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O. F. Anderson

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O. F. Anderson

NIWA
Private Bag 14901
Wellington 6241

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EXECUTIVE SUMMARY

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Records of catch and discards by species from the Ministry of Fisheries (MFish) Observer Programme were used along with commercial catch-effort data to estimate the rate and annual level of fish bycatch and discards in the orange roughy trawl fishery for 1999–2000 to 2004–05. Estimates were made separately for several categories of catch including orange roughy, other commercial species combined, non-commercial species combined, and four commonly caught individual species, smooth oreo, black oreo, hoki, and black cardinalfish.

Linear regression models were applied to the observer data to identify factors influencing variability in bycatch and discard levels, with a focus on those factors which could be used to partition both the observer and catch-effort data. Regression tree methods, which seek to maximise the explanatory power of variables and simultaneously minimise the number of levels of the variables, were used to group data into a number of areas and periods. The area variables created in this way tended to have more explanatory power than any of the other usable variables, and hence were used in almost all cases to stratify data for the calculation of annual totals. In several cases the south Chatham Rise area was separated out from most other areas due to the overlap of the orange roughy fishery with the oreo fishery in this area, which results in frequent large catches of oreos when targeting orange roughy, and vice versa.

A ratio estimator, based on tow duration, was used to calculate bycatch and discard rates for each species category in each area (as determined from the regression analyses) and fishing year. These ratios were then applied to tow duration totals calculated from the catch-effort data to make annual estimates for the target fishery as a whole. Multi-step bootstrap methods, taking into account the effect of correlation between trawls in the same observed trip and area stratum, were used to estimate the variance in the ratios for all trawls in each stratum, and hence calculate confidence intervals for the annual bycatch and discard estimates.

Total annual bycatch estimates ranged from about 6300 to 13 500 t, compared with approximate target species catches in the same period of between about 16 000 and 21 000 t. A large percentage of this bycatch (43–62%) comprised oreo species, and in most years most of it (47–76%) comprised these and other commercial species. Although total bycatch was lower during these six years than estimated in earlier research for the previous nine years, this was mainly due to decreases in commercial species bycatch. Bycatch of non-commercial species has more than doubled since the previous period (and discards have increased by about 50%) and it is suggested that this may be due to increases in mean tow duration in this fishery over the past eight or nine years.

Total annual discards were at a relatively constant level during the six years, ranging from about 2100 t to about 2900 t. Over 95% of these discarded fish were non-commercial species, with only 80–110 t of orange roughy and other commercial species discarded per year. Estimates of discards of these commercial species were considerably less than in the previous period, although confidence limits were relatively wide. The detection of increased bycatch and discard levels of non-commercial species is an important outcome from this research, showing that discards have risen from 0.06 kg to 0.16 kg per kg of orange roughy catch since the previous analysis.

1. INTRODUCTION

The Ministry of Fisheries (MFish) has an obligation under international treaties to determine the impacts of fishing on any stock, area, and the aquatic environment in New Zealand waters. This obligation includes the principle that the abundance of associated or dependent species should be maintained above a level that ensures their long-term viability. To determine this level for each species affected by the orange roughy (*Hoplostethus atlanticus*) fishery would be an enormous task; more achievable is the identification of species or species groups that are impacted and an estimation of the level of that impact. In this project, the level of catch and discards of non-target species in the orange roughy fishery is estimated based on MFish observer records of catch and discards by species.

Discarding of low value fish species is a global problem, with an estimated 7.3 million tonnes of dead or dying fish returned to the sea annually (Kelleher 2004). This is considerably less than in the late 1980s and early 1990s when it was estimated that 20–22 million t were discarded annually (FAO 1996) and is due mostly to higher retention rates and improved fishing methods.

The orange roughy trawl fishery is New Zealand's third most valuable trawl fishery, after hoki (*Macruronus novaezelandiae*), and squid (*Nototodarus* spp.), and was worth NZD 57M in 2007. This fishery is responsible for between 7000 and 10 000 trawls within the New Zealand region each year, stretching from the Norfolk and Kermadec Ridges in the north to the Auckland Islands in the south, and extending outside the EEZ from the South Tasman Rise in the west to the Louisville Ridge in the east. Such a large and widespread fishery has enormous potential for catching and discarding non-target species with no commercial value. These may be species for which there is no economic market or they may be marketable species which are not kept because of damage (crushing in codend or factory line, contamination from being dropped, deterioration of flesh quality from processing delays), because space in the hold is being reserved for more premium species, or because they are of unwanted size. Fish can also be discarded without ever reaching the deck of the boat, when dead or dying fish are forced through the meshes of the net while fishing (unseen mortality), or as a result of a mechanical or other failure or an intentional release of fish from the codend during gear retrieval.

Information on the level of non-target fish catch and discards in commercial fisheries is important for fisheries management, even though this information is frequently overlooked. Accurate estimates of the catch history of the stock are perhaps the single most important input to any stock assessment, yet this aspect often receives little attention. Official landing records are often assumed to accurately reflect total mortality with an arbitrary amount (percentage) added for catch overruns caused by such things as illegal fishing, incorrect conversion factors, and unreported discarding. Estimates of these additional mortalities are also necessary for determining the impact on non-target species, in line with the ecosystem approach to modern fisheries management. The analysis undertaken here provides some quantitative measurements of target species discards which could be used to more accurately estimate fishing mortality, and provides quantitative and qualitative information on the effects of the orange roughy fishery on other fish species. As a by-product of the process of calculating annual estimates, some of the factors that influence the level of bycatch and discards in the orange roughy fishery are identified.

The work undertaken here updates an earlier study which examined discards in this fishery (along with the hoki fishery) for the 1990–91 to 1998–99 (1 October–30 September) fishing years (Anderson et al. 2001). That study found that bycatch in the orange roughy fishery comprised mainly the commercial species smooth oreo (*Pseudocyttus maculatus*), black oreo (*Allocyttus niger*), black cardinalfish (*Epigonus telescopus*), spiky oreo (*Neocyttus rhomboidalis*), and alfonsinos (*Beryx* spp.) and the non-commercial deepwater dogfish (Squalidae). Discards comprised mostly non-commercial species (about 700–2100 $t.y^{-1}$) and generally lesser but more variable amounts of commercial species (about 100–1500 $t.y^{-1}$), and the target species (about 60–220 $t.y^{-1}$). Both bycatch and discard levels were influenced mainly by differences between vessels, area, and fishing year, with the latter two used to stratify the fishery to calculate annual estimates.

This study also complements other recent studies on bycatch and discards in other New Zealand trawl fisheries: e.g., an update for the hoki fishery (Anderson & Smith 2005), the southern blue whiting (*Micromesistius australis*) and oreo (*P. maculatus, A. niger, N. rhomboidalis*) fisheries (Anderson 2004a), and the arrow squid, jack mackerel (*Trachurus* spp.), and scampi (*Metanephrops challengeri*) fisheries (Anderson 2004b). With regular updates carried out for all the major trawl fisheries (as well as for the ling and tuna longline fisheries), the effects of commercial fishing on associated fish species is now being monitored for all the main offshore fisheries in New Zealand waters. This should enable rapid detection of any general trends or sudden changes in levels of bycatch and discards.

This report was prepared as an output from the MFish project ENV2005-18 "Estimation of non-target fish catch and both target and non-target fish discards in orange roughy trawl fisheries" and addresses the following objective.

1. To estimate the quantity of non-target fish species caught, and the target and non-target fish species discarded, in the trawl fisheries for orange roughy for the fishing years 1999/2000 to 2003/04 using data from Scientific Observers and commercial fishing returns.

MFish observers have been collecting bycatch and discard information from the orange roughy fishery since the early 1990s, in most years covering between 10% and 20% of the target fishery catch. Observers record the catch and discards from each trawl or, occasionally for discards, group of trawls, as well as details of the location, depth, tow duration, fishing gear used, and various other fishing parameters. This report provides estimates of bycatch and discards for the entire target fishery, calculated by scaling up estimates determined from the observed fraction, using effort data collected by the fishing industry. The process was fine-tuned by a process of stratification, and precision was estimated using multi-step bootstrap procedures which take into account vessel to vessel differences and variability in the total amount of fishing effort per trip.

2. METHODS

2.1 Definition of terms

For the purposes of this study *non-target fish catch* is interpreted to mean non-target *species* fish catch, which is equivalent to *bycatch*, all fish caught that were not the stated target species for that tow, whether or not they were discarded (McCaughran 1992). This definition is necessary because an alternative interpretation of *non-target fish catch* could include target species of an unwanted size. He further defines *discarded catch* (or *discards*) as "all the fish, both target and non-target species, which are returned to the sea whole as a result of economic, legal, or personal considerations". *Discarded catch* in this report is interpreted to include estimates of any fish lost from the net at the surface.

2.2 Observer data

Collection of catch and processing data is one of the core duties of the Ministry of Fisheries observers, and these data are generally recorded for every tow on each trip. The allocation of observers to vessel trips takes into account a number of data collection requirements and compliance issues for multiple fisheries. For this reason, and because of the logistics involved in placing observers on vessels at short notice and in accommodating observers on smaller vessels, it is difficult

for the Ministry of Fisheries to achieve an even or random spread of observer effort in each fishery. Observer coverage in the orange roughy fishery is generally maintained at a high level due to its size and importance, and therefore a considerable amount of data is available for this study.

Two datasets were prepared from the MFish observer database *obs*; one comprising discard data from a link between the station data table (*new_observer_station*) and the catch processing data table (*new_observer_processed*), and the other comprising bycatch data by linking station data with the catch data table (*new_observer_greenweight*). Records were extracted for all tows with orange roughy recorded as the target species, carried out within the fishing years being examined.

For all records, the trawl distance was calculated from the recorded start and finish positions. Records in which a start or finish position was incompletely recorded, or where the calculated distance was greater than 60 km, were identified and groomed using median imputation to substitute approximate values for those missing. This process substitutes the missing value with the median latitude or longitude for other trawls by the vessel on the same day. Trawl distances were then recalculated from the corrected positions.

Trawl durations were derived from the difference between the start and finish times, less the period (recorded by observers) between those times when the net was not fishing (e.g., when the net was lifted off the bottom to avoid foul ground, brought to the surface during turning, or was temporarily left hanging in the water due to equipment malfunction). Errors resulting from confusion between the 12 and 24 h clock systems were identified and rectified where these were obvious. The top 1% of these derived tow durations were compared with the duration calculated from towing speed and calculated distance and substituted by the latter value where the absolute difference between the two was greater than 50% of the speed and distance derived value. This method was used only in these extreme cases as some trawls (about 1%) were not straight and it was possible for a long tow to finish near to the start position, resulting in an underestimate of the tow duration. Trawl durations of zero were substituted with an arbitrary value of 1 minute.

Individual vessel data (gross registered tonnage (GRT) and company) were obtained from a combination of sources due to incomplete records in any single source; the *obs* database, observer trip reports, and TCEPR catch-effort data for matching vessels.

When fish were lost from the net before it was brought aboard, observers estimated the amount lost by recording “total greenweight on surface” and “total greenweight on board”. These losses came about through a mixture of burst codends, burst windows/escape panels, and rips in the belly of the net, either below the sea surface or at the surface or on the stern ramp of the vessel. Obvious errors in these values were corrected, for example, where the recorded value for “total greenweight on board” was greater than “total greenweight on surface” the weight of fish lost was set to zero unless an obvious typographical error could be uncovered and corrected by comparing greenweight totals from species by species tallies with the two total greenweight figures. In addition, differences in the recorded values for “total greenweight on surface” and “total greenweight on board” were accepted as valid fish losses only if they were accompanied by a code identifying the cause of the loss. After these corrections, real cases of observed fish losses were very few, amounting to only a few kilograms overall, and so were ignored for the remaining analyses.

Each record was assigned to a fishing year (1 October to 30 September) and to a processing type; FR, fresher/ice boat; PR, processing/factory vessel (no meal plant); MP, processing/factory vessel with meal plant. The processing type was determined from notes made in the observer trip reports and from the processed states recorded for the vessel on the *obs* database.

Each record was assigned to an area (Figure 1). Areas were based on those used in the previous report (Anderson et al. 2001) and are based on known stock divisions or management areas and the geographical distribution of observer sampling. The number of tows observed in each area over the six years is shown in Table 1.

Observer data were available from 31 vessels operated by 17 companies. No vessel or company is identified in this report, and alphanumeric codes are presented where necessary.

Table 1: Number of observed trawls targeting orange roughy by area (see Figure 1, OTHR = trawls not in any of the defined areas) and year.

Area							Fishing year
	1999–00	2000–01	2001–02	2002–03	2003–04	2004–05	All years
2A2B	115	22	29	38	0	9	213
3BOTH	47	115	28	17	55	187	449
CHAL	0	0	0	0	0	74	74
COOK	37	1	0	0	0	0	38
HOWE	56	40	179	45	32	0	352
KAIK	16	60	0	0	0	0	76
LOUIS	0	94	173	371	145	39	822
NCHAT	152	170	338	331	243	441	1 675
NWCHAL	278	111	187	9	14	0	599
ORH1	443	0	253	243	189	84	1 212
SCHAT	77	240	163	311	296	350	1 437
STR	250	0	0	0	0	0	250
OTHR	28	0	0	1	0	0	29
All areas	1 499	853	1 350	1 366	974	1 184	7 226

To create the dataset used to estimate discards, the weights of each species retained and discarded in each "processing group" were obtained from the MFish *obs* database. The processing group is the level at which observers record discard information, and although usually represented by a single tow, the discards from two or more trawls are frequently combined into one processing group. This grouping of processing data stems from the difficulty of keeping track of the catch from individual trawls in the factory of a vessel. In order to examine how discard levels varied with fishing depth, area, season, etc., it was necessary to summarise these data over all trawls within each processing group. Hence the catch and discards of each species, and trawls lengths and durations, were summed within each processing group. Some variables, such as fishing year, processing type, and company were always constant between trawls within a processing group, but frequently trawls in a group covered two months or two areas, and usually a range of trawl depths. For this reason depth of trawl was assigned to each processing group as a categorical variable. Examination of individual trawl data showed that the mean depth of all observed trawls (where the depth of each trawl was taken as the average of the depth of the groundline at the start and end of the trawl) was about 970 m. Therefore processing groups made up of trawls which were all shallower than this depth were assigned "shallow", those made up of trawls all deeper than this depth assigned "deep", and those with a mixture of tow depths set to "NULL".

