Basking shark (*Cetorhinus maximus*) bycatch in New Zealand fisheries, 1994–95 to 2007–08

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EXECUTIVE SUMMARY

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Basking sharks (*Cetorhinus maximus*) are a frequent bycatch of New Zealand trawl and set net fisheries but the magnitude of the fishing mortality is unknown. The New Zealand Ministry of Fisheries has recently developed a National Plan of Action for Sharks, and is planning to introduce protection for the species. Information on the status of basking sharks is required to inform that process. The aim of this study was to analyse the nature and extent of fishing-induced mortality of basking sharks in New Zealand waters, and to recommend methods of reducing the catch.

Basking shark catches and landings reported by fishers and fish processors since 1990 were analysed. Landings before 2000 were probably underreported. There were occasional small peaks during the 1990s, large landings in the early 2000s, and low landings for the most recent three years (2005–06 to 2007–08). Observer records also indicated a peak in catches in 1988–89, before the commercial data series began. Most basking shark bycatch occurred in spring–summer in Fisheries Management Areas 3, 5, 6, and 7 (i.e., around the South Island and on the Campbell Plateau). Three trawl fisheries (East Coast EC, West Coast WC, and Southland–Auckland Is SA) accounted for nearly all of the observed catches. Catches were dominated by males. Most sharks were 7–9 m long in WC and SA, but 4–6 m long in EC. It is not known where females, particularly large mature females, live. Most basking sharks were alive when landed, but they were usually in poor condition. Many sharks were finned before discarding, and those that were returned whole were unlikely to have survived.

Bayesian predictive hierarchical models were used to estimate catches and catch rates in the three trawl fisheries between 1994–95 and 2007–08. A total of 95 sharks were observed in 49 165 tows in the 14-year period, an overall unstandardised capture rate of 1.9 per 1000 tows. The overall predicted capture rate was 2.5 sharks per 1000 tows, with area-specific rates of 3.9 (EC), 2.0 (WC), and 1.9 (SA) per 1000 tows. The total predicted number of captures was 922 with a c.v. of 19%. Predicted captures peaked in 1997–98 and then declined steadily to low numbers. Much of the recent decline in basking shark bycatch is probably attributable to a decline in fishing effort in the three areas combined by about 50% between 2002–03 and 2006–08. The predicted strike rates showed no overall trend since 1994–95 in any of the three areas. However, unstandardised catch rates from observer data were much higher in 1988–91 than at any time since then. Our estimates of basking shark bycatch underestimate total New Zealand catches because they don't include trawl fisheries outside the three fishery areas, or other fishing methods. Bycatch in set net fisheries, and in trawl fisheries in shallow coastal waters where observer coverage has been negligible until recently, may be considerable.

Basking sharks have very low productivity, and fisheries for them elsewhere in the world are characterised by boom-and-bust cycles. Large inter-annual variations in surface sightings and fishery captures are a feature of basking shark populations, both in New Zealand and elsewhere. In the face of such variability, it is difficult to draw conclusions about the status of the New Zealand basking shark stocks from currently available data. The number of basking sharks caught in New Zealand fisheries (perhaps 1000 in 14 years) is low relative to numbers caught by directed fisheries elsewhere in the world (1000–3000 per year in northeast Atlantic from 1945 to 1985). However, the apparent absence of large numbers and aggregations of basking sharks during the last decade is cause for some concern. There may not have been large aggregations of basking sharks in New Zealand waters since 1991. Whether such a long period without large aggregations is part of a long-term, natural cycle, or evidence of a decline in population abundance, cannot yet be determined.

Any reduction in fishing effort in the three main fisheries, particularly during peak capture periods, would reduce basking shark bycatch. The Puysegur squid fishery and the north subarea of the WC hoki fishery produce the highest bycatch so effort reductions could be targeted at those subareas. A reduction in midwater trawling effort in WC may also reduce bycatch.

1. INTRODUCTION

Basking sharks (*Cetorhinus maximus*) are the second largest fish in the world, reaching total lengths of up to 10 m. They are most often seen cruising in surface waters straining plankton from the water passing through their massive gills. However, recent work in New Zealand and the northeast Atlantic has shown that basking sharks range down to at least 750–900 m depth (Francis & Duffy 2002, Sims et al. 2003), indicating a much wider niche than previously thought. In fact the disappearance of basking sharks from view in surface coastal waters, sometimes for periods of many years, suggests that deepwater and possibly offshore locations may be important habitats for the species.

Basking sharks occur worldwide in temperate regions (Compagno 2001, Last & Stevens 2009). A recent study of basking shark mitochondrial DNA, which included tissue samples from New Zealand, found very low levels of genetic diversity among ocean basins (Hoelzel et al. 2006). However, ongoing work with other genetic markers has found evidence of separate stocks (L. Noble, University of Aberdeen, Scotland, pers. comm.). Basking sharks are rarely encountered in Australian waters (Last & Stevens 2009), and only occasional reports are available from the Tasman Sea (Sharples et al. 1991) and the South Pacific Ocean east of New Zealand (Yatsu 1995). New Zealand basking sharks therefore appear to be geographically isolated from other large population centres, and may be a distinct stock for fisheries management purposes.

Basking sharks occur throughout New Zealand (Francis & Duffy 2002). They have not been recorded from the southern Campbell Plateau, but probably occur there as they are common around the Auckland Islands. They have also been recorded (rarely) from brackish Lake Ellesmere (Ryan 1974, Dodgshun 1980, Francis & Duffy 2002). Basking sharks are most abundant from the central North Island to the Auckland Islands (39–51^{o} S). Areas of highest abundance, as indicated by incidental capture in trawl fisheries and surface sightings, are off Banks Peninsula–Canterbury Bight, west coast South Island, the Snares shelf, and Auckland Islands Shelf (Francis & Duffy 2002).

Basking sharks have very low productivity and fisheries for basking sharks have followed extreme boom-and-bust cycles. Basking sharks are classified as Vulnerable by IUCN, they are listed on appendix II of the Bern Convention, appendix I of the Convention on Migratory Species, and appendix II of CITES, and they are fully protected in the United Kingdom and eastern USA. All these measures were developed in recognition of the species' vulnerability to overfishing, and aim to ensure the sustainability of basking shark populations.

In New Zealand, basking sharks are a frequent bycatch of trawl and set net fisheries (Francis & Duffy 2002). More than 200 sharks were observed caught by commercial trawlers between 1986 and 1999. Most came from hoki, squid and barracouta target fisheries off Banks Peninsula, west coast South Island and Snares-Auckland Islands Shelf (Francis & Duffy 2002). Because observer coverage in these fisheries is only low to moderate, the extent of the overall fishing mortality is unknown. Furthermore observer coverage of set net vessels is negligible outside areas where Hector's dolphin bycatch is an issue, so the contribution of the set net fishery to basking shark mortality is unknown.

New Zealand has recently developed a National Plan of Action for Sharks (Ministry of Fisheries 2008), and is planning to introduce protection for the species. Information on the status of basking sharks is required to inform that process. In particular, measures are required to reduce the bycatch of basking sharks in trawl and set net fisheries. The aim of this study is to analyse the nature and extent of fishing-induced mortality of basking shark in New Zealand waters, and to recommend methods of reducing the overall catch.

1.1 Objectives

The overall objective of this project was: " To estimate the bycatch of basking sharks taken in New Zealand fisheries". This report addresses Specific Objective 2 of the project: " To describe the nature and extent of fishery-induced mortality of basking sharks in New Zealand waters and recommend methods of reducing the overall catch".

2. METHODS

Basking shark catches in New Zealand fisheries were estimated in two ways:

Catch statistics: Catches and landings of basking shark reported by fishers to the Ministry of Fisheries (MFish) were extracted and summarised. These data cover all fishing methods.

Predictive modelling from observer records: Estimates of basking shark captures in trawl tows were made by modelling the captures and capture rates reported by MFish observers, and then using the models to predict catches by the unobserved trawl fleet. These data cover only specific trawl fisheries, but those fisheries accounted for nearly all of the observed basking sharks in the observer database (see below).

2.1 Catch statistics

Catch and landing data for basking shark (species code BSK) were extracted from Monthly Harvest Return (MHR), Licensed Fish Receiver Return (LFRR), and catch-effort data provided by commercial fishers and fish processors to MFish. These data were groomed and plotted to illustrate annual, seasonal, and spatial patterns in reported catch and landings.

2.2 Predictive modelling from observer records

2.2.1 Data sources

Trawl effort data were extracted from fishing returns to MFish, and trawl catch and effort data were extracted from records of the MFish Observer Programme (OP). Data sources included Trawl Catch Effort Processing Returns (TCEPR), Catch Effort Landing Returns (CELR), Trawl Catch Effort Returns (TCER), and OP databases *COD, obs,* and *obs_lf*. Most of the data used in this study came from the 1994–95 to 2005–06 catch effort and observer data that were gathered and groomed for the prediction of fur seal captures in MFish Project PRO200605 described by Smith & Baird (2009). Additional observer trawl data and catch effort data covering the fishing years 2006–07 and 2007–08 were obtained from the same sources. Only records for fishing south of 38° S (as determined by the start latitude of tows or by the recorded statistical area) were extracted. Basking shark captures obtained from observer diaries were added to the observer data.

Sixty-one observer records of basking sharks caught by trawlers between 2000 and 2008 were extracted from OP databases, and checked against observer logbooks, notebooks, and photographs to confirm species identification, and to record the number of sharks per tow, and their size, sex, life status, and fate. At least eight records appeared to be misidentifications because they had whole weights less than 150 kg (basking sharks are probably born at about 30–50 kg but animals less than 500 kg are very rarely seen [see below]). Previous work with observer data (Francis & Duffy 2002) revealed that seal shark (also known as black shark; species code BSH) and black slickhead (BSL) were often erroneously coded as basking shark (BSK), and that these errors could usually be detected by the low catch weights. Harder to detect were species identification errors involving other large sharks. Collection of tissue samples by observers for a worldwide study of basking shark population genetics revealed the presence of sleeper sharks (*Somniosus* spp) and great white sharks (*Carcharodon carcharias*) among individuals identified as basking sharks. After grooming and removal of likely misidentifications, the 2001–08 records were added to the data file of observers records for 1986–99 previously extracted and groomed by Francis & Duffy (2002).

Grooming of the new observer effort data was carried out following the methods described by Smith & Baird (2009). It was clear (because of the small number of capture incidents) that the prediction of basking shark captures was going to be restricted to a few limited fisheries defined by area and target species. Consequently, initial grooming of the commercial trawl data was confined to checking and making necessary corrections for target species and positions of tows.

For predicting total basking shark captures, three fishery areas were defined (see below). The definitions of these fishery areas were based on the earlier study by Francis & Duffy (2002), and on where basking shark captures were observed and in what target fisheries. After the fishery areas were determined, commercial data sets were prepared for each area. Additional checking of times and dates and other variables was carried out for the last two fishing years of these data sets (because the earlier years had already been groomed for an earlier project).

The unobserved tows among the commercial tows in each fishery area were identified for use in the prediction phase of the capture estimation procedure. The method for matching observed tows to commercial tows used vessel codes and dates, and, if required, times and positions. Within each fishery area some tows were in the observed data but not in the commercial data and a few tows were in the commercial data but not in the observer data. The discrepancies were greater in number in the earlier fishing years when the data records were less reliable. Some of the differences may have been due to the observer recording a different target species to that recorded by the fisher. Occasionally, whole observed trips could not be matched. In all but one case this was due to a different vessel code being used in the commercial data. The one exception, trip 1079 with 86 tows targeting squid, could not be matched. With the exception of this trip, the difference between the sum of the observed and unobserved tows and the number of commercial tows, for each fishery area and each year, was less than 0.2% of the number of commercial tows.

2.2.2 Observed basking shark captures and fishery areas

The total number of observed tows in the 14 fishing years 1994–95 to 2007–08 was 102 452, of which 5028 had start positions outside the New Zealand Exclusive Economic Zone (EEZ). Details of the 97 424 observed tows within the EEZ by fishing year are given in Table 1 and their start positions are plotted in Figure 1. A total of 99 basking sharks were observed captured (in 80 tows) during the same period (Table 2), an overall capture rate of 1.0 per 1000 tows. The target species for these tows are listed in Table 3. As reported by Francis & Duffy (2002), basking sharks were also captured on observed tows that targeted jack mackerel (*Trachurus* spp.), red cod (*Pseudophycis bachus*), and spiny dogfish (*Squalus acanthias*) in fishing years before 1994–95.

When fitting a model for use in predicting total captures, the accuracy of the predictions depends, not on the total number of tows, but on the number of captures. Fitting models using Markov chain Monte Carlo (MCMC) methods becomes difficult when there are large proportions of zeros, as is the case here. Selecting areas having larger capture rates helps offset these difficulties. Three disjoint areas adjacent to the South Island accounted for most of the basking shark captures (Figure 1). These three areas are very similar to the three areas identified by Francis & Duffy (2002) in their study which used observer data for the calendar years 1986 to 1999. Changes have been made to the boundaries used by Francis & Duffy to accommodate captures in the more recent observer data and to enable all of the commercial tows to be included or excluded from any area. The commercial effort (by smaller vessels) that is recorded on CELR forms very rarely includes positional data but does include fisheries statistical area. Therefore, where necessary, parts of boundaries of the areas have been adjusted to coincide with the boundaries of statistical areas. There have been 10 observed basking shark captures in the Puysegur area so it was included in our southern area.

Four observed tows, each with a single basking shark capture, are not included in the three areas. These are: one tow targeting cardinalfish off Coromandel Peninsula, two tows targeting gemfish off the Wairarapa coast, and one tow targeting hoki near the Campbell Islands (Figure 1). In the three areas, all tows that captured basking sharks targeted one of seven species: barracouta, squid, silver warehou, hake, hoki, ling, or white warehou (Table 4). To avoid extrapolation by predicting captures for unobserved tows targeting species for which no basking shark captures have been observed, we restricted tows to those that targeted one of the seven species.

The three fishery areas all have the South Island for part of their boundary and are otherwise defined below.

East coast fishery area (EC): Statistical Areas 020, 021, 022, and 023 (see Figure 7). Target species codes are BAR, SWA, SQU, HAK, HOK, LIN, and WWA.

West coast fishery area (WC): The area bounded by 43° 07´ S, 40° S, 168° E, and 172° 41´ E (see Figure 12). Target species codes are HAK, HOK, LIN, and WWA.

Southland-Auckland Islands fishery area (SA): The area within Fisheries Management Areas (FMAs) 3, 5, and 6 south of 45° 30´ S to the west of the South Island; south of 46° 03´ S to the east of the South Island, west of the rhumb line joining 46° 03´ S and 173° E with 51° 30´ S and 169° E, north of 51° 30´ S, and east of 165° E excluding the Macquarie Ridge (see Figure 17). Target species codes are BAR, SWA, SQU, HAK, HOK, LIN, and WWA.

Observed tows in the three fishery areas in the 14 fishing years total 49 165, which is more than 50% of all observed tows (see Table 1). Of the 99 basking sharks observed, 94 were caught in the three fishery areas, giving an overall strike rate of 1.9 per 1000 tows. It is not possible to calculate the proportion of all commercial tows inside the EEZ that was covered by the three fishery areas. However, using data from Smith & Baird (2009), there were 1 234 458 tows for the 12 fishing years 1994–95 to 2005–06 inside the EEZ and south of 40° S. In the same period there were 355 799 tows in the three fishery areas (see Table 17), which represents about 29% of all commercial tows south of 40° S. The difference in proportions reflects the concentration of OP effort in southern waters of the EEZ.

2.2.3 Model-based predictive method for estimating basking shark bycatch

The predictive method for estimating basking shark bycatch was applied separately to the three areas (described in Section 2.2) where basking shark captures were sufficient for models to be fitted successfully. A fully Bayesian predictive approach using hierarchical models was used to obtain estimates of total captures and strike rates. The method is well established and has been used recently to predict sea lion captures in the SQU 6T fishery (Smith & Baird 2007), fur seal captures in trawl fisheries (Smith & Baird 2009), and seabird captures (Baird & Smith 2007). Each model uses fishing year random effects and selected fixed covariates, and is fitted to the observer data for all years in the study. The fitted model is in the form of a sequence of realisations (usually 5000) of an MCMC sample from the joint posterior distribution of the model parameters. The chain encapsulates the uncertainty in the parameter estimates and is used to provide realisations from the predictive distributions of total basking shark captures and strike rates for each area and fishing year.

Each of the 5000 realisations from the predictive distribution of the total basking shark captures is obtained in five steps. First, the unobserved tows are identified. Second, the capture rate parameter for each unobserved tow is calculated using the current realisation from the posterior distribution of the parameters. Third, a realisation of the actual number of basking shark captures for each tow is drawn from the negative binomial distribution with the capture rate parameter for the tow and the current realisation of the extra-dispersion shape parameter θ. Fourth, the realisations for all the unobserved tows are added to get a realisation from the predictive distribution of the total unobserved captures. Finally, the total observed captures are added to get a realisation from the predictive distribution of the total captures. The mean, coefficient of variation (c.v.), and predictive intervals of the total captures in the 5000 realisations are then calculated. The predictive distribution incorporates uncertainty in the model parameter estimates and variability in the actual number of basking sharks captured on every unobserved tow (through the negative binomial error model).

The realisations from the predictive distribution of the basking shark strike rates are obtained in a slightly different way. The same first two steps are used to generate tow by tow realisations of the capture rate parameter for each unobserved tow. These are then added to get a realisation of the predicted total unobserved basking shark captures, which in turn is added to the total observed captures. The sum is then divided by the total number of commercial tows to get a realisation from the predictive distribution of the strike rate. Note that these realisations only include the uncertainty in the parameter estimates and do not include the added variation from the negative binomial error of the actual unobserved captures. The means, medians, standard deviations, c.v.s, and 95% predictive intervals of the strike rates are then calculated.

The predictive distributions for total captures and for strike rates each incorporate the finite population correction directly because all the uncertainty comes from the unobserved tows.

2.2.4 Model description

The model-based hierarchical approach used for the prediction of total basking shark captures combines random year effects with covariates that model variation in capture rates among tows. The model is fitted to the observer data and then used to predict basking shark captures for the unobserved commercial tows based on their specific covariate values and fishing year.

The model used for fitting the observer data and for the prediction of total basking shark captures is described in terms of the individual mean capture rates for basking sharks, one for each tow. These are denoted μ_{ij}, where *i* is the year and *j* is the j^{th} tow in that year.

Each mean capture rate parameter is built from the other model parameters and covariates in a multiplicative way (log-linear). The model is hierarchical (includes random effects) and has the following components.

1. A set of year strike rate parameters, λ_i at the base levels for the covariates. These are random effects which are assumed to have independent log-normal distributions with common mean and standard deviation hyper-parameters (in the log space).
2. A log-linear component involving covariates and parameter coefficients. This component acts as a scaling of the base year strike rate parameter by an exponential function of the standard form linear model. The sets of covariates used in the models vary among areas.
3. The error distribution assumption is that the numbers of basking captures (y_{ij}) are independent negative binomial random variables with means equal to the mean capture rate parameters (μ_{ij}) and a common shape parameter θ. We report the value of θ indirectly, through its reciprocal, which is the *extra-dispersion variance* of the negative binomial error model.

The mean capture rate parameter for the ij^{th} tow is then given by

$$\mu_{ij} = \lambda_i \exp\left(\mathbf{x}_{ij}\boldsymbol{\beta}\right)$$

where $\mathbf{x}_{ij}$ is the row matrix of the covariate values for tow *ij* and $\boldsymbol{\beta}$ is a column matrix of coefficient parameters.

The distributional assumptions for the year random effects are that the base year strike rate parameters (λ_i) are an independent sample from a single log-normal distribution, with log-mean and log-variance parameters.

Unlike the models used for prediction of seabird, sea lion, and fur seal captures (Baird & Smith 2007, Smith & Baird 2007, 2009), the model used for basking shark captures does not include vessel-year random effects. Preliminary fitting of models indicated that there were too few capture data to allow these effects to be included in the model. Inclusion of these random effects did not improve the model and led to convergence difficulties with the MCMC fitting process.

Models specific to each area were fitted using the observer data for the area. Random year effects appear in the model for each area. The set of covariates that appears in a model is specific to the area. The covariates used in at least one of the area models were chosen because of their availability in the commercial data together with the association between a variable and basking shark capture rate identified by Francis & Duffy (2002). It was also necessary to keep the models as simple as possible because of the paucity of captures in the observer data. The covariates included in the models for at least one area are described below.

day.no: day of fishing year. A variable with sine and cosine transformations to give a two-component periodic covariate. This is the first harmonic of the Fourier series approximation to a periodic function with period 1 year.

gear: type of gear used in trawl. Factor with levels:

BT – bottom trawl gear

MW – midwater trawl gear.

