16	46
Blue grenadier	78	1	75	0	4	1	4	21	18	23
Cuttlefish	75	4	57	4	18	2	24	22	21	16
Silver dory	74	6	33	2	42	4	56	23	26	14
Octopus	62	5	62	5	0	0	0	24	19	57
Common sawshark	49	4	48	4	1	0	1	25	22	45
Rubberlip morwong	48	4	18	1	30	4	63	26	32	15
Red gurnard	47	4	44	4	3	0	7	27	23	24
Shovelnose ray	38	7	36	7	1	0	3	28	25	37
Sharp-beaked gurnard	29	4	29	4	1	0	2	29	27	44
Eagle ray	27	3	25	3	2	1	8	30	28	29
Gummy shark	25	2	24	2	1	1	4	31	29	41
Centrophorus spp. dogfish	20	3	20	3	0	0	0	32	31	64
Long-nosed whaler	18	10	18	10	0	0	0	33	33	69
Banjo shark	17	2	15	2	2	0	11	34	34	32
Splendid perch	15	6	14	5	0	0	2	35	35	49
Spiky oreo	14	6	14	6	0	0	0	36	36	68
Eastern blue-spot flathead	14	1	11	1	3	0	19	37	39	25
Yellowfin bream	13	3	13	2	0	0	3	38	37	47
Whaler shark	13	4	6	2	6	3	50	39	45	19
Southern calamary	12	2	12	1	0	0	3	40	38	48
Tarwhine	12	2	11	2	2	0	12	41	40	36
Red spot whiting	11	2	10	1	2	1	14	42	42	35
Ribaldo	11	4	10	4	0	0	2	43	41	55
Snapper	9	1	4	1	5	1	51	44	51	22
Ogilby's ghost shark	9	2	6	1	3	1	29	45	46	27
Thintail thresher	8	5	1	1	7	5	86	46	77	18
Orange roughy	8	1	6	0	2	1	21	47	48	34
Smooth hammerhead	8	1	8	1	0	0	0	48	43	70
Mosaic leatherjacket	8	2	7	1	0	0	5	49	44	51
Green-eyed dogfish	7	5	6	4	1	1	15	50	47	39
Tailor	7	1	4	1	3	1	38	51	52	26
Blue-eye trevalla	6	0	6	0	0	0	0	52	49	71
Rudderfish	5	2	5	2	0	0	0	53	50	72
Mulloway	4	2	3	1	2	1	39	54	59	33
Blue swimmer crab	4	1	3	1	1	0	24	55	57	40
Spotted wobbegong	4	1	4	1	0	0	2	56	53	60
Pink tilefish	3	1	3	1	0	0	0	57	54	73
Hapuku	3	1	3	1	0	0	0	58	55	74
Spotted gurnard	3	1	1	1	2	1	60	59	75	31
Giant boarfish	3	0	3	0	0	0	1	60	56	65
Herbst's nurse shark	3	2	2	1	1	1	29	61	63	42
Deepwater bug	3	1	3	1	0	0	3	62	58	59
School shark	2	1	2	1	0	0	0	63	60	75
Australian salmon	2	2	2	2	0	0	0	64	61	76
Bastard trumpeter	2	0	2	0	0	0	0	65	62	77
Chinaman leatherjacket	2	0	2	0	0	0	10	66	65	53
White shark	2	1	1	1	1	1	38	67	76	43
Large-toothed flounder	2	0	2	0	0	0	5	68	66	58
Broadbill swordfish	2	1	2	1	0	0	0	69	64	78
Dusky flathead	2	0	2	0	0	0	1	70	67	66
Red mullet	2	0	1	0	0	0	13	71	71	54
Seal shark	2	1	2	1	0	0	3	72	69	63
Goblin shark	2	2	2	2	0	0	0	73	68	79
Balmain bug	2	0	1	0	0	0	4	74	70	62
Slender squid	1	0	1	0	0	0	12	75	74	56
Yellowfin leatherjacket	1	0	1	0	0	0	1	76	72	67
Tasmanian trumpeter	1	0	1	0	0	0	0	77	73	80
Red cod	1	1	0	0	1	1	82	78	80	38
King dory	1	0	1	0	0	0	29	79	79	50
Smooth small-toothed flound	1	0	1	0	0	0	5	80	78	61

down to 280 +/- 30 t per annum (and 161 +/- 2 down to 57 +/- 6 kg per fisher-day) respectively.

Of the 20 commercial species caught in greatest quantity, more than 50 % of the catch of 7 species was discarded (inshore ocean perch, *Helicolenus percoides*, 85 %; jack mackerel, *Trachurus declivis*, 80 %; gemfish, 72 %; southern frostfish, 59 %; velvet leatherjacket, *Meuschenia scaber*, 57 %; piked dogfish, 55 %; redfish, 52 %). A further 5 species were discarded at rates greater than 10 % (barracouta, 44 %; mirror dory, 44 %; blue warehou, 15 %; tiger flathead, 13 %; offshore ocean perch, *Helicolenus barathri*, 40 %). Rates of discard as a proportion of the total catch of individual commercial species varied between 0 and 86 % for the remaining 70 commercial species listed in Table 5.3.

The 10 commercial species discarded in greatest quantity represented approximately 88 % of the weight of the discarded catch of commercial species. Discards of redfish (1,187 +/- 173 t per annum, 243 +/- 36 kg per fisher-day) were the greatest, representing 42 % of the discards of commercial species. Discards of barracouta (7 % of discards of commercial species), southern frostfish (7 %), piked dogfish (6 %), jack mackerel (6 %), gemfish (5 %), velvet leatherjacket (4 %), inshore ocean perch (4 %), tiger flathead (3 %) and mirror dory (3 %) were discarded at rates from 202 +/- 47 t per annum (41 +/- 10 kg per fisher-day) down to 78 +/- 28 t per annum (16 +/- 6 kg per fisher-day) respectively. The next 10 most abundant species amongst commercial discards represent a further 10 %, with 125 species representing the remaining 2 % of the discarded catch of commercial species.

5.3.4 Size composition of retained and discarded catches

Discarded fish were generally smaller than retained fish for 17 of the 18 commercial species analysed (Fig. 5.3). The exception was gemfish. This indicated size-selective sorting and high-grading by fishers. A consequence of this is that the proportion of numbers of fish discarded exceeds the proportion of the weight of discarded fish. For example: 52 % of redfish by weight and 66 % by number were discarded; for tiger flathead, 13 % by weight and 31 % by number; mirror dory 44 % by weight, 72 % by number; offshore ocean perch, 40 % by weight, 70 % by number; inshore ocean perch, 85 % by weight, 93 % by number.

Discards make a major contribution to the size-distribution of the total catch for many species (redfish, tiger flathead, blue warehou, gemfish, mirror dory, offshore ocean perch, inshore ocean perch, rubberlip morwong, eastern blue-spot flathead and snapper). For these species, the length-frequency distribution of retained catch alone is a poor representation of the length-frequency distribution of the total catch.

Figure 5.3, page 1

Size-frequency distributions for retained and discarded catches of 18 species, 3 regions combined, 1993-95

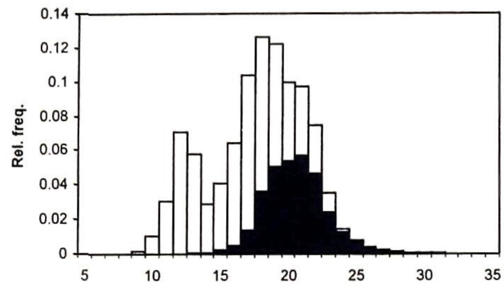
(black bars: retained catch, white bars: discarded catch)

Sample sizes: x(y) denotes a total sample of x fish from y tows (observer survey, "Obs"), or from y landings (co-op. survey, "Co-op")

"Mean L" is mean length of fish (cm)

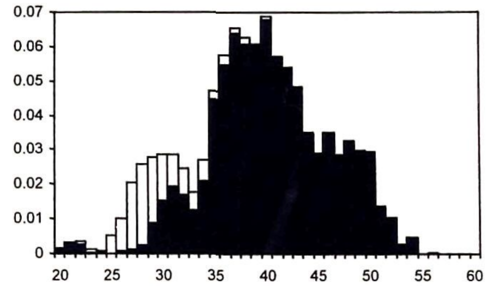
Redfish

	Retained	Discarded	Total
Obs:	7575 (60)	12452 (278)	
Co-op:	9152 (55)		
Mean L:	21.1	17.0	18.3



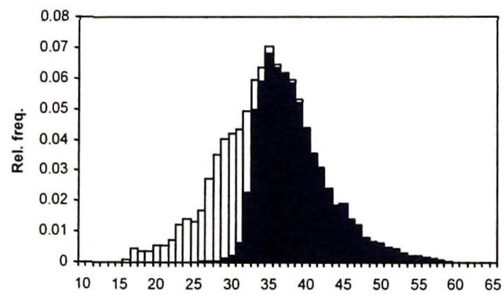
Spotted trevalla

	Retained	Discarded	Total
Obs:	4086 (53)	655 (86)	
Co-op:	2716 (23)		
Mean L:	41.0	30.0	39.5



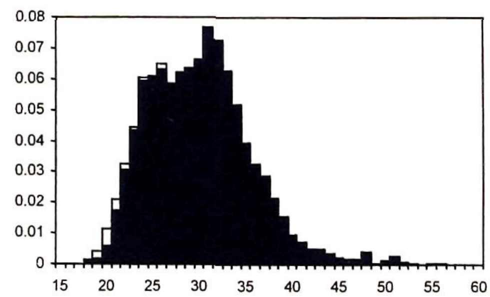
Tiger flathead

	Retained	Discarded	Total
Obs:	22508 (348)	8772 (749)	
Co-op:	10668 (83)		
Mean L:	39.1	28.4	35.8



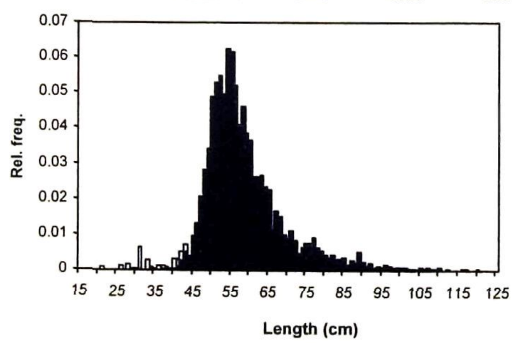
Silver trevally

	Retained	Discarded	Total
Obs:	11031 (197)	332 (43)	
Co-op:	2649 (20)		
Mean L:	30.6	21.8	30.5



Pink ling

	Retained	Discarded	Total
Obs:	3549 (74)	40 (35)	
Co-op:	3288 (53)		
Mean L:	59.5	35.9	58.8



Blue warehou

	Retained	Discarded	Total
Obs:	2587 (30)	547 (74)	
Co-op:	3010 (26)		
Mean L:	33.1	25.6	30.4

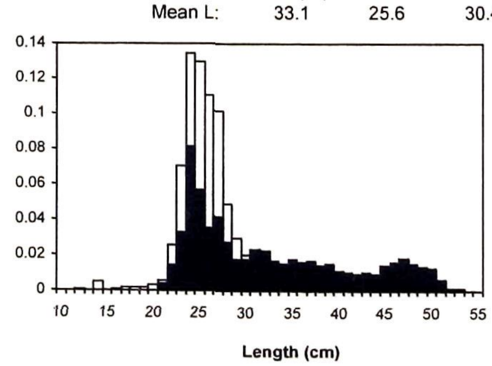
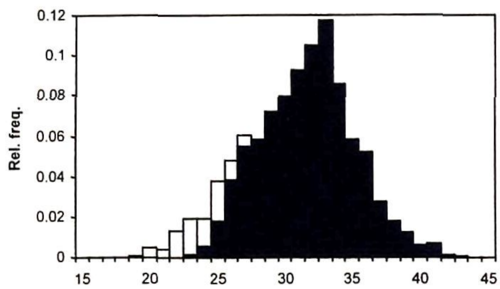


Figure 5.3, page 2

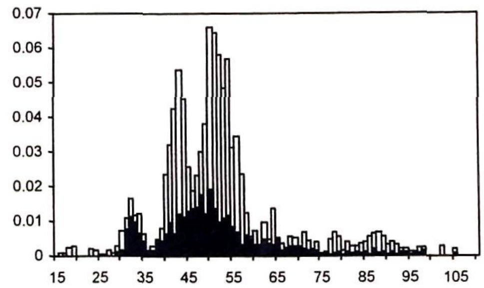
Jackass morwong

	Retained	Discarded	Total
Obs:	3762 (74)	433 (94)	
Co-op:	7623 (53)		
Mean L:	32.2	24.3	31.5



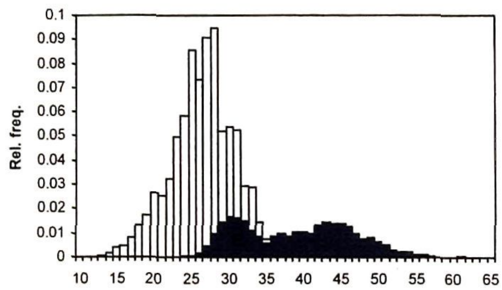
Gemfish

	Retained	Discarded	Total
Obs:	1814 (63)	613 (59)	
Co-op:	78 (5)		
Mean L:	51.9	53.0	52.6



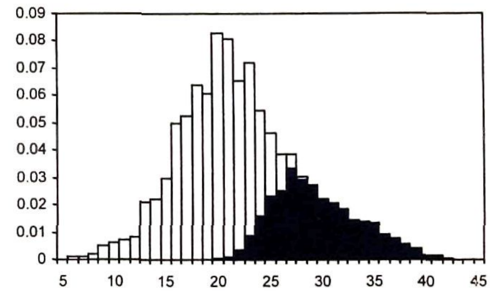
Mirror dory

	Retained	Discarded	Total
Obs:	2480 (64)	3407 (353)	
Co-op:	1663 (30)		
Mean L:	39.5	26.3	29.9



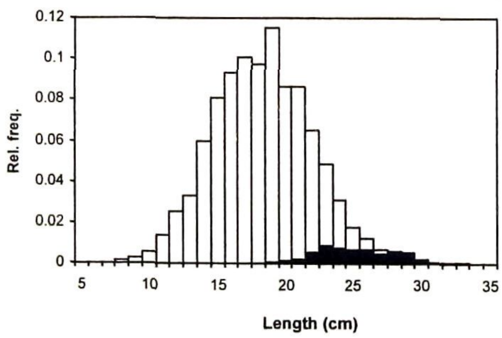
Ocean perch - Offshore

	Retained	Discarded	Total
Obs:	5332 (69)	4518 (366)	
Co-op:	1652 (18)		
Mean L:	30.0	19.8	22.9



Ocean perch - Inshore

	Retained	Discarded	Total
Obs:	747 (19)	9042 (594)	
Co-op:	213 (3)		
Mean L:	25.9	18.5	18.9



John dory

	Retained	Discarded	Total
Obs:	8000 (216)	966 (270)	
Co-op:	885 (15)		
Mean L:	29.0	16.7	27.4

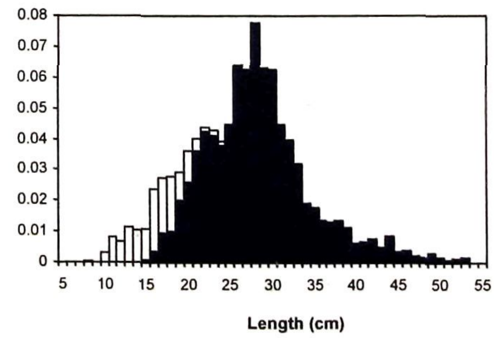
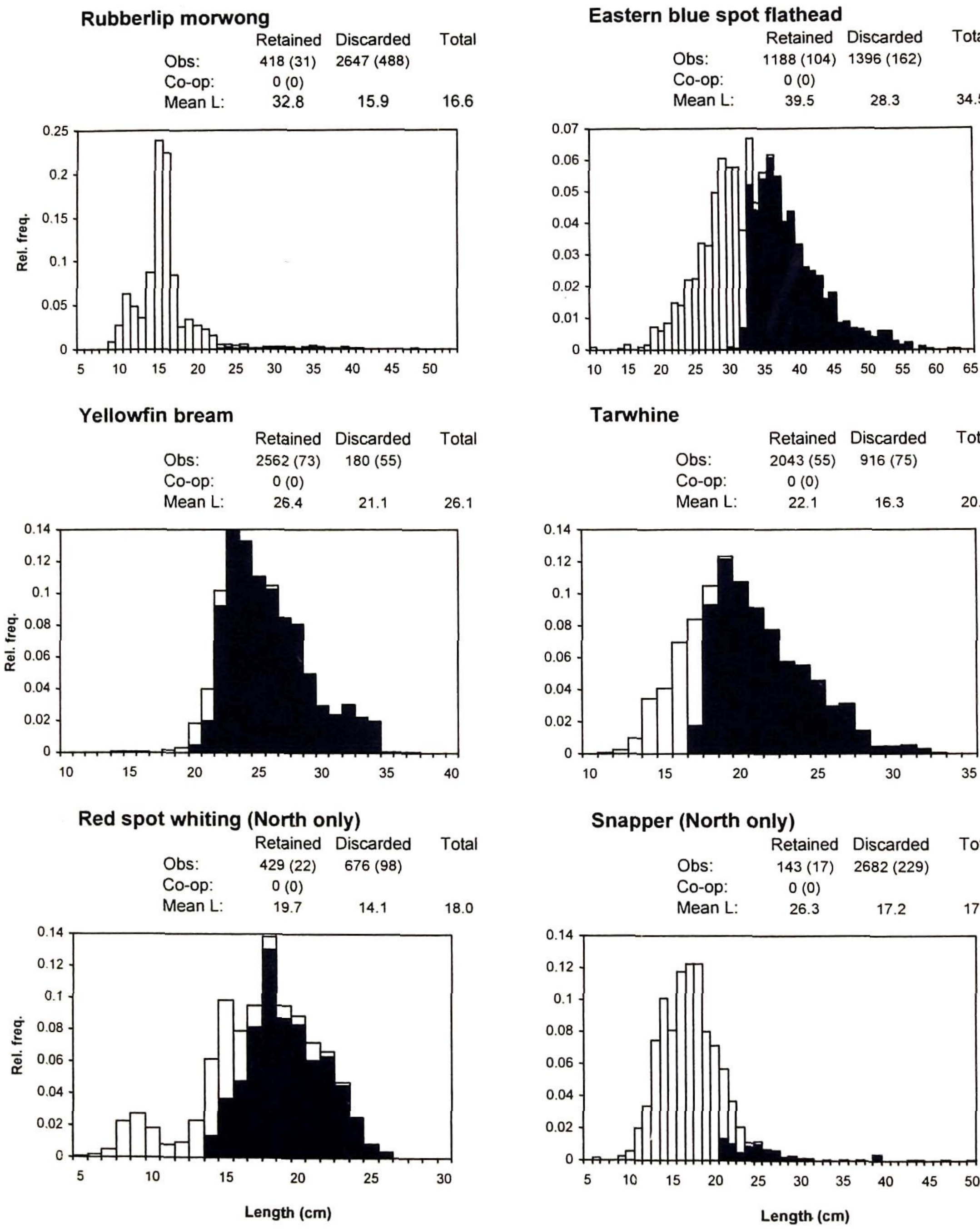


Figure 5.3, page 3



There is also variation among species in the amount of overlap between size-distributions of retained and discarded catches (Fig. 5.3). This overlap represents the range of sizes of fish that were sometimes retained and sometimes discarded during the period 1993-95. Tiger flathead, rubberlip morwong, eastern blue-spot flathead, tarwhine and snapper showed minimal overlap. In contrast, length-distributions for retained and discarded catches of redfish, spotted trevalla, blue warehou, mirror dory, offshore ocean perch, inshore ocean perch, john dory and red spot whiting showed greater overlap. The greatest overlap occurred for gemfish, with discarding occurring across the range of sizes of gemfish caught.

Minimal size of capture also varied among species. Several species were caught in large quantities at sizes less than 15 cm fork-length (e.g. redfish, inshore ocean perch, offshore ocean perch). At the other extreme, relatively few of the spotted trevalla and gemfish caught were smaller than 25 cm fork-length and few pink ling were smaller than 45 cm.

5.4 Discussion

The observer survey was generally consistent with broad generalisations made about the composition of discards from demersal trawl fisheries around the world (see Section 5.1). The first such generalisation was that fin-fishes dominated discarded catches. All of the discards of SEF quota species (372 +/- 39 kg per fisher-day) were fin-fish. The majority of the discards of non-quota commercial species (207 +/- 18 kg per fisher-day) comprised fin-fish (see Fig. 5.2, Table 5.3), the only non-fin-fish discarded at rates greater than 1.0 kg per fisher-day being cuttlefish (3.7 +/- 0.4 kg per fisher-day) and arrow squid (1.3 +/- 0.2 kg per fisher-day). Similarly, most discards of non-commercial species (697 +/- 34 kg per fisher-day) were fin-fish (estimates are not available for individual non-commercial species but 88 / 120 non-commercial taxa were fin-fish and personal observations were that fin-fish were dominant in catches).

The second generalisation was that discarded catches were often dominated by relatively few species. This is a striking feature of the NSW survey. The 10 commercial species discarded in greatest quantity represent approximately 88 % of the weight of the discarded catch of commercial species. Discards of one species, redfish, represented 42 % of the discards of commercial species and 19 % of the discards of all species.

The results were also consistent with the third and fourth generalisations that: discarded fish are generally small; discards of target species are generally smaller than retained fish; discards of commercial fish were usually smaller than 30 cm and consistently smaller than retained fish with the exception being gemfish (Fig. 5.3). The factors influencing these patterns of discarding are considered in Chapter 7.

In 1993-95, fish trawlers operating in the 3 regions surveyed discarded 50 % of the total catch of all species. This rate of discarding is similar to the estimate of 48 % of catch discarded for the Atlantic fish trawl fishery off north eastern United States (Kennelly *et al.*, 1997) and intermediate between the extremes documented by Alverson *et al.* (1994).

Similar rates of discarding have been documented recently for other components of the SEF (44 % off eastern Victoria, 50 % in Bass Strait and 44 % off western Tasmania during 1999; Knuckey, 2000). The striking contrast between the NSW survey and the recent results from similar surveys in other components of the SEF is in the relative proportions of quota species that are discarded. Figures for eastern Victoria of 8 %, Bass Strait 5 % and western Tasmania of 2 % (Knuckey, 2000) are considerably smaller than the 30 % of SEF quota species discarded in NSW during 1993-95. Rates for several species (redfish, 52 % discarded; tiger flathead, 13 %, blue warehou, 15 %, gemfish, 72 %, mirror dory, 44 %, offshore ocean perch, 40 % and inshore ocean perch, 85 %; Table 5.3) contributed to the greater discarding of SEF quota species off NSW.

Accuracy of estimates of rates of catch

The rates of catch and size-distributions for retained and discarded components of catch presented in this chapter represent the combined catches of Ulladulla, Eden and the northern region. It was concluded that estimates of catch for Ulladulla and Eden regions for the 3-year period 1993-95 were unaffected by significant bias (see Chapter 4) but, because of limitations associated with the catch and effort data collected on NSW fishers' monthly returns, the same validation procedure could not be used for the northern region. Assumptions associated with the calculation of estimates of catches for North must therefore be noted. Estimates of annual retained and discarded catches per fisher-day assume that effort (in units of fisher-days) was the same in each quarter of the year. So, if effort and catch-rates differed from quarter to quarter, estimates of mean catch per fisher-day may be biased. The assumed annual fishing effort of 1600 fisher-days (400 fisher-days per quarter) may over- or underestimate the true effort. If so, the weighting of the northern region in the calculation of catch-rate for the combined catches of the 3 regions will be over- or under-estimated and biased accordingly (unless catch-rates are the same for the northern and southern regions). Accuracy of estimates of mean annual catch (as distinct from mean catch per fisher-day) will be less affected for species caught in greater quantities in the southern regions compared to the northern region (see Chapter 6). This is intuitively obvious because a catch-rate per fisher-day of 0 for the northern region will result in an annual catch for the northern region that is close to 0 and a contribution of 0 to the catch across 3 regions, regardless of any bias in effort. With only a few exceptions, catches of most species were considerably larger in the southern regions than in the northern region (see Chapter 6). So, the estimates of mean catch per fisher-day and mean annual catch for the 3 regions combined can probably be considered reliable.

Note also that the precision of estimates of discarded catches were generally very good. For the combined catch across the 3 regions and 3 years, ratios of SE/mean for mean annual discarded catch were: 0.05 for all species combined, 0.10 for SEF quota species, 0.08 for non-quota commercial species and 0.04 for non-commercial species (Table 5.4). For the 17 individual species discarded in greatest quantities (mean annual discards >= 10t per annum), precision was better than or equal to 0.20 for 11 species, better than 0.36 for an additional 5 species and 0.49 for gemfish (Table 5.4). These precisions are the appropriate indicators of "reliability" of mean estimates for the purposes of comparisons among species for all regions and years combined or for comparison with other studies or other fisheries. If annual estimates of discarded catches are to be included in stock assessment models with an annual time-step, it is, however, also important to consider the precision of annual estimates. The precision of annual estimates will be an average of $\sqrt{3}$ (i.e.1.73) times that of the precision for the mean annual estimates based on 3 years (Table 5.4). The effect of the precision of estimates of annual discards on the precision of quantities estimated from fisheries models and subsequent conclusions is considered in Chapter 8.

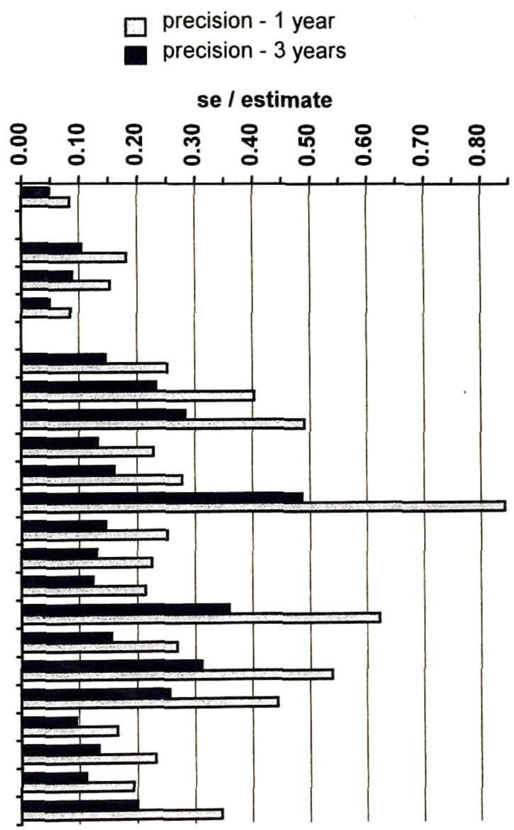
Mortality of discarded catch

Whilst the ultimate consequence of the capture and discard of a given species to stocks of that species depends on the mortality associated with capture and subsequent discarding, relatively few studies have examined this issue (Alverson *et al.*, 1994; Kennelly, 1995). Biological, environmental and operational factors have been shown to influence survival of discards from trawl fisheries (see reviews by: Andrew & Pepperell, 1992; Alverson *et al.*, 1994; Kennelly, 1995). Several studies have concluded that discarded fin-fishes are generally more prone to mortality than are cephalopods or crustaceans (e.g. Wassenberg & Hill, 1989, 1990). Species-specific differences in mortality following capture by trawling have been demonstrated for both prawn trawl fisheries (e.g. Wassenberg & Hill, 1989, 1990; Hill & Wassenberg, 1990) and fish trawl fisheries (Jean, 1963; NRC, 1990; Van Beek *et al.*, 1990). Within a species,

Table 5.4

Precision of estimates of mean annual discarded catches, *3 regions combined*, 1993-95

	Mean annual discards (tonnes, +/- 1 se)		***Precision*** (se/estimate)	
			3 years	**1 year**
All spp. combined	6,223 +/-	302	0.05	0.08
SEF quota spp.	1,815	190	0.10	0.18
Non-quota commercial spp.	1,009	89	0.09	0.15
Non-commercial spp.	3,399	167	0.05	0.09
Redfish	1,187	173	0.15	0.25
Barracouta	202	47	0.23	0.40
Southern frostfish	198	56	0.28	0.49
Piked dogfish	174	23	0.13	0.23
Jack mackerel	156	25	0.16	0.28
Gemfish	146	71	0.49	0.84
Velvet leatherjacket	124	18	0.15	0.25
Inshore ocean perch	123	16	0.13	0.23
Tiger flathead	89	11	0.12	0.21
Mirror dory	78	28	0.36	0.62
Offshore ocean perch	71	11	0.15	0.27
Blue warehou	45	14	0.31	0.54
Spotted trevalla	43	11	0.26	0.44
Silver dory	42	4	0.10	0.16
Rubberlip morwong	30	4	0.13	0.23
Cuttlefish	18	2	0.11	0.19
Jackass morwong	10	2	0.20	0.35



mortality decreases with size (Jean, 1963; Neilson *et al.*, 1989; Richards *et al.*, 1995) but increases with air temperature, depth of fishing, duration of tow, size of catch and sorting time on deck (Jean, 1963; De Veen *et al.*, 1975; Nielson *et al.*, 1989; Wassenberg & Hill, 1989; Van Beek *et al.*, 1990; Richards *et al.*, 1995).

Of particular relevance to the present study are studies concerning depth of fishing, duration of tow and exposure time on deck because the fish trawl fishery off the NSW coast involves: (i) tows lasting several hours (mean duration for North: 2 hr 38 min; Ulladulla: 2 hr 41 min; Eden: 3 hr 17 min.); (ii) fishing in depths such that when catch is brought to the surface, fish experience changes of pressure of many atmospheres (mean depth for North: 57 m; Ulladulla: 215 m; Eden: 210 m); (iii) depending on size of the catch, sorting time and exposure of discards on deck was typically 15 - 90 minutes, depending on the size of the catch.

The relatively long duration of tows in the NSW fishery (approx. 3 hrs) is likely to cause much mortality of discards. Van Beek *et al.* (1990) compared the survival of two species of flatfish for tows between 15 and 120 minutes by keeping the fish in holding tanks for 84 hours. The survival of sole decreased from a mean of 41 % for tows of 15-30 minutes to 21 % for 60-90 minute tows to 7 % for 120 minute tows. Survival of plaice decreased from 15 % for tows of 60 minutes to 11 % for tows of 120 minutes duration. Neilson *et al.* (1989) found that 35 % of small Atlantic halibut caught by trawling were alive after 48 hours, but 77 % survival for fish caught on longlines.

Species with swim-bladders are susceptible to significant injury resulting from decompression when brought rapidly to the surface, because each 10m of depth is equivalent to an increase of pressure of one atmosphere (e.g. Alverson *et al.*, 1994; Wilson & Burns, 1996). A study of the post-capture survival of red groper off the Florida coast, based on shipboard and *in situ* observations and tag-recapture data, suggested decreased survival of fish caught deeper than 44 m compared to more shallow depths (Wilson & Burns, 1996). Survival of fish taken by trawlers off NSW is likely to be small because fish brought to the surface by trawlers in the northern region of NSW undergo a decompression equivalent to a mean of 5.7 atmospheres and fish caught off Ulladulla and Eden experience a mean pressure change of over 20 atmospheres.

Similarly, the relatively long sorting times on deck for the NSW fishery mitigate against survival of discards. Jean (1963) found a 95 % mortality of American Plaice after 30 mins exposure and 100 % mortality after 45 minutes. Similarly, De Veen *et al.* (1975) found a partial mortality after 20 minutes and 100 % mortality after 40 minutes.

In addition to the above, further observations during survey also suggest minimal survival: many discards showed signs of physical damage (e.g. bleeding, scale-loss, crushing); many discards were motionless or did not actively swim when returned to the water; sea-birds and sharks were commonly observed to prey on discards. Given this background, it seems likely that close to 100 % of the fish discarded by fish trawlers off the NSW coast do not survive.

Effects of discarding on stocks and stock assessment

Because discarded fish represent a source of mortality that is not documented in landing statistics, stock assessments will be biased if they are based on the assumption that the magnitude and size- or age-distributions of landings approximate the actual catch (e.g. Hilborn & Walters, 1992; Chen & Gordon, 1997). Estimates of magnitudes and size-distributions of discards from this study demonstrate clearly that catches, size- and age-distributions landed by fish trawlers in NSW are poor representations of the actual catch for many species (Fig. 5.2, Table 5.3, Fig. 5.3).

This is particularly important for SEF quota species because objectives, performance indicators and managerial strategies exist for these commercially-important species and are supported by an assessment (Chesson, 1996, 1997; Tilzey, 1998, 1999). The methods used for assessment vary in complexity and required data, but are all dependent to some degree on information about catch, CPUE and size- or age-distributions of the catch. Results from this study indicate that in excess of 40 % of the catches (in terms of weight) of 5 SEF quota species were discarded by fish trawlers in the 3 regions sampled during 1993-95 (inshore ocean perch 85 %, 123 +/- 16 t per annum; gemfish 72 %, 146 +/- 71 t pa; redfish 52 %, 1,187 +/- 173 t pa; mirror dory 44 %, 78 +/- 28 t pa; offshore ocean perch 40 %, 71 +/- 11 t pa). Discards of a further 2 SEF quota species exceeded 10 % of the catch by weight (blue warehou 15 %, 45 +/- 14 t pa; tiger flathead 13 %, 89 +/- 11 t pa).

Because discarded fish were generally smaller than retained fish (Fig. 5.3), except for gemfish, proportions of the catch discarded are even greater in terms of numbers. For example, 52 % of the catch of redfish by weight (1,187 +/- 173 t per annum), but 66 % of the catch in terms of numbers of fish (8.6 +/- 1.2 million fish) was discarded. Similarly, the size-distributions of landed catches for these quota species are poor representations of the actual size-distributions of the catch because they: (i) exclude catches of sizes of fish that were never landed and (ii) represent, but underestimate the catches of sizes of fish that are sometimes retained and sometimes discarded (Fig. 5.3). Consequently, if the size-distributions of discarded fish are unknown or ignored, fishing mortalities associated with different sizes or ages of fish will be underestimated. These issues are examined in further detail in Chapter 8.

Chapter 6
Spatial and temporal factors affecting discarding

6.1 Introduction

Assessment of the composition of discarded catches is the necessary first step in addressing associated issues (Saila, 1983; Alverson *et al.*, 1994; Kennelly, 1995, 1997). In his much-cited paper, Saila (1983) provided appendices addressing aspects of design and analysis of surveys for estimating rates of discarding, including the use of stratified survey designs for obtaining estimates for subdivisions of populations. In reviewing available information about discarded catch, Alverson *et al.* (1994) note that few surveys had sampled over many seasons or years.

This is surprising, as an understanding of the variability of discarding in space and time (e.g. regions, latitude, depth, seasons, years) may facilitate assessment of alternative strategies for reducing by-catch and discarding and, in particular, the likely utility of spatial and temporal closures (e.g. Alverson *et al.*, 1994; Hall, 1996; Liggins *et al.*, 1996; Kennelly, 1997; Kennelly *et al.*, 1997, 1998). Identification of "hot spots" for discarding key species may also be useful when selecting locations and times for experiments with modified gears that are designed to be more selective (Kennelly, 1999). Knowledge of spatial and temporal variability also facilitates the design of more efficient surveys resulting in improved precision of estimates or cost-benefit (e.g. Saila, 1983; Cochran, 1977; Underwood, 1997). The reliability of stock assessments may also be improved by an increased understanding of spatial and temporal patterns of catch, CPUE, size- and age-distributions (Hilborn & Walters, 1992; Chen *et al.*, 1997, 1998).

Differences in the composition of by-catches and discards in trawl fisheries have been identified at a variety of spatial and temporal scales in prawn (see review by Andrew & Pepperell, 1992) and fish trawling. Studies of fish trawling have found differences in the magnitudes, species- and size-composition of discarded catches: among fisheries (e.g. French *et al.*, 1982; Alverson *et al.*, 1994); among regions within fisheries (Howell & Langan 1987, 1992; Kennelly *et al.*, 1997; Stratoudakis *et al.*, 1998; Tamsett & Janacek, 1999); related to distance offshore (Tamsett *et al.*, 1999b); among depths (Jean, 1963; Stratoudakis *et al.*, 1998; Kennelly *et al.*, 1999; Tamsett & Janacek, 1999); among seasons (Howell & Langan, 1987; Kennelly *et al.*, 1997; Stratoudakis *et al.*, 1998); and among years (Jean, 1963; Jermyn & Robb, 1981; Stratoudakis *et al.*, 1998; Tamsett & Janacek, 1999). Such factors may interact and, indeed, surveys stratified over multiple spatial and temporal scales typically reveal a variety of complex interactions (e.g. Liggins & Kennelly, 1996; Liggins *et al.*, 1996; Stratoudakis *et al.*, 1998). Clearly, if area or seasonal closures are being considered as a potential strategy for reducing discarding, an understanding of area-year and season-year interactions is prerequisite to determining the ongoing effectiveness of such closures.

Another feature of studies of discards is the great variability of rates of discarding at the lowest level of the survey design (usually trips, fisher-days or tows), even after the effects of design factors (e.g. areas, years, quarters, gear-types) and covariates (e.g. gear-types) are taken into account (e.g. Howell & Langan, 1987; Tamsett & Janacek, 1999; Tamsett *et al.*, 1999b). For example, Howell & Langan (1987) used a multiple regression approach to explain variation in observed discards of flounders taken by trawlers in the Gulf of Maine. 33.2 % and 68.8 % of variation was not associated with the explanatory variables. One of the consequences of the great variability in observed rates of discarding is that, unless the size of sample (number of trips, fisher-days or tows) is large, the precision of estimates will be poor and power to detect significant effects of factors will be small. Moreover, the precision of estimates of discarded catches will partially determine the precision of quantities estimated from models.

In the SEF, variation in the magnitudes, species- and size-composition of landings have been documented among locations, seasons and years. Analyses of data from logbooks demonstrated variations in retained catches and rates of retained catches across depths (Tilzey, 1994). Variations in the composition of discarded catches at such spatial and temporal scales have, however, not been documented. Fishery-independent surveys, stratified across regions, depths, years and seasons on the continental shelf and slope in both NSW (Graham *et al.*, 1995, 1996, 1997; Chen *et al.*, 1997) and Tasmania (Jordan, 1997) have demonstrated variations in abundances of many species across these spatial and temporal scales and increasing size with depth for several species of interest here: redfish in NSW; tiger flathead, jackass morwong, spotted trevalla and blue warehou off Tasmania.

Based on the analysis of data from the observer survey (Chapter 2), this Chapter has several objectives. First I test the hypothesis that mean rates of discarding (and retained catches) differ among regions (North, Ulladulla and Eden), years (1993, 1994, 1995) and quarters (January - March, April - June, July - September, October - December) for the major partitions of catch and individual species and subsequently, describe the patterns of variation across these scales. Then I identify differences in size-distributions of discards and discarding practices (sizes at which fish are retained rather than discarded) for commercial species among regions and years. Third, I test the hypothesis, for individual species, that the mean size of fish and proportion of catch retained increase with depth.

6.2 Materials and methods

6.2.1 Variation in rates of discarding among regions, years and quarters

Analyses of variance

Analyses of variance (ANOVA), followed by Student-Newman-Keuls multiple comparisons when appropriate, were used to detect significant differences among mean catch-rates (per fisher-day). These differences were tested between regions (North, Ulladulla, Eden; fixed factor), years (1993, 1994, 1995; fixed factor) and quarters (Jan-Mar, Apr-Jun, Jul-Sep, Oct-Dec; fixed factor). The relative "importance" of the main effects and interactions were estimated from each ANOVA by calculating ratios of the effect due to each factor over the sum of effects due to all factors plus the residual mean square (see discussion in Underwood, 1997). To provide balanced ANOVAs, 21 fisher-days were selected randomly from the fisher-days surveyed in each quarter of each year in each region. Because only 19 fisher-days were sampled in the 3rd quarter of 1993 in the northern region, the mean of these values was used to provide 2 pseudo-values in this stratum and 2 degrees of freedom were subtracted from the error mean-square in the ANOVA (e.g. see Underwood, 1997). Catch data were transformed to $log_e(x+1)$ to normalise the data and stabilise variances.

This methodology was used to test for significant differences and estimate variation in the mean value of 14 variables of interest, across the spatial and temporal scales described above:

- fishing time (duration of fishing)

<u>major partitions of catch</u>

  - retained catch of all species
  - discarded catch of all species
  - retained catch of non-quota species
  - discarded catch of quota species
  - discarded catch of non-quota commercial species
  - discarded catch of non-commercial species

<u>discards of individual species</u>

  - redfish
  - tiger flathead
  - mirror dory (North region excluded)
  - offshore ocean perch (North region excluded)
  - inshore ocean perch (North region excluded)

- rubberlip morwong
- snapper (2-factor analysis, Year x Quarter for North region only)

These species were selected because they were discarded in the greatest quantities and are primary targets of the fishery or are targets in other commercial or recreational fisheries. Analyses of several additional species (e.g. blue warehou; gemfish; tarwhine; and yellowfin bream, *Acanthopagrus australis*) were attempted but were considered unreliable because: (i) variances were heterogeneous and (ii) there were many zero values (i.e. no catch and discard of these species on many fisher-days) so that use of the *log(x+1)* transformation was problematic (e.g. see Underwood, 1997).

Estimates of regional, annual and quarterly rates of catch

Estimates of means and variances of amounts of retained and discarded catch per fisher-day were calculated for: (i) regions (3 years and 4 quarters combined); (ii) years (3 regions and 4 quarters combined); and (iii) quarters (3 regions and 3 years combined). Estimates were made for major partitions of catch and for the 20 species most abundant in catches (based on estimates across all spatial and temporal scales in the survey, Chapter 5). These estimates account for differences in effort (fisher-days) among regions, years and quarters and were calculated using the same methodology described in Chapter 5 (for the calculation of mean rates of catch across combinations of regions, years and quarters).

Interpretation of trends in mean catch from graphs (+/- SEs) is analogous to interpreting results of the ANOVAs (with respect to main effects), but does not correspond exactly because these estimates are weighted means (and variances) that take into account differences in effort (fisher-days) across the levels of each factor.

Estimates of mean annual catch for each region

Estimates of mean catch per fisher-day calculated for each region were multiplied by the mean annual effort (for each regions, North: 1600; Ulladulla: 1203; Eden: 6231 fisher-days per annum) to provide estimates of mean annual catches by the fleet in each region.

6.2.2 Variation in sizes of fish retained and discarded among regions and years

Size-distributions of retained and discarded catches of commercial species were calculated for each year, for each region using the methods outlined in 5.2.4. Size-distributions and

%-discards as a function of length were calculated for several species of interest. Conclusions about differences in size-distributions among years and regions were made if these seemed substantial and number of fish measured and numbers of tows and landings sampled were large. A formal test for detecting differences between distributions (e.g. Kolmogorov-Smirnov) was considered unnecessary because sample-sizes were substantial.

6.2.3 Relationships between depth, sizes of fish caught and rates of discarding

Relationships between depth, sizes of fish caught and rates of discarding were examined for 5 species of interest: redfish, tiger flathead, mirror dory, offshore ocean perch and inshore ocean perch. The following analysis was done for each species.

Mean rates of retained and discarded catch per tow, mean weight per fish and the proportion of catch discarded were calculated for 10 depth strata (0-50m, 50-100m, ..., 450-500m), for each region, using data pooled across the 3 years of the observer survey. Data for an individual depth were only included if: (i) a minimum of 10 tows were observed and (ii) the mean catch-rate for the species multiplied by the number of tows observed exceeded 100 kg. Mean rates of retained and discarded catch per tow, mean weight (kg) per fish caught and %-discards were plotted against depth. Correlations between mean weight per fish, %-discards and depth were calculated if data existed for a minimum of 5 depths.

6.3 Results

6.3.1 Variation in rates of discarding among regions, years and quarters - major partitions of catch

The mean catch of all species per fisher-day did not vary significantly among years, but differed significantly among regions (with North < Ulladulla < Eden) and among quarters (greatest in the 3rd quarter). Mean retained and discarded catches per fisher-day showed similar patterns of variation (North < Ulladulla < Eden and Jan-Mar < Jul-Sep. for retained catch; North < Ulladulla < Eden , Jul-Sep > other quarters and 1995 > other years for discarded catch per fisher-day; Table 6.1, Appendix A.6.1).

The mean retained catch of SEF quota species per fisher-day showed the same general pattern across regions (North < Ulladulla < Eden) and quarters (greatest during Jul-Sep) but also decreased over the period 1993-95 (Fig. 6.1). The Region x Year x Quarter interaction was

Table 6.1, page 1

Comparisons of catches (per fisher-day) among Regions (R), Years (Y) and Quarters (Q): ANOVAs and SNK multiple comparisons for fishing time and major partitions of catch

ns: non significant; +: $p < 0.05$; ++: $p < 0.01$; proportion total variation explained shown in parentheses;
N - North, U - Ulladulla, E - Eden, 93 - 1993, 94 - 1994, 95 - 1995
Q1 - Jan-Mar, Q2 - Apr-Jun, Q3 - Jul-Sep, Q4 - Oct-Dec

			ANOVA								SNK multiple comparisons		
	Model	Transform	R	Y	Q	RxY	RxQ	YxQ	RxYxQ	Error	Regions	Years	Quarters
Fishing time	3-f	-	++ (.19)	ns	ns	ns	ns	ns	ns	(.82)	N = U < E		
Total catch	3-f	ln(x+1)	++ (.44)	ns	++ (.01)	ns	ns	ns	ns	(.55)	N < U < E		Q1 = Q2 = Q4 < Q3
Retained catch	3-f	ln(x+1)	++ (.37)	ns	+ (.01)	ns	ns	ns	ns	(.61)	N < U < E		Q1 Q2 Q4 Q3
Discarded catch	3-f	ln(x+1)	++ (.41)	++ (.01)	++ (.02)	ns	ns	ns	ns	(.56)	N < U < E	93 = 94 < 95	Q1 = Q2 = Q4 < Q3
Retained catch of non-quota species	3-f	ln(x+1)	++ (.11)	+ (.01)	ns	ns	+ (.01)	ns	ns	(.87)	Q1: N < U = E Q2: N < U < E Q3: N = U < E Q4: N < U < E	93 = 94 < 95	N: Q1 = Q2 = Q3 = Q4 U: Q3 < Q2 = Q4 < Q1 E: Q1 = Q2 = Q3 = Q4
Discarded catch of quota species	3-f	ln(x+1)	++ (.41)	++ (.02)	++ (.04)	ns	ns	ns	+ (.01)	(.53)	93,Q1: N < U = E 93,Q2: N < U = E 93,Q3: N < U < E 93,Q4: N < U = E 94,Q1: N < U = E 94,Q2: N < U = E 94,Q3: N < U < E 94,Q4: N < U < E 95,Q1: N < U = E 95,Q2: N < U < E 95,Q3: N < U = E 95,Q4: N < U = E	N,Q1: 93 = 94 = 95 N,Q2: 93 = 94 = 95 N,Q3: 93 = 94 = 95 N,Q4: 93 = 94 = 95 U,Q1: 93 = 94 < 95 U,Q2: 93 = 94 = 95 U,Q3: 93 94 95 U,Q4: 94 < 93 = 95 E,Q1: 93 = 94 = 95 E,Q2: 93 94 95 E,Q3: 93 = 94 = 95 E,Q4: 93 < 94 = 95	N,93: Q1 = Q2 = Q4 < Q3 N,94: Q1 = Q2 = Q3 = Q4 N,95: Q4 Q1 Q2 Q3 U,93: Q1 Q2 Q3 Q4 U,94: Q1 = Q2 = Q3 = Q4 U,95: Q1 = Q2 = Q3 = Q4 E,93: Q1 = Q2 = Q4 < Q3 E,94: Q1 Q2 Q3 Q4 E,95: Q1 = Q2 = Q3 = Q4
Discarded catch of non-quota comm. species	3-f	ln(x+1)	++ (.45)	++ (.01)	ns	ns	++ (.02)	ns	ns	(.52)	Q1: U < N < E Q2: U < N < E Q3: U < N < E Q4: N = U < E	93 < 94 = 95	N: Q1 = Q2 = Q3 = Q4 U: Q1 = Q2 = Q3 < Q4 E: Q1 = Q2 = Q4 < Q3
Discarded catch of non-comm. species	3-f	ln(x+1)	++ (.31)	ns	++ (.01)	++ (.01)	++ (.01)	ns	ns	(.67)	93: N < U < E 94: N < U < E 95: N < U < E Q1: N < U < E Q2: N < U < E Q3: N < U < E Q4: N < U < E	N: 93 = 94 < 95 U: 93 = 94 = 95 E: 93 95 94	N: Q1 = Q2 = Q4 < Q3 U: Q1 Q2 Q4 Q3 E: Q1 = Q2 = Q3 = Q4

Table 6.1, page 2

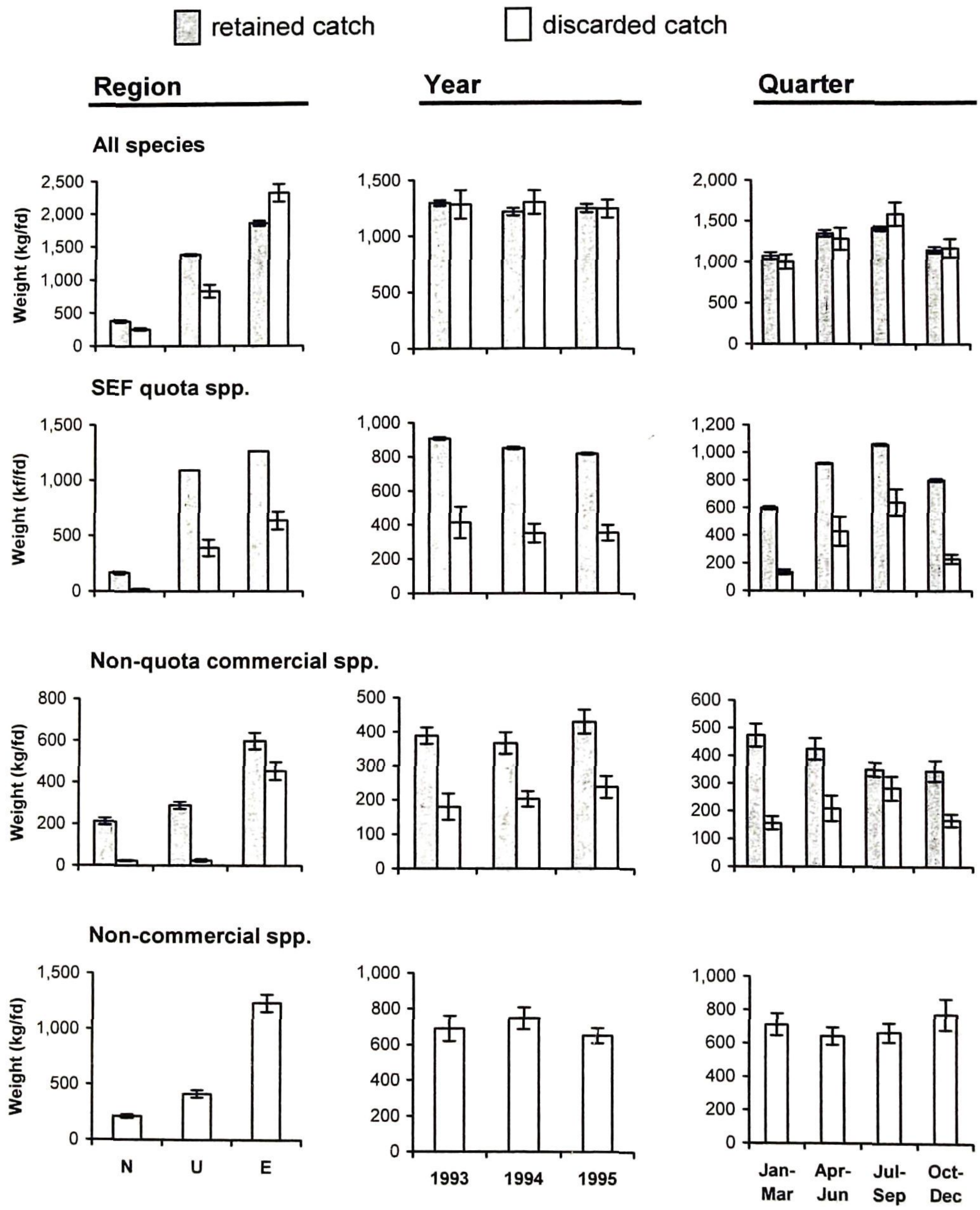
Comparisons of catches (per fisher-day) among Regions (R), Years (Y) and Quarters (Q): ANOVAs and SNK multiple comparisons for fishing time and major partitions of catch

ns: non significant; +: $p < 0.05$; ++: $p < 0.01$; proportion total variation explained shown in parentheses;
N - North, U - Ulladulla, E - Eden, 93 - 1993, 94 - 1994, 95 - 1995
Q1 - Jan-Mar, Q2 - Apr-Jun, Q3 - Jul-Sep, Q4 - Oct-Dec

			ANOVA								SNK multiple comparisons		
	Model	Transform	R	Y	Q	RxY	RxQ	YxQ	RxYxQ	Error	Regions	Years	Quarters
Redfish	3-f	ln(x+1)	++ (.15)	++ (.04)	++ (.08)	++ (.02)	++ (.02)	++ (.01)	++ (.02)	(.67)	93,Q1: N = U = E 93,Q2: N = U = E 93,Q3: N = U < E 93,Q4: N < U = E 94,Q1: N = U = E 94,Q2: N = U < E 94,Q3: N < U = E 94,Q4: N < U < E 95,Q1: N < E < U 95,Q2: N < U = E 95,Q3: N = E < U 95,Q4: N < U = E	N,Q1: 93 = 94 = 95 N,Q2: 93 = 94 = 95 N,Q3: 93 = 94 = 95 N,Q4: 93 = 94 = 95 U,Q1: 93 = 94 < 95 U,Q2: 93 = 94 < 95 U,Q3: 93 < 94 = 95 U,Q4: 93 = 94 = 95 E,Q1: 93 94 95 E,Q2: 93 < 94 = 95 E,Q3: 95 < 93 = 94 E,Q4: 93 95 94	N,93: Q1 = Q2 = Q3 = Q4 N,94: Q1 = Q2 = Q3 = Q4 N,95: Q1 = Q2 = Q3 = Q4 U,93: Q1 = Q2 < Q3 = Q4 U,94: Q1 = Q2 = Q4 < Q3 U,95: Q4 Q2 Q1 Q3 E,93: Q1 < Q2 = Q4 < Q3 E,94: Q1 < Q2 Q4 Q3 E,95: Q1 Q3 Q4 Q2
Tiger flathead	3-f	ln(x+1)	++ (.09)	ns	ns	ns	++ (.02)	ns	ns	(.88)	Q1: N < U = E Q2: N = U < E Q3: N = U = E Q4: N < U < E		N: Q1 = Q2 = Q4 < Q3 U: Q2 Q3 Q4 Q1 E: Q1 = Q2 = Q3 = Q4
Mirror dory (U and E)	3-f	ln(x+1)	++ (.02)	++ (.02)	++ (.03)	ns	+ (.01)	ns	ns	(.91)	Q1: U = E Q2: U < E Q3: U < E Q4: U = E	93 = 94 < 95	U: Q2 Q3 Q4 Q1 E: Q4 Q2 Q3 Q1
"Offshore" Ocean perch (U and E)	3-f	ln(x+1)	++ (.04)	ns	ns	++ (.02)	ns	ns	ns	(.94)	93: U = E 94: U < E 95: U < E	U: 94 = 95 < 93 E: 93 < 94 = 95	
"Inshore" Ocean perch (U and E)	3-f	ln(x+1)	++ (.15)	++ (.03)	++ (.03)	+ (.01)	++ (.03)	ns	ns	(.76)	Q1: U < E Q2: U < E Q3: U < E Q4: U < E 93: U < E 94: U < E 95: U < E	U: 94 < 93 = 95 E: 93 = 94 < 95	U: Q2 Q3 Q4 Q1 E: Q1 = Q2 < Q3 = Q4
Rubberlip morwong	3-f	ln(x+1)	++ (.08)	ns	++ (.03)	ns	+ (.01)	ns	ns	(.89)	Q1: N = U < E Q2: N = U < E Q3: N = U < E Q4: N = U = E		N: Q1 = Q2 = Q4 < Q3 U: Q2 Q1 Q3 Q4 E: Q1 = Q4 < Q2 = Q3
Snapper (N)	2-f	ln(x+1)		ns	++ (.04)			ns		(.95)			Q3 Q4 Q2 Q1

Figure 6.1

Estimates of mean retained and discarded catches (per fisher-day, +/- 1 SE) among Regions, Years and Quarters, for major PARTITIONS of catch



significant for the mean discards of quota species per fisher-day and mean catches were: (i) significantly greater at Ulladulla and Eden than in the northern region for all quarters and years; (ii) significantly less at Ulladulla than Eden for 4 of the 12 combinations of year and quarter and not significantly different for the other 8 combinations; (iii) not significantly different among years in the northern region; (iv) variable among years at Ulladulla and Eden; and (v) variable among quarters depending on year and region for each quarter of each year (Table 6.1, Appendix A.6.1).

