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EXECUTIVE SUMMARY

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New Zealand Fisheries Assessment Report 2003/57. **73 p.**

This report forms part of the output from Research Project ENV2000/03: Estimation of non-target fish catch and both target and non-target fish discards in selected New Zealand fisheries. It addresses the specific objective: *To explore the effects of various factors on the catch rates and discards of non-target fish, particularly oceanic sharks, broadbill swordfish, and marlin species, in the tuna longline fishery for the fishing years 1998/99 and 1999/2000, taking into account the historical data from 1990/91 to 1999/2000.*

The information used comes from the Scientific Observer Programme operating on the tuna longline fishery. The observed sets are stratified into those by the charter vessels (large vessels mainly setting over 2500 hooks) and with greater than 90% observer coverage in recent years, and by domestic vessels (small vessels mainly setting about 1000 hooks) that has had less than 1% observer coverage in recent years. The sets are also stratified into the four areas defined by the Ministry of Fisheries for use with this fishery.

The distribution of the observed tuna longline sets and the catch rates of several species on these sets are plotted for the recent years of the fishery. These plots show that the west coast of the South Island (Area 3) is the only location where the set positions were sufficiently consistent from year to year to allow reliable comparisons. They also show where the non-target fish species of interest are caught and many are caught in Area 3. However, some of the species of interest are only, or predominantly, caught in the north where the (observed) fishing by the charter fleet is sporadic and the observer coverage of the domestic fleet has been low and not representative of that fishery.

Several statistical models are used to formally identify the factors that influence catch of the species of interest. The statistical models generally fitted the data poorly, even when the data appeared adequate for the analyses. It seems that the data distributions do not conform to any of the statistical distributions tried.

However, we can be reasonably certain that a fishery independent variable has a real influence on the catch when it accounts for a large (and significant) amount of the variance (or deviance) in the data. Examples of such factors are the negative correlation between blue shark catch and a diversity index for the species caught, the positive correlation between the illuminated proportion of the moon's disc and the dealfish catch, and positive correlation between sea temperature and striped marlin catch. Fishing year was a significant factor in most models but may be related to the operation of the fishery.

One interesting feature is that the catch rates of broadbill swordfish by the domestic fleet appear to have risen over time. A similar trend is not evident in the catch rates of this species by the charter fleet.

Most bycatch species are discarded, except that some of the shark species are finned, so the factors influencing the discards of these species are the same as the factors influencing the catch. The catch of some species, such as broadbill swordfish, are mainly kept and there are insufficient discards to interpret the reasons for them.

Appendix 1 discusses the representativeness of the observer coverage in 1998–99 and 1999–2000. The coverage was good for the charter fleet and poor for the domestic fleet.

1. INTRODUCTION

The Ministry of Fisheries is responsible for determining the effects of fishing on associated species, including non-target fish species, taken as bycatch during normal fishing operations. This work covers part of that responsibility and uses data collected by the Scientific Observer Programme on the tuna longline fishery.

Tuna longline fishing is often considered a highly specific, environmentally sound fishing technique compared with other methods. However, for some target species, areas, and seasons, bycatch levels can be high (Francis et al. 1999a, 2000). In the New Zealand EEZ, scientific observers recorded more than 70 non-target fish species in the bigeye (*Thunnus obesus*) and southern bluefin (*Thunnus maccoyii*) target fisheries and 13 of the top 17 species (in numbers) were non-target species.

Oceanic sharks are an important bycatch of tuna longline fisheries throughout the Pacific Ocean, and demand for shark fins in Asia has led to an increase in their catch in recent years (Bonfil 1994, Hayes 1996). Oceanic sharks generally have low reproductive rates, long life spans, and possibly slow growth, and they segregate by size and sex. These features make them vulnerable to overfishing (Fogarty et al. 1989, Compagno 1990, Hoenig & Gruber 1990).

Billfish species are commonly caught in longline fisheries targeting tunas. The species vulnerable to tuna longline fisheries vary with area and fishery. Bailey et al. (1996) reported that blue marlin were the most common bycatch species in the western tropical Pacific longline fishery while in Australia short-billed spearfish predominate. In New Zealand, broadbill swordfish are commonly caught, and striped marlin occasionally taken; other marlins are rarely caught (Francis et al. 1999a, 2000). Of these, domestic fishers can retain only swordfish; the other billfish species must be returned to the water alive or dead. Commercial fishers report that with the decrease in foreign tuna longline activity and the "Billfish Moratorium", marlins, especially striped marlin, are now more frequently caught. Commercial fishers view the practice of dumping dead striped marlin (a commercially valuable species) as a waste of a valuable resource of no benefit to any fishing sector or resource. Recreational fishers are concerned about any potential impact on the recreational striped marlin fishery from increased domestic tuna longline activity.

Tuna are oceanic migratory species and vessels targeting them generally follow the migratory patterns of the most desirable species (in New Zealand waters these are southern bluefin and bigeye tuna). When targeting these species, the lines are set roughly between 50 and 200 metres below the surface and often in areas with a steeply shelving seabed. Many of the bycatch species are oceanic migratory species, though not necessarily with the same migratory patterns as the tunas. All necessarily have some pelagic characteristics as the tuna lines are set well off the bottom. The bycatch species are likely to be following food supplies even if they are not migrating over oceanic distances. That is, these fish populations are not static (and neither are the positions of the ocean currents and the upwellings that bring nutrients to the surface). Thus, we need to know a good deal about fish behaviour before we can be assured that the results of any statistical analysis are meaningful.

In this report, the factors influencing the catch (and, by implication, discards) of the following species are investigated: blue sharks, *Prionace glauca*; Ray's bream, *Brama brama*; dealfish, *Trachypterus trachypterus*; porbeagle shark, *Lamna nasus*; mako shark, *Isurus oxyrinchus*; broadbill swordfish, *Xiphias gladius*; and striped marlin, *Tetrapturus audax*. Some exploratory analysis of the school shark, *Galeorhinus galeus*, catch is included since they are the Quota Management species most frequently caught in this fishery.

The first factors influencing the bycatch of a fish species on a tuna longline will be whether they happen to be in the same location (including depth) at the same time as the tuna, that is, how well the migratory pattern and/or habitat preferences of a particular species match the migratory patterns of the tunas. Such factors complicate any statistical analysis to determine temporal and spatial factors influencing the bycatch of fish species. This assumes that vessels are fishing in areas with highest tuna catch rates, but other considerations, such as the probability of catching rare sea birds, may influence where vessels fish. Both fishery dependent and fishery independent factors are used in the analyses.

1.1 Previous related work

Francis et al. (1999b) investigated the factors influencing the catch rates of the main non-target species (blue, porbeagle, and mako sharks, and Ray's bream) using data from the charter fleet targeting southern bluefin tuna. They used data from the following times and areas:
Blue and porbeagle sharks, and Ray's bream: March–July, latitude > 41° S, longitude < 170° E (Westland–Fiordland–Snares shelf).
Mako sharks: June–August, latitude 35.5–38° S, longitude 176–180° E (eastern Bay of Plenty–East Cape).