The extraction of bycatch data was more straightforward because observers estimated or measured the weight of all species caught in each trawl. Bycatch could therefore be estimated and related to trawl parameter data for each tow.

From these datasets the weights of fish caught and fish discarded were calculated for the following species categories:

- the target species, orange roughy (ORH)
- other main commercial species combined (COM)
- all other species combined (OTH)
- individual bycatch species caught in substantial quantities; smooth oreo (SSO), black oreo (BOE), hoki (HOK), and black cardinalfish (CDL)

The abbreviations in parentheses above are used throughout the remainder of this report to refer to these species categories. Summaries by individual species of the overall observed catch and percentage retained are given in Appendix 1.

Commercial species are defined here as those which represented 0.1% or more of the total observed catch during the period and either were quota species or 75% or more of the catch was retained. This definition is somewhat arbitrary, but ensures that species in this category are both saleable and are an important component of the bycatch in the fishery, and is also consistent with the definition used in the previous analysis (Anderson et al. 2001) and analyses of other fisheries (e.g., Anderson & Smith 2005). In this case the category was made up of the following eight species: smooth oreo, black oreo, hoki, black cardinalfish, alfonsino, spiky oreo, hake (*Merluccius australis*), and ribaldo (*Mora moro*). This is exactly the same set of species identified as commercial in the previous (1990–91 to 1998–99) period examined (Anderson et al. 2001). The bycatch and discards of these species were assessed as a group (COM) and those of smooth oreo (SSO, 13% of the observed catch), black oreo (BOE, 3%), hoki (HOK, 1%), and black cardinalfish (CDL, 0.75) were assessed separately.

A total of 7226 observed tows targeting orange roughy (5686 processing groups) was used in the analysis.

2.3 Commercial fishing return data

Catch records from commercial fishing returns were obtained from MFish catch-effort databases for all orange roughy target fishing during the period. This included all fishing recorded on Trawl, Catch, Effort and Processing Returns (TCEPRs), Catch, Effort and Landing Returns (CELRs), and high seas versions of both. Data were groomed for errors using routines developed in the statistical software package R (Ihaka & Gentleman 1996) for orange roughy stock assessment analyses. Assumed errors in the recorded position, depth, towing speed, and tow duration were dealt with using a process of 'median imputation' which identifies, e.g., unusually long tow distances and compares the start and finish positions of the tow with median values for the other tows made by the vessel on that day, replacing them with those medians if necessary. Obvious errors due to confusion of the western with the eastern hemisphere were corrected, and a few remaining tow positions on land were removed. In addition, tow duration was derived from the difference in time between the start and finish of the tow and corrections made using the protocols described for the observer data in Section 2.2.

Records were assigned to the areas defined in Figure 1.

2.4 Examination of factors influencing discards and bycatch

Regression analyses were performed on the observer data to identify the factors with the most influence on the level of bycatch and discards. These factors were then used for stratification. Many variables are available for each observed tow, but only a few are useful for stratifying commercial data. For example, the individual vessel code is available and previous analyses of orange roughy observer data has shown this factor to be highly influential in the level of bycatch and discards; however, not all vessels in the commercial fishery were observed and therefore a ratio could not be calculated for those that were not. Some of these variables were considered along with more useful ones in preliminary regressions, in order to gauge their influence, but were ignored in the final set of regression models. The full set of variables considered in the regressions for each species category were: fishing year, trip number, processing type, vessel key, company, area, month, season (high, June–July; low, August–May), depth, fishing day (day of the fishing year, 1–366) and vessel tonnage. Processing type was set up as a factor with two levels, fresher and factory trawler, with two categories of factory trawler, based on the presence of a meal plant.

The number of fishing periods per year and their start and finish points ("day of the fishing year" for bycatch, month for discards) was determined using recursive partitioning and regression tree analysis. This procedure determines the optimal number of splits in explanatory variables (either numeric or categorical) by repeatedly splitting the data into mutually exclusive groups, each of which is as homogeneous as possible, and then pruning back the number of branches by a process of cross-validation (see, e.g., De'Ath & Fabricius (2000) for details of the procedure). The same regression tree approach was used to find the best combination of fishery areas, so that areas with sufficiently similar patterns of bycatch or discards could be combined to reduce model complexity with minimal loss of explanatory power.

Each species category was examined separately and a combination of normal and binomial regressions applied. Binomial regressions are useful where there are a large fraction of zero values in the data; in this example where there were a large fraction of trawls or processing groups with no catch or discard of the species group. This applied to all species groups in this case, for both bycatch and discard analysis. This enabled an examination of factors influencing both the *probability* and the *level* of a bycatch/discard. The response variable in the binomial regression comprised a binomial vector assigned "0" if no bycatch/discard was recorded and "1" otherwise. The response variable in the normal regressions was determined from the outcome of the process described in Section 2.5, and in all cases a log transformation was used to provide an approximately normal distribution of values. The log transformation was found to be the most appropriate in each case, after visual examination of histograms and normal probability plots of untransformed and transformed data.

Regressions were run in turn for discards of the target species (ORH), bycatch and discards of other commercial species (COM), non-commercial species (OTH), and the four individual species (SSO, BOE, HOK, CDL). A detailed examination of the influence of the main factors identified is beyond the scope of this project, and there is no intention of trying to predict bycatch and discard rates from these regressions, so summaries were made only of the order of variable selection in each model. Variables used to stratify data for bycatch and discard calculations were determined from these summaries.

2.5 Calculation of discard and bycatch ratios

The observer catch and discards data were summed within each species category, for each stratum determined from regression analysis. Similarly, trawl durations were summed within strata. From this the "Discard ratio", $\hat{DR}$, was derived. Initially two versions of the ratio were calculated for several subsets of the data, one based on the total catch of the target species, the other on the total trawl duration. The estimators had the following form,

$$\hat{DR}_1 = \frac{\sum_{i=1}^{m} d_i}{\sum_{i=1}^{m} l_i} \quad \text{and} \quad \hat{DR}_2 = \frac{\sum_{i=1}^{m} d_i}{\sum_{i=1}^{m} t_i}$$

where m processing groups were sampled from a stratum; d_i is the weight of discarded catch from the ith processing group sampled; l_i is the weight of the target species caught in the ith processing group sampled; and t_i is the total towing time for the ith processing group. Variances of these estimates were calculated using standard bootstrap techniques. This involved sampling at random (with replacement) 1000 sets of pairs of ratio values from each data subset. Each of the sets was the same length as the number of records in each subset. This resulted in 1000 estimates of $\hat{DR}$ from which variances and confidence intervals were calculated. A comparison was made, between the two estimators, of the ratio variances derived from each of the initial subsets tested and the estimator with lower variance overall was used for all subsequent calculations.

The standard bootstrap assumes that all tows were sampled with equal probability. This assumption about the assignment of observers to tows is not true, but the spread of observed tow positions compared with all recorded tow positions from each fishery (see Figure 1) showed that there was fairly representative coverage of the spatial extent of each fishery, with the main fishing grounds covered.

Once the best estimator was chosen, estimates of $\hat{DR}$ were derived for each stratum in each fishing year and variances were derived by a more sophisticated bootstrapping procedure that allowed for correlation of discards between sample units, in this case processing groups, within an observed trip. Separate ratios were calculated only for strata with 50 records or more, and overall ratios (e.g., for all areas or all periods within a year) were substituted for strata with fewer than 50 records. The discard ratio calculated for each stratum was then multiplied by either the total estimated catch of orange roughy or the total tow duration in the stratum (depending on the version of the estimator chosen), from commercial catch records, to estimate total discards $\hat{D}$:

$$(1) \qquad \hat{D} = \sum_j \hat{DR}_j \times L_j \text{ (or } T_j \text{)}$$

where L_j is the total catch of orange roughy in stratum j and T_j is the total tow duration in the stratum.

To obtain a 95% confidence interval for the total discards that allows for correlation between sampling units within a trip, 1000 bootstrap samples were generated from the sampling units within each stratum using a three-step sequential sampling procedure. First a trip was chosen at random, then a bootstrap sample of the processing groups that were from that trip in the stratum. These steps were repeated until the effective number of discard groups was approximately equal to the effective number of observed discard groups for the stratum. At step 3 the effective number of trips in the bootstrap sample was calculated. If this was within 5% of the effective number of observed trips in the stratum then the bootstrap sample was accepted. Otherwise a new bootstrap sample was drawn until 1000 samples in all had been accepted. The effective number of discard groups and the effective number of trips was calculated from the effort (either catch or duration) and reflected the contributions to the variance of the discard rate $\hat{DR}$ from the variance of the discards and the covariance between pairs of discards within the same trip and stratum. Matching a bootstrap sample to the stratum on these criteria ensured that the variation in the bootstrap sample estimate matched the sampling variation of $\hat{D}$. An empirical distribution for the total discards was obtained by totalling the bootstrap estimates across the strata, and the 95% confidence interval was obtained from the 2.5% and 97.5% quantiles.

Bycatch estimates were calculated in a similar manner to discards but, because catch estimates are not pooled across tows, it was possible to use tow-by-tow data and hence a different (and slightly larger) set of records for comparing estimators and calculating ratios. Bootstrapping was carried out using the statistical software package R (Ihaka & Gentleman 1996).

3. RESULTS

3.1 Distribution and representativeness of observer data

The positions of all observed tows in the target orange roughy fishery between 1 October 1999 and 30 September 2005 are shown, along with those of all commercial orange roughy target tows recorded on TCEPR forms from the same period, in Figure 1. Observer coverage was well spread over the geographical range of this fishery, with sampling throughout all of the main fishing grounds. One exception to this is the Challenger Plateau fishery in ORH 7A which has been closed since the 2000–01 fishing year. Although this was extensively fished in 999–2000, the first year in the series examined here, the only observer coverage available for this area and period is from 2005. These data came from an industry-led research voyage in the main fishery grounds adjacent to the EEZ boundary. Observer coverage includes all the Chatham Rise stocks and southern ORH 3B fisheries, the east coast stocks in ORH 2A, ORH 2B, and ORH 3A, the ORH 1 and Cook Canyon (ORH 7B) fisheries, and all the major fisheries outside the New Zealand EEZ (Louisville Ridge, Lord Howe, Northwest Challenger, and South Tasman Rise. The grey coloured areas in Figure 1, which indicate fished but unobserved areas, are restricted mainly to lightly fished locations outside the known fishing grounds and, apart from the Challenger fishery in ORH 7A, don't reveal any major fisheries that were overlooked. Examination of density plots (Figure 2) supports this, showing that the observed tows were distributed throughout the latitudinal and longitudinal range of the fishery in each of the six years. These plots also show that the spread of observer coverage over the spatial range of the fishery generally matched that of the commercial fishery, although observer coverage tended to be more concentrated into narrower ranges in some years, e.g., into three distinct peaks of latitude in 1999–2000, and oversampled in some areas while undersampling in other areas in some years. This tended to balance out over time, however, with the "All years" panel in Figure 2 revealing a good match of observer coverage to commercial effort over both the latitudinal and longitudinal ranges of the fishery. If anything, coverage was perhaps a little low around 178° E and 40° S and high around 176° W and 36° S.

The annual number of observed tows ranged from 853 to 1499 and the number of vessels observed from 9 to 19 (Table 2). The percentage of the fishery observed (in terms of the estimated annual target fishery catch) ranged from 11.6% to 29.4%, above the 10% target level usually required by MFish. A total of 31 vessels was observed during this 6-year period. Total target fishery effort fluctuated during the period, from a low of about 11 300 h in 2000–01 to a high of about 16 400 h, in the following year.

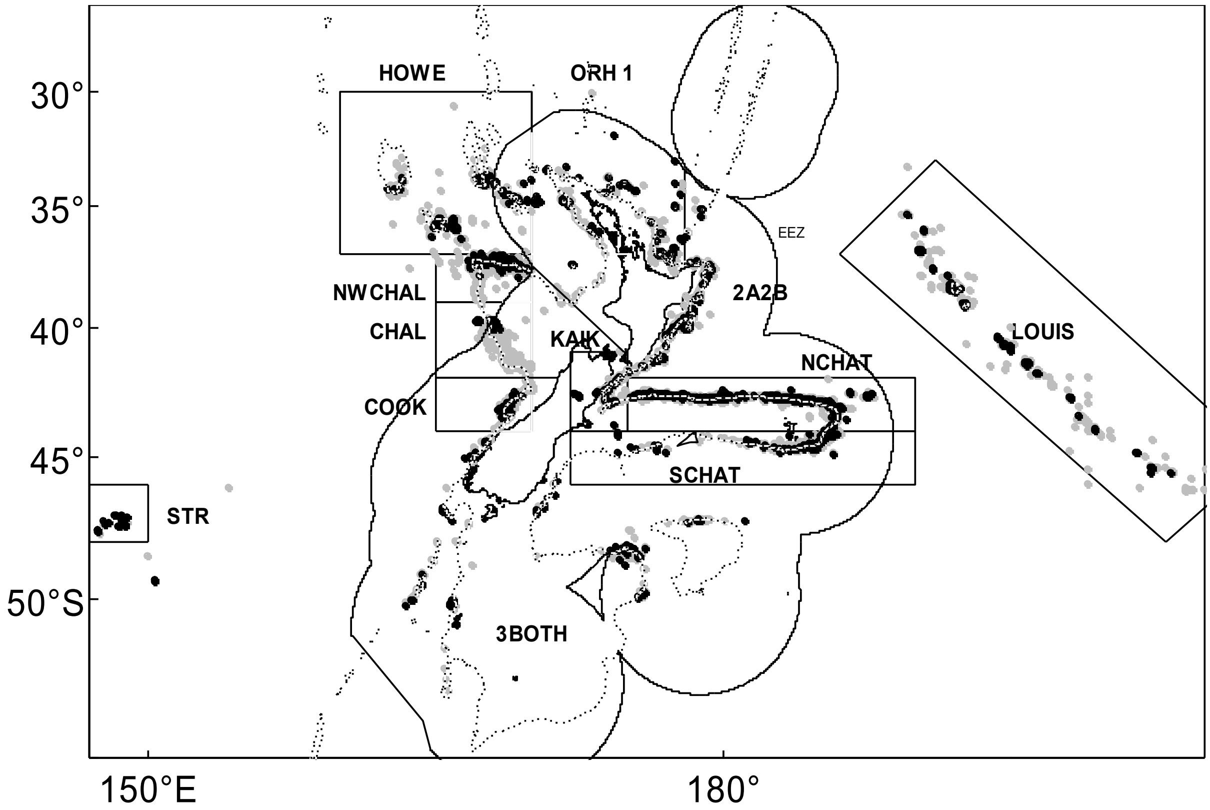

Figure 1: Distribution of tows recorded by observers on vessels targeting orange roughy between 1 October 1999 and 30 September 2005 (black dots), and all commercial tows with recorded position targeting orange roughy in the same period (grey dots). Area divisions are those used in the analyses. The dotted line represents the 1000 m contour.