The mean retained catch of non-quota commercial species per fisher-day was: (i) significantly greater at Eden than in the northern region for all quarters; (ii) significantly greater in 1995 than in the other years and (iii) greatest during the first quarter and smaller in the 3rd quarter at Ulladulla (Table 6.1, Fig. 6.1). Discards of non-quota commercial species were: (i) greatest at Eden during all quarters and smallest at Ulladulla during 3 of the 4 quarters; (ii) smaller in 1993 than in 1994 or 1995; and (iii) greatest in the 3rd quarter at Eden and during the 4th quarter at Ulladulla (Table 6.1, Fig. 6.1).

Discards of non-commercial species were: (i) smallest in the northern region and greatest at Eden for all years and quarters; and (ii) differences among years and quarters varied among regions (Table 6.1, Fig. 6.1).

A common feature of these analyses was that differences among Regions consistently explained a far greater proportion of the total variation in the data than the factors Year, Quarter or any of the interactions (Table 6.1, Appendix A.6.1). This is also apparent in Figure 6.1, in which the variation in catches due to regions, years and quarters are shown for each analysis. Catch per fisher-day generally increased with latitude (North < Ulladulla < Eden), were similar from year to year and were greatest in the 3rd quarter of the year (except for retained catches of non-quota commercial species and discards of non-commercial species).

Relative magnitudes of annual catches among regions differ from the relative magnitudes of mean catches per fisher-day (Fig. 6.1; Table 6.2) because the former account for differences in the number of fisher-days completed by the fleets in each region. The Eden fleet took the greatest annual catch of all species combined, SEF quota species, non-quota commercial species and non-commercial species (Table 6.2). Retained catch and discards of these categories of fish were greater for Eden than for Ulladulla or North. Moreover, the Eden fleet discarded a greater proportion of each of these categories of catch than the fleets at Ulladulla or North. Whilst the fleets of Ulladulla and North discarded approximately 40 % of their total catch (41 % for North, 38 % for Ulladulla), the Eden fleet discarded more than half of their catch (56 %).

The Eden region makes the greatest contribution to the summary statistics for the 3 regions combined (Chapter 5) because the Eden fleet catches 70 % of the total catch, 66 % of the catch of SEF quota species, 74 % of the catch of non-quota commercial species and 75 % of the catch of non-commercial species (calculated from Table 6.2).

6.3.2 Variation in rates of discarding among regions, years and quarters - individual species

Patterns of variation in rates of discarding per fisher-day across regions, years and quarters were species-dependent and diverse (Table 6.1; Fig. 6.2). Patterns of mean rates of discarding for redfish were particularly complex with a significant Region x Year x Quarter interaction. Mean discards per fisher-day did not differ significantly among years or quarters in the northern region and discards per fisher-day in this region did not exceed those at Ulladulla or Eden in any quarter of any year. Patterns in rates of discarding across quarters and years for Ulladulla and Eden were highly variable (Table 6.1, Fig. 6.2, Appendix A.6.1).

The mean discards of tiger flathead per fisher-day: (i) did not vary significantly among years; (ii) in the northern region, were less than or not significantly different to Ulladulla and Eden in all quarters and (iii) were greater at Eden than Ulladulla in 2 of the quarters. Mean discards of mirror dory per fisher-day: (i) were greater in 1995 than in the previous 2 years; and (ii) were greater at Eden than Ulladulla during the period April - September (the 2nd and 3rd quarters). Mean discards of offshore ocean perch per fisher-day were greater at Eden than Ulladulla during 1994 and 1995. Mean discards per fisher-day for inshore ocean perch: (i) were greater at Eden than Ulladulla for each quarter and each year; (ii) lower in 1994 than in 1993 or 1995 at Ulladulla; (iii) greatest in 1995 at Eden; and (iv) greatest in the 3rd and 4th quarters of the year at Eden. Rates of discarding of rubberlip morwong: (i) were greater at Eden than the other regions during the first 3 quarters; (ii) were greatest in the northern region during the 3rd quarter and greatest at Eden during the 2nd and 3rd quarters (Table 6.1, Fig. 6.2).

Despite the diversity of patterns in the rates of discarding per fisher-day for individual species across the spatial and temporal scales examined, several generalisations may be made. Rates of discarding per fisher-day and quantities discarded annually are particularly dependent on the region examined. Region or interactions involving region were significant for all ANOVAs completed for individual species (Table 6.1, Appendix A.6.1). With a single exception (mirror dory), the proportion of variation in the data explained by regions exceeded

Table 6.2

Mean annual catches of major partitions of catch for 3 regions

	North (tonnes, +/- 1 se)			% discarded	Ulladulla (tonnes, +/- 1 se)			% discarded	Eden (tonnes, +/- 1 se)			% discarded
All species												
Retained	601	+/-	33		1,657	+/-	19		3,855	+/-	80	
Discarded	411		29	*41 %*	996		117	*38 %*	4,816		277	*56 %*
	1,012		53		2,653		118		8,671		289	
SEF quota spp.												
Retained	263	+/-	20		1,310	+/-	0		2,616	+/-	0	
Discarded	32		5	*12 %*	466		89	*26 %*	1317		167	*33 %*
	263		21		1,776		89		3,933		167	
Non-quota commercial spp.												
Retained	338	+/-	24		347	+/-	19		1,239	+/-	80	
Discarded	38		4	*10 %*	31		8	*8 %*	939		89	*43 %*
	376		24		378		21		2,178		120	
Non-commercial spp.												
Discarded	341	+/-	26	*100 %*	498	+/-	40	*100 %*	2,559	+/-	161	*100 %*

Figure 6.2, page 1

Estimates of mean retained and discarded catches (per fisher-day, +/- 1 SE) among Regions, Years and Quarters, for 20 SPECIES

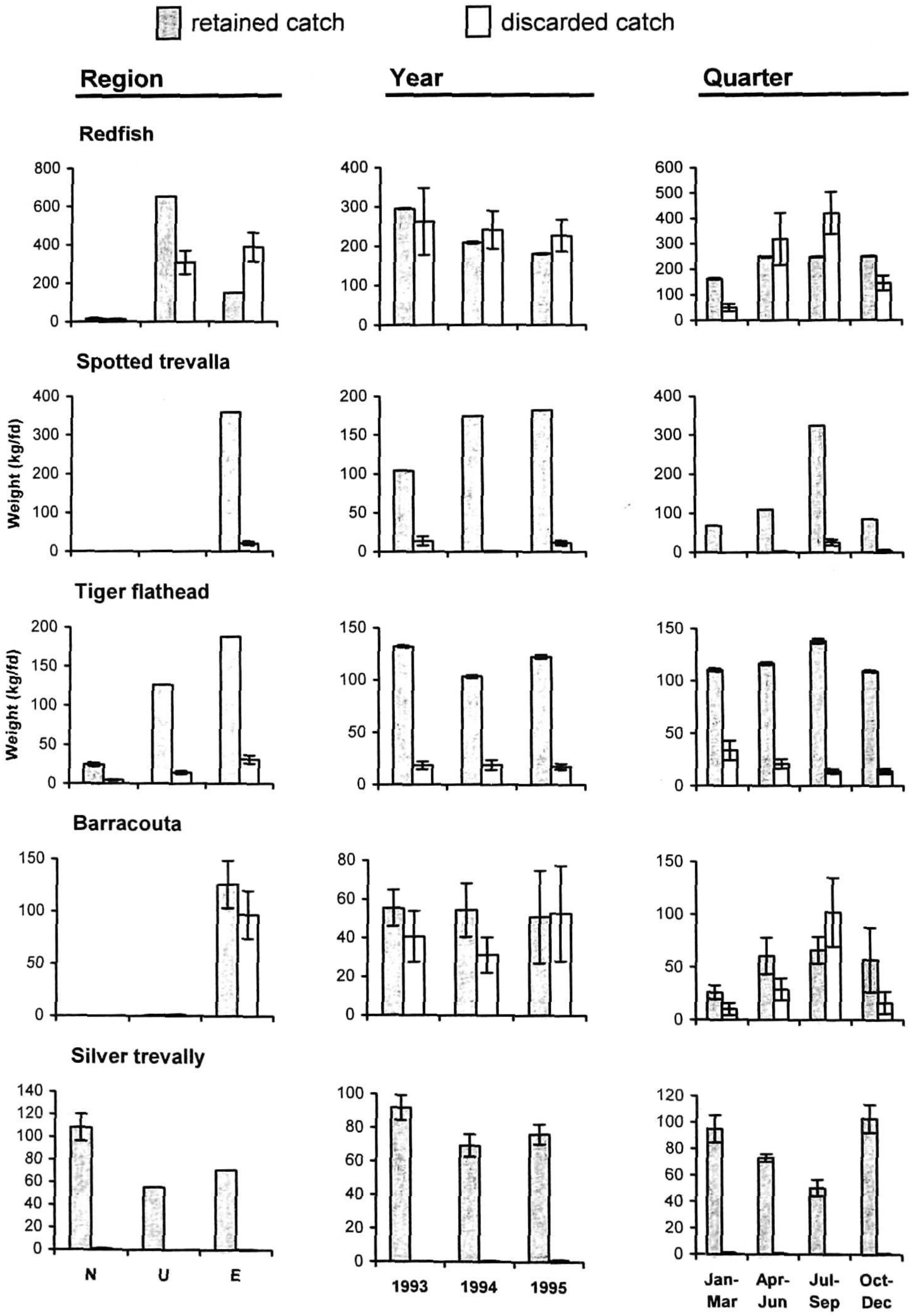


Figure 6.2, page 2

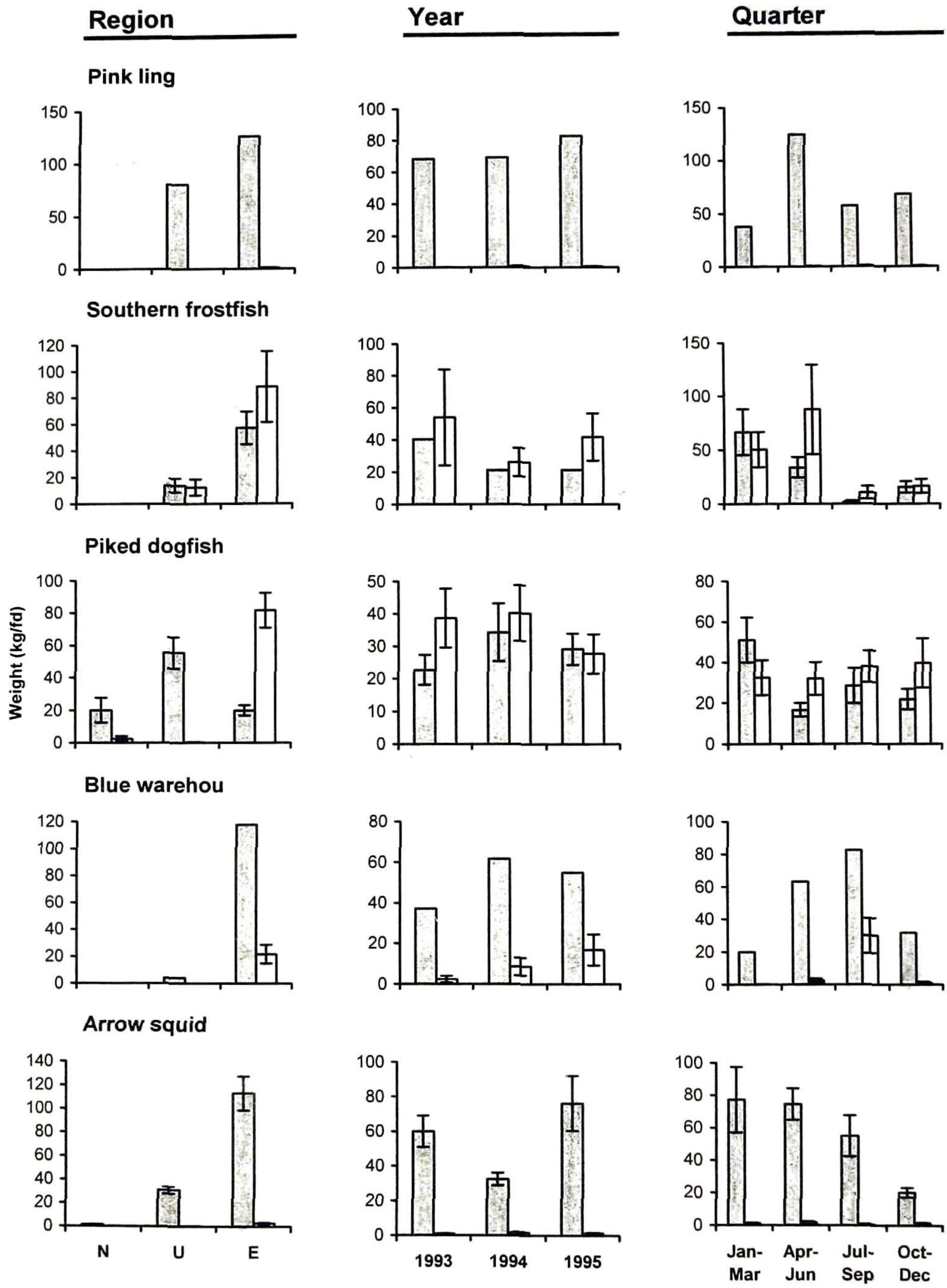


Figure 6.2, page 3

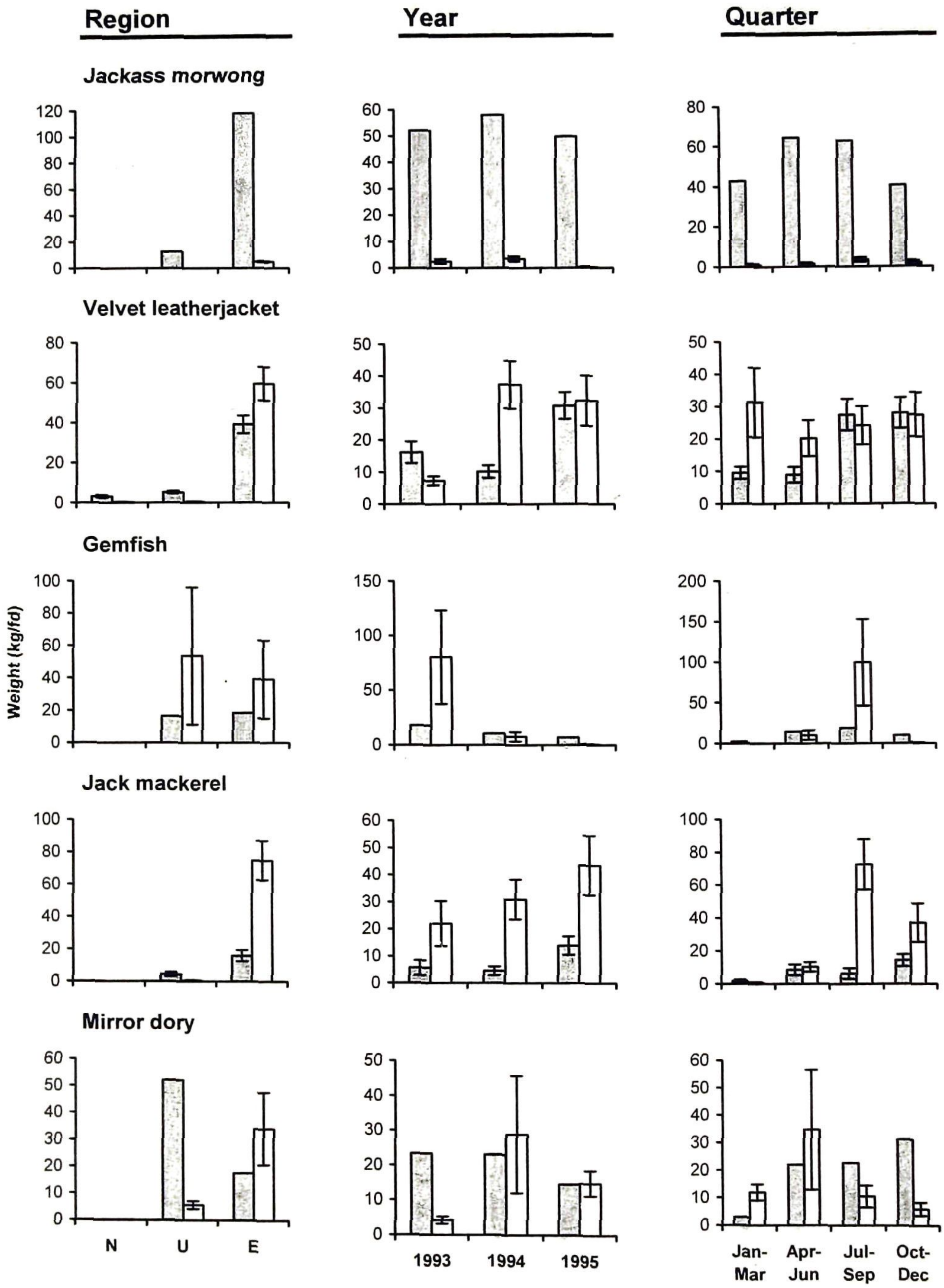
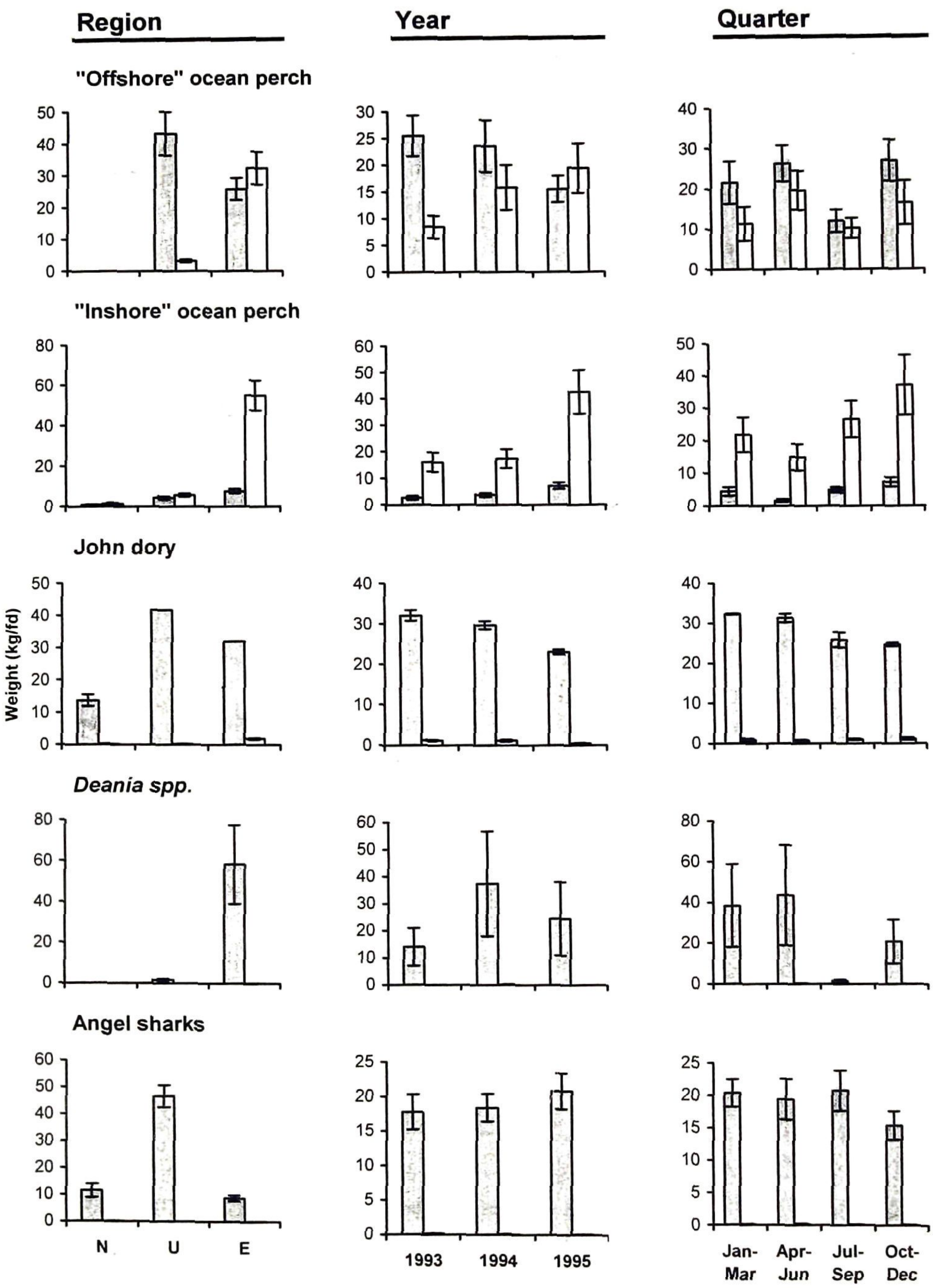


Figure 6.2, page 4



that explained by year, quarter and the various interactions. It is clear from Figure 6.2 that rates of capture and discard per fisher-day for species such as barracouta, southern frostfish, piked dogfish, blue warehou, jackass morwong, velvet leatherjacket, jack mackerel, offshore ocean perch and inshore ocean perch are greater at Eden than at Ulladulla or North, indicating a general trend for discarded catches of many species to increase with latitude. The greater annual effort by the Eden fleet magnifies these differences when catches per fisher-day are scaled by effort to estimate annual quantities discarded (see Appendices A.6.2.1 - A.6.2.3). Further, discards per fisher-day and annual quantities of redfish and gemfish discarded were greater at Ulladulla and Eden than in the northern region.

The factor Year or interactions involving Year was significant in 4 of the 7 ANOVAs for individual species. Based on the proportions of total variation explained by Year in the ANOVAs for individual species and the discard rates shown in Figure 6.2, Year is, however, not as important as Region in explaining the observed variations in rates of discarding. Differences among Quarters or interactions involving Quarters were significant in 6 of the 7 ANOVAs completed for individual species (the exception being offshore ocean perch). There was also a trend for rates of discarding per fisher-day to be greater during the 3rd quarter for several species (e.g. redfish, barracouta, blue warehou, gemfish and jack mackerel). Because effort is greatest during this quarter at Ulladulla and Eden, this trend is magnified when mean catch per fisher-day is scaled by effort to estimate quarterly quantities of discards (Fig. 6.2).

6.3.3 Variation in sizes of fish retained and discarded among regions and years

There were clear differences among regions and years in the size-distributions of discarded catches of redfish (Fig. 6.3) and of tiger flathead, mirror dory, offshore ocean perch and inshore ocean perch (see Appendices A.6.3.1 - A.6.3.4).

Proportionally, greater numbers of redfish smaller than 15 cm were caught and discarded by the Eden fleet. Note also that the distributions of sizes of redfish in catches by the Eden fleet during 1993 and 1994 were distinctly bi-modal, contrasting with the size-distributions for other regions and for Eden in 1995. Consequently, the contribution that the size-distribution of discards makes to the size-distribution of the total catch of redfish also varied among years and regions. This variation was also apparent for mirror dory (Appendix A.6.3.2), less so for tiger flathead (Appendix A.6.3.1), offshore ocean perch (Appendix A.6.3.3) and inshore ocean perch (Appendix A.6.3.4).

There was also variation among years and regions in the amount of overlap between size-distributions for retained and discarded catches (i.e. the range of sizes sometimes retained and

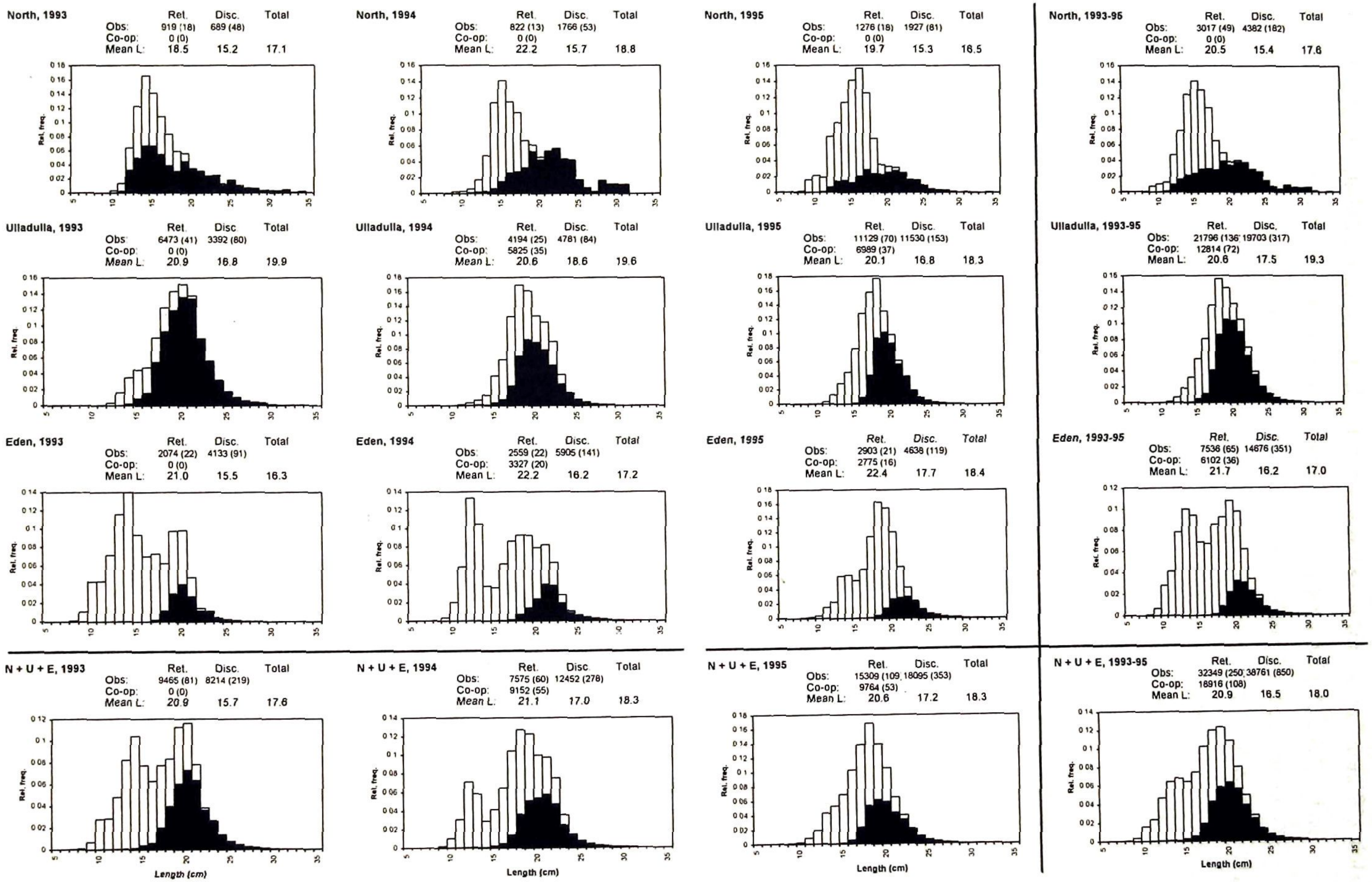
Figure 6.3

Size distributions of retained and discarded catches of Redfish, by region and year

Retained catch: black bars Discarded catch: white bars

Sample sizes: x (y) denotes a total sample of x fish from y tows (observer survey, "Obs"), or from y landings (co-op survey, "Co-op")

"Mean L" is mean length length of fish (cm)



sometimes discarded). The size at which 50 % of redfish were retained by the Eden fleet (22 cm) is greater than at Ulladulla and North (50 % retention at 18 cm for each region; Fig. 6.4). Moreover, these differences were consistent across the 3 years (Appendix A.6.4.1). The Ulladulla fleet retained smaller fish than the Eden fleet for each of the 5 species shown in Figure 6.4 and this pattern existed in each of the 3 years (Appendices A.6.4.1 - A.6.4.5). The length at which 50 % of the catch of tiger flathead was retained by the Ulladulla fleet was 32 cm, approximately 1cm less than the size for 50 % retention for the North and Eden fleets. Note also that the Ulladulla fleet retained some of their catch at lengths between 25 and 30 cm (well below the minimal legal length of 33 cm total length for this species). The length at which 50 % of mirror dory were retained by the Ulladulla fleet was 28 cm compared to 35 cm for Eden. Fifty percent retention of inshore and offshore varieties of ocean perch occurred at 23 cm for Ulladulla compared to 26 cm for the Eden fleet.

With the exception of mirror dory, there was generally less variation among years in the sizes at which these species were retained rather than discarded (Fig. 6.4). Mirror dory were retained at smaller sizes in 1995 (50 % retained at 30 cm) than in 1993 (32 cm) and 1994 (36 cm). This pattern was not consistent between Ulladulla and Eden (Appendix A.6.4.3).

6.3.4 Relationship between depth, sizes of fish caught and discarding

There were significant positive correlations between mean weight per fish caught and depth for each species and region examined: redfish, tiger flathead, mirror dory and offshore ocean perch at Ulladulla and Eden, and inshore ocean perch at Eden (range of r^2: 0.67 - 0.95, Fig. 6.5). Significant negative correlations between mean weight per fish and %-discarded were also found for these species and regions (range of r^2: 0.60 - 0.93) with the single exception of tiger flathead at Ulladulla ($r = -0.63$, $r^2 = 0.40$, $p > 0.05$) (Fig. 6.5). Significant negative correlations between depth and %-discarded were found for all species and regions (range of r^2: 0.49 - 0.89, Fig. 6.5). The relatively narrow range of depths in which fishing occurred in the northern region prevented a similar analysis.

For the species examined, fish were smaller in shallower waters and a greater proportion of the catch was discarded. The proportion of variance explained by the correlations described above (based on values of r^2) exceeded 60 % in 25 of 27 instances suggesting the importance of the relationship between depth and size of fish in determining quantities of discards.

Figure 6.4

% catch retained by length, for 5 species

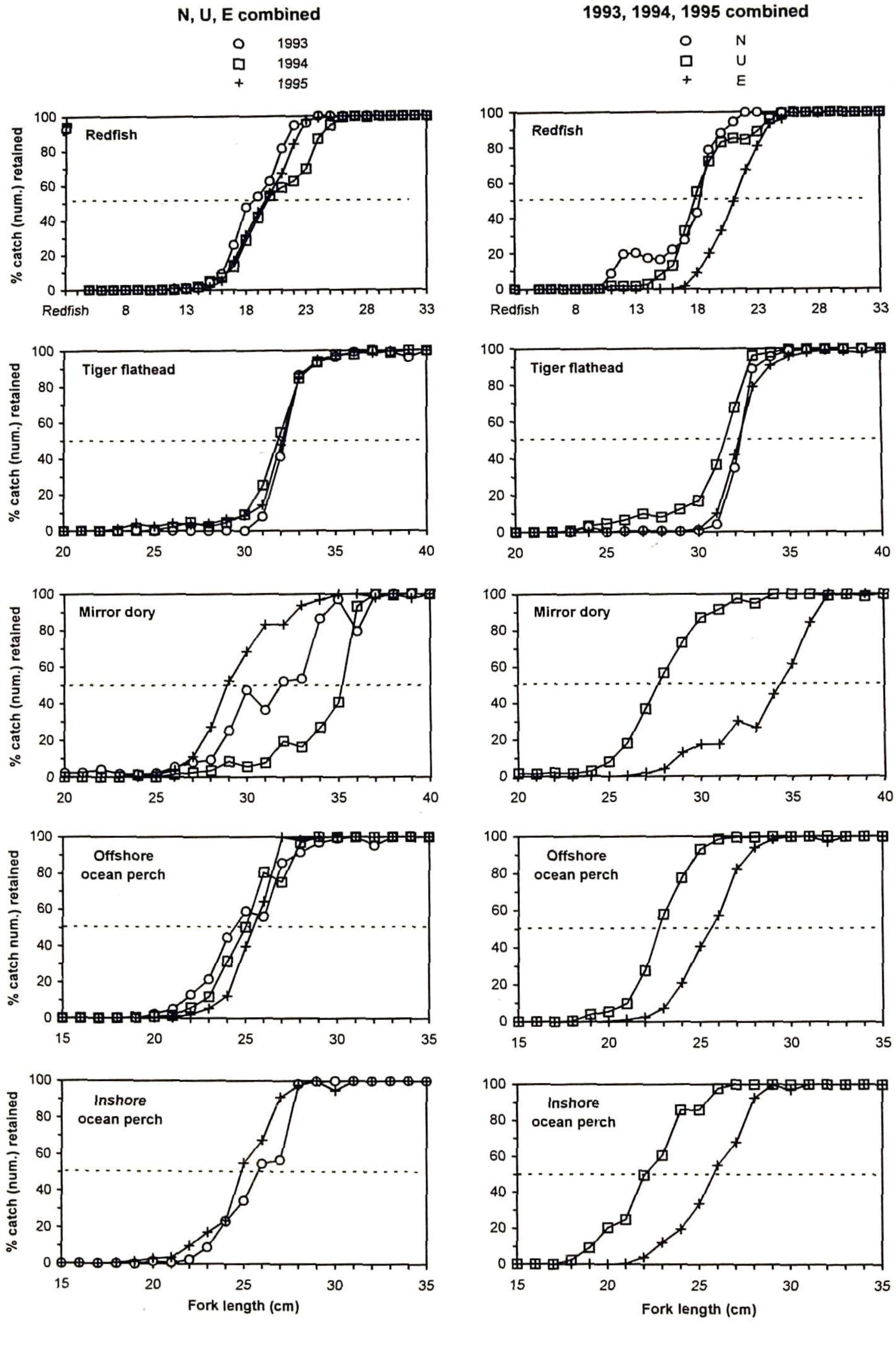
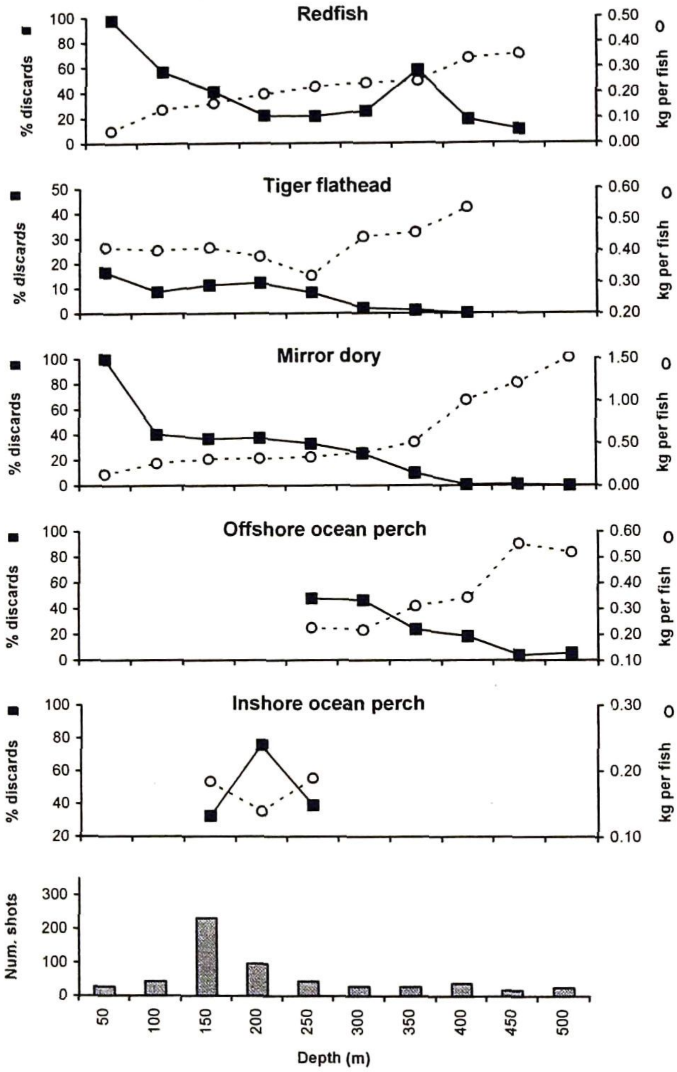


Figure 6.5, page 1

Relationships among % discards, mean weight per fish and depth for 5 species Ulladulla, 1993-95



Correlations

r & (r^2), * significant at p=0.05

	% discard	depth
kg/fish	-0.81 (0.66) *	0.97 (0.95) *
depth	-0.70 (0.49) *	

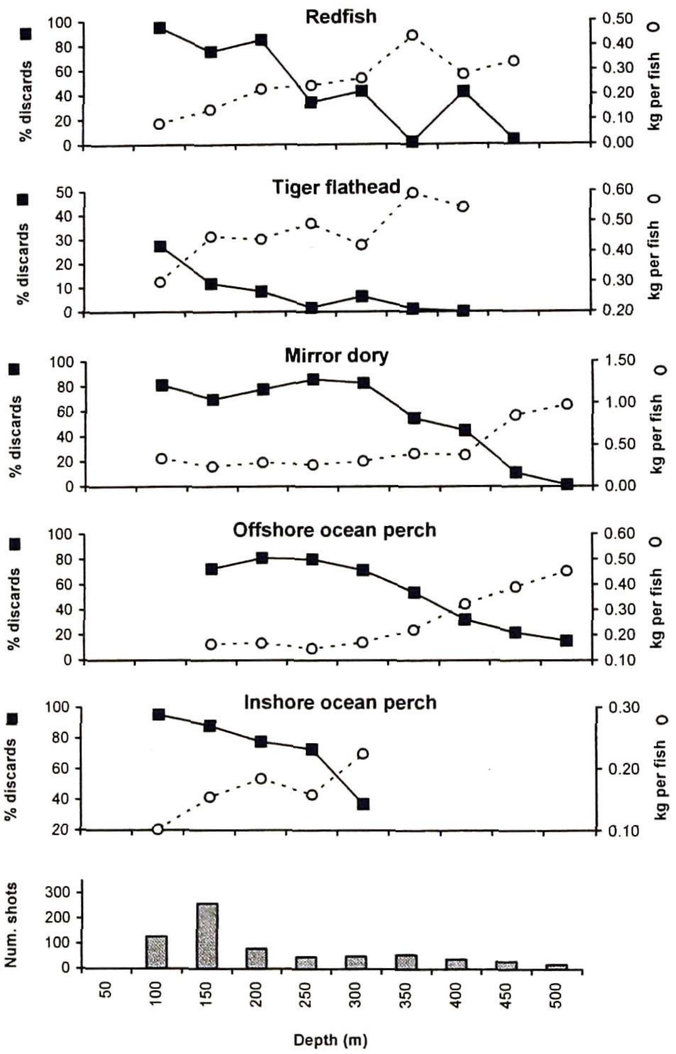
	% discard	depth
kg/fish	-0.63 (0.40)	0.82 (0.67) *
depth	-0.91 (0.83) *	

	% discard	depth
kg/fish	-0.77 (0.60) *	0.94 (0.89) *
depth	-0.86 (0.75) *	

	% discard	depth
kg/fish	-0.95 (0.90) *	0.95 (0.91) *
depth	-0.92 (0.85) *	

Figure 6.5, page 2

Relationships among % discards, mean weight per fish and depth for 5 species
Eden, 1993-95



Correlations
r & (r²), * significant at p=0.05

Redfish

	% discard	depth
kg/fish	-0.90 (0.81) *	0.83 (0.68) *
depth	-0.87 (0.75) *	

Tiger flathead

	% discard	depth
kg/fish	-0.91 (0.83) *	0.82 (0.67) *
depth	-0.87 (0.76) *	

Mirror dory

	% discard	depth
kg/fish	-0.96 (0.92) *	0.86 (0.73) *
depth	-0.89 (0.79) *	

Offshore ocean perch

	% discard	depth
kg/fish	-0.97 (0.93) *	0.95 (0.90) *
depth	-0.94 (0.89) *	

Inshore ocean perch

	% discard	depth
kg/fish	-0.89 (0.80) *	0.88 (0.77) *
depth	-0.92 (0.86) *	

6.4 Discussion

Whilst differences in rates of discarding of individual species among regions, years and quarters were species-dependent, some general patterns were evident. Rates of discarding differed greatly among the regions, more so than among years or quarters (Table 6.1, Appendix A.6.1, Figs. 6.1 & 6.2). Catches were greatest at Eden (the most southern region), intermediate at Ulladulla (the middle region) and smaller in the northern region. This is not surprising, because the NSW coast represents the most northern extent of Australia's main fish trawl fisheries centred in south eastern Australian waters and, historically, fish trawling has been less productive in the northern region compared to Eden on the far south coast of NSW (Tilzey, 1994, 1998, 1999). A latitudinal gradient in by-catch and discarding has also been described for the prawn trawl fishery operating off the coast of northern NSW but, in this fishery, by-catch and discarding was inversely related to latitude (Kennelly, *et al.*, 1998).

Not only were rates of catch greatest at Eden, effort and the proportion of catch discarded was also greatest at Eden. Whilst the species discarded by Ulladulla and Eden trawlers were similar, the total quantities of discards of commercial species for the Eden region was 5 times that of Ulladulla and 10 times that of North (Table 6.2). Seven commercial species were discarded in excess of 100 tonnes per annum at Eden (Appendix A.6.2.3), but only 1 species at Ulladulla (Appendix A.6.2.2). In the northern region, the greatest mean annual discard for any species was only 19 tonnes (Appendix A.6.2.1). The importance of the Eden fleet in contributing to the total quantity of discards is obvious. Note, however, that the Eden fleet was also responsible for the majority of the retained catch.

There were significant seasonal patterns in rates of catch and discarding. Rates of total catch and discarded catch were greatest during the 3rd quarter in each region and year. Although inconsistent across regions and years, rates of discarding of other partitions of catch and several individual species tended to be greatest in the third quarter (Table 6.1, Figs. 6.1 & 6.2). These seasonal patterns in discarding result from the combined effects of the behaviour of individual species and of fishers. For example, gemfish aggregate and migrate northward along the continental slope during winter (e.g. Rowling, 1994) and it was during the 3rd quarter that discarding of this species was greatest (Fig. 6.2). Although the quota for gemfish was restrictive (TAC = 0, but a small "by-catch" trip limit, see Chapter 7), fishers caught and discarded large quantities during the months of July and August. Seasonal peaks in discarding have also been associated with migratory behaviour of species in other fisheries. Discarding of scup (*Stenotomus chrysops*) was consistently greater during November and December in a particular area off the northeastern USA and this was associated with an annual post-spawning migration (Kennelly, 1999).

Seasonal patterns in the targeting of particular species on particular grounds resulting in peaks of discarding of these species have also been demonstrated in several fish trawl fisheries (e.g. Howell & Langan, 1987; Stratoudakis *et al.,* 1998; Tamsett & Janacek, 1999; Kennelly *et. al.,* 1997; Kennelly, 1999). The greater quantities of discards of redfish and blue warehou during winter compared to summer off the NSW coast (Table 6.1; Fig. 6.2) provide a local example of this pattern. Indeed, the positive association between rates of retained or discarded catch for the partitions of catch "all species" and "quota species" (Fig. 6.1) and a similar pattern in fishing effort (Fig. 2.2) provides the most general example of quantities of discarding varying seasonally with abundance of fish and fishing effort.

A general feature of the analyses of discards of individual species and for the partitions of catch that combined discards of multiple species (with the single exception of the partition for discards of "all species") was the significance of interactions among various combinations of the factors Region, year and Quarter (Table 6.1, Appendix A.6.1). Such interactions are typical of studies of by-catch and discarding that have used similar designs and balanced analyses (e.g. Liggins & Kennelly, 1996; Liggins *et al.,*1996; Kennelly *et al.,* 1998), alternative formal analyses (e.g. Stratoudakis *et al.*, 1998; Tamsett & Janacek, 1999) or have been implied by less formal analyses (e.g. Jermyn & Robb, 1981; Kennelly *et al.*, 1997; Kennelly, 1999). The significance of such interactions is not surprising given that the distribution and abundance of individual species, environmental conditions, fishing effort and gears and factors affecting the decisions by fishers to retain or discard catch (e.g. regulations, market economics) vary in space and time in a complex way (e.g. Howell & Langan, 1987; Andrew & Pepperell, 1992; Hilborn & Walters, 1992; Alverson *et al.*, 1994; Stratoudakis *et al.*, 1998).

Another important and general result from the ANOVAs was that a large proportion of variability remains unexplained by the factors examined. The proportion of variance not accounted for by the main factors and interactions was between 55 % and 67 % for the major partitions of catch and between 67 % and 93 % for individual species (Table 6.1, Appendix A.6.1). This is not surprising given the repeated accounts in the literature of the great variability in rates of by-catch and discarding (e.g. Andrew & Pepperell, 1992; Kennelly, 1995; Alverson *et al.,* 1994). Moreover, other analyses in which the proportion of observed variation could be attributed among the factors examined and to residual unexplained sources have also found similar results (e.g. Howell & Langan, 1987; Tamsett & Janacek, 1999; Tamsett *et al.*, 1999a, 1999b).

The analysis of differences in size-distributions of discards among regions and years showed clear differences for redfish and mirror dory among regions and years. It was also shown that high-grading practices differed between the fleets of Ulladulla and Eden. The Ulladulla fleet retained smaller fish. This partially explains the smaller %-discards for species in the Ulladulla region compared to Eden. The likely explanations for these different high-grading practices concern economics and the quota management system (see Chapter 7). The considerable variation in sizes at first capture and size at which fish are retained for different species taken by trawlers also poses particular challenges for attempts to reduce capture and subsequent discard of fish through modification of gears (discussed in Chapter 9). Moreover, the documented regional and annual differences in discarding implies that modifications of gear to reduce capture and subsequent discarding of particular sizes of fish must vary among regions and years.

Similarly, the demonstrated variations in sizes of discards have important consequences for the reliability and utility of length- and age-based models of populations, the stock assessments based on such models and the need for ongoing monitoring programmes. As previously discussed (Chapter 5), the size-distributions of landed catches for several important quota species are poor representations of the actual size-distributions of the fish caught. Consequently, fishing mortalities associated with the sizes or ages of fish that are discarded will be underestimated. Annual variations in the size-distributions of discards (e.g. redfish and mirror dory) indicate that the impact of this unaccounted mortality on size- or age-classes will vary among years. Annual variation in year-class strength and the capture of newly recruited size- and year-classes is a typical feature of many fisheries, as is the consequent annual variation in discarding of these new recruits (e.g. Kulka & Waldron, 1983; Hilborn & Walters, 1992; Alverson *et al.*, 1994). Such observations have underlined the need for ongoing annual observer-based surveys, so that the annual variations in fishing mortalities of individual age- and length-classes can be incorporated in models and assessments of the fisheries.

The relationships demonstrated between mean weight per fish, depth and the proportion of fish discarded, demonstrate the importance of depth as a determinant of discarding. It would seem appropriate to include depth as a covariate in analyses of patterns of discarding. Because depth is an attribute associated with a tow rather than a fisher-day, it could only be included as a covariate if it was reasonable to calculate a mean-depth across all tows completed within each fisher-day. Some fisher-days included tows on the continental slope (depths in the range 200 - 500 m) followed by a tow on the continental shelf (< 200 m depth) on the way back to port. The concept of a mean depth in this situation is not reasonable. These fisher-days could be excluded from the analysis, but would create unbalanced analyses or further sub-sampling to provide balanced analyses. This has not been attempted in this project. Note, however, that the size-dependent offshore distribution of redfish in waters off NSW has been described from an independent survey (Chen *et al.*, 1997). Moreover, an approach to incorporating this information and information about rates of size-dependent discarding into models of fish population dynamics and stock assessment has been developed (Chen *et al.*, 1998; and see Chapter 8).

The identification of region, depth and quarter as factors affecting discarding by fish trawlers off the NSW coast suggests the potential use of spatial and/or temporal closures to trawling as strategies for reducing discarding. Such closures provide a means of reducing the catch of species or sizes that are currently discarded if locations or times associated with consistently large levels of discarding and small retained catches can be identified (Alverson *et al.*, 1994; Hall, 1996; Kennelly, 1997, 1999). The potential for such a strategy to reduce discarding in this fishery is considered in Chapter 9 (Section 9.2.5).

Chapter 7
Influence of management regulations and market forces on discarding

7.1 Introduction

Influences on magnitudes and composition of discards are numerous and differ among fisheries, as do various schemes classifying these factors. Alverson *et al.* (1994) provided the most comprehensive listing of factors affecting discarding and classified them as "physical-biological interaction", "economic" and "legal". Physical-biological factors include: the distribution, abundance, species- and size-composition of fish on fishing grounds (Jean 1963; Jermyn & Robb 1981; Alverson *et al.,* 1994); the behaviour of fish when encountering fishing gears (Alverson *et al* 1994) and the selectivity of fishing gears (Jean, 1963; Alverson *et al.* 1994; Kennelly, 1995; Broadhurst, 2000). These factors influence the magnitude, species- and size-composition of the catch landed on the deck. A second phase determining discards then occurs when fishers make decisions about what is to be retained and discarded from a catch, based on economic and legal considerations.

Legal or regulatory factors that affect discarding include: minimal legal length of fish (Neilson *et al.,* 1989; Crean & Symes 1994; Alverson *et al.,* 1994; Evans *et al.,* 1994; Wilson & Burnes, 1996; Huse & Soldal, 2000; Stratoudakis *et al.,* 1998); regulations concerning prohibited species (French *et al.,* 1982; Marasco *et al.,* 1991; Evans *et al.,* 1994; Richards *et al.,* 1995); regulations that limit the catch per trip (Pikitch *et al.,* 1988; Pikitch, 1991; Squires & Kirkley, 1991; Sampson 1994; Gillis *et al.,* 1995a); and annual catch quotas (Pikitch *et al.,* 1988; Crean & Symes 1994; Stratoudakis *et al.*, 1998). Economic factors include: lack of a market for particular species (Jean 1963, Stratoudakis *et al.,* 1998); lack of a market for particular sizes (Jean 1963; Howell & Langan, 1987; Pikitch, 1991; Stratoudakis *et al.,* 1998); lack of a market for damaged fish (Templeman & Andrew 1956, cited in Jean, 1963; Powles, 1961, cited in Jean, 1963); high-grading, resulting from interactions between market forces and quotas (Crean & Symes 1994; Erickson *et al.,* 1996; Crowder & Murawski 1998); and high-grading resulting from interactions between market forces and limited capacity for storing catch on board vessels (Gillis *et al.*, 1995a).

Individual factors do not usually influence discarding. Rather, interactions between factors determine the magnitude and composition of discards (e.g. Stratoudakis *et al.*, 1998). For example, high-grading often involves an interaction of a regulatory trip limit or quota and a price differential across sizes of fish in the catch. Minimum size regulations will not necessarily produce a "knife-edge" determination of what is discarded because economic or other regulatory factors may also be influential. Even in the absence of these additional factors, the care and accuracy of a vessel's crew in sorting legal from illegal-sized fish and their will to operate according to the regulations will partially determine the magnitude and size-distributions of discards.

Other schemes of classification, similar in structure and rationale, to that used by Alverson *et al.* (1994) have been used. One of the earliest (Saila, 1983) comprised availability (of fish on grounds), selectivity of fishing gear, fishery regulations and market conditions as general categories. Hall (1996) discussed general categories of factors that affect composition of by-catches, specifically environmental, biological, ecological and technological factors. This categorisation concerns by-catch rather than discards, and thus, incorporated only those factors affecting the untargeted component of catch that is landed on deck. In contrast, Crean and Symes (1994) classified discards by concentrating on the sorting decisions made on deck. This classification includes: (i) "by-catch discards", the component of discards that is caught incidentally while targeting other species; (ii) "quota discards", where part of the catch is returned to the sea to comply with legal requirements; and (iii) discards resulting from pre-market selection, including high-grading of species and/or sizes of little market value.

A scheme used by Gillis *et al.* (1995a) is fundamentally different from those described above because factors affecting discarding following capture are classified into 3 functional categories using alternative criteria. The first and simplest category is "exclusion discarding", in which all individuals of a species or size-class will be removed from the catch. This may be because of a lack of a market, due to regulations prohibiting taking of a protected species or a minimal legal length. The second form of discarding, "capacity discarding" occurs when the hold of a vessel is full or a regulatory landing limit is reached and all additional individuals that are caught will be discarded. On average, the species and size-distribution of the discards will be the same as those of the retained catch. For a single species fishery, capacity discarding should only occur during the last haul of the trip (or more generally, at the end of the trip for other fishing methods). The final form of discarding is high-grading of marketable fish. The retained fish may be in the same haul as the discards or may be expected to appear in future hauls before the trip is over. Species and sizes of fish discarded due to high-grading will be biased toward less valuable individuals.

Several approaches have been used to investigate the influence of factors affecting discarding. Many authors have simply reported a list of possible factors without specifically presenting details of how such deductions were made. Surveys of fishers' explanations for their decisions to discard have been reported by some authors (e.g. Pikitch, 1991). Several attempts have also been made to examine the decision-making involved in discarding using models derived from behavioural ecology and micro-economics (e.g. Sampson, 1994; Gillis *et al.*, 1995a, 1995b). There have been, however, surprisingly few studies in which data from observer surveys are combined with data describing regulatory factors and economic factors (e.g. market prices and volumes) to test specific hypotheses concerning the influence of regulatory and economic factors.

An exception to this was a study of discards in Scottish trawl fisheries (Stratoudakis *et al.*, 1998). This study used data from observers from the period 1975-1993 (see also Jermyn & Robb, 1981) and examined associations between proportions of each species discarded at length and various biological and regulatory variables. Associations between temporal changes in the proportions discarded at length and changes in prevailing managerial measures were also considered. The approach used was based on the concept of a "discard selection curve" that relates the probability of discarding or retaining a fish to its length (see also Jean, 1963) and is similar to the use of gear-selectivity curves. The concepts of $L_{50\%}$ and inter-quartile range ($L_{75\%}$ - $L_{25\%}$) were used as measures of the midpoint and spread of the curve describing selection of discards.

The sizes at which fish are discarded by the fish trawl fishery off the coast of NSW is likely to be complex. First, it is well recognised that discarding is generally complex and dynamic in mixed species demersal fisheries (e.g. Pikitch, 1991; Stratoudakis *et al.*, 1998). Fish trawling off NSW occurs in 2 jurisdictions, with different regulations. Enforcement of compliance in these jurisdictions, either side of "lines on the water" is not easy. Many species come under quota management in the SEF, but are not subject to quotas in NSW waters. Trip limits apply for some species within SEF waters and for other species in NSW waters. Minimal legal lengths apply for a subset of species, some of which are also subject to annual quotas in the SEF or trip limits in one jurisdiction or the other. Fishers report that "markets" or "economics" are major factors determining what they discard. Consequently, there is a good basis for suspecting that, in addition to factors affecting magnitude and composition of catches landed on deck, regulatory factors (minimal legal lengths, trip limits, annual quotas) and market factors (market existence, price/volume determinants) and interactions among these factors will affect discarding patterns in this fishery.

In this chapter, discarding of the various species caught by fish trawlers off the NSW coast during 1993-95 is attributed among several factors or interactions between these factors:

non-existence of a market for particular species;
non-existence of a market for particular sizes of particular species;
protected species regulations;
minimal legal length regulations;
trip limit regulations;
direct effects of a TAC;
high-grading due to market/economic forces.