For each fishery, the most commonly used gear type in the observer data was used as the base level in the fitted model.

subarea: a fishery area was divided into sub-areas producing a factor covariate. The sub-areas were specific to the individual fishery areas and were used only in WC and SA.

targ.g: target species group, a factor variable. This covariate was used in the EC and SA fishery areas. The two target groups (factor levels) are:

shallow – BAR, SQU, and SWA.

mid depth – HAK, HOK, LIN, and WWA.

The use of a periodic transformation of the *day.no* variable ensures that the values of the transformed covariate coincide at the beginning and the end of the fishing year. It is important to ensure that any *day.no* effects are less likely to get incorporated into the base year effects because of different distributions of effort in different fishing years.

For each area, the grouping of target species for the *targ.g* factor is dictated primarily by the target species composition of the observer data, but the target groups for a fishery area do include species for which no captures were observed on tows with that target (Table 4). The aim was to group together the targets that are fished commercially using similar fishing practices and vessels.

Depth was identified as being associated with capture rates by Francis & Duffy (2002), but we did not use it as a covariate in any area because a moderate number of observed and unobserved tows lacked depth information, and because depth is related to *targ.g* and to a lesser extent *subarea*.

For fitting the models using Bayesian methods, prior distributions are required for the model parameters and for the hyper-parameters associated with the distribution of the base year strike rate parameters. The priors used are those used in earlier work and were described in detail by Smith & Baird (2007). The prior distributions on the components of the covariate parameter $\boldsymbol{\beta}$ are normal distributions with mean 0 and standard deviation 100. For the extra-dispersion parameter θ, the prior distribution is the uniform shrinkage prior with median equal to the overall mean number of observed captures per tow. The prior distribution for the mean hyper-parameter for the distribution of the base year strike rates is normal with mean -6 and standard deviation of 100, while the prior distribution for the standard deviation hyper-parameter is the folded Student's-t distribution with 1 degree of freedom and dispersion of 25. All prior distributions are mutually independent.

Models for each of the three areas were fitted to the observer data using WinBUGS (Spiegelhalter et al. 2003), run from within the statistics package R (R Development Core Team 2008). MCMC samples from the joint posterior distribution of the parameters for the fitted model in each area were obtained by running the chains for 50 000 iterations keeping every 10^{th} iteration following a burn in of 50 000 iterations. This resulted in samples of 5000 iterations for use in the predictions of total basking shark captures and strike rates. Convergence of the chains was checked using Geweke (1992) and Heidelberger & Welch (1983) criteria.

3. RESULTS

3.1 Catch statistics

The weight-frequency distribution of catch-effort data records was bimodal, with a large peak of very low catch weights below 500 kg, and many records greater than 2.5 tonnes (Figure 2). Observer records showed only a few fish under 500 kg, and this declined even further when confirmed species identification errors were removed. It is likely that weights up to 500 kg are the result of species identification or coding errors in all data sets, and so they were omitted.

Comparison of processed and whole weights reported on catch-effort returns revealed further possible errors (Figure 3). A line of data points along the 1:1 line represents basking sharks that were discarded whole, and a line of points with a gradient of 1:30 represents sharks that were finned (the conversion factor for shark fins is 30). Closer inspection of the data showed a line of points having processed weights much greater than whole weights (Figure 3, panel B), which is impossible.

Annual trends in catches and landings from various sources showed considerable variability both among sources and among years (Figure 4). The big differences in some years between 'landed' weights and LFRR and MHR weights result from discarding of whole sharks at sea that are subsequently entered on the catch landing return (CLR) with a 'discard' destination code. Some unusual anomalies existed. For example, the LFRR total exceeded all other sources in 1994–95, and the MHR total exceeded all other sources in 2002–03.

Despite these issues, the general patterns in all commercial data sources were similar, indicating low landings with occasional small peaks during the 1990s, large landings in the early 2000s, and low landings for the three most recent years (2005–06 to 2007–08). Observer records were generally similar to the commercial records, apart from under-representation during the landing peaks of the 2000s. Observer records also indicated a peak in catches in 1988–89, before the commercial data series began.

Most basking shark bycatch was reported taken in spring and summer with little catch in winter (Figure 5). Nearly all of the basking shark bycatch came from Fisheries Management Areas 3, 5, 6, and 7 (i.e., around the whole South Island and on the Campbell Plateau, but excluding the Chatham Rise) (Figure 6).

3.2 Predictive modelling from observer records

3.2.1 East coast fishery area (EC)

Model fitting

The boundaries of this area were changed from the EC area studied by Francis & Duffy (2002) to match the boundaries of statistical areas to allow the inclusion of commercial tows recorded on CELR forms (about 9% of all commercial tows, Table 5). The target species were increased from barracouta and hoki to include the other five species caught at similar depths. No subarea covariate was defined for the EC fishery area.

The EC area was difficult to model because of what appeared to be a problem with identifiability of model parameters. Initially, fitting was attempted with all four covariates, but this produced lack of convergence and implausible parameter values (the random year effects drifted to very large values as the chain progressed). Attempts at fitting models with fewer covariates led to the conclusion that the only viable model was that which included only random year effects and the periodic(*day.no*) covariate

The model used for EC had the covariate component:

periodic(*day.no*).

The model fit appeared to be satisfactory because the predicted frequencies of basking shark captures per tow coincided as well as might be expected with the observed frequencies (Table 6).

The use of random year effects for the base strike rates means that they will have been smoothed, and consequently they are all greater than 0.25 captures per 1000 tows, even in years when there were no observed captures (see Table 8). The base rates could be interpreted as standardised relative catch per unit effort (CPUE) indices, except that in this fishery there was only one covariate used in the standardisation. Because of the effect of the periodic(*day.no*) covariate the base strike rates are all much smaller than the predicted strike rates (Tables 7 & 8) and hence they can only be treated as relative CPUE indices. The periodic(*day.no*) covariate multiplicative effect has a peak in mid January and a low in mid July. The 95% credibility interval for the sine function coefficient was a long way from including zero and the 95% credibility interval for the cosine function coefficient only just included zero (see Table 7), which means that the periodic(*day.no*) covariate multiplicative effect was significant.

Predicted basking shark captures

Over the 14-year period, commercial trawl effort declined from a high of 11 318 tows in 1997–98 to a low of 4118 tows in 2006–07 (see Table 5). Many of the inshore tows in the Canterbury Bight, where very few tows were observed (Figures 7 & 8), would have been recorded on the CELR forms used by smaller vessels targeting species in the shallow group. This is of concern in this fishery because the observer coverage (which averaged 7.6%) is not representative of the shallow species group (Figure 9) and it was not possible to fit a model that included the *targ.g* variable. Consequently any potential difference in capture rates between the two species groups will not have been taken into account in the total basking shark predictions.

Observer coverage varied among fishing years (Figures 8 & 9), but overall predicted total basking shark captures will include adjustments for these differences via the individual base year effects. Observer coverage was representative for the *day.no* covariate (Figure 9), and any differences would have been adjusted for using the coefficients of the periodic transformation.

A total of 29 basking sharks was caught on 8229 observed tows in the 14 fishing years. No captures were observed in eight of the fishing years, but in 1997–98 17 sharks were caught including five in one tow targeting barracouta and three in another tow targeting hoki (see Table 6). The average observed strike rate was 3.5 basking sharks per 1000 tows (Table 8).

Predicted basking shark captures over the 14 fishing years varied between five in 2006–07 and 2007–08 and 177 in 1997–98 (Table 8). Coefficients of variation were large (because there were only 29 observed captures) and varied between 130% and 26% (in the year of most captures.). The c.v.s were 99% or more in 9 of the 14 years. Total basking shark captures for the 14 years were predicted to be 418 with a c.v. of 25%. Plots of the predictive distributions of the total captures show large differences among years (Figure 10). The predicted strike rates varied between 0.8 and 15.6 per 1000 tows and are plotted with 95% prediction intervals and compared with the observed strike rates in Figure 11.

3.2.2 West coast fishery area (WC)

Model fitting

The WC fishery area incorporates tows targeting the mid depth group of target species (HAK, HOK, LIN, and WWA). Few observed tows (386 tows with no basking shark captures, see Table 4) targeted any of the shallow species group (BAR, SQU, and SWA). Consequently there is no information in the observer data concerning captures for any of the species in the shallow group.

The boundaries of the WC fishery area extend those used by Francis & Duffy (2002) and relate to the boundaries of the Statistical Areas 034, 035, 036, and 703, in order to accommodate commercial data on CELR forms (Table 9). In the north, the boundary of 40° S bisects the statistical areas 036 and 703 and there is the issue as to whether any unobserved tows recorded on CELR forms were north of 40° S. Only eight tows recorded on CELR forms were in Area 036 or Area 703, and all were by the same vessel in the same month and year and were surrounded and interspersed in time by tows in 034. It therefore seems very unlikely that any of those tows were outside the WC fishery area.

The *targ.g* covariate factor was not included in the model because the target species of all tows in the WC fishery area are in the mid depth group. The capture rate of basking sharks was much higher in the north of the fishery area (Figures 12 & 13), especially as most effort was concentrated in the vicinity of the Hokitika Canyon in the south. The WC area was subdivided into two subareas, north and south, at 41° 45´ S, which is the boundary between Statistical Areas 034 and 035. With the inclusion of the *gear* factor and the periodic function of *day.no* the covariate component of the model used for predicting shark captures in the WC fishery area was:

gear + *subarea* + periodic(*day.no*).

The model fit appeared to be satisfactory because the predicted frequencies of basking shark captures per tow agreed well with the observed frequencies (Table 10) except for single tows of four sharks in 1996–97 and eight sharks in 2004–05.

The base year rates show the effects of smoothing in the years of no observed captures and in the years of high observed capture rates (Tables 11 & 12). Again these rates can be interpreted as relative standardised CPUEs. The year base rates are for the north subarea where there were fewer tows (Figure 14) but a capture rate that was more than 30 times higher than in the south subarea. The subarea effect of south relative to north had a posterior mean of 0.027, i.e., less than 3% that of the north area (everything else being equal). The gear effect was also marked, with bottom trawl nets catching basking sharks at only 2% of the rate of midwater nets (everything else being equal). Both effects were highly significant as their 95% credibility intervals were a long way from one (no multiplicative effect). The periodic(*day.no*) covariate multiplicative effect had a peak in early June and a low in early December. Despite the very large c.v.s, the 95% credibility intervals both include zero close to the end of each interval (see Table 11). The over-dispersion variance was much larger than that for the EC fishery area, reflecting the two catches of four and eight basking sharks in the observer data.

Predicted basking shark captures

During the 14 fishing years, commercial effort targeting the mid depth species group declined from highs of over 9000 tows in 1994–95, 1996–97, and 2000–01 to a low of just over 2500 tows in 2007–08 (see Table 9). About 5% of the tows were recorded on CELR forms. However, no tows were recorded on CELR forms in the last two years because of the introduction of the new catch effort form. Observer coverage increased from 10% to 30%, mostly because of the decreased effort. Observer coverage overall was representative spatially (see Figures 12 & 13), by gear use, by subarea, and by time of the year (Figure 14). Coverage varied annually, being low in the 1990s and high in the mid 2000s (Figure 14).

Nineteen basking sharks were caught in 14 286 observed tows in the 14 years of the study (Table 12). In eight of the 14 years no captures were observed. In 2004–05 the only observed capture incident was a bag of eight basking sharks caught in a tow targeting hoki, while in 1996–97 the only incident was a bag of four basking sharks caught in a tow also targeting hoki (see Table 10). All other incidents were single captures. All capture incidents occurred on tows targeting hoki (see Table 4). The average observed strike rate was 1.3 sharks per 1000 tows (Table 12)

Predicted numbers of basking shark captures over the 14 years totalled 199 with a c.v. of 65%. Predicted captures varied between 1 in 2005–06 and 45 in 1996–97 (Table 12). There is a great deal of uncertainty in the predictions with all but three of the c.v.s being more than 100%. This was because only 19 basking shark captures were observed in 6 of the 14 years. The bag of eight captures in one tow in 2004–05 was the only observed incident in the last five years. Density plots of the predictive distributions (Figure 15) also show the variation among years and the uncertainty in the captures. Predicted strike rates show similar variation among years and uncertainty in their predicted values (although the c.v.s were usually a little smaller than those for the corresponding predicted capture). Predicted strike rates averaged 2 per 1000 tows overall, were less than 0.8 per 1000 tows in years when there were no captures, and were about 5 per 1000 tows in the three years when the greatest numbers of captures occurred. Smoothing that results from using random year effects is evident when the predicted and observed strike rates are compared (Figure 16).

3.2.3 Southland-Auckland Islands fishery area (SA)

Model fitting

The SA fishery area extended the SA area of Francis & Duffy (2002) to include more of the Stewart-Snares Shelf, the area of the hoki fishery to the east and northeast of the Auckland Islands, and the area of the Puysegur hoki and squid fishery (Figure 17). The SA area included all the observed basking captures south of 45° S except for one capture in a tow targeting hoki near Campbell Island (Figure 1). About 4.4% of tows were recorded on CELRs, with none in the last two years (Table 13).

Basking sharks were observed caught in tows for all target species except barracouta. Most observed tows targeted either squid or hoki. The target species groups in the *targ.g* factor for the SA model were shallow (shal) and mid depth (midd). There were different capture rates in different subareas so a *subarea* factor covariate was used. The levels of the *subarea* factor were Puysegur (puys), Stewart-Snares (stew), and Auckland Islands (auck). stew and auck are separated by the line 49° 30′ S and stew and puys are separated by the rhumb line joining 166° E and 47° 30′ S with 166° 55.2′ E and 46° 13.2′ S (Figure 17).

It was also evident that there was interaction between the *targ.g* and the *subarea* factors in relation to capture rates and, consequently, the covariate component model included interactions as well as main effects. Capture rates for the shallow group were higher than for the mid depth group in the puys and auck subareas, but the opposite was true in the stew subarea. If only main effects were allowed (*targ.g* + *subarea*) the two covariate factors would have required three parameters (one for *targ.g* and two for *subarea*). If the fully crossed factors (*targ.g* * *subarea*) were used in the model there would have been six levels with five (2×3 – 1) parameters. Because there were similar numbers of mid depth tows observed in each of the puys and auck subareas and only one capture was observed for each, it was decided to combine both those levels into one in the crossed factor variable *subtar*. This factor then has the five levels: auck:shal (base level), auck+puys:midd, puys:shal, stew:shal, and stew:midd. Therefore four parameters (for the effects relative to the base level) needed to be estimated.

The covariate component model used for predicting captures in the SA fishery area was:

gear + *subtar* + periodic(*day.no*).

The model fit appeared to be satisfactory because the predicted frequencies of basking shark captures per tow coincided reasonably well with the observed frequencies (Table 14). SA area model was the easiest to fit because of the relatively large number of capture incidents and the paucity of multiple captures.

The base year rates show the effects of smoothing in the years of no observed captures and in the years of high observed capture rates (Tables 15 and 16). As in the other areas, the base year rates can be interpreted as relative standardised CPUEs. The capture rate effect for tows targeting the shallow species group (mostly SQU tows) in Puysegur subarea was almost 10 times that for shallow targets in the Auckland Islands subarea (the base level), while the effect for tows targeting shallow species in the Stewart-Snares subarea was less than 10% of that for the base level. Tows targeting mid depth species in Puysegur or the Auckland Islands caught basking sharks at about one-third of the rate for shallow targets in the Auckland Islands. Each of these three effects was significant as each 95% credibility interval did not include one. Stew:midd was not significantly different from the base level.

The *gear* effect showed that midwater nets caught basking sharks at a 40% greater rate than bottom trawl nets, but this was not significantly different from one. The periodic(*day.no*) covariate multiplicative effect had a peak at the end of November and a low at the end of May. Despite the very large c.v.s the 95% credibility intervals both included zero close to the end of each interval (see Table 15). The extra dispersion parameter was much smaller than for the other two areas. This was expected because only three tows had multiple captures, and all three were double captures.

Predicted basking shark captures

Commercial effort in the SA fishery area generally declined over the 14 years from about 14 000 tows in the mid 1990s to 6737 tows in 2007–08 (see Table 13). Less than 0.5% of the effort was recorded on CELR forms. Observer coverage generally increased from about 7% in 1994–95 to about 33% in 2007–08. The high coverage in 2000–01 (34%) was mainly in the squid fishery. Spatially, observers covered most areas well (Figures 17 and 18) but coverage was not representative for the other model variables (Figure 19). Observer coverage increased through time; it was greater for midwater trawls than bottom trawls, and it was concentrated in part of the fishing season. The differences between observed and unobserved proportions were less marked for the six combinations of the *subarea* and *targ.g* variables.

Forty-seven basking sharks were observed in the 14 years at an observed strike rate of 1.8 per 1000 tows, but no captures were observed in the four years 1994–95 to 1997–98 or in 2005–06 (Table 16). All capture incidents were singles except for three tows which each captured two sharks (see Table 14).

Predicted basking shark captures for the SA fishery area totalled 306 with a c.v. of 17% (Table 16). Predicted captures for the 14 years ranged between 7 in 2005–06, and 48 in 1998–99 and 47 in 2002–03. Coefficients of variation of the predictive distributions were smaller than for the other fishery areas, ranging between 28% and 82%. Smaller c.v.s were expected because there were many more captures. Density plots of the predictive distributions of the yearly basking shark captures show variation in the yearly estimates (Figure 20).

The overall predicted strike rate was 1.9 sharks per 1000 tows with a c.v. of 17% (Table 16). The predicted strike rates in years where there were no captures were 0.7 to 0.8 per 1000 tows and, for the other years, they ranged from 1.4 per 1000 in 2004–05 to 4.3 per 1000 in 1998–99. C.v.s were similar to, but a little smaller than, those for the predicted captures. Smoothing resulting from using random year effects was evident when comparing the predicted strike rates with the observed strike rates (Figure 21), however no particular trend was apparent.

3.2.4 Total basking shark captures in New Zealand waters

Predicted basking shark catch rates, and predicted numbers of captures, are summarised for all three areas, and all areas combined, in Tables 17 and 18 and Figures 22 and 23. The total predicted number of captures in the 14 years was 922 with a c.v. of 19%. The annual number of predicted captures ranged from 15 (c.v. 56%) in 2005–06 to 228 (c.v. 64%) in 1997–98. Total predicted captures peaked in 1997–98 and then declined steadily to low numbers thereafter.

Except for the two years 1995–96 and 2005–06 when no captures were recorded by observers, captures were not very correlated among the three areas. For example, in 1997–98, when the most captures were predicted, predicted strike rates were high in the EC and WC fishery areas but low in the SA fishery area (see Table 17). The large capture peak in 1997–98 was attributable to high catches in EC, and that area continued to contribute a high proportion of the captures up to 2003–04. Since then, EC captures have been very low. From 1998–99, SA contributed a high proportion of catches, with WC captures only being important occasionally.

3.3 Basking shark catch composition and fate

About one-third of sharks recorded by observers were measured (36.1%) or sexed (36.9%), but only about one-quarter (27.0%) were both measured and sexed. Catches were dominated by males in all fishery areas, but particularly in West Coast and Southland-Auckland Islands (Figure 24): the percentages of males were: EC, 65.4%; WC, 87.5%; and SA, 96.8%. Most basking sharks were 7–9 m in the WC and SA fishery areas, but the EC area was dominated by smaller sharks of 4–6 m. Because of among-area differences in size and sex composition of catches, it appears that different components of the basking shark population inhabit different areas. It is not known where females, particularly large mature females, live.

Most basking sharks (76.5%) were reported to be alive when landed on the deck of the vessel, but they were usually in poor condition. Many sharks were finned before discarding, and those that were returned whole were usually out of the water for a long time. Furthermore, the process of returning animals to the sea requires winching, often involving rope or wire strops fastened around the gills or tail. In some cases, tails were ripped off the sharks. Observers sometimes stated that they believed that live sharks would have died despite being returned to the sea. The mortality rate of sharks that were returned the sea whole was likely to have been near 100%.

4. DISCUSSION

4.1 Data limitations

The observer data used in our analyses are observational data rather than data from a designed experiment. Therefore, statistical associations between capture rates and covariates can be recognised, but these do not necessarily imply any causal relationships. This is particularly the case in the present study where observer coverage was concentrated on vessels targeting hoki in the EC and WC fishery areas and squid and hoki in the SA area (see Table 4). Target species, subarea, type of net used, time of year, and the depth the net is towed at (together with other potential covariates recorded or not recorded in the data) are all correlated, making it difficult to disentangle these effects. Furthermore, the observed numbers of captures was very low (19–47 per fishery area over the 14 years of the study) (see Table 4). For count data, the uncertainty associated with estimates and predictions is related directly to the (mean) number of captures, not to sample size. Because of the low numbers of captures many c.v.s are large. With so few captures a single additional capture incident can change parameter estimates quite markedly. The paucity of capture incidents therefore means that it is impossible to distinguish which if any, of the covariates might be causally related to capture rate.