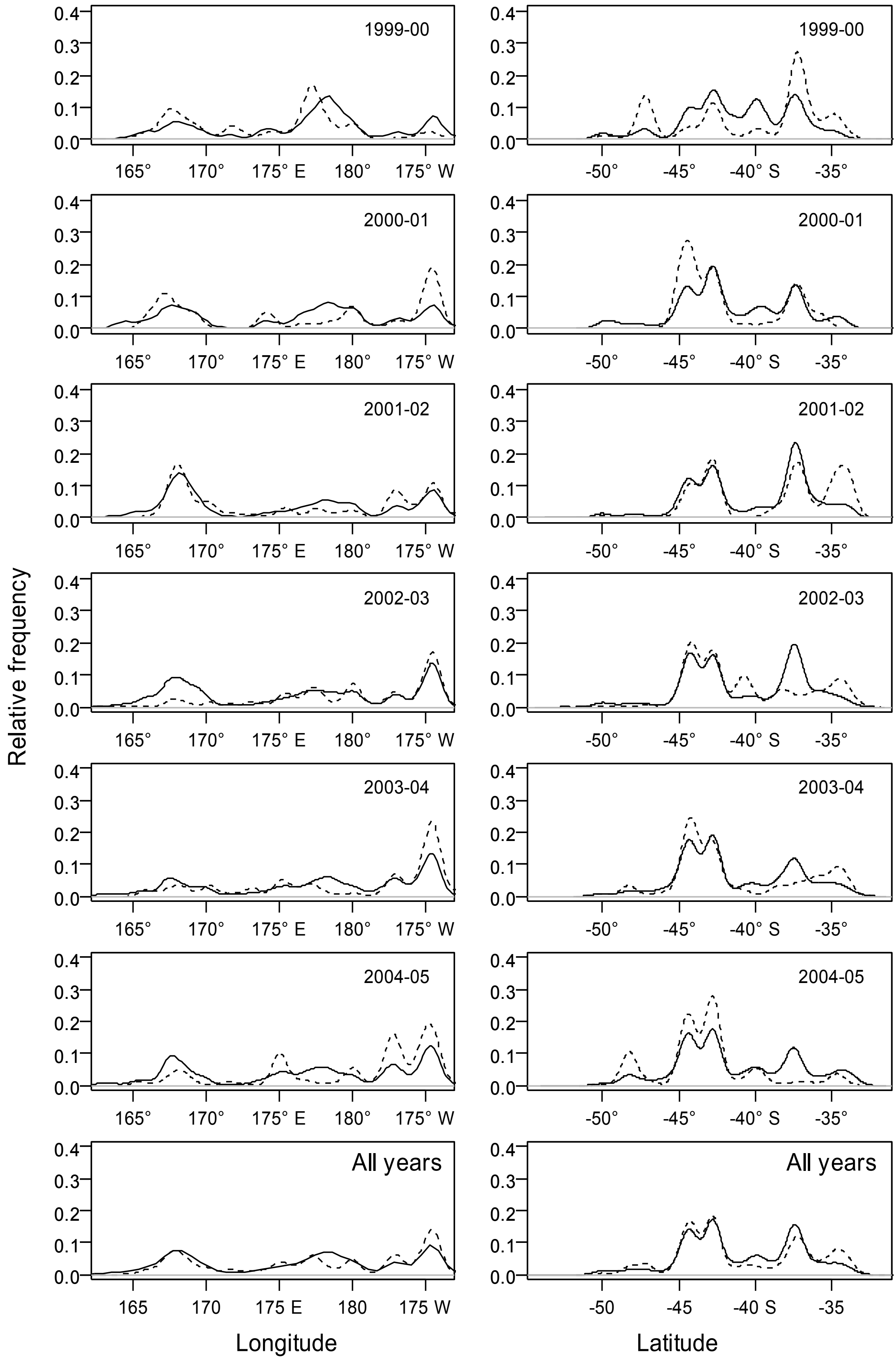

Figure 2: Comparison of position (latitude and longitude) of observed trawls (dashed lines) versus all trawls captured on TCEPR forms (solid line) for each fishing year from 1999–2000 to 2004–05, and for all six fishing years combined. The relative frequency was calculated from a density function which used linear approximation to estimate frequencies at a series of equally spaced points.

Table 2: Number of tows, vessels, and trips observed, the fraction of the target fishery catch observed, and the total target fishery effort in the orange roughy fishery, by fishing year.

Fishing year	Total tows observed	Total vessels observed	Total no. trips	Observed catch (% of target fishery catch)	Total fishery effort (h)
1999–00	1 499	19	34	11.6	15 123
2000–01	853	9	16	11.9	11 275
2001–02	1 350	14	21	22.1	16 419
2002–03	1 366	16	22	25.3	14 214
2003–04	974	9	20	12.7	11 855
2004–05	1 184	10	17	29.4	12 340
All years	7 226	31	129	19.1	81 226

The spread of observer effort over the range of vessel sizes was compared to the spread of vessel sizes over the entire target fishery using density plots (Figure 3). These plots indicate, firstly, that there is a very wide range of vessel sizes operating in this fishery, from 76 t to over 3000 t. Such large differences in vessel size, and therefore power, are likely to be reflected in the mixture of bycatch species caught. Secondly, the plots show that observers covered much of the range of vessel sizes; from 76 t to about 2500 t. The plot appears to show total effort and observer coverage for individual vessels or small groups of very similar sized vessels (e.g., the spike at about 1900 t) and indicates that the most active vessels were all well covered by observers. It's also reassuring that, although the coverage was lower, the smaller vessels in the fleet (less than about 300 t) were also represented by the observer data.

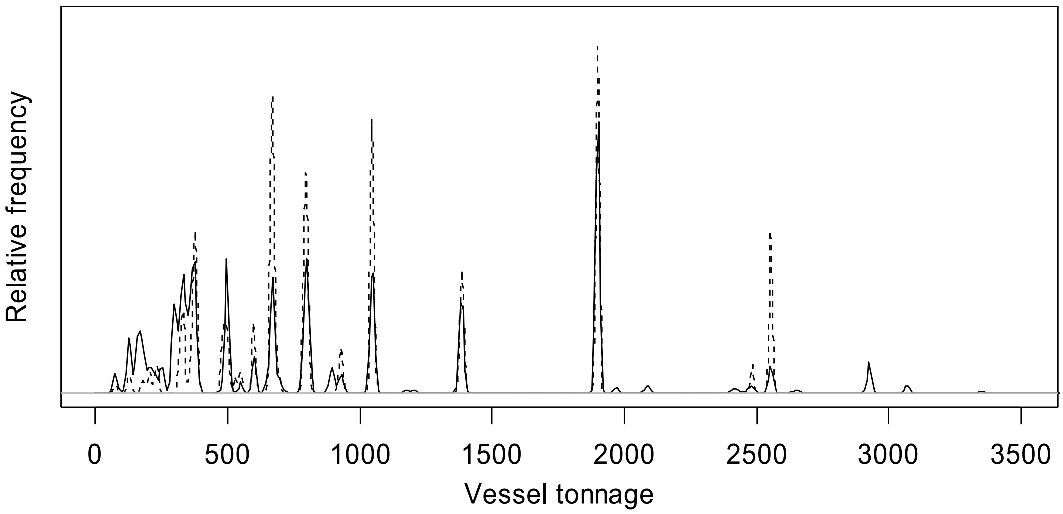

Figure 3: Comparison of vessel sizes (Gross Registered Tonnage) in observed trawls (dashed lines) versus all trawls captured on TCEPR forms (solid line) for all fishing years combined. The relative frequency was calculated from a density function which used linear approximation to estimate frequencies at a series of equally spaced points.

The spread of observer effort over each fishing year was determined and compared to the spread of effort for the whole fishery, by applying a density function to numbers of trawls per day (Figure 4). These plots show a very similar pattern of effort from year to year, with a fairly stable level of effort from the beginning of the fishing year through to about the end of April, except for a brief drop around the end of December. This was followed by an increase in effort through May and June, peaking in late June or early July during the orange roughy spawning period, after which effort dropped off steadily, with August and September generally the quietest months in this fishery. Observer effort was more variable within each year, but similar over all years, except for a slight over-representation during the spawning period, and almost no coverage during late December–early January, August, and September. Coverage was usually good early in the fishing year, during June and July, and also, in a few years, around February.

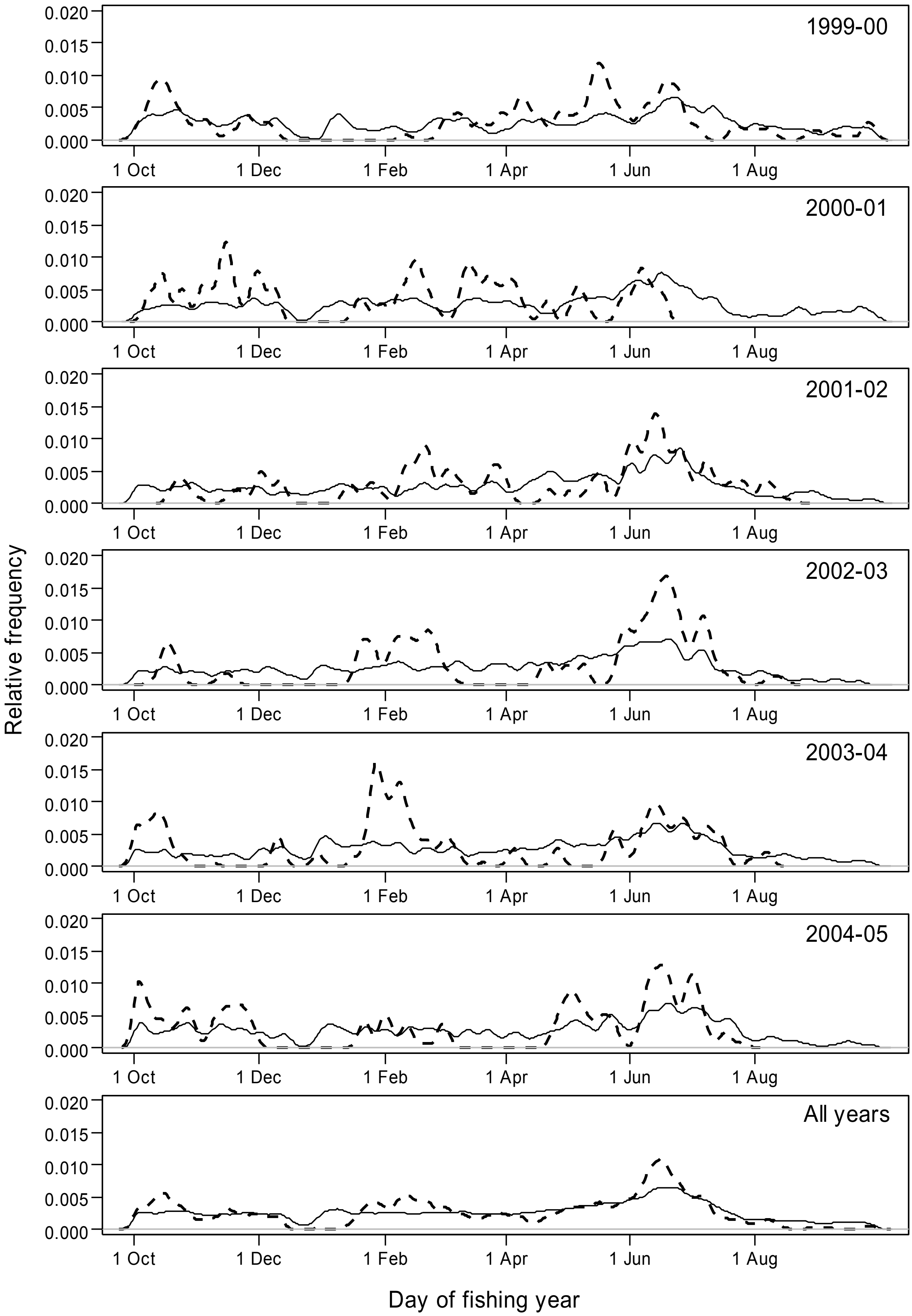

Figure 4: Comparison of the temporal spread of observed trawls (dashed lines) with all trawls recorded on TCEPR forms (solid line) for each fishing year from 1999–2000 to 2004–05, and for all six fishing years combined. The relative frequency of the numbers of trawls was calculated from a density function which used linear approximation to estimate frequencies at a series of equally spaced points.