Identification of discarding due to the non-existence of a market for particular species and for protected species is straightforward. Direct effects of TACs in forcing discarding are examined by comparing the magnitudes of landed catches (for the entire SEF) and the TAC for each of the SEF species and thereby including/excluding the possibility of a direct effect of a TAC. The concepts of location and steepness of a discard/retention selection curve (similar to that used by Stratoudakis, 1998) are used to identify discarding due to: lack of market for particular sizes of particular species; minimal legal length regulations; and high-grading. High-grading of redfish is examined in more detail, using prices and volumes from the Sydney Fish Market and testing specific hypotheses about associations between market prices, volumes and quantities of redfish discarded.

7.2 Materials and methods

7.2.1 Identification of species discarded due to non-existence of a market

This is the most straightforward of determinations. By definition, provided that there was no regulation preventing retention and landing of a species, species that were always discarded were identified as discards due to non-existence of a market for these species.

7.2.2 Discarding due to regulations about protected species

This is also a straightforward determination. Species listed as "protected" under *the "Fisheries Management (General) Regulation 1995"* under the *"New South Wales Fisheries Management Act 1994"* cannot be landed legally in NSW. Similarly, species protected under Commonwealth legislation cannot legally be landed in NSW.

7.2.3 Discarding due to minimal legal length (MLL) regulation

In theory, all fish less than the MLL should be discarded. All fish greater than or equal to the MLL will be retained if it is the MLL alone that determines whether a fish is retained. The proportions of fish retained at length (per 1 mm length class) were plotted for the 7 species for which a MLL applies and for which size-distributions were available: tiger flathead, jackass morwong, rubberlip morwong, eastern blue spot flathead, yellowfin bream, tarwhine and snapper. For each species, I calculated the minimal size captured (L_{min} , defined as the length corresponding to the 0.001 point of the cumulative relative frequency distribution of catch at length), maximal size captured (L_{max} , defined as the length at the 0.999 point of the same distribution), size at which 5 % of the catch was retained ($L_{5\%Ret}$), size at which 50 % of the catch was retained ($L_{50\%Ret}$), size at which 95 % of the catch was retained ($L_{95\%Ret}$), $L_{5\%Ret}$ - MLL, $L_{50\%Ret}$ - MLL, $L_{95\%Ret}$ - MLL, $L_{95\%Ret}$ - $L_{5\%Ret}$ and $(L_{95\%Ret} - L_{5\%Ret})/(L_{max} - L_{min})$. These provide measures of the size range above and below the MLL that are captured, the size range of fish above and below the MLL that are sometimes retained and sometimes discarded and the proportion of the effective size distribution of the catch that is sometimes retained and sometimes discarded. For comparison, the same graphical information and calculations are made for the 7 commercial species discarded in greatest quantities for which

MLLs do not exist. If the MLL regulation is principally responsible for determining the sizes at which the species with MLLs are retained or discarded the hypothesis is that, compared to the non-MLL species, the selection curve should be steeper and approaching "knife-edge". Based on this prediction, the hypothesis that the mean value of $L_{95\%Ret}$ - $L_{5\%Ret}$ is less for MLL species than for non-MLL species is tested using a one-tailed, two sample t-test. An equivalent test is also made of the hypothesis that $(L_{95\%Ret} - L_{5\%Ret})/(L_{max} - L_{min})$ is less for MLL species.

7.2.4 Discarding due to trip limit regulation

Only one species, gemfish, was subject to a trip limit within the SEF during the period 1993-95. Although gemfish are subject to a TAC, the TAC for this species has been set at 0 since 1993, due to concerns about over-fishing of the stock. The trip limit was set to make some allowance for by-catch of gemfish when fishers were targeting other species, mirror dory in particular. The trip limit for gemfish was 200 kg in 1993-94 and 100 kg for the period May 15 - September 30 (the timing of the main spawning migration targeted by fishers) and 200 kg at other times during 1995. Quantities of gemfish retained and discarded on individual trips were compared with these trip limits to assess whether the trip limit was the main determinant of whether gemfish were retained or discarded.

Trip limits applied to gemfish and redfish in NSW waters during 1993-94 and for additional quota species during 1995. This was mainly to prevent vessels fishing in the SEF claiming that they had taken catches of SEF quota species in State waters. This was believed to be a widespread practice given the difficulty of enforcing compliance across the 3 nm boundary between State and SEF waters on the south coast of NSW. The imposition of these State trip limits limited the ability of fishers to exploit this loophole because catches of quota species in SEF waters could only be attributed to catches in NSW waters up to the NSW trip limit. Similarly, in the event that fish in excess of a State trip limit was actually taken in State waters, this excess catch could be claimed against the SEF quota for that species by claiming that some fishing had occurred in SEF waters. Consequently, there is no basis for these State trip-limits to make a major contribution to discarding behaviour.

7.2.5 Discarding directly attributable to TACs

The definition of discarding directly attributable to TACs used here is very specific and restricted. It is only possible that discarding of fish is a direct result of the existence of a TAC if the TAC for that species is exceeded in any year and there is subsequent capture and therefore discarding of that species. It is possible and indeed likely, that individual fishers caught their ITQ (individual transferable quota) for some species and then subsequently discarded fish. These fishers could, however, have purchased additional quota from other fishers if they considered this economically desirable. If they chose not to purchase additional quota and subsequently discarded catch, this is deemed to represent discarding due to an economic factor interacting with the TAC, not a direct result of the TAC.

7.2.6 Market forces (prices/volumes) and high-grading

Size-distributions from the observer survey demonstrated size-selective discarding for many species (see Chapter 5, Fig. 5.3) in which small fish below some length are consistently discarded. Between this length and some greater length they are sometimes retained and sometimes discarded with the probability of retention increasing with size. Above some length, they are consistently retained. Fishers reported that market forces and economics contributed to their decisions to retain or discard many of the commercial species (e.g. Tilzey 1998). Fishers claim that the price they receive per kg depends on size and prices paid vary with market volume and this fluctuates seasonally and over shorter time-scales.

The consistency of this explanation was tested using the data available for redfish. Redfish are an important commercial species and large quantities were discarded during 1993-95. Size-selective discarding occurred for redfish in each of these years in each of the 3 regions examined (North, Ulladulla and Eden; see Fig. 6.3).

Daily volume and \$-values, for each size grading of redfish, were obtained from Sydney Fish Markets (SFM) for the period 1993-95. Quarterly volume, \$-value and mean price-per-kg were calculated from these data. To remove effects of annual changes in volume, \$-value and mean price-per-kg, each of these variables was transformed. For example, mean price-per-kg (\$/kg) for quarter q of year y was calculated as :

$$"transformed"\$/kg_{qy} = \frac{\$/kg_{qy} - mean.\$/kg_y}{mean.\$/kg_y}$$

Using the transformed data, the following hypotheses were tested: (i) that quarterly volume would be positively correlated with quarterly value; (ii) that quarterly mean \$/kg would be negatively correlated with quarterly volume and (iii) that quarterly mean \$/kg would be negatively correlated with quarterly value. This was done for all grades of redfish combined (ungraded, small - S, medium - M, large - L and extra large - XL). The equivalent hypotheses were tested for a subset of these grades (ungraded, S and M). This subset of market grades matched the sizes of redfish that were sometimes retained and sometimes discarded by fishers. Given that redfish between 15 cm and 23 cm were sometimes retained and sometimes discarded by the North, Ulladulla and Eden fleets during the period 1993-95 and fishers claim that seasonal fluctuations in market prices affect their decision to retain or discard redfish, it would follow that quarterly discard rates for the largest redfish discarded in a given year within a given region should be inversely related to quarterly price-per-kg. For the purposes of this analysis, the "largest redfish discarded in a given year in a given region", referred to as "L-discards" are defined as redfish of length greater than the length at which > 33 % of the catch was retained for each year in each region. To examine the relationship between quarterly discarding and mean price for each region and within each year, independent of annual fluctuations, "transformed" L-discards were calculated for quarter q of year y as follows:

$$"transformed"\ L-discards_{qy} = \log\left(\frac{L-discards_{qy}}{mean.quarterly.Ldiscards_y}\right)$$

For each region (North, Ulladulla and Eden), the hypothesis that "transformed" L-discards and "transformed" \$/kg were inversely correlated was tested.

7.3 Results

7.3.1 Discarding due to non-existence of a market

Discarding of the 220 taxa defined as non-commercial (see Appendix A.5.1) was, by definition, due to the lack of a market for these species. Consequently, the capture of these species combined with the lack of a market existing for these species resulted in annual discards of 3,399 +/- 167 t (697 +/- 34 kg per fisher-day; see Section 5.3.2).

7.3.2 Discarding due to regulations about protected species

Of the taxa identified during the observer survey (see Appendix A.5.1), 3 taxa were protected. Herbst's nurse shark (*Odontapsis ferox*) is protected under NSW legislation and turtles and fur seals are protected under Commonwealth legislation.

Because Herbst's nurse sharks were retained occasionally by fishers, in contravention of regulations, this species was treated as a "commercial" species in this study (estimates of retained and discarded catches were only made for individual commercial species). Capture of this species was rare. Seven were caught during the observer survey in 5 of the total 2199 tows observed. Six of the 7 caught were, however, retained. The estimated mean annual catch of Herbst's nurse shark was 2.9 +/- 1.4 t of which 2.1 +/- 1.3 t was retained and 0.8 +/- 0.8 t discarded.

Three turtles were caught from 3 of the 2199 observed tows. All were released in accordance with regulations. Fur seals were caught on 18 of the 2199 tows observed during the survey, none of these captures being retained by fishers. Consequently, discarding of turtles and fur seals represent discarding due to protected species regulations.

7.3.3 Discarding due to minimal legal length (MLL) regulations

The sizes over which species were sometimes retained and sometimes discarded, $L_{95\%}$ - $L_{5\%}$, were significantly less for species with MLLs compared to species for which MLL regulations did not apply (t-test: one-tailed, homogeneous variances; $t = -6.45$, df = 12, $p < 0.01$). Similarly, the mean of this size range expressed as a proportion of the size-range of fish captured, $(L_{95\%} - L_{5\%})/(L_{max} - L_{min})$, was significantly smaller for species for which MLL regulations applied (t-test: one-tailed, heterogeneous variances; $t = -5.25$, df = 6, $p < 0.01$). Values of $L_{95\%} - L_{5\%}$ for all MLL species (range 3 - 6 cm) were less than or equal to those for all non-MLL species (range 6 - 12 cm). Values of $(L_{95\%} - L_{5\%})/(L_{max} - L_{min})$ for all MLL species (range 0.07 - 0.17 cm) were less than or equal to those for all non-MLL species (range 0.17 - 0.43 cm) (Table 7.1). The graphs showing %-retention of fish at length (Figs. 7.1.a and 7.1.b) illustrate clearly the steeper slope of the discard selection curves for MLL-species compared to non-MLL species.

For all MLL species, the MLL was between $L_{5\%Ret}$ and $L_{95\%Ret}$ and within 1 cm of $L_{50\%Ret}$ (Table 7.1 and Fig. 7.1.a). Lengths at which 5 % of fish were retained for these species were within 4 cm of MLL and lengths at which 95 % of fish were retained were within 3 cm of MLL.

Graphs showing %-retention of tiger flathead by size (1-cm increments) for each of the 3 years, for each of the 3 regions (see Section 6.3.3 and Appendix A.6.4.2) are consistent with a trend reported by the observers. During 1993, crews at Ulladulla retained or discarded tiger flathead based on the MLL regulation. In 1994, an increasing number of flathead were, however, retained on Ulladulla trawlers at sizes less than the MLL and this occurred to a greater extent in 1995. $L_{95\%Ret}$ was 33 cm during each year at Ulladulla but $L_{5\%Ret}$ decreased from 33 cm in 1993 to 26 cm in 1994 and 22 cm in 1995. The explanation provided by fishers was that, as the project progressed, their trust increased that observers would not pass on information to compliance officers. Note that the patterns of discarding across lengths for tiger flathead did not differ among years for the other 2 regions (Appendices A.6.3.1 & A.6.4.2).

Figure 7.1.a

Proportion of fish retained at length, species WITH A MINIMAL LEGAL LENGTH

range of lengths on x axis is L_{min} to L_{max}

dashed vertical lines represent $L_{5\%Ret}$, $L_{50\%Ret}$ and $L_{95\%Ret}$, solid vertical line represents MLL

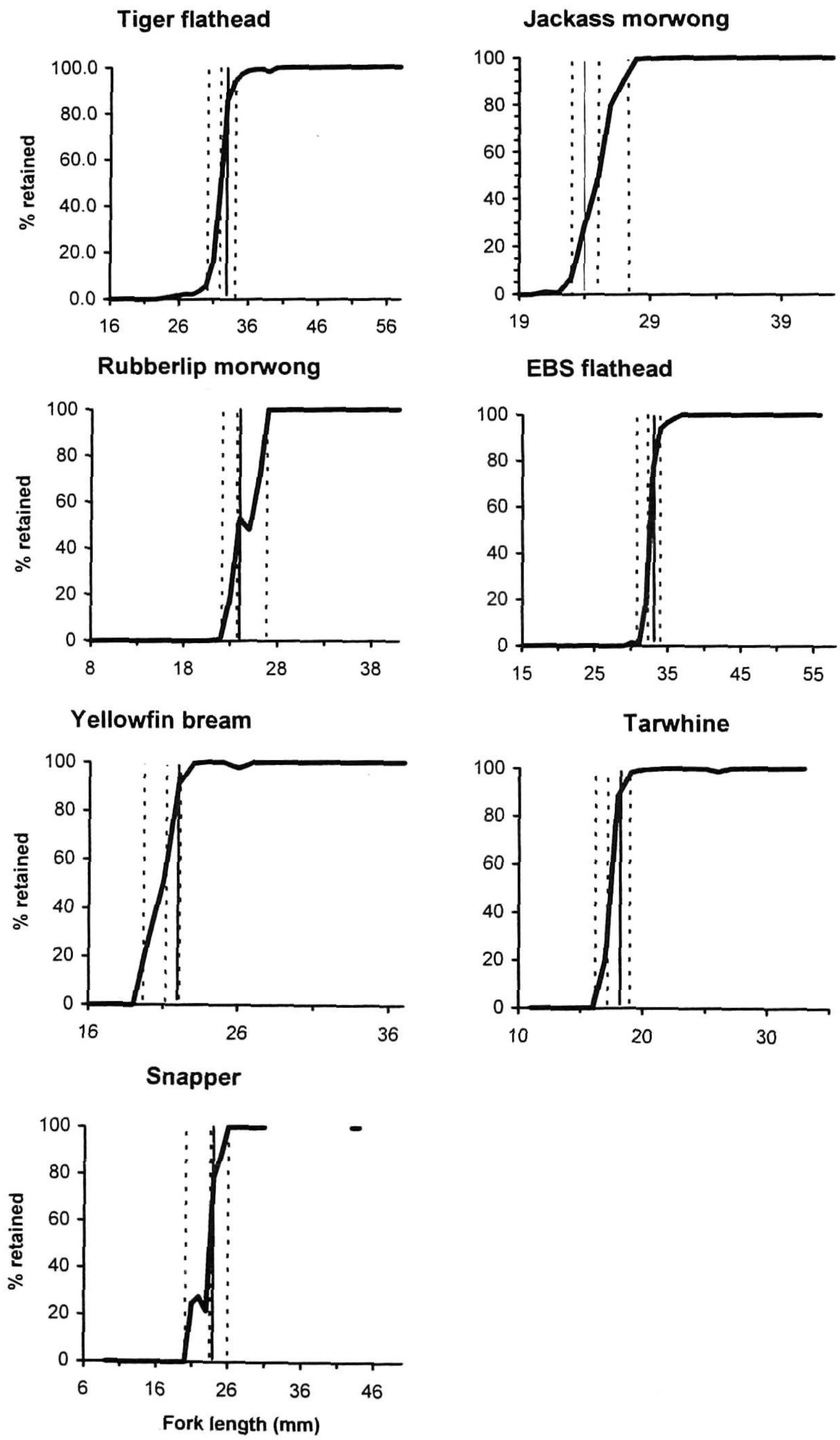


Figure 7.1.b

Proportion of fish retained at length, species WITHOUT a minimal legal length

range of lengths on x axis is L_{min} to L_{max}

dashed vertical lines represent $L_{5\%Ret}$, $L_{50\%Ret}$ and $L_{95\%Ret}$

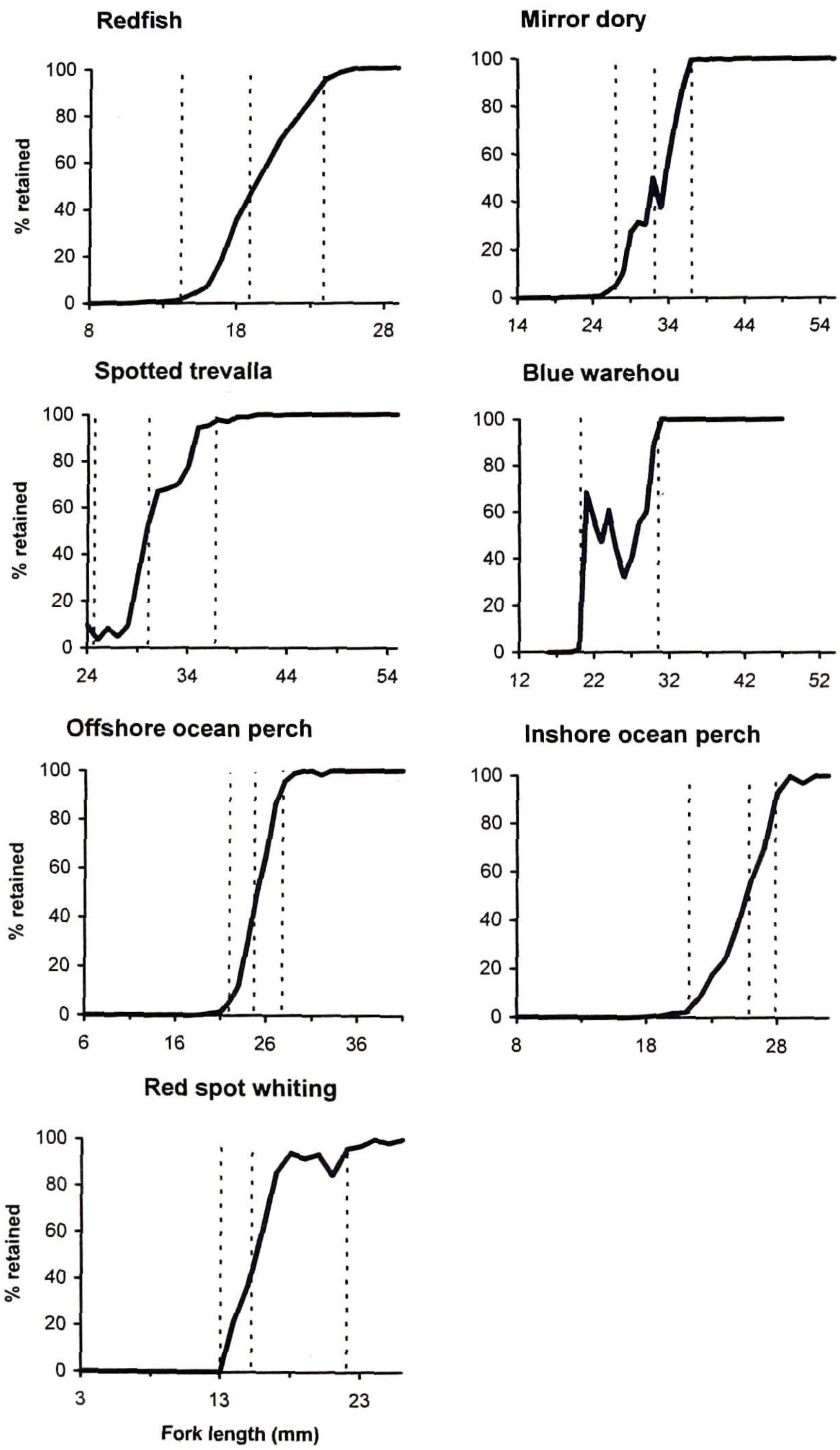


Table 7.1

Characteristics of discard selection curves for species with and without minimum legal lengths

MLL is the minimum legal length; L_{min} is the minimum and L_{max} the maximum length captured (0.001 and 0.999 points of the cumulative frequency distribution respectively)

$L_{5\%Ret}$, $L_{50\%Ret}$, $L_{95\%Ret}$ are the lengths at which 5%, 50% and 95% of the catch was retained

Species	MLL Fork length & [Total length] (cm)	L_{min} (cm)	L_{max} (cm)	$L_{5\%Ret}$ (cm)	$L_{50\%Ret}$ (cm)	$L_{95\%Ret}$ (cm)	$L_{5\%Ret}$ - MLL (cm)	$L_{50\%Ret}$ - MLL (cm)	$L_{95\%Ret}$ - MLL (cm)	$L_{95\%Ret} - L_{5\%Ret}$ (cm)	$\frac{(L_{95\%Ret} - L_{5\%Ret})}{(L_{max} - L_{min})}$
Tiger flathead	33 [33]	16	58	30	32	34	-2	-1	1	4	0.10
Jackass morwong	24 [28]	19	43	23	25	27	-1	1	3	4	0.17
Rubberlip morwong	24 [28]	8	41	22	24	27	-2	0	3	5	0.15
Eastern blue-spot flathead	33 [33]	15	58	31	32	34	-2	-1	1	3	0.07
Yellowfin bream	22 [25]	16	37	19	21	22	-3	-1	0	3	0.14
Tarwhine	18 [20]	10	33	16	17	19	-2	-1	1	3	0.13
Snapper	24 [28]	6	50	20	24	26	-4	0	2	6	0.14
Redfish	-	8	29	15	19	24				9	0.43
Mirror dory	-	14	56	27	32	37				10	0.24
Spotted trevalla	-	24	55	24	30	36				12	0.39
Blue warehou	-	16	53	20		31				11	0.30
Offshore ocean perch	-	6	41	22	25	28				6	0.17
Inshore ocean perch	-	8	32	21	26	30				9	0.38
Red spot whiting	-	3	26	13	15	22				9	0.39

7.3.4 Discarding due to trip limits

In the Ulladulla region, 84 % of the observed catch of gemfish in 1993 came from the one trip observed on which the trip limit of gemfish was caught. Of the 9,780 kg of gemfish caught on this trip, 280 kg were retained (exceeding the trip limit of 200 kg by 80 kg) and 9,500 kg were discarded (Table 7.2). In Ulladulla, the trip-limit of gemfish was not caught on 96 fisher-days observed during 1993. The total catch of gemfish from these trips was 1,869 kg, of which 42 kg was discarded. Of the total 9,542 kg of gemfish discarded on observed trips, 99.6 % of discards were observed on trips in which the trip limit was caught (Table 7.2). A similar pattern occurred at Ulladulla during 1994 and at Eden in 1993 (99.8 % and 99.9 % of observed discards from trips in which the trip limit was caught). Although the trip limit of gemfish was caught on a single trip at Ulladulla in 1995 and on several trips at Eden in 1994 and 1995, catches exceeded the trip limit by a small margin only and discarding did not occur (Table 7.2).

Large catches of gemfish were observed rarely during the observer survey. This was not unexpected because schools of migrating gemfish are only concentrated on the south coast of NSW for a couple of months each year and fishers should not have been targeting these fish (the TAC was set at 0). Trips involving large quantities of gemfish discards were rare and few were observed. It is therefore not appropriate to conclude that the observed proportion of gemfish discarded on trips when the trip limit was caught (99.6 %) provides an accurate estimate across the whole fleet and fishing year. It is, however, reasonable to conclude that the trip limit was the major factor contributing to discards of gemfish at Ulladulla and Eden during 1993-95 because: (i) discards of gemfish were minimal on all observed trips when the trip limit was not caught (a total of 254 kg discarded from 556 observed trips) and (ii) very large quantities of gemfish were discarded on several trips observed when catches were much greater than the trip limit.

The size-distributions of discards and of retained catches of gemfish (for the combined fleets of Ulladulla and Eden during 1993-95) were similar (Fig. 5.3). This pattern differs markedly to the size- distributions of the other species examined (Fig. 5.3) where there is typically a partial overlap of size-distributions of discarded and retained fish.

Table 7.2

Comparison of retained and discarded catches of gemfish for trips on which the trip limit was caught and from trips on which the trip limit was not caught

	Trip limit caught ?	Fisher-days (num)	Catch (kg)		Retained (kg)		Discarded (kg)	
Ulladulla								
1993	Yes	1	9,780	*84.0%*	280	*13.3%*	9,500	*99.6%*
	No	96	1,869	*16.0%*	1,826	*86.7%*	42	*0.4%*
		97	11,649		2,106		9,542	
1994	Yes	3	4,008	*83.5%*	992	*55.8%*	3,015	*99.8%*
	No	91	791	*16.5%*	786	*44.2%*	5	*0.2%*
		94	4,799		1,778		3,020	
1995	Yes	1	312	*24.9%*	312	*26.4%*	0	*0.0%*
	No	95	943	*75.1%*	872	*73.6%*	70	*100.0%*
		96	1,255		1,184		70	
Eden								
1993	Yes	6	9,239	*87.0%*	1,004	*42.3%*	8,235	*99.9%*
	No	90	1,377	*13.0%*	1,367	*57.7%*	9	*0.1%*
		96	10,616		2,371		8,244	
1994	Yes	6	1,074	*49.9%*	1,073	*51.0%*	0	*0.0%*
	No	88	1,079	*50.1%*	1,032	*49.0%*	47	*100.0%*
		94	2,153		2,105		47	
1995	Yes	0	0	*0.0%*	0	*0.0%*	0	*0.0%*
	No	96	1,354	*100.0%*	1,272	*100.0%*	81	*100.0%*
		96	1,354		1,272		81	
Ulladulla + Eden								
1993-95	Yes	17	24,413	*76.7%*	3,661	*33.8%*	20,750	*98.8%*
	No	556	7,413	*23.3%*	7,155	*66.2%*	254	*1.2%*
		573	31,826		10,816		21,004	

7.3.5 Discarding directly attributable to TACs

The TAC, total landings from the SEF and proportion of TAC caught are shown for 9 SEF quota species for each of the 3 years (1993-95) in Table 7.3. These species are the subset of the SEF quota species caught off the NSW coast for which a minimum of 5 % discarding occurred in any year. Note that, because the SEF quota (and SEF records of landings) does not distinguish between inshore ocean perch and offshore ocean perch, these species are presented as "ocean perches" in this table.

The TAC was landed in any year for only 2 species: gemfish in each of the 3 years and ocean perches in 1993. Landings of gemfish exceeded the TAC of 0 in each of the 3 years because of the existence of the by-catch trip limit and the major factor determining discarding of gemfish was clearly this trip limit (see Sections 7.2.4 and 7.3.4). Consequently, discarding of gemfish during 1993-95 was not directly attributable to the TAC.

There was some discarding attributable to the direct effects of the TAC for ocean perches during 1993 when the TAC of 302 t was caught. According to the definition of "discarding directly attributable to TACs" used here, only those discards of ocean perches after the date in 1993 on which the TAC of 302 t was landed would be classified as being directly attributable to the TAC. Discarding of ocean perches before this date would be defined as high-grading due to market forces.

It is therefore concluded that the TAC did directly induce discarding of ocean perches during late 1993.

7.3.6 Market forces (prices/volumes) and high-grading

Quarterly volume of redfish handled by the SFM was positively correlated with \$-value for all grades of redfish combined ($r = 0.98$, df = 10, $p < 0.01$) and for the subset of small grades examined ($r = 0.94$, df = 10, $p < 0.01$). Quarterly volumes of redfish were negatively correlated with \$/kg for all grades of redfish ($r = -0.92$, df = 10, $p < 0.01$) and for the subset of small grades ($r = -0.81$, df = 10, $p < 0.01$). Quarterly \$-value of redfish was negatively

Table 7.3

TAC, SEF landings and % of TAC caught, for SEF quota species for which discarding exceeded 5% in any year between 1993 and 1995 off NSW

Note that the TAC and SEF landings figures refer to the entire SEF, not only the area off the NSW coast

Shading in the table indicates instances in which the TAC was caught

	Year	TAC (t)	SEF landings (t)	*(% of TAC)*	% discards
Blue grenadier	93	5,495	3,348	***61***	0
	94	12,351	3,155	***26***	0
	95	12,281	2,761	***22***	31
Blue warehou	93	1,010	762	***75***	6
	94	1,070	849	***79***	12
	95	1,087	757	***70***	23
Tiger flathead	93	3,000	1,474	***49***	12
	94	3,823	1,497	***39***	16
	95	4,195	1,712	***41***	12
Eastern gemfish	93	0	253	-	82
	94	0	134	-	42
	95	0	93	-	8
Jackass morwong	93	1,593	851	***53***	5
	94	1,626	793	***49***	6
	95	1,764	817	***46***	1
Mirror dory	93	803	312	***39***	15
	94	879	302	***34***	56
	95	953	268	***28***	50
Ocean perch	93	302	302	***100***	47
(Inshore & Offshore	94	509	276	***54***	55
combined)	95	574	275	***48***	73
Redfish	93	601	538	***90***	47
	94	1,030	699	***68***	54
	95	1,842	1,214	***66***	56
Spotted trevalla	93	2,020	1,784	***88***	12
	94	2,604	1,866	***72***	1
	95	2,823	2,065	***73***	6

correlated with $/kg for all grades of redfish (r = -0.86, df = 10, $p < 0.01$) and for the subset of small grades (r = -0.58, df = 10, $p < 0.05$; Fig. 7.2).

Quarterly discards of L-redfish, were negatively correlated with $/kg for each of the 3 regions: North (r = -0.70, df = 10, $p < 0.05$); Ulladulla (r = -0.76, df = 10, $p < 0.01$); and Eden (r = -0.82, df = 10, $p < 0.01$; Fig. 7.3).

These analyses were done using transformations to remove inter-annual effects for volume, $-value, $/kg and L-discards. Additionally, numbers of L-discards were log transformed. Interpretation of these results is, nevertheless, straightforward. During the quarters in which the quantity of redfish handled by SFM was greatest, the mean price-per-kg paid to fishers for redfish was smallest and fishers tended to discard larger quantities of sizes of redfish that were marketable. These results are consistent with the claims of fishers that discarding of redfish is driven by market economics.

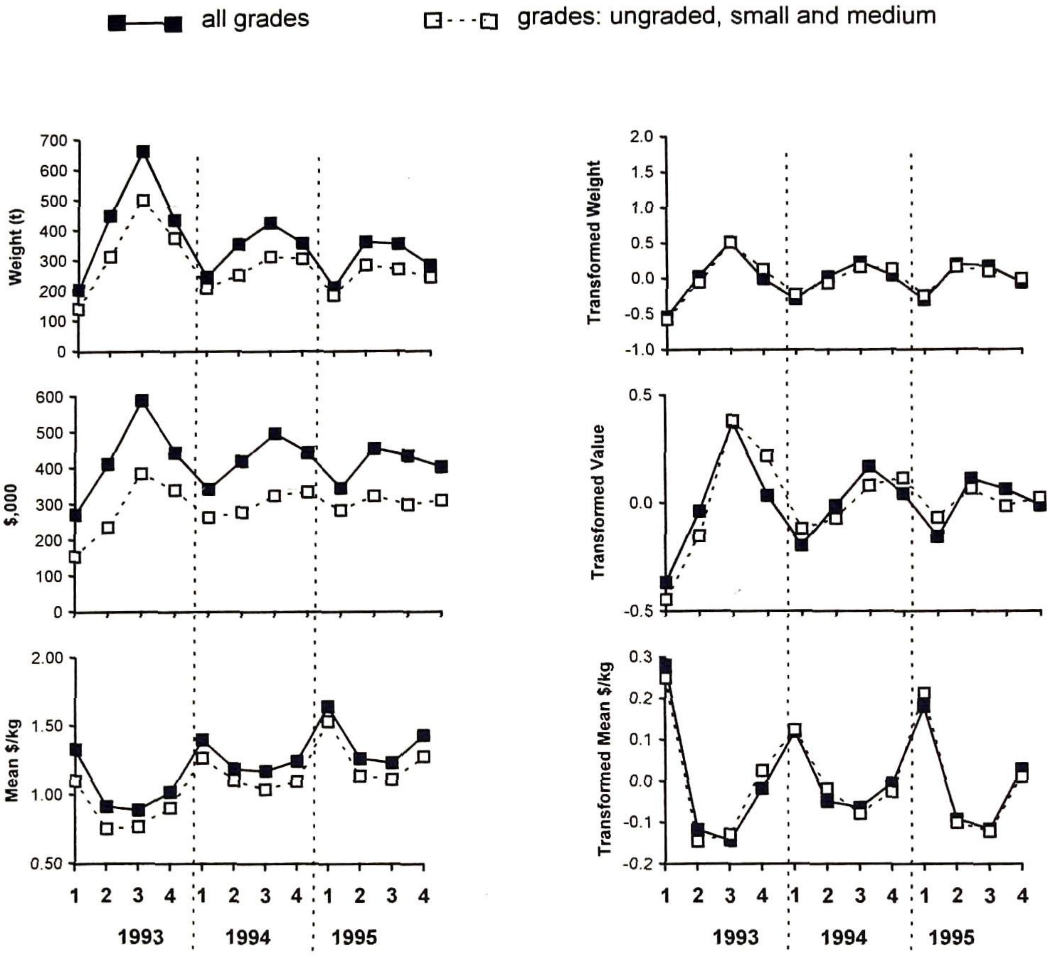
7.4 Discussion

Summary of factors affecting decisions by fishers to discard catches

Protected species regulations forced discarding of 3 species (Herbst's nurse shark, turtles and seals), although there was some illegal retention of Herbst's nurse sharks (Table 7.4). MLLs for 7 species determined the length at which fish could legally be retained and fish shorter than the MLL were generally discarded (Table 7.4). Trip limits were the major factor affecting discarding of a single species, gemfish. The direct effects of TAC regulations were only important in determining discarding of ocean perches during the latter part of 1993. Other than the species for which MLL regulations applied, factors concerning markets and economics were the major determinants of whether fish were retained or discarded. All non-commercial species (220 taxa) were discarded because of the lack of a market for these species. For many commercial species, fish were consistently discarded during 1993-95 because there was no market for very small fish. For example, approximately 33 % of redfish caught during 1993-95 were less than 15 cm CL (i.e. $< L_{5\%}$). Similarly, 3 % of the discards of

Figure 7.2

Weight (t), $value and mean price per kg for redfish at the Sydney fish markets, 1993-95



Correlation coefficients:

All grades		
Weight & Value	0.98	$p < 0.01$
Weight & $/kg	-0.92	$p < 0.01$
Value & $/kg	-0.86	$p < 0.01$
Grades: ungraded, small and medium		
Weight & Value	0.94	$p < 0.01$
Weight & $/kg	-0.81	$p < 0.01$
Value & $/kg	-0.58	$p < 0.05$

Figure 7.3

Relationship between discards of L-redfish ("large" redfish) and mean price per kg of redfish (SFM)

refer to text in section 7.2.6 for definition of L-discards and details of transformations

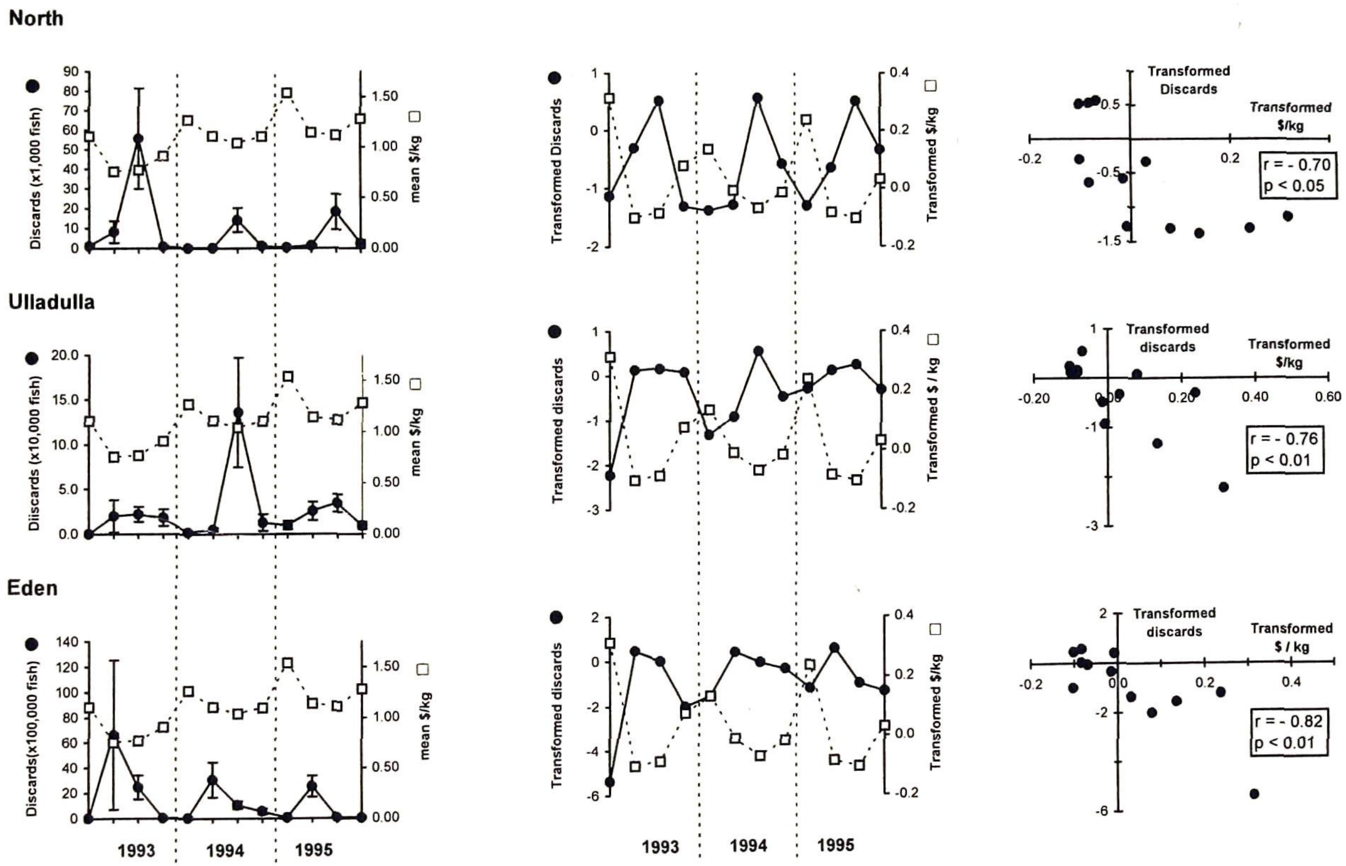


Table 7.4

Summary of factors affecting decisions to retain or discard fish

Q denotes a SEF quota species; MLL denotes a species for which a minimum legal length applies

% figures in table are estimates of the proportion of fish discarded due to the given factor
? denotes that the given factor is important but that the % of fish discarded due to this factor cannot be determined

Species		Proportion discarding (% num. fish) due to:						
		Regulations				Markets / economics		
		Protected sp.	MLL	Trip limit	TAC direct	No mkt. for sp.	No mkt. for sizes	High-grading
All non-commercial spp.						100%		
"Protected" spp.		100%						
<u>Commercial spp.</u>								
Redfish	Q						33%	67%
Spotted trevalla	Q							100%
Tiger flathead	Q, MLL		100%					
Barracouta							?	?
Southern frostfish							?	?
Piked dogfish								
Blue warehou	Q						3%	97%
Jackass morwong	Q, MLL		100%					
Velvet leatherjacket							?	?
Gemfish	Q, TL			100%				
Mirror dory	Q						55%	45%
Offshore ocean perch	Q				? (1993 only)		70%	30%
Inshore ocean perch	Q				? (1993 only)		76%	24%
Cuttlefish							?	?
Silver dory							?	?
Rubberlip morwong	MLL		100%					
Eastern blue-spot flathead	MLL		100%					
Yellowfin bream	MLL		100%					
Tarwhine	MLL		100%					
Red spot whiting							31%	69%
Snapper	MLL		100%					

blue warehou, 55 % of the discards of mirror dory and 31 % of the discards of red spot whiting occurred because of the lack of market for small fish. Up to 70 % of the discards of offshore ocean perch and 76 % of the discards of inshore ocean perch were also attributable to this lack of a market for small fish, but these figures are uncertain because the TAC may have also influenced discarding of these species in 1993.

High-grading of catches of redfish occurred during 1993-95 and 67 % of discards of redfish were attributed to this factor (67 % of discards occurred at lengths > $L_{5\%}$). High-grading also occurred for spotted trevalla, blue warehou, mirror dory, offshore ocean perch, inshore ocean perch and red spot whiting (size-distributions in Fig. 5.3) and it is reasonable to assume that this high-grading was based on the greater value of larger fish (data not presented here). Because size-distributions of retained and discarded catches are not available for all commercial species, high-grading for species such as barracouta, southern frostfish, velvet leatherjacket, cuttlefish and silver dory cannot be demonstrated directly. Weights and numbers of retained and discarded catches of these species were, however, routinely recorded by observers, so it was possible to calculate the mean weight per fish of retained and discarded catches. Although not presented in this thesis, the mean weight of retained fish exceeded the mean weight of discarded fish for each of the species listed above and for many other species. It is therefore likely that for these species: (i) small fish were consistently discarded because of a lack of market and (ii) some sizes were high-graded due to price differences for different sizes.

Protected species legislation mandated the discard of 3 taxa (Herbst's nurse sharks, turtles and fur seals) and only a few of these animals were caught. The few turtles and the majority of seals that were caught were released alive and in apparently healthy condition. Similarly, trip limits and the direct effects of TACs were responsible for relatively small quantities of discards.

Although MLL legislation determined the sizes at which some species were discarded, MLL regulations applied to relatively few species: flatheads, morwong, bream, tarwhine, snapper and whiting. Despite these conclusions and the widely acknowledged fact that MLLs may result in discarding of fish that would otherwise be retained (e.g. Alverson *et al.*, 1994), in the absence of any MLL, it is very likely that many fish of these species would still be discarded given their small size. Whilst the discarding of these species is classified as MLL-enforced discarding, in the absence of MLLs, the majority of these fish would probably become "no market for sizes" or "high-grading" discards. It is therefore concluded that factors concerning markets and economics were the main determinants of decisions by fishers to discard fish during the period 1993-95. The absence of a market for many species and for small sizes of commercial species and the high-grading of commercial species were widespread and common practices.

The major factors: lack of markets & high-grading

Whilst of minimal significance as a direct cause of discarding, note that the TAC/ITQ system of management in the SEF may be an important component driving some of the high-grading of several species. Although the TAC was not landed for redfish in any of the 3 years, nor for ocean perches in 1994 or 1995 or for spotted trevalla in 1993, it is likely that the total catches (landed + discarded) of these species exceeded the TAC in these years. This conclusion is based on applying the %-discards estimates from the NSW observer survey to the landings statistics for the whole SEF (Table 7.2). Potentially, the existence of TACs may have provided incentive for fishers to discard small redfish, despite the availability of quota (currently held by the fisher, or available on the market from other fishers), so that the limited quota could be reserved for larger, higher-value fish. It is problematic to disentangle this motivation for high-grading from the more general economic incentive for high-grading that is unrelated to the existence of TACs. Nevertheless, in the case of redfish, the discard selection curve for redfish for 1993-95 was similar for regions North (where TACs did not apply) and for Ulladulla (where TACs did apply; Chapter 6, Fig. 6.4). Consequently, it appears unlikely that the TAC/ITQ system played the major role in driving high-grading during 1993-95. Note also that fishers at Eden consistently discarded larger redfish than did the Ulladulla or North fleets (Chapter 6, Fig. 6.4). The explanation offered by Eden fishers was that greater costs for transporting fish from Eden compared to the costs from Ulladulla or North (closer to Sydney) meant that landing smaller, less valuable fish was not profitable. This provides an example of a market/economics motivation for discarding that differs among regions.

As noted by Kaufmann *et al.* (1999), discarding fish is often perceived as a feature of management by TAC/ITQ. This perception may seriously undermine public and industry confidence in this form of management. Because discarding in trawl fisheries is such a widespread practice, it is important to disentangle the influences of the TAC/ITQ system and other factors affecting discarding. In this chapter, the case has been argued that the predominant motivations for discarding during 1993-95 were concerned with market and economic factors rather than the direct effect of the TAC/ITQ system or indirectly via an incentive to high-grade. A similar situation existed in Iceland where opponents of an ITQ system argued that the system is responsible for discarding of catches. In fact, evidence from observations on these multi-species demersal fisheries have found no discernible increase in discarding since the introduction of TAC/ITQ management (Arnason & Gissurarson, 1999).

It is important to note that there is potential for quota-related high-grading to become a problem in the SEF if quotas become increasingly restrictive on fishers. Whilst the theory of TAC/ITQ management is that transferability of quota should be sufficient to prevent over-quota discarding (e.g. Sissenwine & Mace, 1992), this assumes that TACs are set in accordance with availability and that the market for transferring quota operates effectively (Kaufmann *et al.*, 1999). Moreover, particularly in multi-species fisheries (such as the SEF), TACs for individual species determined on biological grounds may not match amounts caught, the latter being determined by harvesting technology, biological, environmental and economic conditions (Squires *et al.*, 1998). Hindrances to an effective market for trading of quota identified by Kaufmann *et al.* (1999) include: (i) a "thin" market resulting from a relatively small number of operators, effectively discouraging emergence of quota-broking businesses and limited availability of information about available quota; (ii) reliance on relatively limited personal networks in this environment and (iii) ineffective pricing resulting from the thin market.

Interaction of factors that affect catch and factors that affect decisions to retain or discard

In addition to the reasons for discarding and factors affecting discarding discussed above, discarding also occurs for a much broader reason - because unwanted fish are caught in the first place. While this statement may seem obvious, it does emphasise the influence of: (i) biological and environmental factors influencing the distribution and abundance of species;

(ii) the distribution and intensity of fishing effort in space; and (iii) the selectivity of fishing gears (particularly the mesh-size and construction of cod-ends in trawl fisheries) on the quantities and sizes of fish caught and subsequently discarded. Magnitudes and size-distributions of discarded catches will be determined by interactions among the factors that affect the magnitudes and size-distributions of catches and factors that affect subsequent decisions by fishers (based on regulations or market/economic considerations) to retain or discard catch.

The most thorough analysis and discussion of interacting factors affecting discarding practices based on data from an observer programme was provided by Stratoudakis *et al.* (1998) in the North Sea. The Scottish observer programme was similar to that used off NSW. It was based on stratified random sampling by area, year, quarter and gear. Analysis involved examination of the dependency of two summary statistics, $L_{50\%}$ (the length at which 50 % of the catch was retained) and the inter-quartile range ($L_{75\%}$ - $L_{25\%}$) for each of 3 species (cod, haddock and whiting) on explanatory variables that included: (i) the stratification variables; (ii) catch variables (CPUE for each of the 3 species); and (iii) "annual" variables (variables that change annually or every few years, e.g. quotas, MLL, nominal mesh size). No systematic dependency was found between inter-quartile range and any of the explanatory variables. Differences in $L_{50\%}$ were identified between offshore and inshore areas for cod and haddock, independent of other factors. $L_{50\%}$ for whiting was greater when the median size of whiting in catches was greater than 30 cm, independent of other factors. Most influences of factors affecting $L_{50\%}$ involved interactions of factors, for example: (i) increases in $L_{50\%}$ for cod and haddock in inshore areas that coincided with an increases in MLL and an increased nominal mesh-size; (ii) for inshore areas and years prior 1989, $L_{50\%}$ for haddock was less for fishers landing catch into small compared to large harbours; (iii) in offshore areas, $L_{50\%}$ was greater when the median size of haddock in catches was greater than 36 cm; (iv) for catches of whiting of median length less than 30 cm, $L_{50\%}$ was greater after 1979 when the MLL increased and (v) $L_{50\%}$ for whiting differed between inshore and offshore areas after 1979 for catches in which the median length of whiting was less than 3 0cm. Stratoudakis *et al.* (1998) concluded that changes in $L_{50\%}$ were more complicated than could be explained by biological and regulatory variables alone because of the variety of interactions identified.

Consequences for stock assessment and development of strategies to reduce discarding

Future changes to MLLs, prohibited species regulations, trip limits, TAC/ITQs or factors influencing markets and fishery economics are likely to affect the decisions by fishers to retain or discard components of catch. This underlines the need for ongoing monitoring of magnitudes and size-distributions of discards so that apparent changes in abundance of sizes-composition of stocks are not confounded by changes in factors that affect discarding practices.

Given the conclusion that TACs were not a major factor affecting discarding during the period 1993-95, any review of the appropriateness of this management regime in the SEF, based on the argument that it promotes discarding, is unwarranted. Although trip limits for gemfish interacting with a TAC of zero did influence the discarding of gemfish, there is no reasonable argument that the TAC or trip limit should be changed. The rationale for the TAC of 0 t is that the stock is overexploited and the trip-limit is provided to allow for retention of small by-catches of gemfish associated with the targeting of mirror dory. Whilst the justification for the MLLs currently regulated for particular species may be tenuous, removal or reduction of these MLLs on the basis that discarding will be reduced is not necessarily sensible. For instance, it is a widely held belief that the 33 cm MLL for flathead species prevents targeting of smaller tiger and eastern blue spot flathead on shallow inshore fishing grounds. If, for example, fishers were able to target flathead between say 27 and 33 cm on these grounds, there would probably be an increased mortality of flathead less than 26 cm and of juveniles of other species that inhabit these shallow inshore grounds. It is, however, likely that many fish would be discarded due to small size and a lack of markets for these sizes in the absence of MLLs. Based on these arguments, the real opportunity for reduction of discards is in the development of more selective fishing gears and/or the development of markets for components of catch currently discarded (see Chapter 9, General discussion).

Chapter 8

Consequences of discarding for stock assessment

8.1 Introduction

Fishery management and stock assessment

Management of exploited fish populations depends on the conservatory, biological, economic and social objectives for the fishery (e.g. Hilborn & Walters, 1992; Pitcher *et al.*, 1998; Quinn & Deriso, 1999). Fisheries management, encompassing development of plans and monitoring the performance of a fishery against established objectives, may be done in several different ways. Hilborn & Walters (1992) described three general methods by which decisions may be made: (i) decisions may mimic those made by other managerial agencies in similar circumstances, on the basis that previous decisions involved careful evaluation of alternatives; (ii) a reasonable choice may be made on intuitive grounds which is then systematically varied while biological and economic responses are monitored so that the best choice is eventually selected by an empirical process of trial and error; or (iii) formal stock assessment and evaluation of alternative harvest strategies provides the basis for assessing status of stocks and harvesting strategies.

A stock assessment is a determination of the status of some aspect of a stock (e.g. abundance, biomass, length- or age-composition) at some point in time. At any point in time, the state of a stock is determined by the preceding history of reproduction, growth and mortality for the stock. Assessments may be retrospective, if they concern the past or present state of the stock, or prospective, if they consider the likely state of the stock in the short- or long-term (e.g. Gulland, 1988; Hilborn & Walters, 1992). Hilborn and Walters (1992) defined stock assessment as *"the use of various statistical and mathematical calculations to make quantitative predictions about the reactions of fish populations to alternative management choices."* This definition emphasises the relationship between stock assessment and fisheries management and these authors also stress the clear separation of these functions. The key role of stock assessment in this approach is to provide the best possible technical support to the decisions of the fishery manager. Fundamental to stock assessment is an understanding of fish population dynamics, the study of how and why a population changes. Quantitative population dynamics is the mathematical and statistical representation of a population and its changes using mathematical and statistical expressions to represent principles of biological life history (e.g. Quinn & Deriso, 1999). Whilst it is beyond the scope of this thesis to provide a review of the vast range of population dynamics models available as tools for assessment of fisheries and for formulation of hypotheses and designing experiments, several broad classes of models are considered below.

Biomass dynamic models (also referred to as production or surplus production models) are the simplest models commonly used for assessment of stocks. Such models describe the dynamics of a stock in terms of biomass, rather than numbers at age or numbers in a given length-class. Hilborn & Walters (1992) note that biomass dynamics models have been regarded as "poor cousins" of age-structured models and that most biologists would prefer to use age-structured models that incorporate a more detailed representation of biological and fishery processes. These authors noted that many of the failures of biomass dynamic models have been due to failure of data, rather than failure of the model. Specifically, the data provided poor capacity to contrast between trends in fishing effort and stock abundance as these variables were positively correlated. Since these same data failures affect age-structured analyses, biomass dynamic models cannot be dismissed on this account (Hilborn & Walters, 1992).

Age-structured models explicitly model biological processes such as growth, stock-recruitment relationships, natural mortality, fishing mortality and processes related to fishing methods such as the vulnerability of fish to fishing and selective properties of fishing gears. Unlike age-structured approaches, length-structured models consider the biological and fishery processes described above with respect to length-classes rather than ages of fish. Many variations exist on these age- and length-structured themes as alternative assumptions are made about the biological, ecological, economic and social processes included in the models (e.g. Gulland, 1988; Hilborn & Walters, 1992; Quinn & Deriso, 1999).

A basic requirement of data for each these models involves some combination of catch, catch-per-unit-effort (CPUE), catch-at-age or catch-at-length data (Doubleday & Rivard, 1983; Gulland, 1983; Hilborn & Walters, 1992). Whilst the catch data, by definition, are fishery-dependent (i.e. they come from the commercial and/or recreational fisheries), indices of abundance based on CPUE data and size- or age-distributions of fish populations may be provided by fishery-dependent or fishery-independent sources. Despite the often tenuous assumptions that fishery-dependent CPUE and age- or size-distribution data provide estimates of population abundance, age- or size-structure, analysis based on commercial catch and effort data and/or catch at age data form the backbone of most stock assessments (e.g. Hilborn & Walters, 1992).

Consequences of discarding for stock assessment

Whilst estimates of magnitudes of discards have been made for some fisheries, comparatively little effort has been applied to determining the effects of these discards on the dynamics of fish populations (Andrew & Pepperell, 1992; Alverson *et al.*, 1994; Crowder & Murawski, 1998). Studies that quantify by-catches or discards typically draw conclusions that the associated mortality may be reducing the potential yield of associated fisheries or words to the effect that the scale of discarding is potentially deleterious to stocks (e.g. Howell & Langan, 1987; Kennelly *et al.*, 1997). Some publications have reported that data concerning discards are routinely incorporated in stock assessments but there has been minimal analysis or discussion of how the assessments are affected by inclusion of the data (e.g. Alverson *et al.*, 1994; Stratoudakis *et al.*, 1999). Characterisation and reduction of discards are necessary steps in understanding and solving some of the problems of by-catch and discards, but of critical importance is the question of how discards affect populations of fish, stock assessment and yields to commercial and recreational harvesters (Crowder & Murawski, 1998). Relatively few studies have directly addressed this issue, but a few have suggested that the predictions from models, outcomes of assessment and subsequent advice to management regarding harvesting strategies are significantly affected by the inclusion of data about discards.

As part of a study examining the effects of uncertainty associated with several input variables on a stock assessment for Spanish mackerel in the US Gulf of Mexico, Erhardt and Legault (1997) considered the effects of including estimates of quantities of discards. Estimates of discarded by-catches and the uncertainty associated with these estimates were incorporated in a virtual population analysis by a bootstrapping procedure that drew samples from the data-set of observed by-catches over an 8 year period. The "allowable biological catches" generated by the model varied considerably when applied to each of 250 bootstraps of the by-catch data set. It was concluded that the inclusion of, and uncertainties associated with, the by-catch data had important influences on the distribution of allowable biological catches generated by the model and, ultimately, the selection of a total allowable catch.

Alverson *et al.* (1994) discussed the consequences of excluding discards from an assessment of yellowtail flounder in southern New England (USA). Exclusion of discards resulted in over-estimates of long-term yield and spawning potential for a range of assumed fishing mortalities. Short-term forecasts of yield were particularly sensitive to the inclusion of discards when particular year-classes were abundant, as was the case for a particular year-class in this fishery. Inclusion of data about discards of juvenile cod and haddock in assessments of stocks of these species on the Scotian Shelf, showed that these discards were one of the most significant factors in reduced yields for these species (Kulka & Waldron, 1983).