4.2 Temporal patterns in trawl bycatch

In the period covered by the present study (1994–95 onwards), overall basking shark bycatch in the three fishery areas peaked in 1997–98 and then declined steadily to low levels in recent years (Figure 22). Much of this decline is probably attributable to a decline in fishing effort in all three areas: the total number of commercial tows for all areas combined declined by about 50% from 28 000–33 000 per year up to 2002–03 to fewer than 15 000 in 2006–08 (see Table 17). This decline in effort was mainly a result of a progressive reduction of hoki quotas by more than 64% from 250 000 t in 2001–02 to 90 000 t in 2007–08. The predicted strike rates showed no overall trend in any of the three areas (see Figures 11, 16 and 21). Note, however, that WC strike rate shows a strong decline if the data point for 2004–05 is omitted; that point is strongly influenced by a single tow (see below).

Francis & Duffy (2002) estimated raw basking shark CPUE using observer data from 1986 to 1999, creating a series (hereafter called F&D CPUE) that began eight years earlier than our CPUE series. They used the same data sources, but focussed on smaller fishery areas (that were contained within our fishery areas) and fewer target species (which were subsets of our target species). The F&D CPUE series therefore allows us to place our results into a longer-term context. We extended the F&D CPUE series to 2008 using their methods, including the same areas and target species (see Figure 23).

The WC and SA F&D CPUE series are probably reasonably reliable because many years in those areas had more than 1000 observed tows. The EC series may be unreliable because the number of observed tows in the small areas analysed by Francis & Duffy was usually less than 500 per year. Nevertheless, there is good agreement between the extended F&D CPUE series and our predicted strike rates, apart from a big discrepancy for WC in 2004–05. Inspection of the raw data revealed that the only basking shark observation that year was a single tow containing eight sharks in a location outside the smaller area analysed for the F&D CPUE series (hence the latter series had a zero CPUE in 2004–05). The very low observed and predicted CPUEs in EC during the last decade (see Figure 23) are consistent with a dearth of sightings of basking sharks in the northern inshore waters of Canterbury Bight over the same period by commercial fishers, ecotourism operators, and during aerial dolphin surveys (C. Duffy, Department of Conservation, pers. comm.).

For all three fishery areas, the F&D CPUE series show high catch rates in the late 1980s or early 1990s that far exceed anything observed since then (see Figure 23). It is implausible that population abundance of a low fecundity species could have increased and declined so rapidly (over 1–2 years). Consequently the high early catch rates probably resulted from a temporary increase in the availability or vulnerability of sharks in the three fishery areas. The early part of the time series had a much higher proportion of multiple captures than the late part of the series: in the 12-year period from 1985–86 to 1996–97, 26 out of 88 basking shark tows (29.5%) contained multiple sharks, whereas in the 11-year period from 1997–98 to 2007–08, only 6 out of 76 tows (7.9%) contained multiple sharks. This suggests that the high catch rates of the late 1980s and early 1990s may have resulted from increased aggregation of sharks in the region.

4.3 Other sources of bycatch

The model-based method adopted in this study used observer data from three defined fishery areas, and therefore provided no estimates of basking shark captures elsewhere in the EEZ. Only four basking shark captures were observed outside these three areas during the 14 years of the study (they were in the northern Bay of Plenty, off Wairarapa (two captures) and near Campbell Rise), despite large numbers of tows being observed elsewhere, particularly around the southern North Island and on the Chatham Rise and Campbell Rise (see Figure 1). The lack of basking shark records from around southern North Island from 1994–95 onwards (apart from the two Wairarapa records) is surprising. There are observer records from South Taranaki Bight before 1994–95, unobserved commercial trawl captures from Hawke Bay (including 32 caught by two trawlers in a three-month period in 1997), and a number of set net captures, strandings, and sightings from Taranaki to Cook Strait (Francis & Duffy 2002). The lack of observer records from Chatham Rise from 1994–95 onwards may be a result of their absence from the region, as only a single record is known from the Chatham Rise, and it was from near Chatham Island (Francis & Duffy 2002).

A large proportion of commercial trawl tows around the South Island target flatfish in shallow (inner continental shelf) waters, yet this fishery has received negligible observer coverage (Smith & Baird 2009) (see Figure 7). It is not known whether this fishery catches significant numbers of basking sharks, though the strike rate is possibly low because the trawlers, net widths, and headline heights are all relatively small. However, the large number of tows made by these vessels means that even a low strike rate could result in a considerable number of captures.

Set nets also catch basking sharks, but their bycatch cannot be quantified. A 'miscellaneous' dataset compiled by Francis & Duffy (2002) included 19 set net captures, and other reports ('caught', 'strandings') that may have been, or have resulted from, set net captures (MPF and CD, unpublished data). Set nets account for a negligible proportion of basking shark catches reported to MFish (less than 1 t out of a total of 991 t estimated catch between 1989–90 and 2007–08), but this may reflect the difficulty of landing or processing large basking sharks from small set net vessels rather than a low encounter rate.

Three basking shark captures have been reported by observers on tuna longline vessels, all off Fiordland. The sharks were presumably entangled in the lines rather than hooked. This source of fishing mortality appears to be very low given that over 7000 longline sets have been observed in the EEZ since 1988.

Our estimates of basking shark bycatch in trawl fisheries in the three defined fishery areas underestimate the total bycatch in the New Zealand EEZ because they don't take account of trawl fisheries outside the three areas, or of other fishing methods. Bycatch in set net fisheries, and in trawl fisheries in shallow coastal waters where observer coverage has been negligible until recently, may be considerable.

4.4 Susceptibility to overfishing and stock status

Basking sharks have very low productivity, driven by low reproductive rates, low growth rates, and low natural mortality rates. Fisheries for basking sharks elsewhere in the world are characterised by boom-and-bust cycles. Regions displaying these cycles include the northeast Atlantic (especially Ireland and Scotland), west Canada, California, and China (Phillips 1948, Rae 1956, Lien & Fawcett 1986, Kunzlik 1988, Squire 1990, Berrow & Heardman 1994, Darling & Keogh 1994, Fairfax 1998, Fowler 2005). It is clear that basking shark populations are unable to sustain high catch levels.

Large inter-annual variations in surface sightings and fishery captures are a feature of basking shark populations, both in New Zealand and elsewhere (Fairfax 1998). In the face of such variability, it is difficult to draw conclusions about the status of the New Zealand basking shark stocks from currently available data. The number of basking sharks caught in New Zealand fisheries (perhaps 1000 in 14 years) is low relative to numbers caught by directed fisheries elsewhere in the world (1000–3000 per year in northeast Atlantic from 1945 to 1985). However, the apparent absence of large numbers and aggregations of basking sharks in Canterbury Bight during the last decade is cause for some concern. The northern Canterbury Bight has previously been regarded as an important part of the habitat of basking sharks in which large aggregations of animals were frequently seen during spring–summer (Francis & Duffy 2002). Observer records of trawl bycatch in three fishery areas suggest that there may not have been large aggregations of basking sharks in New Zealand waters since the early 1990s, i.e., almost 20 years. Whether such a long period without large aggregations is part of a long-term, natural cycle, or evidence of a decline in population abundance, cannot yet be determined.

4.5 Stock range – a larger spatial context

Basking sharks are most abundant in cool temperate regions of the northern and southern Pacific and Atlantic oceans. Recent global distribution maps indicate that they are absent from subtropical and tropical waters of both oceans (Last & Stevens 2009). However, recent satellite tagging of basking sharks in the North Atlantic is changing our view of their distribution and migratory capabilities. A shark tagged off Isle of Man in the Irish Sea travelled 9600 km across the Atlantic to near Canada (Gore et al. 2008), and five sharks tagged off New England in the United States migrated up to 6500 km to tropical waters of the Caribbean and Brazil (Skomal et al. 2009). This proves that basking sharks may travel large distances and that at least some periodically inhabit tropical waters.

Given this evidence from the Atlantic, it is unlikely that New Zealand basking sharks are restricted to our waters; they probably form part of a much wider ranging stock. Basking sharks are rare in Australia (Last & Stevens 2009), and they have only occasionally been recorded in the Tasman Sea and central South Pacific (Sharples et al. 1991, Yatsu 1995). Nevertheless, they may be much more common in those regions than is currently realised. Migrations of New Zealand sharks to western South America and perhaps even the North Pacific (e.g. Japan) are possible. Assessment of the status of the New Zealand basking shark population therefore needs to take into account possible long-range migrations to other countries, and also the effect of fishery bycatch in those countries on the greater population.

4.6 Recommendations for reducing basking shark bycatch

Much of the New Zealand basking shark bycatch comes from trawl fisheries operating in three relatively small parts of the New Zealand EEZ. Any reduction in fishing effort in these areas would reduce the bycatch, and in fact there has been a substantial decline in effort in all three areas over the last five years. However, a recovery in the hoki stocks could lead to increased quotas and fishing effort in future years, so specific measures to reduce basking shark bycatch may be warranted.

Developing recommendations for reducing bycatch from our analysis of observed captures is difficult because of data limitations. Nevertheless, it is useful to highlight some associations between basking shark capture rates and some covariates. Predictive models for all three areas showed very strong (but different) periodic time of year effects (Figure 25). These effects were all phase-shifted relative to the observer effort for each area (see Figures 9, 14, and 19) and the commercial fishing effort (see Figure 25). This means that shark captures were likely less than if the capture rate effect coincided with peak fishing effort. It further suggests that reductions in fishing effort during the peak of the shark capture rate effect would reduce bycatch; the peak periods are November–March for EC, April–July for WC, and September–March for SA (see Figure 25).

There were very clear differences (significant because the 95% credibility intervals do not include one) for the relative effects associated with subarea in WC and for some of the combined subarea-target effects in SA. The south subarea in WC had a much lower capture rate effect than the north subarea (1/37th, Table 11), which may be fortunate for basking sharks because almost 75% of the fishing effort was in the south (see Figure 14). In SA, where there are a number of distinct fisheries, all but the stewt:midd subtar effect were significantly different from auck:shal (the base level) (see Table 15). There was a more than 100-fold variation among the individual fisheries in the basking shark capture rate. The level with the highest relative effect was puys:shal (primarily a squid fishery), which caught basking sharks at about 10 times the rate of the auck:shal fishery. The lowest capture rate was for stew:shal, which was about 1/11th that for auck:shal. Basking shark bycatch could be reduced by a reduction in fishing effort in the Puysegur squid fishery, and the north subarea of the WC hoki fishery.

The gear effect for midwater trawl nets relative to bottom trawl nets was estimated to be about 45 times (1/0.022) in WC (which is highly significant, see Table 11) but was only 1.4 times (not significantly different from one) in SA. That they differ so much between areas is perhaps due to this covariate substituting for other possible covariates. It may also be due in part to the different proportions of tows using midwater nets in the two areas. Nevertheless, basking shark bycatch was considerably higher in midwater trawl nets than in bottom trawl nets in WC, so a reduction in use of midwater trawl nets in this area may reduce basking shark bycatch.

Other factors almost certainly affect basking shark catch rates. Seabed depth and time of day may be important factors, because they may drive variations in the habitat and behaviour of sharks. Francis & Duffy (2002) found that basking shark CPUE varied with depth in their East Coast and West Coast areas. We were unable to include these factors as covariates in our models because of missing depth data in commercial records, and convergence difficulties in fitting models with more than a few covariates to datasets with few captures. Thus we cannot make any recommendations in relation to these variables, but note that the highest shark catch rates occurred in shallow (200–400 m) EC tows, and deep (700–800 m) WC tows (Francis & Duffy 2002).

The behaviour of basking sharks in the New Zealand region has been little studied, and we are unable to suggest reasons for higher catch rates occurring in some regions, seasons and years. They are unlikely to represent breeding aggregations because mature females are rarely caught by New Zealand fisheries. Basking sharks in New Zealand and elsewhere are well known to aggregate in shallow coastal waters to feed along fronts where plankton is concentrated. However, the main fisheries catching basking sharks in New Zealand are not in shallow coastal waters. It is possible that sharks being taken as bycatch in the deeper water fisheries are aggregating to exploit other food sources such as deepwater crustaceans and hoki eggs (Francis & Duffy 2002).

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Table 1: Numbers of observed trawl vessels, trips, and tows in the New Zealand EEZ and individual fishery areas by fishing year. Fishery areas: EC, East coast; WC, West coast; SA, Southland-Auckland Islands. The column headed 'Other' includes all observed tows outside the three fishery areas and inside the areas but targeting species other than those included in the definitions of the fishery areas.

Fishing year	Vessels	Trips	Tows EC	WC	SA	Other	Total
1994–95	44	67	257	851	980	2 938	5 026
1995–96	41	58	665	1 075	1 046	1 586	4 372
1996–97	48	67	308	700	1 370	2 400	4 778
1997–98	67	93	976	914	1 283	3 661	6 834
1998–99	69	93	752	1 123	1 647	3 736	7 258
1999–00	65	98	542	1 159	1 719	4 231	7 651
2000–01	62	117	1 027	1 098	3 646	3 344	9 115
2001–02	60	99	681	1 341	2 110	3 587	7 719
2002–03	56	86	576	962	1 910	3 392	6 840
2003–04	55	98	438	1 389	2 148	2 574	6 549
2004–05	55	100	374	1 087	2 737	3 514	7 712
2005–06	51	83	589	1 134	2 017	3 112	6 852
2006–07	63	124	447	675	1 821	4 981	7 924
2007–08	54	112	597	778	2 216	5 203	8 794
All	173	1 211	8 229	14 286	26 650	48 259	97 424

Table 2: Observed basking shark captures by fishing year and target species within the New Zealand EEZ. Numbers of incidents (tows) are in parentheses. See Table 3 for species codes.

Fishing year	Species code BAR	CDL	HAK	HOK	LIN	SKI	SQU	SWA	WWA	Total
1994–95				2 (2)						2 (2)
1995–96										
1996–97				5 (2)						5 (2)
1997–98	5 (1)			14 (12)		1 (1) *				20 (14)
1998–99				8 (8)		1 (1) *	2 (2)			11 (11)
1999–00		1 (1) *		2 (2)			5 (5)			8 (8)
2000–01	1 (1)			3 (3)			3 (3)			7 (7)
2001–02							1 (1)	2 (1)		3 (2)
2002–03				5 (5) †			10 (10)			15 (15)
2003–04			3 (2)	2 (2)			1 (1)		2 (2)	8 (7)
2004–05				8 (1)	2 (1)		1 (1)			11 (3)
2005–06										
2006–07							6 (6)			6 (6)
2007–08				1 (1)			1 (1)		1 (1)	3 (3)
All	6 (2)	1 (1)	3 (2)	50 (38)	2 (1)	2 (2)	30 (30)	2 (1)	3 (3)	99 (80)

* Basking shark captures outside of the three defined fishery areas
† One basking shark was caught in a hoki tow south of the SA area

Table 3: Target species groups by common name, scientific name, and species code.

Group	Common name	Scientific name	Code
Shallow	Barracouta	*Thyrsites atun*	BAR
	Silver warehou	*Seriolella punctata*	SWA
	Squid	*Nototodarus sloanii, N. gouldi*	SQU
Mid depth	Hake	*Merluccius australis*	HAK
	Hoki	*Macruronus novaezelandiae*	HOK
	Ling	*Genypterus blacodes*	LIN
	White warehou	*Seriolella caerulea*	WWA
Other	Cardinalfish	*Epigonus telescopus*	CDL
	Gemfish	*Rexea solandri*	SKI

Table 4: Numbers of observed tows and basking shark captures by target species within the spatial boundaries of the three fishery areas. For comparison with the other fishery areas, we have included the 386 tows targeting the shallow species BAR, SQU, and SWA in the WC fishery area even though those species are not part of the WC fishery as modelled.

Target	EC		WC		SA		Total	
species	Tows	Captures	Tows	Captures	Tows	Captures	Tows	Captures
BAR	422	6	330	0	794	0	1 546	6
HAK	17	0	1 146	0	317	3	1 480	3
HOK	7 347	22	13 133	19	5 389	8	25 869	49
LIN	2	0	7	0	568	2	577	2
SQU	341	1	1	0	19 104	29	19 446	30
SWA	100	0	55	0	321	2	476	2
WWA	0		0		157	3	157	3
Other	2 426	0	1 347	0	4 388	0	8 161	0
All species	10 655	29	16 019	19	31 038	47	57 712	95

Table 5: Observed and commercial trawl effort by fishing year for the EC fishery area. 'Tows for prediction' are the number of observed tows plus the number of commercial tows minus the number of commercial tows matched to observed tows.

Observed

Fishing year	Vessels	Trips	Tows	Coverage (%)
1994–95	9	12	257	3.9
1995–96	13	16	665	6.4
1996–97	12	14	308	3.3
1997–98	22	24	976	8.6
1998–99	20	21	752	7.7
1999–00	16	17	542	5.2
2000–01	24	32	1 027	10.2
2001–02	13	15	681	9.4
2002–03	20	24	576	6.5
2003–04	11	12	438	8.2
2004–05	13	17	374	7.5
2005–06	11	15	589	11.4
2006–07	15	20	447	10.9
2007–08	14	21	597	14.4
All	68	252	8 229	7.6

Commercial

	All forms		CELR forms		Tows for
Fishing year	Vessels	Tows	Vessels	Tows	Prediction
1994–95	79	6 656	12	359	6 658
1995–96	101	10 442	13	538	10 429
1996–97	103	9 449	17	598	9 460
1997–98	95	11 318	14	459	11 338
1998–99	81	9 754	14	904	9 763
1999–00	63	10 397	11	704	10 406
2000–01	63	10 089	11	1 629	10 087
2001–02	59	7 245	15	756	7 251
2002–03	63	8 880	15	1 443	8 887
2003–04	50	5 339	16	630	5 344
2004–05	60	4 986	16	821	4 985
2005–06	51	5 180	15	810	5 185
2006–07	35	4 118	0	0	4 120
2007–08	40	4 152	0	0	4 165
All	191	108 005	45	9 651	108 078

Table 6: Comparison of observed and expected basking shark capture frequencies for the observer data in the EC fishery area.

Observed numbers of tows

	Number of BSK captures per tow			
Year	0	1	3	5
1994-95	257			
1995-96	665			
1996-97	307	1		
1997-98	965	9	1	1
1998-99	748	4		
1999-00	542			
2000-01	1 024	3		
2001-02	681			
2002-03	573	3		
2003-04	437	1		
2004-05	374			
2005-06	589			
2006-07	447			
2007-08	597			

Expected numbers of tows

	Number of BSK captures per tow			
	0	1	2	3+
1994–95	257	0.2	0.0	0.0
1995–96	664	0.5	0.0	0.0
1996–97	308	0.5	0.0	0.0
1997–98	961	13.4	1.1	0.1
1998–99	748	3.5	0.1	0.0
1999–00	542	0.4	0.0	0.0
2000–01	1 024	3.0	0.1	0.0
2001–02	680	0.8	0.0	0.0
2002–03	574	2.2	0.1	0.0
2003–04	437	0.9	0.0	0.0
2004–05	373	0.6	0.0	0.0
2005–06	589	0.5	0.0	0.0
2006–07	446	0.5	0.0	0.0
2007–08	597	0.4	0.0	0.0

Table 7: Characteristics of the posterior distribution of the parameters in the fitted model for the EC fishery area.

Parameter	Mean	sd	Median	95% credibility interval	
94–95 base strike rate (per 10^3 tows)	0.67	0.88	0.41	0.01	3.03
95–96 base strike rate (per 10^3 tows)	0.31	0.32	0.21	0.02	1.21
96–97 base strike rate (per 10^3 tows)	1.47	1.69	0.96	0.08	5.90
97–98 base strike rate (per 10^3 tows)	3.93	1.88	3.53	1.33	8.40
98–99 base strike rate (per 10^3 tows)	1.09	0.81	0.90	0.26	3.36
99–00 base strike rate (per 10^3 tows)	0.47	0.53	0.31	0.03	1.88
00–01 base strike rate (per 10^3 tows)	0.72	0.51	0.59	0.13	2.06
01–02 base strike rate (per 10^3 tows)	0.27	0.23	0.22	0.01	0.85
02–03 base strike rate (per 10^3 tows)	1.22	0.88	0.98	0.22	3.61
03–04 base strike rate (per 10^3 tows)	0.91	0.93	0.63	0.11	3.43
04–05 base strike rate (per 10^3 tows)	0.44	0.43	0.31	0.03	1.56
05–06 base strike rate (per 10^3 tows)	0.36	0.40	0.22	0.01	1.44
06–07 base strike rate (per 10^3 tows)	0.50	0.51	0.36	0.03	1.79
07–08 base strike rate (per 10^3 tows)	0.45	0.45	0.32	0.03	1.65
sin(day.no) coefficient	2.49	0.46	2.50	1.58	3.38
cos(day.no) coefficient	-0.67	0.38	-0.67	-1.37	0.10
Extra-dispersion variance	4.61	1.11	4.57	2.38	6.64

Table 8: Observed and predicted basking shark strike rates, and predicted basking shark captures by fishing year for all tows in the EC fishery area.