3.2 Comparison of estimators

From observer data, the orange roughy estimated catch-based and tow duration-based forms of the bycatch and discard ratio estimators were examined and compared with the aim of selecting and using the one which would provide ratios with the least amount of associated error. For each of the two forms in turn, ratios were calculated for the bycatch and discards in the COM and OTH species categories, without any stratification, and c.v.s estimated by bootstrapping. Individual species categories (including discards of orange roughy) were not considered as they were represented by far fewer non-zero value observations, and would carry less weight. The results of these comparisons are shown in Table 3. The estimated c.v.s were smaller for bycatch than for discards, especially in the COM category, and smaller for OTH species than for COM species, especially for discards. Coefficients of variation were small for bycatch of both species categories and for discards of OTH species, for both forms of the estimator (range 3.8% to 5.4%), and much greater for discards of COM species (31.6% for both forms of the estimator). Differences in c.v.s between the two forms were small (range 0.01% to 1.10%), but in three out of the four comparisons the tow duration-based estimator provided a lower c.v. than the orange roughy estimated catch based estimator.

On the basis of these comparisons, although there was very little difference between the two forms, the tow-duration-based estimator was selected for all bycatch and discard calculations. A similar exercise carried out when examining bycatch and discards in the southern blue whiting, oreo, and hoki fisheries (Anderson 2004a, 2004b, Anderson & Smith 2005) produced similar results, and also led to the use of a tow duration-based estimator.

Table 3: Comparison of estimators.

Bycatch/discards	Species category	Estimator	Bycatch ratio	c.v. (%)
Bycatch	COM	ORH catch	0.215	5.38
	COM	Tow duration	621.8	5.33
	OTH	ORH catch	0.079	4.93
	OTH	Tow duration	227.0	3.83
Discards	COM	ORH catch	0.0015	31.57
	COM	Tow duration	4.1	31.58
	OTH	ORH catch	0.069	5.30
	OTH	Tow duration	192.5	4.44

3.3 Observer bycatch data

3.3.1 Overview of raw bycatch data

Orange roughy accounted for 75% of the total estimated catch from all observed trawls targeting orange roughy between 1 October 1999 and 30 September 2005. The remaining 25% mostly comprised other commercial species, especially smooth oreo (13.5%), black oreo (3.2%), and hoki (1.0%), and non-commercial species groups; unidentified sharks (1.2%) and corals (0.8%). Altogether, over 94% of the observed catch comprised species which were commercial (as defined in Section 2.2). About 240 species or species groups were identified by observers, the great majority of which were non-commercial species caught in low numbers. Chondrichthyans, often unspecified but including shovelnosed spiny dogfish, and *Etmopterus* species (likely to be mostly Baxter's dogfish) accounted for much of the non-commercial catch. Echinoderms, squids, crustaceans, and other unidentified invertebrates were also well represented among the main bycatch species groups caught in this fishery (see Appendix 1 for a list of the top 50 bycatch species).

Exploratory plots were prepared to examine total bycatch per tow (plotted on a log scale) with respect to the available variables (Figure 5). Total bycatch was highly variable between trawls, ranging from none to 65 t, and tended to increase with increasing tow duration. There was an increase in bycatch with increasing bottom depth, from a median of about 100 kg in depths shallower than 1000 m up to 400–800 kg at depths greater than this. Bycatch varied little between ice boats and factory vessels (medians of about 130 $kg.tow^{-1}$), and although vessels with meal plants recorded higher bycatch levels (about 900 $kg.tow^{-1}$), this was based on data from only 85 trawls. There was considerable variability in bycatch among the 17 companies and 28 vessels for which there were more than 20 records. Median bycatch ranged from 24 to 645 $kg.tow^{-1}$ among companies with 4 below 50 $kg.tow^{-1}$ and three above 400 $kg.tow^{-1}$. In comparison, eight vessels were below 50 $kg.tow^{-1}$ and six above 400 $kg.tow^{-1}$, with one vessel having a median bycatch of over 2500 $kg.tow^{-1}$.

Bycatch was more consistent between fishing years, with slightly higher levels in 2000–01 than in the other 5 years, but varied widely among areas, from low levels (about 30 $kg.tow^{-1}$) in the ET (extra-territorial) areas LOUIS and STR to much higher levels (over 600 $kg.tow^{-1}$) in areas SCHAT, COOK, and KAIK. Bycatch levels also varied considerably from month to month, with lower medians in the main orange roughy spawning months of June and July compared to other months.

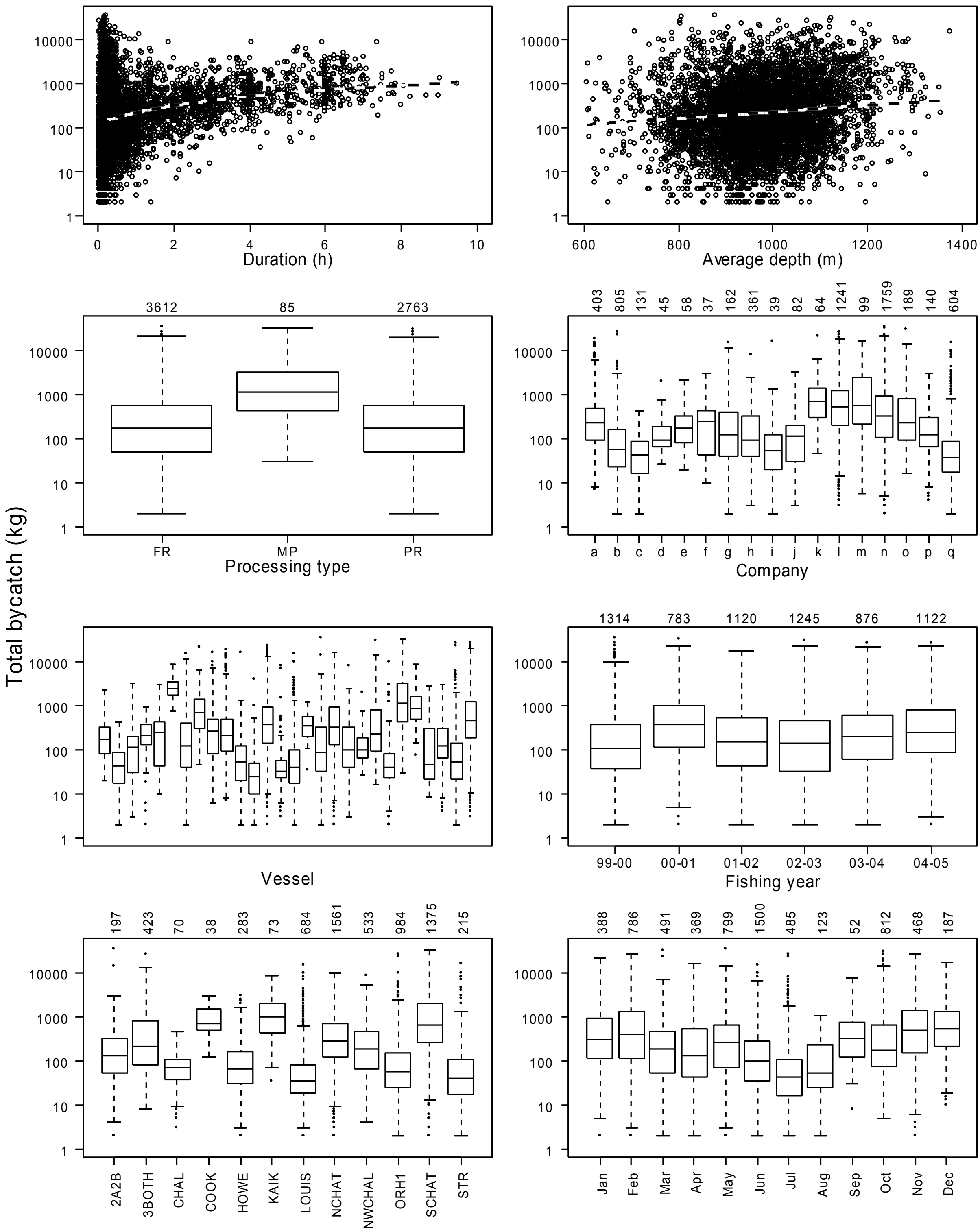

Figure 5: Total bycatch per tow plotted against some of the available variables. Total bycatch is plotted on a log scale. The dashed lines in the top two panels represent mean fits (using a locally weighted regression smoother) to the data. The box and whisker plots show medians and lower and upper quartiles in the box, whiskers extending up to 1.5x the interquartile range, and outliers individually plotted beyond the whiskers. The numbers above each plot indicate the number of records associated with that level of the variable: companies and vessels represented by fewer than 20 records were not plotted. Average depth is the average of the start and finish gear depths. See Figure 1 for area codes; FR, fresher; PR, factory vessel; MP, factory vessel with meal plant.

3.3.2 Regression modelling and stratification of bycatch data

Regression tree analysis, using the log of the bycatch ratio as the predictand and examining each predictor in turn, indicated that for bycatch of each species group the most parsimonious split of the fishing year resulted in it being partitioned into between two and five periods (Table 4). The same process combined the 13 areas to produce "super-areas" with similar patterns of bycatch. There were three such super-areas for the COM, OTH, SSO, BOE, and HOK species groups, and two for CDL. These super-areas tended to group adjacent areas (e.g., CHAL with HOWE and NWCHAL) but did not produce patterns that were repeated strongly across species (Table 4). For some of the less frequently caught species there were no recorded catches in some areas (e.g., hoki and cardinalfish on the South Tasman Rise) and these areas were treated separately. The splitting process included the constraint that there must be a minimum of 20 observations in a branch for a split to be attempted. This can result in a stratum with a much lower number of observations. The smallest strata produced in this case were the BOE: COOK+HOWE super-area with 16 observations, and the BOE: fishing day less than 2.5 (9 observations).

Table 4: Results of regression tree analyses on the optimal stratification of fishing day and area variables for describing rates of bycatch. Split points are "day of the fishing year" where 1 = 1 October and 365 = 30 September.

Species category	Number of periods (split points)	Area groupings
COM	5(5, 154, 97, 241)	1) OTHR+SCHAT
		2) 3BOTH+KAIK+NCHAT
		3) 2A2B+CHAL+COOK+HOWE+LOUIS+NWCHAL+ORH1+STR
OTH	2(160)	1) KAIK+OTHR+SCHAT
		2) NCHAT+STR
		3) 2A2B+3BOTH+CHAL+COOK+HOWE+LOUIS+NWCHAL+ORH1
SSO	4(5, 149, 241)	1) SCHAT
		2) 3BOTH+KAIK+NCHAT+OTHR
		3) 2A2B+CHAL+COOK+HOWE+LOUIS+NWCHAL+ORH1+STR
BOE*	5(2.5, 248, 285, 293)	1) COOK+HOWE
		2) 3BOTH+SCHAT
		3) 2A2B+KAIK+LOUIS+NCHAT+NWCHAL+ORH1+OTHR+STR
HOK*	5(69, 139, 186, 296)	1) COOK+HOWE+NWCHAL+ORH1
		2) 3BOTH+OTHR+SCHAT
		3) 2A2B+CHAL+KAIK+LOUIS+NCHAT
CDL*	5(263, 269, 279, 318)	1) 2A2B+COOK+KAIK+LOUIS+NWCHAL
		2) 3BOTH+CHAL+HOWE+NCHAT+ORH1+SCHAT

* There were no observed catches of BOE in CHALL, of HOK in STR, or of CDL in STR or OTHR

The unit of interest in the GLM models was the bycatch ratio, expressed as the log of catch (kg) per hour trawled. Of the 7226 observed trawls examined, 23% did not record any bycatch of COM species, and 16% did not record any bycatch of OTH species. The equivalent percentages for the individual bycatch species were smooth oreo (SSO), 56%; black oreo (BOE), 79%; hoki (HOK), 75%; black cardinalfish (CDL), 83%. In each case, because of the high fraction of trawls with no bycatch, a combination of linear and binomial models was run.

In initial models the variable *trip* had the most explanatory power in almost every case, followed by *duration* and *area* (Table 5). The *trip* variable is of no use in stratification as not all trips were observed, and when removed from consideration in the models it was almost invariably replaced by *area* and *vessel*, with little loss in the models' explanatory power. It is to be expected that longer trawls would produce more bycatch than shorter trawls (as shown in Figure 5), but these results indicate that longer trawls also have a higher catch rate (catch per hour) of bycatch species. The variable *area* (i.e., the species specific super-area) was the most influential variable in all of the final normal models except that for CDL, and was also the most important variable in the binomial models. Trawl *duration* had a marked influence on the bycatch of black cardinalfish, perhaps because they are able to swim in front of the net for long periods before tiring. Trawl *duration* also was important in the bycatch of both main fish groups, COM and OTH, and *vessel* was of similar importance to duration overall. The time of year factor, *period*, had only a small influence in most models although had an influence on the bycatch of CDL. The *depth* and *fishing year* variables were also of lower importance in most of the models. Because of the uneven spread of observer data, stratification of ratios to use for total bycatch estimates for each species group was restricted to a single factor, *area*. Although the individual *vessel* cannot be used for stratification, as explained above, to acknowledge the influence that this factor has on rates of bycatch, separate ratios were calculated only where at least two vessels were represented in each stratum.

Table 5: Summary of GLM modelling of bycatch in the orange roughy fishery. The numbers denote the order in which the variable entered the model; –, not selected; *fyr*, fishing year.