The importance of data about discards to the assessment of likely impacts of changes in selectivity of fishing gears and changes in regulated minimal sizes has been demonstrated. Estimates of discards of 10 species of fish caught in a mixed-species trawl fishery off California, Oregon and Washington were incorporated in a mixed species YPR model used to evaluate changes in yields and revenues that would result from changes to minimum mesh-size regulations (Pikitch, 1987, 1991). An increase in mesh size would increase fishery yields and revenues in the long term, but catch-rate and revenues ($ per hour) would decline in the short term. Chen and Gordon (1997) developed a length-structured YPR model to evaluate the impacts of discarding in the Oregon flatfish fishery described by Pikitch (1987). This study estimated losses in YPR due to discarding and concluded that such losses would decrease if mesh size increased from 104 mm to 127 mm, but any further increase in mesh size up to 140 mm would have minimal additional impact on losses in YPR due to discarding. Moreover, this study indicated that potential loss in revenues was much larger than loss of biological yield for smaller meshes.

The effectiveness of minimal size limits for increasing YPR can be reduced because of discarding (Walters & Huntsman, 1986; Lowe *et al.*, 1991). If the introduction or increase of an existing minimal size limit is accompanied by no change in targeting practices and all discarded fish die, magnitudes and size-distributions of catches will be unchanged and the minimal size limit will not have reduced mortality for any size of fish. Lowe *et al.* (1991) used a YPR model that incorporated mortality of discards for undersized fish to examine the potential of increasing yield in the fishery for sablefish in the Gulf of Alaska. Their approach specifically examined the influence of including or excluding the mortality of discards in the analysis. With great fishing mortality and no mortality of discards, YPR increased with increasing size limits. When mortality of discards was included, yields decreased with increasing size-limits. They concluded that minimal size-limits would be ineffective because fishing mortality in the fishery was less than that necessary for an increase in YPR and that a size-limit could be detrimental because of discard mortality.

Chen *et al.* (1998) described a YPR model for sequential fisheries that incorporated a size-dependent difference in spatial distribution of fish and differences in selection patterns of fishing gears between inshore and offshore waters. This model was applied to a simulated fishery based on the fishery for redfish off the coast of NSW and demonstrated a linkage between the fishing mortality on inshore grounds (< 60 m depth) where the majority of the catch was discarded and YPR from the commercial fishery in offshore waters (> 60 m depth).

A review of the theoretical impact of including data about discards in models to assess fisheries was provided by ICES (1986, cited in Alverson *et al.*, 1994). A conclusion from this review was that inclusion of data about discards could, in some cases, drastically alter perceptions of the status of exploitation of stocks and the yields accruing from changes in regulations. Consequences of ignoring discards were considered separately for the retrospective and predictive components of models. Retrospective assessments often combine estimates of catch-at-age or catch-at-length with relative indices of abundance, resulting in trends in size of stock and rates of fishing mortality. Failure to account for discards (or more generally any unaccounted fishing mortality) may have several effects: (i) if discards are mainly relatively small/young fish, then fishing mortality and, in particular, the stock size of small/young fish will be underestimated; (ii) this may or may not have significant consequences for stock sizes at older ages and larger sizes; (iii) overall goodness-of-fit of the model may be compromised, particularly if indices of relative abundance exclude small/young fish, but this effect may be variable; (iv) exclusion of discards of older/larger fish will have a negative effect on estimates of biomass, recruitment and numbers-at-age in the stock and the overall goodness-of-fit of the model; (v) the effect on fishing mortality of excluding discards of older/larger fish may be variable. The consequences of ignoring discards, in making predictions about a fishery, depends on the types of predictions being made, assumptions about the magnitude of future discarding, whether this discarding is constant or variable and whether partial recruitment (exploitation patterns at age or length) is constant or changed (e.g. as a result of changes in selectivity of fishing gear). In the case of a short-term TAC forecast, assuming constant partial recruitment and a constant fraction of discards in the catch, exclusion of discards from the model will have no effect on predictions of yield. In contrast, if discards are variable from year to year but predictable, then there will be some impact on the calculations. Long-term calculations, such as equilibrium YPR, particularly for variable proportions of discards are the most sensitive to excluding data about discarding. For models assuming a changing partial recruitment and variable recruitment, predictions of yield are very sensitive to the exclusion of data about discards (ICES, 1986, cited in Alverson *et al.*, 1994).

Managerial objectives and stock assessment in the SEF

As for any fishery, the influence of including information about discarding in stock assessments for species caught by fish trawlers off the NSW coast depends on the methods used for stock assessment. These methods are dictated by the particular managerial objectives, strategies and performance indicators for the fishery. Although fish trawling off the NSW coast occurs in two jurisdictions, the majority of the catch occurs in the Commonwealth-managed SEF and the process of stock assessment for SEF quota species is managed by AFMA. Objectives, strategies and performance indicators for the SEF are documented within published fisheries assessments (Chesson, 1996, 1997; Tilzey, 1998, 1999). AFMA has both "overall" and "immediate" objectives for management of the SEF as follow:

OVERALL OBJECTIVES:

- *To ensure that SEF resources are utilised in a manner consistent with the principles of ecologically sustainable development and to maximise economic efficiency in the utilisation of fisheries resources.*
- *To promote the rebuilding of depleted fish stocks and to promote the identification and development of additional or under-utilised fish resources of the fishery.*

- *To implement effective and efficient fisheries management on behalf of the Commonwealth.*

IMMEDIATE OBJECTIVES (for the management of quota species):

- *To ensure the spawning or recruited biomass of specified species does not significantly decline below recent levels*
- *To maintain the long-term productivity of stock of specified species*
- *To rebuild the stocks of specified species to levels at which targeted commercial fishing may recommence*
- *To develop or increase the utilisation of species*
- *To develop mechanisms to forecast future catches of specified species*

AFMA's strategy for meeting these objectives is based on an annual review of stock assessments and associated review of TACs for quota species. Of the various strategies documented by AFMA (e.g. see Tilzey, 1999), those of most relevance to the stock assessment process are:

- *Where estimates of biomass are available and subject to specific biological advice to adopt an alternative figure, to ensure that the spawning biomass of particular species do not decline below 30 % of their level at the onset of significant commercial fishing.*
- *Where estimates of biomass are not yet available, but may be at some point in the future, to ensure that catch per unit effort (CPUE) is maintained above its lowest annual average level from 1986 to 1994.*

Associated performance indicators for these strategies are:

- *Estimation of current spawning biomass, where possible, compared to spawning biomass at the onset of significant commercial fishing*
- *The current annual CPUE for specified species is above its lowest annual average from 1986 to 1994.*

A summary of the methods and data contributing to stock assessments for SEF quota species are provided annually in a Fishery Assessment Report (see Staples & Tilzey, 1995; Chesson, 1996, 1997; Tilzey, 1998, 1999). During the period 1993-95 and in years subsequent to this, stock assessments have mainly been based on catch and effort data and a relatively small amount of biological information. As a result, most assessments were based on analyses of fishery-dependent CPUE trends rather than fishery-independent data and more complex models of population dynamics. Of particular relevance to this thesis are the methods used for the quota species that are important to the fishery off NSW and for which discarding is an issue. These are redfish, spotted trevalla, tiger flathead, blue warehou, gemfish, mirror dory and inshore and offshore ocean perch. Stock assessments for spotted warehou, mirror dory and ocean perches were based on analysis of "CPUE trends" (Chesson, 1996) and were therefore dependent on the quality of catch and CPUE data. Assessments based on "CPUE trends" and "Size-structure trends" (Chesson, 1996) were used for blue warehou and redfish. "Size- and age-structure trends" (Chesson, 1996) provided the basis for assessment of gemfish. Note that research effort has been applied to development of various age-structured models for gemfish, redfish and blue warehou in recent years (Tilzey, 1999). Whilst these models are making some contribution to an understanding of the dynamics of these stocks, they cannot yet be used in the formal assessment of the status of these stocks (against AFMA's performance criteria) because AFMA's performance indicators and strategies for managing these stocks still concern the maintenance of CPUE above the 1986-94 reference level rather than the 30 % spawning biomass objective/performance indicator appropriate for stocks "where estimates of biomass are available" (Tilzey, 1999; Rowling, pers. comm.).

Objectives of this chapter

Analysis of the strengths, weaknesses and alternatives for the objectives, strategies and performance indicators adopted by AFMA for this fishery is beyond the scope of this thesis. Similarly, analysis of the appropriateness of the various methods used for stock assessments and the assumption that fishery-dependent CPUE provides a useful index of abundance is not specifically considered. Rather, the objectives of the analyses presented in this chapter concern only the impact of excluding or including data about magnitudes, size- and age-distributions of discards from assessments, as they are currently done or may be done in the near future.

The first objective of this chapter concerns how the inclusion of data about discards affects trends in CPUE, this being the basis of current stock assessment methods and performance criteria for the species of interest. Trends in CPUE, including and excluding the discarded component of catch, are compared to examine whether the inclusion of discards affects conclusions about trends in abundance. Specifically, the hypothesis that trends in CPUE based on total catch (including discards) will differ from trends in CPUE based on retained catch alone is tested for 6 SEF quota species.

Second, a biomass dynamics model is used to examine the issue of how the inclusion of estimates of discards of redfish affect estimates of parameters and conclusions about the current status of the redfish stock. The discarded component of catch and CPUE data on which this analysis is based is derived from observer-based estimates during the period 1993-97 and on multiple scenarios based on estimates provided by fishers for the period 1960-1992. This analysis provides some insight into the importance of including data about discards in a model of the population that provides estimates of biomass over the history of the fishery and one that has been widely used for fisheries assessments around the world. The biomass dynamic model is also used to examine the influence of the precision of estimates of discards on the precision of estimates of parameters in the model and biomass.

Third, observer-based size-distributions for retained and discarded redfish and a length-at-age matrix for this species are used to provide estimates of annual retained and discarded age-distributions of redfish during the period 1993-97. Such distributions provide the basis for age-structured models of the redfish population, so this analysis allows a test of the hypothesis that inclusion of data about discards is likely to affect estimates of parameters and conclusions based on age-structured modelling.

8.2 Materials and methods

8.2.1 Data used in this chapter

Data from the observer-survey for the period 1993-95 (upon which this thesis is based) was supplemented with data from an additional 2 years for the analyses completed in this chapter. During 1996-97, the NSW component of the "Scientific Monitoring Program" (SMP) for the SEF included an observer survey of identical design to that used during 1993-95 except that: (i) region "North", being outside the SEF, was not surveyed; and (ii) the targeted number of fisher-days per month for each of the regions surveyed (Ulladulla and Eden) was 18 fisher-days per quarter (Liggins, 1997, 1998), in contrast to the 24 fisher-days per quarter for the period 1993-95.

8.2.2 Differences in CPUE for retained and total catches during the period 1993-97

Estimates of CPUE calculated for retained and total catches were compared across the 5-year period 1993-97 for 6 species: redfish, spotted trevalla, tiger flathead, blue warehou, gemfish and mirror dory. These species were selected because they are SEF quota species (for which stock assessments are particularly important) and at least 5 % of the catch of each species was discarded during the period 1993-95 (see Chapter 5). The proportional difference between CPUE in year y relative to the mean CPUE for the period 1993-97 ($P\Delta CPUE_y$) was calculated for each year for each of these species:

$$P\Delta CPUE_y = \frac{CPUE_y - CPUE_{93-97}}{CPUE_{93-97}} \qquad \text{(Eq. 8.1)}$$

The standard error of $P\Delta CPUE_y$ was estimated using formulae for estimating standard errors of combinations of sample estimates (e.g. Mood *et al.*, 1974):

$$s(P\Delta CPUE_y) = \sqrt{P\Delta CPUE_y^2 . \left(\frac{s^2(CPUE_y - CPUE_{93-97})}{(CPUE_y - CPUE_{93-97})^2} + \frac{s^2(CPUE_{93-97})}{CPUE_{93-97}^2} \right)}$$

(Eq. 8.2)

with

$$s^2(CPUE_y - CPUE_{93-97}) = s^2(CPUE_y) + s^2(CPUE_{93-97})$$

(Eq. 8.3)

If, for any year, $P\Delta CPUE_y$ calculated for retained catch was significantly different to $P\Delta CPUE_y$ for total catch, it was concluded that trends in CPUE for that species during the period 1993-97 were dependent on whether discards were included in the calculation of CPUE. If proportional changes in CPUE for each of retained and discarded catch were identical during 1993-97, $P\Delta CPUE_y$ calculated annually for retained and total catch, would be identical. A statistical test for comparisons of retained and total $P\Delta CPUE_y$ was constructed such that the Type-I error rate across the 5 tests (one for each year) for each species was controlled at $P < 0.05$. $P\Delta CPUE_y$ for retained catches of these 6 species was calculated without error because catch, effort and CPUE for SEF quota species were known (not based on estimates from the observer survey). Approximate 99 % confidence intervals were calculated for annual estimates of $P\Delta CPUE_y$ for total catch as:

$P\Delta CPUE_t \pm t_{(\alpha=0.01,df=20)} \cdot s(P\Delta CPUE_t)$. The Type-I error rate was set at 0.01 for each comparison so that the Type-I error rate across 5 tests of significance (one per year) for each species was controlled below 0.05. A conservative estimate of $df = 20$ was based on the logic that annual estimates of CPUE were calculated using estimators stratified across 4 quarters with a sample size of approximately 24 fisher-days per quarter during 1993-95 and 18 fisher-days per quarter during 1996-97. The number of *df* associated with each annual estimate is between $(n-1)$ and $4(n-1)$ (e.g. Cochran, 1977), which corresponds to df = 23 to 92 for 1993-95 and df = 17 to 68 for 1996-97. Hence, df=20 is a conservative choice.

If, for any year, $P\Delta CPUE_y$ calculated for retained catch lies outside the confidence interval of $P\Delta CPUE_y$ calculated for total catch, then it is concluded that the pattern of CPUE for that species during the period 1993-97 depends on whether discards are included or excluded.

8.2.3 Effects of discarding on a biomass dynamic model for redfish

8.2.3.1 Model description

Specifications of biomass dynamic models and the methods used to fit them to observed catch and relative abundance data vary (Hilborn & Walters, 1992). Specification of a model and procedures for estimation described here are based on an implementation used for annual stock assessments of lobsters by NSW Fisheries and is described in Liggins *et al.* (1999).

A production model was used to represent the dynamics of the redfish stock as follows:

$$B_{t+1} = B_t + G_t - C_t \qquad \text{(Eq. 8.4)}$$

where B_t and B_{t+1} represent stock biomass at the beginning of years t and $t+1$, C_t is the total catch during the year t, and G_t is the natural increase of stock biomass during year t. A Schaefer or logistic type of model (see Hilborn & Walters, 1992) was used to calculate G_t:

$$G_t = r.\frac{B_t + B_{t+1}}{2}.(1 - \frac{B_t + B_{t+1}}{2.K}) \qquad \text{(Eq. 8.5)}$$

where parameter r is the instantaneous growth rate of the stock and K is the carrying capacity or biomass of the exploitable virgin stock. Replacing G_t in equation (8.4) with equation (8.5), B_{t+1} can be calculated as:

$$B_{t+1} = \frac{\sqrt{g^2 + 4A.h} - g}{2h} \qquad \text{(Eq. 8.6)}$$

where $g = 1 + \frac{r.B_t}{2.K} - \frac{r}{2}$, $h = \frac{r}{4.K}$ and $A = B_t + \frac{r}{2}B_t\ (1 - \frac{B_t}{2.K}) - C_t$

Thus, biomass at the beginning of a year can be estimated from the biomass at the beginning of the previous year if the catch C_t and parameters r and K are known.

Because biomass cannot be measured directly, B must be related to an index of abundance (I) that can be observed in the fishery. In this analysis, the index is provided by a CPUE series derived from the commercial fishery for redfish (see 8.2.2.2) and it was assumed that biomass is directly proportional to CPUE and thus:

$$I_t = q.B_t e^{\varepsilon_{I,t}} \qquad \text{(Eq. 8.7)}$$

where q is the catchability coefficient, $\varepsilon_{I,t} \in N(0,\sigma_I^2)$ is the error term and I_t is the CPUE observed in year t.

For this analysis, it was assumed that the biomass of the stock at the beginning of 1960 (B_{1960}) was an estimate of the exploitable virgin biomass (K). Thus, there were 3 parameters to be estimated (r, K, and q).

Because the reported landings of redfish for the period 1960-97 and the CPUE based on reported landings for the period 1975-97 do not include discarded catches, an adjustment factor was incorporated in the model using the mean estimate of the proportion of total catch discarded in a given year (mpD_t) and upper and lower limits for the proportion discarded in a year ($ulpD_t$ and $llpD_t$ respectively). The adjustment factor pD_t (the proportion of total catch discarded in year t) that was used to adjust catch and CPUE data in year t was estimated by randomly sampling a truncated normal distribution $N(mpD_t, s^2(mpD_t))$ with the upper and lower limits of $ulpD_t$ and $llpD_t$. Thus, in a single run of the model, the total catch and CPUE for each year (t), could be estimated as:

C_t = *(reported landings of redfish) / (1-pD_t)* and

$CPUE_t$ = *"reported landings" $CPUE_t$ / (1-pD_t)*

The probability sampling of the adjustment factor for proportional discards described above incorporates the uncertainty associated with estimates of the proportional discards factor into the model and estimation of parameters. By fitting the model to replicates of the catch and effort data (replicate data-sets being based on randomly sampling pD_t for each year in each replicate run of the model), uncertainties in estimates of discards will be reflected in the estimated confidence limits of the estimated parameters of the biomass dynamics model (r, K and q).

A least-squares (L) based observation-error estimator (e.g. Hilborn & Walters 1992) was used to fit the model to the observed catch and CPUE data:

$$L(C_t, I_t / \hat{r}, \hat{K}, \hat{q}) = \sum_{t=1975}^{1997} (\hat{\upsilon}_t)^2 \qquad \text{(Eq. 8.8)}$$

in which: $\hat{\upsilon}_t = \ln(I_t) - \ln(q.B_t)$

where I_t is the CPUE in fishing year t. By including Equations (Eq 8.4) and (Eq. 8.5) and minimising L in Equation (Eq. 8.8), parameters r, K and q can be estimated.

8.2.3.2 Catch and CPUE data used to fit the model

Annual landed catches of redfish since 1960 were based on data described in recent stock assessments for redfish (e.g. Rowling, 2001). A CPUE series for the years 1975-1997 was used to provide an index of abundance with which to fit the biomass dynamics model. This CPUE series was based on: (i) estimates of fishing effort for depths in which redfish are caught (50-400 m) for the years 1975-1993 (K. Rowling, pers. comm; and see Appendix 3 of Rowling, 2001) and (ii) estimates of CPUE from the observer survey during 1993-97.

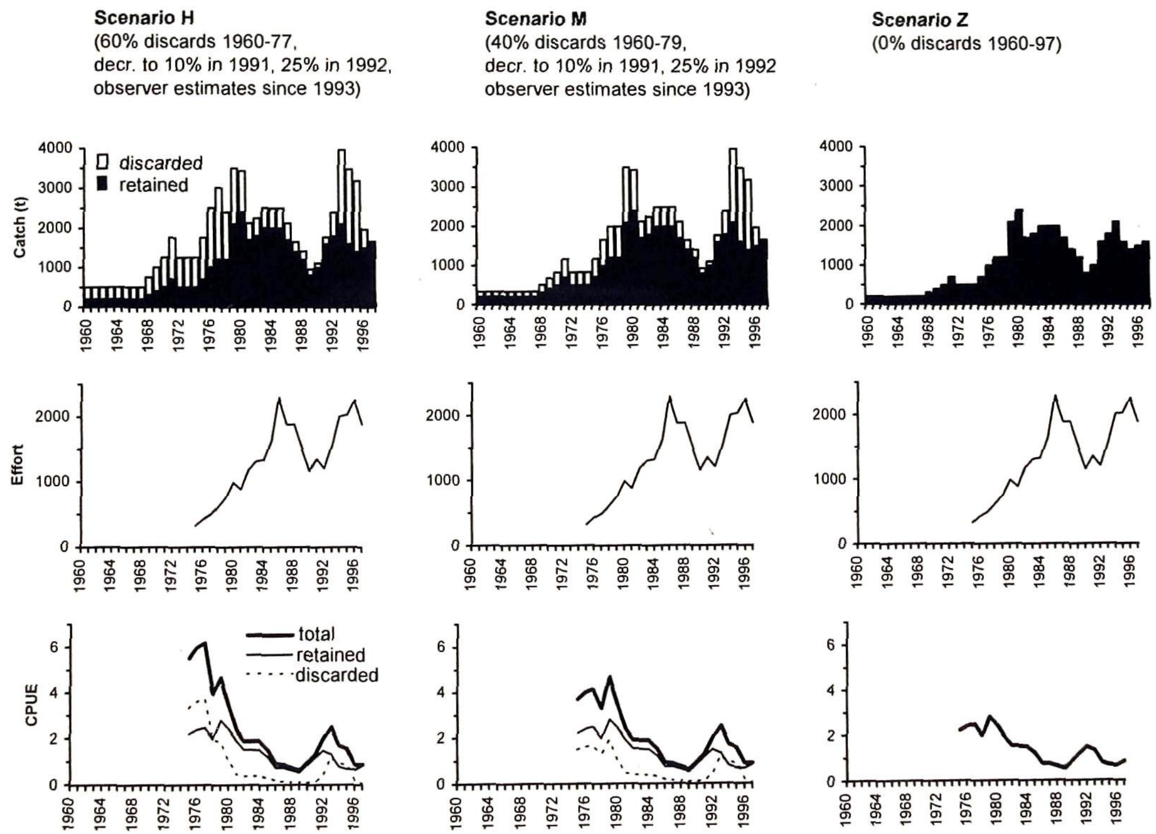
Because observer-based estimates of rates of discarding are only available for redfish for years since 1993, several scenarios representing alternative histories of discarding were used to fit the biomass dynamic model. The first, "Scenario-H", assumes relatively great discarding (60 % of total catch) during the period 1960-1977, decreasing to 10 % discards in 1991, 25 % discards in 1992 and then the observer-based estimates for the years 1993-1997 (Fig. 8.1, Appendix A.8.1.1). This scenario is based on a time-series of estimates of discarded proportions of total catch provided by experienced fishers to the Redfish Stock Assessment Group (Rowling, 2001). Note that these fishers estimated that 80 % of the catch of redfish was discarded during the period 1960-75 whereas Scenario-H assumes slightly less discarding (60 %) during these years. Preliminary attempts to fit the biomass dynamic model to data incorporating 80 % discards failed. A second scenario "Scenario-M" assumes a medium level of discarding (40 % of catch) during the years 1960-1979 and from then on is identical to Scenario-H (Fig. 8.1, Appendix A.8.1.2). A third scenario "Scenario-Z" assumes zero discards for all years (Fig. 8.1, Appendix A.8.1.3).

8.2.3.3 The effect of discarding on parameter estimates

To measure the sensitivity of parameter estimates (r, K and q) to different historical levels of discarding, the biomass dynamic model was fitted to the catch and CPUE data for each of the 3 discarding scenarios (scenarios H, M and Z). Model parameters were estimated using a

Figure 8.1

Three scenarios of historical catch and CPUE data used to fit a biomass dynamic model for redfish



deterministic model that ignored the uncertainty associated with estimates of discards for individual years (i.e. $pD_t = mpD_t$ for each year). Based on the resulting estimates of *K*, *r* and *q*, the maximum sustainable yield ($MSY = r.K/4$) and the depletion of exploitable biomass (B_{1998}/B_{1960}, with $B_{1960} = K$) were calculated. Estimates of exploitable biomass were plotted for the period 1960-1998.

The deterministic model was also used to estimate parameters *r* and *q* of the biomass dynamic model for a range of assumed values of initial biomass: $K = B_{1960} =$ 10,000 t; 20,000 t; 30,000 t; 40,000 t and 50,000 t. These assumed values of B_{1960} were selected as being reasonable, based on: (i) the range of estimates of K; and (ii) estimates from a cohort analysis described in Rowling (2001). This analysis provided measurement of the effect of the different historical levels of discarding (the 3 scenarios) on the model outputs for different values of $K = B_{1960}$. As before, *MSY* and B_{1998}/B_{1960}, were calculated and observed and fitted CPUE for the period 1975-97 and estimates of annual exploitable biomass were plotted for the period 1960-1998.

8.2.3.4 Effect of precision of estimates of discarding on precision of estimates of parameters

To assess the effect of the precision of estimates of discards on the precision of estimates of parameters (*r*, *K* and *q*) and derived variables (*MSY*, B_{1998}/B_{1960}), the biomass dynamics model was fitted 1000 times, for each of 3 scenarios. For scenario "Prec-7.5%", the CV of estimates of the proportion of catch discarded was set at 0.075 and the distribution was truncated at +/- 0.15 times the mean proportion of catch discarded (i.e. pD_t was randomly sampled from $N(mpD_t, s^2(mpD_t))$ with $s(mpD_t)/mpD_t = 0.075$ and with $llpD_t = mpD_t - 0.15.mpD_t$ and $ulpD_t = mpD_t + 0.15.mpD_t$). The precision of estimates was halved (i.e. the CV was doubled) for a second scenario "Prec-15%" and halved again for the third scenario "Prec-30%".

For each of these scenarios, the mean, SD, SD/mean, median, 5th and 95th percentiles of the 1000 estimates of *K*, *r*, *q*, *MSY*, B_{1998}, B_{1998}/B_{1960} were calculated.

8.2.4 Catch at age for redfish

Between 1991 and 1997, a sample of 5,064 redfish was obtained from commercial catches for the purpose of estimating an age-length relationships for redfish (Rowling, 2001). Recorded lengths and otoliths extracted from these fish were supplied to the Central Ageing Facility (CAF). The age-length key for all redfish aged by the CAF between 1991 and 1997 (produced by the CAF and published in Rowling (2001), see Appendix A.8.2) was used to convert size-distributions of retained and discarded redfish catches for the period 1993-97 to age-distributions of retained and discarded redfish for each year.

8.3 Results

8.3.1 Trends in CPUE for retained and total catches during the period 1993-97

Significant differences between $P\Delta CPUE_t$ calculated for retained and total catch were found for 5 of the 6 species examined (Fig. 8.2). It was therefore concluded that trends in CPUE during the period 1993-97 for redfish, tiger flathead, blue warehou, gemfish and mirror dory are dependent on whether or not discards are included in the calculation of CPUE. Blue warehou was the only species examined for which inclusion of discarded catches did not affect trends in CPUE.

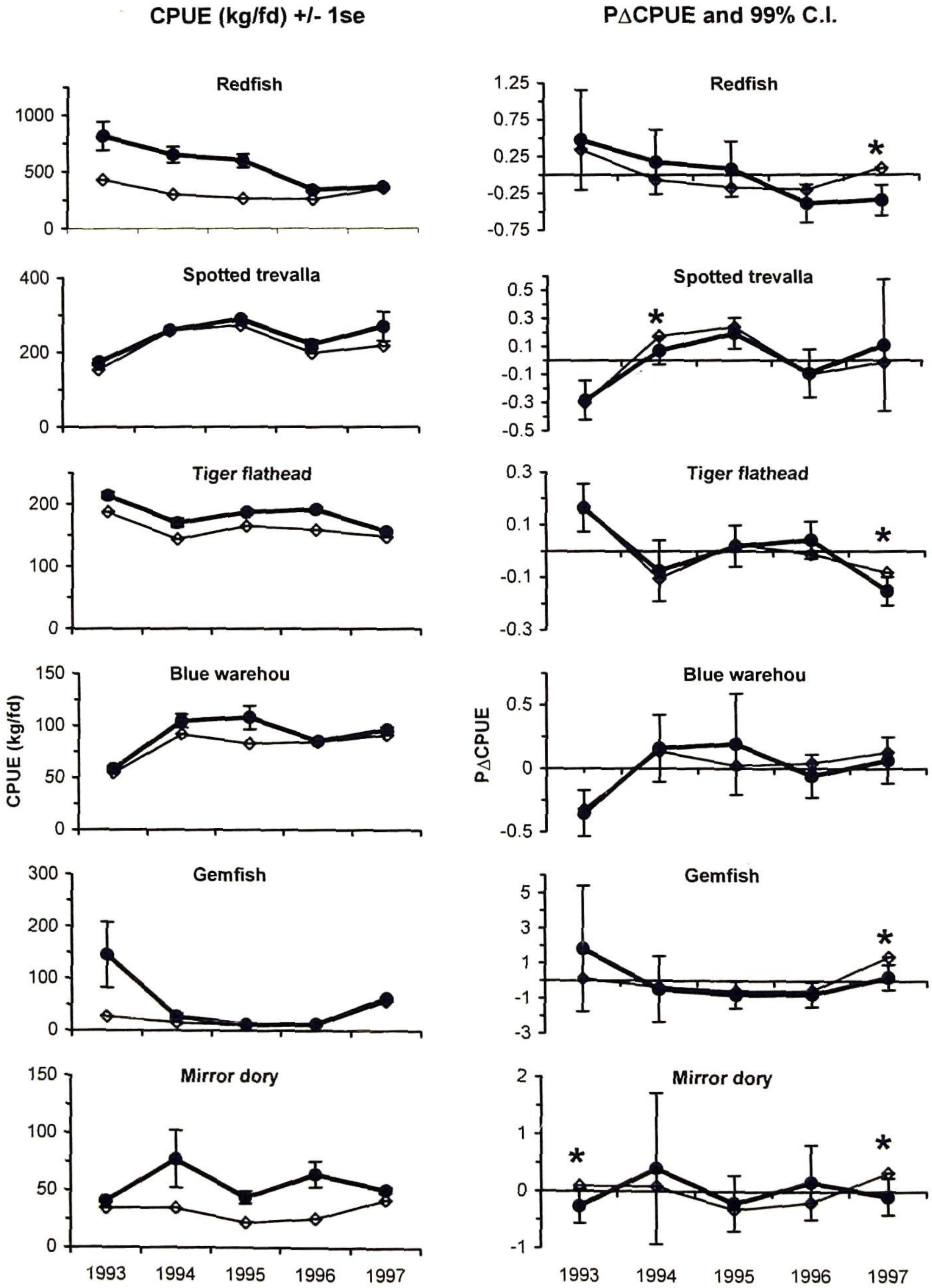
$P\Delta CPUE_{1997}$ for the total catch of redfish was -0.34 (99 % C.I.: -0.55 to -0.13) compared to 0.09 for retained catch. In 1997, CPUE for total catch was approximately 34 % less than the 1993-97 average whilst CPUE for retained catch was approximately 9 % greater than the 1993-97 average (Fig. 8.2). For spotted trevalla, CPUE trends for retained and total catches diverge in 1994 when $P\Delta CPUE_{1994}$ for total catch was 0.07 (99 % C.I.: -0.03 to 0.167) compared to 0.17 for retained catch. For tiger flathead, $P\Delta CPUE_{1997}$ for total catch (-0.15, 99 % C.I.: -0.21 to -0.10) was significantly less than $P\Delta CPUE_{1997}$ for retained catch (-0.08). For gemfish, $P\Delta CPUE_{1997}$ for total catch (0.22, 99 % C.I.: -0.50 to 0.93) was significantly less than $P\Delta CPUE_{1997}$ for retained catch (1.37). Significant differences between $P\Delta CPUE$ for retained and total catch were found for both 1993 and 1997 for mirror dory. For this species,

Figure 8.2

CPUE and proportional change in CPUE (PΔCPUE), for retained and total catch, during 1993-97, for 8 SEF quota species

——— Retained catch, ——— Total catch,

** denotes significant difference between PΔCPUE for retained and total catch (note that the critical p-value for individual tests = 0.01, so that the Type-I error rate across the 5 significance tests for each species is approx. p = 0.05)*



$P\Delta CPUE_{1993}$ for total catch (-0.26, 99 % C.I.: -0.56 to 0.03) was significantly smaller than for retained catch (0.09) and $P\Delta CPUE_{1997}$ for total catch (-0.09, 99 % C.I.: -0.40 to 0.23) was significantly smaller than for retained catch (0.33).

8.3.2 Effects of discarding on a biomass dynamic model for redfish

8.3.2.1 The effect of discarding on parameter estimates

Estimated values of the parameters K, r and q depended on the levels of historical discarding of redfish included in the model through the various scenarios examined. Estimated values of K (i.e. B_{1960}) were 51,900 t for Scenario-H, 25,400 t for Scenario-M and 4,800 t for Scenario-Z (Table 8.1). Estimates of r were 0.64, 0.26 and 1.46 respectively for the 3 scenarios. Estimates of the catchability coefficient, q, were 1.30 x 10^{-4}, 1.59 x 10^{-4} and 6.18 x 10^{-4} for scenarios H, M and Z (Table 8.1). As the level of historical discarding increased (scenario Z: zero discards; M: 40 % initially; H: 60 % initially), estimates of K increased and estimates of r and q decreased. Estimated MSY was greatest for the zero discards scenario, Z, (1,800 t) and least for the greatest level of discards (Scenario-H, 800 t). Exploitable biomass was depleted to 14.8 % of original biomass (B_{1998}/B_{1960}) using Scenario-Z, 15.3 % using Scenario-M and 8.2 % using Scenario-H (Table 8.1).

When various values of K were assumed so that only model parameters r and q were estimated, estimates of r and q decreased as the level of historical discarding was increased (progression through scenarios Z, M and H), for all values of K. Similarly, for each assumed value of K, estimates of MSY increased with levels of historical discarding and estimates of B_{1998}/B_{1960} decreased with historical discarding (Table 8.1). Depletion of the exploitable stock at the commencement of 1998 was greatest for Scenario-H and least for Scenario-Z for all assumed values of K and also when parameter K was estimated from the model. This pattern applied for most years within the period 1960-1997, except for the early 1990's when, assuming values of K in the range 10,000 – 40,000 t, depletion of biomass was greater for Scenario-Z than for Scenario-M and/or Scenario-H (Fig. 8.3).

Table 8.1

Estimates of parameters (*K, r, q*) and derived quantities (*MSY*, B_{1998}/B_{1960}) for a biomass dynamic model of the redfish population

Parameters of the biomass dynamic model were estimated for various scenarios: based on 3 different historical patterns of discarding (H - high; M - medium and Z - zero discards); and whether parameter *K* was estimated (fit K) or set at given values

Description of scenarios			Parameter estimates			Derived variables	
Scenario	Historical discarding	Set or fit K ($\times 10^3$ t)	$K = B_{1960}$ ($\times 10^3$ t)	r	q ($\times 10^{-4}$)	MSY ($\times 10^3$ t)	B_{1998}/B_{1960} (%)
H-10	60% initially, 1993-97 observed	set K = 10	(10.0)	-	-	-	-
H-20		set K = 20	(20.0)	0.391	3.33	1.96	4.9
H-30		set K = 30	(30.0)	0.215	2.33	1.61	6.6
H-40		set K = 40	(40.0)	0.126	1.68	1.26	7.5
H-50		set K = 50	(50.0)	0.072	1.35	0.90	8.1
H-fit		fit K	51.9	0.064	1.30	0.83	8.2
M-10	40% initially, 1993-97 observed	set K = 10	(10.0)	0.891	4.02	2.23	8.6
M-20		set K = 20	(20.0)	0.369	2.03	1.85	14.4
M-fit		fit K	25.4	0.263	1.59	1.67	15.3
M-30		set K = 30	(30.0)	0.202	1.34	1.52	15.9
M-40		set K = 40	(40.0)	0.118	1.00	1.18	16.9
M-50		set K = 50	(50.0)	0.067	0.79	0.84	17.5
Z-fit	Zero discards	fit K	4.8	1.462	6.18	1.75	14.8
Z-10		set K = 10	(10.0)	0.595	2.62	1.49	19.5
Z-20		set K = 20	(20.0)	0.231	1.20	1.16	23.1
Z-30		set K = 30	(30.0)	0.112	0.77	0.84	24.5
Z-40		set K = 40	(40.0)	0.051	0.56	0.51	25.1
Z-50		set K = 50	(50.0)	0.014	0.44	0.18	25.5

The general result is that estimated values of parameters (K, r and q) and derived variables used in fisheries management (MSY, stock depletion) depended on the assumed levels of historical discarding.

8.3.2.2 The effect of the precision of estimates of discarding on precision of parameter estimates

Precisions of estimates of K, R, q, MSY, B_{1998} and B_{1998}/B_{1960} decreased as the precision of the estimated proportion of discarded catch in each year decreased (Table 8.2). When the precision of the estimated proportion of catch discarded was increased by a factor of 4 (i.e. Scenario-Prec-0.075 compared to Scenario-Prec-0.30), the precision of: estimates of K increased by a factor of 3.7 (CV=SD/mean = 0.145 compared to 0.535); estimates of r by a factor of 7.1 (CV = 0.216 compared to 1.542); estimates of q by 5.5 (CV = 0.17 compared to 0.93); estimates of MSY by 6.4 (CV = 0.066 compared to 0.421); estimates of B_{1998} by 3.8 (CV = 0.184 compared to 0.693); estimates of B_{1998}/B_{1960} by 8.4 (CV = 0.054 compared to 0.452).

An important consequence of precision achieved for the 3 scenarios presented here is the effect on confidence intervals. The 5^{th} percentile of the distribution of estimates of B_{1998}/B_{1960} was 0.137 for scenario Prec-0.075, 0.114 for Prec-0.15 and 0.023 for Prec-0.30. If an objective for the fishery was that biomass should be maintained above some specified level (in terms of B_{1998}/B_{1960}) with some specified level of confidence (say 95 %), then the precision of estimates of discards clearly has a huge impact on assessment against this objective.

8.3.3 Catch at age for redfish

Not surprisingly, general patterns in the variation among annual size-distributions are also apparent among the age-distributions (Fig. 8.4). In contrast to the years 1993-96, comparatively few redfish less than 15 cm in length and less than 3 years of age were caught during 1997. Relative numbers of redfish less than 15 cm were greatest during 1993 and 1994 and, consequently, the numbers of redfish of ages 1+, 2+ and 3+ were greatest during these

Figure 8.3

Depletion of exploitable biomass of redfish - biomass dynamic model

for multiple scenarios of the biomass dynamic model describing historical levels of discarding and for scenarios in which parameter *K* is estimated (fit) or set at given values (up to 60,000 t)

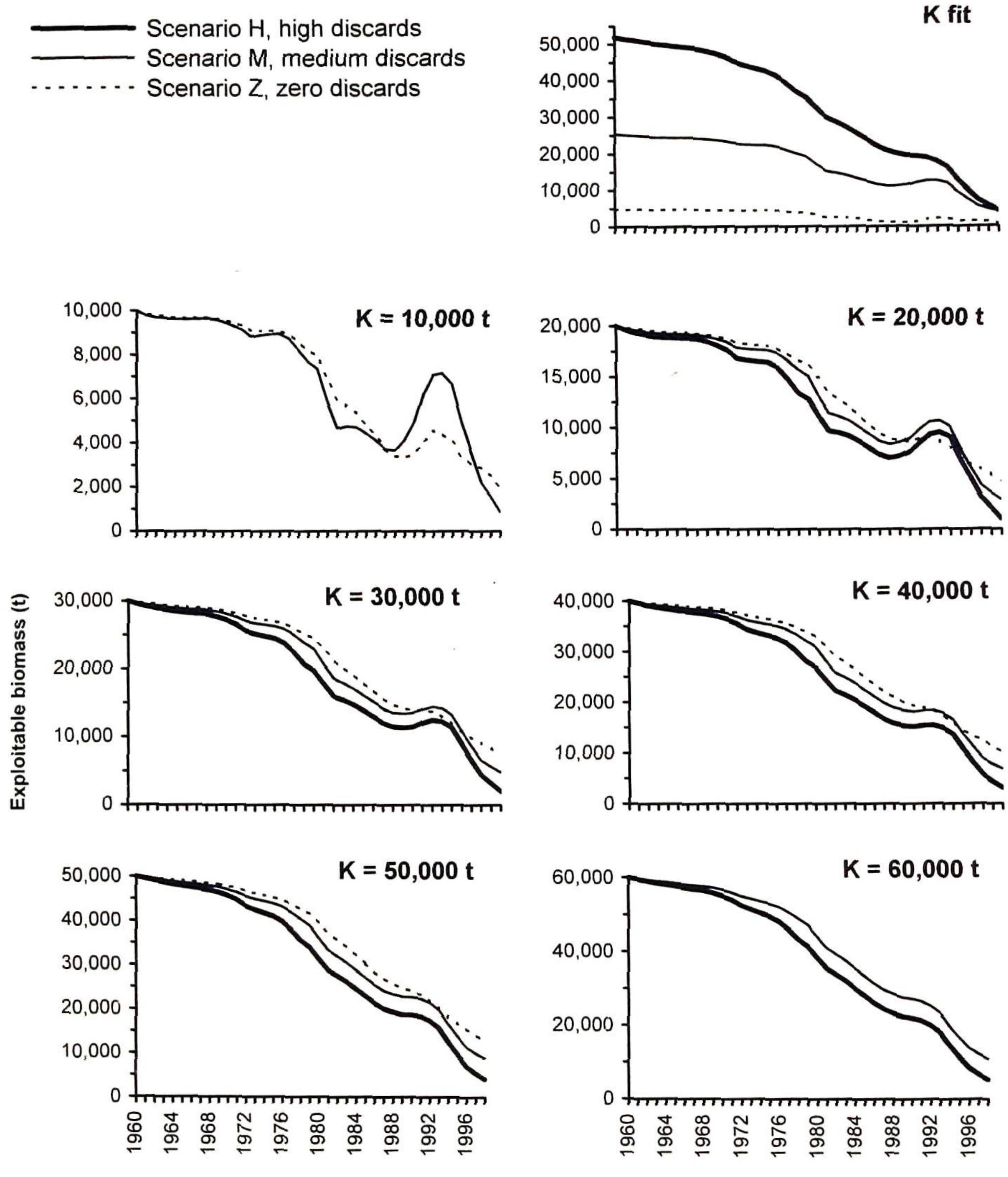


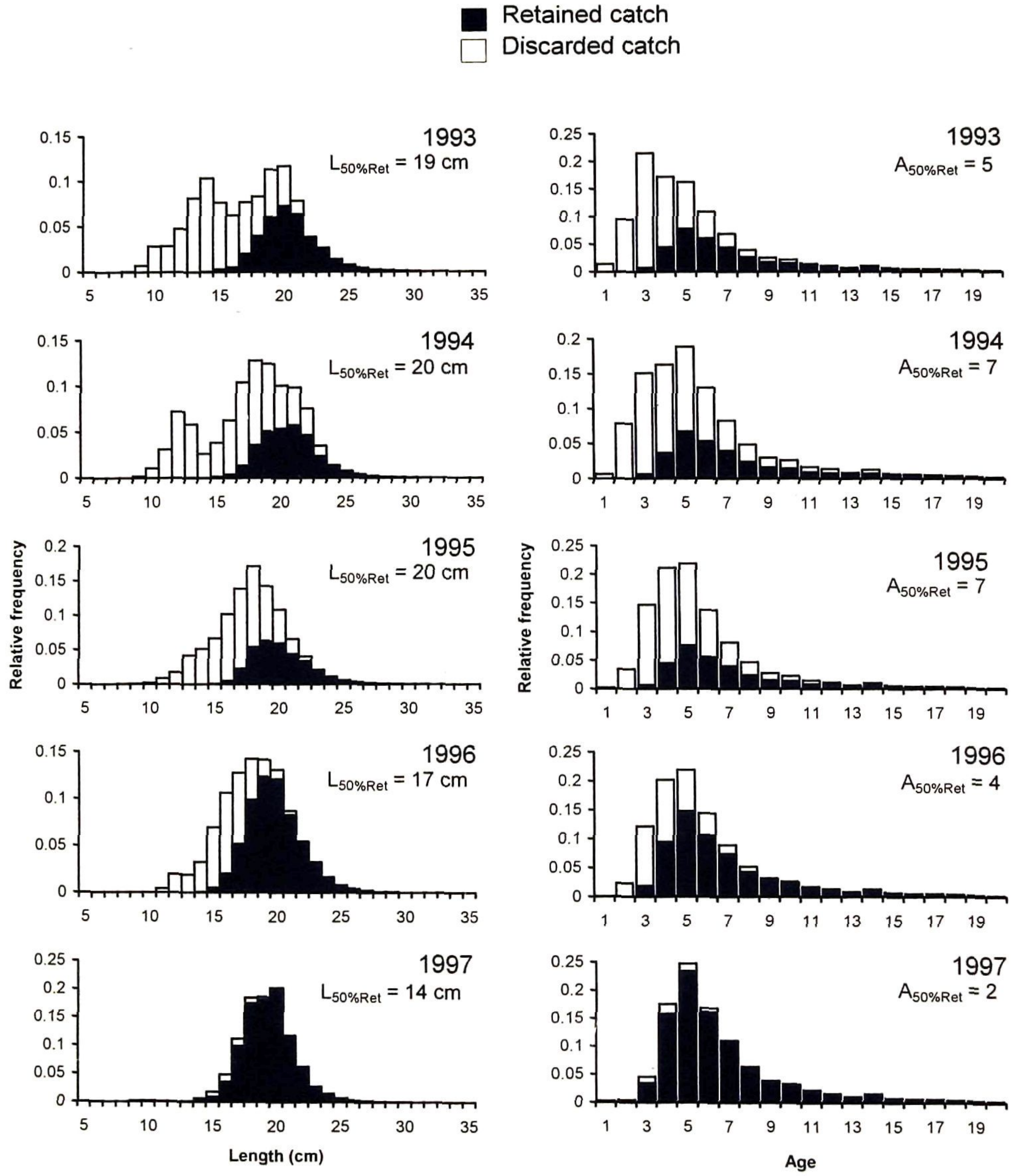
Table 8.2

Effect of precision of the estimated proportion of catch discarded on on the precision of estimated parameters of the biomass dynamic model

CV discard proportion =	**0.075**	**0.15**	**0.30**
Truncate distribution at +/- :	**0.15**	**0.30**	**0.60**
$K = B_{1960}$ (t)			
mean	25,464	28,027	32,797
SD	3,680	9,287	17,552
SD/mean	0.145	0.331	0.535
median	25,410	27,303	30,802
5th percentile	19,448	12,935	8,168
95th percentile	31,939	43,967	63,614
r			
mean	0.269	0.282	0.362
SD	0.058	0.188	0.558
SD/mean	0.216	0.667	1.542
median	0.261	0.238	0.202
5th percentile	0.186	0.102	0.032
95th percentile	0.378	0.632	1.174
q			
mean	1.64E-04	1.72E-04	2.22E-05
SD	2.78E-05	9.30E-05	2.06E-05
SD/mean	0.170	0.544	0.93
median	1.60E-04	1.48E-04	1.40E-05
5th percentile	1.24E-04	8.90E-05	6.00E-06
95th percentile	2.17E-04	3.55E-04	6.80E-05
MSY (t)			
mean	1,662	1,614	1,549
SD	110	291	652
SD/mean	0.066	0.181	0.421
median	1,664	1,628	1,556
5th percentile	1,475	1,145	490
95th percentile	1,838	2,076	2,473
B_{1998} (t)			
mean	3,872	4,374	4,719
SD	711	1,776	3,271
SD/mean	0.184	0.406	0.693
median	3,861	4,270	4,319
5th percentile	2,695	1,416	180
95th percentile	5,073	7,405	10,503
B_{1998}/B_{1960}			
mean	0.151	0.151	0.127
SD	0.008	0.021	0.058
SD/mean	0.054	0.137	0.452
median	0.152	0.155	0.136
5th percentile	0.137	0.114	0.023
95th percentile	0.163	0.179	0.187

Figure 8.4

Annual size- and age-distributions for retained and discarded catches of redfish, regions Ulladulla and Eden combined, 1993-97



years. The overlap of annual age-distributions of retained and discarded catches corresponds with the overlap for the annual retained and discarded size-distributions. The length at which 50 % of the redfish catch ($L_{50\%Ret}$) was retained and the age at which 50 % of the catch was retained ($A_{50\%Ret}$) in each year were positively correlated ($r = 0.971$, df = 3, $p < 0.01$).

As for the length-frequency distributions, age-distributions for retained redfish provided a poor representation of the age-distributions for the total catch of redfish during the years 1993-96 (Fig. 8.4). Moreover, the contribution of discarded redfish to the relative abundance of specific age-classes varied among age-classes and years. Therefore, the component of fishing mortality for each year-class of redfish that was attributable to the discarded component of catch, varied across the period 1993-97. Whilst the contribution of discards to the fishing mortality on ages greater than 14 did not vary among years, the importance of discards to fishing mortality on ages 1 - 14 varied greatly among years, evident by the variation of $A_{50\%Ret}$ among years: 5, 7, 7, 4 and 2 for the years 1993-97 respectively.

8.4 Discussion

The result that trends in CPUE differed depending on whether discards were included (total catch / effort) or excluded from the calculation (retained catch / effort) has important consequences for stock assessments for redfish, spotted trevalla, gemfish and mirror dory. For these species, AFMA's strategy for meeting its objectives is to "ensure that CPUE is maintained above its lowest annual average level from 1986 to 1994". CPUE calculated for the retained component of catch has been used as the performance indicator in assessments for these species between 1993 and the present (Staples & Tilzey, 1995; Chesson, 1996, 1997; Tilzey, 1998, 1999). Because estimates of discards for these species were not available during the first 7 years (1986-1992) of the reference period (1986-94), CPUE based on total catch cannot be used as a performance indicator. Consequently, on the basis that (i) fishery-dependent CPUE provides an index of abundance and (ii) a variable proportion of the catch is unaccounted for in the calculation of CPUE due to the exclusion of discards, the index of relative abundance based on CPUE is corrupted. It is therefore concluded that the existing assessment methodology for these species, based on measurements of changes in CPUE and excluding discarded catch, is biased by an unknown amount in any given year. The existing performance indicators and the strategies for meeting objectives for the SEF are therefore inappropriate.

The strategy to maintain CPUE above the average value for the reference period 1988-94 is applicable if estimates of biomass are unavailable for a given species. If biomass estimates are available, AFMA's strategy is to maintain spawning biomass above 30 % of the pre-exploitation level. Results from the analyses in which a biomass dynamic model was fitted to catch and CPUE data for redfish demonstrated the influence of the inclusion of discards. In particular, estimates of B_{1998}/B_{1960} differed among scenarios in which discarding was ignored and those that assumed 40 % or 60 % of the catch of redfish were historically discarded (Table 8.1 and Fig. 8.3). Estimates of B_{1998}/B_{1960} for scenarios based on zero discarding ranged between 14.8 % and 25.5 %, considerably more optimistic than estimates for the scenarios in which discarding was incorporated (range 8.6 - 17.5 % for 40 % historical discarding and range 4.9 - 8.2 % for 60 % historical discarding). This clearly demonstrates the importance of including discards in assessment methodologies based on models that produce estimates of biomass.

Because the size-distributions of landed catches of many quota species are poor representations of size distributions of the total catch, the implication is that age-distributions that exclude discarded catches will also be biased in their representation of total catch. Annual age-distributions, calculated for retained and discarded components of redfish catches during 1993-97, confirmed that age-distributions of retained catches: (i) exclude catches of redfish aged 1+ and 2+ that are discarded; (ii) represent, but underestimate, the catches of redfish of ages 3+ and greater that are sometimes retained and sometimes discarded (Fig. 8.4). Consequently, if the age-distributions of discarded catches are unknown or ignored, fishing mortalities associated with ages of fish in these categories will be underestimated. The specific consequences of the observed patterns in age-distributions of retained and discarded catches suggest that age-structured models for redfish that ignore discards will underestimate fishing mortality and stock sizes for many age-classes (but particularly redfish of age 1+ to 10+) and underestimate exploitable biomass. Similarly, spawning biomass will be underestimated because female redfish mature at about 5-7 years of age (Tilzey, 1999) and large quantities of redfish aged 5-7 years and greater were discarded in years between 1993 and 1996. If spawning biomass were underestimated, estimates of recruitment would also be affected, unless recruitment is modelled as being independent of spawning biomass. A key feature of the annual age-distributions of redfish catches is that the proportion of redfish discarded at ages 3+ to approximately 14+ (Fig. 8.4), varied annually. Such annual variation in the proportions of redfish discarded at age combined with variable and unpredictable annual recruitment (implied by the annual variations in the number of 1+ and 2+ fish in catches in Fig. 8.4) suggest that, when discards are ignored, long-term predictions of yield and biomass will be biased and precision of such forecasts will be reduced.

This thesis has not used an age-structured model to explore the effects of the exclusion of discard data on this type of model. Just as it was necessary to use estimates of historical levels of discarding obtained from fishers to adjust time-series of catch and CPUE data based on landed catch, it is necessary to obtain historical estimates of age-distributions of retained and discarded catches of redfish if parameters of age-structured models are to be estimated using "observed" age-distributions. Whilst such historical age-distributions have been obtained by interviewing skippers who have been involved in the fishery since the 1960's (Rowling, 2001), the accuracy of such "observed" data is questionable. An age-structured model has, however, been developed (Rowling, 2001) which examined several scenarios, including one which assumed 40 % historical discarding and another that assumed 80 % discarding. Both scenarios assumed the same size- and age-distributions of historical discarding. Size-distributions of discards were assumed to be similar to those of retained catches during the 1960's and 70's with the mean and standard deviation of the sizes of discarded redfish decreasing through the 1980's through to 1992. Observed size-distributions were used for years since 1993. Estimates of the exploitable biomass in 1960 were 53,975 t for the "40 % discards" scenario and 74,118 t for the "80 % discards" scenario. Estimates for biomass at the commencement of 1999 were 5,786 t and 5,784 t respectively. Estimates of B_{1999}/B_{1960} were 11 % and 8 % respectively. These results demonstrate, as was the case with the biomass dynamic model described in this thesis, that the estimate of pre-exploitation biomass increased as the assumed level of historical discarding was increased and that the depletion of biomass was underestimated (i.e. B_{1999}/B_{1960} was overestimated) if historical discarding was underestimated.

Two of the conclusions drawn from the analyses presented here were that are: (i) trends in CPUE during the period 1993-97 differed significantly, depending on whether or not discards were included in the calculation; and (ii) estimates of parameters for the biomass dynamic model and biomasses differ, depending on whether discards were included. These are consistent with the few published studies that have addressed such issues. Inclusion of data about discards has affected conclusions from assessments of the effect on YPR of changes in selectivity of gears and mesh-size regulations (Walters & Huntsman, 1986; Pikitch, 1987, 1991; Lowe *et al.*, 1991; Chen *et al.*, 1998). The selection of a total allowable catch for the Spanish mackerel was affected by the inclusion of discards in the virtual population analysis used by Erhardt and Legault (1997). Similarly, forecasts of short- and long-term yields for yellowtail flounder in southern New England were sensitive to the inclusion of data about discards (Alverson *et al.*, 1994).

The conclusions from the present study have important consequences for future assessments of stocks and management of the SEF. First, these results demonstrate that the discarded component of catches should not be ignored because they significantly affect estimates of the status of stocks. Second, the question of how to estimate historical levels of discarding (magnitudes and size-distributions) becomes an important one, because of the dependence of estimates of pre-exploitation biomass and depletion over time on historical discarding. Third, the importance of an ongoing monitoring programme that includes estimation of magnitudes and size-distributions of discarded catches is clear. Moreover, the influence of the precision of estimates of discarded catches on the precision of estimates of parameters and biomass from the biomass dynamic model has been demonstrated (Table 8.2). Simulations using the models that are proposed for future assessments should be done so that, combined with a knowledge of variation in rates of discarding observed in the fishery, sample sizes can be chosen that will result in the necessary precision of estimates of discards which will, in turn, result in the desired precision of model-based estimates of biomass or depletion.