The variables available from the observer database were investigated for their affect on catch rates.

Francis et al. (1999b) log transformed raw catch rates after adding 0.1 fish per 1000 hooks. The log transformation improves the normality of skewed catch rate data, and increases the homogeneity of the variances, but replacing the zeros by a constant can distort the results. For blue and porbeagle sharks, and Ray's bream, a series of generalised linear models were applied to the data:
Model 1 – Main effects. All categorical and continuous variables were fitted to the data from 1993–94 to 1997–98 in a model without interaction terms.
Model 2 – All interaction terms. The model included significant main effects from Model 1 that contributed at 1% of the model sum of squares, plus all first order interaction terms for the main effects in the model except for fishing year. (The Type III adjusted sum of squares, and associated F tests, were used as recommended by SAS for unbalanced data sets.)
Model 3 – All interaction terms, subset of vessels. Same as Model 2, except that the input data set included only the four foreign and charter vessels that fished in each of the years 1993–94 to 1997–98. By limiting the analysis to these four vessels, it was possible to explore the effect of using a model with balanced vessel interaction terms.
Model 4 – Significant interactions. Same as Model 2, but with non-significant interaction terms removed. In all cases, the remaining significant interaction terms contributed more than 1% of the model sum of squares.
Model 5 – Extended time series. Same as model 4 but extended to cover 1990–91 to 1997–98. For porbeagle sharks, Models 4 and 5 were identical because there were no catch rate data before 1992–93, and no squid bait and lure percentage for 1992–93.
Model 6 – No zeros. Same as Model 5 with the zero catches removed.

For mako shark, data limitations meant that only main effects could be investigated and some factors with incomplete recording were omitted.

Francis et al. (1999b, 2000) investigated the factors influencing the catch of striped marlin using a discriminant function analysis and pairwise non-parametric tests. The data used came from all observed sets within the area where striped marlin were thought likely to be caught. The species diversity (see Species diversity, p. 6) was considered as a factor that might influence the catch of striped marlin.

The original intention had been to follow the approach taken by Francis et al. (1999a). However, examination of the data and experience with similar data in the school shark fishery (Bradford 2001) led to modifications to the type of models used. The approach to be adopted here restricts the data so that all levels of the categorical variables are well populated, to limit some of the problems that can arise with unbalanced data. For example, a dummy vessel that includes all those that made less than about 100 sets is defined. The zeros are considered an integral part of the model, some variables are defined as categorical rather than continuous, interactions with year are included (a year index is not being sought) but other interactions were not because of difficulty in interpreting them or because the relevant main effects explained a small amount of the variance, and the results are considered with scepticism (because of general ill fitting of the models).

In this report, striped marlin are considered within the same framework as the other species and a few more species are included.

Formally, the specific objective 2 of the Ministry of Fisheries Project ENV2000/03 is addressed: *To explore the effects of various factors on the catch rates and discards of non-target fish, particularly oceanic sharks, broadbill swordfish, and marlin species, in the tuna longline fishery for the fishing years 1998/99 and 1999/2000, taking into account the historical data from 1990/91 to 1999/2000.*

2. DATA

Data from the Ministry of Fisheries Observer EMPRESS database ***l_line*** (administered by NIWA) were extracted by position (latitude and longitude) at the start and end of each set. All data from 1987 to 2000 were extracted, but because of lower observer coverage in the early years, only data from 1992 onwards were used. Each set was allocated to the following areas defined by the Ministry of Fisheries (see Figures 1–16):

- **Area 1** – east of the QMA 1/QMA 9 boundary at longitude 172°02.8' E south to the intersection of the QMA 2/QMA3/QMA 4 boundary at latitude 42°10.0' S;
- **Area 2** – south of the QMA 2/QMA3/QMA 4 boundary at latitude 42°10.0' S to a line at longitude 167° E;
- **Area 3** – west of longitude 167° E north to latitude 38° S; and
- **Area 4** – north of latitude 38° S to the QMA 1/QMA 9 boundary at longitude 172°02.8' E.

Nowadays, two "fleets" are considered to operate in the tuna longline fishery (Murray et al. 1999).

- **Charter** – Japanese vessels chartered for operation in New Zealand waters and one large New Zealand owned vessel that usually fishes with the chartered vessels. These vessels normally set lines with more than 2500 hooks, fish mainly in winter, and mainly target southern bluefin tuna.

- **Domestic** – New Zealand owned vessels that set lines with about 1000 hooks, mainly fish in northern waters, and operate throughout the year. They mainly target bigeye and albacore tuna, *Thunnus alalunga*.

The observers record various factors relating to the vessel operation and environmental conditions at the time of the set. They record the catch of all species, and should record the fate of each animal caught, but for some sets only catch numbers are available.

Species diversity

The diversity of species caught on the tuna longlines gives an overall measure of the bycatch and may be a factor that influences the probability of catching a particular species. The species diversity is codified in a form suitable for analysis using the Shannon diversity index (Pielou 1969)

$$-\sum_i p_i \log_2 p_i$$

where p_i is the proportion of species i caught in a set.

3. EXPLORATORY ANALYSIS

We begin with an overview of where the fishery operated and where several of the more important species are caught.

Figures 1 and 2 show the observed set trajectories for the charter fleet (1992–2000) and the domestic fleet (1997–2000). For these purposes, the set is assumed to be made along a straight line; this is not necessarily true. The charter fleet did not operate in New Zealand waters in 1996. The domestic longline effort targeting tuna species expanded during the 1990s. Observer coverage has generally been low, with 12 observed sets in 1992, 50 in 1995, and 66 in 1996 that are not shown.

The charter fleet spends only a few months in New Zealand waters. While there it fishes in Area 2 mainly in March and April; in Area 3 mainly in April to June; in Area 4 mainly in June; and in Area 1 mainly in June to August. That is, set positions and date of the set are confounded. Area 3 is the only area where the observed set positions are reasonably consistent from year to year. Since catch rates may vary temporally and spatially, this has the consequence that statistical analyses will satisfy only the underlying requirements for their validity in Area 3.

The domestic fleet fishes throughout the year mainly in northern waters from about 38° S on the west coast to 42° S on the east coast and out to about 100 nautical miles from the coast. The observer coverage is low (less than 1% of the sets) and does not follow the fishery very well either spatially or temporally (Appendix 1). The observer coverage of this fishery in Area 4 has been sparse and these data are ignored. In Area 1, there has been no recent coverage north of about 36° S and little or no coverage in the winter months (Appendix 1). Analyses are given using the Area 1 observer data, but are likely to give results that are not representative of the fishery.

Figure 3 shows the Shannon diversity index for all sets (charter and domestic) for 1997–2000. The plotting position is the mid-point of the given start and end positions of the set. The area of the circle is proportional to the diversity index. The species diversity (but not the actual species caught, see following plots) is roughly constant throughout the fishery with some local and year to year variation.