	Obs.	Obs. strike	Predicted basking shark captures				Predicted strike rate	
Fishing year	captures	rate ($\times 10^3$)	Captures	c.v. (%)	95% pred. interval		Rate ($\times 10^3$)	c.v. (%)
1994–95	0	0	15	130	0	69	2.2	128
1995–96	0	0	12	104	0	46	1.2	98
1996–97	1	3.2	51	130	3	224	5.3	129
1997–98	17	17.4	177	26	103	279	15.6	24
1998–99	4	5.3	38	47	13	82	3.8	44
1999–00	0	0	22	107	1	88	2.1	104
2000–01	3	2.9	26	51	8	57	2.6	48
2001–02	0	0	6	93	0	19	0.8	83
2002–03	3	5.2	34	56	9	81	3.8	53
2003–04	1	2.3	15	88	2	52	2.8	84
2004–05	0	0	6	99	0	22	1.2	91
2005–06	0	0	6	105	0	22	1.2	99
2006–07	0	0	5	102	0	21	1.3	96
2007–08	0	0	5	108	0	18	1.2	101
All	29	3.5	418	25	273	657	3.9	24

Table 9: Observed and commercial trawl effort by fishing year, for the WC fishery area. 'Tows for prediction' are the number of observed tows plus the number of commercial tows minus the number of commercial tows matched to observed tows.

Observed

Fishing year	Vessels	Trips	Tows	Coverage (%)
1994–95	9	10	851	9.4
1995–96	15	15	1 075	14.2
1996–97	12	13	700	7.7
1997–98	15	15	914	10.7
1998–99	14	14	1 123	14.4
1999–00	17	18	1 159	14.5
2000–01	21	26	1 098	11.9
2001–02	16	17	1 341	16.2
2002–03	13	13	962	11.6
2003–04	16	17	1 389	18.9
2004–05	14	15	1 087	22.9
2005–06	15	20	1 134	24.1
2006–07	16	17	675	22.9
2007–08	14	18	778	30.4
All	64	228	14 286	14.6

Commercial

	All forms		CELR forms		Tows for
Fishing year	Vessels	Tows	Vessels	Tows	Prediction
1994–95	74	9 070	7	174	9 079
1995–96	73	7 588	10	212	7 610
1996–97	89	9 034	9	391	9 037
1997–98	77	8 518	9	233	8 533
1998–99	69	7 824	10	368	7 830
1999–00	62	7 972	10	518	7 972
2000–01	72	9 219	9	635	9 228
2001–02	66	8 273	10	491	8 274
2002–03	60	8 324	9	662	8 326
2003–04	61	7 334	10	702	7 336
2004–05	48	4 753	9	401	4 742
2005–06	45	4 703	8	365	4 703
2006–07	34	2 942	0	0	2 943
2007–08	34	2 559	0	0	2 559
All	160	98 113	25	5 152	98 172

Table 10: Comparison of observed and expected basking shark capture frequencies for the observer data in the WC fishery area.

Observed numbers of tows

	Number of basking shark captures per tow			
Year	0	1	4	8
1994-95	849	2		
1995-96	1 075			
1996-97	699		1	
1997-98	912	2		
1998-99	1 122	1		
1999-00	1 158	1		
2000-01	1 098			
2001-02	1 341			
2002-03	961	1		
2003-04	1 389			
2004-05	1 086			1
2005-06	1 134			
2006-07	675			
2007-08	778			

Expected numbers of tows

	Number of basking shark captures per tow				
	0	1	2	3	4+
1994–95	849	1.4	0.1	0.0	0.0
1995–96	1 075	0.3	0.0	0.0	0.0
1996–97	697	2.9	0.2	0.0	0.0
1997–98	912	1.6	0.1	0.0	0.0
1998–99	1 122	1.0	0.1	0.0	0.0
1999–00	1 158	1.3	0.1	0.0	0.0
2000–01	1 097	0.7	0.0	0.0	0.0
2001–02	1 340	0.9	0.1	0.0	0.0
2002–03	961	1.1	0.0	0.0	0.0
2003–04	1 389	0.4	0.0	0.0	0.0
2004–05	1 084	2.3	0.2	0.0	0.0
2005–06	1 134	0.2	0.0	0.0	0.0
2006–07	674	0.9	0.0	0.0	0.0
2007–08	778	0.4	0.0	0.0	0.0

Table 11: Characteristics of the posterior distribution of the parameters in the fitted model for the WC fishery area.

Parameter	Mean	sd	Median	95% credibility interval	
94–95 base strike rate (per 10^3 tows)	7.00	4.81	5.89	1.01	19.28
95–96 base strike rate (per 10^3 tows)	3.98	4.47	2.66	0.00	15.57
96–97 base strike rate (per 10^3 tows)	13.85	8.13	11.94	3.52	33.42
97–98 base strike rate (per 10^3 tows)	9.06	7.10	7.17	2.05	27.83
98–99 base strike rate (per 10^3 tows)	4.16	4.19	2.82	0.16	15.96
99–00 base strike rate (per 10^3 tows)	5.02	4.59	3.62	0.71	18.48
00–01 base strike rate (per 10^3 tows)	2.76	2.31	2.12	0.32	9.14
01–02 base strike rate (per 10^3 tows)	1.94	1.83	1.41	0.06	6.98
02–03 base strike rate (per 10^3 tows)	4.61	3.85	3.59	0.17	14.83
03–04 base strike rate (per 10^3 tows)	3.47	4.10	2.26	0.04	14.80
04–05 base strike rate (per 10^3 tows)	27.11	20.18	21.83	6.33	74.92
05–06 base strike rate (per 10^3 tows)	5.09	5.16	3.45	0.27	18.91
06–07 base strike rate (per 10^3 tows)	3.11	2.99	2.34	0.00	10.63
07–08 base strike rate (per 10^3 tows)	4.33	4.62	3.07	0.14	16.18
subarea south	0.027	0.017	0.024	0.005	0.067
gear BT	0.022	0.043	0.009	0.001	0.169
sin(day.no) coefficient	-4.80	3.37	-5.15	-11.17	1.56
cos(day.no) coefficient	-2.55	1.57	-2.56	-5.35	0.82
Extra-dispersion variance	7.36	1.04	6.94	5.79	8.93

Table 12: Observed and predicted basking shark strike rates, and predicted basking shark captures by fishing year for all tows in the WC fishery area.

Fishing year	Obs. captures	Obs. strike rate ($\times 10^3$)	Predicted basking shark captures: Captures	c.v. (%)	95% pred. interval		Predicted strike rate: Rate ($\times 10^3$)	c.v. (%)
1994–95	2	2.4	26	72	5	76	2.9	68
1995–96	0	0	5	133	0	21	0.7	110
1996–97	4	5.7	45	157	12	120	5.0	80
1997–98	2	2.2	41	100	8	134	4.8	101
1998–99	1	0.9	19	254	1	65	2.5	249
1999–00	1	0.9	16	111	2	68	2.0	106
2000–01	0	0	5	129	0	20	0.6	112
2001–02	0	0	2	115	0	9	0.3	91
2002–03	1	1.0	8	91	1	25	0.9	90
2003–04	0	0	3	134	0	14	0.4	121
2004–05	8	7.4	22	44	11	47	4.7	40
2005–06	0	0	1	166	0	7	0.3	113
2006–07	0	0	2	125	0	9	0.7	102
2007–08	0	0	2	163	0	9	0.6	134
All	19	1.3	199	65	89	390	2.0	62

Table 13: Observed and commercial trawl effort by fishing year, for the SA fishery area. 'Tows for prediction' are the number of observed tows plus the number of commercial tows minus the number of commercial tows matched to observed tows.

Observed

Fishing year	Vessels	Trips	Tows	Coverage (%)
1994–95	12	12	980	7.2
1995–96	13	16	1 046	7.9
1996–97	19	20	1 370	9.6
1997–98	17	19	1 283	10.3
1998–99	25	28	1 647	14.8
1999–00	25	26	1 719	17.2
2000–01	31	54	3 646	33.6
2001–02	18	27	2 110	17.3
2002–03	24	34	1 910	16.3
2003–04	25	36	2 148	18.7
2004–05	28	36	2 737	22.5
2005–06	24	27	2 017	20.1
2006–07	26	35	1 821	23.7
2007–08	24	34	2 216	32.9
All	82	394	26 650	16.9

Commercial

	All forms		CELR forms		Tows for
Fishing year	Vessels	Tows	Vessels	Tows	Prediction
1994–95	77	13 628	5	19	13 628
1995–96	75	13 273	5	20	13 280
1996–97	76	14 198	2	7	14 189
1997–98	69	12 463	6	17	12 585
1998–99	62	11 131	1	12	11 165
1999–00	46	9 968	1	11	9 964
2000–01	47	10 857	2	23	10 873
2001–02	46	12 220	2	28	12 225
2002–03	49	11 702	5	130	11 703
2003–04	43	11 493	4	142	11 501
2004–05	45	12 185	4	207	12 194
2005–06	44	10 024	3	85	10 029
2006–07	34	7 692	0	0	7 695
2007–08	34	6 737	0	0	6 744
All	167	157 571	21	701	157 775

Table 14: Comparison of observed and expected basking shark capture frequencies for the observer data in the SA fishery area.

Observed numbers of tows

	Number of BSK captures per tow		
Year	0	1	2
1994–95	980		
1995–96	1 046		
1996–97	1 370		
1997–98	1 283		
1998–99	1 642	5	
1999–00	1 713	6	
2000–01	3 642	4	
2001–02	2 108	1	1
2002–03	1 900	10	
2003–04	2 142	5	1
2004–05	2 735	1	1
2005–06	2 017		
2006–07	1 815	6	
2007–08	2 213	3	

Expected numbers of tows

	Number of BSK captures per tow		
	0	1	2+
1994–95	979	0.7	0.0
1995–96	1 045	0.8	0.0
1996–97	1 368	1.5	0.0
1997–98	1 282	1.2	0.0
1998–99	1 643	3.6	0.0
1999–00	1 714	4.9	0.0
2000–01	3 642	3.7	0.0
2001–02	2 106	3.7	0.1
2002–03	1 901	8.6	0.2
2003–04	2 143	5.1	0.0
2004–05	2 733	3.6	0.0
2005–06	2 015	1.7	0.0
2006–07	1 816	5.0	0.0
2007–08	2 213	3.3	0.0

Table 15: Characteristics of the posterior distribution of the parameters in the fitted model for the SA fishery area.

Parameter	Mean	sd	Median	95% credibility interval	
94–95 base strike rate (per 10^3 tows)	1.215	0.858	1.006	0.182	3.472
95–96 base strike rate (per 10^3 tows)	1.295	1.272	0.982	0.080	4.644
96–97 base strike rate (per 10^3 tows)	1.093	0.624	0.923	0.291	2.703
97–98 base strike rate (per 10^3 tows)	1.246	0.940	1.035	0.209	3.595
98–99 base strike rate (per 10^3 tows)	7.323	4.629	6.241	1.437	18.051
99–00 base strike rate (per 10^3 tows)	4.375	2.885	3.810	1.016	12.301
00–01 base strike rate (per 10^3 tows)	2.024	1.160	1.769	0.445	5.253
01–02 base strike rate (per 10^3 tows)	1.500	0.758	1.420	0.185	3.224
02–03 base strike rate (per 10^3 tows)	2.725	1.358	2.479	0.904	6.144
03–04 base strike rate (per 10^3 tows)	3.802	1.949	3.379	1.408	8.779
04–05 base strike rate (per 10^3 tows)	1.994	0.954	1.751	0.687	4.460
05–06 base strike rate (per 10^3 tows)	1.166	0.690	1.044	0.224	2.628
06–07 base strike rate (per 10^3 tows)	3.547	1.616	3.286	1.097	7.051
07–08 base strike rate (per 10^3 tows)	2.038	0.920	1.820	0.895	4.649
subtar puys+auck:midd†	0.329	0.242	0.273	0.050	0.976
subtar puys:shal†	9.95	5.74	8.53	2.95	25.13
subtar stew:shal†	0.089	0.043	0.077	0.030	0.203
subtar stew:midd†	0.834	0.385	0.797	0.224	1.787
gear MW	1.43	0.56	1.32	0.64	2.82
sin(day.no) coefficient	0.950	0.322	0.963	0.316	1.574
cos(day.no) coefficient	0.565	0.273	0.547	0.092	1.118
Extra-dispersion variance	1.36	0.59	1.15	0.60	2.48

† Effects are relative to that for the base level, auck:shal

Table 16: Observed and predicted strike rates, and predicted basking shark captures by fishing year for all tows in the SA fishery area.

Fishing year	Obs. captures	Obs. strike rate ($\times 10^3$)	Predicted basking shark captures: Captures	c.v. (%)	95% pred. interval		Predicted strike rate: Rate ($\times 10^3$)	c.v. (%)
1994–95	0	0	10	69	1	27	0.7	60
1995–96	0	0	11	82	0	34	0.8	75
1996–97	0	0	12	61	2	30	0.8	54
1997–98	0	0	10	73	1	27	0.8	65
1998–99	5	3.0	48	57	13	117	4.3	55
1999–00	6	3.5	39	44	15	82	3.9	41
2000–01	4	1.1	18	42	7	36	1.7	36
2001–02	3	1.4	19	42	6	37	1.6	36
2002–03	10	5.2	47	28	26	77	4.0	25
2003–04	7	3.3	34	37	16	64	2.9	34
2004–05	3	1.1	17	42	6	35	1.4	35
2005–06	0	0	7	63	1	18	0.7	50
2006–07	6	3.3	23	35	11	41	2.9	30
2007–08	3	1.4	11	42	4	22	1.6	33
All	47	1.8	306	17	217	433	1.9	17

Table 17: Summary of predicted basking shark strike rates (per 1000 tows) and overall strike rates, with c.v.s (%) for the three modelled fishery areas, and all areas combined. The entries in the 'Tows' columns are the numbers of observed plus unobserved tows.

Fishing	EC			WC			SA			All areas		
year	Tows	Rate	c.v.	Tows	Rate	c.v.	Tows	Rate	c.v.	Tows	Rate	c.v.
1994–95	6 658	2.2	128	9 079	2.9	68	13 628	0.7	60	29 365	1.7	53
1995–96	10 429	1.2	98	7 610	0.7	110	13 280	0.8	75	31 319	0.9	55
1996–97	9 460	5.3	129	9 037	5.0	80	14 189	0.8	54	32 686	3.3	69
1997–98	11 338	15.6	24	8 533	4.8	101	12 585	0.8	65	32 456	7.0	26
1998–99	9 763	3.8	44	7 830	2.5	249	11 165	4.3	55	28 758	3.7	55
1999–00	10 406	2.1	104	7 972	2.0	106	9 964	3.9	41	28 342	2.7	42
2000–01	10 087	2.6	48	9 228	0.6	112	10 873	1.7	36	30 188	1.6	31
2001–02	7 251	0.8	83	8 274	0.3	91	12 225	1.6	36	27 750	1.0	32
2002–03	8 887	3.8	53	8 326	0.9	90	11 703	4.0	25	28 916	3.1	25
2003–04	5 344	2.8	84	7 336	0.4	121	11 501	2.9	34	24 181	2.1	34
2004–05	4 985	1.2	91	4 742	4.7	40	12 194	1.4	35	21 921	2.1	27
2005–06	5 185	1.2	99	4 703	0.3	113	10 029	0.7	50	19 917	0.7	49
2006–07	4 120	1.3	96	2 943	0.7	102	7 695	2.9	30	14 758	2.0	29
2007–08	4 165	1.2	101	2 559	0.6	134	6 744	1.6	33	13 468	1.3	37
All years	108 078	3.9	24	98 172	2.0	62	157 775	1.9	17	364 025	2.5	18

Table 18: Summary of predicted basking shark captures (observed plus predicted unobserved) with c.v.s (%) for the three modelled fishery areas, and all areas combined.

Fishing	EC		WC		SA		All areas	
year	Caps	c.v.	Caps	c.v.	Caps	c.v.	Caps	c.v.
1994–95	15	130	26	72	10	69	51	55
1995–96	12	104	5	133	11	82	29	60
1996–97	51	130	45	157	12	61	108	90
1997–98	177	26	41	100	10	73	228	27
1998–99	38	47	19	254	48	57	105	56
1999–00	22	107	16	111	39	44	77	44
2000–01	26	51	5	129	18	42	49	34
2001–02	6	93	2	115	19	42	27	37
2002–03	34	56	8	91	47	28	89	27
2003–04	15	88	3	134	34	37	52	36
2004–05	6	99	22	44	17	42	46	30
2005–06	6	105	1	166	7	63	15	56
2006–07	5	102	2	125	23	35	30	33
2007–08	5	108	2	163	11	42	18	43
All years	418	25	199	65	306	17	922	19

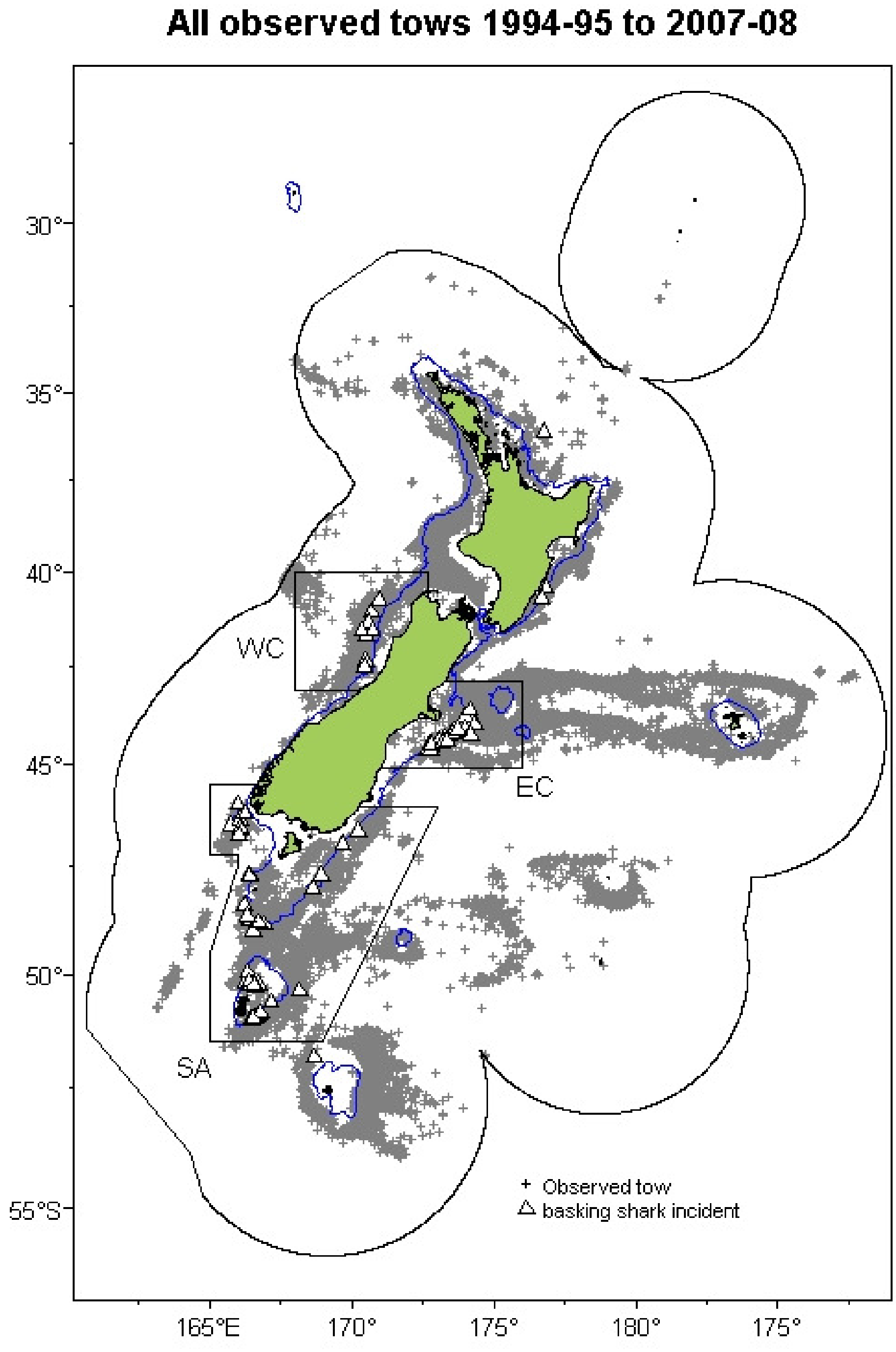


Figure 1: Start positions of all observed tows (all target species) inside the New Zealand EEZ in the fishing years 1994–95 to 2007–08, with start positions of observed tows on which basking shark captures occurred. Also shown are the boundaries of the three fishery areas used for analysis, the EEZ, and the 200 m depth contour.