Chapter 9
Conclusions and general discussion

The logical structure of this thesis was based on a synthesis of several frameworks that have been proposed for dealing with the multiple issues associated with discarded catch and the step-wise approach of the framework used is reflected in the structure of this thesis (Chapter 1, Fig. 1.2). In this final chapter, the conclusions and discussion of the topics raised in this thesis are separated into 3 sections. First, a summary of the conclusions drawn from each phase of the project is provided (Section 9.1). Second, conclusions concerning the consequences for the fish trawl fishery off NSW is presented in Section 9.2. Finally, Section 9.3 concerns conclusions relating to issues that seem significant from a more global perspective.

9.1 Summary of conclusions from chapters in this thesis

The first phase of this thesis concerned the design and implementation of an observer survey to estimate the quantities and size-distributions of retained and discarded catches by fish trawlers off the coast of NSW (Chapter 2). Based on a pilot survey, it was concluded that the precision of estimates of magnitudes of discarded catches from the full-scale survey would be acceptable if 24 fisher-days were observed in each quarter (8 fisher-days per month), in each of the 3 regions in each of 3 years. The resultant design of the full-scale observer survey, logistics, methods for sub-sampling catches and collecting data and the strategies for achieving the co-operation and support of the fishing industry were ultimately successful. Despite some variation in the number of fisher-days sampled in each quarter of each year in each region, mean sample sizes per quarter were only slightly smaller than planned (mean samples per quarter being 23.2 fisher-days for North, 23.8 for Ulladulla and 23.8 for Eden) (Section 2.3 & Fig. 2.2).

The objective of the next phase of the project (Chapter 3) was to compare a range of alternative estimators to determine a method that was optimal, in terms of bias and precision, for estimating annual discards and total catches from the data collected. Bias and precision of stratified mean-per-unit (SMPU), combined ratio (Rc), combined regression (LRc), separate ratio (Rs) and separate regression (LRs) estimators for estimating 15 components of catch were compared. Using a bootstrap methodology to assess the relative importance of bias compared to 'root-mean-square-error" (RMSE, a measure comprising both precision and bias) it was concluded that Rs and LRs resulted in significant bias and were therefore unsuitable for use in this project (Section 3.3.1, Fig. 3.1). Based on comparisons of the relative precision of the SMPU, Rc and LRc estimators, it was concluded that: (i) precision of Rc and LRc estimates, using IRQS as auxiliary variable, exceeded the precision of SMPU estimates for 2 species (tiger flathead and jackass morwong) and (ii) precision of the SMPU estimator was equal to, or exceeded, that of Rc and LRc estimators for all other components of catch (Section 3.3.2, Table 3.1). It was concluded, therefore, that an optimal strategy for estimating rates of catch from the observer survey would be to use the SMPU estimator for components of catch with the exception of 2 species (tiger flathead and jackass morwong), for which the combined ratio estimator (Rc, using IRQS) would provide greater precision.

The "randomness" of the selection of fisher-days sampled during the observer survey was affected because: (i) some fishers refused to participate in the survey; (ii) it was not possible to identify the sampling frame (i.e. the population could not be enumerated) prior to sampling in each quarter; and (iii) fisher-days surveyed on multi-day trips at Eden were not sampled independently (Section 2.3 and Chapter 4). Moreover, the presence of an observer onboard a trawler may potentially have influenced fishing and discarding practices (Chapter 4). As a consequence of these factors, the issue of detecting bias in observer-based estimates of retained and discarded catches was addressed in the next phase of the project (Chapter 4 and Appendix A.4.1: Liggins *et al.*, 1997). Observer-based estimates of the magnitudes and size-distributions of retained catches were compared with independent, unbiased estimates (reported landings and size-distributions obtained from an auxiliary survey of catches landed at fishing co-operatives) that were available for a subset of species (species managed by catch quotas) caught in the fishery. Conclusions about bias in estimates of discarded components of catch were based on the premise that bias was unlikely to affect such estimates without also affecting estimates of retained catches of quota species. It was concluded that estimates of retained and discarded catches for the 3 year period 1993-95 were unaffected by significant bias. There was, however, some evidence of bias in estimates of magnitude of catch for each of the regions (Ulladulla and Eden) in 1 of the 3 years. Observer-based size-distributions were not significantly biased.

Based on data from the observer survey (Chapter 2), comparisons of the relative performance of alternative methods of estimating rates of catch (Chapter 3) and an evaluation of the significance of bias (Chapter 4), the objective of the next phase of the project was to provide a description of the composition of retained and discarded catches by fish trawlers off the NSW coast during the period 1993-95 (Chapter 5). The observer survey documented catches of 365 taxa, comprising 309 fin-fish, 34 crustacean, 12 mollusc, 4 echinoderm, 3 cnidarian, 1 annelid, 1 mammal and 1 reptile taxa (Section 5.3.1, Appendix A.5.1). Fin-fishes dominated discarded catches. Discarded catches were dominated by relatively few species (Section 5.3.3) and the fish discarded were usually smaller than 30 cm and consistently smaller than retained fish (with the exception of gemfish) (Section 5.3.4, Fig. 5.3). An estimated mean annual catch of 12,336 +/- 316 t (2,528 +/- 65 kg per fisher-day) of these taxa was taken by the combined fleets of the 3 regions (North, Ulladulla and Eden) surveyed in this study. Approximately 50 % of this catch, 6,223 +/- 302 t (1,275 +/- 62 kg/fisher-day) was discarded. An estimated 30 % of the catch of SEF quota species (1,815 +/- 190 t annually, 372 +/- 39 kg/fisher-day), 34 % of the catch of non-quota commercial species (1,009 +/- 89 t annually, 207 +/- 18 kg/fisher-day) and the entire catch of non-commercial species (3,399 +/- 167 t annually, 697 +/- 34 kg/fisher-day) were discarded (Section 5.3.2, Table 5.2, Fig. 5.1). Although no experiments were done to estimate the survival of discards, it was concluded that the mortality of discards was likely to be close to 100 % because of the relatively long duration of tows, the rapid decompression experienced by fish in being brought to the surface, the relatively long sorting time on deck prior to being discarded and observations of physical damage, obvious mortality and predation by sea-birds and sharks following discarding (Section 5.4). It was concluded that estimates of the magnitudes and size-distributions of retained (landed) catches were poor representations of the magnitudes and size-distributions of total catches for many species (Fig. 5.2, Table 5.3, Fig. 5.3).

Spatial and temporal factors affecting discarding were considered in Chapter 6. The hypothesis that mean rates of discarding (and retained catches) differed among regions, years and quarters was tested for the major partitions of catch and individual species and patterns of variation across these scales were described. It was concluded that rates of discarding differed among regions, years and quarters and was species-dependent (Sections 6.3.1 and 6.3.2, Figs. 6.1 and 6.2, Tables 6.1 and 6.2). There were, however, some general patterns. Rates of discarding differed greatly among regions, more so than among years and quarters. Catches were greatest at Eden, intermediate at Ulladulla and smaller in the northern region. The proportion of catch discarded and fishing effort were also greatest at Eden. There were significant seasonal patterns in rates of catch and discarding. Rates of total catch and discarded catch were greatest during the 3rd quarter in each region and year. Although inconsistent across regions and years, rates of discarding of other partitions of catch and several individual species tended to be greatest during the 3rd quarter. A general feature of the analyses of discards of individual species and for the partitions of catch that combined discards of multiple species (with the single exception of the partition for discards of "all species") was the significance of interactions among various combinations of the factors Region, Year and Quarter (Table 6.1). Another general result from the ANOVAs was the large proportion of variability that was unexplained by the factors examined (between 55 % and 67 % for the major partitions of catch and between 67 % and 93 % for individual species, Table 6.1). Differences in size-distributions of discards and discarding practices were identified among regions and years for commercial species (Section 6.3.3, Figs. 6.3 and 6.4, Appendices A.6.2.2 - A.6.2.5, Appendices A.6.3.1 - A.6.3.5). It was concluded that size-distributions of discards varied among regions and years for redfish and mirror dory. High-grading practices differed between the fleets of Ulladulla and Eden with the Ulladulla fleet retaining smaller fish. The hypothesis that the mean size of fish and proportion of catch retained increased with depth was tested for individual species. It was concluded that depth was an important determinant of discarding for the 5 species examined. Fish were smaller and a greater proportion of catches were discarded in shallower waters (Section 6.3.4, Fig. 6.5).

The influences of managerial regulations and market forces on discarding were examined in Chapter 7. Discarding of the various species caught off the NSW coast during 1993-95 was attributed among several factors or interactions between these factors (Table 7.4). It was concluded that protected species regulations forced the discarding of 3 species (Herbst's nurse shark, turtles and seals) although there was some illegal retention of Herbst's nurse sharks (Section 7.3.2). Fish shorter than the minimal legal length were generally discarded (Section 7.3.3, Fig. 7.1.a). Trip limits were the major factor affecting discarding of a single species (gemfish; Section 7.3.4). The direct effects of TAC regulations were only important in determining the discarding of ocean perch species during the latter part of 1993 (Section 7.3.5, Table 7.3). Factors concerning markets and economics were the major determinants of patterns of discarding for the majority of species (Section 7.4, Table 7.4). All non-commercial species (220 taxa) were discarded because of the lack of market for these species (Sections 7.3.1 and 7.4). For many commercial species, fish were consistently discarded because there was no market for very small fish (Section 7.4). High-grading of redfish, spotted trevalla, blue warehou, mirror dory, offshore ocean perch, inshore ocean perch and red-spot whiting was demonstrated (Section 7.4, Figs. 5.3, Table 7.4). It was also concluded that high-grading also occurred for many other species (based on mean weights of individual fish in retained and discarded catches) even though size-distribution data were not available for these species. Seasonal differences in high-grading practices, based on seasonal differences in market volumes and prices, were demonstrated for redfish (Section 7.3.6, Figs. 7.2 and 7.3). Although of minimal significance as a direct cause of discarding, it was also argued that the TAC/ITQ system of management in the SEF may have been an important component driving some of the high grading of several species (e.g. redfish in during 1993-95, ocean perches in 1994-95, spotted trevalla in 1993). The potential for quota-related high-grading to become a problem in the SEF if quotas become increasingly restrictive on fishers was also recognised. In addition to the conclusions made above, it was recognised that discarding also occurs for the broader reason that unwanted fish are caught in the first place. This simple statement emphasises the influence of: (i) biological and environmental factors influencing the distribution and abundance of species; (ii) the distribution and intensity of fishing effort in space and time and (iii) the selectivity of fishing gears, particularly the mesh-size and construction of cod-ends in trawl fisheries.

Consequences of discarding for assessment of stocks were considered in Chapter 8. Specifically, I considered the impact of excluding or including data about magnitudes, size- and age-distributions of discards from assessments, as they are currently done or may be done in the near future. The hypothesis that trends in CPUE based on total catch (including discards) differed from trends in CPUE based on retained catch alone was tested for 6 SEF quota species. It was concluded that trends in CPUE during the period 1993-97, for 5 of the 6 species examined, depended on whether or not discards were included in the calculation of CPUE (Section 8.3.1, Fig. 8.2). This conclusion has important consequences for stock assessments for redfish, spotted trevalla, gemfish and mirror dory. For each of these species, trends in CPUE provide the basis for one of the performance indicators for management of these species in the SEF (see Section 9.2.4). The hypothesis that the inclusion of estimates of discarded catches would affect estimates of parameters and trends in annual biomass for a biomass dynamic model of the redfish stock was tested. It was concluded that parameters of the model and estimates of biomass depletion (B_{1998}/B_{1960}) differed significantly among the various scenarios of historical discarding that were examined (Section 8.3.2.1, Figs. 8.2 and 8.3, Table 8.1). A positive relationship between the precision of estimates of discarded catches and the precision of estimates of model parameters and trends in biomass was also demonstrated (Section 8.3.2.2, Table 8.2). Size-distributions for retained and discarded catches of redfish and a length-at-age matrix for this species were used to provide estimates of annual retained and discarded age-distributions of redfish during the period 1993-97. As such distributions provide the basis for age-structured models of the redfish population, this analysis allowed a test of the hypothesis that inclusion of data about discards is likely to affect estimates of parameters and conclusions based on age-structured modelling. Patterns in annual age-distributions of retained versus total catches of redfish demonstrated that age-structured models that ignored discards would underestimate fishing mortality and stock sizes for many age-classes (Section 8.3.3, Fig. 8.4) and that exploitable biomass and spawning biomass would be underestimated. The general conclusion from this chapter was that the discarded component of catches should not be ignored during stock assessments because doing so would result in significant biases in the results and conclusions of assessments.

9.2 Consequences for the fish trawl fishery

9.2.1 Recognising issues concerning discards

Prior to the work reported in this thesis, knowledge of magnitudes, species compositions or size-compositions of discarded catches by fish trawlers off the NSW coast, operating in either NSW or Commonwealth SEF jurisdictions, was negligible. It had been reported that more than 90 species of finfish and invertebrates were routinely taken in the SEF (e.g. Staples & Tilzey, 1995) and, whilst the discarding of juveniles or unmarketable quantities of quota species and non-target species had been a long established practice, little was known of the extent of this practice (Tilzey, 1994). This project has documented catches of 365 taxa and an estimated mean annual catch of 12,336 +/- 316 t (2,528 +/- 65 kg per fisher-day) of which 6,223 +/- 302 t (1,275 +/- 62 kg/fisher-day) was discarded. The scale of discarding demonstrated in this fishery (Chapter 5, Table 5.2 & Fig. 5.1) and in other Australian fisheries (e.g. Kennelly, 1995; Buxton & Eayres, 1998) demanded that increased focus be placed upon the development of policies concerning discarding and strategic plans for research.

There have been several significant developments to this end during recent years. At the broadest scale within Australia, "*The National Policy on Fisheries Bycatch*" (AFFA, 2000a) was intended to provide a national framework for co-ordinating efforts to reduce by-catch and comprises guiding principles, strategies and a checklist for the development of fisheries specific action plans. Consistent with this policy, the "*Commonwealth Policy on Fisheries Bycatch*" (AFFA, 2000b) has been developed for fisheries managed by the Commonwealth and therefore includes the SEF. This policy incorporates guiding principles and core objectives. Interestingly and at odds with the definition of by-catch used in this thesis and in major reviews of the subject (e.g. Saila, 1983; Alverson *et al.*, 1994), the term "by-catch" as used in these policy documents includes: (i) the discarded catch and (ii) that part of the catch that does not reach the deck of the fishing vessel but is affected by interaction with the fishing gear. Thus, using the terminology used in this thesis, these policies actually concern discarded catch and several other sources of "unaccounted fishing mortality" (F_O, F_A, F_G, F_P and perhaps F_H, described in Section 1.2). Such a definition is confusing and potentially misleading because it is at odds with generally accepted definitions of by-catch, discarded catch and unaccounted fishing mortalities. Nonetheless, the guiding principles of these policies concern co-operative and transparent approaches, short-term and long-term considerations, the precautionary principle and, in particular,:

- the maintenance and improvement of *"the quality, diversity and availability of fisheries resources, and the integrity of the marine ecosystem into the future"*

- *"use of robust and practical biological reference points relating to by-catch, where possible, to make decisions on by-catch management. Develop by-catch reference points in consultation with stakeholders, recognising that in many cases there are limitations to the costs of determining these reference points. Where the use of biological reference points is not feasible, the precautionary principle will be used as the basis for decision making."*

- *"recognise the unique biological, ecological, economic and social nature of individual fisheries by developing by-catch action plans to address by-catch issues"*

Objectives of the policy are to: (i) reduce "by-catch" (i.e discards and other unaccounted fishing mortality); (ii) improve protection of vulnerable species; and (iii) arrive at decisions on the acceptable extent of ecological impacts. Possible strategies suggested to meet these objectives echo the various issues and management options discussed in this thesis. However, in addition to the unusual definition of the term "by-catch" in these policies, it is also unclear what specifically is meant by phrases such as "integrity of the marine ecosystem". Despite such deficiencies, the formulation of what are essentially policies concerning discarding (and other "unaccounted fishing mortalities") represents acknowledgement of the importance of these issues in the upper levels of Australia's bureaucracies.

Strategic research plans published by AFMA during the 1990's (e.g. AFMA, 2000) and, in particular, strategic research plans for the SEF (e.g. SETMAC, 1998) have also placed an increasing emphasis on issues concerning discarding. For example, the strategic research plan for the SEF (SETMAC, 1998) noted that an ongoing integrated scientific monitoring programme (incorporating an observer programme) underpins stock assessment as well as other research programmes for the SEF. Of the six major issues identified as requiring research in the future, 3 explicitly or implicitly concerned discarding: sustainability of stocks of quota species; discarding; and impacts of fishing on the marine environment.

Similarly, in contrast to fishery assessments for the SEF from the early 1990's (e.g. Staples & Tilzey, 1995), recent assessments (e.g. Tilzey, 1999): (i) distinguish between catch, retained catch and discarded catch; (ii) report summary data about discarded catches from observer surveys; and (iii) provide summaries of species assessments that incorporate information about discards.

9.2.2 The need for an ongoing monitoring programme

Following publication of estimates of magnitudes of discarded catches by fish trawlers off the NSW coast (preliminary reports to SEFAG and Liggins, 1996), the South East Trawl Management Advisory Committee (SETMAC) recognised the need for an ongoing monitoring programme in the fishery that included estimates of discarded catches. Consequently, an "Integrated scientific monitoring programme including port measuring and on-board sampling" (ISMP) was included in the strategic research plan for the SEF for the period 1995-2000 (SETMAC, 1995). The ISMP comprised an observer survey operating in SEF waters off NSW, Victoria and Tasmania and has been operating since 1996. Initially (1996-97), State fisheries agencies were funded to do the surveys in waters off their respective coasts. Since 1998, the Marine and Freshwater Resources Institute (MAFRI, Victoria) has taken responsibility for the ISMP in all SEF waters (Knuckey & Sporcic, 1999; Knuckey 2000).

Thus, annual estimates of rates of discarding have been available for the NSW component of the SEF since 1993 and for components of the SEF off Victoria and Tasmania since 1996. Databases managed by NSW Fisheries, MAFRI and BRS, annual reports from the ISMP (e.g. Knuckey & Sporcic, 1999; Knuckey 2000) and inclusion of data summaries in Fisheries assessment reports for the SEF (e.g. Tilzey, 1999) provide an important resource for stock assessments for this and interacting fisheries.

9.2.3 Interactions with other fisheries

Although discussion in this thesis has concentrated on the main species targeted in the fish trawl fishery off NSW, stocks and stock assessments for species targeted in other fisheries may also be directly affected by mortality that results from fish trawling. Many of the species caught by fish trawlers in NSW are also caught (as targeted catch or by-catch) in other regions and fisheries. Whilst information about the retained (landed) catch from fish trawling in NSW has previously been available for inclusion in stock assessments for other fisheries, estimates of discards provided by this project represent information that has previously been unavailable. Species discarded by fish trawlers in NSW that are important catches in other fisheries and regions are considered here.

Discards of SEF quota species (excluding species primarily caught in waters off NSW: eastern gemfish and redfish) are of obvious importance to the sectors of the SEF off the coasts of Victoria and Tasmania (see Tilzey, 1994, 1998). Snapper, rubberlip morwong, mulloway, gemfish, blue-eye trevalla and hapuku are species targeted in the NSW trap and line fishery (e.g. Fletcher & McVea, 2000, Tanner & Liggins, 1999, 2000) and were discarded by fish trawlers at mean rates per annum exceeding 1 tonne (Chapter 5). Similarly, species such as bream are retained and discarded by: fish trawlers in the northern region of the fishery in NSW (see Appendix A.6.2.1); several other fishing methods in the estuaries, beach and trap and line commercial fisheries of NSW (Fletcher & McVea, 2000, Tanner & Liggins, 1999, 2000); by commercial fisheries in Queensland; and recreational angling in NSW (Steffe *et al.*, 1996b) and Queensland. Several of the major target species of the fish trawl fishery are also taken by recreational anglers (redfish, tiger flathead, silver trevally, jackass morwong, ocean perches and john dory; Fletcher & McVea, 2000; Steffe *et al.*, 1996a, 1996b). A major conflict between the recreational sector and commercial sector concerns the capture and discard by trawlers of juveniles of inshore species targeted by recreational anglers (e.g. Kennelly, 1995; Harnwell, 1996; Liggins & Kennelly, 1996; Liggins *et al.*, 1996; Kennelly *et al.*, 1998; Schott, 1999). Species in this category that were discarded by fish trawlers at mean rates per annum exceeding 1 tonne include: eastern blue spot flathead, tarwhine, snapper, tailor, mulloway and rubberlip morwong (Chapter 5).

The total fishing mortality for a stock comprises components resulting from retained and discarded catch, in multiple commercial and recreational fisheries, in multiple jurisdictions (e.g. States). Consequently, it is important to have some measure of the catch, retained and discarded, for each of these components of mortality. In NSW, estimates of retained catches from commercial fisheries have been available since 1940-41 (Pease & Scribner, 1995) and recent surveys of discarding in estuarine and oceanic prawn trawl fisheries (Liggins & Kennelly, 1996; Liggins *et al.*, 1996; Kennelly *et al.*, 1998), the stow net fishery for prawns (Andrew *et al.*, 1995) and estuarine hauling fisheries (Gray *et al.*, 2001) are providing further data. The lack of information about the magnitude of catches by the recreational sector does, however, represent a significant gap. Whilst surveys of recreational catches in individual estuaries, sections of the coast or fisheries (e.g. Steffe *et al.*, 1996a, 1996b) suggest that such catches are significant for many species also taken by commercial fisheries, estimates of annual catches for the whole of NSW are not available. This situation is, however, about to change. A national survey of recreational catch, currently being done across all states of Australia, will provide an estimate of the total recreational catch for individual species in regions, states and for the whole of Australia. Moreover, there are plans to continue this survey in NSW, to provide an ongoing series of estimates of recreational catch (G. Henry, pers. comm.).

In summary, there has been considerable progress made in NSW in recent years to document retained and discarded catches from commercial and recreational fisheries. The results from the present project represent a significant contribution to this research effort. Note, however, that understanding the effects of fish trawling off the NSW coast are poorly understood. They potentially result from physical disturbance to benthic habitats by trawl gear and indirect effects of removals of fish on the ecosystem . This lack of knowledge is a general feature of fisheries globally and is discussed in Section 9.3.3.

9.2.4 The need to incorporate estimates of discards in stock assessments

The scale of discarding documented in this thesis and the results concerning the impacts of including data about discarding in fisheries models and stock assessments (Chapter 8) have clearly demonstrated the need to incorporate estimates of magnitudes, size- and age-distributions in methodologies for assessments. As a consequence of this work, data about discarding are now routinely included in fisheries models for SEF species such as redfish, gemfish and blue grenadier (e.g. Tilzey, 1999; Rowling, 2001). Whilst observer-based estimates of magnitudes and size-distributions are available for recent years, it is unavoidable that assumptions must be made about magnitudes and size-distributions of discarded catches in years prior to 1993. The only reasonable way to do this is to fit models to alternative sets of data. This was the approach used by the Redfish Stock Assessment Group (Rowling, 2001) and in this thesis (i.e. the alternative "scenarios" of historical discarding of redfish used in the biomass dynamic model; Section 8.2.2.2). This approach essentially amounts to analysing the sensitivity of estimates of model parameters to alternative histories of discarding.

Whilst the inclusion of data about discards in fisheries models and assessments represents a significant advance, there remains a particular problem with one of AFMA's performance criteria for the SEF. For redfish, spotted trevalla, gemfish and mirror dory, trends in CPUE provide the basis for one of the performance indicators for management of these species. Specifically, AFMA's strategy is to "ensure that CPUE is maintained above its lowest annual average level from 1986 to 1994". A conclusion from this thesis was that trends in CPUE during the period 1993-97, for 5 of the 6 species examined, depended on whether or not discards were included in the calculation of CPUE (Section 8.3.1 and 8.4). Thus, CPUE based on total, rather than retained catches, should be used for this performance indicator. CPUE calculated for the retained component of catch has been used as the performance indicator in assessments for these species between 1993 and the present (Staples & Tilzey, 1995; Chesson, 1996, 1997; Tilzey, 1998, 1999). Because estimates of discards for these species were not available during the first 7 years (1986 - 1992) of the reference period (1986-94), CPUE based on total catch cannot be used as a performance indicator. It is therefore recommended that the use of this particular performance indicator be reviewed.

9.2.5 Research and development of strategies to reducing discards

Given the range of issues identified in this thesis that concern discarding of significant amounts of catch, strategies for the reduction of discards clearly need to be evaluated and implemented in this fishery. Potential strategies include: spatial and temporal closures to fishing; development of trawl nets, cod-ends and fishing practices that are more selective for the species and sizes of fish targeted by the fishery; and increased utilisation of components of the catch that are currently discarded.

The identification of region, depth and quarter as factors affecting discarding by trawlers off the NSW coast (Chapter 6) suggests the use of spatial and/or temporal closures to trawling as strategies for reducing discarding may have some potential. Such closures provide a means of reducing the catch of species or the sizes that are currently discarded if locations or times associated with consistently large levels of discarding and small levels of retained catches can be identified (Alverson *et al.*, 1994; Kennelly, 1995; Hall, 1996; Liggins & Kennelly, 1996; Kennelly *et al.,* 1997, 1998). However, the species-specific spatial and temporal variabilities in discarded catches identified in this study and the positive association between quantities of retained and discarded catches preclude such options. Closures cannot be a general solution unless reductions of discards of specific species are assigned priority over retention of other species. Similar situations have prevented the widespread use of closures to reduce discarding in other fisheries (Alverson *et al.,* 1994) and in NSW (Liggins & Kennelly, 1996; Liggins *et al.,* 1996; Kennelly *et al.,* 1998) although there have been some successes (Rijnsdorp and van Beek, 1991). Note, however, that understanding species-specific variability of discarding at the spatial and temporal scales examined for the NSW coast provides a sound basis for estimating likely impacts on catches and on fishing operations in different areas. If priorities and targets for the reduction of discards of individual species are to be set, this information is crucial.

Given the conclusion that TACs were not a major factor affecting discarding during the period 1993-95 (Chapter 7), any review of the appropriateness of this management in the SEF, based on the argument that it promotes discarding, is unwarranted. Although trip limits for gemfish interacting with a TAC of zero did influence the discarding of gemfish (Chapter 7), there is no reasonable argument that the TAC or trip limit should be changed. The rationale for the zero TAC is that the stock is overexploited and the trip-limit is provided to allow the retention of small by-catches of gemfish associated with the targeting of mirror dory. Similarly, whilst the justification for the minimum legal lengths currently in place for particular species may be tenuous, removal or reduction of these minimal legal lengths on the basis that discarding could be reduced is not necessarily sensible. For instance, it is believed that the 33 cm minimal legal length for flathead species prevents the targeting of smaller, juvenile tiger and eastern blue spot flathead on shallow inshore fishing grounds. If, for example, fishers were able to target flathead between say 27 cm and 33 cm on these grounds, there would probably be an increased mortality on flathead less than 26 cm and on juveniles of other species that inhabit these shallow inshore grounds. Regardless of this argument, it is likely that many fish would be discarded due to lack of markets for small sizes of fish in the absence of minimal legal lengths. Consequently, there is minimal scope to bring about major changes in quantities of fish discarded by changing existing management concerning TACs, trip-limits and minimal legal lengths.

Based on these arguments, the real opportunity for reduction of discards is in the development of more selective fishing gears and/or the development of markets for components of catch that are currently discarded. The development of fishing gears (trawl nets and cod-ends) and fishing practices that are more selective for the species and sizes of fish targeted in a fishery has been the strategy of choice for reducing by-catch and discarding in several fisheries

(Walsh *et al.*, 1992; Isaksen *et al.*, 1992; Alverson *et al.*, 1994; Kennelly, 1995; Broadhurst & Kennelly, 1995; Broadhurst, 2000). Given the capture and subsequent discard of small fish of many species as a result of the lack of market for small fish, high-grading and minimal legal length regulations in the trawl fishery off NSW, an increase in the size at which trawl gears selectively caught fish would seem to offer a potential solution. There are, however, certain concerns. The considerable variation among species in sizes at first capture and the sizes at which fish are retained poses particular challenges for attempts to reduce capture and subsequent discard of fish through modifications of gears. Inevitably, there will need to be some balancing of the benefits that accrue from reducing discards of some species with the costs associated with not catching fish of other species, of sizes that could have been marketed. Moreover, the regional, quarterly and annual differences in magnitudes and size-distributions of discarded catches documented in this project imply that modifications of gears to reduce capture and subsequent discarding of particular sizes of fish will vary among regions, quarters and years.

Following the results and conclusions of this work (see also: Liggins, 1996; Liggins, 1997, Liggins, 1998; Liggins & Knuckey, 1999;) and estimates of discarded catches obtained for components of the SEF off the coasts of Victoria and Tasmania (Knuckey & Liggins, 1999; Knuckey & Sporcic, 1999; Knuckey, 2000), a project to investigate the selectivity of existing and modified fishing in the SEF has commenced (FRDC project 98/204: "Maximising yield and reducing discards in the South East Trawl Fishery through gear development and evaluation"). The final phase of this project involves an assessment of short-term costs and benefits to the fishery and long-term benefits for yields from the fishery that could be achieved through introducing alternative gears.

The other potential strategy for reducing discarded catches concerns increased utilisation of components of the catch that are currently discarded. The lack of a market for all non-commercial species and for particular sizes of commercial species in the fishery was an important determinant of discarding. Indeed, a group of south coast fishers has shown recent interest in exploring opportunities for the increased utilisation of catch. A proposal from these fishers is seeking to establish a joint venture with another partner to establish a processing plant for fish meal and associated products on the south coast of NSW. If deemed to be profitable by the involved parties, there would clearly also need to be some assessment of the short- and long-term costs and benefits of such an option by AFMA.

9.2.6 Consequences for fish trawling of negative publicity following this project and industry initiatives

Despite progress in the development of national policies concerning by-catch and discards and ongoing monitoring and research to develop strategies for reducing discards, the publication of estimates of thousands of tonnes of discards (12,366 +/- 316 t per annum for the 3 regions studied) will continue to increase concerns of the public and fishers in interacting fisheries regarding waste. Publication of by-catch statistics for prawn trawl fisheries in NSW (Liggins & Kennelly, 1996; Liggins *et al.*, 1996; Kennelly *et al.*, 1998) and frequently published editorials in recreational fishing magazines concerning by-catch from trawling (e.g. Harnwell, 1996; Schott, 1999) have fuelled the conflict between recreational and commercial prawn trawl fishers. Moreover, with the introduction of a recreational fishing licence in NSW in 2001, recreational fishers and lobbyists have been demanding reductions in commercial fishing effort, and discontinuation of fishing methods perceived as detrimental to stocks targeted by recreational fishers (e.g. Schott, 1999). In addition to the recreational sector, fishers in interacting fisheries express concern regarding deleterious impacts of discards from fish trawling on "their stocks". For example, fishers who target snapper in the NSW trap and line fishery blame the decline in snapper stocks on the discards of undersize fish by prawn and fish trawlers. Such conflicts are a major cause of concern for the fish trawl fishery and the documentation of estimates of discards is already producing public relations problems and threats to the industry.

The peak industry body for fishers operating in the SEF, The South East Trawl Fishing Industry Association (SETFIA), has responded to this threat by producing two policy documents:

- *"Industry Code of Conduct for Responsible Fishing in the South East Trawl Fishery"*
- *"Code of Fishing Practice to Minimise Incidental By-Catch of Marine Mammals in the South East Trawl Fishery"*

and a general promotional brochure:

- *"South East Fishery, Where fishers go down to the sea ..., To help feed a nation"*

The documents outline voluntary codes of conduct (except for particular agreements and legislation) concerning strategies for responsible fishing activities and collaboration between fishers and other parties with interests in utilisation, conservation and management of fish resources. Objectives and strategies outlined in these codes of conduct include: conservation and management based on long-term objectives to ensure sustainability of fish resources; adoption of "world best practice" to protect juveniles, avoid wastage and reduce the catch which is not sought or retained; adoption of technical measures such as minimal landing size limits, mesh or gear restrictions, closed areas or closed seasons; disputes relating to fishing activities to be resolved in a timely, peaceful and co-operative manner; encouragement of those involved in processing, distribution and marketing to improve utilisation of by-catch; minimisation of the by-catch of seals and other marine mammals; and assisting with the collection of data.

The promotional brochure promotes the existence of the policy and discusses support by the industry for sustainability of resources, conservation of biodiversity and involvement with research and the management of the fishery. In particular, SETFIA's involvement as a co-investigator of the research project "Maximising yield and reducing discards in the SETF through gear development and evaluation" and support of the ISMP is promoted.

The formulation and documentation of these policies by the fishing industry indicates a desire to contribute to the management of the fishery and to face the difficult issues associated with discarding. This is significant because the co-operation of fishers is fundamental to ongoing monitoring programmes and the development and successful implementation of strategies for reducing discards (Kennelly, 1997).

9.3 Larger-scale and international issues

9.3.1 Issues concerning methodology

Several of the methodologies used in this project may prove to be useful in research about discards in other fisheries around the world.

The pilot survey done here prior to implementing the full-scale observer survey provided: (i) data to determine that precision of estimates from the full-scale observer survey would be acceptable; (ii) an opportunity to understand logistics and determine appropriate methods for sub-sampling catches; and (iii) an opportunity to involve fishers in the design of the project prior to commencement of the 3-year survey so that the fishing industry understood that they had an active, rather than passive, role in the project. Given the poor precision of estimates of rates of discarding from many observer surveys and the major challenges to achieving co-operation from fishers with such programmes (e.g. Saila, 1983; Andrew & Pepperell, 1992; Alverson *et al.*, 1994) it is apparent that a more widespread use of pilot surveys would achieve greater cost-benefit from observer surveys of discarding.

Another important feature of this project was the examination of alternative estimators. Typically, the rationale for using a particular estimator of by-catch or discards is rarely discussed in publications that provide estimates of discards (see Chapter 3). In this project, the precision and bias of a range of methods for estimating discards were compared, so that an optimal method could be selected for routine application. The range of possible estimators that can be used for estimating discards from a fishery is partially determined by the availability of auxiliary data (e.g. fishing effort, landed catch). The approach used here demonstrated the type of analysis that could be done during the initial stages of any large-scale observer programme. Because observer surveys are expensive and discards very variable, methodological approaches that increase precision and reduce the bias of estimates, should be used more often.

It is surprising that the approach used in this project to detect bias in observer-based estimates of retained catches and, by implication, discarded catches, has not been previously reported. The scope of this approach depends on the number of species for which independent unbiased estimates of magnitudes and size-distributions of landed catches are available. It is likely that magnitudes of landed catches of major target species will be available for most fisheries for which an observer survey is contemplated. Size-distributions of landed catches will sometimes be available from shore-based sampling programmes. When such data are available, it seems ludicrous that observer-based estimates of discarded catches are claimed to be reliable when it cannot be demonstrated that estimates of retained catches from the survey are themselves reliable.

The approach used in this project to examine the factors affecting discarding may also have more widespread application. In particular, the demonstration of the relationship between discarding of redfish, market volume and market price, provides a quantitative demonstration of high-grading based on fluctuations in price. Whilst size-selective discarding is a common feature of fisheries and high-grading due to price variations is often assumed to be the determining factor, the approach used in this project provides a quantitative description of this process.

The logical framework for the project described in this thesis (Fig. 1.2) may be successfully applied to studies of by-catch and discarding in other fisheries. Whilst the framework used here was derived from those suggested by other authors (e.g. Saila, 1983; Kennelly, 1997; Hall, 1996; Crowder & Murawski, 1998), it specifically includes logical steps that concern: selection of estimation methods based on analyses of relative accuracy and bias of estimators; detection of bias in observer-based estimates and the assessment of the consequences of discarding for stock assessment. Note also that the research currently being done concerning the potential of modifications to gear to reduce discarded catches in the SEF represents the next logical step from the research done here. Furthermore, doing this research with the fishing industry as a key participant is consistent with the logical framework proposed by Kennelly (1997) for solving by-catch problems, the key components of which concern reduction of by-catch and discarding with an emphasis on consultation and co-operation of fishers.

9.3.2 Filling a regional gap in the global knowledge-base

Little information has been available describing the composition of discards in New Zealand and Australian fish trawl fisheries (Alverson *et al.*, 1994; Kennelly, 1995; Annala, 1996). Alverson *et al.* (1994) noted in their global assessment of fisheries by-catch and discards that the majority of the information they reviewed came from northern hemisphere fisheries. Documenting the magnitude, species- and size-composition of discarding by fish trawlers off the coast of NSW and the factors affecting discarding in this fishery has provided information that has important consequences for the management of this and interacting fisheries (see Section 9.2). This work also provides information about discarding from a fish trawl fishery in a region of the world from which few such data have been previously available. Consequently, the information provided here fills a geographic gap in the knowledge of global patterns of discarding.

The work done here shows that several generalisations that apply to studies of by-catch and discarding in other fisheries around the globe also apply to fish trawling off the NSW coast: (i) fin-fishes commonly dominate by-catches and discards; (ii) a relatively small number of species dominates by-catches and discards; (iii) sizes of fish in by-catches and discarded catches are generally small; and (iv) if a component of the catch of targeted species is discarded, sizes of discarded fish are generally smaller than sizes of retained fish (e.g. Jean, 1963; Jermyn & Robb, 1981; Howell & Langan, 1987; Alverson *et al.*, 1994; Stratoudakis *et al.*, 1998).

9.3.3 Understanding direct and indirect effects of trawling and consequences for ecosystems

Whilst this thesis has concentrated on the direct effects of mortality (removals of organisms via retained and discarded components of catch) on stocks of the species caught, trawling may also produce other direct and indirect effects (e.g. Botsford *et al.*, 1997; Crowder & Murawski, 1998; Jennings & Kaiser, 1998; Hall, 1999). Direct effects include: (i) impacts on populations of species that benefit from an increased availability of food through discarding of fish and offal; or (ii) through the physical disturbance or destruction of benthic habits by trawl gear. Indirect effects are those that follow from the direct effects and which affect the structure of communities and ecosystems, mediated by predator-prey and competitive interactions.

Given the observations that discards from fish trawlers off NSW are often eaten, at or just below the surface, by seabirds, seals and sharks (pers. obs), there may be increases in those species because of increased availability of food due to discarding. Feeding of seabirds has been modified to take advantage of discards from several trawl fisheries (e.g. Hudson & Furness, 1988; Blaber & Wassenberg, 1989). As a consequence, larger than normal populations of these seabirds were maintained. Similarly, supply of the component of discarded catch that sinks to the benthos, may have direct effects on species that feed on this material. This concept has been noted with respect to the enhancement of numbers of sand crabs in Moreton Bay, Queensland, where a third of the diet of these crabs comprised fish discarded from prawn trawlers (Wassenberg & Hill, 1987). Given the large quantities of discards documented for fish trawling off NSW, it is likely that dead or moribund animals represent a significant food supply for pelagic and bottom-dwelling fish and invertebrates in these areas.

Trawling may directly affect the benthos through the physical impact of the gear (otter boards and ground-ropes) in scouring or scraping the sea-floor (e.g. DeGroot, 1984; Sainsbury, 1987, 1988, 1991; Botsford *et al.*, 1997; Jennings & Kaiser, 1998; Hall, 1999). Evidence of this in the fishery off NSW is restricted to the observation of captures of benthic organisms (e.g. various cnidarians, annelids, crustaceans) and substrata (rocks, sand and mud).
Physical disturbance to benthic habitats (e.g. DeGroot, 1984; Sainsbury, 1987, 1988, 1991, Jennings & Kaiser, 1998) and removals of fish (via retained and discarded catch) may indirectly produce changes in species assemblages and food-web dynamics via differential mortality of competitors, predators and prey (e.g. DeGroot, 1984; Berghahn, 1990; Harris & Poiner, 1991; Jennings & Kaiser, 1998; Hall, 1999). Whether or not a fishery causes such significant indirect effects depends on how closely the dynamics of populations of species are coupled. Hall (1999) noted that ideas about how particular sets of species could interact are legion, but the data to support one alternative over another are generally weak. Moreover, against this background, *"the weaknesses in our data leave ample opportunity for the development of 'just so' stories"* (Hall, 1999). Recent reviews (Jennings & Kaiser, 1998; Hall, 1999) concluded that there is some evidence of top-down control in some hard

substratum communities and some convincing evidence that fishing has reduced abundances of predators, with consequent trophic cascades in these communities. Examples of control by predators are, however, less easy to find in pelagic systems. This may not necessarily mean that such control is less important in pelagic systems, but that it is more difficult to get data to support the theory in this environment. This is not the case for seashore and sea-floor communities which are well-suited to manipulative experiments (Estes & Peterson, 2000). Strong top-down control by consumers has been demonstrated in many rocky intertidal communities and there is a growing body of evidence that bottom-up processes can also have important effects on the structure of these communities (Menge, 2000).

The difficulties of obtaining data and providing critical tests of hypotheses about ecological interactions in fisheries systems are formidable (Andrew & Pepperell, 1992; Tillman, 1993; Alverson *et al.*, 1994; Kennelly, 1995; Jennings & Kaiser, 1998; Hall, 1999). Many studies have documented changes in abundance and species composition of communities before and after the commencement of trawling. Many of these have been interpreted to demonstrate effects of trawling, but it is not clear that the observed changes resulted from indirect effects of trawling, the direct effects of removals, or indeed, whether they were independent of trawling and resulted from natural fluctuations in abundances (e.g. Sainsbury, 1987, 1988; Jones, 1992; Andrew & Pepperell, 1992; but see Sainsbury, 1991). Sainsbury (1987, 1988) recognised these alternative explanations for observed decreases in abundances of tropical snappers (*Lethrinus*, *Lutjanus* and *Epinephelus* species) coincident with increases in catches of threadfin bream (*Nemipterus* spp.) and lizard fish (*Saurida* spp.). Nevertheless, he favoured the explanation that changes in availability of habitat caused by trawling were the major factor resulting in the observed shift in composition of species. His argument was based on: (i) an observed decline in catch-rates of sponges and gorgonians since trawling commenced and (ii) underwater photographic evidence that *Lutjanus* and *Lethrinus* species were commonly associated with sponges in contrast to *Nemipterus* and *Saurida* species which preferred more open substrata. Subsequently, this hypothesis was supported with an experiment that compared abundances of species in trawled areas compared to areas closed to trawling (Sainsbury, 1991).

The need for this experimental approach to explore the importance of effects of trawling and discarding on ecosystems off the NSW coast is no different from the widespread need for such studies throughout the world (Botsford *et al.*, 1997; Crowder & Murawski, 1998; Jennings & Kaiser, 1998; Estes & Peterson, 2000; Murawski, 2000) . The challenge to understand and manage the effects of fishing within a wider, more environmentally sensitive framework than is presently possible is probably the most important issue facing world fisheries at the present time (Hall, 1999).

9.3.4 The importance of discarding and other unaccounted fishing mortalities

This thesis has concentrated on issues concerning estimation of discards, factors influencing discarding, impacts of discarding on stock assessment and fisheries management. Specifically, these issues concern the "unaccounted fishing mortality" associated with discarding, F_D in the formula presented by Chopin *et al.* (1996):

$$F = [F_{CL} + F_{AL} + F_{RL}] + F_B + F_D + F_O + F_A + F_E + F_G + F_P + F_H$$

Whilst there has been progress in accounting for mortalities associated with landed catches (F_{CL}, F_{AL} and F_{RL}) in many of the world's fisheries, estimates of F_D are not generally available. As a direct result of the research described in this thesis (and subsequently, from the ISMP operating in the SEF), estimates of F_D are now available for fish trawl fisheries off the coast of NSW and south-eastern Australia. It must, however, be recognised that other components of fishing mortality remain unaccounted. Mortalities associated with fish passively dropping off or out of fishing gears (F_O), fish avoiding fishing gear (F_A), escape from fishing gear (F_E), ghost fishing (F_G), predation after escape (F_P) and as a consequence of gear-induced changes to habitat (F_H) are generally unknown throughout the world's fisheries. Just as the importance of F_D has been demonstrated in this thesis, a lack of knowledge of these other sources of mortality may be responsible for significant biases in estimates of fishing mortality and the failure of fisheries models to represent accurately the affects of fishing on stocks. The most recent publication on the theme of the failure of fisheries models and management (Schnute & Richards, 2001) discussed failures of models resulting from process error, measurement error and model uncertainty. These authors noted that:

"The first two elements can be represented fairly rigorously through the use of probability distributions. Statistical theory then gives estimates of hidden quantities, although often with

high uncertainty. The third element, however, introduces a complete unknown, not subject to quantification. Perhaps the proposed arithmetic was wrong in the first place. If so, all bets are off, and the seemingly rigorous statistical analyses have no real meaning."

The implication is clear. If the multiple components of fishing mortality are not recognised within models or if the estimates are biased, "all bets are off". Against a background of the collapse of important fish stocks and the recognition of discarding as a major "unaccounted mortality" in many of the world's fisheries, it is obvious that scientifically-based research programmes are needed to: (i) quantify discards and other sources of mortality; (ii) include these estimates in fishery models and assessment methodologies; and (iii) examine options for reducing these sources of mortality.

The present work justifies a particular methodological and logical framework and demonstrates what can successfully be achieved when rigorous approaches are used consistently. The challenge is to extend such rigour to other fisheries and to other components of mortality due to fishing.

References

ABARE, 1993. *Fisheries Surveys Reports 1993.* Australian Bureau of Agricultural and Resource Economics, Canberra.

AFFA, 2000a. *National bycatch policy.* Agriculture, Fisheries and Forestry - Australia, Canberra.

AFFA, 2000b. *Commonwealth policy on fisheries bycatch.* Agriculture, Fisheries and Forestry - Australia, Canberra.

AFMA, 2000. *Strategic research plan, 1992-2004.* Australian Fisheries Management Authority, Canberra.

Alaska Sea Grant College Program, 1995. *Solving bycatch: considerations for today and tomorrow, Alaska Sea Grant College Program report, 96-03,* University of Alaska, Fairbanks.

Alverson, D. L., Freeberg, M. H., Pope, J. G., and Murawski, S. A., 1994. A global assessment of fisheries bycatch and discards. *FAO Fisheries Technical Paper*, No. 339. FAO, Rome.

Alverson, D. L., and Hughes, S. E., 1996. Bycatch: from emotion to effective natural resource management. *Reviews in Fish Biology and Fisheries,* 6: 443-462.

Andrew, N. L., Jones, T., Terry, C., and Pratt, R., 1995. By-catch of an Australian stow net fishery for school prawn (*Metapenaeus macleayi*). *Fisheries Research,* 22: 119-136.

Andrew, N. L., and Mapstone, B. D., 1987. Sampling and the description of spatial pattern in marine ecology. *Oceanography and Marine Biology an Annual Review,* 25: 39-90.

Andrew, N. L., and Pepperell, J. G., 1992. The by-catch of shrimp trawl fisheries. *Oceanography and Marine Biology an Annual Review,* 30: 527-565.

Annala, J. H., 1996. New Zealand's ITQ system: have the first eight years been a success or failure? *Reviews in Fish Biology and Fisheries,* 6: 43-62.

Arnason, R., and Gissurarson, H. H. (eds.), 1999. *Individual transferable quotas in theory and practice.* The University of Iceland Press, Reykjavik.

Atkinson, D. B., 1984. Discarding of small redfish in the shrimp fishery off Port au Choix, Newfoundland, 1976-1980. *Journal of Northwest Atlantic Fisheries Science,* 5: 99-102.

Baird, J. W., and Stevenson, S. C., 1983. Levels of precision - sea versus shore sampling. In, W. G. Doubleday and D. Rivard (eds.), Sampling commercial catches of marine fish and invertebrates, *Canadian Special Publication of Fisheries and Aquatic Sciences*, 66, pp. 185-188.

Berghahn, R., 1990. On the potential impact of shrimping on trophic relationships in the Wadden sea. In, M. Barnes & R. N. Gibson (eds.), *Trophic relationships in the Marine Environment, Proc. 24th Europ. Mar. Biol. Symp.,* Aberdeen University Press, Aberdeen, pp. 130-140.

Blaber, S. J. M., and Wassenberg, T. J., 1989. Feeding ecology of the piscivorous birds *Phalacrocorax varius*, *P. melanoleucas* and *Sterna bergii* in Moreton Bay, Australia: diets and dependence on trawler discards. *Marine Biology,* 101: 1-10.

Botsford, L. W., Castilla, J. C., and Peterson, C. H., 1997. The management of fisheries and marine ecosystems. *Science*, 277: 509-515.

Broadhurst, M. K., 2000. Modifications to reduce by-catch in prawn trawls: a review and framework for development. *Reviews in Fish Biology and Fisheries*, 10: 27-60.

Broadhurst, M. K., and Kennelly, S. J., 1995. Effects of an increase in mesh size on the catches of fish trawls off New South Wales, Australia. *Marine and Freshwater Research,* 46: 745-750.

Buxton, C., and Eayrs, S. (eds), 1999. *Establishing meaningful targets for bycatch reduction in Australian fisheries. Australian society for Fish Biology Workshop proceedings, Hobart, September 1998.* Australian Society for Fish Biology, Sydney.

Chen, Y., and Gordon, G. N. G., 1997. Assessing discarding at sea using a length-structured yield-per-recruit model. *Fisheries Research,* 30: 43-55.

Chen, Y., Liggins, G. W., Graham, K. J., and Kennelly, S. J., 1997. Modelling the length-dependent offshore distribution of redfish, *Centroberyx affinis. Fisheries Research,* 29: 39-54.

Chen, Y., Liggins, G. W., and West, R. J., 1998. A yield-per-recruit model for sequential fisheries and its application in evaluating the management strategy of changing incidental inshore fishing mortality. *Aquatic Sciences,* 60: 130-144.

Chesson, J. (ed.), 1996. *The South East Fishery 1995*, Fishery Assessment Report compiled by the South East Fishery Assessment Group. Australian Fisheries Management Authority, Canberra.

Chesson, J. (ed.), 1997. *The South East Fishery 1996*, Fishery Assessment Report compiled by the South East Fishery Assessment Group. Australian Fisheries Management Authority, Canberra.

Chopin, F. S., and Arimoto, T., 1995. The condition of fish escaping from fishing gears - a review. *Fisheries Research*, 21: 315-327.

Chopin, F., Inoue, Y., and Arimoto, T., 1996. Development of a catch mortality model. *Fisheries Research,* 25: 377-382.

Cochran, W. G., 1977. *Sampling techniques.* 3rd edn., John Wiley & Sons, New York.

Crean, K., and Symes, D., 1994. The discards problem: towards a European solution. *Marine Policy,* 18: 422-434.

Crone, P. R., 1995. Sampling design and statistical considerations for the commercial groundfish fishery for Oregon. *Canadian Journal of Fisheries and Aquatic Sciences,* 52: 716-732.

Crowder, L. B., and Murawski, S. A., 1998. Fisheries bycatch: Implications for management. *Fisheries (Bethesda)*, 23, No. 6: 8-17.

Dannevig, H. C., 1904. *Preliminary report upon the prawning industry in Port Jackson.* Department of Fisheries NSW, William Applegate Gullick, Government Printer, Sydney.

Davison, A. C., and Hinkley, D. V., 1997. *Bootstrap methods and their application.* Cambridge University Press, Cambridge, New York.

DeGroot, S. J., 1984. The impact of bottom trawling on benthic fauna of the North Sea. *Ocean Management.,* 9: 177-90.

DeVeen, J. F., Huwae, P. H. M., and Lavaleye, M. S. S., 1975. On discarding in the sole fishery and preliminary observations on survival rates of discarded plaice and sole in 1975. *ICES/CM* 1975/F:28: 1-9.

Doubleday, W. G., and Rivard, D., (eds.), 1983. Sampling commercial catches of marine fish and invertebrates, *Canadian Special Publication of Fisheries and Aquatic Sciences*, 66.

Efron, B., and Tibshirani, R. J., 1993. *An introduction to the bootstrap*. Monogr. Stat. Appl. Prob., No. 57,. Chapman & Hall, London.

Erhardt, N. M., and Legault, C. M., 1997. The role of uncertainty in fish stock assessment and management: A case study of the Spanish mackerel, *Scomberomorus maculatus*, in the US Gulf of Mexico. *Fisheries Research,* 29: 145-158.

Erickson, D. L., Perez-Comas, J. A., Pikitch, E. K., and Wallace, J. R., 1996. Effects of catch size and codend type on the escapement of walleye pollock (*Theragra chalcobramma*) from pelagic trawls. *Fisheries Research,* 28: 179-196.

Estes, J. A., and Peterson, C. H., 2000. Marine ecological research in seashore and seafloor systems: accomplishments and future directions. *Marine Ecology Progress Series*, 195: 281-289.

Evans, S. M., Hunter, J. E., Elizal, and Wahju, R. I., 1994. Composition and fate of the catch and bycatch in the Farne Deep (North Sea) *Nephrops* fishery. *ICES Journal of Marine Science,* 51: 155-168.

Fairbridge, W. S., 1951. The New South Wales tiger flathead, *Neoplatycephalus macrodon* (Ogilby), I. Biology and Age determination. *Australian Journal of Marine and Freshwater Research,* 2: 117-178.

Fairbridge, W. S., 1952. The New South Wales tiger flathead, *Neoplatycephalus macrodon* (Ogilby), II. The age composition of the commercial catch, overfishing of the stocks and suggested conservation. *Australian Journal of Marine and Freshwater Research,* 3: 1-31.

FAO, 1997. *Review of the state of the world fishery resources: marine fisheries.* Food and Agriculture Organisation of the United Nations, Rome.

Fennessy, S. T., 1994. The impact of commercial prawn trawlers on linefish off the north coast of Natal, South Africa. *South African Journal of Marine Science,* 14: 263-279.

Fletcher, W., and McVea, T., (eds.), 2000. *NSW Fisheries, 1998/99 status of fisheries resources.* NSW Fisheries Research Institute, Cronulla.

Foldren, W., 1989. Shrimpers' by-catch depletes recreational angling species. *International Angler,* 51: 1-5.

Fowle, S., and Bierce, R. (eds.), 1992. *Proceedings of the Shrimp Trawl Bycatch Workshop, November 22-23, 1991, St Petersburg, Florida.* Center for Marine Conservation, Washington D.C.

French, R. J., Nelson Jr., R., and Wall, J., 1982. Role of the United States observer program in management of foreign fisheries in the northeast Pacific Ocean and eastern Bering Sea. *North American Journal of Fisheries Management,* 2: 122-131.

Garcia, S. M., and Newton, C., 1997. Current situation, trends and prospects in world capture fisheries. In, E. K. Pikitch, D. D. Huppert and M. P. Sissenwine (eds.), *Global trends: fisheries management,* American Fisheries Society Symposium No. 20, American Fisheries Society, Bethesda.

Gillis, D. M., Peterman, R. M., and Pikitch, E. K., 1995a. Implications of trip regulations for high-grading: a model of the behaviour of fishermen. *Canadian Journal of Fisheries and Aquatic Sciences,* 52: 402-415.

Gillis, D. M., Peterman, R. M., and Pikitch, E. K., 1995b. Dynamic discarding decisions: foraging theory for high-grading in a trawl fishery. *Behavioral Ecology,* 6: 146-154.

Graham, K. J., Liggins, G. W., Wildforster, J., and Wood, B., 1995. NSW Continental shelf trawl-fish survey, results for year 1, 1993. Kapala Cruise Report, No. 114, NSW Fisheries, Fisheries Research Institute, Cronulla.

Graham, K. J., Liggins, G. W., and Wildforster, J., *1996. NSW Continental shelf trawl survey, results for year 2, 1994. Kapala Cruise Report, No. 115*, NSW Fisheries, Fisheries Research Institute, Cronulla.

Graham, K. J., Wood, B. R., and Andrew, N. L., 1997. *The 1996-97 survey of upper slope trawling grounds between Sydney and Gabo Island (and comparisons with the 1976-77 survey). Kapala Cruise Report, No. 117*, NSW Fisheries, Fisheries Research Institute, Cronulla.

Gray, C. A., Kennelly, S. J., Hodgson, K. E., Ashby, C. J. T., and Beatson, M. L., 2001. Retained and discarded catches from commercial beach-seining in Botany Bay, Australia. *Fisheries Research*, 50: 205-219.

Gray, C. A., MacDonall, V. C., and Reid, D. D., 1990. By-catch from prawn trawling in the Hawkesbury River, New South Wales: species composition, distribution and abundance. *Australian Journal of Marine and Freshwater Research,* 44: 401-409.