Species category	Model type	Model R^2 (%)	Variable					
			area	*duration*	*vessel*	*depth*	*period*	*fyr*
COM	Normal	56.0	1	2	3	4	5	6
COM	Binomial	17.1	3	2	1	6	4	5
OTH	Normal	20.4	1	3	2	5	7	4
OTH	Binomial	14.8	–	1	2	3	–	4
SSO	Normal	54.4	1	2	3	6	4	5
SSO	Binomial	39.9	1	5	2	4	–	3
BOE	Normal	45.2	1	2	3	–	4	5
BOE	Binomial	34.6	1	4	2	6	5	3
HOK	Normal	60.2	1	3	2	4	5	6
HOK	Binomial	26.7	5	2	1	3	4	6
CDL	Normal	43.6	5	1	3	4	2	6
CDL	Binomial	15.4	3	–	1	2	4	5

3.4 Observer discard data

3.4.1 Overview of raw discard data

The associated species most affected by discarding in this fishery were sharks (mostly unidentified but likely to be mainly Baxter's dogfish, shovelnose dogfish, *Centroscymnus* species, and seal sharks) which together made up more than 2% of the catch, with only 10–15% being retained. Corals and slickheads (Alepocephalidae) were also caught in relatively large amounts, and virtually all discarded. Next most affected were rattails (again usually unidentified by observers but likely to be mostly javelinfish (*Lepidorhynchus denticulatus*), four-rayed rattails (*Coryphaenoides subserrulatus*), serrulate rattails (*C. serrulatus*), notable rattails (*Coelorinchus innotabilis*), and white and unicorn rattails (*Trachyrinchus* spp.). Some rattails were retained by the vessel and presumably mealed, but 85–90% were discarded. Other groups frequently discarded included morid cods (Moridae), non-commercial squid species, basketwork eels (*Diastobranchus capensis*), and echinoderms (see Appendix 1 for details).

Exploratory plots were prepared to examine the variability in the total level of discards per processing group with respect to some of the available factors (Figure 6). As for bycatch, the quantity of discards tended to increase with increasing trawl duration. The combined trawl length of most processing groups (97%) was less than 5 hours, but the combined duration of several tows (max. 72) within a processing group was as much as 82 hours. Processing groups comprising trawls all deeper than 900 m produced slightly more discards than groups comprising all shallow tows, although this small difference is unlikely to be significant. Discard levels were lower on vessels with meal plants (median 33 kg.group^{-1}) than on either factory vessels without meal plants (90 kg.group^{-1}) or ice boats (65 kg.group^{-1}). As was the case for bycatch above, the factors showing the most variability were company and vessel, for which median discard levels ranged from 20 to 602 kg.group^{-1} and 12 to 1800 kg.group^{-1}, respectively. There was some variation in total discards from year to year, but no obvious trend over time, with medians ranging from 50 kg.group^{-1} (in 2002–03) to 105 kg.group^{-1} (in 2000–01). Discards varied considerably between areas, with the highest levels in COOK and KAIK and lowest levels in STR, LOUIS, and ORH1. Discards were at a constant level between January and May (67–87 kg.group^{-1}), and then dropped to lower levels during winter (28–57 kg.group^{-1}) before returning to moderate to high levels (80–200 kg.group^{-1}) between September and December.

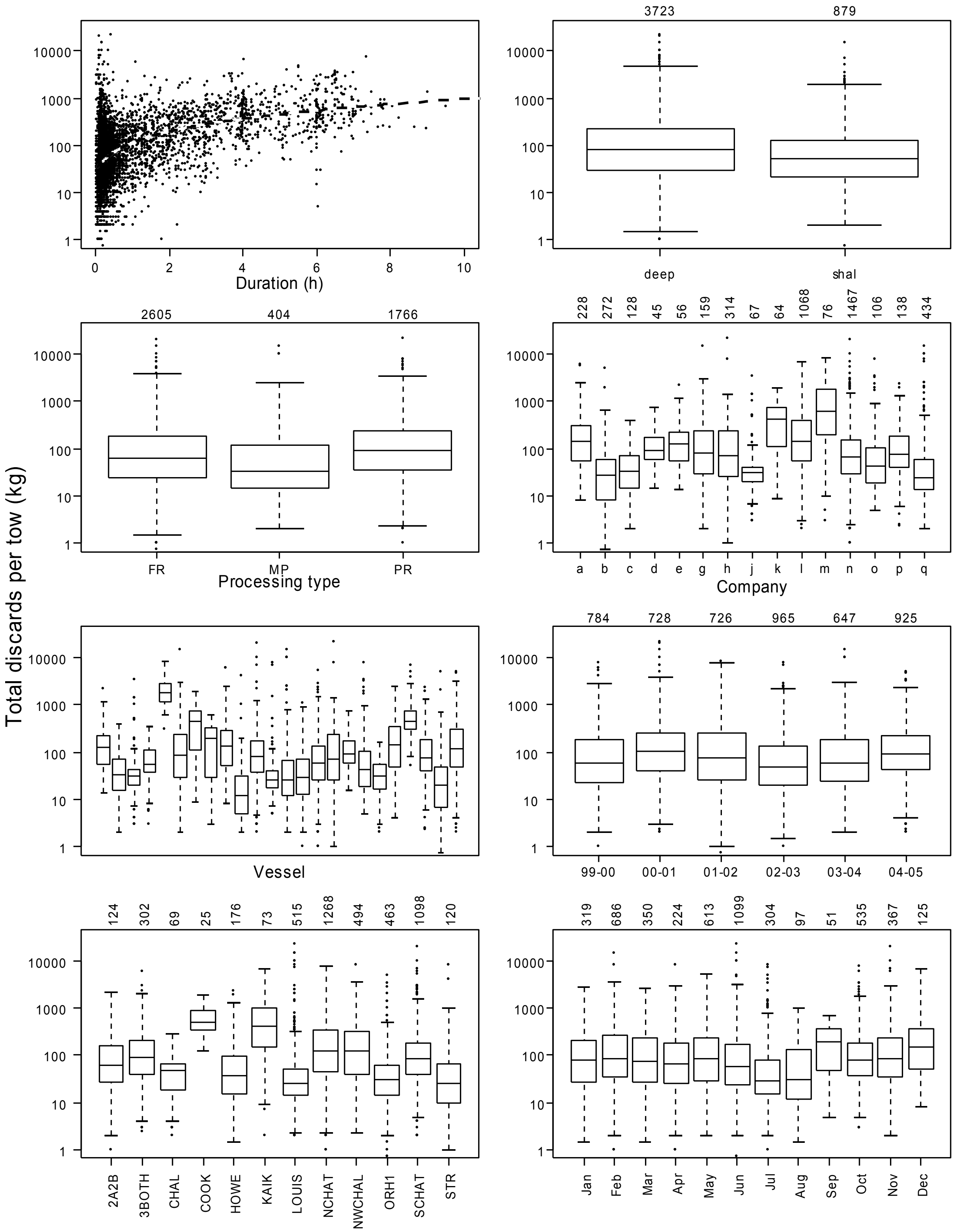

Figure 6: Total discards per tow (total discards per processing group divided by the number of tows in the group) plotted against some of the available variables (records with no discards excluded). Discards are plotted on a log scale. The dashed line in the top left panel represents a mean fit (using a locally-weighted regression smoother) to the data. The box and whisker plots show medians and lower and upper quartiles in the box, whiskers extending up to 1.5x the interquartile range, and outliers individually plotted beyond the whiskers. Levels of variables represented by fewer than 20 records were not plotted. See Figure 1 for area codes; deep, tows 900 m or deeper; shal, tows shallower than 900 m; FR, fresher; PR, factory vessel; MP, factory vessel with meal plant.

3.4.2 Regression modelling and stratification of discard data

Regression tree analysis, using the log of the discard ratio as the predictand, indicated that five periods should be used for COM species discards regressions and three periods for OTH species regressions (Table 6). Month was used instead of fishing day as processing groups often ran for two or more days. The optimising procedure reduced the number of areas for COM discards from 12 to 4, with the result that the 4 ET areas were grouped together, and four areas with no observed discards of COM species were also naturally grouped together. Area groupings for OTH species separated out mostly spatially close regions also, while retaining a large group of widespread areas with similar patterns of discarding.

Table 6: Results of regression tree analyses on the optimal stratification of month and area variables for describing rates of discards in the COM and OTH species categories.

Species category	Month groupings	Area groupings
COM	1) Dec	1) NCHAT+ORH1
	2) Mar+Apr	2) HOWE+LOUIS+NWCHAL+STR
	3) Jan+May+Jul+Sep	3) 3BOTH+SCHAT
	4) Feb+Oct	4)* 2A2B+CHAL+COOK+KAIK
	5) Jun+Aug+Nov	
OTH	1) Mar+Jun+Jul+Aug+Sep	1) 2A2B+CHAL+COOK+HOWE+LOUIS+NWCHAL+ORH1
	2) Apr+May+Oct+Nov+Dec	2) 3BOTH+NCHAT+STR
	3) Jan+Feb	3) KAIK+SCHAT

* There were no recorded discards of COM species in these four areas.

The unit of interest in the regression analyses was the discard ratio, expressed as the log of discards (kg) per hour. The observer data indicated that discarding of orange roughy was very rare, occurring in only 68 (or 1.2%) of the 5686 processing groups observed. Discarding of COM species was more common (472 groups, 8.3%), but not so common for each of the individual bycatch species (SSO, 0.8%; BOE, 0.7%, HOK, 2.1%, CDL, 1.3%). In contrast, discarding was frequent in the non-commercial (OTH) group of species, occurring in 84.6% of the processing groups examined. Both linear and binomial regressions were run for the COM and OTH categories but, with such a low frequency of discarding, the individual species, including orange roughy, were not able to be examined in this way and no stratification of the data was attempted.

Individual *vessel*, *area*, and trawl *duration* were the key factors in these regressions but, as for bycatch, initial models considering *trip* as a factor found this variable to have the most influence in each case (Table 7). Clearly there are differences in the way that vessels treat the catch of non-target species, both commercial and non-commercial, but these differences are difficult to correlate with vessel characteristics that may underlie these differences. For example, removal of the factor vessel from the model might have been expected to elevate the importance of the variable *proctype* in the models, as one might expect vessels with meal plants to discard less, but this was found not to be the case. As for bycatch, stratification by *area* becomes the obvious option for both COM and OTH discards. Although *period* was similarly influential overall in the two COM discard models, it makes sense to use the same factor to stratify all ratio estimates. Fishing year (*fyr*) was also important, in the binomial models, but estimates will in any case be made separately for each year.

As in the bycatch calculations above, separate ratios were calculated only where at least two vessels were represented in each stratum.

Table 7: Summary of regression modelling for discards in the orange roughy fishery. The numbers denote the order in which the variable entered the model; –, not selected.

Species category	Model type	Model R^2 (%)	Variable					
			vessel	*area*	*duration*	*fyr*	*period*	*depth*
COM	Linear	60.2	2	4	1	6	3	5
COM	Binomial	55.3	1	3	5	2	4	6
OTH	Linear	25.7	2	1	3	4	5	6
OTH	Binomial	34.5	1	5	3	2	–	4

3.5 Calculation of bycatch

3.5.1 Bycatch rates

Bycatch ratios for COM species were calculated from the observer data separately for each of the three super-areas in Table 1 and each of the six fishing years. The variance in these bycatch rates was calculated using the bootstrap methods described above.

These ratios not only provide the basis from which total bycatch can be determined from target fishery effort totals, but they also provide a guide to the rate at which bycatch species were caught in each of the areas used for stratification, and how this may have changed over time. Annual median bycatch rates of COM species in areas SCHAT and OTHR ranged from 4000 to over 10 000 $kg.h^{-1}$, a level far greater than estimated for any other area (Figure 7). High bycatch rates of SSO in area SCHAT and BOE in areas SCHAT and 3BOTH, with similar patterns over time, show that these two species are mostly responsible for this pattern of commercial species catch rates. Annual bycatch rates of OTH species were greatest in the KAIK+OTHR+SCHAT super-area, with median values ranging from 400 to 700 $kg.h^{-1}$, and were at a relatively constant rate of about 200 $kg.h^{-1}$ in all other areas. Bycatch rates of HOK were 50 $kg.h^{-1}$ or less in all years and areas except for area 3BOTH+OTHR+SCHAT in 2000–01, when the rate jumped to about 140 $kg.h^{-1}$. Bycatch rates of CDL were similarly low, mostly less than 40 $kg.h^{-1}$, but were higher in 1999–2000 than in other years. A summary of the bycatch rates in each species category, with standard deviations, is given in Appendix 2.

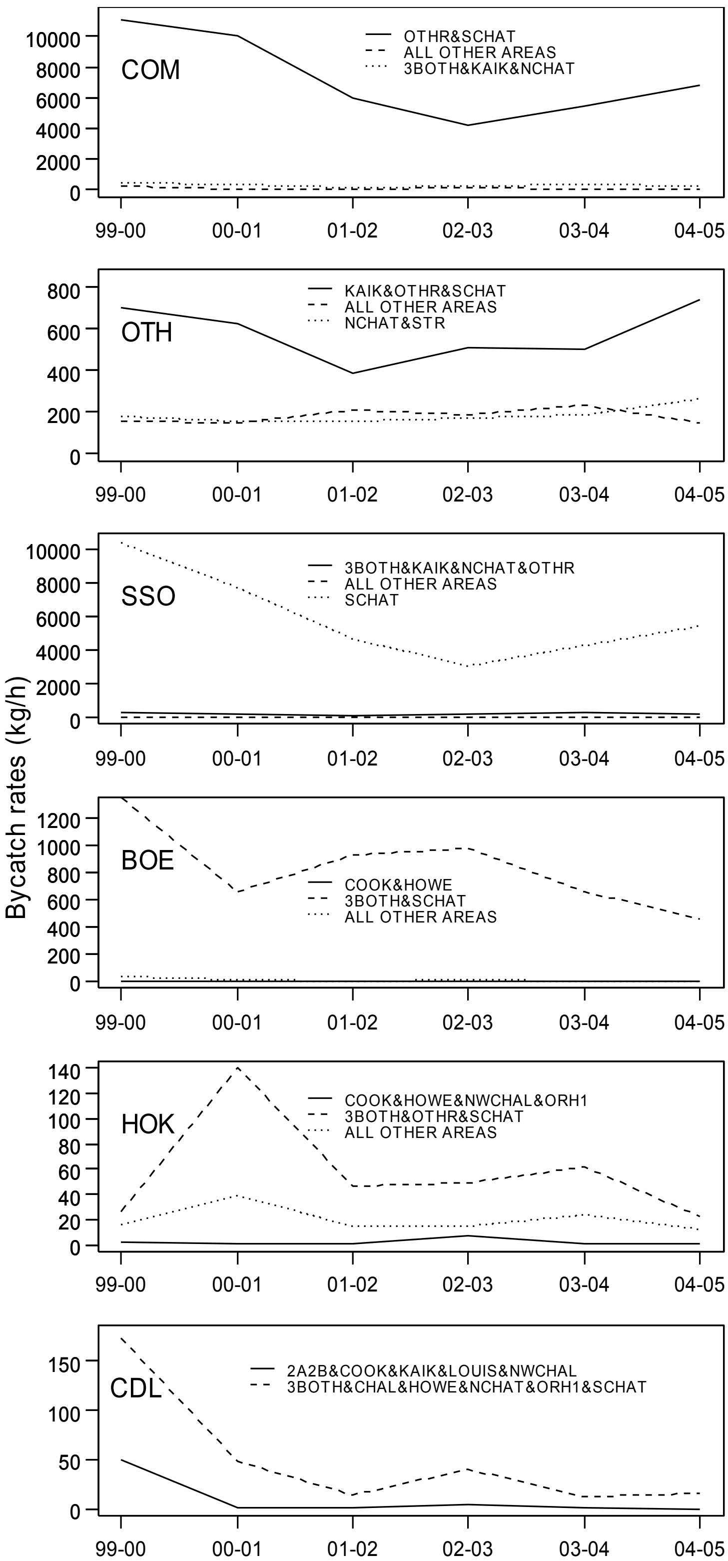

Figure 7: Annual bycatch rates by the areas used for stratification for six species categories, in the orange roughy trawl fishery. Bycatch rates shown are the median of the bootstrap sample of 1000.