3.1 Catch rates

Figures 4–16 show the catch rate of various species plotted at the mid-point of the given start and end of set positions with the area of the circle proportional to the catch rate (in numbers per 1000 hooks). The scaling varies depending on the size of the catch of the species. Most of the figures show catch rates in the years 1997–2000. Figures 17–19 show the same data as numbers of fish caught per set by area and fleet.

3.1.1 Target species

The catch rates of southern bluefin and albacore tuna by the charter fleet in 1997–2000 are shown in Figures 4 and 5 as examples of the target fishery. Albacore tuna are overall the numerically largest catch (Francis et al. 2000), but most of the albacore catch is taken in the north. Southern bluefin catch rates are highest in Area 3 and in the East Cape Eddy in Area 1. Sets north of latitude 35° S with no southern bluefin catch probably targeted bigeye. The annual catch of southern bluefin is controlled and the fishery is closed when the catch limit is reached. If the season is closed while the vessels are in Area 3, they may limit the amount of fishing they do in Area 1 before moving away, thus possibly limiting the bycatch of species that are mainly found in Area 1. Southern bluefin tuna catch rates used to be high in Area 2 in the early 1980s but declined to 1995 and have risen subsequently (Richardson et al. 2001). Fishing in Area 2 became sporadic before 1996 but is now more consistent. Albacore tend to be a bycatch species for the charter fleet, and are mainly caught in Areas 1 and 4 where the water is warmer than in the south.

Regulatory requirements and other efforts by fishing vessels to mitigate against seabird capture have tended to change the fishing patterns of the charter tuna longline fleet in recent years. The measures directed at reducing seabird captures have meant that such captures have become low, especially in Area 3 (Baird 2001).

3.1.2 Bycatch species

The bycatch species on tuna longlines of most interest are: blue sharks, Ray's bream, dealfish, porbeagle sharks, mako sharks, swordfish, striped marlin, and school shark. The smaller school shark catches are included at this stage since they are a Quota Management species.

Figures 6–10 show the catch rates by the charter fleet of blue sharks (1992–2000), Ray's bream (1997–2000), dealfish (1997–2000), porbeagle sharks (1997–2000), and mako sharks (1997–2000). Figure 11 shows the catch rates by the domestic fleet of blue sharks, Ray's bream, dealfish, and porbeagle sharks lumped over all years (because of the low observer coverage of this fishery). Most of the observed sets by the domestic fleet in Area 3 were made in 1996, when the charter fleet did not fish in New Zealand waters. Figures 12 and 13 show the swordfish catch rates by the charter and domestic fleets (1997–2000), and similarly Figures 14 and 15 show the striped marlin catch rates by the charter and domestic fleets (1997–2000). Swordfish and striped marlin catch rates are shown in some detail because they are explicitly part of this project and there is considerable interest shown in these species. Finally, Figure 16 shows the school shark catch rates by the charter fleet (1997–2000).

Blue shark

Blue sharks are an oceanic pelagic species caught on almost all tuna longline sets (Figures 6 and 11). Eight years of catch rates by the charter fleet are shown because blue sharks are usually the second largest catch (in numbers) on tuna longlines (Francis et al. 2000). Year to year variations in blue shark catch rate may not reflect true changes in abundance, but rather changes in local abundance or availability at the time and location of the tuna sets. Zero and low catches in 1992 and 1993 could be due to low availability or to inadequate recording of the blue shark catches in those years. Blue sharks are not always brought on board and a catch could be missed. Blue shark catch rates seem generally high on the east coast of the North Island and in the deeper water off the west coast of the South Island. Blue sharks are generally unwanted and probably avoided if possible.

Ray's bream and dealfish

Ray's bream are caught predominantly in Areas 2 and 3 with only small and occasional catches in Areas 1 and 4 (Figures 7 and 11). Dealfish are almost only caught in Area 3 (Figures 8 and 11).

Little is apparently known about the distribution of these species though they appear to be oceanic, pelagic, and sporadically widespread. They may normally live deeper in the water column than the tuna longlines are set in Areas 1 and 4, or prefer waters over a steeply shelving seabed such as the location of the tuna longline fishery in Area 3 (Paul (2000) and Larry Paul, NIWA, pers. comm.).

Porbeagle and mako sharks

Porbeagle sharks tend to have higher catch rates in southern waters (Areas 2 and 3) than in northern waters (Areas 1 and 4) with few being caught in the most northern latitudes (Figures 9 and 11). Mako sharks have generally lower catch rates than porbeagle sharks (especially in Areas 2 and 3), and are possibly more likely to be caught in the north than the south (Figure 10).

Porbeagle and mako sharks are oceanic pelagic. They are superficially similar in appearance and tended to be confused in the earlier observer records.

Swordfish

Catch rates of broadbill swordfish are highest from the Bay of Plenty and the East Cape area south to about 40° S (Figures 12 and 13). They tend to be caught mainly by the domestic fleet.

Information on factors influencing the swordfish catch will be highly uncertain due to the sporadic fishing by the charter fleet in northern waters and the low and unrepresentative observer coverage of the domestic fleet.

Striped marlin

Very few striped marlin are caught by the charter fleet (Figure 14). The domestic fleet appear to catch striped marlin throughout Areas 1 and 4 as far south as about 40° S (Figure 15).

Again, the low and unrepresentative coverage of the domestic fleet means that any information on factors influencing striped marlin catch will be uncertain.

School shark

School shark catch rates by the charter fleet are usually low but variable and tend to be highest in Area 3 (Figure 16). The main target fisheries for school shark use set nets or bottom longlines, not surface longlines (Paul & Sanders 2001). Their catch on tuna surface longlines indicates that they are not solely bottom dwelling.

4. GENERALISED LINEAR MODELS

The standard investigation of the factors influencing the bycatch of species uses a generalised linear model. This approach is followed here, although the conditions under which the models are valid are probably violated in some cases. As the number of observer tuna longline sets available is relatively small, care is needed to ensure that the results are not driven entirely by a few outliers. Outliers in this context may be genuine data points but so few in number that their statistical distribution (or at least its mean and especially its variance) cannot be defined adequately.

The analysis is effectively the same as that used when seeking an annual standardised catch rate index, but here the interest is on the predictor variables, not the catch rate index. As we are not producing an annual index, any problems associated with interactions with the year variable are of no concern.

Where practical, we tried to achieve year to year consistency in the positions of the observed sets included. As the data are unbalanced, effort is made to (roughly) equalise the numbers of sets per level when defining categorical variables. Vessels are treated individually except that those vessels that had few observed sets are lumped into a dummy vessel. As results for this dummy vessel appear to be within the results for the individual vessels, dropping it from the analysis did not seem necessary.