Green, R. (Chair of working group), 1991. *Ecologically sustainable development working groups, Final report, Fisheries.* Australian Government Publishing Service, Canberra.

Gulland, J.A., (ed.) 1988. *Fish population dynamics.* 2nd edn, John Wiley & Sons, New York.

Gutherz, E. J., and Pellegrin, G. J., 1988. Estimate of the catch of red snapper, Lutjanus campechanus, by shrimp trawlers in the U.S. Gulf of Mexico. *US National Marine Fisheries Service Marine Fisheries Review,* 50: 17-25.

Hall, M. A., 1996. On bycatches. *Reviews in Fish Biology and Fisheries,* 6: 319-352.

Hall, S. J., 1999. *The effects of fishing on marine ecosystems and communities.* Blackwell Science Ltd, Oxford.

Harnwell, J., 1996. Time's running out (editorial). *Fishing World*, October, 1996, p 7.

Harris, A. N., and Poiner, I. R., 1990. By-catch of the prawn fishery of Torres Strait; composition and partitioning of the discards into components that float or sink. *Australian Journal of Marine and Freshwater Research*, 41: 37-52.

Harris, A. N., and Poiner, I. R., 1991. Changes in species composition of demersal fish fauna of southeast Gulf of Carpentaria, Australia, after 20 years of fishing. *Marine Biology*, 111: 503-519.

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

Hill, B. J., and Wassenberg, T. J., 1990. Fate of discards from prawn trawlers in Torres Strait. *Australian Journal of Marine and Freshwater Research,* 41: 53-64.

Houston, T. W., 1955. The New South Wales trawl fishery: review of past course and examination of present condition. *Australian Journal of Marine and Freshwater Research*, 6: 165-208.

Howell, W. H., and Langan, R., 1987. Commercial trawler discards of four flounder species in the Gulf of Maine. *North American Journal of Fisheries Management,* 7: 6-17.

Howell, W. H., and Langan, R., 1992. Discarding of commercial groundfish species in the Gulf of Maine shrimp fishery. *North American Journal of Fisheries Management,* 12: 568-580.

Hudson, A. V., and Furness, R. W., 1988. Utilization of discarded fish by scavenging seabirds behind whitefish trawlers in Shetland. *Journal of Zoology,* 215: 151-166.

Huse, I., and Soldal, A. V., 2000. An attempt to improve size selection in pelagic longline fisheries for haddock. *Fisheries Research,* 48: 43-54.

ICES, 1986. Report of the working group on methods of fish stock assessment, November 20-26, 1985. *ICES C.M.* 1986/Assess:10.

IDRC, 1982. *Fish by-catch, bonus from the sea.* Report of a technical consultation on shrimp by-catch utilization held in Georgetown, Guyana, 27-30 October 1981, International Development Research Centre, Ottawa.

Isaksen, B., Valdemarsen, J. W., Larsen, R. B., and Karlsen, L., 1992. Reduction of fish bycatch in shrimp trawl using a rigid separator grid in the aft belly. *Fisheries Research,* 13: 335-352.

Iudicello, S., Weber, M., and Wieland, R., 1999. *Fish, markets and fishermen, the economics of overfishing.* Island Press, Washington D.C.

Jean, Y., 1963. Discards of fish at sea by northern New Brunswick draggers. *Journal of the Fisheries Research Board of Canada,* 20: 497-523.

Jennings, S., and Kaiser, M. J., 1998. The effects of fishing on marine ecosystems. *Advances in Marine Biology,* 34: 201-352.

Jermyn, A. S., and Robb, A.P., 1981. Review of cod, haddock and whiting discarded in the North Sea by Scottish fishing vessels for the period 1975-80. *ICES CM* 1981/G:47.

Jones, J. B., 1992. Environmental impact of trawling on the seabed: a review. *New Zealand Journal of Marine and Freshwater Research,* 26: 59-67.

Jordan, A., 1997. *Demersal trawl surveys of the continental shelf of southern and eastern Tasmania 1993-95, Technical Report No. 50,* Marine Research Laboratories - Taroona, Dept. Primary Industry and Fisheries, Tasmania.

Kaufmann, B., Geen, G., and Sen, S., 1999. *Fish futures: Individual transferable quotas in fisheries.* Fisheries Economics, research and Management Pty Ltd., Kiama, Australia.

Keiser Jr., R. K., 1977. Magnitude and utilization of the incidental catch of the South Carolina shrimp fishery. *Proceedings of the Gulf and Caribbean Fisheries Institute,* 29: 127-43.

Kennelly, S. J., 1995. The issue of by-catch in Australia's trawl fisheries. *Reviews in Fish Biology and Fisheries,* 5: 213-234.

Kennelly, S. J., 1997. A framework for solving by-catch problems: examples from New South Wales, Australia, the eastern Pacific and the northwest Atlantic. In, D. A. Hancock, D. C. Smith, A. Grant and J. P. Beumer (eds.), *Developing and sustaining world fisheries resources - the state of science and management - 2nd World Fisheries Congress proceedings*, CSIRO Press., pp. 544-550.

Kennelly, S. J., 1999. Areas, depths, and times of high dicard rates of scip, Stenotomus chrysops, during demersal fish trawling off the northeastern United States. *Fisheries Bulletin*, 97: 185-192.

Kennelly, S. J., Graham, K. J., Montgomery, S. S., Andrew, N. L., and Brett, P. A., 1993. Variance and cost-benefit analysis to determine optimal duration of tows and levels of replication for sampling relative abundances of species using demersal trawling. *Fisheries Research,* 16: 51-67.

Kennelly, S. J., Drew, S. C., and Delano Gagnon, C. D., 1997. Rates of retained and discarded catches from demersal fish trawling off the north-eastern United States. *Marine and Freshwater Research,* 48: 185-199.

Kennelly, S. J., Liggins, G. W., and Broadhurst, M. K., 1998. Retained and discarded by-catch from oceanic prawn trawling in New South Wales, Australia. *Fisheries Research,* 36: 217-236.

Knuckey, I. A., 2000. South East Fishery Integrated Scientific Monitoring Program 1999, report to the South East Fishery Assessment Group. Marine and Freshwater Resources Institute, Queenscliff, Victoria.

Knuckey, I. A., and Liggins, G. W., 1999. Focussing on bycatch issues in Australia's South East Trawl Fishery. In, C. Buxton and S. Eayrs (eds.), *Establishing meaningful targets for bycatch reduction in Australian fisheries,* Australian society for Fish Biology Workshop proceedings, Hobart, September 1998, Australian Society for Fish Biology, Sydney, pp 46-55.

Knuckey, I. A., and Sporcic, M. I., 1999. South East Fishery Integrated Scientific Monitoring Program, 1998 report to the South East Fishery Assessment Group. Marine and Freshwater Resources Institute, Queenscliff, Victoria.

Kotz, S., and Johnson, N. L., (eds.), 1982. *Encyclopaedia of statistical science.* John Wiley and Sons, New York.

Kulka, D. W., and Waldron, D., 1983. The Atlantic observer programs - a discussion of sampling from commercial catches at sea. In, W. G. Doubleday and D. Rivard (eds.), Sampling commercial catches of marine fish and invertebrates, *Canadian Special Publication of Fisheries and Aquatic Sciences*, 66, pp. 255-262.

Liggins, G. W., 1996. The interaction between fish trawling in NSW and other commercial and recreational fisheries, Final report to Fisheries Research and Development Corporation, project No. 92/79. NSW Fisheries, Sydney.

Liggins, G. W., 1997. Integrated Scientific Monitoring Program for the SEF in 1996 (NSW component), Report to the Australian Fisheries Management Authority. NSW Fisheries Research Institute, Cronulla.

Liggins, G. W., 1998. Integrated Scientific Monitoring Program for the SEF in 1997 (NSW component), Report to the Australian Fisheries Management Authority. NSW Fisheries Research Institute, Cronulla.

Liggins, G. W., and Kennelly, S.J., 1996. By-catch from prawn trawling in the Clarence River estuary, New South Wales, Australia. *Fisheries Research,* 25: 347-367.

Liggins, G. W., Kennelly, S. J., and Broadhurst, M. K., 1996. Observer-based survey of the by-catch from prawn trawling in Botany Bay and Port Jackson, New South Wales. *Marine and Freshwater Research,* 47: 877-888.

Liggins, G. W., Bradley, M. J., and Kennelly, S. J., 1997. Detection of bias in observer-based estimates of retained and discarded catches from a multi-species trawl fishery. *Fisheries Research,* 32: 133-147.

Liggins, G. W., and Knuckey, I. A., 1999. Factors affecting discarding in the South East Fishery - implications for stock assessment and bycatch reduction. In, C. Buxton and S. Eayrs (eds.), *Establishing meaningful targets for bycatch reduction in Australian fisheries,* Australian Society for Fish Biology Workshop proceedings, Hobart, September 1998, Australian Society for Fish Biology, Sydney, pp. 46-55.

Liggins, G. W., Scandol, J. P., Montgomery, S., Craig, J., and Macbeth, W., 1999. An assessment of the NSW eastern rock lobster resource for 1999-00. Resource Assessment Annual Report, NSW Fisheries, Cronulla.

Lowe, S. A., Fujioka, J. T., and Terry, J. M., 1991. Bioeconomic analysis of a minimum size limit for Gulf of Alaska sablefish using a yield per recruit model. *Fisheries Research,* 11: 307-320.

Marasco, R., Baldwin, R., Max, N., and Landen, T., 1991. By-catch: a bioeconomic assessment of North Pacific groundfish fisheries. ICES *ICES Marine Science Symposia,* 193: 275-280.

Menge, B. A., 2000. Top-down and bottom-up community regulartion in marine rock intertidal habitats. *Journal of Experimental Marine Biology and Ecology*, 250: 257-289.

McAllister, M. K., and Peterman, R. M., 1992. Experimental design in the Management of Fisheries. *North American Journal of Fisheries Management,* 12: 1-18.
Mood, A. M., Graybill, F. R., Boes, D. C., 1974. *Introduction to the theory of statistics*. 3rd edn., McGraw-Hill.

Murawski, S. A., 1992. The challenges of finding solutions in multispecies fisheries. In, R. W. Schoning, R. W. Jacobson, D. L. Alverson, T. G. Gentle and J. Auyong (eds.), *Proceedings of the National Industry Bycatch workshop, February 4-6, 1992, Newport, Oregon,* Natural Resources Consultants Inc., Seattle, Washington, pp. 35-45.

Murawski, S. A., 2000. Definitions of overfishing from an ecosystem perspective. *ICES Journal of Marine Science*, 57: 649-658.

Neilson, J. D., Waiwood, K. G., and Smith, S. J., 1989. Survival of Atlantic hailbut (*Hippoglossus hippoglossus*) caught by longline and otter trawl gear. *Canadian Journal of Fisheries and Aquatic Sciences,* 46: 887-897.

NRC, 1990. The nature and scope of fishery dependent mortalities in the commercial fisheries of the Northeast Pacific. Natural Resources Consultants, Seattle, Washington.

Pease, B. C., and Grinberg, A., 1995. New South Wales commercial fisheries statistics, 1940 to 1992. NSW Fisheries, NSW Fisheries Research Institute, Cronulla.

Pelletier, D., and Gros, P., 1991. Assessing the impact of sampling error on model-based management advice: comparison of equilibrium yield per recruit variance estimators. *Canadian Journal of Fisheries and Aquatic Sciences,* 48: 2129-2139.

Peterkin, F. A., 1982. Developing a shrimp by-catch utilization program. *Proceedings of the Gulf and Caribbean Fisheries Institute,* 34: 112-119.

Pikitch, E. K., 1987. Use of a mixed-species yield-per-recruit model to explore the consequences of various management policies for the Oregon flatfish fishery. *Canadian Journal of Fisheries and Aquatic Sciences,* 44: 349-359.

Pikitch, E. K., 1991. Technological interactions in the US West Coast groundfish trawl fishery and their implications for management. *ICES Marine Science Symposia,* 193: 253-263.

Pitcher, T. J., Hart, J. B., and Pauly, D., (eds.), 1998. *Reinventing fisheries management.* Fish and Fisheries Series, 23, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Poiner, I. R., Buckworth, R. C., and Harris, A. N. M., 1990. Incidental capture and mortality of sea turtles in Australia's northern prawn fishery. *Australian Journal of Marine and Freshwater Research,* 41: 97-110.

Pope, J. G., and Gray, D. 1983. An investigation of the relationship between the precision of assessment data and the precision of total allowable catches. In, W. G. Doubleday and D. Rivard (eds.), Sampling commercial catches of marine fish and invertebrates, *Canadian Special Publication of Fisheries and Aquatic Sciences*, 66, pp. 151-157.

Quinn, T. J. II, and Deriso, R. B., 1999. *Quantitative Fish Dynamics*. Oxford University Press, New York.

Ramm, D. C., Pender, P. J., Willing, R. S., and Buckworth, R. C., 1990. Large-scale spatial patterns of abundance within the assemblage of fish caught by prawn trawlers in northern Australian waters. *Australian Journal of Marine and Freshwater Research,* 41: 79-95.

Rao, J. N. K., and Wu, C. F. J., 1988. Resampling inference with complex survey data. *Journal of the American Statistical Association*, 83: 231-41.

Richards, L. J., Fargo, J., and Schnute, J. T., 1995. Factors influencing bycatch mortality of trawl-caught Pacific halibut. *North American Journal of Fisheries Management,* 15: 266-276.

Rijnsdorp, A. D., and van Beek, F. A., 1991. The effects of the plaice box on the reductions in discarding and on th elevel of recruitment of North Sea sole. *ICES C.M.* 1991/G:47.

Rowling, K., 1994. Species synopsis - Gemfish, *Rexea solandri*. In, R. D. J. Tilzey (ed.), *The South East Fishery,* Australian Government Publishing Service, Canberra, pp. 115-123.

Rowling, K., 2001. Redfish 1999, Stock Assessment Report, South East Fishery Assessment Group. Australian Fisheries Management Authority, Canberra.

Saila, S. B. 1983. Importance and assessment of discards in commercial fisheries. *FAO Fisheries Circular,* No. 765.

Sainsbury, K. J., 1987. Assessment and management of the demersal fishery on the continental shelf of northwestern Australia. In, J. J. Polovina and S. Ralston (eds.), *Tropical Snappers and Groupers- Biology and Fisheries Management,* Westview Press, Boulder, Colorado, pp. 465-503.

Sainsbury, K. J., 1988. The ecological basis of multispecies fisheries and management of a demersal fishery in tropical Australia. In, J. A. Gulland (ed.), *Fish Population Dynamics*, 2nd edn, John Wiley, London, pp. 349-382.

Sainsbury, K. J., 1991. Application of an experimental approach to management of a tropical multispecies fishery with highly uncertain dynamics. *ICES Marine Science Symposia,* 193: 301-320.

Sampson, D. B., 1994. Fishing tactics in a two-species fisheries model: the bioeconomics of bycatch and discarding. *Canadian Journal of Fisheries and Aquatic Sciences*, 51: 2688-2694.

Schnute, J. T., and Richards, L. J., 2001. Use and abuse of fishery models. *Canadian Journal of Fisheries and Aquatic Sciences*, 58: 10-17.

Schott, G., 1999. Taxing times - the saltwater licence issue. *Saltwater Fishing Australia*, 14: 52-54.

Schwiegert, J. F., and Sibert, J. R., 1983. Optimizing survey design for determining age structure of fish stocks: an example from British Colombia Pacific Herring (*Clupea harengus pallasi*). *Canadian Journal of Fisheries and Aquatic Sciences*, 40: 588-597.

Sen, A. R., 1986. Methodological problems in sampling commercial rockfish landings. *Fisheries Bulletin* (U.S.), 84: 409-21.

SETMAC, 1995. *South East Fishery, Strategic research plan, 1995-2000.* South East Trawl Management Advisory Committee, Australian Fisheries Management Authority, Canberra.

SETMAC, 1998. *South East Fishery, Strategic research plan, 1997-2002*. South East Trawl Management Advisory Committee, Australian Fisheries Management Authority, Canberra.

SFA, 1992. *International conference on shrimp bycatch, May 24-27, 1992, Lake Buena Vista, Florida.* Southeastern Fisheries Association, Tallahassee, Florida.

Sissenwine, M. P., and Mace, P. M., 1992. ITQs in New Zealand: the era of fixed quota in perpetuity. *Fishery Bulletin,* 90: 147-160.

Sitter, R. R., 1992. Comparing three bootstrap methods for survey data. *Canadian Journal of Statistics*, 20: 135-154.

Smith, S. J., 1997. Bootstrap confidence limits for groundfish trawl survey estimates of mean abundance. *Canadian Journal of Fisheries and Aquatic Sciences*, 54: 616-30.

Squires, D., and Kirkley, J., 1991. Production quota in multiproduct Pacific fisheries. *Journal of Environmental Economics and Management,* 21: 109-126.

Squires, D., Campbell, H., Cunningham, S., Dewees, C., Grafton, R. Q., Herrick, S. F., Kirkley, J., Pascoe, S., Salvanes, K., Shallard, B., Turris, B., Vestergaard, N., 1998. Individual transferable quotas in multispecies fisheries. *Marine Policy*, 22: 135-159.

Staples, D., and Tilzey, R. (eds), 1995. *The South East Fishery 1994*, Fishery Assessment Report compiled by the South East Fishery Assessment Group. Australian Fisheries Management Authority, Canberra.

Stratoudakis, Y., Fryer, R. J., and Cook, R. M., 1998. Discarding practices for commercial gadoids in the North Sea. *Canadian Journal of Fisheries and Aquatic Sciences*, 55: 1632-1644.

Stratoudakis, Y., Fryer, R. J., Cook, R. M., and Pierce, G. J., 1999. Fish discarded from Scottish demersal vessels: estimators of total discards and annual estimates of targeted gadoids. *ICES Journal of Marine Science,* 56: 592-605.

Steffe, A. S., Murphy, J. J., Chapman, D. J., Tarlington, B. E., Gordon, G. N. G., and Grinberg, A., 1996a. *An assessment of the impact of offshore recreational fishing in New South Wales waters on the management of commercial fisheries*, Final report to the Fisheries research and Development Corporation, project No. 94/053. NSW Fisheries Research Institute, Cronulla, NSW.

Steffe, A. S., Staines, J. F., and Murphy, J., 1996b. *Recreational use of fisheries resources in northern NSW.* NSW Fisheries Research Institute, Cronulla, NSW.

Sukhatme, P. V., Sukhatme, B. V., Sukhatme, S., and Asok, C., 1984. Sampling theory of surveys with applications. 3rd edn., Iowa State University Press.

Tamsett, D., and Janacek, G., 1999. Sampling trips for measuring discards in commercial fishing based on multilevel modelling of measurements in the North sea from NE England. *Fisheries Research,* 42: 103-115.

Tamsett, D., Janacek, G., and Emberton, M. 1999a. A comparison of methods for onboard sampling of discards in commercial fishing. *Fisheries Research,* 42: 127-135.

Tamsett, D., Janacek, G., Emberton, M. Lart, B., and Course, G., 1999b. Onboard sampling for measuring discards in commercial fishing based on multilevel modelling of measurements in the Irish Sea from NW England and N Wales. *Fisheries Research,* 42: 117-126.

Tanner, M., and Liggins, G. W., 1999. *New South Wales commercial fisheries statistics, 1992/93.* NSW Fisheries, NSW Fisheries Research Institute, Cronulla.

Tanner, M., and Liggins, G. W., 2000. *New South Wales commercial fisheries statistics, 1998/99.* NSW Fisheries, NSW Fisheries, Cronulla.

Thompson, S. K., 1992. *Sampling.* John Wiley and Sons, New York.

Tillman, M. F., 1993. Bycatch - the issue of the 90's. In, R. P. Jones (ed.), *International conference on shrimp by-catch, May, 1992, Lake Buena Vista, Florida*, Southeastern Fisheries Association, Tallahassee, FL, pp. 13-18.

Tilzey, D. J. (ed.), 1994. *The South East Fishery.* Australian Government Publishing Service, Canberra.

Tilzey, R. D. J. (ed.), 1998. *The South East Fishery 1997*, Fishery Assessment Report compiled by the South East Fishery Assessment Group. Australian Fisheries Management Authority, Canberra.

Tilzey, R. D. J. (ed.), 1999. *The South East Fishery 1998*, Fishery Assessment Report compiled by the South East Fishery Assessment Group. Australian Fisheries Management Authority, Canberra.

Underwood, A. J., 1997. *Experiments in ecology, their logical design and interpretation using analysis of variance.* Cambridge University Press.

Van Beek, F. A., Van Leeuwen, P. I., and Rijnsdorp, A. D., 1990. On the survival of plaice and sole discards in the otter-trawl and beam-trawl fisheries in the North Sea. *Netherlands Journal of Sea Research,* 26: 151-160.

Walsh, S. J., Millar, R. B., Cooper, C. G., and Hickey, W. M., 1992. Codend selection in American plaice, diamond versus square mesh. *Fisheries Research*, 13: 235-254.

Walters, J. R., and Huntsman, G. R., 1986. Incorporating mortality from catch and release into yield-per-recruit analyses of minimum-size limits. *North American Journal of Fisheries Management,* 6: 463-471.

Wassenberg, T. J., and Hill, B. J., 1987. Feeding by the sand crab Portunus pelagicus on material discarded from prawn trawlers in Moreton Bay, Australia. *Marine Biology,* 95: 387-393.

Wassenberg, T. J., and Hill, B. J., 1989. The effect of trawling and subsequent handling on the survival rates of the by-catch of prawn trawlers in Moreton Bay, Australia. *Fisheries Research,* 7: 99-110.

Wassenberg, T. J., and Hill, B. J., 1990. Partitioning of material discarded from prawn trawlers in Moreton Bay. *Australian Journal of Marine and Freshwater Research,* 41: 27-36.

Wilson Jr., R. R., Burns, K. M., 1996. Potential survival of released groupers caught deeper than 40m based on shipboard and in-situ observations, and tag-recapture data. *Bulletin of Marine Science,* 58: 234-247.

Appendix A.4.1

ELSEVIER

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FISHERIES RESEARCH

Detection of bias in observer-based estimates of retained and discarded catches from a multi species trawl fishery

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Abstract

Observer-based estimates of quantities, size and age distributions of by-catches and discarded catches may be biased by nonrepresentative selection of sampling units (fisher-days or trips) or by changes in fishing practices onboard trawlers when observers are present. In this study, we examined the accuracy of estimates of catch derived from an observer survey of retained and discarded catches in a multispecies fish trawl fishery off the coast of NSW, Australia. Observer-based estimates of magnitudes and size-distributions of retained catches were compared with independent, unbiased estimates that were available for a subset of species (species managed by catch quotas) caught in the fishery. Conclusions about bias in estimates of other components of catch (especially discards) are based on the premise that bias is unlikely to affect these estimates without also affecting estimates of retained catches of quota species. We conclude that estimates of catch, based on the 3-year period 1993–1995, were unaffected by significant bias. Observer-based estimates of magnitudes of retained catches did not differ significantly from reported landings for 6 out of 7 species and the combined catch of quota species (CQS) for the Ulladulla fleet, 11 out of 11 species and CQS for the Eden fleet and 10 out of 11 species and CQS for the 2 fleets combined. There was, however, some evidence of bias in estimates of catch for each fleet in 1 of the 3 years. Observer-based size-distributions were not significantly biased. We conclude that our approach to validating observer-based estimates of catch would also be of use in observer surveys of other fisheries. © 1997 Elsevier Science B.V.

Keywords: Bias; Observer survey; Discards; Fish trawling

1. Introduction

Observer-based surveys, in which data is collected onboard fishing vessels during normal commercial fishing, have been used in a variety of fisheries. In particular, they have been used to estimate quantities and size/age distributions of by-catches and discarded catches from demersal trawling (e.g., Jean, 1963; Howell and Langan, 1987; Liggins and Kennelly, 1996; see also reviews by: Andrew and Pepperell, 1992; Alverson et al., 1994; Kennelly, 1995). Such information is fundamental to assessing effects of discarding on fish populations and resultant losses to fisheries (Gulland, 1983; Saila, 1983; Hilborn and Walters, 1992; Alverson et al., 1994).

An implicit assumption of observer-based surveys of retained, discarded or total catches is that the errors associated with estimates of catch (e.g., magnitudes and size-distributions) arise solely from ran-

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dom sampling error. If, however, nonsampling errors are present, estimates of catch will be inaccurate, or biased, reducing the reliability of subsequent fishery assessments. Nonsampling errors may arise from many sources (e.g., Cochran, 1977; Andrew and Mapstone, 1987; Thompson, 1992) but several are of particular concern in observer surveys of fisheries (Saila, 1983; Alverson et al., 1994). Nonrandom selection of sampling units (e.g., observed fisher-days or trips) from the sampled population may result in bias. Random selection of sampling units is difficult when the sample population cannot be enumerated until the period from which the sample is taken is complete. Refusals by masters of vessels to allow an observer onboard will also bias estimates unless the retained and discarded catches of respondents and nonrespondents are similar. Another problem for observer-based surveys is the influence that the process of observation may have on the process being observed. Bias could occur if fishers perceive that their interests may be enhanced by changing their normal practices when an observer is present (e.g., by discarding more/less or by fishing in an area or in a way such that discards will be maximised/minimised).

Despite warnings regarding the dangers of ignoring potential biases in observer surveys (e.g., Saila, 1983), few attempts have been made to detect the presence or absence of bias in estimates of catch from such surveys. In this study, we present an evaluation of the accuracy of estimates of catch derived from an observer-based survey of a multispecies fish trawl fishery off the coast of New South Wales (NSW), Australia.

The observer-based survey of the retained and discarded catches of fish trawlers operating along the coast of NSW was established in 1993. Trawlers working from two of the ports surveyed, Ulladulla and Eden, fish mainly in the South East Fishery (SEF), a multispecies fishery in which 16 species are managed by a system of total allowable catches (TACs) and individual transferable quotas (ITQs). In this fishery, fishers are legally required to report the landed catches of quota species to the Australian Fisheries Management Authority (AFMA) but discarding of juveniles and unmarketable quantities of commercial and noncommercial species is a long established and little studied practice (Tilzey, 1994). The principal objectives of the observer survey were to estimate quantities and size-distributions of discarded quota species and total catches (retained and discarded components) of nonquota species, with a view to evaluating the effects of discarding on the SEF and other interacting fisheries.

Perceptions of fishers concerning the likely results and consequences of the survey (anecdotal accounts) were diverse, and these perceptions each had particular consequences for the accuracy of the survey. That is, there was a potential for fishers to increase or decrease the quantities of discarded catches seen by observers, and so bias observer-based estimates of catch. Some fishers believed that eventual publication of estimates of discarded catches could have a negative effect on their future livelihood and so provided a potential motive for fishers to reduce the amount of discarding seen by observers. Other fishers asserted that the introduction of TACs and ITQs in this fishery (in 1992) resulted in increased high-grading and discarding of quota species. They argued that TACs (and ITQs) should be increased to reduce discarding and so provided a potential motive to increase the amount of discarding seen by observers. Further, nonrepresentative selection of fisher-days could also positively or negatively bias observer-based estimates of discarded catches and retained and discarded catches of nonquota species.

We examined the accuracy of observer-based estimates of catch magnitudes and size-distributions (of all components of catch) by comparing such estimates for retained catches of quota species with independent and unbiased measures of catch and size-distribution. Observer-based estimates of retained catches of quota species were compared with reported landings. Size-distributions (and mean sizes and variances of mean sizes of samples) derived from the observer survey were compared with estimates from an auxiliary survey of catches landed at fishing cooperatives. In assessing the accuracy of observer-based estimates of discards, we assume that such estimates for retained catches of quota species would be biased if similar estimates for nonquota species and discarded quota species were biased. This is a reasonable assumption for this fishery because quota species are the main species targeted in the fishery, and subsets of these species are caught across the full range of depths and latitudes encompassed by the fishery (Tilzey, 1994). Consequently, it is difficult to construct scenarios whereby discarded catches of quota species and catches of non-quota species could be biased without affecting magnitudes or size-distributions of retained catches of quota species. Consider, for example, a scenario whereby: (i) total catches are the same on observed and unobserved fisher-days; but (ii) fewer (or more) fish are discarded on observed fisher-days. With this scenario, retained catches will be greater (or less) on observed than on unobserved fisher-days. Moreover, observer-based estimates of retained catches will be greater (or less) than reported landings. Other, more complex scenarios, in which (i) quantities of retained catches are the same on observed and unobserved fisher-days; but (ii) quantities and/or size-distributions of discarded catches differ, result in differences in size-distributions of retained catches of quota species on observed and unobserved fisher-days.

Given the above premise, significant differences between observer-based and independent, unbiased estimates of quantities and sizes of retained catches of quota species would indicate that observer-based estimates of other components of catch were also biased.

2. Materials and methods

2.1. Observer survey

Retained and discarded catches of fish trawlers were surveyed on approximately 24 fisher-days during each quarter (Jan.–Mar., Apr.–June, July–Sept., Oct.–Dec.) of each of 3 years (1993, 1994, 1995) in each of 2 regions (fleets based in Ulladulla and Eden) in NSW, Australia. Fishing trips out of Eden, of intended duration of more than 3 days, were excluded from the sampled population of the survey because fishing generally took place far to the south of the study area. Fishing trips targeting royal red prawns, *Haliporoides sibigae*, were also excluded from the sampled population because the survey was designed to estimate catches from fish trawling. In each region, we attempted to select fisher-days at random for inclusion in the survey. At Eden, where fishing trips were between 1 and 3 days duration, we attempted to select fishing trips randomly until the targeted number of fisher-days had been observed. We assumed that fisher-days on multiday trips at Eden were independent because trawlers generally stayed out for the preplanned number of days, and there was no obvious relationship between catch rates and decisions to reduce or extend the duration of trips.

The number of fisher-days sampled during each quarter, in each year, in each region, averaged 23.8 fisher-days, the minimal sample being 22 fisher-days and the maximum 27 fisher-days (Fig. 1). During the 3 years surveyed, 97, 93 and 96 fisher-days were observed at Ulladulla. These represented sampling fractions of 7.5%, 7.5% and 8.8% for the 3 years. At Eden, 96, 94 and 96 fisher-days were surveyed during the 3 years, with sampling fractions of 4.6%, 4.6% and 4.5%, respectively.

Although sample sizes of approximately 24 fisher-days were achieved in each quarter, of each year, in each region (Fig. 1), estimated catches may be biased if the fisher-days sampled were not representative of fisher-days completed by the fleets. A variety of factors (e.g., weather patterns, availability of fish) contributed to the pattern of effort by individual vessels within each quarter. Thus, the distribution of fishing effort within a quarter cannot be predicted in advance. Consequently, the fairly even distribution of sampling effort across the 90 or so days in each quarter (approximately 2 fisher-days per week in each region) will not always reflect the distribution of fishing effort by the fleets.

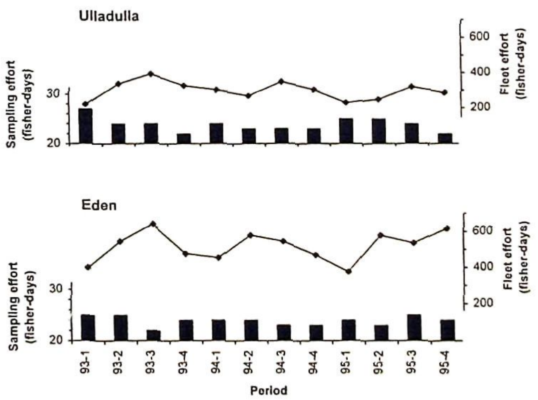

Fig. 1. Quarterly sampling effort and fishing effort, Ulladulla and Eden, 1993–1995.

Bias may also result from disproportionate sampling of individual vessels within each quarter and throughout the year (Fig. 2). Discrepancies between 'ideal' sampling coverage of vessels and that achieved occur for several reasons. Target sampling effort could not be determined for individual trawlers because fishing effort (the population of fisher-days being sampled) could not be enumerated until after the completion of each year. Furthermore, individual vessels were not surveyed if: (i) skippers or owners refused access to observers, or (ii) vessels did not meet the minimal safety requirements necessary for carrying an additional person. Differences in the ease with which skippers of different boats could be contacted when observers were attempting to arrange trips also influenced the disproportionate sampling coverage of vessels.

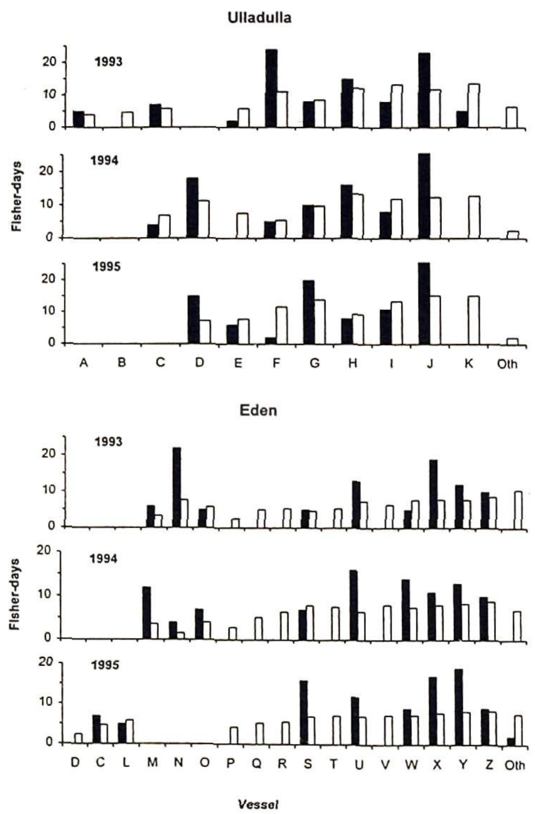

Fig. 2. Actual (black bars) and 'ideal' (white bars) sampling effort for individual trawlers at each port in each year. The number of fisher-days observed on each trawler is actual sampling effort. 'Ideal' sampling effort represents the number of fisher-days that would have been observed on each trawler if the sampling fraction was constant across all trawlers in the port. Individual trawlers that completed a minimum of 50 fisher-days effort are denoted by 'A', 'B', 'C', etc. Trawlers not meeting this criteria are combined in the category 'Oth'.

For each tow of each fisher-day sampled, observers recorded weights and numbers of the retained and discarded catches of each commercial species and size-distributions for each commercial species present in the discards. Size-distributions of retained catches were recorded opportunistically as time permitted. Operational data (location, depth, time, duration of tow) and a list of noncommercial species present in the catch were also recorded.

Retained weights of each species were estimated by weighing each box of fish or a subsample of boxes, and counting the total number of boxes. On occasions when fishers graded species into separate size-classes for marketing purposes, the average weight of fish was estimated from a subsample of each grade of each species (usually a 30–40 kg box of fish) and used to estimate the total number of each species of each grade, and consequently, the total number of each species retained. The total weight of discards was estimated using one of two methods. If the catch was relatively small, total weight of discards was estimated from the catch remaining on deck after the crew had sorted out the fish to be retained. If the catch was relatively large, the crew discarded fish as the catch was sorted. In these circumstances, the weight of total catch was estimated, and an estimate of total discards was calculated by subtracting the estimated total weight of retained catch from estimated weight of total catch. Composition and abundances of species and size-distributions were estimated from a subsample of discards (usually a 30–40 kg box) and an estimate of the sampling fraction. All species present in the discards were recorded.

2.2. Reported fishing effort and weights of landings

All fishers in the SEF are required to report landed catches of quota species and the duration of each fishing trip (dates of departure and return to port) to the Australian Fisheries Management Authority (on 'SEF-2', 'Disposal of catch' returns). Only those fishing trips that conformed to the criteria for the sampled population of the observer survey were included in calculations of fishing effort and landed catch (i.e., trips of less than 3 days' duration and trips not targeting *H. sibogae*).

Quarterly fishing effort (in units of fisher-days), for the ports of Ulladulla and Eden, was calculated as follows: (i) trips for which the reported dates of departure and return to port were identical, each contributed 1 fisher-day of effort; (ii) trips for which the dates of departure and return to port differed by d days contributed an estimated $d-0.5$ fisher-days.

Annual weights of landed catches of each quota species and the combined weight of all quota species (CQS) were calculated from the data reported by fishers making landings into Ulladulla and Eden. Landed weights that were reported for 'processed' fish (gutted, or headed and gutted) were converted to 'whole' weights using approximate conversion factors (1.1 for pink ling, *Genypterus blacodes*; 1.25 for gemfish, *Rexea solandri*; 1.5 for blue grenadier, *Macruronus novaezelandiae*).

2.3. Survey of size-distributions of landed catches

Size-distributions of catches landed at Ulladulla and Eden were surveyed during May/June and September/October of 1994 and 1995. The fishers' cooperatives in each port were visited on each of 8 days during each period of each year. On each visit, we attempted to estimate the size-distributions for the two most abundant species in the catch of each trawler landing fish on that day.

If the catch of a species was landed ungraded, a minimum of one box was weighed and measured. When catches were graded prior to landing, a minimum of one box (approximately 30 kg) of each grade of fish was weighed, and its contents measured. The total landed weight of each grade of each species from each trawler was recorded from the records maintained by the cooperative. Using the number and weight of fish in the sample of each grade and the size-distribution of the sample, the total weight of each grade landed, the size-distribution of the landed catch was estimated.

2.4. Comparison of reported landings and observer-based estimates of retained catches

Reported annual catches of the quota species landed into Ulladulla and Eden were compared with observer-based estimates of retained catches (with 95% confidence limits). For each region, comparisons were made only for species with average annual landings exceeding 20 t during the period 1993–1995. Consequently, comparisons were made for 7 species at Ulladulla (redfish, *Centroberyx affinis*; pink ling, *Genypterus blacodes*; tiger flathead, *Neoplatycephalus richardsoni*; silver trevally, *Pseudocaranx dentex*; gemfish, *Rexea solandri*; mirror dory, *Zenopsis nebulosis*; and john dory, *Zeus faber*), 11 species at Eden (as for Ulladulla, plus blue grenadier, *Macruronus novaezelandiae*; jackass morwong, *Nemadactylus macropterus*; blue warehou, *Seriolella brama*; and spotted trevalla, *Seriolella punctata*) and the combined weight of all quota species (CQS) for each region. Observer-based estimates of annual retained catches were calculated using a stratified mean-per-unit estimator (e.g., Cochran, 1977). With a simple random sample of fisher-days taken in each quarter of each year, the estimated annual catch, $\hat{Y}$, and associated standard error, $s(\hat{Y})$, were calculated as follows:

$$\hat{Y}=\sum_{q=1}^{4} N_q \cdot \bar{y}_q \quad (1)$$

$$s(\hat{Y})=\sqrt{\sum_{q=1}^{4}\frac{N_q^2\cdot(1-f_q)}{n_q}\cdot s^2(y_q)} \quad (2)$$

in which N_q is the number of fisher-days done by the fleet (see below) in quarter q, $\bar{y}_q$ is the mean retained catch, $s^2(y_q)$ is the variance of retained catch, n_q is the sample size and $f_q=n_q/N_q$ is the sampling fraction, in each quarter of the year. Confidence limits (95%) were calculated as:

$$\hat{Y}\pm t'\cdot s(\hat{Y}) \quad (3)$$

where t' is the value of Student's t corresponding to the 'effective' number of degrees of freedom associated with annual estimates. The effective number of degrees of freedom is somewhere between 21 and 92, the smallest of the values (n_q-1) and their sum (Cochran, 1977). Because the difference between values of t for 21 df ($t = 2.08$) and 93 df ($t = 1.99$) is minimal, a t' value of 2 was used.

Comparisons of landed catches from the 2 sources of data were also made at larger spatial and temporal scales, i.e., combined annual catches of the Ulladulla and Eden fleets in each of the 3 years (1993–1995); mean annual catches across the 3 years for each region; mean annual catches for the combined fleets of Ulladulla and Eden across the 3 years. Observer-based estimates of annual catches (± standard errors) for each region ($\hat{Y}_U$ and $\hat{Y}_E$) were used to estimate annual catches of the combined fleets of Ulladulla and Eden, $\hat{Y}_{UE}$ as follows (e.g., Cochran, 1977):

$$\hat{Y}_{UE} = \hat{Y}_U + \hat{Y}_E \tag{4}$$

$$s(\hat{Y}_{UE}) = \sqrt{s(\hat{Y}_U)^2 + s(\hat{Y}_E)^2} \tag{5}$$

Estimates of mean annual catches across the period 1993–1995, $\bar{Y}_{3y}$, were calculated as:

$$\bar{Y}_{3y} = \frac{\sum_{i=93}^{95} \hat{Y}_i}{3} \tag{6}$$

$$s(\bar{Y}_{3y}) = \frac{\sqrt{\sum_{i=93}^{95} s(\hat{Y}_i)^2}}{3} \tag{7}$$

for $\hat{Y}_i = \hat{Y}_U$, $\hat{Y}_E$ and $\hat{Y}_{UE}$. Confidence limits of estimates were calculated as $\hat{Y} \pm 2 \cdot s(\hat{Y})$.

At all spatial and temporal scales, significant differences between observer-based estimates of retained catches and reported landings were indicated if the weight of reported landings was outside the 95% confidence limits of the observer-based estimate.

2.5. Comparison of shore-based and observer-based estimates of size-distributions of retained catches

Size-distributions derived from the observer survey between April and November of each year were compared with size-distributions from the shore-based survey of cooperatives in each port (Ulladulla, Eden) and year (1994, 1995). It is assumed that size-distributions derived from the shore-based survey during the periods May–June and September–October are representative of size-distributions landed at the ports during the period April–November. Comparisons were made for each species, in each region and in each year (1994, 1995), if the following criteria were met: (i) a minimum of 400 fish measured across a minimum of 10 tows from the observer-based survey and (ii) a minimum of 400 fish measured across 10 landings from the cooperative survey. Two types of comparison were made.

First, for both the observer-based and shore-based surveys, annual size-distributions (for the period April–November) were calculated by combining the sizes from each sample after weighting each sample by the inverse of the sampling fraction (i.e., by the number of fish in the retained or landed catch/the number measured). Resulting size-distributions from each source were converted to relative frequency distributions and graphed.

Second, two-sample t-tests were used to detect significant differences between the means (of mean lengths of samples) from the observer-based and shore-based surveys. Variances (of mean lengths of samples) were calculated for each source of data and significant differences were detected by calculating an F ratio (maximum variance/minimum variance). In these procedures, each sample received equal weighting, regardless of sampling fraction.

3. Results

3.1. Comparison of reported landings and observer-based estimates of retained catches

For 1993, observer-based estimates of the weights of retained catches of all quota species and of CQS were consistent with reported landings (i.e., no significant differences at $p = 0.05$) for the fleets of Ulladulla and Eden (Table 1) and for the combined fleets of these ports (Fig. 3).

For the Ulladulla fleet, in 1994, observer-based estimates of retained catches of 4 out of 7 species were consistent with reported landings. Observer-based estimates of catches of redfish, silver trevally, john dory and CQS were underestimated (Table 1). Observer-based estimates and reported landings were consistent for CQS and all but one species (tiger flathead) taken by the Eden fleet (Table 1). Observer-based estimates of catches of each quota species and CQS by the combined fleets of Ulladulla

Table 1
Observer-based estimates (with 95% C.I.) of retained catches and reported landings (t) of quota species for Ulladulla and Eden during 1993, 1994 and 1995

Species	Year	Ulladulla				Eden			
		Reported landing	Obser-ved	(with 95% C.I.)	Diff.	Reported landing	Obser-ved	(with 95% C.I.)	Diff.
Redfish	1993	1078	1086	±346	+	365	351	±436	−
	1994	644	454	172	−[a]	338	453	166	+
	1995	625	761	242	+	222	418	263	+
Pink ling	1993	96	147	72	+	242	203	80	−
	1994	104	86	34	−	233	218	86	−
	1995	89	84	44	−	307	491	203	+
Blue grenadier	1993	0				102	60	58	−
	1994	3				88	73	100	−
	1995	4				15	24	28	+
Jackass morwong	1993	14				244	174	92	−
	1994	17				265	321	134	+
	1995	15				224	133	62	−[a]
Tiger flathead	1993	167	169	54	+	463	543	170	+
	1994	181	140	50	−	290	407	116	+[a]
	1995	109	106	22	−	417	386	44	−
Silver trevally	1993	50	42	34	−	165	112	64	−
	1994	76	46	26	−[a]	114	160	96	+
	1995	73	73	35	−	160	99	59	−[a]
Gemfish	1993	36	34	14	−	53	53	28	−
	1994	15	22	14	+	36	46	32	+
	1995	8	14	8	+	25	31	16	+
Blue warehou	1993	2				181	186	136	+
	1994	0				300	411	236	+
	1995	12				252	199	117	−
Spotted trevalla	1993	1				514	1120	748	+
	1994	0				848	659	294	−
	1995	2				870	1167	966	+
Mirror dory	1993	77	101	46	+	39	59	38	+
	1994	75	125	72	+	38	40	20	+
	1995	37	46	21	+	32	35	9	+
John dory	1993	52	47	20	−	79	77	24	−
	1994	56	33	10	−[a]	64	85	28	+
	1995	43	35	10	−	56	44	11	−[a]
All quota species (CQS)	1993	1646	1711	342	+	2536	3011	869	+
	1994	1231	996	189	−[a]	2676	2943	567	+
	1995	1054	1168	241	+	2634	3113	1042	+

[a] Indicates the difference is significant at $p = 0.05$.
'Diff.' indicates that the observer-based estimate is greater than (+) or less than (−) the reported tonnage.

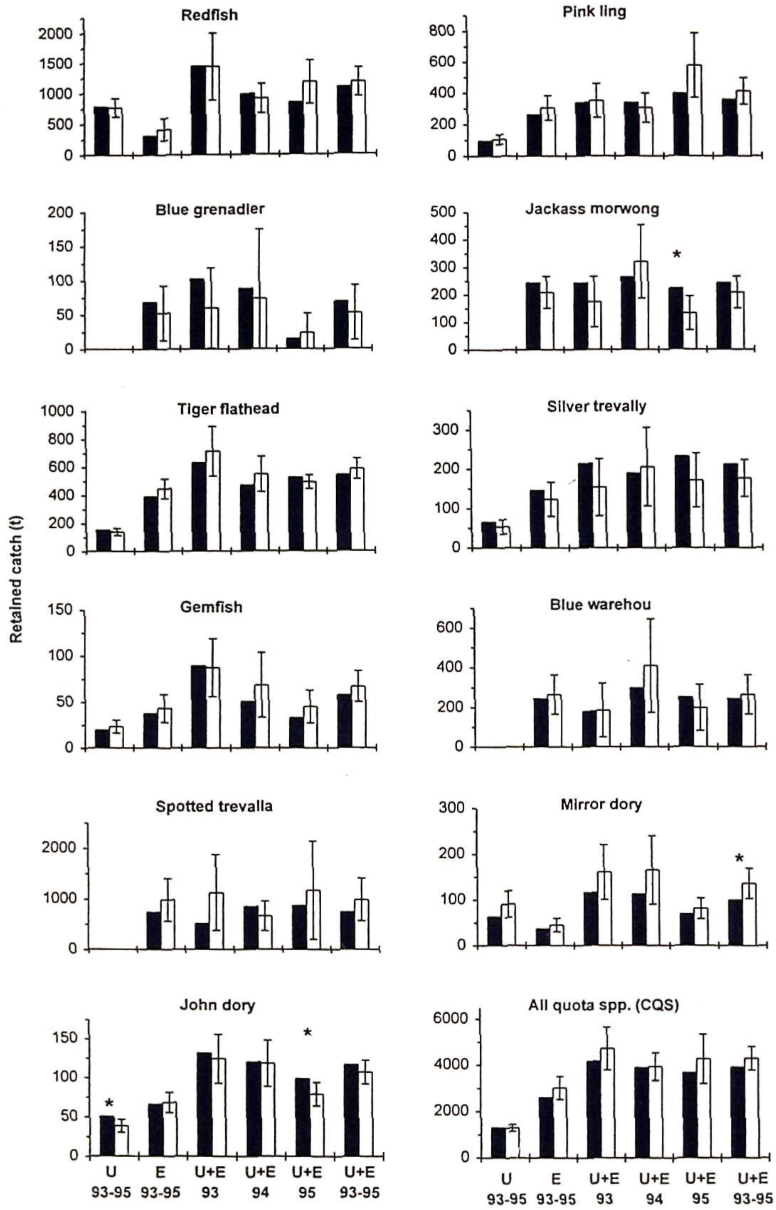

Fig. 3. Reported landings (black bars) and observer-based estimates of retained catches (white bars, with 95% confidence intervals) of quota species at Ulladulla and Eden during 1993–1995. 'U 93–95' and 'E 93–95' denote mean annual catches for Ulladulla and Eden across all years; 'U + E 93', 'U + E 94' and 'U + E 95' denote combined Ulladulla and Eden catches in each year; and 'U + E 93–95' denotes the mean annual combined catch of Ulladulla and Eden. * Indicates significant difference between observer-based estimates and reported landings ($p < 0.05$).

and Eden were consistent with reported landings (Fig. 3).

For 1995, comparisons of landings of each quota species and of CQS, derived from the two sources of data, were consistent for the Ulladulla fleet (Table 1). Observer-based estimates of retained catches of 8 out of 11 species were consistent with reported landings into Eden. Retained catches of jackass morwong, silver trevally and john dory were underestimated (Table 1). The combined catches of the Ulladulla and Eden fleets were underestimated for two of these species (jackass morwong and john dory) (Fig. 3).

Observer-based estimates of mean annual landings (for the period 1993–1995) were consistent with reported landings for CQS and 6 out of 7 species taken by Ulladulla trawlers (john dory the exception), CQS and all 11 species taken by Eden trawlers and for CQS and 10 of the 11 species taken by the combined fleets (mirror dory being the exception; Fig. 3).

The discrepancies between observer-based estimates and reported landings described above were all detected using a critical p-value of 0.05. In interpreting the results of such comparisons, note that Type I errors across the sets of tests will exceed the nominal $p = 0.05$ for each test. For each year of the survey, comparisons were made for landings of 7 species and of CQS (a total of 8 comparisons) by the Ulladulla fleet. Twelve comparisons were made for the Eden fleet. The probability of detecting 2 out of 8 or more inconsistencies for the Ulladulla data, and 2 out of 12 or more inconsistencies for the Eden data, by chance alone, is less than 0.05 (based on binomial distributions for 2 or more out of $n = 8$ and 2 or more out of $n = 12$ events, each with a chance $p = 0.05$ of occurring). Consequently, we conclude that bias is present in observer-based estimates of catches by the Ulladulla fleet in one of the 3 years surveyed (1994), by the Eden fleet in one of the 3 years (1995), and by the combined fleets of Ulladulla and Eden in one of the 3 years (1995) (Table 2).

Biases in observer-based estimates were not consistent across years for Ulladulla, Eden nor for the combined fleets of these ports. Nor were they consistent across the fleets of the 2 ports. Furthermore, at neither port was the retained catch of a given species under- or over-estimated (significantly) in more than one year. Similarly, estimated retained catches of no individual species was under- or over–estimated at both ports in any one year (Table 2).

Having concluded that bias is not constant across ports or across years, it is not surprising that observer-based estimates of retained catches were inconsistent with reported landings in fewer instances when compared at larger spatial and temporal scales

Table 2
Incidence of significant differences between observer-based estimates of retained catches and reported landings at different spatial and temporal scales

Temporal scale		Spatial scale					
		Single fleets				Combined fleets	
		U		E			
Annual	1993	0/8		0/12		0/12	
	1994	4/8[c]	Redfish[a] Silver trevally[a] John dory[a] CQS[a]	1/12	Tiger flathead[b]	0/12	
	1995	0/8		3/12[c]	Jackass morwong[a] Silver trevally[a] John dory[a]	2/12[c]	Jackass morwong[a] John dory[a]
3 Years		1/8	John dory[a]	0/12		1/12	Mirror dory[b]

x/y Indicates that x (of a total y) observer-based estimates of retained catch were significantly different from reported landings Species for which differences were detected are listed.
[a]Indicates an underestimate.
[b]Indicates an overestimate.
[c]Indicates the presence of bias (i.e., the probability of detecting the given number, or more, significant differences by chance alone < 0.05).

(Fig. 3 and Table 2). In 1994, inconsistencies were detected for 3 species at Ulladulla and 1 species at Eden, but no inconsistencies were detected for the combined catches of the 2 ports in that year. Similarly, in 1995, the number of inconsistencies identified for catches by the combined fleets was less than the number identified for individual ports. Landings of a given species may be overestimated (not necessarily significantly) in some years and underestimated (not necessarily significantly) in others or overestimated at one port and underestimated at the other (Table 1).

Not only were fewer inconsistencies detected at larger spatial and temporal scales, but the power to detect differences at these scales was increased (Fig. 4). Coefficients of variation of estimated retained catches made over 3 years were improved by approximately $1/\sqrt{3}$, i.e., a 42% increase in precision, relative to annual estimates (Fig. 4a). Precision is associated with size of sample and, in this comparison, size of sample is associated with the number of years over which mean catches are calculated. Similarly, CVs of estimates made for the combined catches of Ulladulla and Eden fleets were improved, with several exceptions, by approximately $1/\sqrt{2}$ i.e., a 29% increase in precision (Fig. 4b). In addition to

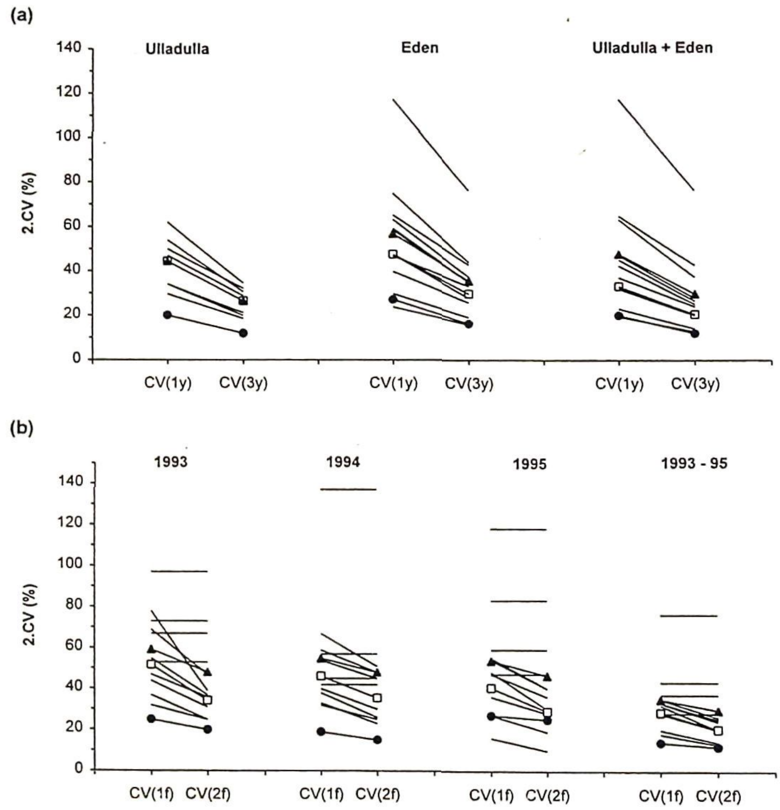

Fig. 4. Precision of observer-based estimates of retained catches at different spatial and temporal scales: (a) compares the mean coefficient of variation of annual estimates of catch, CV(1y), with the CV of mean annual estimates, CV(3y), for the fleets of individual ports and for the combined fleets; (b) Compares the mean CV of estimates of catch for individual fleets, CV(1f), with the CV of estimates of catch by the combined fleets, CV(2f), for each year and for the 3-year period (———— individual quota species; □ ———— □ mean CV for the 7 species taken by both the Ulladulla and Eden fleets; ▲ ———— ▲ mean CV for all 11 species examined; ● ———— ● CQS). Note that the unit of measurement on the y-axis is $2 \cdot CV$ (%) so that the relative magnitude of ± half the 95% confidence interval to the estimate is shown.