3.5.2 Annual bycatch levels

Annual bycatch was determined by multiplying the ratios calculated for each stratum by the target fishery tow duration totals for the equivalent stratum, as described in Section 2.5, and precision of the estimates was determined from the variability in the bootstrap samples of 1000 ratios (Table 8, Figures 8 & 9).

Bycatch of COM species was high in 1999–2000 (10 300 t), low in 2001–02 (3000 t), and constant at about 5000–5900 t in the other four years. The estimates of individual commercial species bycatch during this period show that the annual bycatch of SSO, BOE, and CDL were all at their highest level in 1999–2000 (Table 9), but the estimates for this year were relatively imprecise, with wide confidence intervals (Figure 9). SSO was the main bycatch species in all years (2000–7000 $t.y^{-1}$), followed by BOE (600–1500 $t.y^{-1}$). Bycatch of HOK and CDL was variable between years, but similar overall and mostly less than 400 $t.y^{-1}$. When considered together, these four species make up 80–100% of the COM bycatch in each year.

Bycatch of OTH species was relatively constant from year to year during this period, ranging from 2300 t in 2000–01 to 3300 t the following year. OTH species bycatch was slightly greater than COM species bycatch in 2001–02, but in all other years was only about a third to a half of COM bycatch. The pattern in total annual bycatch is strongly influenced by the high level of COM bycatch in 1999–2000, with an estimated 13 500 t in that year compared with a more constant level of 6300–8400 $t.y^{-1}$ over the next five years. The 95% confidence intervals around the COM bycatch overlap between most years (Figure 8) and show a wide range for the 1999–2000 value, suggesting that this figure was influenced by a few large values and that there were may have been little real change during this time.

Bycatch of commercial and non-commercial species in the orange roughy fishery for 1990–91 to 1998–99 was estimated by Anderson et al. (2001). Their estimates can be compared with those from the current study as the COM category comprised the same nine species in each case; however, it should be noted that precision was estimated differently in the earlier study and the ratio estimator was based on target species catch rather than effort. These earlier values are shown in Figure 8 for comparison with the current estimates. Although total bycatch may have declined slightly from the levels of the 1990s, this was caused mainly by falling levels of COM species bycatch, and OTH species bycatch has increased considerably since that time.

Table 8: Estimates of bycatch (rounded to the nearest 10 t) in the target orange roughy trawl fishery by fishing year and species categories COM, OTH, and overall (TOT), with 95% confidence intervals in parentheses.

	Species category					
	COM		OTH		TOT	
1999–00	10 260	(5 220–16 340)	3 220	(2 500–4 260)	13 480	(7 720–20 600)
2000–01	5 900	(4 500–8 450)	2 300	(1 590–4 240)	8 200	(6 090–12 690)
2001–02	2 950	(2 070–4 470)	3 310	(1 890–5 050)	6 260	(3 960–9 520)
2002–03	5 000	(3 400–7 260)	2 920	(2 260–3 850)	7 920	(5 660–11 110)
2003–04	5 470	(3 170–7 960)	2 950	(1 850–5 300)	8 420	(5 020–13 260)
2004–05	5 100	(3 200–7 130)	2 640	(2 020–3 760)	7 740	(5 220–10 890)

Table 9: Estimates of bycatch (rounded to the nearest 10 t) in the target orange roughy trawl fishery by fishing year for the species categories (smooth oreo (SSO), black oreo (BOE), hoki (HOK), and black cardinalfish (CDL)) examined separately, with 95% confidence intervals in parentheses.

								Species category
		SSO		BOE		HOK		CDL
1999–00	6 960	(4 080–11 770)	1 470	(240–2 620)	210	(90–330)	2 100	(290–5 600)
2000–01	4 130	(3 070–5 840)	710	(410–1 020)	360	(230–530)	230	(30–670)
2001–02	2 010	(1 410–3 610)	680	(270–1 160)	120	(70–180)	80	(20–180)
2002–03	2 700	(1 800–4 070)	920	(520–1 610)	180	(110–260)	260	(60–620)
2003–04	4 220	(2 450–6 240)	630	(210–1 350)	200	(70–320)	80	(30–160)
2004–05	3 420	(1 860–4 870)	600	(70–1 090)	100	(70–140)	90	(40–160)

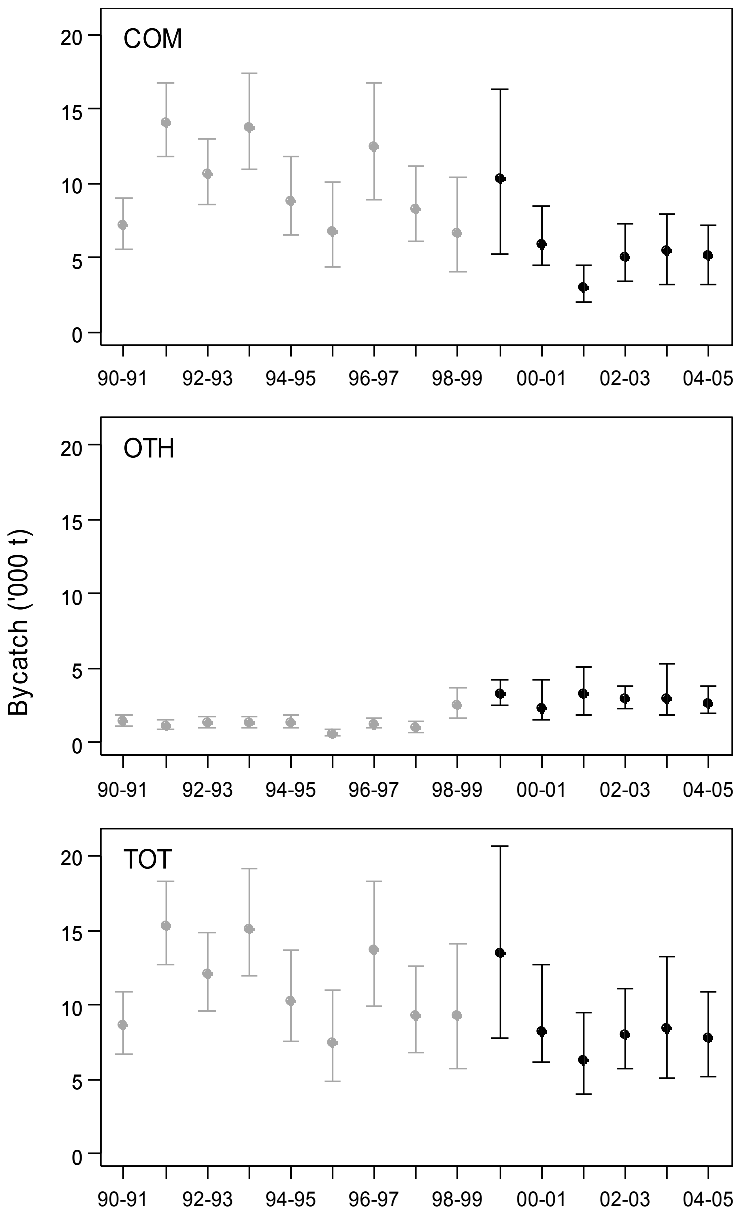

Figure 8: Annual estimates of fish bycatch in the target orange roughy trawl fishery, calculated for commercial species (COM), non-commercial species (OTH), and overall (TOT) for 1999–2000 to 2004–05 (in black). Also shown (in grey) are the bycatch estimates calculated for 1990–91 to 1998–99 by Anderson et al. (2001). Error bars show the 95% confidence intervals.

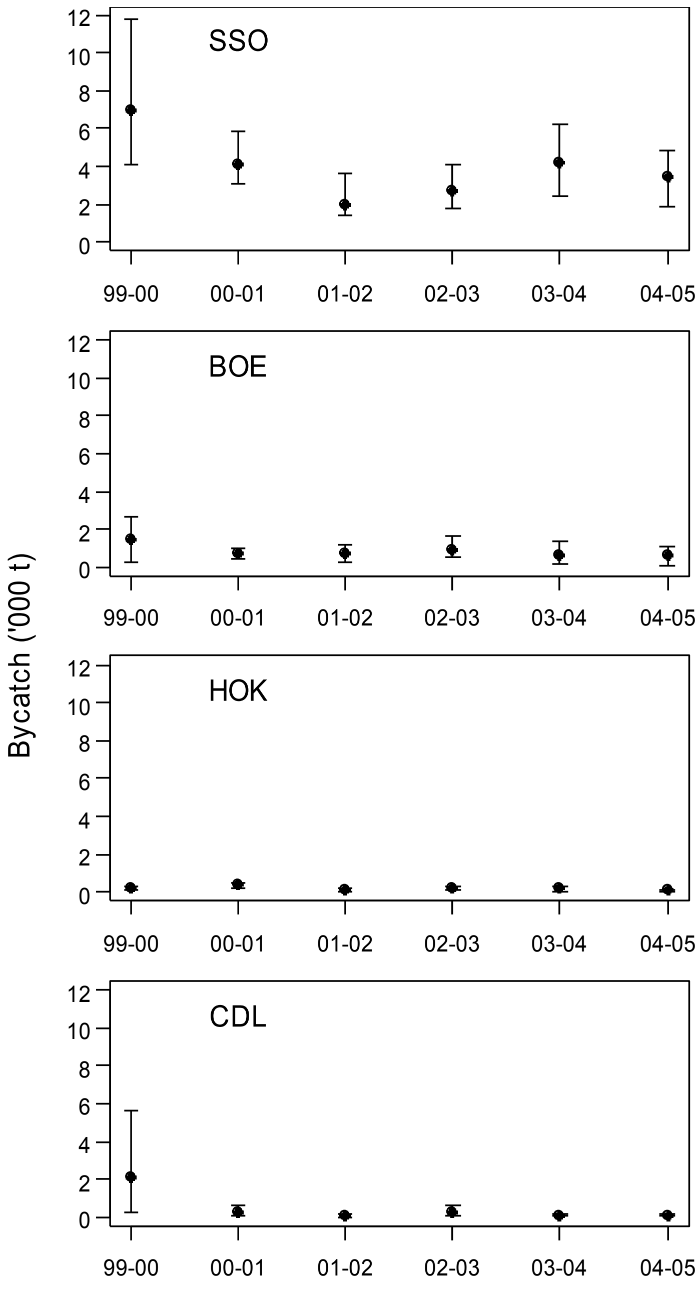

Figure 9: Annual estimates of the bycatch of smooth oreo (SSO), black oreo (BOE), hoki (HOK), and black cardinalfish (CDL) in the orange roughy target trawl fishery for the 1999–2000 to 2004–05 fishing years. Error bars show the 95% confidence intervals.

3.6 Calculation of discards

3.6.1 Discard rates

Because only 68 of the observed tows (1%) recorded a discard of orange roughy, no stratification was applied to the calculation of discard ratios for the ORH category, and a single ratio was calculated for all areas and all years. Discards of commercial species were also rare in some areas and years and ratios were calculated for year/area combinations only where data were sufficient. Hence ratios in the COM category were calculated for super-area 2 (see Table 6) separately for each year except for 2004–05. For each year in areas 1 and 3, and for area 2 in 2004–05, a single ratio calculated from all years was substituted. Discards of non-commercial species (OTH) were much more common and sufficient to calculate separate discard ratios for each year in each of the three super-areas. Discards were not calculated for the individual bycatch species (SSO, BOE, HOK, CDL) as too few discard events were recorded by observers to enable reliable ratios to be calculated.

The overall discard rate of ORH, averaged over all areas and fishing years, was just over 4 $kg.h^{-1}$ (Figure 10).

Discard rates of COM species was greatest in super-area 3 (the south Chatham Rise and southern ORH 3B), with an all-years level of about 17.5 $kg.h^{-1}$. This is not surprising as these areas, especially the south Chatham Rise, include major oreo fisheries. In contrast, discard rates of commercial species in super-area 1 (the north Chatham Rise and ORH 1) were close to zero (and no COM discards were recorded in any of the observed tows in the areas not shown in Figure 10, i.e., 2A2B, CHAL, COOK, and KAIK). Discard rates in super-area 2 decreased from about 12 $kg.h^{-1}$ in 1999–2000, to about 3–5 $kg.h^{-1}$ over the following 5 years.