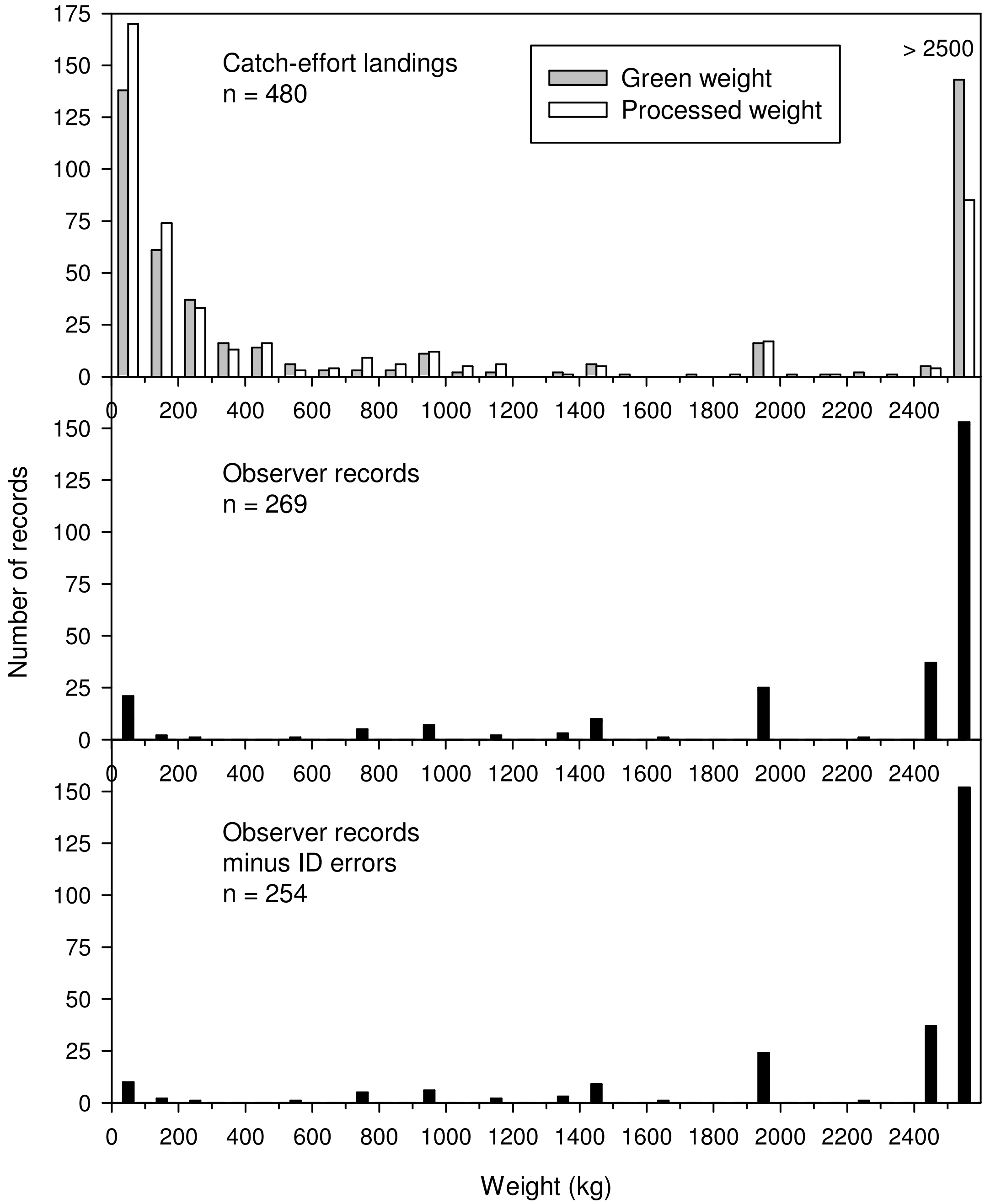


Figure 2: Weight-frequency distributions of basking shark records from catch effort returns, and observer records before and after grooming for species identification errors.

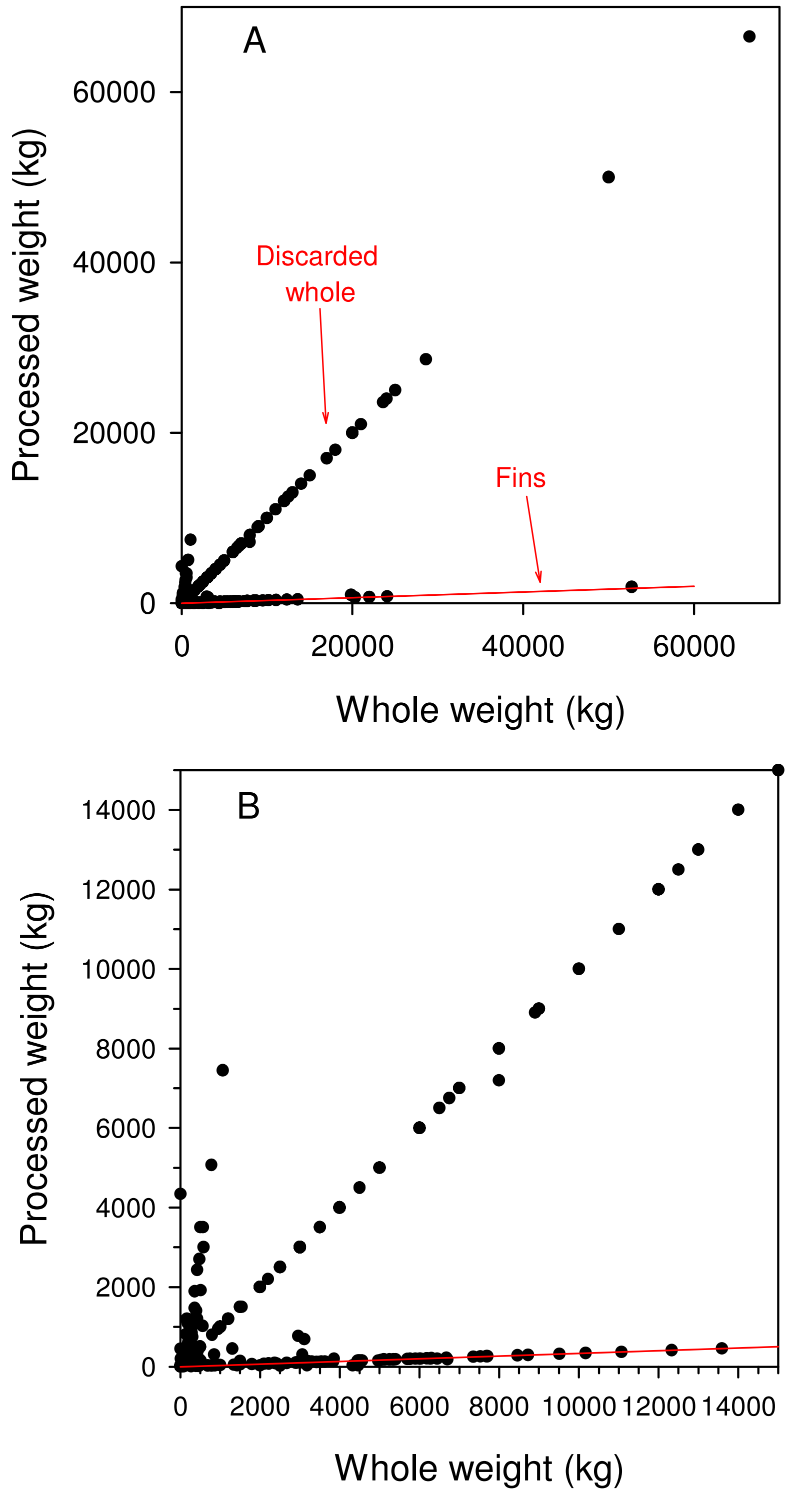


Figure 3: Comparison between whole and processed basking shark weights reported on catch effort landing returns. Panel B is an enlargement of part of panel A.

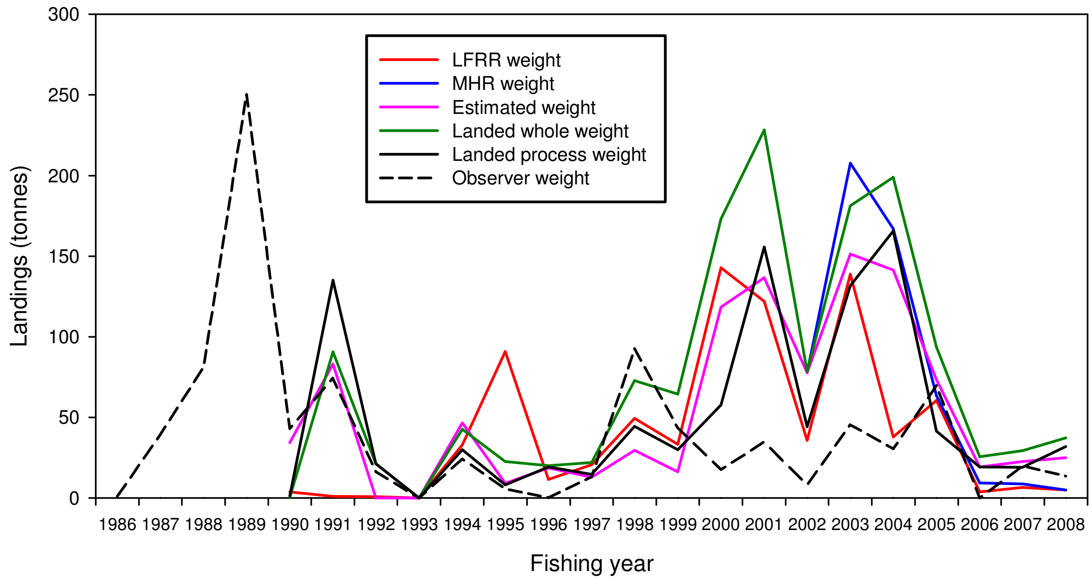


Figure 4: Annual trends in basking shark commercial fishing data and observer records. LFRR, Licensed Fish Receiver returns; MHR, Monthly Harvest Returns.

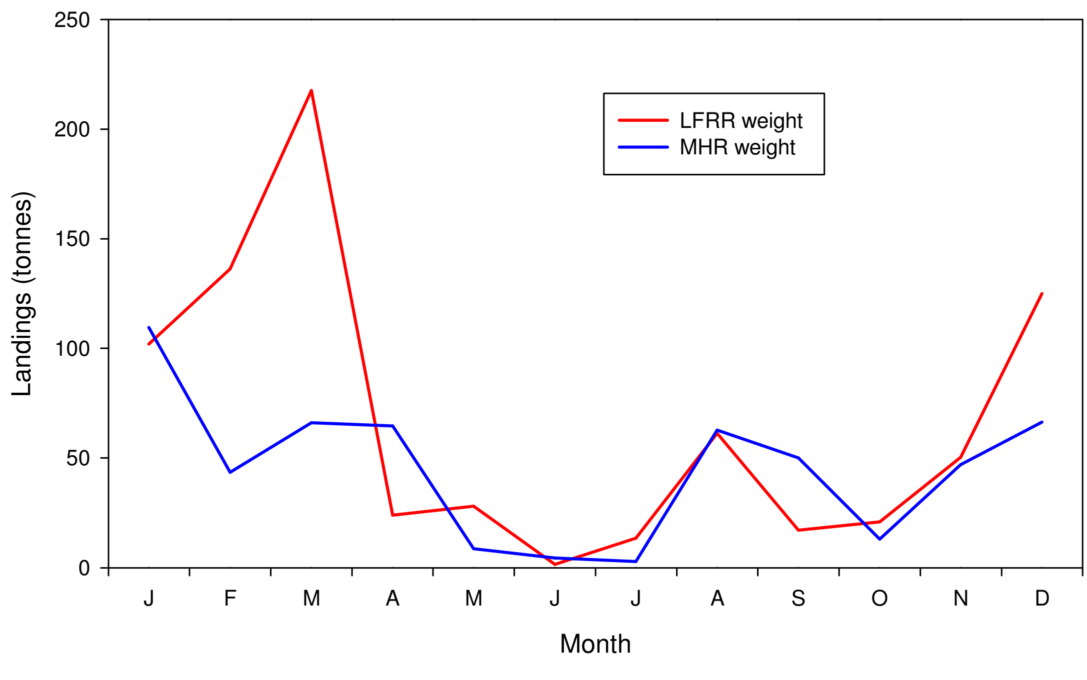
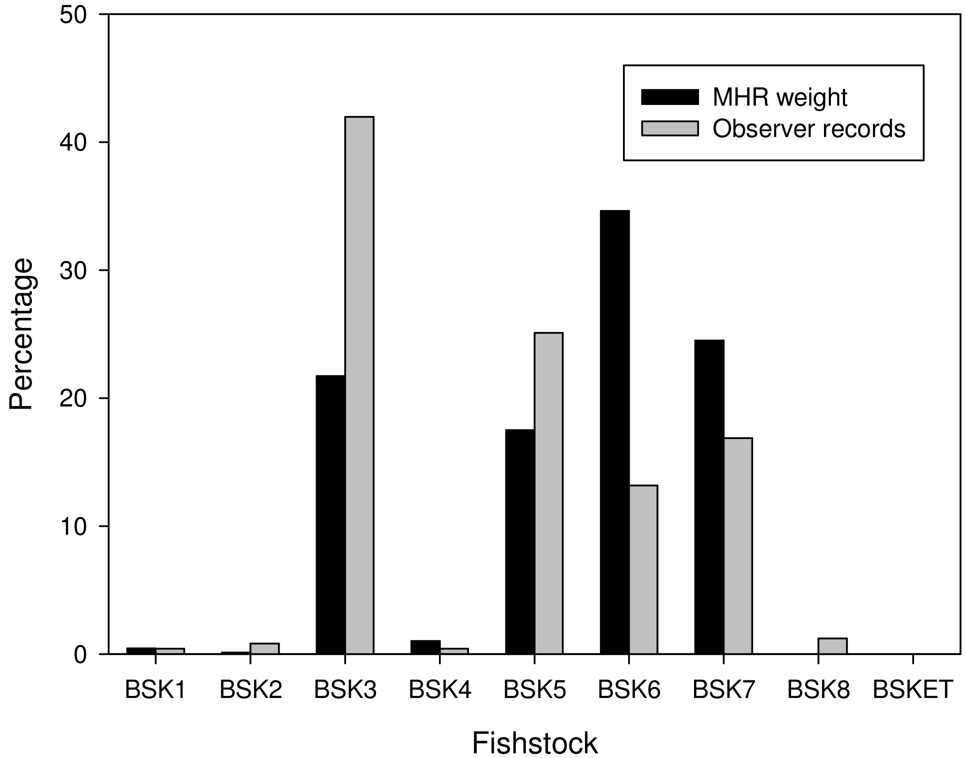


Figure 5: Seasonal trends in basking shark landings from LFRR (1989–90 to 2007–08) and MHR (2001–02 to 2007–08) data.



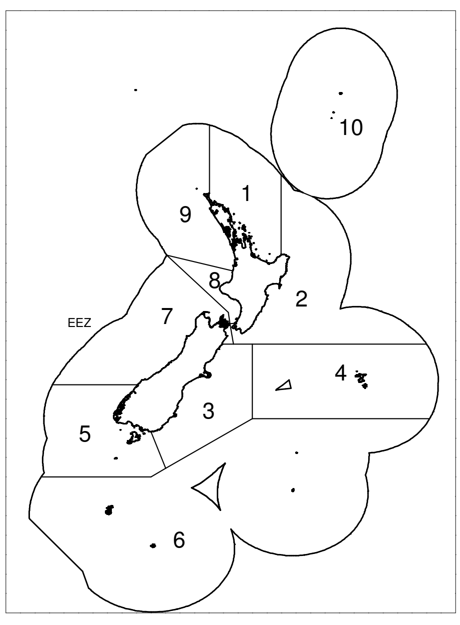


Figure 6: Reported and observed basking shark catches by Fisheries Management Area. MHR, Monthly Harvest Returns; EEZ, Exclusive Economic Zone; ET, extra-territorial catches from outside the EEZ.

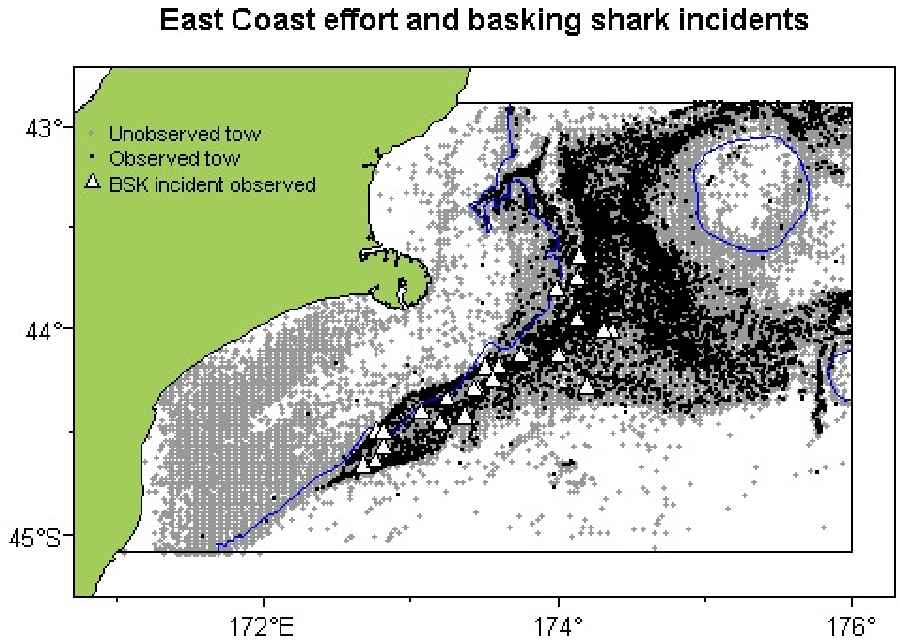


Figure 7: Plot of start positions of all unobserved tows, observed tows, and observed basking shark incidents for the EC fishery area. The 250 m depth contour is shown.