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size of sample, the precision of estimates made across fleets is related to the relative magnitude and precision of estimates for each fleet. In the most extreme case, there was no improvement in the precision of estimates of retained catches for the four species caught only at Eden (blue grenadier, jackass

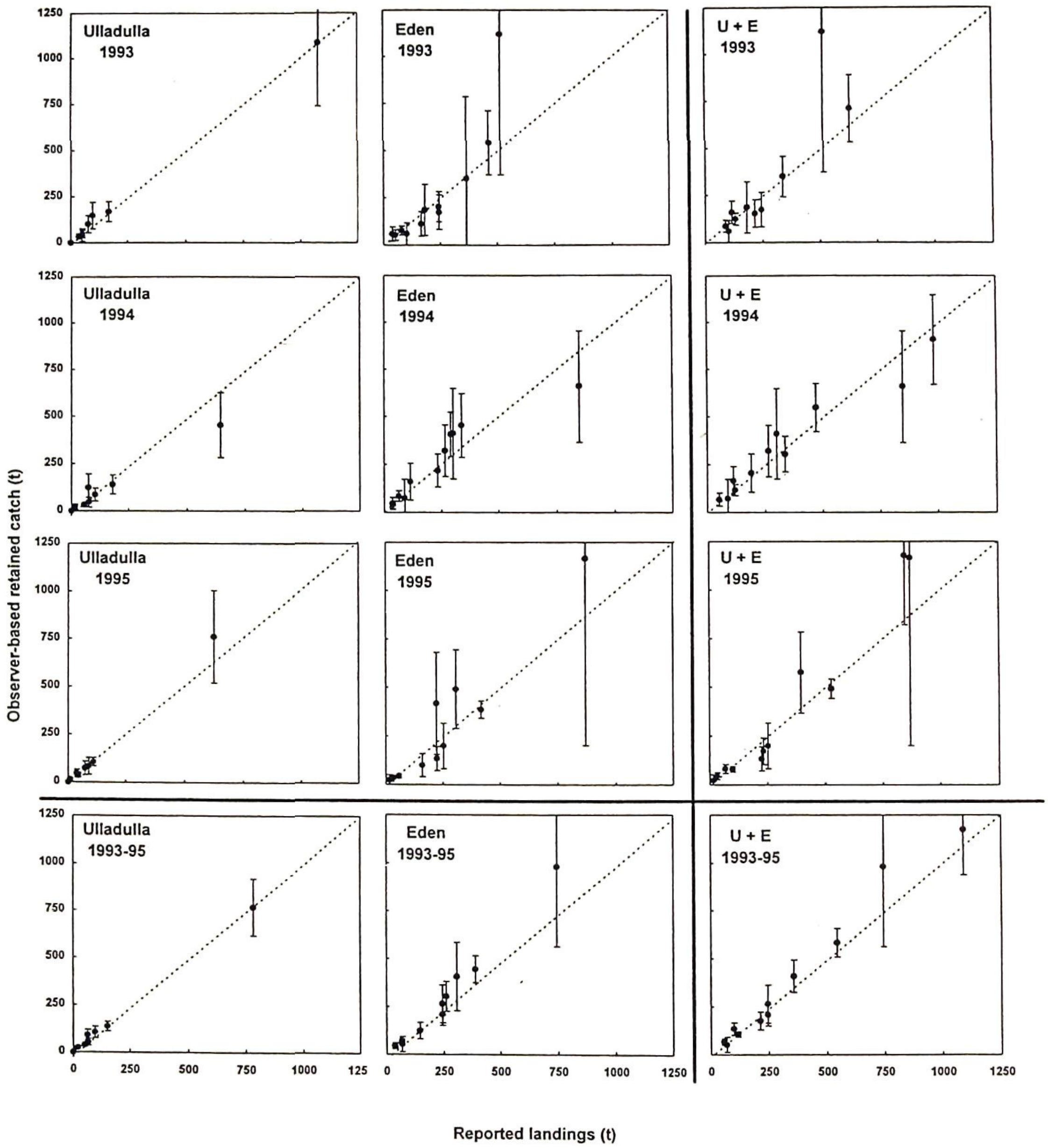

Fig. 5. Reported landings vs. observer-based estimates of retained catches (with 95% confidence intervals) of quota species. Data points above the line of equality (dashed line) indicate that observer-based estimates overestimate landings; points below the line are underestimates.

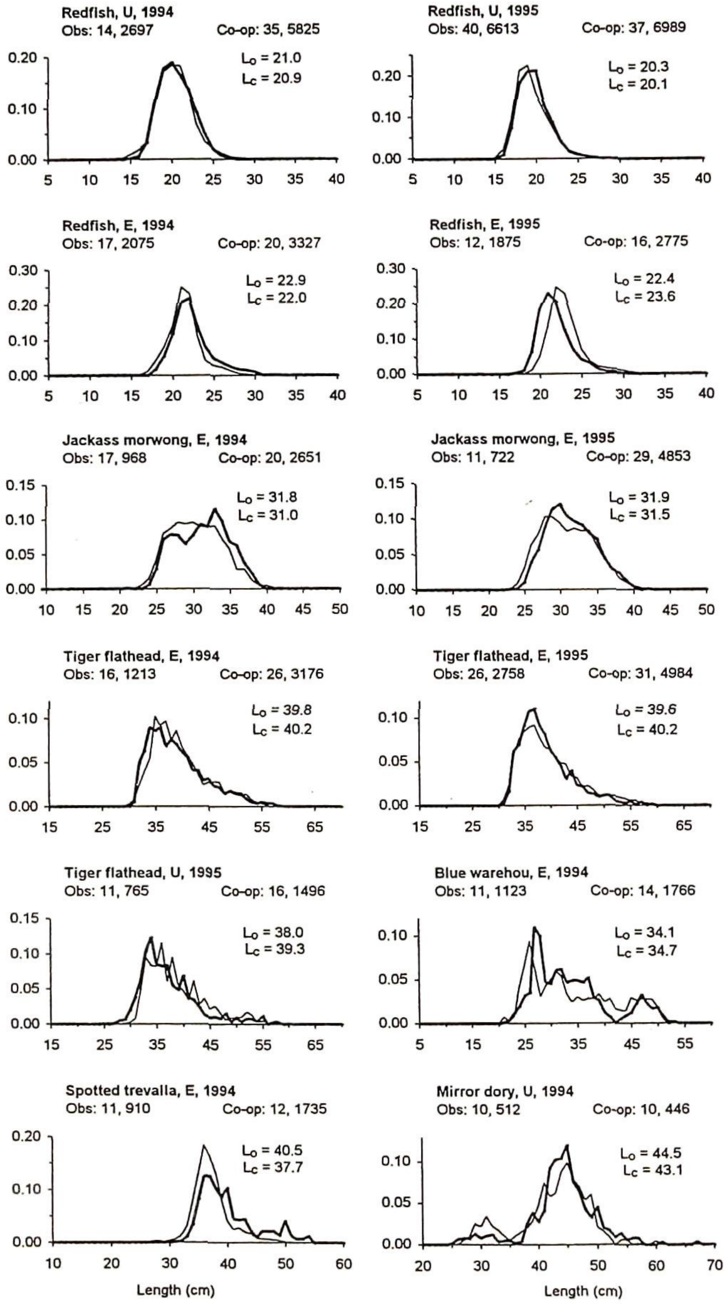

Fig. 6. Observer-based (bold line) and shore-based (thin line) size-distributions of retained/landed catches for Ulladulla and Eden during 1994 and 1995. Number of samples and the number of fish measured, for observer-based and cooperative surveys, are shown above each graph. L_o and L_c are the mean lengths of fish sampled from the observer and cooperative surveys, respectively.

morwong, blue warehou and spotted trevalla; Fig. 4b). In summary, both accuracy and precision of observer-based estimates of retained catches of quota species increased with spatial and temporal scale (Fig. 5).

3.2. Comparisons of shore-based and observer-based estimates of size-distributions of retained catches

Annual observer-based and shore-based size-distributions were similar for all species examined (Fig. 6). Among the 12 comparisons shown in Fig. 6, observer-based and shore-based size-distributions corresponded most closely when sample sizes (number of samples and number of fish measured across samples) were relatively large. This suggests that differences between size-distributions result from sampling error rather than bias.

No significant differences were detected between mean lengths (means of mean lengths calculated from each sample) calculated from the 2 sources of data, for any of the combinations of species, port and year examined (Table 3). The ability of *t*-tests to detect differences in mean length is indicated by 'minimal significant difference' (MSD) specified in Table 3. Differences of approximately 1 cm would have been detected as significant for redfish or jackass morwong, approximately 1.5 cm for tiger flathead, and approximately 2 cm for spotted trevalla. The ability of the *t*-tests to detect differences for blue warehou and mirror dory was less useful.

Note that the discrepancy between observer-based and shore-based estimates of mean lengths of redfish at Eden in 1995 was 0.04 cm when all samples were given equal weighting in the determination of mean length (Table 3). In contrast, when samples were given a weighting in the overall distribution in proportion to magnitude of catch (from which each sample was obtained), the discrepancy between mean lengths was 1.2 cm, and the observer-based distribution was shifted to the left of the shore-based distribution (Fig. 6). Two of the 12 samples of redfish from the observer survey came from particularly large catches of comparatively small fish. These two

Table 3
Observer-based and port-based mean sizes of catch: comparisons of variances (*F* ratio) and of mean lengths (*t*-tests)

Species	Region	Year	Observer survey				Coop. survey				Ratio of variances		Difference between means		MSD
			n	Var.	Mean *L*	se	*n*	Var.	Mean *L*	se					
Redfish	U	1994	14	2.59	21.70	0.43	35	2.94	21.17	0.29	1.14	ns	0.53	ns	1.08
	U	1995	40	1.60	20.74	0.20	37	2.50	20.49	0.26	1.56	ns	0.25	ns	0.65
	E	1994	17	4.25	23.69	0.50	20	4.05	22.45	0.45	1.05	ns	1.24	ns	1.35
	E	1995	12	2.43	23.49	0.45	16	1.08	23.45	0.26	2.25	ns	0.04	ns	1.01
Jackass morwong	E	1994	17	2.08	31.65	0.35	20	2.45	31.27	0.35	1.18	ns	0.38	ns	1.00
	E	1995	11	2.43	31.86	0.47	29	1.81	31.44	0.25	1.34	ns	0.42	ns	1.00
Tiger flathead	U	1995	11	9.51	39.03	0.93	16	6.15	38.73	0.62	1.55	ns	0.30	ns	2.22
	E	1994	16	5.20	40.35	0.57	26	4.37	39.82	0.41	1.19	ns	0.53	ns	1.40
	E	1995	26	4.59	39.75	0.42	31	4.02	40.57	0.36	1.14	ns	−0.82	ns	1.11
Blue warehou	E	1994	11	37.65	33.80	1.85	14	59.99	35.95	2.07	1.59	ns	−2.15	ns	5.90
Spotted trevalla	E	1994	11	6.87	38.12	0.79	12	2.32	37.88	0.44	3.28	*	0.24	ns	1.93
Mirror dory	U	1995	10	34.23	44.92	1.85	10	21.32	42.87	1.46	1.61	ns	2.05	ns	4.95

Sample size (*n*), variance (Var.), mean length (Mean *L*) and standard error (se) of observer-based and coop-based estimates of mean length of fish.
Ratio of variances = largest variance/smallest variance; ns indicates no significant difference by *F* ratio; * indicates significance at p = 0.05.
Difference between means = difference between mean lengths from observer survey and coop survey; ns denotes no significant difference by *t*-test; t-tests for all species except spotted trevalla use pooled estimates of variance; MSD is the minimum difference between means that would have been significant.

catches represent 56% of the total catch sampled, and consequently, these catches of small fish contribute more than 56% of the information to the weighted distribution.

There were no significant differences between variances (of mean lengths calculated from each sample) for 11 of the 12 comparisons (Table 3). The variance of sample means from the observer survey was greater than that derived from the shore-based survey for spotted trevalla at Eden in 1994. The probability, however, of detecting one or more significant difference (from the set of 11 tests) by chance alone is greater than 0.05. Thus, one significant difference does not provide evidence that variances actually differed between observer-based and shore-based estimates.

4. Discussion

Observer-based estimates of the magnitudes and size-distributions of catches by the trawl fleets of Ulladulla, Eden and the combined fleets of both ports, over the 3-year period 1993–1995, were not significantly biased. Over this 3-year period, the effects of (i) nonrepresentative selection of fisher-days, (ii) any changes in fishing practices when an observer was onboard and (iii) other potential sources of bias, were insignificant.

Observer-based estimates of catch were unaffected by bias in 2 of the 3 years surveyed in each region. There was, however, evidence of bias for the Ulladulla fleet in 1994, the Eden fleet in 1995 and the combined fleets in 1995. Observer-based estimates of catch for these regions in these years must be considered less reliable than estimates for other years in these regions. Note that, despite evidence of bias, the majority of observer-based estimates of retained catches of quota species in these regions in these years were consistent with reported landings (4 out of 7 species for Ulladulla in 1994, 8 out of 11 species for Eden in 1995, 9 out for 11 species for Ulladulla and Eden in 1995). Furthermore, no significant differences were detected from comparisons of size-distributions for these regions in these years. Intuitively, this suggests that observer-based estimates of catch for the majority of species, in these regions in these years, were unaffected by bias. In practice, it is probably reasonable to assume that observer-based estimates of catch for the combined fleets of Ulladulla and Eden in 1995 (comparisons for 9 out of 11 species were consistent) were unaffected by bias.

These conclusions have implications for the analysis of data collected from this observer survey during the period 1993–1995. Analyses based on data collected across the 3-year period, will be unaffected by bias. Analyses based on year-to-year changes in catches from a single region must be interpreted with more caution.

It is particularly important to obtain reliable estimates of magnitudes and size-distributions of discarded catches of commercial species. Discarded catches represent real losses from stocks and may reduce the potential biomass and yield from stocks (Gulland, 1983; Howell and Langan, 1987) and inclusion of data about discards in standard assessment models may alter the conclusions derived from these models (Pikitch, 1991; Alverson et al., 1994). Changes in discarding practices over time may be confused with trends in abundance, if discarding is not properly documented throughout the period examined (Gulland and Garcia, 1984). Just as stock assessments may be biased by the absence of data about discarding, they may be biased by the inclusion of inaccurate data about discarding (e.g., Saila, 1983; Alverson et al., 1994). The need for scientifically supportable estimates of rates of discarding and consideration of bias have been stressed by several authors (Saila, 1983; Howell and Langan, 1987; Alverson et al., 1994). In particular, Saila (1983) noted that "the fishery scientist will sometimes have to assess the level of accuracy of obtained information using his/her own quality control techniques". It is therefore somewhat surprising that the issue of detecting bias in observer-based estimates of catch has received such little attention.

The approach used in this study would seem to have application for examining the accuracy of observer-based estimates of catch in other fisheries for which landing statistics are available. The recommended strategy is to examine the accuracy of observer-based estimates of catch for all components of catch for which independent, unbiased estimates are available. In prawn (shrimp) fisheries, this may be limited to a comparison of observer-based estimates of prawn catch with reported landings. This strategy, however, has greater utility in multispecies fisheries for which landing statistics are available for several species. If shore-based surveys of size-distributions of landings exist, comparisons of another dimension of catch can be made but in their absence, a survey designed specifically to validate observer-based size-distributions of retained catches should be considered.

We reinforce the argument made by Saila (1983) that assessment of the accuracy of observer-based estimates of catch is of fundamental importance. While direct assessment of accuracy of observer-based estimates of discarded catches is impossible, accuracy should be assessed for all components of catch for which independent, unbiased estimates are available.

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References

Alverson, D.L., Freeberg, M.H., Murawski, S.A., Pope, J.G., 1994. A global assessment of fisheries by catch and discards. FAO Fisheries Technical Paper 339, 233.

Andrew, N.L., Mapstone, B.D., 1987. Sampling and the description of spatial pattern in marine ecology. Annu. Rev. Oceanogr. Marine Biol. 25, 39–90.

Andrew, N.L., Pepperell, J.G., 1992. The by-catch of shrimp trawl fisheries. Annu. Rev. Oceanogr. Marine Biol. 30, 527–565.

Cochran, W.G., 1977. Sampling Techniques, 3rd edn. Wiley, New York, 428 pp.

Gulland, J.A., 1983. Fish Stock Assessment: A Manual of Basic Methods. Wiley, New York, 223 pp.

Gulland, J.A., Garcia, S., 1984. Observed patterns in multispecies fisheries. In: May, R.M. (Ed.), Exploitation of Marine Communities. Springer, Berlin, pp. 155–90.

Hilborn, R., Walters, C.J., 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman & Hall, London, 570 pp.

Howell, W.H., Langan, R., 1987. Commercial trawler discards of four flounder species in the Gulf of Maine. North Am. J. Fisheries Manage. 7, 6–17.

Jean, Y., 1963. Discards of fish at sea by northern New Brunswick draggers. J. Fisheries Res. Board of Canada 20, 497–523.

Kennelly, S.J., 1995. The issue of by-catch in Australia's trawl fisheries. Rev. Fish Biol. Fisheries 5, 213–234.

Liggins, G.W., Kennelly, S.J., 1996. By-catch from prawn trawling in the Clarence River estuary New South Wales, Australia. Fisheries Res. 25, 347–367.

Pikitch, E.K., 1991. Use of a mixed species yield-per-recruit model to explore the consequences of various management policies for the Oregon flatfish fishery. Can. J. Fisheries Aquatic Sci. 44, 349–359.

Saila, S.B., 1983. Importance and assessment of discards in commercial fisheries. FAO Fisheries Circular 765, 62.

Thompson, S.K., 1992. Sampling. Wiley, New York, 343 pp.

Tilzey, D.J., 1994. The Southeast Fishery. Bureau of Resource Sci. Australian Government Publishing Service, Canberra, 360 pp.

Appendix A.5.1

List of taxa

C : commercial species, CQ : SEF quota species

Family	Species		Common name
Fish			
ALOPIIDAE	*Alopias vulpinus*	C	Thintail thresher
ANTENNARIIDAE	*Antennarius striatus*		
ARRIPIDAE	*Arripis trutta*	C	Australian salmon
AULOPIDAE	*Aulopus curtirostris*		
	Aulopus purpurissatus		
BATRACHOIDIDAE	*Batrachonoeus dubius*		
BERYCIDAE	*Beryx decadactylus*	C	Imperador
	Beryx splendens	C	Alfonsin
	Centroberyx affinis	CQ	Redfish
BOTHIDAE	*Chascanopsetta lugubris*		
	Lophonectes gallus		
	Pseudorhombus arsius	C	Large-toothed flounder
	Pseudorhombus jenynsii	C	Rough small-toothed flounder
	Pseudorhombus tenuirastrum	C	Smooth small-toothed flounder
BRACHAELURIDAE	*Brachaelurus waddi*	C	Blind shark
BRANCHIOSTEGIDAE	*Branchiostegus serratus*		
	Branchiostegus wardi	C	Pink tilefish
CALLIONYMIDAE	*Callionymus moretonensis*		
	Eocallionymus papilio		
	Foetorepus calauropomus		
	Repomucenus calcaratus		
CALLORHYNCHIDAE	*Callorhynchus milii*	C	Elephant fish
CAPROIDAE	*Antigonia rhomboidea*		
CARANGIDAE	*Alectis indicus*	C	Diamond trevally
	Carangoides chrysophrys	C	Long-nosed trevally
	Pseudocaranx dentex	CQ	Silver trevally
	Seriola dumerili	C	Amberjack
	Seriola hippos	C	Samson fish
	Seriola lalandi	C	Yellowtail kingfish
	Trachurus declivis	C	Jack mackerel
	Trachurus novaezelandiae		
CARCHARHINIDAE	*Carcharhinus brevipinna*	C	Long-nosed whaler
	Carcharhinus spp.	C	Whaler sharks
CENTROLOPHIDAE	*Centrolophus niger*	C	Rudderfish
	Hyperoglyphe antarctica	CQ	Blue-eye trevalla
	Seriolella brama	CQ	Blue warehou
	Seriolella caerulea	C	White trevalla
	Seriolella punctata	CQ	Spotted trevalla (Blue warehou)
CHAETODONTIDAE	*Chelmonops howensis*		
CHAUNACIDAE	*Chaunax endeavouri*		
CHEILODACTYLIDAE	*Cheilodactylus fuscus*	C	Red morwong
	Cheilodactylus vestitus		
	Nemadactylus douglasi	C	Blue morwong (Rubberlip morwong)
	Nemadactylus macropterus	CQ	Jackass morwong
CHIMAERIDAE	*Chimaera* sp. A	C	Deepwater (Southern) ghostshark

	Hydrolagus ogilbyi	C	Ogilby's ghost shark
CHLOROPHTHALMIDAE	*Chlorophthalmus nigripinnis*		
CLINIDAE	*Cristiceps aurantiacus*		
CLUPEIDAE	*Hyperlophus vittatus*		
	Sardinops neopilchardus		
CONGRIDAE	*Conger* spp., *Gnathophis* spp.		
CYNOGLOSSIDAE	*Paraplagusia unicolor*		
DACTYLOPTERIDAE	*Dactyloptera orientalis*		
DASYATIDIDAE	*Dasyatis brevicaudata*		
	Dasyatis fluviorum		
	Dasyatis guileri		
	Dasyatis kuhlii		
	Dasyatis thetidis		
	(unidentified stingrays)		
DINOLESTIDAE	*Dinolestes lewini*		
DIODONTIDAE	*Allomycterus pilatus*		
	Dicotylichthys punctulatus		
	Diodon nicthemerus		
ECHENEIDIDAE	*Remora remora*		
EMMELICHTHYIDAE	*Emmelichthys nitidus*		
ENGRAULIDIDAE	*Engraulis australis*		
ENOPLOSIDAE	*Enoplosus armatus*		
FISTULARIIDAE	*Fistularia commersonii*		
	Fistularia petimba		
GEMPYLIDAE	*Rexea antefurcata*	C	
	Rexea solandri	CQ	Gemfish
	Ruvettus pretiosus	C	Oilfish
	Thyrsites atun	C	Barracouta
GERREIDAE	*Gerres subfasciatus*		
GIRELLIDAE	*Girella tricuspidata*	C	Luderick
HALOSAURIDAE	*Halosaurus pectoralis*		
HARPADONTIDAE	*Saurida* spp.		
HETERODONTIDAE	*Heterodontus galeatus*		
	Heterodontus portusjacksoni		
HEXANCHIDAE	*Heptranchias perlo*		
	Hexanchus griseus		
	Notorynchus cepedianus		
HOPLICHTHYIDAE	*Hoplichthys haswelli*		
HYPNIDAE	*Hypnos monopterygium*		
LABRIDAE	*Bodianus* sp. 1	C	Eastern foxfish
	Bodianus vulpinus	C	Blackspot pigfish
LAMNIDAE	*Carcharodon carcharias*	C	White shark
LATRIDIDAE	*Latridopsis forsteri*	C	Bastard trumpeter
	Latris lineata	C	Tasmanian trumpeter
LOPHIIDAE	*Lophioides mutulis/naresi*		
MACRORHAMPHOSIDAE	*Centriscops humerosus*		
	Macrorhamphosus scolopax		
	Notopogon fernandezianus		
	Notopogon lilliei		
MACROURIDAE	*Coelorinchus australis*		
	Coelorinchus fasciatus		
	Coelorinchus innotabilis		
	Coelorinchus kaiyomaru		
	Coelorinchus matamua		
	Coelorinchus mirus		
	Coelorinchus sp. C		
	Coelorinchus sp. D		
	Coryphaenoides leonis		
	Lepidorhynchus denticulatus		
	Malacocephalus laevis		

	Mesobius antipodum		
	Ventrifossa nigromaculata		
	(unidentified whiptails)		
MERLUCCIIDAE	*Macruronus novaezelandiae*	CQ	Blue grenadier
MITSUKURINIDAE	*Mitsukurina owstoni*	C	Goblin shark
MOLIDAE	*Mola ramsayi*		
MONACANTHIDAE	*Aluterus monoceros*	C	Unicorn leatherjacket
	Eubalichthys bucephalus	C	Black reef leatherjacket
	Eubalichthys mosaicus	C	Mosaic leatherjacket
	Meuschenia freycineti	C	Six-spined leatherjacket
	Meuschenia hippocrepis	C	Horseshoe leatherjacket
	Meuschenia scaber	C	Velvet leatherjacket
	Meuschenia trachylepis	C	Yellowfin leatherjacket
	Nelusetta ayraudi	C	Chinaman leatherjacket
	Penicipelta vittiger		
	Scobinichthys granulatus	C	Rough leatherjacket
	Thamnaconus modestoides	C	Modest leatherjacket
MONOCENTRIDIDAE	*Cleidopus gloriamaris*		
MORIDAE	*Halargyreus johnsonii*		
	Lepidion microcephalus		
	Lotella rhacinus	C	Beardie
	Mora moro	C	Ribaldo
	Pseudophycis spp.	C	Red cod
MULLIDAE	*Upeneichthys lineates*	C	Red mullet
	Upeneus tragula	C	Bar-tailed goatfish
MURAENESOCIDAE	*Muraenesox bagio*	C	Common pike eel
MYLIOBATIDIDAE	*Myliobatis australis*	C	Eagle ray
NARCINIDAE	*Narcine tasmaniensis*		
NEOSCOPELIDAE	*Neoscopelus macrolepidotus*		
NOTACANTHIDAE	*Notocanthus sexspinus*		
ODONTASPIDIDAE	*Odontapsis ferox*	C	Herbst's nurse shark (Sand tiger shark)
OGCOCEPHALIDAE	*Halieutaea brevicauda*		
OPHICHTHIDAE	*Myrichthys colubrinus*		
OPHIDIIDAE	*Genypterus blacodes*	CQ	Pink ling
OPICHTHIDAE	*Ophisurus serpens*		
ORECTOLOBIDAE	*Orectolobus maculatus*	C	Spotted wobbegong
	Orectolobus ornatus		
OREOSOMATIDAE	*Neocyttus rhomboidalis*	C	Spiky oreo
	Pseudocyttus maculatus	C	Smooth oreo
OSTRACIDAE	*Lactoria fornasini*		
	Anoplocapros inermis		
	Aracana aurita		
	Kentrocapros flavofasciatus		
	Lactoria cornuta		
	Lactoria diaphana		
	Tetrasomus republicae		
OXYNOTIDAE	*Oxynotus bruniensis*		
PARASCYLLIDAE	*Parascyllium collare*		
PATAECIDAE	*Pataecus fronto*		
PEMPHERIDIDAE	*Pempheris affinis*		
	Pempheris compressa		
	Pempheris multiradiata		
PENTACEROTIDAE	*Paristiopterus labiosis*	C	Giant boarfish
	Pentaceropsis recurvirostris		
	Pentaceros decacanthus		
	Zanclistius elevatus		
PERCICHTHYIDAE	*Apogonops anomalus*		
	Macquaria novemaculeata	C	Australian bass
	Polyprion moeone	C	Bass groper

	Polyprion oxygeneios	C	Hapuku
	Synagrops japonicus		
PINGUIPEDIDAE	*Parapercis allporti*		
PLATYCEPHALIDAE	*Neoplatycephalus richardsoni*	CQ	Tiger flathead
	Platycephalus arenarius	C	Northern sand flathead
	Platycephalus caeruleopunctatus	C	Eastern blue-spot flathead
	Platycephalus fuscus	C	Dusky flathead
	Platycephalus longispinus		
	Platycephalus marmoratus	C	Marble flathead
	Ratabulus diversidens	C	Spiky flathead
PLEURONECTIDAE	*Ammotretis rostratus*		
	Azygopus pinnifasciatus		
PLOTOSIDAE	*Cnidoglanis macrocephalus*		
	Plotosus lineatus		
POMATOMIDAE	*Pomatomus saltatrix*	C	Tailor
PRIACANTHIDAE	*Cookeolus boops*		
	Priacanthus macracanthus		
PRISTIOPHORIDAE	*Pristiophorus* spp.	C	Sawsharks
PSYCHROLUTIDAE	*Psychrolutes marcidus*		
RACHYCENTRIDAE	*Rachycentron canadus*	C	Cobia
RAJIDAE	*Irolita waitii*		
	Notoraja sp. A		
	Pavoraja nitida		
	Raja australis		
	Raja gudgeri		
	Raja lemprieri		
	Raja polyommata		
	Raja sp. 1		
	Raja sp. B		
	Raja whitleyi		
REGALECIDAE	*Regalecus glesne*		
RHINOBATIDAE	*Aptychotrema rostrata*	C	Shovelnose ray
	Trygonorrhina sp.	C	Banjo shark
RHINOCHIMAERIDAE	*Harriotta raleighana*		
RHYNCHOBATIDAE	*Rhynchobatus djiddensis*	C	White-spotted shovelnose ray
SCIAENIDAE	*Argyrosomus hololepidotus*	C	Mulloway
	Atractoscian aequidens	C	Teraglin
SCOMBRIDAE	*Euthynnus affinis*	C	Mackeral tuna
	Sarda australis	C	Australian bonito
	Scomber australasicus		
SCORPAENIDAE	*Centropogon australis*		
	Gymnapistes marmoratus		
	Helicolenus percoides	CQ	Inshore ocean perch
	Helicolenus barathri	CQ	Offshore ocean perch
	Neosebastes incipinnis		
	Neosebastes scorpaenoides		
	Neosebastes thetidis		
	Notesthes robusta		
	Scorpaena cardinalis	C	Red rock cod
	Scorpaena papillosus		
SCORPIDIDAE	*Atypichthys strigatus*		
	Microcanthis strigatus		
	Scorpis aequipinnis	C	Sea sweep
SCYLIORHINIDAE	*Apristurus longicephalus*		
	Asymbolus analis		
	Cephaloscyllium laticeps		
	Cephaloscyllium sp. a		
	Galeus boardmani		
SERRANIDAE	*Anthias pulchellus*		
	Caesioperca lepidoptera		

	Callanthias allporti	C	Splendid perch
	Caprodon longimanus	C	Long-finned perch
	Epinephelus septemfasciatus	C	Bar cod
	Lepidoperca brochata		
SIGANIDAE	*Siganus fuscescens*		
SILLAGINIDAE	*Sillago ciliata*	C	Sand whiting
	Sillago flindersi	CQ	Red spot whiting (Eastern school whiting)
	Sillago maculata	C	Trumpeter whiting
	Sillago robusta	C	Stout whiting
SOLEIDAE	*Aesopia microcephala*		
	Pardachirus hedleyi		
	Synaptura nigra	C	Black sole
	Synclidopus macleayanus		
SPARIDAE	*Acanthopagrus australis*	C	Yellowfin bream
	Allotaius spariformes		
	Pagrus auratus	C	Snapper
	Rhabdosargus sarba	C	Tarwhine
SPHYRAENIDAE	*Sphyraena africana*		
SPHYRNIDAE	*Sphyrna zygaena*	C	Smooth hammerhead
SQUALIDAE	*Centrophorus spp.*	C	
	Centroscymnus crepidater		
	Centroscymnus owstoni		
	Dalatias licha	C	Seal shark
	Deania calcea, Deania quadrispinosa	C	Brier shark, Long-snouted dogfish
	Etmopterus lucifer		
	Etmopterus puscillus		
	Squalus acanthias	C	White-spotted dogfish
	Squalus megalops	C	Piked dogfish
	Squalus mitsukurii	C	Green-eyed dogfish
SQUATINIDAE	*Squatina spp.*	C	Angel sharks
STEGOSTOMATIDAE	*Stegostoma fasciatum*		
SYNGNATHIDAE	*Solegnathus spinosissimus* (unidentified sea-horse)		
SYNODONTIDAE	*Trachinocephalus myops*		
TERAPONIDAE	*Pelates quadrilineatus*		
TETRAODONTIDAE	*Arothron firmamentum*		
	Contusus richei		
	Lagocephalus chesmonia		
	Lagocephalus inermis		
	Omegophora armilla		
	Reicheltia halsteadi		
	Sphoeroides pachygaster		
	Tetractenos hamiltoni		
	Torquigener altipinnis		
	Torquigener hicksi		
	Torquigener pleurogramma		
TORPEDINIDAE	*Torpedo macneilli*		
TRACHICHTHYIDAE	*Gephyroberyx darwini*	C	Darwin's roughy
	Hoplostethus atlanticus	CQ	Orange roughy
	Hoplostethus intermedius		
	Optivus sp. 1		
	Paratrachichthys sp. 1		
TRIAKIDAE	*Galeorhinus galeus*	C	School shark
	Mustelus antarcticus	C	Gummy shark
TRICHIURIDAE	*Benthodesmus elongatus*		
	Lepidopus caudatus	C	Southern frostfish
	Trichiurus lepturus	C	Hairtail
TRIGLIDAE	*Chelidonichthys kumu*	C	Red gurnard

	Lepidotrigla argus		
	Lepidotrigla modesta		
	Lepidotrigla mulhalli		
	Lepidotrigla papilio		
	Peristedion picturatum		
	Pterygotrigla picta	C	Spotted gurnard
	Pterygotrigla polyommata	C	Sharp-beaked gurnard (Latchet)
URANOSCOPIDAE	*Gnathagnus innotabilis*		
	Kathetostoma laeve		
	Kathetostoma sp. 1		
	Pleuroscopus pseudodorsalis		
UROLOPHIDAE	*Trygonoptera* sp. B		
	Trygonoptera testaceus		
	Urolophus bucculentus		
	Urolophus cruciatus		
	Urolophus paucimaculatus		
	Urolophus sufflavus		
	Urolophus viridis		
	Urolophus hybrid sp.		
	(unidentified stingarees)		
VELIFERIDAE	*Metavelifer multiradiatus*		
XIPHIIDAE	*Xiphias gladius*	C	Broadbill swordfish
ZEIDAE	*Cyttus australis*	C	Silver dory
	Cyttus novaezelandiae		
	Cyttus traversi	C	King dory
	Zenopsis nebulosis	CQ	Mirror dory
	Zeus faber	CQ	John dory

Annelids

(POLYCHAETE WORM)	(polychaete worm)		

Cnidarians

(ANEMONE)	(anemone)		
(JELLYFISH)	(jellyfish)		
(SPONGE)	(sponge)		

Crustaceans

ARISTAEIDAE	*Aristeomorpha foliacea*	C	Red prawn
CALAPPIDAE	*Calappa philargius*		
	Matuta planipes		
LATRIELLIDAE	*Latriellopsis petterdi*		
MAJIDAE	*Leptomithrax tuberculata*		
	Leptomithrax waitei		
PALINURIDAE	*Jasus lalandii*	C	Southern crayfish
	Jasus verreauxi	C	Eastern crayfish
	Linuparis trigonus	C	Slipper lobster
PENAEIDAE	*Metapenaeus macleayi*	C	School prawn
	Penaeus esculentus	C	Tiger prawn
	Penaeus plebejus	C	King prawn
	Plesiopenaeus edwardsianus		
PORTUNIDAE	*Charybdis bimaculata*		
	Charybdis cruciata	C	Coral crab
	Charybdis miles		
	Charybdis natator		
	Ovalipes australiensis		
	Ovalipes molleri		
	Portunus pelagicus	C	Blue swimmer crab

	Portunus sanguinolentus		
	Scylla serrata	C	Mud crab
RANINIDAE	*Lyreidus tridentatus*		
	Ranina ranina	C	Spanner crab
SCYLLARIDAE	*Ibacus altricrenatus*	C	Deepwater bug
	Ibacus peronii	C	Balmain bug
	Ibacus chacei	C	Smooth bug
	Ibacus brucei	C	Bruce's bug
SOLENOCERIDAE	*Haliproides sibogae*	CQ	Royal red prawn
XANTHIDAE	*Pseudocarcinus gigas*	C	Giant deepsea crab
(CARID PRAWN)	(carid prawn)		
(HERMIT CRAB)	(hermit crab)		
(UNID. CRAB)	(unidentified crabs)		
(UNID. MANTIS SHRIMP)	(unidentified mantis shrimps)		

Echinoderms

(HOLOTHURIAN)	(holothurian)		
(SAND DOLLAR)	(sand dollar)		
(SEA URCHIN)	(sea urchin)		
(STARFISH)	(starfish)		

Mammals

(FUR SEAL)	(Fur seal)		

Molluscs

LOLIGINIDAE	*Loligo chinensis*	C	Broad squid
	Loligo sp.	C	Slender squid
	Loliolus sp.	C	Bottle squid
	Sepioteuthis australis	C	Southern calamary
	(unidentified squid)		
SEPIIDAE	*Sepia* spp.	C	Cuttlefish
SEPIOLIDAE	*Sepioloida lineolata*		
TEUTHOIDAE	*Nototodarus gouldi*	C	Arrow squid
(BIVALVE)	(Bivalves)		
(GASTROPOD)	(Gastropods)		
(NUDIBRANCH)	(Nudibranchs)		
(OCTOPUS)	*Octopus spp.*	C	Octopus

Reptiles

(TURTLE)	(Turtles)		

Appendix A.6.1

Comparisons of catches (per fisher-day) among Regions (R), Years (Y) and Quarters (Q)
ANOVA summary tables

(1) indicates that 2 df have been subtracted from the Error MS (see Section 6.2.1)
* indicates p < 0.05, ** indicates p < 0.01
Column "Mag. Effect" is the magnitude of the effect
Column "% Var." is the percentage of variability explained (i.e. relative importance)

Fishing time

Source	Levels	DF	SS	MS	F	P		Mag. Effect	*% Var.*
Region	3	2	5,902,373	2,951,187	86.5620	0.000	**	7,717	*19*
Year	3	2	21,166	10,583	0.3104	0.733		-62	*0*
Quarter	4	3	99,768	33,256	0.9754	0.404		-3	*0*
R*Y		4	320,352	80,088	2.3491	0.053		243	*1*
R*Q		6	109,401	18,234	0.5348	0.782		-126	*0*
Y*Q		6	109,583	18,264	0.5357	0.781		-126	*0*
R*Y*Q		12	189,577	15,798	0.4634	0.936		-290	*-1*
Error		(1) 718	24,479,002	34,093				34,093	*82*
Total		755	31,231,222					41,446	

Total catch, ln(x+1)

Source	Levels	DF	SS	MS	F	P		Mag. Effect	*% Var.*
Region	3	2	87.4384	43.71920	302.9673	0.000	**	0.115	*44*
Year	3	2	0.5804	0.29020	2.0110	0.135		0.000	*0*
Quarter	4	3	2.5347	0.84490	5.8550	0.001	**	0.003	*1*
R*Y		4	0.6419	0.16048	1.1121	0.350		0.000	*0*
R*Q		6	1.0781	0.17968	1.2452	0.281		0.000	*0*
Y*Q		6	1.2326	0.20543	1.4236	0.203		0.000	*0*
R*Y*Q		12	1.5502	0.12918	0.8952	0.552		0.000	*0*
Error		(1) 718	103.6098	0.14430				0.144	*55*
Total		755	198.6661					0.263	

Retained catch, ln(x+1)

Source	Levels	DF	SS	MS	F	P		Mag. Effect	*% Var.*
Region	3	2	73.8876	36.94380	227.9214	0.000	**	0.097	*37*
Year	3	2	0.569	0.28450	1.7552	0.174		0.000	*0*
Quarter	4	3	1.481	0.49367	3.0456	0.028	*	0.001	*1*
R*Y		4	0.6985	0.17463	1.0773	0.367		0.000	*0*
R*Q		6	1.7548	0.29247	1.8043	0.096		0.001	*0*
Y*Q		6	1.3014	0.21690	1.3381	0.238		0.000	*0*
R*Y*Q		12	2.9128	0.24273	1.4975	0.120		0.001	*0*
Error		(1) 718	116.3807	0.16209				0.162	*61*
Total		755	198.9858					0.264	

Discarded catch, ln(x+1)

Source	Levels	DF	SS	MS	F	P		Mag. Effect	*% Var.*
Region	3	2	117.2439	58.62195	277.1882	0.000	**	0.155	*41*
Year	3	2	3.2914	1.64570	7.7815	0.000	**	0.004	*1*
Quarter	4	3	5.7417	1.91390	9.0497	0.000	**	0.007	*2*
R*Y		4	1.0472	0.26180	1.2379	0.293		0.000	*0*
R*Q		6	0.7573	0.12622	0.5968	0.733		-0.001	*0*
Y*Q		6	1.0318	0.17197	0.8131	0.560		0.000	*0*
R*Y*Q		12	1.7278	0.14398	0.6808	0.771		-0.001	*0*
Error		(1) 718	151.8483	0.21149				0.211	*56*
Total		755	282.6895					0.375	

Retained catch of non-quota species, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	*% Var.*
Region	3	2	20.2584	10.12920	50.5961	0.000 **	0.026	*11*
Year	3	2	1.3411	0.67055	3.3494	0.036 *	0.001	*1*
Quarter	4	3	1.4749	0.49163	2.4557	0.062	0.001	*1*
R*Y		4	0.756	0.18900	0.9441	0.438	0.000	*0*
R*Q		6	3.1103	0.51838	2.5894	0.017 *	0.003	*1*
Y*Q		6	1.4446	0.24077	1.2026	0.303	0.000	*0*
R*Y*Q		12	2.0958	0.17465	0.8724	0.575	0.000	*0*
Error		(1) 718	143.7417	0.20020			0.200	*87*
Total		755	174.2227				0.231	

Discarded catch of quota species, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	*% Var.*
Region	3	2	327.344	163.67200	294.4220	0.000 **	0.432	*41*
Year	3	2	17.808	8.90400	16.0170	0.000 **	0.022	*2*
Quarter	4	3	32.11	10.70333	19.2537	0.000 **	0.040	*4*
R*Y		4	2.326	0.58150	1.0460	0.382	0.000	*0*
R*Q		6	1.522	0.25367	0.4563	0.841	-0.002	*0*
Y*Q		6	2.768	0.46133	0.8299	0.547	-0.001	*0*
R*Y*Q		12	12.803	1.06692	1.9192	0.029 *	0.008	*1*
Error		(1) 718	399.143	0.55591			0.556	*53*
Total		755	795.824				1.055	

Discarded catch of non-quota commercial species, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	*% Var.*
Region	3	2	302.2048	151.10240	325.1494	0.000 **	0.399	*45*
Year	3	2	5.3704	2.68520	5.7781	0.003 **	0.006	*1*
Quarter	4	3	2.7849	0.92830	1.9976	0.113	0.002	*0*
R*Y		4	1.618	0.40450	0.8704	0.481	0.000	*0*
R*Q		6	15.5716	2.59527	5.5846	0.000 **	0.017	*2*
Y*Q		6	3.3931	0.56552	1.2169	0.295	0.001	*0*
R*Y*Q		12	5.6724	0.47270	1.0172	0.431	0.000	*0*
Error		(1) 718	333.6667	0.46472			0.465	*52*
Total		755	670.2818				0.888	

Discarded catch of non-commercial species, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	*% Var.*
Region	3	2	76.0114	38.00570	176.6273	0.000 **	0.100	*31*
Year	3	2	1.2784	0.63920	2.9706	0.052	0.001	*0*
Quarter	4	3	2.705	0.90167	4.1904	0.006 **	0.003	*1*
R*Y		4	3.1763	0.79408	3.6904	0.006 **	0.003	*1*
R*Q		6	3.8871	0.64785	3.0108	0.007 **	0.003	*1*
Y*Q		6	0.8723	0.14538	0.6757	0.669	-0.001	*0*
R*Y*Q		12	0.9234	0.07695	0.3576	0.977	-0.002	*-1*
Error		(1) 718	154.4953	0.21517			0.215	*67*
Total		755	243.3492				0.323	

Discarded REDFISH, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	% Var.
Region	3	2	702.331	351.16550	84.1412	0.000 **	0.918	*15*
Year	3	2	200.85	100.42500	24.0624	0.000 **	0.255	*4*
Quarter	4	3	375.077	125.02567	29.9569	0.000 **	0.480	*8*
R*Y		4	133.521	33.38025	7.9981	0.000 **	0.155	*2*
R*Q		6	108.521	18.08683	4.3337	0.000 **	0.110	*2*
Y*Q		6	70.318	11.71967	2.8081	0.010 **	0.060	*1*
R*Y*Q		12	129.55	10.79583	2.5867	0.002 **	0.105	*2*
Error		(1) 718	2996.591	4.17353			4.174	*67*
Total		755	4716.758				6.256	

Discarded TIGER FLATHEAD, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	% Var.
Region	3	2	175.583	87.79150	39.6004	0.000 **	0.226	*9*
Year	3	2	0.329	0.16450	0.0742	0.928	-0.005	*0*
Quarter	4	3	3.514	1.17133	0.5284	0.663	-0.004	*0*
R*Y		4	19.105	4.77625	2.1544	0.073	0.014	*1*
R*Q		6	61.087	10.18117	4.5924	0.000 **	0.063	*2*
Y*Q		6	7.48	1.24667	0.5623	0.760	-0.008	*0*
R*Y*Q		12	46.259	3.85492	1.7388	0.055	0.026	*1*
Error		(1) 718	1591.761	2.21694			2.217	*88*
Total		755	1905.118				2.529	

Discarded MIRROR DORY, Ulladulla & Eden, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	% Var.
Region	2	1	26.365	26.36500	12.5628	0.000 **	0.048	*2*
Year	3	2	31.627	15.81350	7.5350	0.001 **	0.054	*2*
Quarter	4	3	41.604	13.86800	6.6080	0.000 **	0.070	*3*
R*Y		2	0.249	0.12450	0.0593	0.943	-0.008	*0*
R*Q		3	17.251	5.75033	2.7400	0.043 *	0.022	*1*
Y*Q		6	17.532	2.92200	1.3923	0.216	0.010	*0*
R*Y*Q		6	14.66	2.44333	1.1642	0.324	0.004	*0*
Error		480	1007.359	2.09866			2.099	*91*
Total		503	1156.647				2.299	

Discarded OFFSHORE OCEAN PERCH, Ulladulla & Eden, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	% Var.
Region	2	1	49.638	49.63800	22.4071	0.000 **	0.094	*4*
Year	3	2	0.038	0.01900	0.0086	0.992	-0.009	*0*
Quarter	4	3	1.922	0.64067	0.2892	0.147	-0.009	*0*
R*Y		2	27.46	13.73000	6.1979	0.002 **	0.046	*2*
R*Q		3	11.975	3.99167	1.8019	0.146	0.011	*0*
Y*Q		6	15.885	2.64750	1.1951	0.307	0.005	*0*
R*Y*Q		6	13.981	2.33017	1.0519	0.391	0.001	*0*
Error		480	1063.334	2.21528			2.215	*94*
Total		503	1194.234				2.354	

Discarded INSHORE OCEAN PERCH, Ulladulla & Eden, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	*% Var.*
Region	2	1	252.548	252.54800	98.9754	0.000 **	0.496	*15*
Year	3	2	56.697	28.34850	11.1100	0.000 **	0.102	*3*
Quarter	4	3	51.156	17.05200	6.6828	0.000 **	0.086	*3*
R*Y		2	16.467	8.23350	3.2268	0.041 *	0.023	*1*
R*Q		3	55.329	18.44300	7.2279	0.000 **	0.095	*3*
Y*Q		6	20.696	3.44933	1.3518	0.233	0.011	*0*
R*Y*Q		6	21.298	3.54967	1.3911	0.216	0.012	*0*
Error		480	1224.78	2.55163			2.552	*76*
Total		503	1698.973				3.376	

Discarded RUBBERLIP MORWONG, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	*% Var.*
Region	2	2	214.648	107.32400	33.2345	0.000 **	0.275	*8*
Year	3	2	0.621	0.31050	0.0962	0.908	-0.008	*0*
Quarter	4	3	79.628	26.54267	8.2193	0.000 **	0.093	*3*
R*Y		4	12.87	3.21750	0.9963	0.409	0.000	*0*
R*Q		6	46.113	7.68550	2.3799	0.028 *	0.035	*1*
Y*Q		6	16.305	2.71750	0.8415	0.538	-0.004	*0*
R*Y*Q		12	51.004	4.25033	1.3162	0.204	0.016	*0*
Error		(1) 718	2318.631	3.22929			3.229	*89*
Total		755	2739.818				3.637	

Discarded SNAPPER, North, ln(x+1)

Source	Levels	DF	SS	MS	F	P	Mag. Effect	*% Var.*
Year	3	2	0.1943	0.09715	0.1134	0.893	-0.006	*-1*
Quarter	4	3	11.1847	3.72823	4.3532	0.005 **	0.034	*4*
Y*Q		6	10.335	1.72250	2.0112	0.065	0.021	*2*
Error		(1) 238	203.8323	0.85644			0.856	*95*
Total		251	225.5463				0.905	

Appendix A.6.2.1

Estimates of annual retained, discarded and total catches (estimates +/- 1 se) of commercial species
North

	Total catch (t)		Retained catch (t)		Discarded catch (t)		% Discarded	Relative catch magnitude		
								Total	Retained	Discarded
Silver trevally	174	19	173	19	2	1	*1*	1	1	15
Tiger flathead	46	5	39	4	7	1	*15*	2	2	2
Redfish	44	10	25	5	19	5	*44*	3	5	1
Shovelnose ray	36	7	35	7	1	0	*3*	4	3	18
Piked dogfish	36	14	32	12	4	2	*11*	5	4	4
Eagle ray	23	3	21	3	2	1	*9*	6	7	10
John dory	22	3	22	3	0	0	*2*	7	6	25
Angel shark	18	4	18	4	0	0	*1*	8	8	26
Sawsharks	18	3	18	3	0	0	*1*	9	9	27
Long-nosed whaler	18	10	18	10	0	0	*0*	10	10	43
Cuttlefish	14	2	13	2	1	0	*7*	11	11	19
Red gurnard	14	2	12	1	2	0	*12*	12	13	12
Banjo shark	13	2	12	2	2	0	*13*	13	14	11
Yellowfin bream	13	3	13	2	0	0	*3*	14	12	23
Eastern blue-spot flathead	13	1	10	1	3	0	*20*	15	16	5
Tarwhine	12	2	11	2	2	0	*12*	16	15	16
Smooth hammerhead	7	1	7	1	0	0	*0*	17	17	44
Southern calamary	7	1	7	1	0	0	*1*	18	18	33
Whaler shark	7	3	4	1	2	2	*36*	19	21	7
Tailor	7	1	4	1	3	1	*38*	20	22	6
Snapper	6	1	1	0	5	1	*76*	21	36	3
Rubberlip morwong	5	1	3	1	2	0	*39*	22	23	8
Velvet leatherjacket	*5*	*1*	*5*	*1*	*0*	*0*	*8*	23	19	24
Sharp-beaked gurnard	5	1	5	1	0	0	*3*	24	20	30
Red spot whiting	4	2	3	1	1	1	*32*	25	28	17
Mulloway	4	2	3	1	2	1	*39*	26	29	13
Blue swimmer crab	4	1	3	1	1	0	*24*	27	27	20
Tilefish	3	1	3	1	0	0	*0*	28	24	45
Gummy shark	3	1	3	1	0	0	*3*	29	25	34
Inshore ocean perch	3	1	1	0	2	1	*65*	30	44	9
Spotted wobbegong	3	1	3	1	0	0	*2*	31	26	35
Arrow squid	2	0	2	0	0	0	*7*	32	31	28
Australian salmon	2	2	2	2	0	0	*0*	33	30	46
White shark	2	1	1	1	1	1	*38*	34	42	22
Large-toothed flounder	2	0	2	0	0	0	*5*	35	33	31
Giant boarfish	2	0	2	0	0	0	*1*	36	32	40
Spotted gurnard	2	1	0	0	2	1	*93*	37	47	14
Dusky flathead	2	0	2	0	0	0	*1*	38	34	39
Balmain bug	2	0	1	0	0	0	*4*	39	35	37
Slender squid	1	0	1	0	0	0	*12*	40	41	29
Chinaman leatherjacket	1	0	1	0	0	0	*7*	41	39	32
Red mullet	1	0	1	0	0	0	*3*	42	38	38
Yellowfin leatherjacket	1	0	1	0	0	0	*1*	43	37	41
Herbst's nurse shark	1	1	1	1	0	0	*0*	44	40	47
Centrophorus dogfish	1	1	1	1	0	0	*0*	45	43	42
Smooth small-toothed flounder	1	0	1	0	0	0	*6*	46	45	36
Ogilby's ghost shark	1	0	0	0	1	0	*88*	47	46	21

Appendix A.6.2.2

Estimates of annual retained, discarded and total catches (estimates +/- 1 se) of commercial species
Ulladulla

	Total catch (t)		Retained catch (t)		Discarded catch (t)		% Discarded	Relative catch magnitude		
								Total	Retained	Discarded
Redfish	1,150	+/- 74	782	+/- 0	368	+/- 74	*32*	1	1	1
Tiger flathead	170	3	152	0	17	3	*10*	2	2	3
Pink ling	96	0	96	0	0	0	*0*	3	3	26
Gemfish	84	51	20	0	65	51	*77*	4	13	2
Mirror dory	70	2	63	0	7	2	*10*	5	6	6
Piked dogfish	67	12	67	12	0	0	*1*	6	4	14
Silver trevally	66	0	66	0	0	0	*0*	7	5	34
Angel shark	56	5	56	5	0	0	*0*	8	7	24
Offshore ocean perch	56	8	52	8	4	1	*7*	9	8	7
John dory	50	0	50	0	0	0	*1*	10	9	20
Arrow squid	37	4	37	4	0	0	*1*	11	10	19
Southern frostfish	32	11	17	6	15	7	*47*	12	15	4
Sharp-beaked gurnard	23	4	23	4	0	0	*2*	13	11	16
Common saw shark	21	2	21	2	0	0	*1*	14	12	23
Cuttlefish	20	2	19	2	0	0	*2*	15	14	17
Jackass morwong	15	0	15	0	0	0	*0*	16	16	31
Splendid perch	15	6	14	5	0	0	*2*	17	17	18
Centrophorus spp. dogfish	12	3	12	3	0	0	*0*	18	18	28
Inshore ocean perch	12	2	5	1	7	1	*58*	19	25	5
Rubberlip morwong	*10*	*1*	*8*	*1*	*2*	*0*	*18*	*20*	*19*	*9*
Blue grenadier	7	0	6	0	1	0	*8*	21	22	13
Red gurnard	7	2	7	2	0	0	*4*	22	20	21
Velvet leatherjacket	*7*	*1*	*6*	*1*	*0*	*0*	*6*	*23*	*21*	*15*
Jack mackerel	6	1	5	1	1	0	*13*	24	24	12
Octopus	5	2	5	2	0	0	*1*	25	23	27
Silver dory	5	1	3	0	2	0	*39*	26	30	8
Blue warehou	5	0	5	0	0	0	*0*	27	26	35
Gummy shark	5	1	5	1	0	0	*0*	28	27	36
Rudderfish	4	1	4	1	0	0	*0*	29	28	37
Banjo shark	3	1	3	1	0	0	*5*	30	29	22
Eagle ray	3	1	3	1	0	0	*3*	31	31	25
Deania spp. dogfish	2	1	2	1	0	0	*0*	32	32	32
Barracouta	2	1	1	0	1	1	*72*	33	39	10
Deepwater bug	2	0	2	0	0	0	*1*	34	33	30
Herbst's nurse shark	2	1	1	1	1	1	*51*	35	38	11
Shovelnose ray	1	0	1	0	0	0	*2*	36	34	29
Whaler shark	1	1	1	1	0	0	*0*	37	35	38
Spotted trevalla	1	0	1	0	0	0	*0*	38	36	33
Broadbill swordfish	1	0	1	0	0	0	*0*	39	37	39

Appendix A.6.2.3

Estimates of annual retained, discarded and total catches (estimates +/- 1 se) of commercial species
Eden