Hence, when there are sufficient observed sets, the analyses are based on the data from the charter fleet fishing in Area 3 where the fishing pattern is roughly consistent from year to year. Where appropriate, two time periods are used: 1993–2000 with sets from April to June and 1997–2000 with sets from May and June and excluding sets from latitudes below 47° S. A few sets made outside the main fishing months and fishing areas are excluded to avoid low set numbers in some categories. The more recent data are considered separately as the recording of catch and the fate of bycatch species has generally improved over time. The non-appearance of the charter fleet in New Zealand waters in 1996 provides a convenient break in the data. Also, the regulations aimed at mitigating seabird catches were in place. The requirement for night setting could influence the bycatch of some non-target fish species.

The northern data *have* to be used to investigate factors influencing species that have zero or very low catches in Area 3 (mako and porbeagle sharks, broadbill swordfish, and striped marlin). Two data sets are used: the observed sets for the charter fleet in Areas 1 and 4 in years 1993–2000 for June to August; and the observed sets for the domestic fleet in Area 1 in years 1995–2000. Months are grouped for the domestic fleet.

There were problems identifying mako and porbeagle sharks in the early years of the observer programme. There could be misidentifications in the earlier years of the data used in northern waters. The variable fishing pattern of the charter fleet in these waters and the non-representative coverage of the domestic fleet are likely to make the results of statistical analysis uncertain.

4.1 Factors available for analysis

The observers record several factors relating to each set, including positions of the start and end of the set, the time of start and end of the set, number of hooks set and observed, line depths, bait used, sea surface temperature, and various other environmental variables. They also record the catch and nominally record the fate of each animal or bird caught. However, they are allowed the option of tallying the numbers of non-target species caught and do not always record fate of individuals. The observers have an onerous set of duties and some, necessarily, have higher priority than others.

The predictor variables used in the analyses are listed below.

Factor	Description
Year	Fishing year October to September in which the set was made. Used as a categorical variable
Month	Months are grouped (not used individually) for the domestic fleet, and used individually for the charter fleet. Used as a categorical variable.
Latitude	Mid-point of the start and end of set positions. Either, in Area 3 only, divided into 2 degree latitude bands with divisions at 47° S, 45° S, and 43° S and used as a categorical variable; or as a linear predictor or polynomial. Other means of categorising the set position in Area 3 were tried with the blue shark data, including using a longitude division roughly parallel to the coast and using a two dimensional polynomial, but no substantial improvements in variance explained were achieved and such methods were abandoned.
Sea surface temperature	Sea temperature is measured several times during the haul; sea surface temperature is highly correlated with latitude. The mean value is used as a linear predictor.
Temperature range	Tuna longline sets are often made across temperature fronts as tunas are thought to congregate there. Used as a linear predictor or a polynomial.
Line depth	Estimates of minimum and maximum line depth are provided. There are 5–10% missing values in these data and these missing values are omitted in the analyses which tends to distort the results. These variables are used as linear predictors.

Start of set time	As a consequence of seabird capture mitigation measures most sets by the charter fleet in Area 3 start at roughly the same time each night. Used as a linear predictor, or a categorical (AM/PM) variable for the domestic fleet.
Moon phase	Actually the proportion of the moon's disc that is illuminated, calculated from the date and position of the set (Duffet-Smith 1990). Used as a linear predictor or a polynomial.
Cloud cover	Given as a percentage of the sky that is covered by cloud. Used as a categorical variable usually with three categories, less than 50%, 50–80% and greater than 80% cloud cover. The few missing values are assigned to the most frequent category.
Wind force	Given as a number on the Beaufort scale. Used as a three level categorical variable, less than 4, 4 and less than 6, and higher values. The few missing values are assigned to the most frequent category.
Barometric pressure	Used as a linear predictor, but contains many missing values that are omitted in the analyses.
Vessel	Those vessels that have fished consistently are treated as individual levels (at least about 100 observed sets). Other vessels are lumped. Vessel is not used as a predictor variable for the domestic fleet. Used as a categorical variable. Note: letters (the same in all analyses) identify the vessels. Z represents the lumped vessels.
Observer	Those observers who covered at least 100 trips are treated as individual levels. Other observers are lumped. Used as a categorical variable. Note: numbers identify the observers. 100 represents the lumped observers.
Species diversity	Used as a linear predictor.
Other catch	Total number of other species caught. This was used originally as a rough estimate of species diversity. Either the number or its logarithm is used as a linear predictor.
Number of hooks	In models where the catch rather than catch rate is used, this is included as an offset. The logarithm of the number of hooks is used as a predictor in binomial models.
Bait type	Information on bait type has been collected since mid 1994. The type of bait used on each set has been categorised as the percentage of squid baits; percentage of fish baits; percentage of lures; and percentage of other types. These percentages do not make useful predictors. The percentages of squid are divided into three categories: 50%, less than 50%, and greater than 50%; and the percentages of lures are divided into: less than 10%, 10% to less than 12.6%, and other (no more than about 20% lures were used). In Areas 1 and 4 only two categories are defined. The use of fish baits is negatively correlated with the use of squid. Ideally, the bait types need to be grouped (say, 100% squid, or 50% squid and 50% fish) but it becomes difficult to achieve meaningful groupings of roughly equal size. Missing values are assigned to the most common category. Used as a categorical variable.

Interactions between these variables are possible but few are investigated, either because they have no obvious physical or biological meaning, or because the "main-effects" are small. Interaction terms between categorical variables rapidly deplete the available degrees of freedom in the data set and, unless considerable care is taken, can result in missing or poorly supported terms. Interaction terms between a categorical variable and a linear predictor mean that the linear predictor has a different "slope" for each level of the categorical variable; this can be realistic. Interactions between linear or polynomial predictors are best treated as two-dimensional polynomials. The interactions used involved position and time and are included in an attempt to remove fishery influences. (A two dimensional polynomial involving latitude and longitude was investigated with the blue shark data in Area 3 but did not appear to give illuminating results, and neither did the use of a generalised additive model involving these variables.) No attempt is made to fit interaction terms using data from Areas 1 and 4 because of the small data set sizes and the year to year changes in set position for the charter fleet and the non-representative coverage of the domestic fleet.

Francis et al. (1999b) produced models with and without interactions. This is not done here; in the default model fitting procedure in Splus©, the interaction terms enter the model last, so we get a sense of their importance, given that the other factors are already in the model.

Few (about five) charter vessels are involved each year in the fishery. Some vessels have returned for several years. The vessels tend to fish as a fleet and may fish close together. Observers are generally on the same vessel for several weeks, so a high correlation between the vessel and observer predictor is expected. Some vessel/observer terms may be due to fishing pattern, for example, if a vessel regularly fishes at the outside of the fleet.

Outliers

Some very high catches are excluded in case they are overly influential in the analyses. Occasional outlying (say, set position some distance from other sets) or unlikely values (say, sea surface temperature too low) of predictor variables are excluded for the same reason.