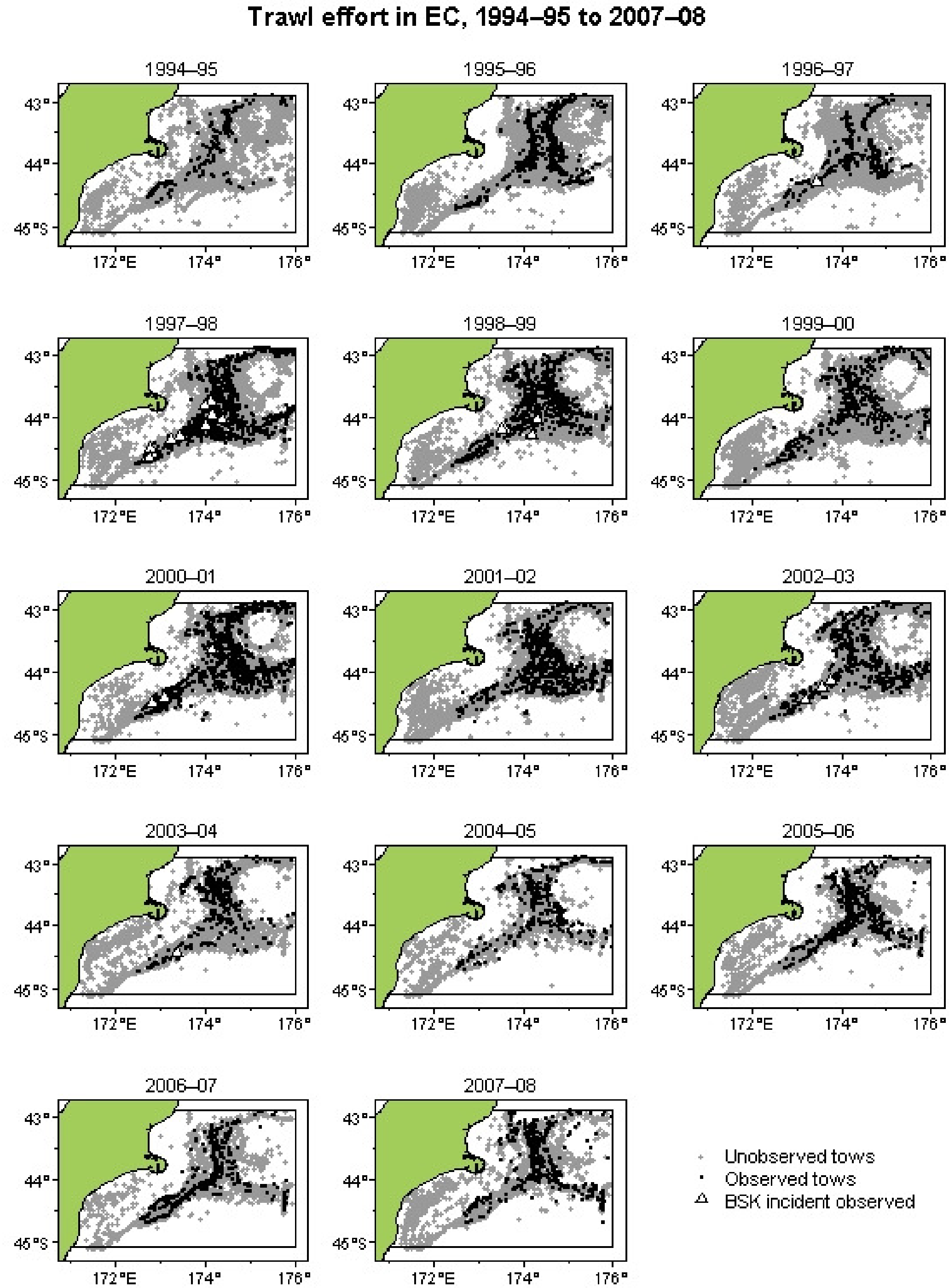


Figure 8: Plots by fishing year of the start positions of unobserved tows, observed tows, and observed basking shark incidents for the EC fishery area.

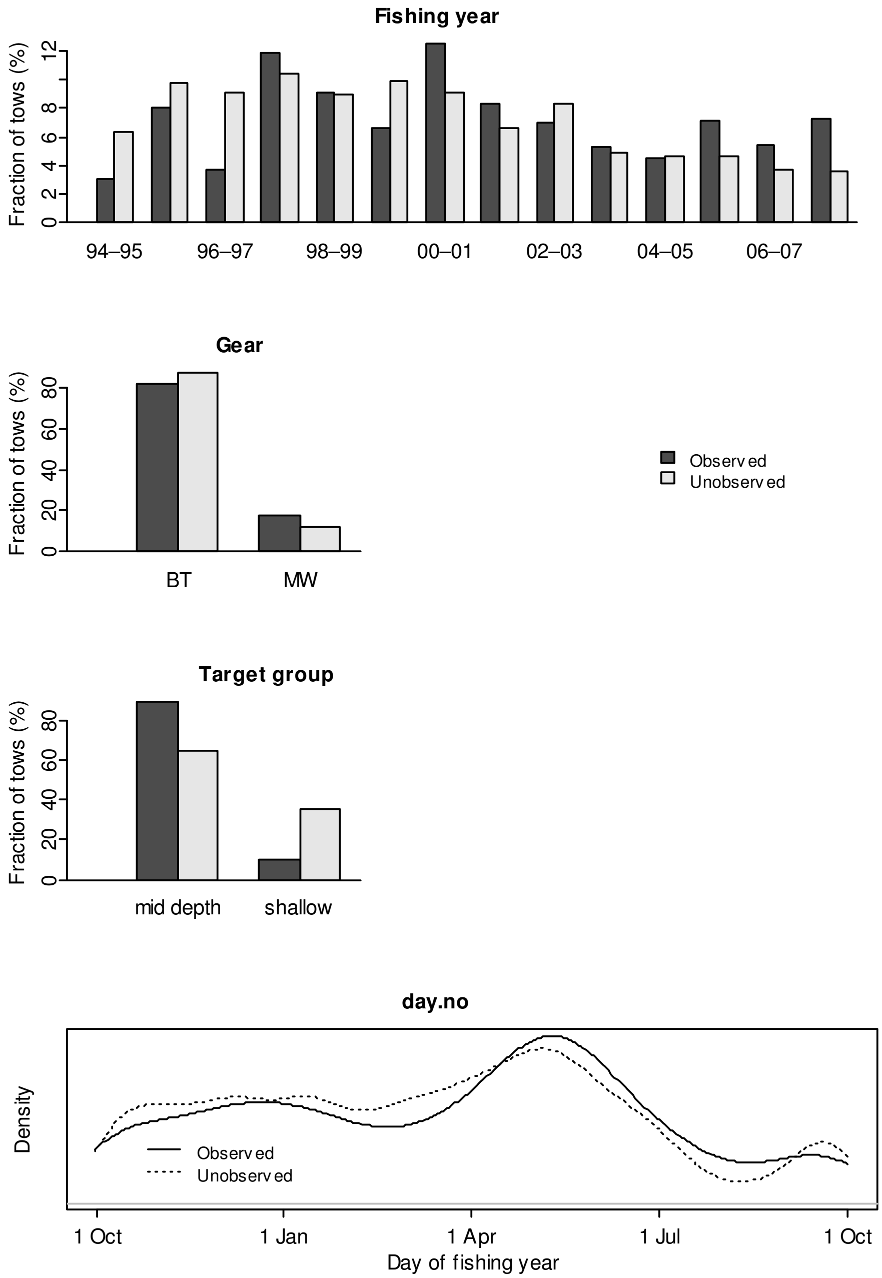


Figure 9: Comparison of the distributions of observed and unobserved tows by fishing year, gear type, target species group and time of year for the EC fishery area.

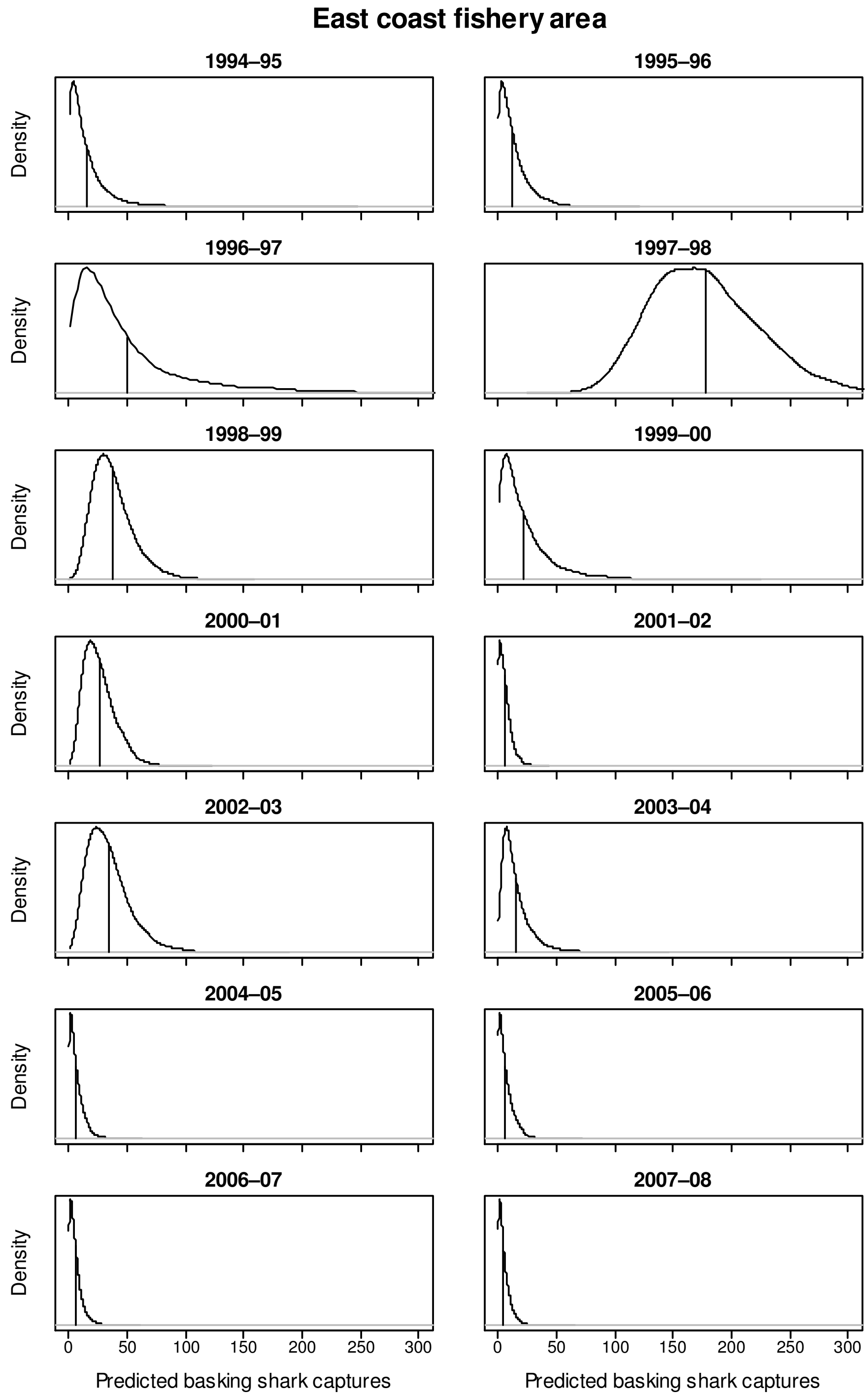


Figure 10: Plots of the predictive densities, by fishing year, for basking shark captures for all tows in the EC fishery area.

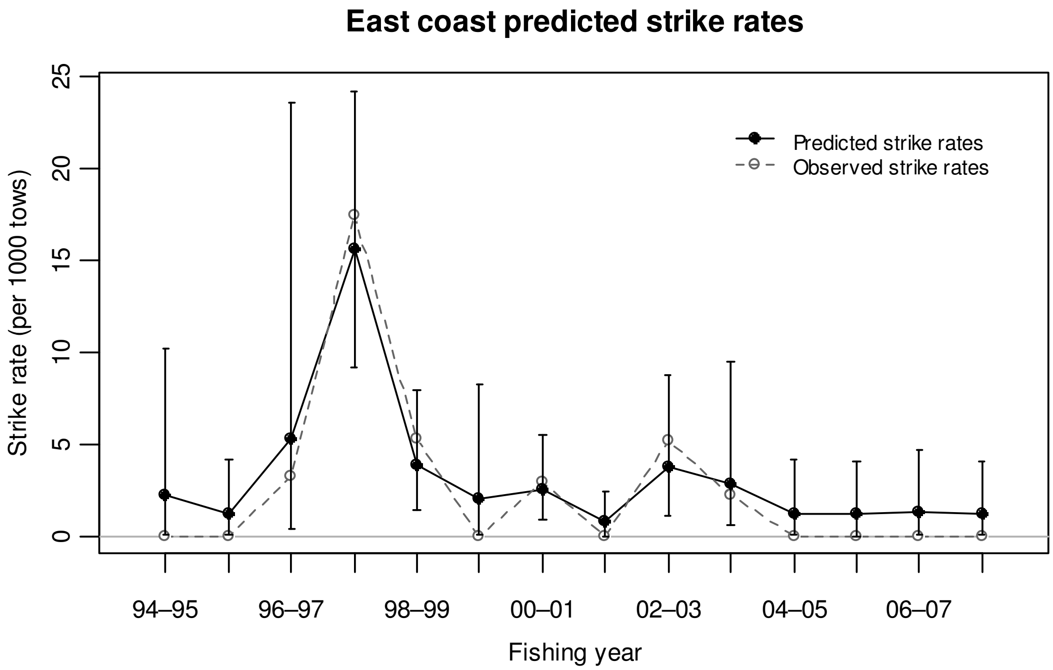


Figure 11: Predicted and observed basking shark strike rates, with 95% prediction intervals, for all tows in the EC fishery area.

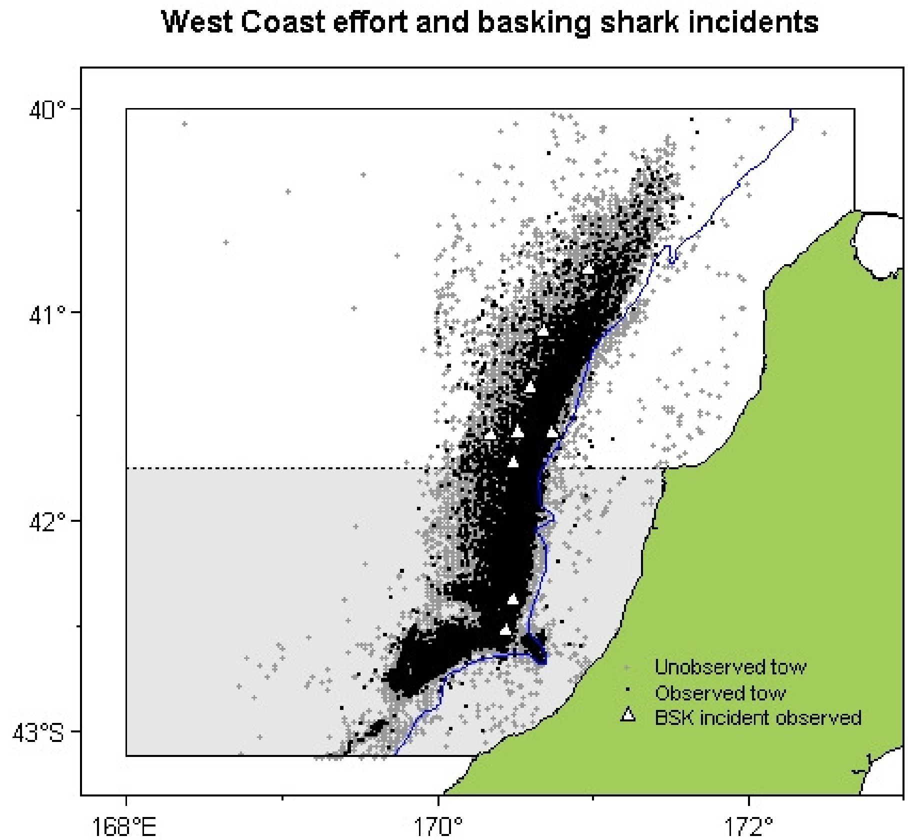


Figure 12: Plot of start positions of unobserved tows, observed tows, and observed basking shark incidents for the WC fishery area. The 250 m depth contour is shown and the south subarea is shaded.

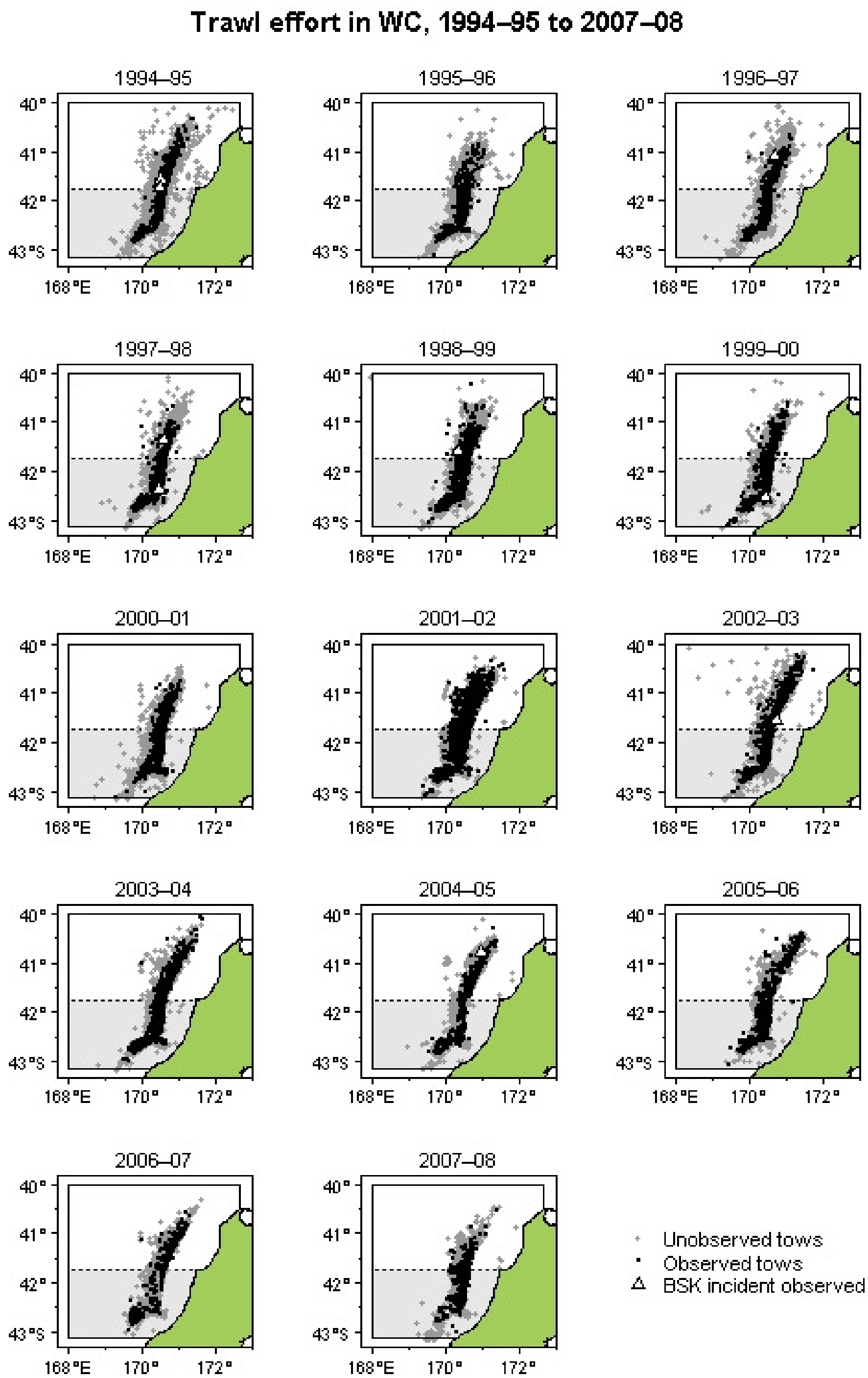


Figure 13: Plots by fishing year of start positions of unobserved tows, observed tows, and observed basking shark incidents for the WC fishery area. The south subarea is shaded.