As expected, rates of fish discarding were greatest in the non-commercial species category (OTH), at 100–200 $kg.h^{-1}$ in super-areas 1 and 3 in all years, and between 400 and 700 $kg.h^{-1}$ in super-area 3. A summary of the discard rates in each species category, with standard deviations, is given in Appendix 3.

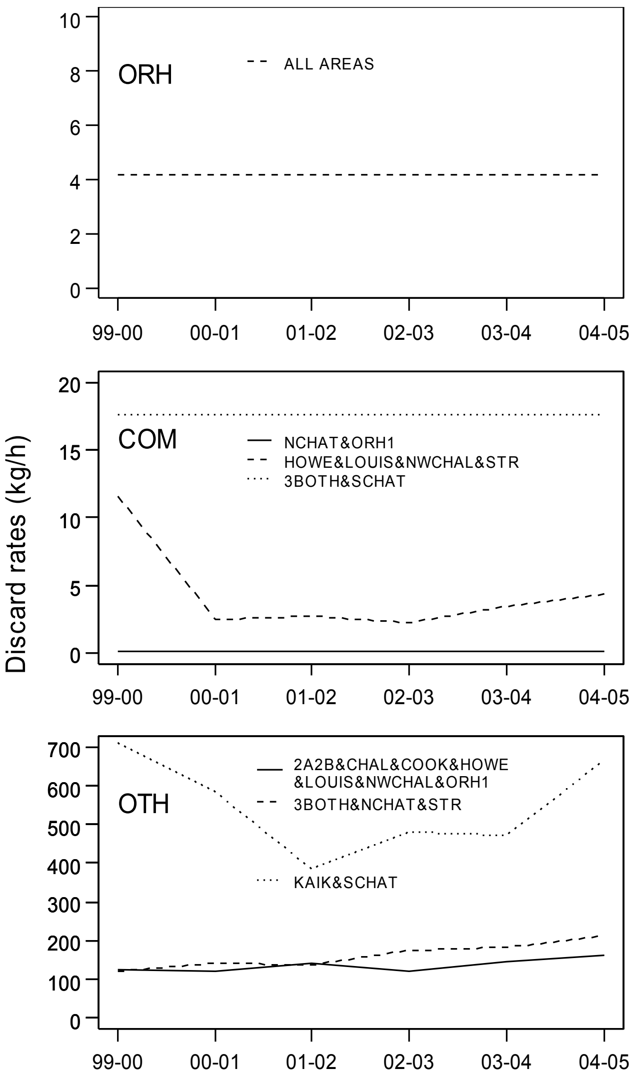

Figure 10: Annual discard rates of orange roughy (ORH), commercial species (COM), and non-commercial species (OTH) in the orange roughy trawl fishery, in the area strata used for calculation of total discards. Discard rates shown are the median of the bootstrap sample of 1000.

3.6.2 Annual discard levels

Annual discard levels were determined by multiplying the ratios calculated for each stratum by the target fishery tow duration totals for the equivalent stratum, as described in Section 2.5. The constant level of ORH discards (50–70 $t.y^{-1}$) comes from applying a single ratio to effort totals for each year (Table 10). Wide confidence intervals around these values reflect the low number of records with ORH discards and the occasional large discard event (over 22 t were discarded from one tow on the Louisville Ridge in June 2001). Annual discards of orange roughy between 1999–2000 and 2004–05 were at a similar level to the previous nine years, as estimated by Anderson et al. (2001) (Figure 11), but have much greater confidence limits due partly to the more sophisticated bootstrap methods used for calculating variance in the current study and partly to more real variability in ORH discards in the current data (wider confidence intervals using the more sophisticated bootstrap methods were also noted in a recent analysis of bycatch and discards in the hoki fishery (Anderson & Smith 2005)). Discards of COM species were also very low (30–50 $t.y^{-1}$) but confidence intervals were narrow, mainly because large discards of commercial species were rarely recorded by observers. Intentional discarding of quota species (which include all species in the COM category) is not permitted (under

Section 72 of the 1996 Fisheries Act) and so discards of these species should be limited to fish accidentally lost from the net during landing. It is debatable whether discards are greater when observers are present (and quota species can be legally discarded in certain circumstances) or when they are not present and illegal discarding can take place unseen. Discarding of non-commercial species (OTH) was at a higher level (2000–2800 $t.y^{-1}$, Table 10) than in both the other categories and the previous nine years (Figure 11). Discards of OTH were constant over the last six years, although confidence intervals were wide, but there appears to have been an increase in volume over the previous nine years when discards were mostly less than 2000 $t.y^{-1}$. For all species categories combined, discard levels seem be at a higher level now than they were during the 1990s, although the increase may not be statistically significant, as the confidence intervals are wide. The best estimates of current total annual discards are in the range 2100–2900 $t.y^{-1}$, compared with 1000–2700 for the 1990s period.

Table 10: Estimates of discards (rounded to the nearest 10 t) in the target orange roughy trawl fishery by year, for the species categories ORH, COM, OTH, and overall (TOT), with 95% confidence intervals in parentheses.

	Species category							
Fishing year	ORH		COM		OTH		TOT	
1999–00	60	(10–1 740)	30	(10–70)	2 800	(2 020–3 740)	2 890	(2 040–5 550)
2000–01	50	(10–1 740)	30	(10–80)	1 990	(1 220–3 720)	2 070	(1 240–5 540)
2001–02	70	(10–1 740)	40	(10–80)	2 440	(1 360–3 760)	2 550	(1 380–5 580)
2002–03	60	(10–1 740)	40	(10–90)	2 220	(1 370–3 360)	2 320	(1 390–5 190)
2003–04	50	(10–1 740)	30	(0–80)	2 670	(1 360–4 410)	2 750	(1 370–6 230)
2004–05	50	(10–1740)	50	(20–110)	2 740	(1 910–4 290)	2 840	(1 940–6 140)

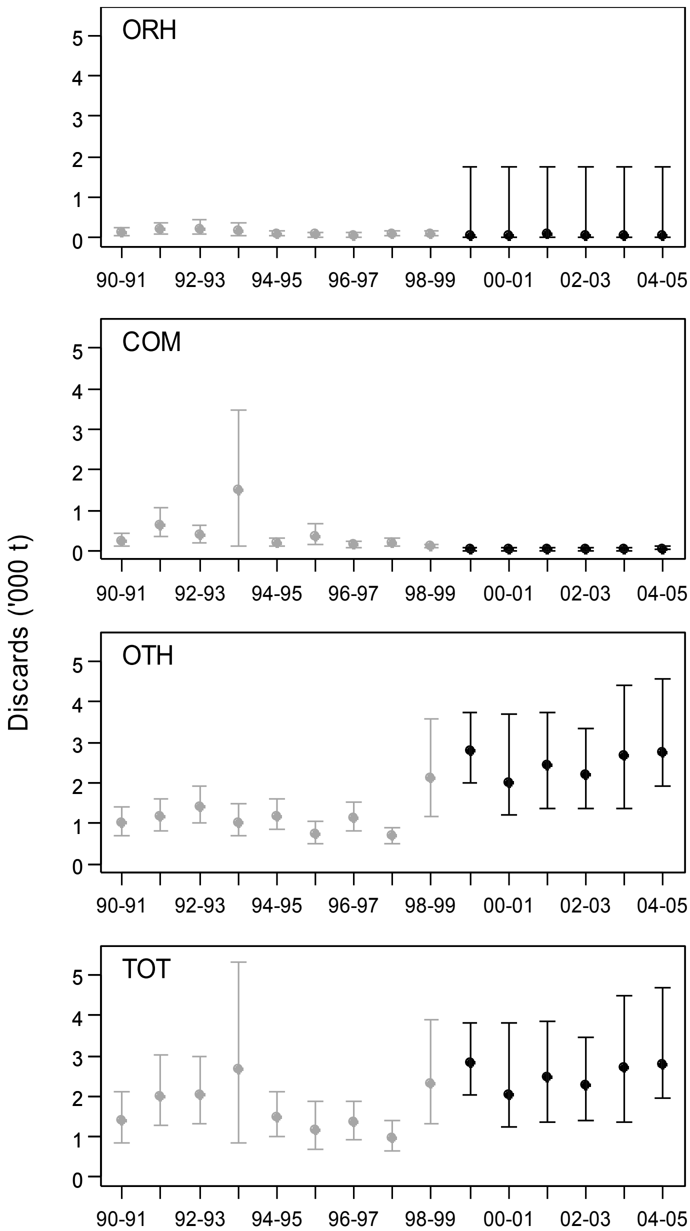

Figure 11: Annual estimates of fish discards in the target orange roughy trawl fishery, calculated for orange roughy (ORH), commercial species (COM), non-commercial species (OTH), and overall (TOT) for 1999–2000 to 2004–05 (in black). Also shown (in grey) are estimates of discards calculated for 1990–91 to 1998–99 by Anderson et al. (2001). Error bars show the 95% confidence intervals.

3.7 Fraction of the orange roughy fishery represented by the target trawl fishery

Estimated annual catches from the orange roughy target trawl fishery represented between 76% and 98% of the total annual landings of this species during the period examined (Table 11). Discarding associated with orange roughy caught (and subsequently landed) while trawling for other species (the catch which accounts for the remainder of the orange roughy trawl fishery, and is not considered here) therefore is likely to contribute only a small fraction of the total orange roughy trawl fishery discards.

Table 11: Estimated catch totals of orange roughy from the target trawl fishery, and all reported landings of orange roughy from the QMS, by year.

Fishing year	Target fishery estimated catch (t)	Total fishery reported catch (t)*	Target/total (%)
1999–00	16 561	20 963	0.76
2000–01	14 904	16 027	0.86
2001–02	17 553	17 085	0.98
2002–03	16 779	17 358	0.92
2003–04	14 819	15 952	0.89
2004–05	17 183	18 266	0.88

* From M. Clark (NIWA) unpublished data.

4. DISCUSSION

The precision of the estimates of bycatch and discard levels using these methods is strongly linked to the coverage of the fishery achieved by observers. Not only must a reasonable fraction of the target fishery be observed, but also observer placements must be well spread over the spatial extent of the fishery, the different types of vessels, and times of the year.

The level of observer coverage in this fishery represented between about 12% and 30% of the target fishery catch in the years examined, slightly better than achieved during the years examined in the previous analysis (Anderson et al. 2001). Graphical analysis showed that this coverage was spread amongst all the major fisheries currently operating in the New Zealand region, both within and outside the EEZ, in fair proportion to the level of fishing activity in each area. An exception to this was in the Challenger Plateau fishery (ORH 7A) where target orange roughy fishing was widespread in 1999–2000 (the year before this fishery was closed) without any observer coverage. Despite the wide size range of the approximately 50 vessels involved in this fishery the fleet was well covered by observers, who over six years collected data from 31 vessels, ranging in size from 76 t to 2500 t. Temporal coverage of fishing effort by observers was less ideal, with sharps peaks in relative coverage at certain times of the year, and virtually no coverage at other times but, averaged over all years, sampling was reasonably well spread over the fishing year. Despite the good coverage achieved, the precision of the final estimates of bycatch and discards was modest. Variability in bycatch and therefore discards among tows is inherently high, with observer data typically including large numbers of small values and zeros, with the occasional very large value, for most species categories. For example, the mixed nature of the fishery on the south Chatham Rise, where oreos are frequently caught, adds to the imprecision in estimates for this species as well as the commercial species categories because of the frequent capture of large amounts of these species when orange roughy is the stated target species.

The multi-level bootstrap methods used to calculate precision provided more realistic estimates than in the previous analysis as they took into account the effect of correlation between tows in the same trip and stratum. The difference between the methods can be gauged to a certain extent by comparing confidence intervals from the two methods in Figures 8 and 9. These show considerably wider ranges for the updated method in some cases, e.g., discards of orange roughy, but similar ranges in other species categories. However, a further difference between the two studies which may affect estimates of precision was in the form of the ratio estimator. In the former study, bycatch in each tow was measured relative to the estimated catch of orange roughy, whereas in this study it was measured relative to tow duration. This means that differences in orange roughy catch rates (catch per hour) between strata would produce differences in estimates of bycatch for each method.

Regression tree modelling was a further development in the methodology from the previous analysis. This technique enabled a refinement of the approach used to stratify the fishery and, by combining areas with similar pattern of bycatch and discards, reduced the number of strata and therefore simplified the bootstrap procedures. Although *trip* was identified as being the primary influence on bycatch and discards in most of the initial regression models, this factor could not easily be used to stratify the calculations, and when removed from consideration, it was generally replaced by *area* with little loss in explanatory power. The individual vessel was also influential in most of the models, but the use of this factor in stratification of the calculations is also difficult. The effect of the individual vessel on the variability in bycatch rates as well as target species catch rates has been well documented in this and many other New Zealand fisheries (see, e.g., Clark & Anderson 2001, O'Driscoll 2003, Horn 2004, Anderson & Smith 2005). This effect was acknowledged in the methods used here by ensuring that a minimum number of vessels were included in each stratum for which rates were calculated separately. Clearly some vessels are better at avoiding unwanted bycatch and minimising discards than others, demonstrating that there is potential for reducing discard levels. The variable *period* (as determined from regression tree partitioning) proved to be of limited value in explaining variability, and so ultimately *area* was used to stratify all calculations of bycatch and discards.

The orange roughy fishery has previously been shown to be among New Zealand's less wasteful fisheries, with about 0.06 kg of discards per kg of orange roughy caught in 1990–91 to 1998–99 (Anderson et al. 2001). This study shows that this may have changed, as total discards have increased, while total catch has declined. The equivalent value for the current period (1999–2000 to 2004–05) is 0.16 for the six years combined. Equivalent values for other New Zealand fisheries are: hoki and jack mackerel, 0.06 kg; oreos, 0.05 kg; southern blue whiting 0.02 kg; arrow squid, 0.14 kg; scampi 3.5 kg (Anderson et al. 2000, Anderson 2004a, 2004b, Anderson & Smith 2005). The increase in annual discards in the orange roughy fishery goes against the global trend of decreasing discards (Kelleher 2004), but this trend may have as much to do with an overall decline in the total availability of all fish species as it has to improvements in avoidance and utilisation of low value species (Zeller & Pauly 2005).