4.2 Determining factors influencing catch

The approach is similar to that used by Bradford (2001) to produce standardised catch rate indices for school shark. The approach is somewhat different from that adopted by Francis et al. (1999b) in that more model types are tried, data before the 1992–93 fishing year are always ignored, a "dummy" vessel is used to cover those vessels that fished infrequently, and interaction terms that are difficult to interpret are ignored. A multiplicative model is used.

$$\frac{C}{E} = e^{\mu+\alpha_y+\cdots} \quad \text{or} \quad C = e^{\mu+\alpha_y+\cdots}E$$

where C is the catch of the species on a set, E is the effort in thousands of hooks, μ is the global mean, α_y is the factor for year y (for example) and … means other factors that influence the catch.

It is necessary to specify the distribution of the errors in the dependent variables in the standardisation models before fitting to the data. Several are used.

1. Lognormal — this error model has been used in most attempts at standardising catch and effort data (for example, Gavaris 1980, Kimura 1981, Vignaux 1994). In this case, the lognormal model is used for positive catch rates only, and depending on the shape of the distribution of numbers caught per set either ignores zero catches or zero and small catches (small means less than 3).
2. Binomial — this error model investigates whether a catch is zero (or small) or not using a Bernoulli random variable and is the counterpart of the lognormal model for positive catches. The models are not combined as indices are not sought. Fitting the binomial model to the data involves specifying a model of the form:
   $$g(V) = \mu + \alpha_y + \cdots$$

where g is the logit link function.

3. Poisson — one advantage of using this error-model is that it allows zero catches to be included in the analyses. The dependent variable in this case is catch per set. A log link function is used. The logarithm of the effort variable is included as an offset (Bradford 1996, 2001, Nishida 1996).
4. Negative binomial — this error-model allows for a more general relationship ($V(\mu) = \mu + \mu^2/\theta$) between the residual variance, V, and the expected catch, μ. The parameter, θ, is determined during the fitting procedure (Venables & Ripley 1994). The dependent variable is catch per set. The logarithm of the effort variable is included as an offset.

The variable that explained the most variance was included in the model first. An informal forward stepping approach was used with factors that appeared to best explain the remaining variance included at each step. The results were tested using an ANOVA for significance of each added term (in the order specified). Variables were included until there appeared to be no significant improvement in the percentage of variance or deviance explained. This occurred when the expected change in variance or deviance was between 0.5% and 2% of the original sum of squares or deviance depending on the size of the data set and the number of extra degrees of freedom used when the last variable was added.

Because many of the predictor variables used are correlated and one variable or group of variables might explain some part of the variance structure as well as another, the variables are not necessarily unique in their influence on the catch of a particular species and it is difficult to rank them in a strict order of importance. Also, how should a categorical variable with several levels be compared with a linear predictor? Francis (2001) used the Akaike Information Criterion (AIC) for this. It turns out that most of the models used fitted the data poorly which means that the model coefficients are ill-determined hence they are not given. Instead, variables that entered models are listed in an approximate order of importance within the categories: probably important; and possibly important. The variables that are ranked as probably important in several models are likely to be factors that do influence the catch of the species. We must remember that all the results are conditional on how the fishery was operating.

Diagnostic plots were used during the fitting process to look for outlying values of predictor variables, and evidence of poor model fitting and highly influential points. Even so, poor model fits frequently occurred. Plots of residuals versus fitted values for the models used are presented in Figures 20, 22, 24, 26, and 28. Extremely large residuals occurred in many Poisson and negative binomial models and this is why they are not considered acceptable.

Plots are produced to show how well the predictor variables were fitted for one model for each species (Figures 21, 23, 25, 27, and 29). Models from the 1997 to 2000 data were chosen in preference to models from the 1993 to 2000 data because the later data were assumed to be more consistent than the earlier data. The plots show the "main effects" only, and do not show the effects of any interaction terms in the model. Similar plots for the other models are qualitatively similar. These plots are obtained using one of the Splus© plotting routines that uses the fitted values from the model, that is, log transformed values with the mean removed. For demonstrating the nature of the fit, transforming to actual predicted values did not seem necessary.

Figure 1 suggests that the charter fleet did not fish as far north in Area 3 in 1994 as in the other years after 1992. In fact, it seems that instead of following the general pattern of moving north with time, some sets were made after turning south. The results of this fishing pattern may show up as either a marked increase in catch (or catch rate) in one month or in one latitude band based on a few data points (signalled by a strong year:month or year:latitude effect). This is a clear example of how vessel behaviour might influence catch rates, but, because only a few points are involved, interpreting statistical significance is difficult or impossible.

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4.3 Results of model fitting

Figures 17, 18, 19 show the overall catch per set distributions for the models to be fitted. The overriding impression of these distributions is that they decay away from zero (or low values) to a few high values. They resemble flattened negative binomial distributions, or when the catches are low, Poisson distributions. Only the distribution of the blue shark catch per set by the charter fleet in 1997–2000 in Area 3 has the appearance of a lognormal distribution. (The change in distribution shape for the blue shark catch per set when the earlier data are added is indicative of a marked change in mean catch of blue sharks recorded over time. Species such as blue sharks are apparently often cut off the line as it is being hauled on board and may not have been recorded in earlier years or may not be noticed if the observer is busy with other tasks.)

Tables 1–7 contain the results of model fitting for blue shark, Ray's bream, dealfish, porbeagle shark, mako shark, striped marlin, and broadbill swordfish. The first lines of these tables contain some information about the model fits.

- Model convergence – includes whether the model is used (negative binomial models were dropped when there was severe mis-fitting; the lognormal model was not used when the number of sets with catch was small);
- Deviance explained – is either the standard R^2 for lognormal models or the percentage of the null deviance that is explained by the model in the other cases;
- Dispersion – is estimated as the Pearson chi-squared statistic divided by the residual degrees of freedom and should be 1 for the Poisson and binomial models (Chambers & Hastie 1992);
- θ and s.e.(θ) – are output from the negative binomial fitting routine (Venables & Ripley 1994).
- Dependent variable

Many of the Poisson models have dispersion much greater than 1, that is, are over-dispersed. An important consequence of this is that the statistical tests used will have inflated significance levels, and some of the possible factors may not be significant (especially those that do not appear in other models).

The data from fishing by the charter fleet in Area 3 in 1997–2000 appear to represent a period of reasonable stability in the fishery and the observer programme and should best represent the situation in the last two fishing years (1998–1999 and 1999–2000) required by the objective. Models covering these data are fitted for blue shark, Ray's bream, dealfish, porbeagle shark, mako shark, and broadbill swordfish. Catches of the last three species are low. More credence is given to the results from the 1997–2000 models than the 1993–2000 models when describing the factors that seem to influence the bycatch of species.

Blue shark

As expected, there is a strong dependence on fishing year when the early data are included.