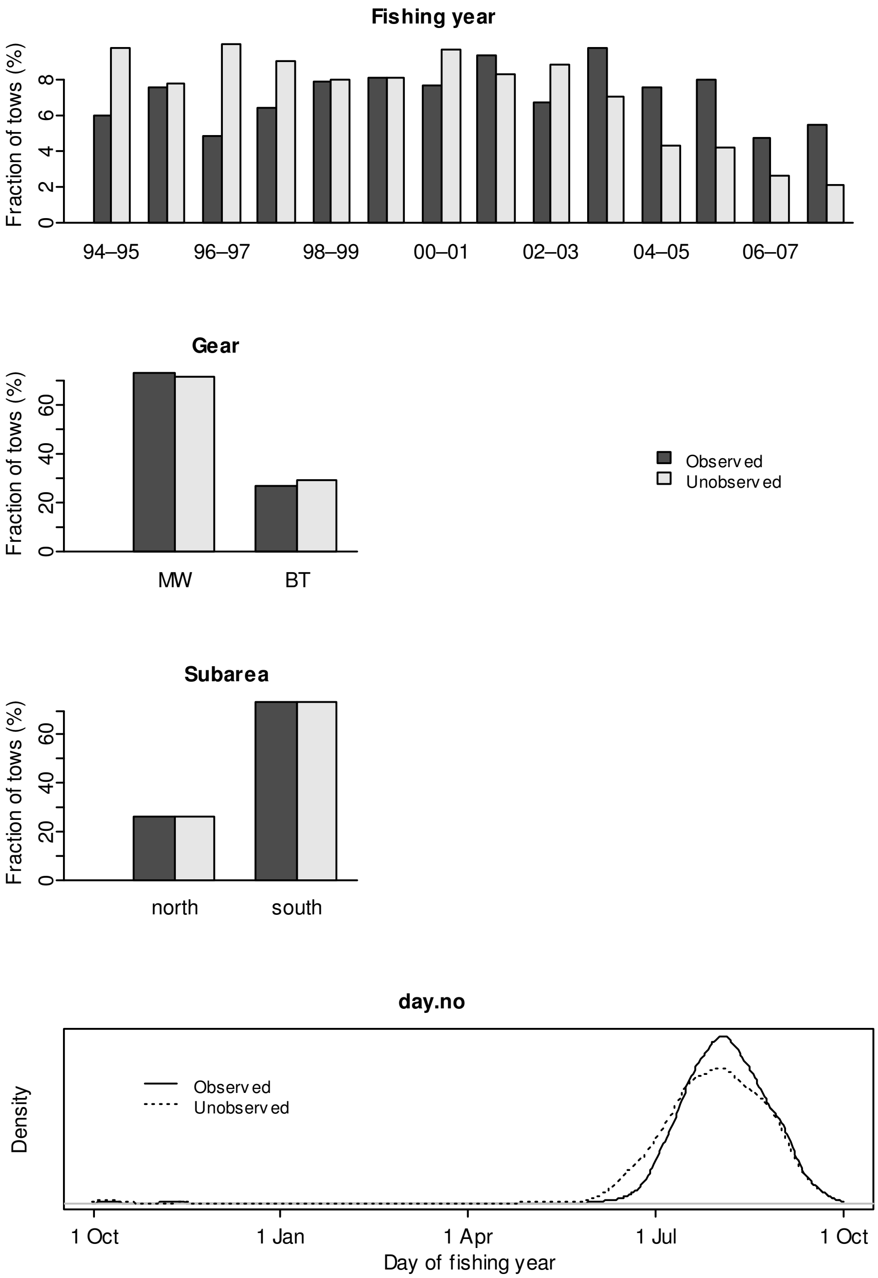


Figure 14: Comparison of the distributions of observed and unobserved tows by fishing year, gear type, target species group and time of year for the WC fishery area.

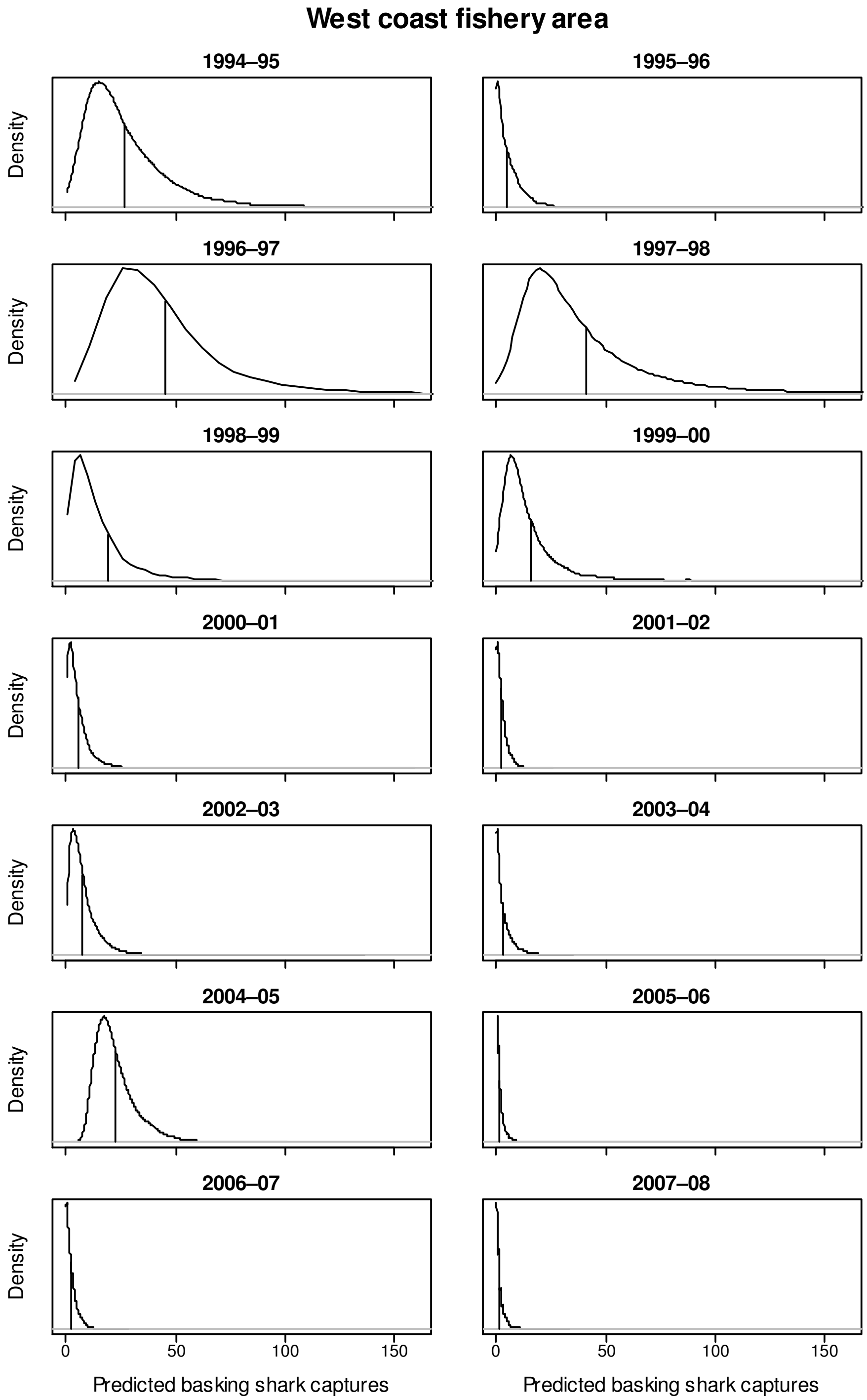


Figure 15: Plots of the predictive densities, by fishing year, for basking shark captures for all tows in the WC fishery area.

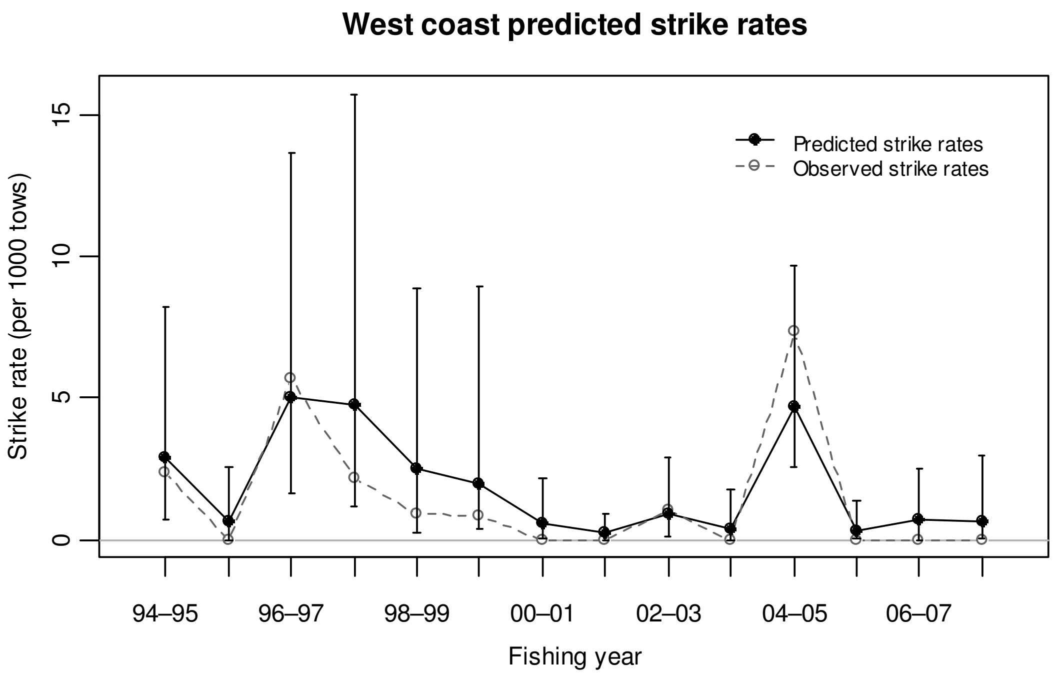


Figure 16: Predicted and observed basking shark strike rates, with 95% prediction intervals, for all tows in the WC fishery area.

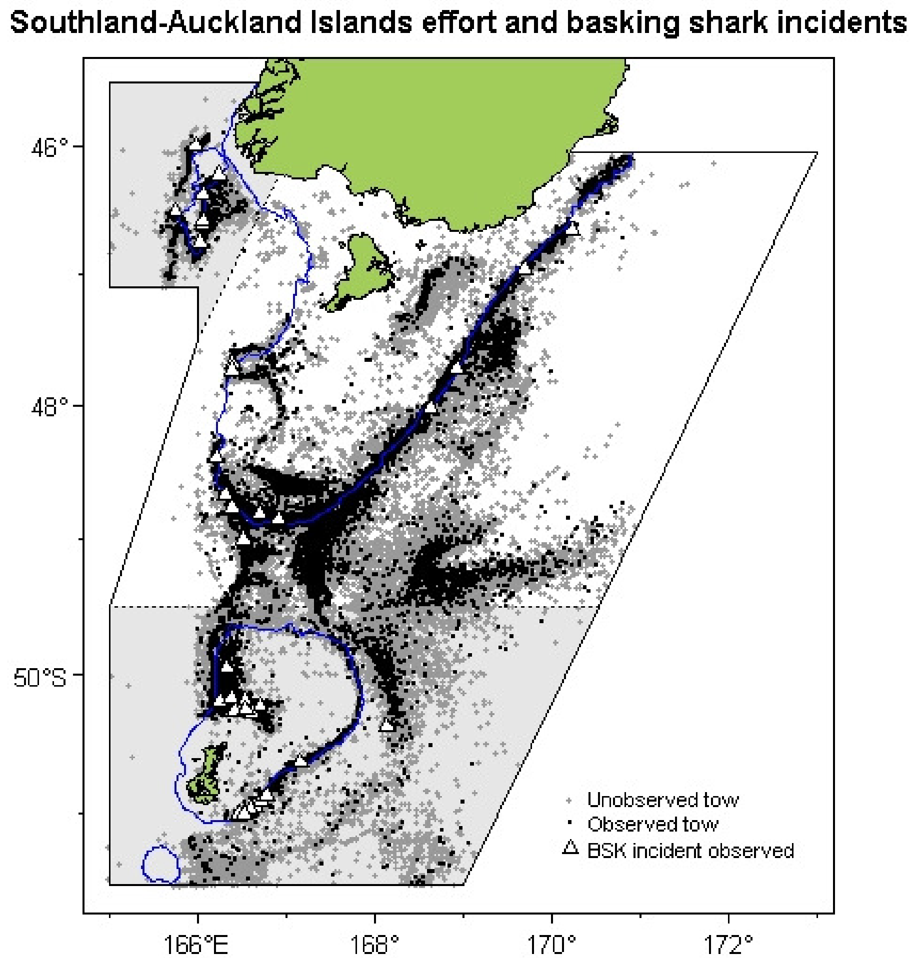


Figure 17: Plot of start positions of all unobserved tows, observed tows, and observed basking shark incidents for the SA fishery area. The 250 m depth contour is shown and the Puysegur and Auckland Islands subareas are shaded.

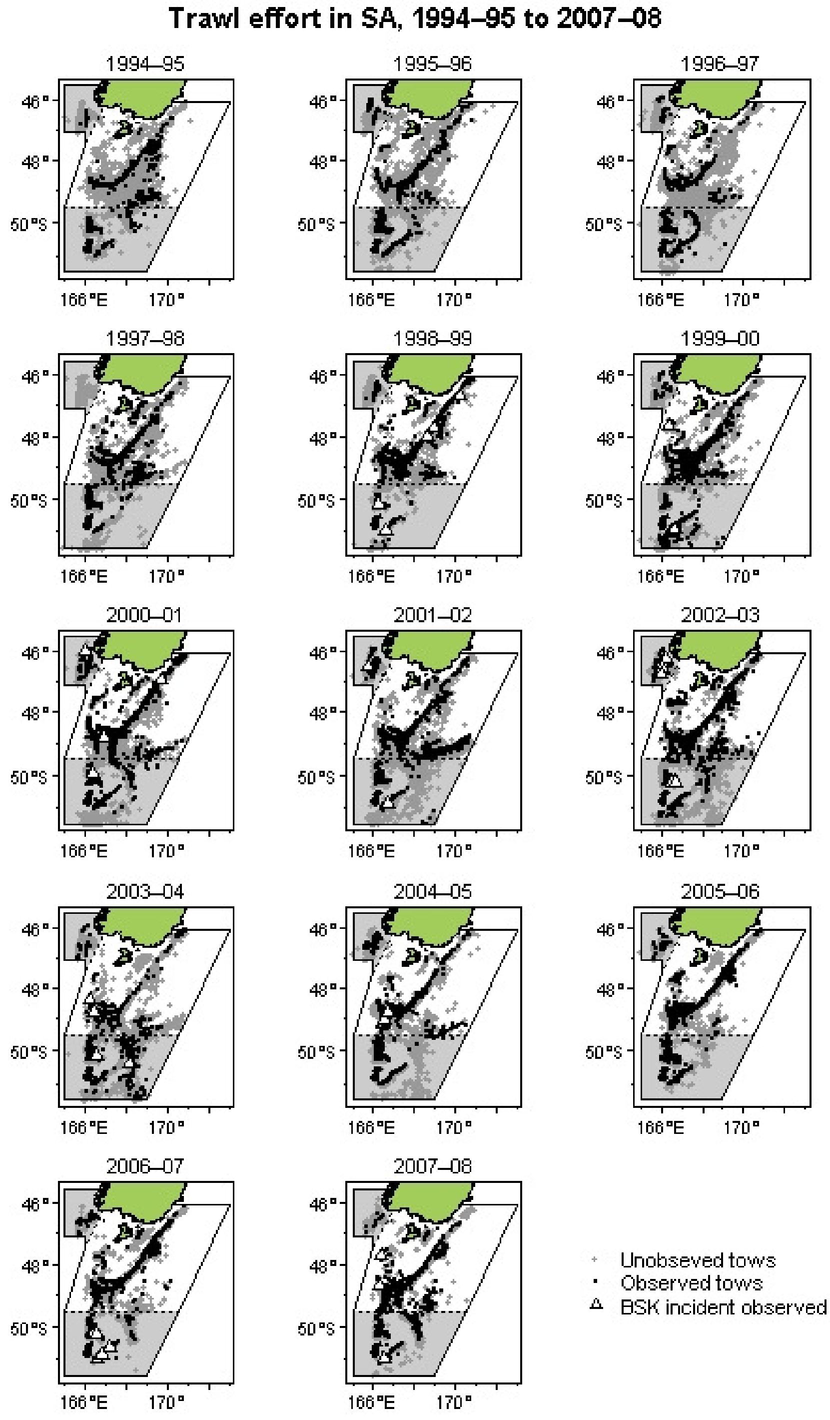


Figure 18: Plots by fishing year of the start positions of unobserved tows, observed tows, and observed basking shark incidents for the SA fishery area. The Puysegur and Auckland Islands subareas are shaded.

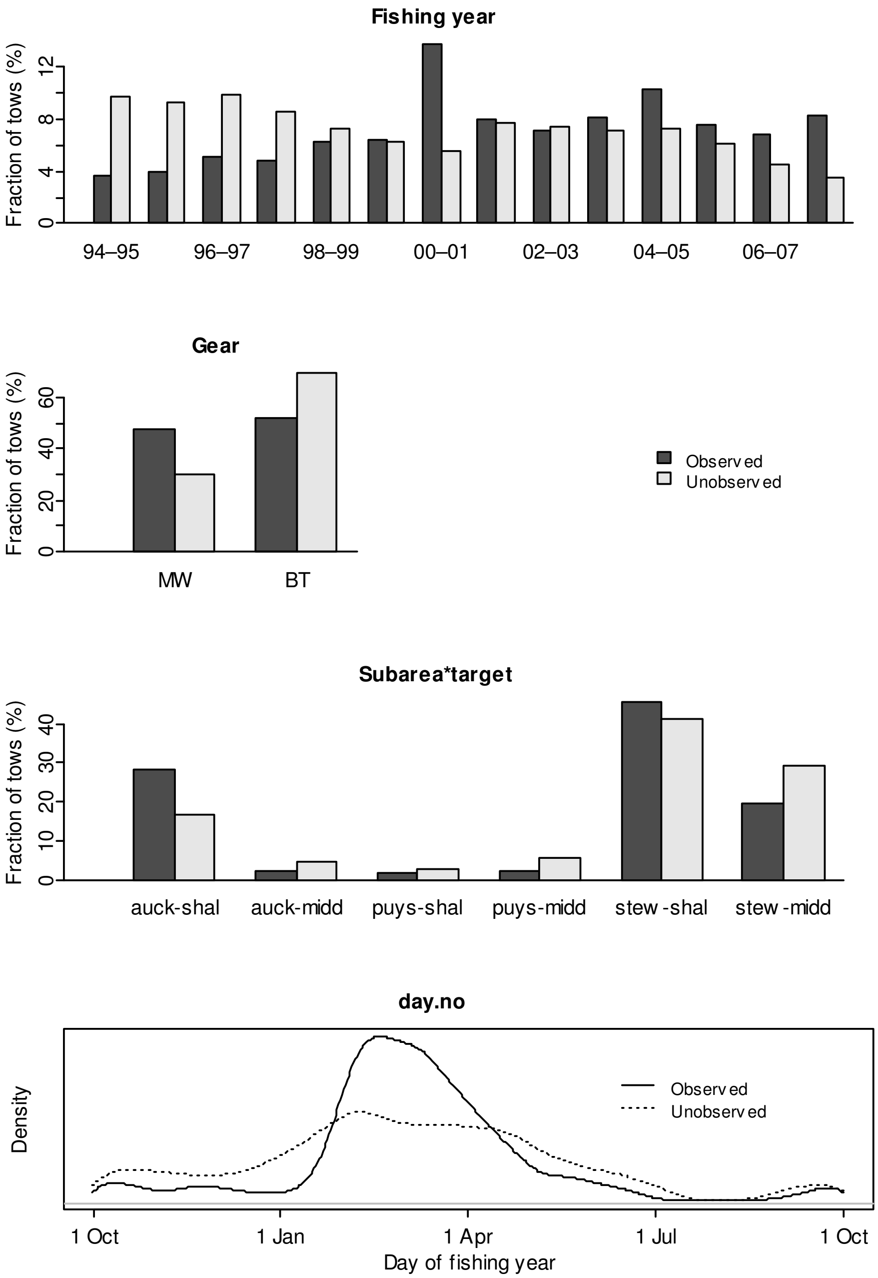


Figure 19: Comparison of the distributions of observed and unobserved tows by fishing year, gear type, target species group and time of year for the SA fishery area.