The increasing bycatch of non-commercial species identified in this study is of concern as, by definition, these species are usually discarded. The analyses showed that not only do longer trawls catch a larger quantity of non-commercial species, as might be expected, but they also catch them at a faster rate than shorter trawls. Examination of the catch effort data for orange roughy target tows shows that mean trawl duration has been increasing in recent years, after a sharp decline in the late 1980s resulting from the development of hill fishing (Figure 12). Changes in the level of bycatch of non-commercial species have followed a similar pattern to these changes in mean trawl length, since the first estimates of bycatch in this fishery were made.

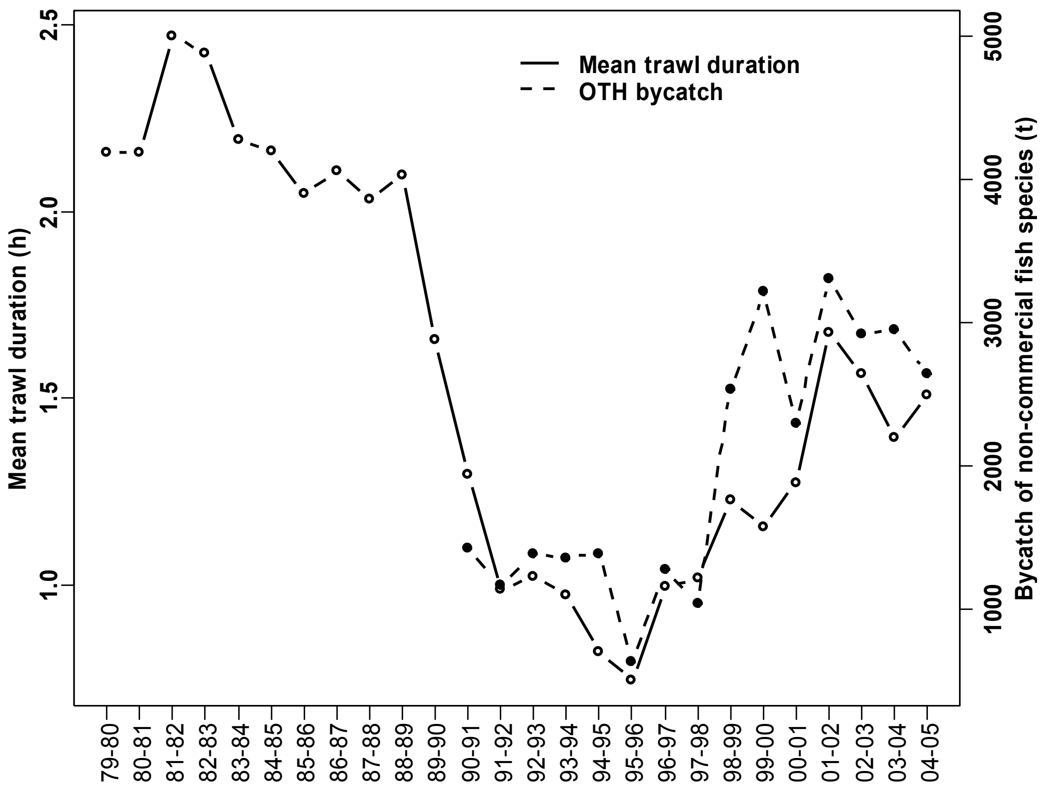

Figure 12: Changes in mean trawl duration over time in the orange roughy fishery, from commercial catch effort data, compared with changes in the estimated bycatch of non-commercial fish species.

5. ACKNOWLEDGMENTS

I acknowledge the continuing efforts of observers of the Ministry of Fisheries for their careful and thorough recording of catch and processing data, and Ralph Coburn (NIWA) for his review of a draft of this report. This work was funded by the Ministry of Fisheries (Project ENV2005/18).

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Appendix 1: Species codes, common and scientific names, estimated catch weight, percentage of the total catch, and overall percentage retained, of the top 50 species or species groups by weight from all observer records for the target fishery for orange roughy from 1 Oct 1999 to 30 Sep 2005. Records are ordered by decreasing percentage of catch; codes in bold are those species combined in the COM category

Species code	Common name	Scientific name	Estimated catch (t)	% of catch	% retained
ORH	Orange roughy	*Hoplostethus atlanticus*	17 246	75.05	99.85
SSO	Smooth oreo	*Pseudocyttus maculatus*	3 093	13.46	99.87
BOE	Black oreo	*Allocyttus niger*	732	3.18	98.20
SHA	Shark		275	1.19	13.58
HOK	Hoki	*Macruronus novaezelandiae*	235	1.02	99.48
COU	Coral (unspecified)		187	0.81	0.05
CDL	Cardinalfish	Black cardinalfish	171	0.75	99.61
SLK	Slickheads	Alepocephalidae	167	0.73	0.24
RAT	Rattails	Macrouridae	123	0.54	14.14
ETM		*Etmopterus* sp.	118	0.51	9.42
SND	Shovelnose spiny dogfish	*Deania calcea*	86	0.37	16.46
BYS	Alfonsino	*Beryx splendens*	68	0.29	99.81
MOD	Morid cods	Moridae	54	0.24	1.49
WSQ	Warty squid	*Moroteuthis* spp.	44	0.19	0.20
LCH	Long-nosed spookfish	*Harriotta raleighana*	38	0.17	59.52
JAV	Javelinfish	*Lepidorhynchus denticulatus*	38	0.17	5.50
SOR	Spiky oreo	*Neocyttus rhomboidalis*	38	0.16	94.31
HAK	Hake	*Merluccius australis*	37	0.16	98.14
RIB	Ribaldo	*Mora moro*	37	0.16	90.92
BEE	Basketwork eel	*Diastobranchus capensis*	36	0.16	1.30
WHR/WHX	Unicorn & white rattails	*Trachyrinchus* spp	29	0.12	33.71
HJO	Johnson's cod	*Halargyreus johnsonii*	20	0.09	0.37
ECH	Echinoderms	Echinodermata	14	0.06	0.14
GSP	Pale ghost shark	*Hydrolagus bemisi*	10	0.04	91.21
LIN	Ling	*Genypterus blacodes*	7	0.03	99.72
BNS	Bluenose	*Hyperoglyphe antarctica*	6	0.02	100.00
WOE	Warty oreo	*Allocyttus verrucosus*	5	0.02	50.68
EPR	Robust cardinalfish	*Epigonus robustus*	4	0.02	0.00
CYP	Longnose velvet dogfish	*Centroscymnus crepidater*	4	0.02	1.20
SPD	Spiny dogfish	*Squalus acanthias*	4	0.02	0.00
SQX	Squid (unspecified)		3	0.01	21.65
SKA	Skates	Rajidae, Arhynchobatidae	3	0.01	46.65
BSL	Black slickheads	*Xenodermichthys* spp.	3	0.01	0.00
SMC	Small-headed cod	*Lepidion microcephalus*	3	0.01	2.35
EPL	Bigeye cardinalfish	*Epigonus lenimen*	3	0.01	0.00
CRU	Crustaceans (unspecified)		2	0.01	11.36
SPE	Sea perch	*Helicolenus* spp.	2	0.01	67.46
GSH	Ghost shark	*Hydrolagus novaezealandiae*	2	0.01	94.70
GRC	Grenadier cod	*Tripterophycis gilchristi*	2	0.01	97.84
INV	Invertebrates (unspecified)		2	0.01	2.91
DWE	Deepwater eel		1	0.01	0.00
PLS	Plunket's shark	*Centroscymnus plunketi*	1	0.01	61.87
SRI	Knifetooth dogfish	*Scymnodon ringens*	1	0.01	0.00
CHI	Chimaeras	*Chimaera* spp.	1	0.01	35.52
LEG	Giant lepidion	*Lepidion schmidti* & *L. inosimae*	1	0.01	12.80
RCH	Widenosed spookfish	*Rhinochimaera pacifica*	1	0.01	47.26
BSK	Basking shark	*Cetorhinus maximus*	1	0.00	0.00
DSS	Deepsea smelt	*Bathylagus* spp.	1	0.00	0.00
RUD	Rudderfish	*Centrolophus niger*	1	0.00	18.09
BYX	Alfonsino & long-finned beryx	*Beryx splendens* & *B. decadactylus*	1	0.00	100.00

Appendix 2: Bycatch rates in the orange roughy fishery by fishing year and "super-area" for each of the six species categories examined. Standard deviations calculated from bootstrap samples are shown in parentheses. See Figure 1 for area boundaries

COM

	Mean bycatch rate kg.h^{-1}		
Fishing year	COM1	COM2	COM3
1999–00	10 707(3 688)	279(142)	524(403)
2000–01	10 149(1 542)	32(9)	365(177)
2001–02	6 147(1 498)	19(10)	186(78)
2002–03	4 455(1 131)	142(67)	287(99)
2003–04	5 310(1 769)	44(22)	342(102)
2004–05	6 901(1 607)	72(51)	283(76)

COM1 = OTHR+SCHAT
COM2 = 3BOTH+KAIK+NCHAT
COM3 = 2A2B+CHAL+COOK+HOWE+LOUIS+NWCHAL+ORH1+STR

OTH

	Mean bycatch rate kg.h^{-1}		
Fishing year	OTH1	OTH2	OTH3
1999–00	746(224)	153(19)	203(114)
2000–01	717(373)	179(89)	197(115)
2001–02	388(150)	208(71)	156(39)
2002–03	522(99)	191(42)	172(15)
2003–04	496(145)	274(157)	190(18)
2004–05	738(116)	156(55)	267(38)

OTH1 = KAIK+OTHR+SCHAT
OTH2 = NCHAT+STR
OTH3 = 2A2B+3BOTH+CHAL+COOK+HOWE+LOUIS+NWCHAL+ORH1

SSO

	Mean bycatch rate kg.h^{-1}		
Fishing year	SSO1	SSO2	SSO3
1999–00	418(382)	31(26)	10 472(2 753)
2000–01	218(123)	2(1)	7 732(1 171)
2001–02	141(72)	0.4(0.3)	4 920(1 313)
2002–03	213(79)	11(6)	3 211(886)
2003–04	283(98)	14(15)	4 238(1 339)
2004–05	194(47)	0.5(0.2)	5 489(1 426)

SSO1 = SCHAT
SSO2 = 3BOTH+KAIK+NCHAT+OTHR
SSO3 = 2A2B+CHAL+COOK+HOWE+LOUIS+NWCHAL+ORH1+STR

BOE

	Mean bycatch rate kg.h^{-1}		
Fishing year	BOE1	BOE2	BOE3
1999–00	0.2(0.1)	1 326(718)	35(25)
2000–01	0(0)	667(159)	7(6)
2001–02	0.2(0.2)	971(365)	0.9(0.8)
2002–03	0(0)	1 052(345)	8(5)
2003–04	0.8(0.3)	701(356)	1.2(0.7)
2004–05	0.2(0.1)	491(258)	1.7(0.9)

BOE1 = COOK+HOWE
BOE2 = 3BOTH+SCHAT
BOE3 = 2A2B+KAIK+LOUIS+NCHAT+NWCHAL+ORH1+OTHR+STR

Appendix 2 — *continued*

HOK

	Mean bycatch rate kg.h^{-1}		
Fishing year	HOK1	HOK2	HOK3
1999–00	2.5(0.5)	29(15)	16(6)
2000–01	1.2(0.3)	146(68)	39(7)
2001–02	0.9(0.4)	46(16)	15(5)
2002–03	7.8(3.7)	51(12)	14(4)
2003–04	0.5(0.1)	62(15)	23(10)
2004–05	0.9(0.3)	24(14)	13(2)

HOK1 = COOK+HOWE+NWCHAL+ORH1
HOK2 = 3BOTH+OTHR+SCHAT
HOK3 = 2A2B+CHAL+KAIK+LOUIS+NCHAT

CDL

	Mean bycatch rate kg.h^{-1}	
Fishing year	CDL1	CDL2
1999–00	87(103)	203(166)
2000–01	0.7(0.7)	55(42)
2001–02	0.6(0.4)	15(9)
2002–03	4.4(4.7)	46(29)
2003–04	0.2(0.2)	13(5)
2004–05	0(0)	17(6)

CDL1 = 2A2B+COOK+KAIK+LOUIS+NWCHAL
CDL2 = 3BOTH+CHAL+HOWE+NCHAT+ORH1+SCHAT

Appendix 3: Discard rates in the orange roughy fishery by fishing year and "super-area" for the commercial and non-commercial species categories. Standard deviations calculated from bootstrap samples are shown in parentheses. See Figure 1 for area boundaries

COM

	Mean discard rate $kg.h^{-1}$		
Fishing year	one	two	three
1999–00	0.2(0.1)	11.7(5.5)	22(20)
2000–01	0.2(0.1)	2.5(0.7)	22(20)
2001–02	0.2(0.1)	2.8(1.5)	22(20)
2002–03	0.2(0.1)	2.6(1.9)	22(20)
2003–04	0.2(0.1)	3.6(2.8)	22(20)
2004–05	0.2(0.1)	4.6(1.9)	22(20)

one = NCHAT+ORH1
two = HOWE+LOUIS+NWCHAL+STR
three = 3BOTH+SCHAT

OTH

	Mean discard rate $kg.h^{-1}$		
Fishing year	one	two	three
1999–00	124(25)	135(56)	763(231)
2000–01	141(77)	157(80)	673(341)
2001–02	145(53)	146(44)	399(161)
2002–03	126(52)	176(16)	494(110)
2003–04	175(145)	184(16)	490(166)
2004–05	188(89)	216(29)	659(105)

one = 2A2B+CHAL+COOK+HOWE+LOUIS+NWCHAL+ORH1
two = 3BOTH+NCHAT+STR
three = KAIK+SCHAT