The diagnostic plots suggest that none of the models fitted particularly well (Figure 20). The Poisson models are over-dispersed (Table 1) as well as having poor residual structure. Though the negative binomial model gives a superficially good fit, the wide range of the residuals tells us that this is not so. The distribution of catch per set is possibly too flat to be adequately described by a negative binomial (or Poisson). The binomial model is under-dispersed when using data from 1993. No binomial model could be used for the 1997–2000 data because of the low number of zero catches of blue sharks in those years. The lognormal models are perhaps best by default.

Probable factors influencing the blue shark catch that may be fishery dependent are vessel, observer, and fishing year (Table 1 and Figure 21).

An interesting factor is the strong negative correlation with species diversity (Table 1 and Figure 21). That is, when blue shark catches are high, fewer other species are caught. This provides a reason to avoid those areas where blue sharks are most abundant.

Possible factors influencing the catch of blue shark are a large temperature range, the fraction of squid baits used, and the line depth. Blue sharks appear more likely to be caught when the longline is set close to the surface (Table 1 and Figure 21), but information about the line depth often missing and possibly of dubious quality. Blue sharks may make vertical migrations (Carey & Scharold 1990).

Bait type is apparently significant in many models. It was noted earlier that a single characterisation of bait type should be used. Even this would not be entirely adequate, as the real interest will lie with the bait on the particular hook on which the shark was caught. Though we can infer the hook position for target species with reasonable reliability, the hook position for bycatch species is unreliable, especially where the only information given is a tally of the numbers caught.

Ray's bream

The diagnostic plots suggest poorly fitting models (Figure 22). The comments under blue shark apply though the binomial models have dispersion closer to one than those for blue shark.

Probable factors influencing the Ray's bream catch that may be fishery dependent are observer, fishing year, and vessel (Table 2 and Figure 23).

Ray's bream are possibly more likely to be caught in southern areas, when the vessel is travelling at higher speed, the moon is full, the line was set across a front (large temperature range), and the wind was very strong (Table 2 and Figure 23).

Dealfish

The diagnostic plots suggest poorly fitting models (Figure 24). The comments under blue shark apply; the binomial models are somewhat under-dispersed but not as badly as for blue shark.

A probable factor influencing the catch of dealfish that may be fishery dependent is fishing year (Table 3 and Figure 25).

Dealfish are more likely to be caught when the moon is full (as are the target species, southern bluefin tuna) (Table 3 and Figure 25).

They are possibly more likely to be caught in May, in the middle and northern parts of Area 3, and when the proportion of squid baits used is lower (Table 3 and Figure 25).

Low catches of porbeagle and mako sharks, and striped marlin and broadbill swordfish by the charter fleet in Area 3 mean we have to use the less consistent data from the charter fleet in Areas 1 and 4 and the very unrepresentative data from the domestic fleet in Area 1. Consequently the factors found influencing the catch of these species are, at best, indicative.

Porbeagle and mako sharks

Figure 26 shows diagnostic plots for some models. Catches per set are smaller on average than the previous species discussed. Negative binomial models were severely non-fitting; lognormal models were not tried when the number of sets that caught a species was small. Poisson and binomial models may be fitting reasonably well when the catch per set was low (see Figure 18) but not for the porbeagle catches by the charter fleet.

These sharks appear to be most likely caught, at least by the domestic fleet, around latitude 38° S (Tables 4 and 5 and Figure 27). Figures 9 and 10 show that highest catch rates of porbeagle sharks by the charter fleet occurred in Area 3, whereas for mako sharks the highest catch rates are in Area 1 and near 38° S. Both these shark species appear more likely to be caught when the sea temperatures are lower, and both have shown an apparent decline in catch rate (by the domestic fleet) over time. Mako sharks are more likely to be caught at some times of the year. In the analysis, some months were grouped (shown by brackets) as follows: December, January, February, (March, April), (May, June), and (July, August, September). Conclusions drawn from these data are speculative due to the low, non-representative observer coverage of the domestic fleet and the sporadic coverage by the charter fleet in the northern regions.

Striped marlin and broadbill swordfish

Figure 28 shows diagnostic plots for some models. Negative binomial models were severely non-fitting; lognormal models were not tried when the number of sets that caught a species was small. The Poisson and binomial models may be giving reasonable fits.

The domestic fleet catches most of the striped marlin (Figures 14 and 15) and then discards them.

Striped marlin are more likely to be caught when the sea temperature is warmer, if low to medium numbers of the hooks have squid bait, and possibly if the lines are set deeper (Table 6 and Figure 29). The diversity index had been found to be significant in previous models examining the factors influencing striped marlin catch (Francis et al. 1999b). It did not appear to be significant in any of the models used here, though it is was perhaps marginally important.

Swordfish catch rates by the domestic fleet have increased over time (Table 7 and Figure 29). The swordfish catch rates by the charter fleet vary from year to year but do not appear to have a consistent trend. Swordfish are more likely to be caught when the set started in the afternoon, the diversity is high, and the moon is full (Table 7 and Figure 29). They also appear less likely to be caught in summer months. In this case, the months were grouped as follows: (December, January), February, March, (April to September).

5. FACTORS INFLUENCING DISCARDS

The observers should give the fate of all animals caught on the tuna longlines. However, especially for non-target fish species this information was not always given, especially in the past, but, it does seem that most non-target fish are discarded, except that some sharks are finned (Francis et al. 2000). Therefore, the factors influencing discards are the same as factors influencing catch. Obviously, a fish has to be caught before it can be discarded, and in general, there seems to be a positive correlation between catches and discards.

Figures 30–33 show the number of instances of catch of a species and the number discarded. For sharks, they also show the number discarded versus the number caught minus the number finned. The sets used are those where a catch of the species was recorded and where the fate was recorded for at least 90% of the species caught. The plots show data for blue sharks caught by the charter fleet in Area 3 (Figure 30), Ray's bream and dealfish caught by the charter fleet in Area 3 (Figure 31), and porbeagle and mako sharks caught by the domestic fleet in Areas 1 & 4 (Figures 32 and 33).

It is clear that (almost all) Ray's bream and dealfish caught are discarded. Also, (almost all) the sharks caught are either finned or discarded. The lack of complete information on the fate of bycatch species means that the quality of the data is such that a statistical investigation of the factors influencing finning of sharks, and, by implication, the factors influencing discarding, is unlikely to be meaningful.

Presumably, at least some of the factors influencing shark finning are the amounts of crew time and freezer space available, and the state of the market for shark fins.

Striped marlin are (nearly all) discarded, as is required (which is probably the main reason for discarding). Swordfish are nearly all kept and so few are discarded that no analysis of factors influencing discards is possible.

6. DISCUSSION AND CONCLUSIONS

The data used give some insights into where and when the various fish bycatch species are caught, though we have to view this information through the distorting lens of how the tuna longline fishery operates. The absence of substantial catch of Ray's bream and dealfish in some areas is unexplained. These species are apparently oceanic wanderers caught (sporadically) throughout the Pacific Ocean, yet are infrequently caught in northern New Zealand waters (on tuna longlines). Other species like mako sharks and striped marlin are not caught in colder waters, which is easy to understand.