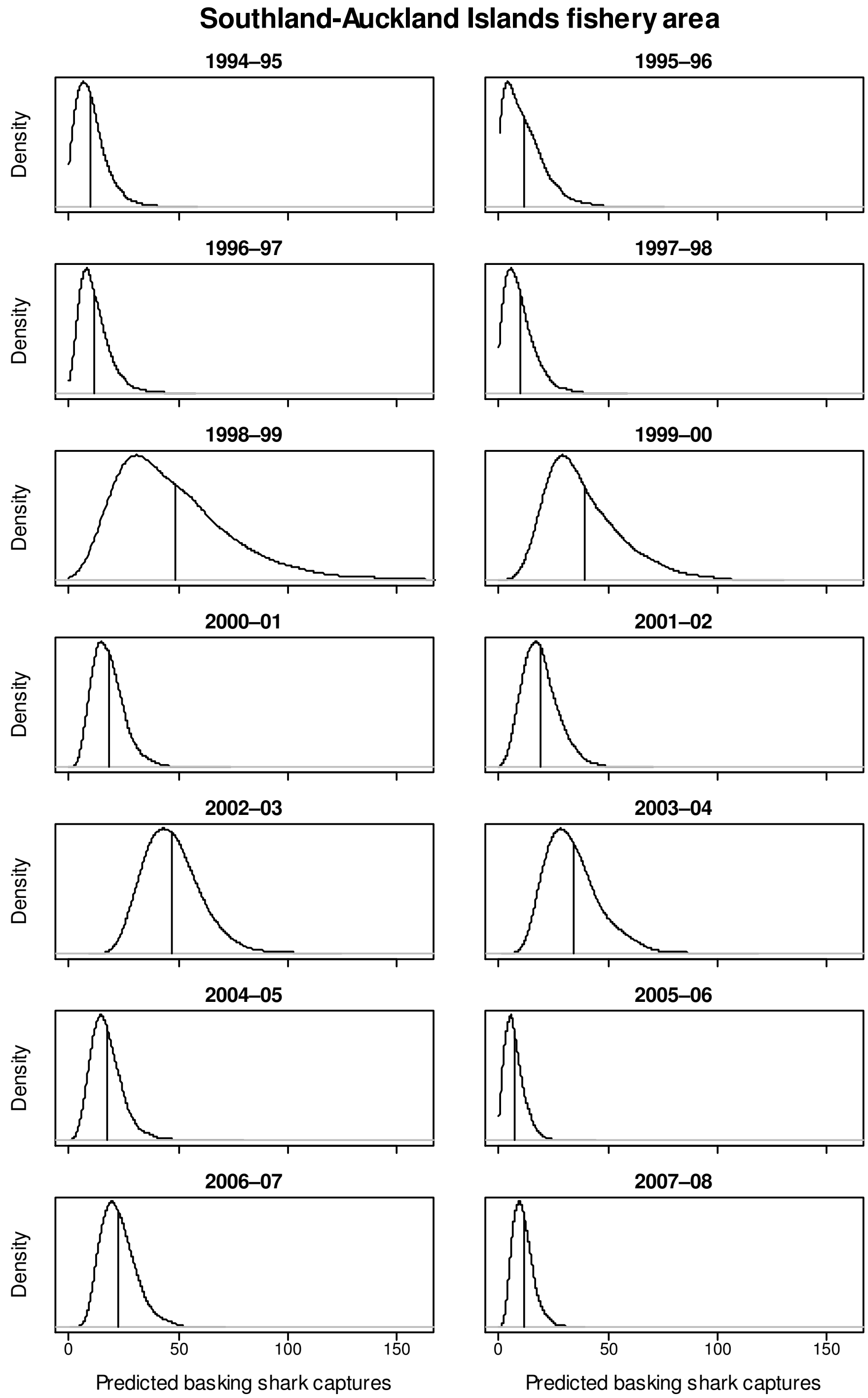


Figure 20: Plots of the predictive densities, by fishing year, for basking shark captures for all tows in the SA fishery area.

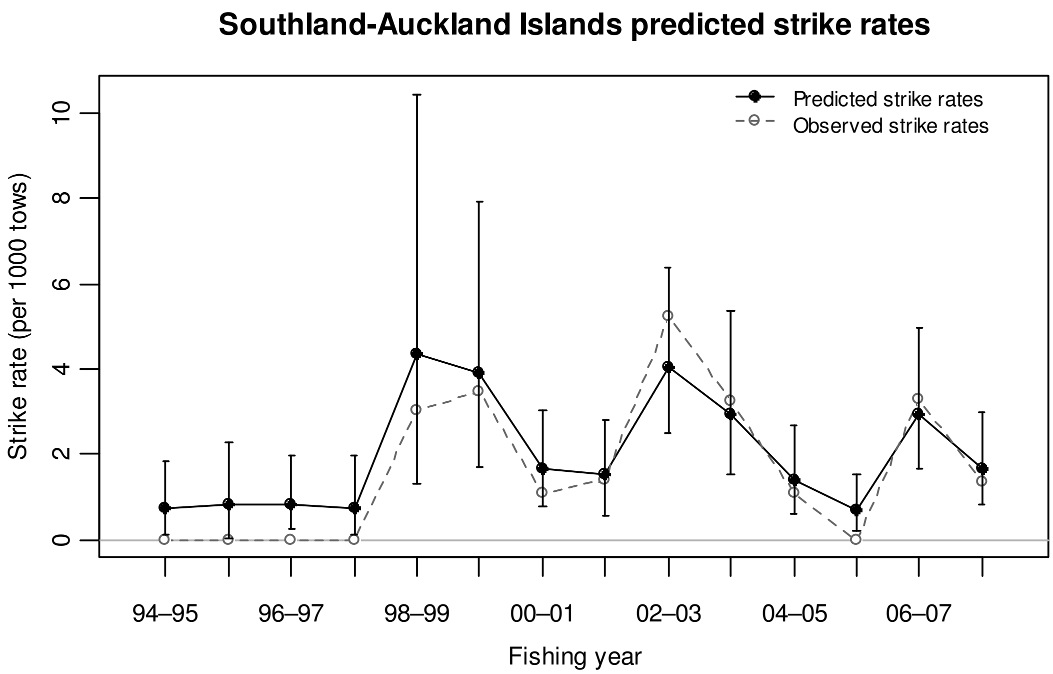


Figure 21: Predicted and observed basking shark strike rates, with 95% prediction intervals, for all tows in the SA fishery area.

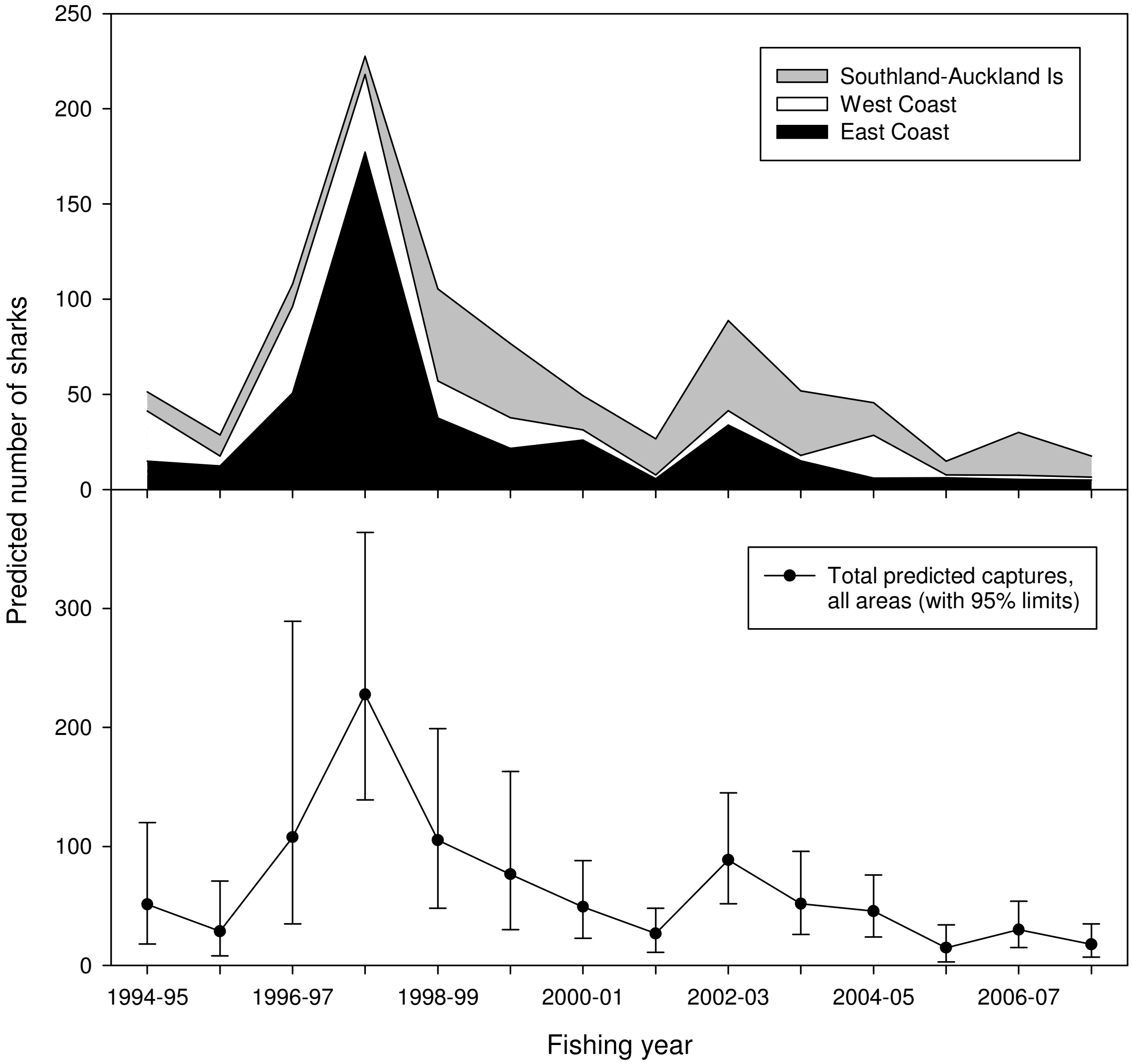


Figure 22: Predicted number of basking shark captures by fishery area (top) and for all areas combined (bottom).

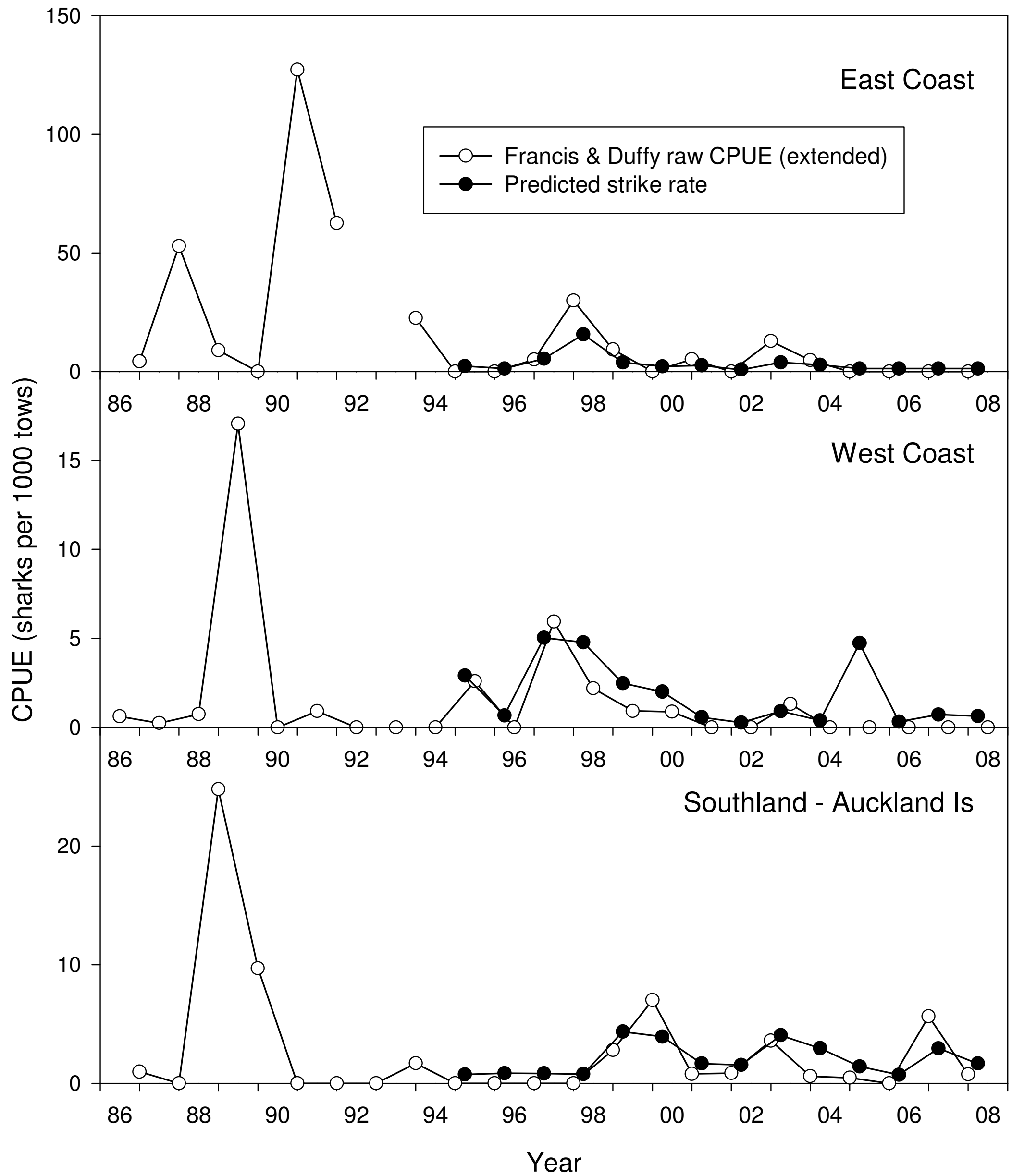


Figure 23: Comparison of predicted basking shark strike rates (present study) with raw catch per unit effort (CPUE) (1986–99 after Francis & Duffy (2002); 2000–08 present study). The Francis & Duffy series are based on smaller areas and fewer target species than the predicted strike rates. Data points represent different time periods: Francis & Duffy East Coast and Southland–Auckland Is series – July–June years; Francis & Duffy West Coast series – calendar years; predicted strike rate (present study) – fishing years (October–September).

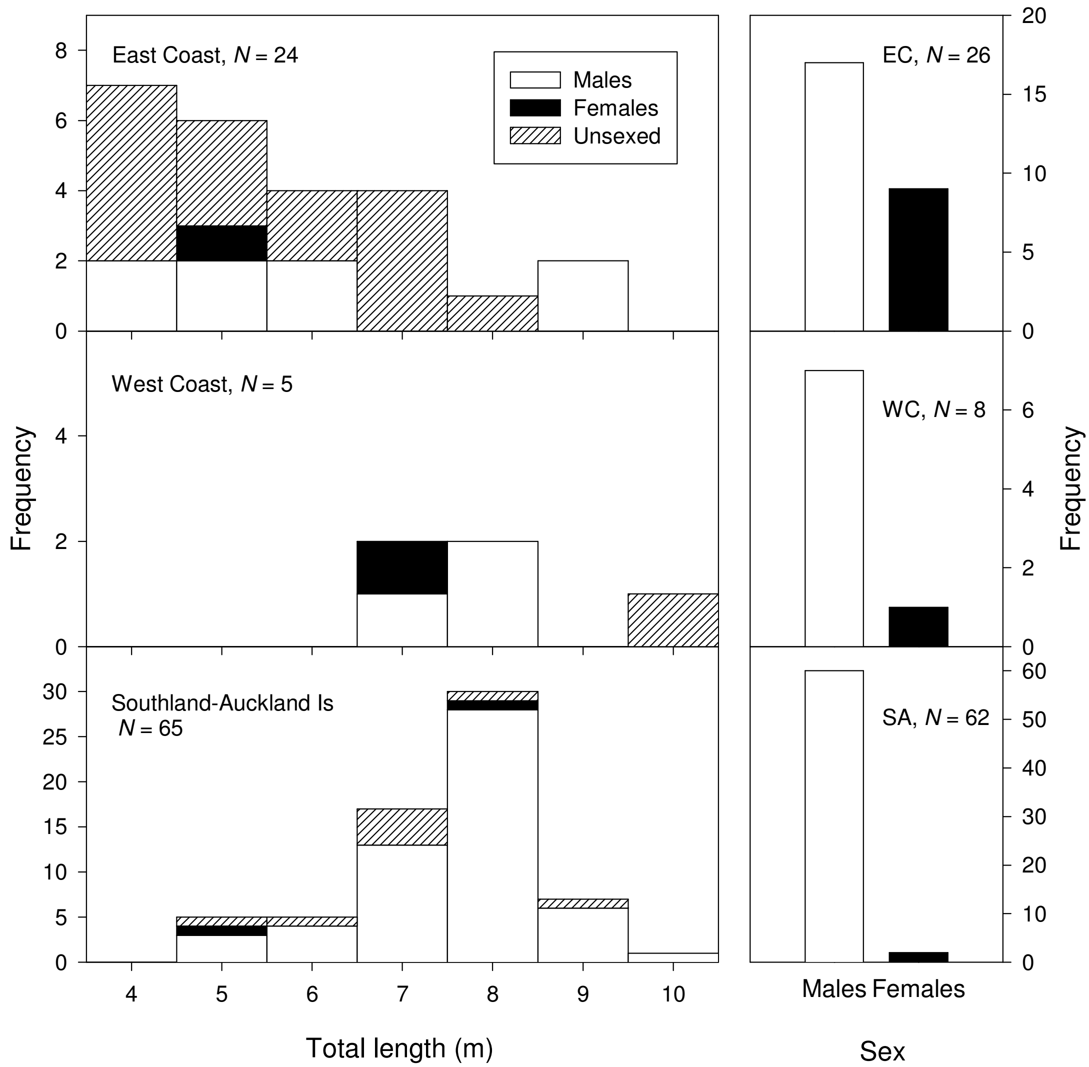


Figure 24: Basking shark length-frequency distributions and sex ratios recorded by observers aboard trawlers in three fishery areas. Total lengths were rounded down to the metre below actual or estimated length.

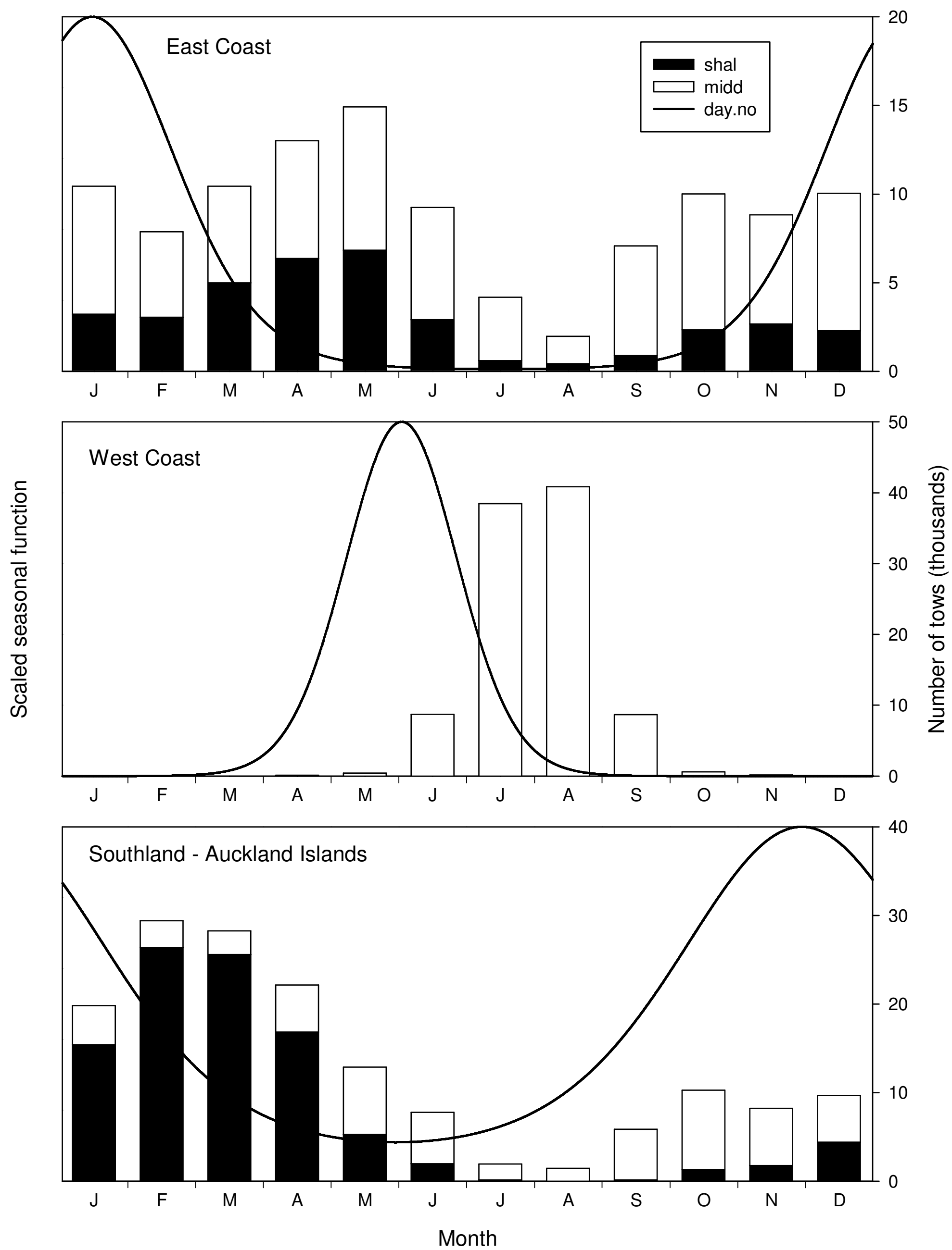


Figure 25: Comparison of modelled basking shark seasonal catch rate function (day.no) and the seasonal distribution of commercial trawl tows in three fishery areas, 1994–95 to 2007–08. The catch rate functions are scaled to the same maximum value in all three panels, although the amplitude of the day.no function varied among areas. Commercial tows are classified by the target fisheries used in the models.