	Total catch (t)		Retained catch (t)		Discarded catch (t)		% Discarded	*Relative catch magnitude*		
								Total	Retained	Discarded
Redfish	1108	+/- 157	308	+/- 0	800	+/- 157	72	1	3	1
Spotted trevalla	787	11	744	0	43	11	5	2	1	13
Barracouta	461	70	261	47	201	47	44	3	5	2
Tiger flathead	455	10	390	0	64	10	14	4	2	11
Southern frostfish	302	68	118	26	183	56	61	5	11	3
Blue warehou	289	14	245	0	45	14	16	6	7	12
Pink ling	263	0	261	0	2	0	1	7	4	23
Jackass morwong	255	2	245	0	10	2	4	8	6	17
Arrow squid	240	30	235	30	6	1	2	9	8	19
Piked dogfish	210	25	41	7	169	23	80	10	17	4
Velvet leatherjacket	204	22	81	9	123	18	60	11	12	6
Jack mackerel	188	28	33	7	155	25	82	12	20	5
Silver trevally	147	0	146	0	1	0	1	13	9	29
Inshore ocean perch	130	17	16	2	114	16	88	14	26	7
Deania spp. dogfish	121	40	121	40	0	0	0	15	10	32
Offshore ocean perch	120	15	53	7	67	11	56	16	16	10
Gemfish	119	50	38	0	81	50	68	17	18	8
Mirror dory	107	28	36	0	71	28	66	18	19	9
Blue grenadier	71	1	68	0	3	1	4	19	13	22
John dory	70	1	66	0	4	1	6	20	14	20
Silver dory	69	6	30	2	40	4	57	21	21	14
Octopus	55	4	55	4	0	0	0	22	15	40
Cuttlefish	41	3	25	2	17	2	40	23	23	16
Rubberlip morwong	32	4	6	1	26	4	82	24	35	15
Red gurnard	27	3	25	3	1	0	5	25	22	26
Angel shark	18	2	18	2	0	0	1	26	24	37
Gummy shark	17	2	16	2	1	1	5	27	25	30
Spiky oreo	14	6	14	6	0	0	0	28	27	43
Ribaldo	11	4	10	4	0	0	2	29	28	35
Sawsharks	10	2	10	1	0	0	2	30	29	36
Thintail thresher	8	5	0	0	7	5	94	31	52	18
Orange roughy	8	1	6	0	2	1	21	32	33	24
Ogilby's ghost shark	8	2	6	1	1	1	20	33	32	25
Red spot whiting	7	0	6	0	0	0	2	34	31	38
Centrophorus spp. dogfish	7	2	7	2	0	0	0	35	30	44
Mosaic leatherjacket	6	2	6	1	0	0	5	36	34	31
Green-eyed dogfish	6	5	5	4	1	1	17	37	36	28
Whaler shark	5	3	1	0	4	2	82	38	50	21
Blue-eye trevalla	5	0	5	0	0	0	0	39	37	45
Southern calamary	5	1	4	1	0	0	6	40	38	33
Hapuku	3	1	3	1	0	0	0	41	39	46
Snapper	2	1	2	1	0	0	0	42	40	47
Bastard trumpeter	2	0	2	0	0	0	0	43	41	48
School shark	2	1	2	1	0	0	0	44	42	49
Sharp-beaked gurnard	2	0	1	0	0	0	6	45	44	39
Goblin shark	2	2	2	2	0	0	0	46	43	50
Seal shark	1	1	1	1	0	0	3	47	45	42
Tasmanian trumpeter	1	0	1	0	0	0	0	48	46	51
Red cod	1	1	0	0	1	1	82	49	53	27
Spotted gurnard	1	1	1	1	0	0	6	50	48	41
Eagle ray	1	1	1	1	0	0	0	51	47	52
King dory	1	0	1	0	0	0	25	52	51	34
Rudderfish	1	1	1	1	0	0	0	53	49	53

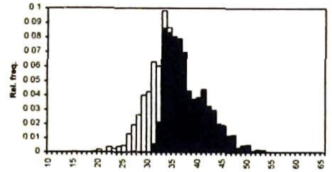
Appendix 6.3.1

Size distributions of retained and discarded catches of Tiger flathead, by region and year

Retained catch: black bars Discarded catch: white bars
Sample sizes: x (y) denotes a total sample of x fish from y tows (observer survey, "Obs"), or from y landings (co-op survey, "Co-op")
"Mean L" is mean length length of fish (cm)

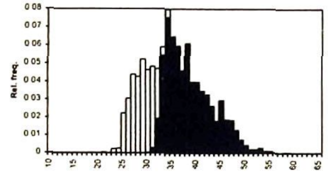
North, 1993

	Ret.	Disc.	Total
Obs:	1440 (36)	587 (46)	
Co-op:	0 (0)		
Mean L:	38.2	30.0	36.0



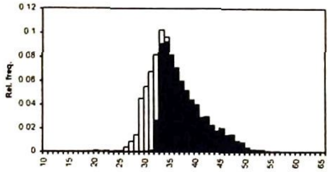
North, 1994

	Ret.	Disc.	Total
Obs:	2220 (56)	674 (52)	
Co-op:	0 (0)		
Mean L:	39.2	29.3	35.9



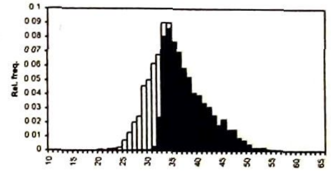
North, 1995

	Ret.	Disc.	Total
Obs:	4288 (69)	982 (89)	
Co-op:	0 (0)		
Mean L:	38.2	30.9	36.2



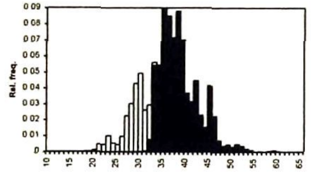
North, 1993-95

	Ret.	Disc.	Total
Obs:	7948 (161)	2243 (187)	
Co-op:	0 (0)		
Mean L:	38.4	30.2	36.1



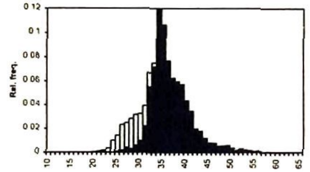
Ulladulla, 1993

	Ret.	Disc.	Total
Obs:	1575 (27)	1826 (90)	
Co-op:	0 (0)		
Mean L:	39.0	29.0	36.7



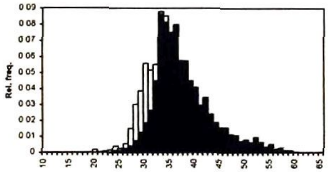
Ulladulla, 1994

	Ret.	Disc.	Total
Obs:	682 (10)	1533 (92)	
Co-op:	1012 (10)		
Mean L:	37.1	28.6	35.2



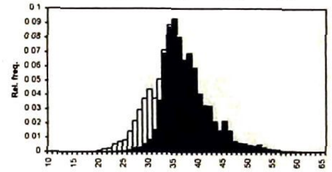
Ulladulla, 1995

	Ret.	Disc.	Total
Obs:	1955 (30)	656 (77)	
Co-op:	1496 (16)		
Mean L:	38.1	29.9	36.6



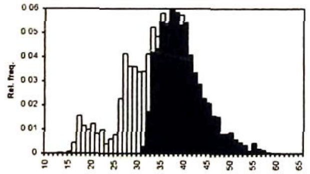
Ulladulla, 1993-95

	Ret.	Disc.	Total
Obs:	4211 (67)	4015 (259)	
Co-op:	2508 (26)		
Mean L:	38.0	29.0	36.0



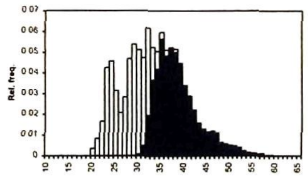
Eden, 1993

	Ret.	Disc.	Total
Obs:	3867 (57)	1261 (105)	
Co-op:	0 (0)		
Mean L:	39.8	27.5	36.1



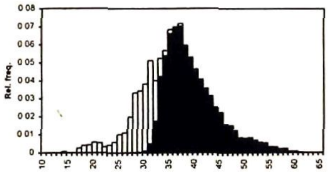
Eden, 1994

	Ret.	Disc.	Total
Obs:	1818 (21)	695 (108)	
Co-op:	3176 (26)		
Mean L:	39.1	28.3	35.0



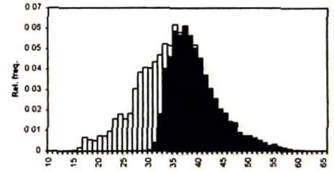
Eden, 1995

	Ret.	Disc.	Total
Obs:	4663 (42)	558 (90)	
Co-op:	4984 (31)		
Mean L:	39.9	28.9	36.8



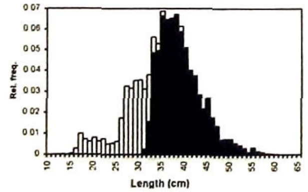
Eden, 1993-95

	Ret.	Disc.	Total
Obs:	10348 (120	2514 (303)	
Co-op:	8160 (57)		
Mean L:	39.7	28.2	36.0



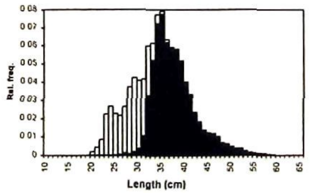
N + U + E, 1993

	Retained	Discardec	Total
Obs:	6882 (120)	3674 (241)	
Co-op:	0 (0)		
Mean L:	39.5	27.9	36.2



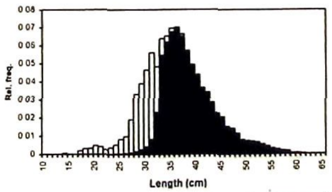
N + U + E, 1994

	Ret.	Disc.	Total
Obs:	4720 (87)	2902 (252)	
Co-op:	4188 (36)		
Mean L:	38.3	28.4	35.1



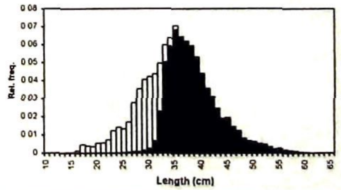
N + U + E, 1995

	Ret.	Disc.	Total
Obs:	10906 (141	2196 (256)	
Co-op:	6480 (47)		
Mean L:	39.4	29.3	36.7



N + U + E, 1993-95

	Ret.	Disc.	Total
Obs:	22508 (348	8772 (749)	
Co-op:	10668 (83)		
Mean L:	39.1	28.5	36.0



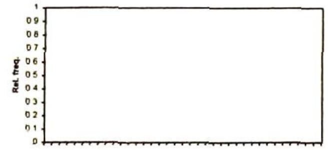
Appendix A.6.3.2

Size distributions of retained and discarded catches of Mirror dory, by region and year

Retained catch: black bars Discarded catch: white bars
Sample sizes: x (y) denotes a total sample of x fish from y tows (observer survey, "Obs"), or from y landings (co-op survey, "Co-op")
"Mean L" is mean length length of fish (cm)

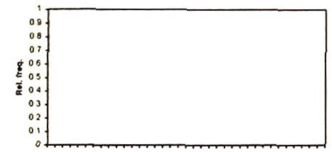
North, 1993

	Ret.	Disc.	Total
Obs:	0 (0)	0 (0)	
Co-op:	0 (0)		
Mean L:			



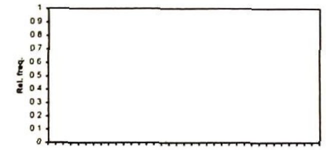
North, 1994

	Ret.	Disc.	Total
Obs:	0 (0)	3 (3)	
Co-op:	0 (0)		
Mean L:			



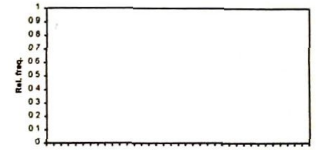
North, 1995

	Ret.	Disc.	Total
Obs:	12 (1)	42 (5)	
Co-op:	0 (0)		
Mean L:			



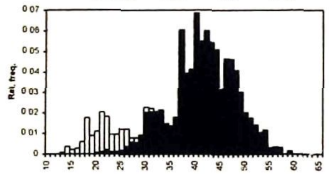
North, 1993-95

	Ret.	Disc.	Total
Obs:	12 (1)	45 (8)	
Co-op:	0 (0)		
Mean L:			



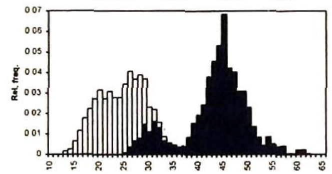
Ulladulla, 1993

	Ret.	Disc.	Total
Obs:	866 (22)	266 (48)	
Co-op:	0 (0)		
Mean L:	42.0	21.9	39.3



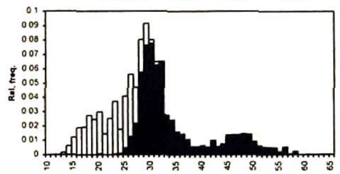
Ulladulla, 1994

	Ret.	Disc.	Total
Obs:	554 (12)	946 (45)	
Co-op:	446 (10)		
Mean L:	43.8	23.8	35.6



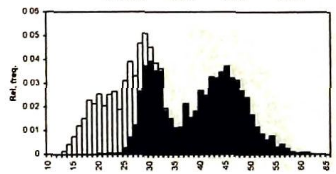
Ulladulla, 1995

	Ret.	Disc.	Total
Obs:	388 (7)	396 (54)	
Co-op:	891 (15)		
Mean L:	35.0	23.0	30.4



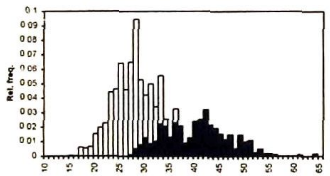
Ulladulla, 1993-95

	Ret.	Disc.	Total
Obs:	1808 (41)	1608 (147)	
Co-op:	1337 (25)		
Mean L:	40.0	23.2	34.5



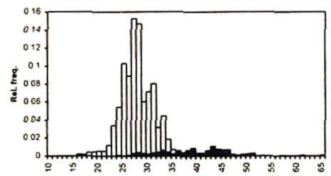
Eden, 1993

	Ret.	Disc.	Total
Obs:	274 (15)	575 (61)	
Co-op:	0 (0)		
Mean L:	40.8	27.3	32.5



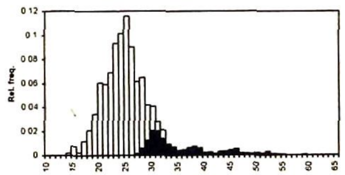
Eden, 1994

	Ret.	Disc.	Total
Obs:	94 (3)	621 (67)	
Co-op:	55 (1)		
Mean L:	39.9	28.0	29.3



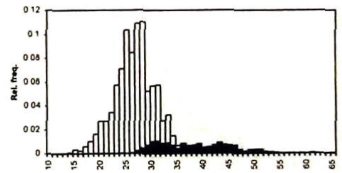
Eden, 1995

	Ret.	Disc.	Total
Obs:	292 (4)	558 (70)	
Co-op:	271 (4)		
Mean L:	36.0	24.5	26.2



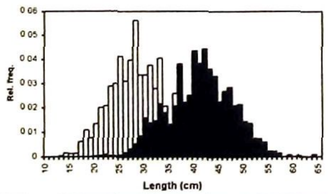
Eden, 1993-95

	Ret.	Disc.	Total
Obs:	660 (22)	1754 (198)	
Co-op:	326 (5)		
Mean L:	38.8	26.6	28.5



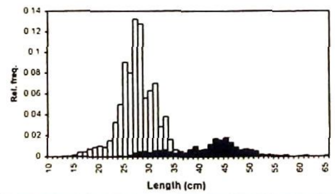
N + U + E, 1993

	Ret.	Disc.	Total
Obs:	1140 (37)	841 (109)	
Co-op:	0 (0)		
Mean L:	41.6	26.5	35.5



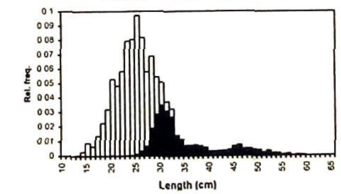
N + U + E, 1994

	Ret.	Disc.	Total
Obs:	648 (15)	1570 (115)	
Co-op:	501 (11)		
Mean L:	42.0	27.6	30.4



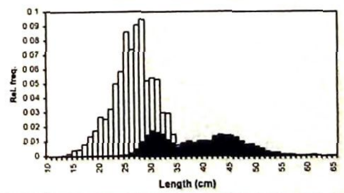
N + U + E, 1995

	Ret.	Disc.	Total
Obs:	692 (12)	996 (129)	
Co-op:	1162 (19)		
Mean L:	35.4	24.3	27.2



N + U + E, 1993-95

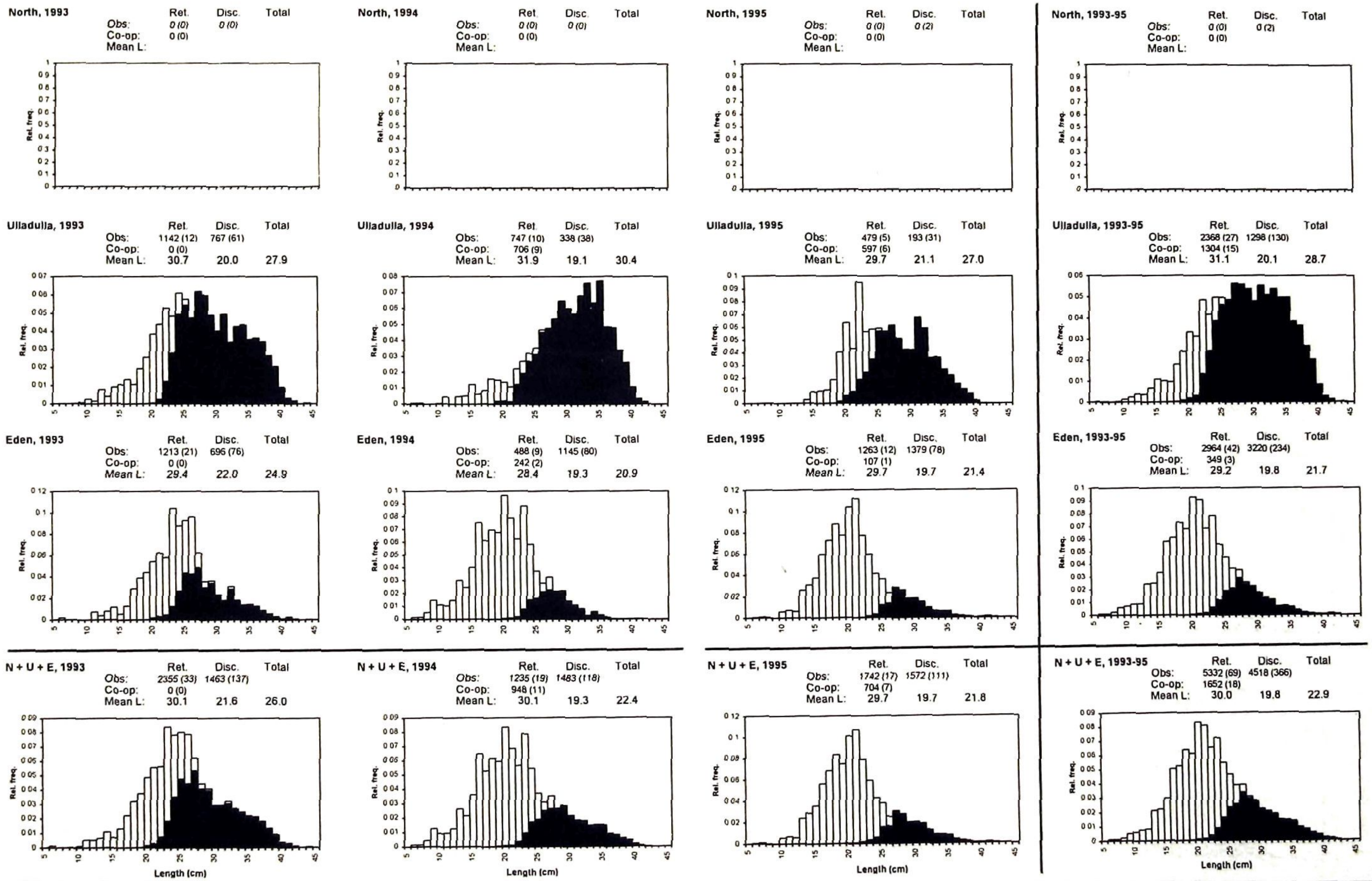
	Ret.	Disc.	Total
Obs:	2480 (64)	3407 (353)	
Co-op:	1663 (30)		
Mean L:	39.5	26.3	29.9



Appendix A.6.3.3

Size distributions of retained and discarded catches of Offshore ocean perch, by region and year

Retained catch: black bars   Discarded catch: white bars
Sample sizes: x (y) denotes a total sample of x fish from y tows (observer survey, "Obs"), or from y landings (co-op survey, "Co-op")
"Mean L" is mean length length of fish (cm)



Appendix A.6.3.4

Size distributions of retained and discarded catches of Inshore Ocean perch

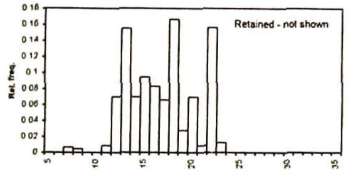
Retained catch: black bars Discarded catch: white bars

Sample sizes: x (y) denotes a total sample of x fish from y tows (observer survey, "Obs"), or from y landings (co-op survey, "Co-op")

"Mean L" is mean length length of fish (cm)

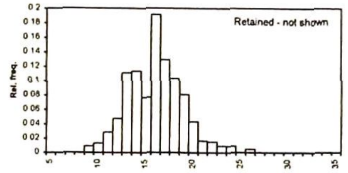
North, 1993

	Ret.	Disc.	Total
Obs:	0 (0)	127 (17)	
Co-op:	0 (0)		
Mean L:		17.2	



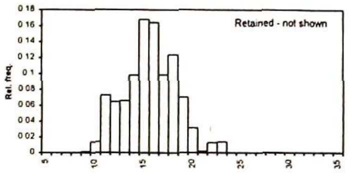
North, 1994

	Ret.	Disc.	Total
Obs:	0 (0)	264 (18)	
Co-op:	0 (0)		
Mean L:		16.5	



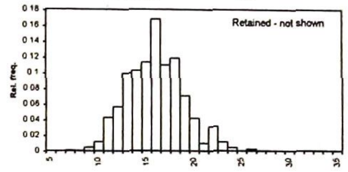
North, 1995

	Ret.	Disc.	Total
Obs:	106 (3)	237 (32)	
Co-op:	0 (0)		
Mean L:		16.1	



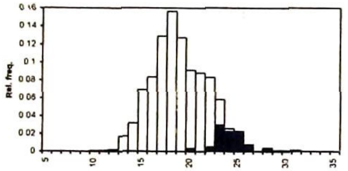
North, 1993-95

	Ret.	Disc.	Total
Obs:	106 (3)	628 (67)	
Co-op:	0 (0)		
Mean L:		16.4	



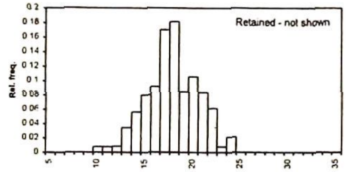
Ulladulla, 1993

	Ret.	Disc.	Total
Obs:	56 (5)	1613 (70)	
Co-op:	0 (0)		
Mean L:	24.7	18.8	19.4



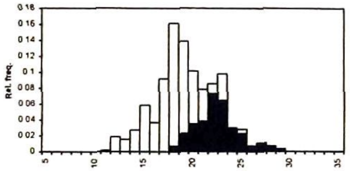
Ulladulla, 1994

	Ret.	Disc.	Total
Obs:	0 (0)	324 (24)	
Co-op:	22 (1)		
Mean L:		18.3	



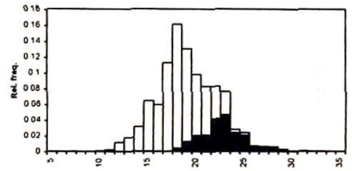
Ulladulla, 1995

	Ret.	Disc.	Total
Obs:	112 (2)	630 (71)	
Co-op:	0 (0)		
Mean L:	22.9	18.5	19.9



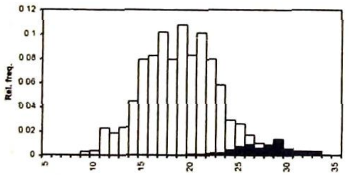
Ulladulla, 1993-95

	Ret.	Disc.	Total
Obs:	168 (7)	2567 (165)	
Co-op:	22 (1)		
Mean L:	23.2	18.6	19.6



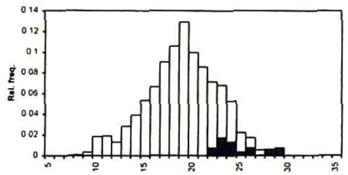
Eden, 1993

	Ret.	Disc.	Total
Obs:	72 (4)	1803 (111)	
Co-op:	0 (0)		
Mean L:	28.1	19.0	19.6



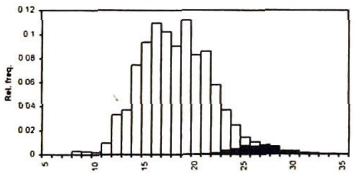
Eden, 1994

	Ret.	Disc.	Total
Obs:	26 (1)	1136 (116)	
Co-op:	0 (0)		
Mean L:	25.2	19.1	19.4



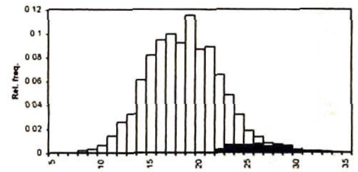
Eden, 1995

	Ret.	Disc.	Total
Obs:	375 (4)	2908 (135)	
Co-op:	191 (2)		
Mean L:	27.0	18.2	18.6



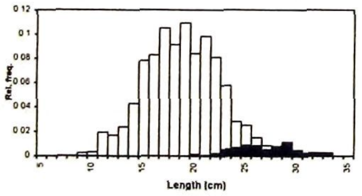
Eden, 1993-95

	Ret.	Disc.	Total
Obs:	473 (9)	5847 (362)	
Co-op:	191 (2)		
Mean L:	26.8	18.5	19.0



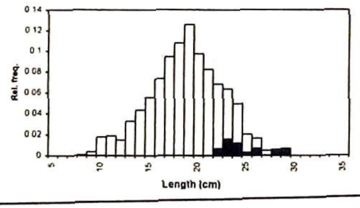
N + U + E, 1993

	Ret.	Disc.	Total
Obs:	128 (9)	3543 (198)	
Co-op:	0 (0)		
Mean L:	27.4	18.9	19.5



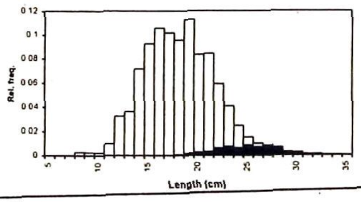
N + U + E, 1994

	Ret.	Disc.	Total
Obs:	26 (1)	1724 (158)	
Co-op:	22 (1)		
Mean L:	25.2	18.9	19.2



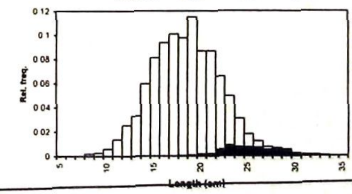
N + U + E, 1995

	Ret.	Disc.	Total
Obs:	593 (9)	3775 (238)	
Co-op:	191 (2)		
Mean L:	25.5	18.2	18.6



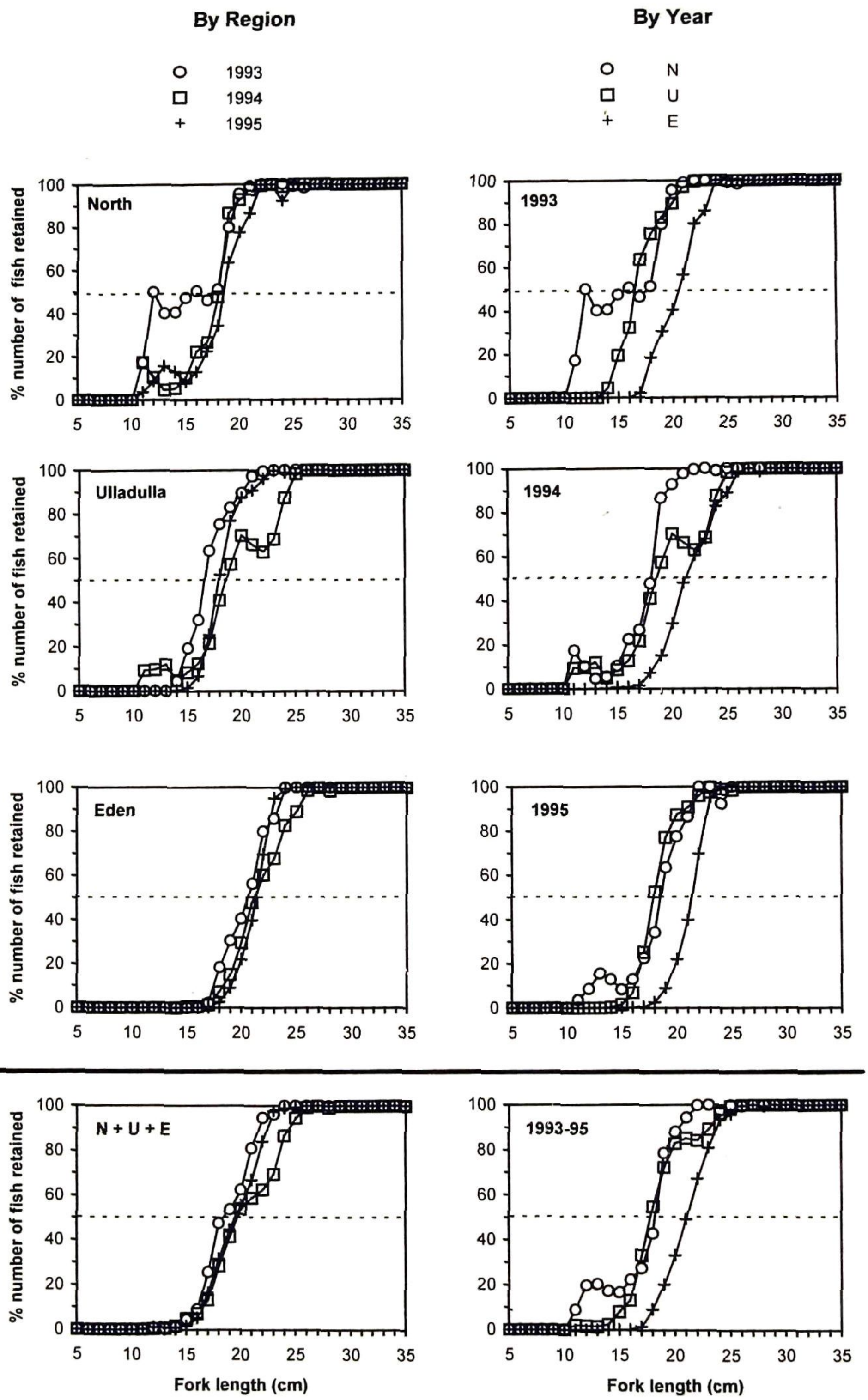
N + U + E, 1993-95

	Ret.	Disc.	Total
Obs:	747 (19)	9042 (594)	
Co-op:	213 (3)		
Mean L:	25.9	18.5	18.9



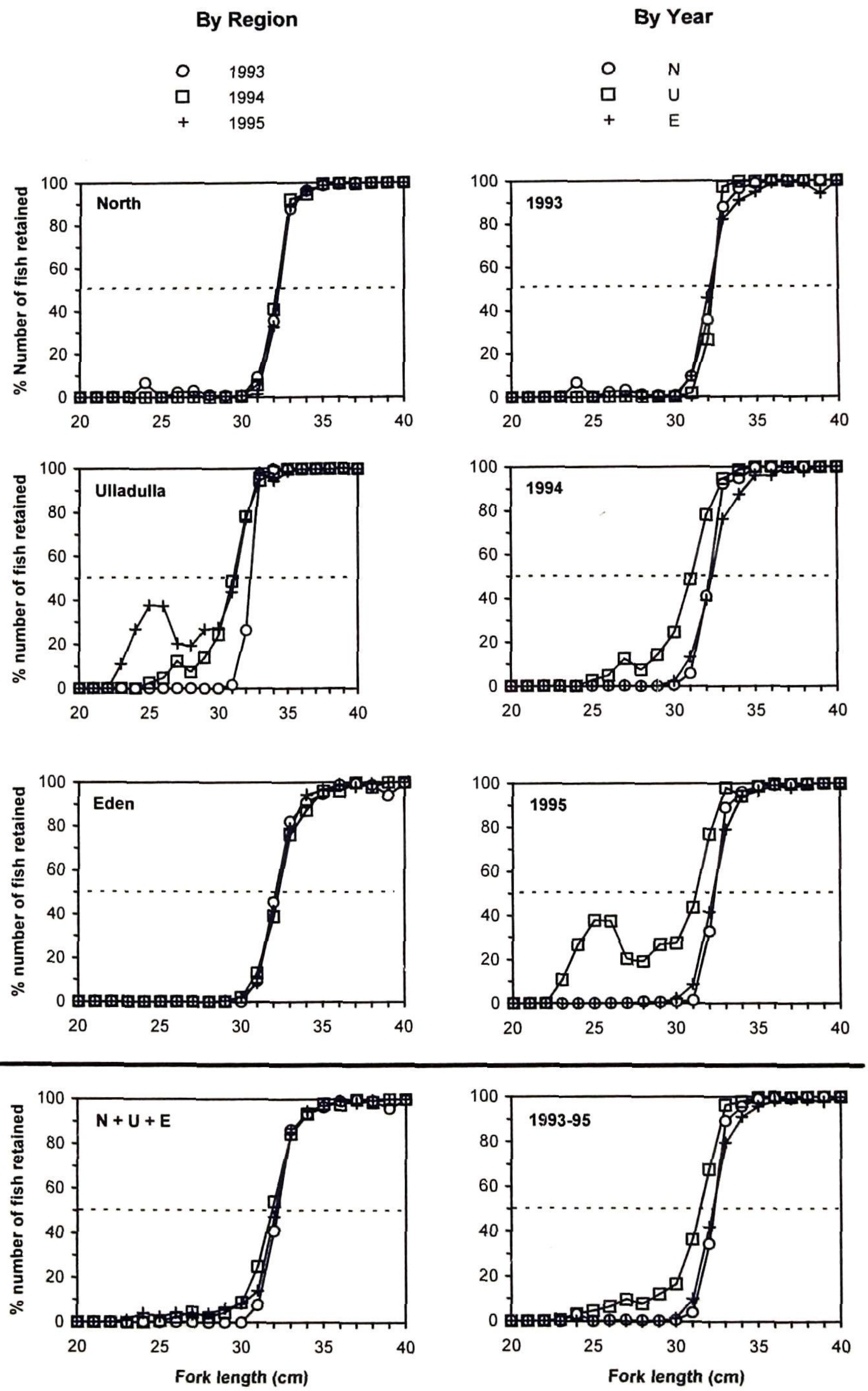
Appendix A.6.4.1

% catch retained by length, for Redfish



Appendix A.6.4.2

% catch retained by length, for Tiger flathead



Appendix A.6.4.3

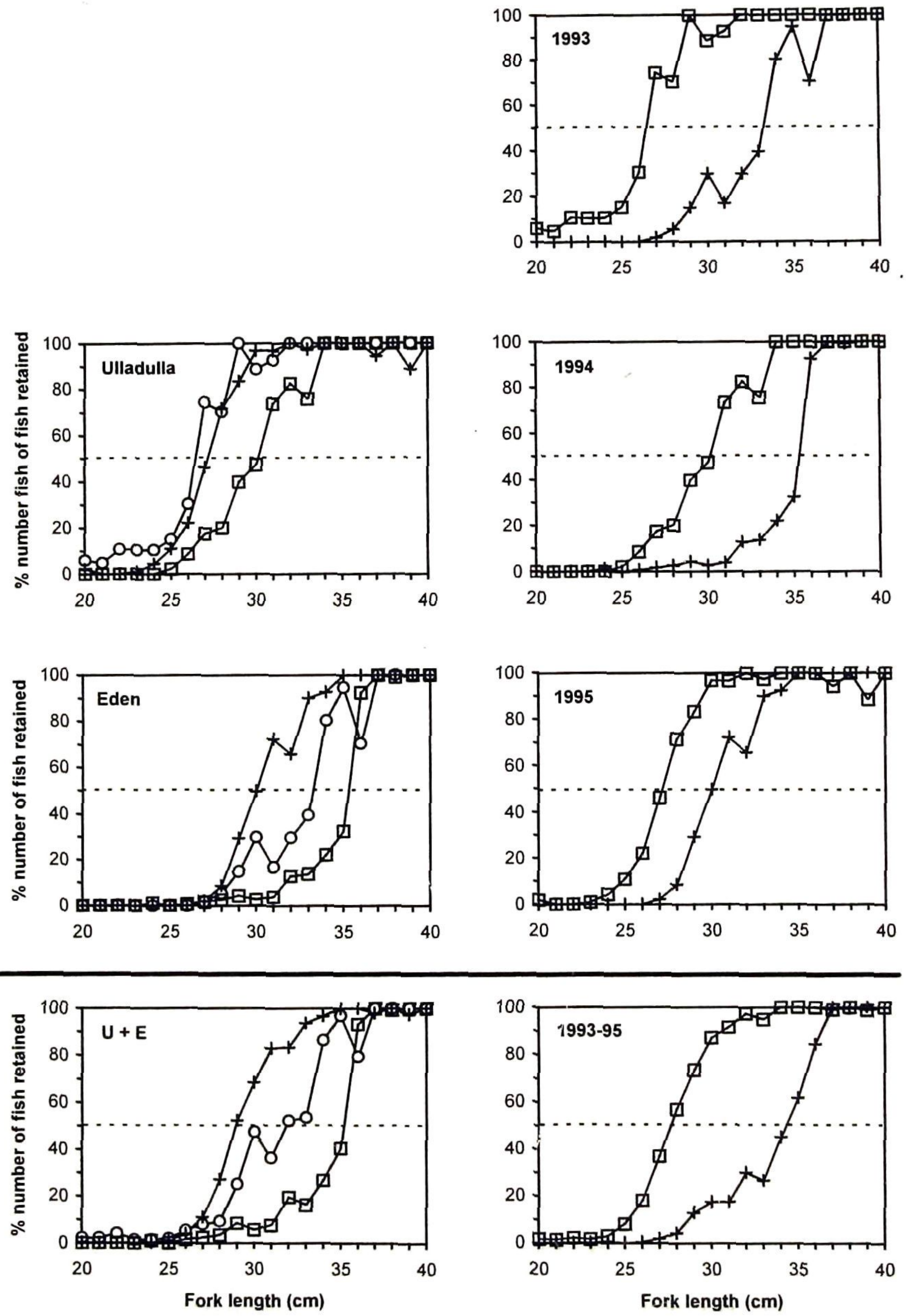
% catch retained by length, for Mirror dory

By Region

○ 1993
□ 1994
+ 1995

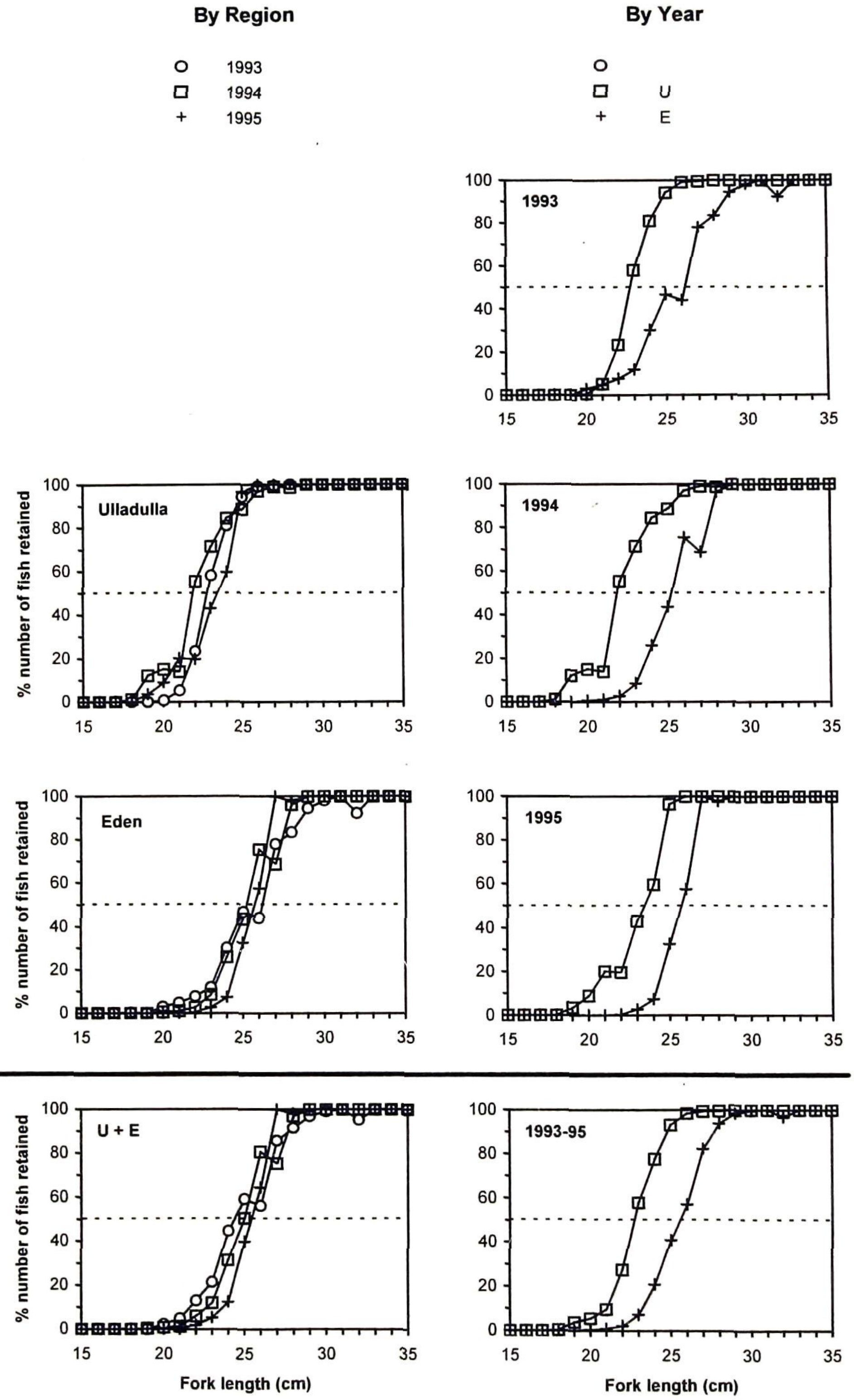
By Year

□ U
+ E



Appendix A6.4.4

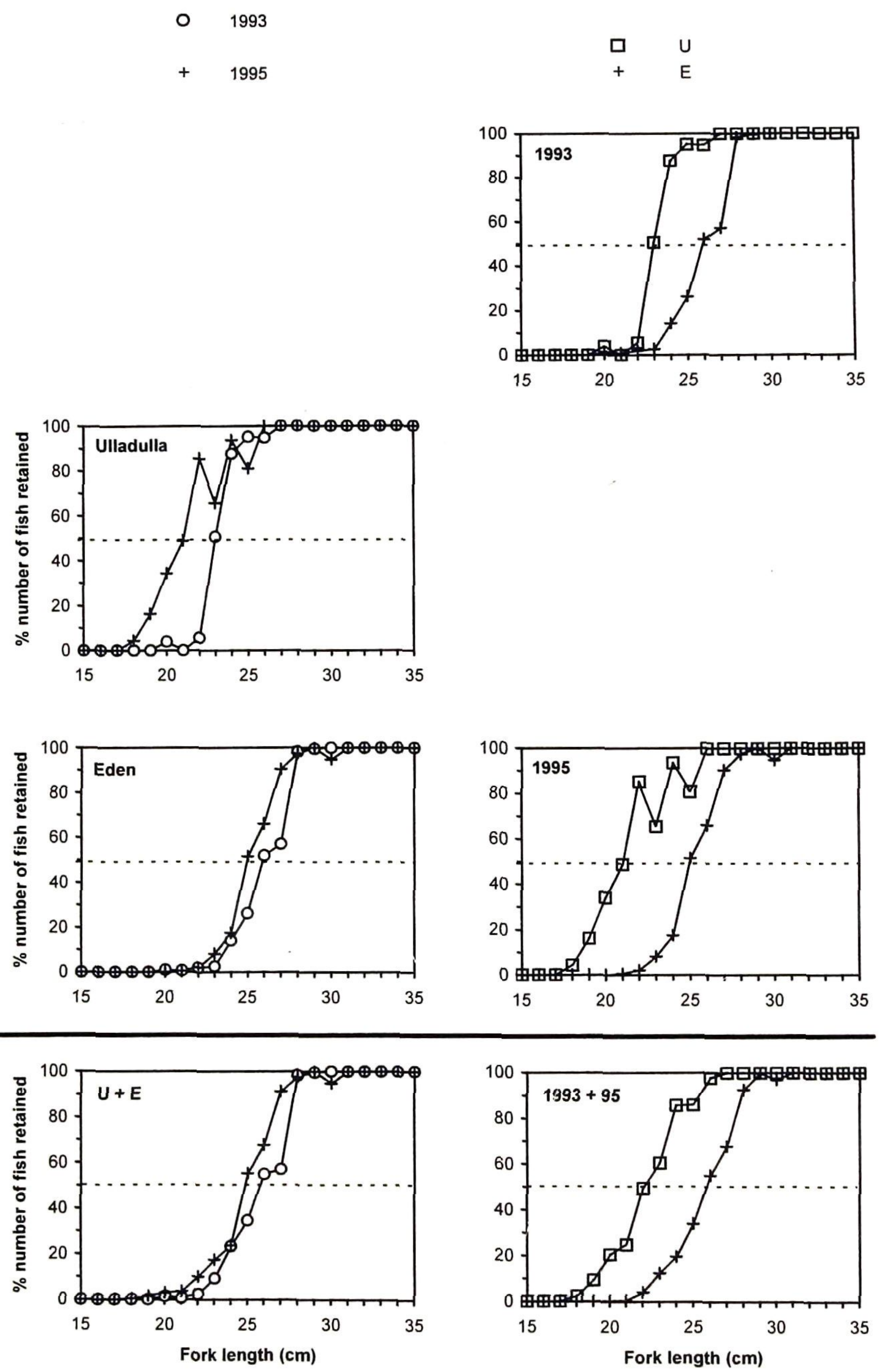
% catch retained by length, for Offshore Ocean perch



Appendix A.6.4.5

% catch retained by length, for Inshore Ocean perch

By Region | **By Year**



Appendix A.8.1.1

Catch, effort and CPUE time series for Scenario-H of the biomass dynamic model of the redfish population

Year	Propn discards	Catch (t)			Effort	CPUE		
		Total	Retained	Discards		Total	Retained	Discards
1960	0.60	500	200	300				
1961	0.60	500	200	300				
1962	0.60	500	200	300				
1963	0.60	500	200	300				
1964	0.60	500	200	300				
1965	0.60	500	200	300				
1966	0.60	500	200	300				
1967	0.60	500	200	300				
1968	0.60	750	300	450				
1969	0.60	1000	400	600				
1970	0.60	1250	500	750				
1971	0.60	1750	700	1050				
1972	0.60	1250	500	750				
1973	0.60	1250	500	750				
1974	0.60	1250	500	750				
1975	0.60	1750	700	1050	317	5.521	2.208	3.312
1976	0.60	2500	1000	1500	418	5.981	2.392	3.589
1977	0.60	3000	1200	1800	485	6.186	2.474	3.711
1978	0.50	2400	1200	1200	606	3.960	1.980	1.980
1979	0.40	3500	2100	1400	749	4.673	2.804	1.869
1980	0.30	3429	2400	1029	987	3.474	2.432	1.042
1981	0.20	2125	1700	425	883	2.407	1.925	0.481
1982	0.20	2250	1800	450	1180	1.907	1.525	0.381
1983	0.20	2500	2000	500	1311	1.907	1.526	0.381
1984	0.20	2500	2000	500	1328	1.883	1.506	0.377
1985	0.20	2500	2000	500	1640	1.524	1.220	0.305
1986	0.20	2125	1700	425	2293	0.927	0.741	0.185
1987	0.15	1647	1400	247	1884	0.874	0.743	0.131
1988	0.15	1412	1200	212	1885	0.749	0.637	0.112
1989	0.15	941	800	141	1510	0.623	0.530	0.093
1990	0.10	1111	1000	111	1162	0.956	0.861	0.096
1991	0.10	1778	1600	178	1354	1.313	1.182	0.131
1992	0.25	2400	1800	600	1212	1.980	1.485	0.495
1993	0.47	3962	2100	1862	1574	2.517	1.334	1.183
1994	0.54	3478	1600	1878	2007	1.733	0.797	0.936
1995	0.56	3182	1400	1782	2033	1.565	0.689	0.876
1996	0.24	1974	1500	474	2254	0.876	0.665	0.210
1997	0.04	1667	1600	67	1891	0.881	0.846	0.035

Appendix A.8.1.2

Catch, effort and CPUE time series for Scenario-M of the biomass dynamic model of the redfish population

Year	Propn discards	Catch (t) Total	Catch (t) Retained	Catch (t) Discards	Effort	CPUE Total	CPUE Retained	CPUE Discards
1960	0.40	333	200	133				
1961	0.40	333	200	133				
1962	0.40	333	200	133				
1963	0.40	333	200	133				
1964	0.40	333	200	133				
1965	0.40	333	200	133				
1966	0.40	333	200	133				
1967	0.40	333	200	133				
1968	0.40	500	300	200				
1969	0.40	667	400	267				
1970	0.40	833	500	333				
1971	0.40	1167	700	467				
1972	0.40	833	500	333				
1973	0.40	833	500	333				
1974	0.40	833	500	333				
1975	0.40	1167	700	467	317	3.680	2.208	1.472
1976	0.40	1667	1000	667	418	3.987	2.392	1.595
1977	0.40	2000	1200	800	485	4.124	2.474	1.649
1978	0.40	2000	1200	800	606	3.300	1.980	1.320
1979	0.40	3500	2100	1400	749	4.673	2.804	1.869
1980	0.30	3429	2400	1029	987	3.474	2.432	1.042
1981	0.20	2125	1700	425	883	2.407	1.925	0.481
1982	0.20	2250	1800	450	1180	1.907	1.525	0.381
1983	0.20	2500	2000	500	1311	1.907	1.526	0.381
1984	0.20	2500	2000	500	1328	1.883	1.506	0.377
1985	0.20	2500	2000	500	1640	1.524	1.220	0.305
1986	0.20	2125	1700	425	2293	0.927	0.741	0.185
1987	0.15	1647	1400	247	1884	0.874	0.743	0.131
1988	0.15	1412	1200	212	1885	0.749	0.637	0.112
1989	0.15	941	800	141	1510	0.623	0.530	0.093
1990	0.10	1111	1000	111	1162	0.956	0.861	0.096
1991	0.10	1778	1600	178	1354	1.313	1.182	0.131
1992	0.25	2400	1800	600	1212	1.980	1.485	0.495
1993	0.47	3962	2100	1862	1574	2.517	1.334	1.183
1994	0.54	3478	1600	1878	2007	1.733	0.797	0.936
1995	0.56	3182	1400	1782	2033	1.565	0.689	0.876
1996	0.24	1974	1500	474	2254	0.876	0.665	0.210
1997	0.04	1667	1600	67	1891	0.881	0.846	0.035

Appendix A.8.1.3

Catch, effort and CPUE time series for Scenario-Z of the biomass dynamic model of the redfish population

Year	Propn discards	Catch (t) Total	Catch (t) Retained	Catch (t) Discards	Effort	CPUE Total	CPUE Retained	CPUE Discards
1960	0.00	200	200	0				
1961	0.00	200	200	0				
1962	0.00	200	200	0				
1963	0.00	200	200	0				
1964	0.00	200	200	0				
1965	0.00	200	200	0				
1966	0.00	200	200	0				
1967	0.00	200	200	0				
1968	0.00	300	300	0				
1969	0.00	400	400	0				
1970	0.00	500	500	0				
1971	0.00	700	700	0				
1972	0.00	500	500	0				
1973	0.00	500	500	0				
1974	0.00	500	500	0				
1975	0.00	700	700	0	317	2.208	2.208	0.000
1976	0.00	1000	1000	0	418	2.392	2.392	0.000
1977	0.00	1200	1200	0	485	2.474	2.474	0.000
1978	0.00	1200	1200	0	606	1.980	1.980	0.000
1979	0.00	2100	2100	0	749	2.804	2.804	0.000
1980	0.00	2400	2400	0	987	2.432	2.432	0.000
1981	0.00	1700	1700	0	883	1.925	1.925	0.000
1982	0.00	1800	1800	0	1180	1.525	1.525	0.000
1983	0.00	2000	2000	0	1311	1.526	1.526	0.000
1984	0.00	2000	2000	0	1328	1.506	1.506	0.000
1985	0.00	2000	2000	0	1640	1.220	1.220	0.000
1986	0.00	1700	1700	0	2293	0.741	0.741	0.000
1987	0.00	1400	1400	0	1884	0.743	0.743	0.000
1988	0.00	1200	1200	0	1885	0.637	0.637	0.000
1989	0.00	800	800	0	1510	0.530	0.530	0.000
1990	0.00	1000	1000	0	1162	0.861	0.861	0.000
1991	0.00	1600	1600	0	1354	1.182	1.182	0.000
1992	0.00	1800	1800	0	1212	1.485	1.485	0.000
1993	0.00	2100	2100	0	1574	1.334	1.334	0.000
1994	0.00	1600	1600	0	2007	0.797	0.797	0.000
1995	0.00	1400	1400	0	2033	0.689	0.689	0.000
1996	0.00	1500	1500	0	2254	0.665	0.665	0.000
1997	0.00	1600	1600	0	1891	0.846	0.846	0.000

Appendix A.8.2

Age-length key for redfish - sourced from Rowling (2001), results for all redfish aged by Central Ageing Facility 1991-97

Age:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	29	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	N
Length (cm)																																													
0																																													0
1																																													0
2																																													0
3																																													0
4	1																																												1
5	7																																												7
6	7																																												7
7	6																																												6
8	18	1																																											19
9	39	11																																											50
10	9	31	6																																										46
11	3	41	23	2																																									69
12	3	57	70	2																																									132
13		41	88	18	1																																								148
14		20	119	44	5	3																																							191
15		10	115	75	31	8	2																																						241
16		1	72	119	57	21	5	4	2		1																																		282
17		1	18	93	71	53	16	7	2	1	1																																		263
18			13	66	104	47	30	20	6	4	3	3																																	296
19			4	70	129	83	48	18	21	13	5	5	3	5	2	1	3	3	1	1			1																						416
20			4	59	121	92	75	47	27	25	22	8	9	14	7	5	3	2	2	1	3	1							1																528
21			5	48	108	102	83	45	29	31	21	22	12	14	6	9	8	3	3	2	8	2	1	1	1			2																	566
22				16	61	70	48	35	25	25	18	16	11	21	12	9	4	9	5	4	4		2	2	3	2						1													403
23				4	25	50	49	30	22	21	7	12	8	8	6	5	6	3	4	3	2	3	2	1	2		1	1	1		1			1	1										279
24				1	19	23	27	26	13	16	12	14	6	11	11	6	7	4	6	4	2	4	5	1		1	2			1	1														223
25					12	19	34	24	13	13	6	5	5	6	4	6	6	5	3	2	3	2	5	1	1	3	2	4	1	2															187
26					4	11	23	24	17	12	5	5	4	6	3	3	8	5		5	4	3	2	3	2	2	1				1	1											1		155
27					2	9	19	16	15	16	13	7	4	11	4	2	3	1	2	3	3	2	3	1			3	2	3	1				1	1										147
28						2	12	11	17	19	11	7	9	8	2	4	6	7	2	3	3	1	1	2	1	1		1	1	2		1		1			1	1							137
29						3	2	6	11	10	9	10	3	10	7	3	3	6	7			2		1	2		1			1	2			1		1									101
30						1		2	2	9	14	9	6	7	5	3	3	3	2	1	1	1			2	4		2	1		2	1	1	1	1									1	85
31								1			1	2	2	4	2	7	3	3	1	2	3	2	2	2		1			1																39
32						1						1	1		1	2		2	2	2	1		1	1	1	1	2		1	1				1											22
33																1	2		1	2	1	2		2	1	2					1														15
34																			1																	2									3
N:	93	214	537	617	750	598	473	316	222	215	149	126	83	125	72	66	65	56	42	35	38	25	25	18	16	17	12	12	10	8	8	4	1	6	3	3	1	1	0	0	0	0	1	1	###