The statistical models generally fitted the data poorly. For many species, the data distributions appear not to conform to any of the standard statistical distributions that were tried. Subsequent analyses suggest that both the mean and shape of the distribution may change as the factor level changes (Bradford 2002). Analyses for those species caught only or predominantly in the northern waters (Areas 1 and 4) are suspect due to sporadic fishing by the charter fleet and the low and non-representative observer cover of the domestic fleet in these waters.

For the charter fleet fishing in Area 3, the models that used the last four years data (1997 to 2000) will best represent the factors influencing the bycatch of blue sharks, Ray's bream, and dealfish under the current mode of operation of this fishery and the observer coverage of it. The quality of the information for non-target fish species caught by the charter fleet in other areas or by the domestic fleet is poor due to the sporadic fishing pattern of the charter fleet and the low observer coverage of the domestic fleet.

Fishing year often turns out to be a significant factor influencing the bycatch of non-target fish species. However, a year index would represent changes in catchability or availability of the bycatch species at the time and place that the tuna fleet is fishing and may be more related to differing migration patterns of the tunas and the bycatch species from year to year rather than to changes in abundance. (Francis et al. (2001) give the recorded and estimated annual catches of many fish bycatch species; these vary from year to year.) Vessel and/or observer often appear to be have a significant influence on the bycatch. These two variables are somewhat correlated as observers spend long periods on a vessel. They may be representing something about the fishing pattern of the fleet, such as one vessel always fishing furthest from the shore. Some fish may be discarded as the line is being hauled on board, and this could easily be missed if the observer is performing other duties at the time.

We can be reasonably certain that a fishery independent variable has a real influence on the catch when it has a large (and significant) effect on the analyses. Examples of such factors are the negative correlation between blue shark catch and a diversity index for the species caught, the positive correlation between the illuminated proportion of the moon's disc and the dealfish catch, and positive correlation between sea temperature and striped marlin catches.

Bait type often appears to be a factor influencing the bycatch. The results involving the bait variables are indicative as the variables as used probably did not fully describe the bait being used. Another factor that often appeared to be important was the depth at which the line had been set. Missing values made the inclusion of this variable in models frustrating.

Some analyses used the Area 3 data only. There may be other or different factors influencing the catch of species like blue sharks that are caught throughout the tuna fishery. If the catch of a species is high in Area 3, no further analysis was attempted as the fishing patterns outside Area 3 are not consistent from year to year.

The results reported here are similar to those reported by Francis et al. (1999b), but included diversity and moon phase which turned out to be significant factors for some species and often appeared in the models.

Most bycatch species tend to be discarded, except that some of the shark species are finned, so the factors influencing the discards of these species are the same as the factors influencing the catch. Some species, such as broadbill swordfish, are mainly kept and there are insufficient discards to interpret the reasons for them.

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Table 1a: Model results for blue shark catches by the charter fleet in Area 3, 1993–2000. – not applicable. Sets with catches greater than 205 fish were omitted. Small catches were assumed to be less than 3 fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Yes	Yes	Yes	No
Deviance explained (%)	*61.2*	*72.4*	*58.6*	*55.5*
Dispersion	1.21	6.13	–	0.54
θ	2.77	–	–	–
s.e.(θ)	0.14	–	–	–
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch < 3, >2
Probable factors	Fishing year Diversity Latitude band Observer Vessel	Fishing year Diversity Latitude band Observer Vessel Sea surface temp.	Fishing year Diversity Sea surface temp. Vessel Observer	Fishing year Latitude band Observer
Possible factors	Wind force Maximum depth	Wind force Temp. range Minimum depth Month	Temp. range Latitude band	Minimum depth Squid bait Sea surface temp. Diversity Month
Interactions	Year:latitude	Year:latitude Year:month	Year:latitude	Year:latitude

Table 1b: Model results for blue shark catches by the charter fleet in Area 3, 1997–2000. – not applicable. Sets with catches greater than 205 fish were omitted. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Yes	Yes	Yes	Insufficient data
Deviance explained (%)	58.5	65.6	53.2	
Dispersion	0.91	6.13	–	
θ	5.24	–	–	
s.e.(θ)	0.34	–	–	
Dependent variable	Catch	Catch	Catch per 1000 hks	
Probable factors	Diversity Observer Vessel Log(other catch)	Diversity Vessel Observer Fishing year Log(other catch)	Diversity Vessel Observer Fishing year	
Possible factors	Fishing year Minimum depth Temp. range Squid bait	Temp. range Minimum depth Latitude band Wind force	Temp. range Minimum depth Squid bait	
Interactions		Year:latitude		

Table 2a: Model results for Ray's bream catches by the charter fleet in Area 3, 1993–2000. – not applicable. Small catches were assumed to be less than 3 fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Yes	Yes	Yes	Yes
Deviance explained (%)	62.1	70.5	58.4	36.5
Dispersion	1.07	6.56	–	1.01
θ	2.27	–	–	–
s.e.(θ)	0.11	–	–	–
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch < 3, >2
Probable factors	Latitude	Latitude	Fishing year	Latitude
	Fishing year	Fishing year	Month	Vessel
	Vessel	Vessel	Vessel	Fishing year
	Observer	Observer	Observer	Observer
	Moon phase	Diversity	Latitude band	
	Diversity	Moon phase	Diversity	
Possible factors	Vessel speed	Vessel speed	Moon phase	Moon phase
	Squid bait	Squid bait	Vessel speed	Set duration
	Wind force	Wind force	Wind force	Diversity
	Month	Temp. range		Month
		Month		
Interactions	Year:latitude	Year:month	Year:month	Year:month
		Year:latitude	Year:latitude	Year:latitude

Table 2b: Model results for Ray's bream catches by the charter fleet in Area 3, 1997–2000. – not applicable. Small catches were assumed to be less than 3 fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Yes	Yes	Yes	Yes
Deviance explained (%)	50.0	65.6	44.1	35.8
Dispersion	1.09	6.13	–	1.01
θ	1.96	–	–	–
s.e.(θ)	0.13	–	–	–
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch < 3, >2
Probable factors	Fishing year	Observer	Observer	Fishing year
	Observer	Fishing year	Fishing year	Observer
	Vessel	Latitude	Latitude	Latitude
	Latitude	Vessel	Vessel	Vessel
	Moon phase	Squid bait		Moon phase
		Moon phase		Diversity
Possible factors	Squid bait	Vessel speed	Vessel speed	Temp. range
	Vessel speed	Wind force	Moon phase	Set duration
	Temp. range	Temp. range	Wind force	Month
	Diversity	Diversity	Temp. range	
		Month		
		Minimum depth		
		Set duration		
Interactions		Year:latitude		
		Year:month		

Table 3a: Model results for dealfish catches by the charter fleet in Area 3, 1993–2000. – not applicable. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Yes	Yes	Yes	Yes
Deviance explained (%)	57.6	70.4	55.2	37.4
Dispersion	1.60	5.61	–	0.92
θ	0.992	–	–	–
s.e.(θ)	0.056	–	–	–
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors	Moon phase Fishing year Lures Latitude band Vessel	Moon phase Fishing year Lures Vessel Latitude band Observer	Moon phase Fishing year Lures Squid bait Month Vessel	Sea surface temp. Moon phase Diversity Latitude band Vessel Observer
Possible factors	Month Observer Diversity Set duration	Month Wind force Set duration	Latitude Observer	Set duration
Interactions		Year:latitude Year:month		Year:latitude

Table 3b: Model results for dealfish catches by the charter fleet in Area 3, 1997–2000. – not applicable. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Yes	Yes	Yes	Yes
Deviance explained (%)	60.3	69.0	56.1	24.8
Dispersion	1.12	6.70	–	0.87
θ	1.339	–	–	–
s.e.(θ)	0.096	–	–	–
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors	Moon phase Fishing year Lures Vessel Observer	Moon phase Fishing year Lures Observer Vessel Wind force	Moon phase Fishing year Month	Moon phase Vessel
Possible factors	Month Set duration Diversity Latitude band	Latitude Set duration Month Diversity	Lures Squid bait Latitude band Observer Vessel	Lures Set duration Diversity
Interactions	Year:month Year:latitude	Year:latitude Year:month	Year:latitude Year:month	

Table 4a: Model results for porbeagle shark catches by the charter fleet in Area 3, 1997–2000. – not applicable. Catches over 30 in a set were omitted. Small catches were assumed to be less than 3 fish. Latitude (n) indicates an n^{th} order polynomial in this table and those below.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Yes	Yes	Yes	Yes
Deviance explained (%)	57.3	60.6	46.3	37.3
Dispersion	1.20	1.85	–	1.50
θ	7.40	–	–	–
s.e.(θ)	1.09	–	–	–
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch < 3, > 2
Probable factors	Fishing year Latitude (3) Moon phase Month Sea surface temp.	Fishing year Latitude (3) Sea surface temp. Month Moon phase	Fishing year Latitude (3) Moon phase Month	Fishing year Latitude (3)
Possible factors	Vessel	Vessel		Moon phase Month
Interactions	Year:month	Year:month	Year:month	Year:month

Table 4b: Model results for porbeagle shark catches by the charter fleet in Areas 1 & 4, 1993–2000. – not applicable. Catches over 20 in a set were omitted. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Yes	Yes	Not used	Yes
Deviance explained (%)	52.8	56.5		51.0
Dispersion	1.16	2.28		1.22
θ	4.33	–		–
s.e.(θ)	0.68	–		–
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors	Latitude (2) Fishing year	Latitude (2) Fishing year		Latitude (3) Fishing year
Possible factors		Target Vessel		

Table 4c: Model results for porbeagle shark catches by the domestic fleet in Area 1, 1995–2000. – not applicable. Catches over 20 in a set were omitted. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Not used	Yes	Not used	Yes
Deviance explained (%)		64.2		33.3
Dispersion		1.56		0.96
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors		Sea surface temp. Fishing year		Sea surface temp. Fishing year
Possible factors		Latitude (2)		Latitude (2) Minimum depth

Table 5a: Model results for mako shark catches by the charter fleet in Area 3, 1997–2000. – not applicable. Small catches were assumed to be zero fish. Latitude (n) means and nth order polynomial in this table and those below.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Not used	Yes	Not used	Yes
Deviance explained (%)		4.7		2.4
Dispersion		1.11	–	1.00
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Possible factors		Latitude (2) Vessel		Latitude (2) Vessel

Table 5b: Model results for mako shark catches by the charter fleet in Areas 1 & 4, 1993–2000. – not applicable. Catches over 10 in a set were omitted. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Not used	Yes	Not used	Yes
Deviance explained (%)		25.8		21.8
Dispersion		1.24	–	0.99
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors		Fishing year Diversity		Diversity
Possible factors		Sea surface temp. Vessel Latitude (2) Month		Fishing year Vessel Log(hooks obs.) Wind force Month

Table 5c: Model results for mako shark catches by the domestic fleet in Area 1, 1995–2000. – not applicable. Catches over 10 in a set were omitted. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Not used	Yes	Not used	Yes
Deviance explained (%)		26.8		13.4
Dispersion		1.38	–	1.08
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors		Combined months		Combined months
Possible factors		Sea surface temp. Fishing year Latitude (3) Diversity		Log(hooks obs.) Temp. range Moon phase

Table 6: Model results for striped marlin catches by the domestic fleet in Area 1, 1995–2000. – not applicable. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Not used	Yes	Not used	Yes
Deviance explained (%)		29.0		19.6
Dispersion		1.36		1.03
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors		Sea surface temp.		Sea surface temp.
Possible factors		Squid bait		Squid bait
		Maximum depth		Observer

Table 7a: Model results for broadbill swordfish catches by the charter fleet in Area 3, 1997–2000. – not applicable. Small catches were assumed to be zero fish. Latitude (n) and moon phase (n) means an nth order polynomial was fitted here and in the Tables below.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Not used	Yes	Not used	Yes
Deviance explained (%)		48.3		35.0
Dispersion		1.07	–	0.77
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors		Fishing year		Fishing year
		Latitude (2)		Latitude (2)
Possible factors		Moon phase		Moon phase
		Vessel		Vessel
		Sea surface temp.		Observer
		Observer		
		Diversity		

Table 7b: Model results for broadbill swordfish catches by the charter fleet in Areas 1 & 4, 1993–2000. – not applicable. Catches over 20 in a set were omitted. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Yes	Yes	Not used	Yes
Deviance explained (%)	31.0	34.9		22.8
Dispersion	1.11	1.83	–	1.12
θ	4.00	–	–	–
s.e.(θ)	0.78	–	–	–
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors	Fishing year	Fishing year		Fishing year
	Latitude (2)	Latitude (2)		
Possible factors	Moon phase	Moon phase		Latitude (2)
	Diversity	Diversity		Log(hooks obs.)
	Vessel	Minimum depth		Moon phase (2)
	Minimum depth	Cloud cover		Diversity
		Observer		
		Vessel		

Table 7c: Model results for broadbill swordfish catches by the domestic fleet in Area 1, 1995–2000. – not applicable. Small catches were assumed to be zero fish.

	Negative binomial	Poisson	Lognormal	Binomial
Model convergence	Not used	Yes	Not used	Yes
Deviance explained (%)		44.7		17.2
Dispersion		1.82		1.00
Dependent variable	Catch	Catch	Catch per 1000 hks	Catch = 0, > 0
Probable factors		Fishing year AM/PM start Combined months		Fishing year
Possible factors		Diversity Moon phase		AM/PM start Diversity

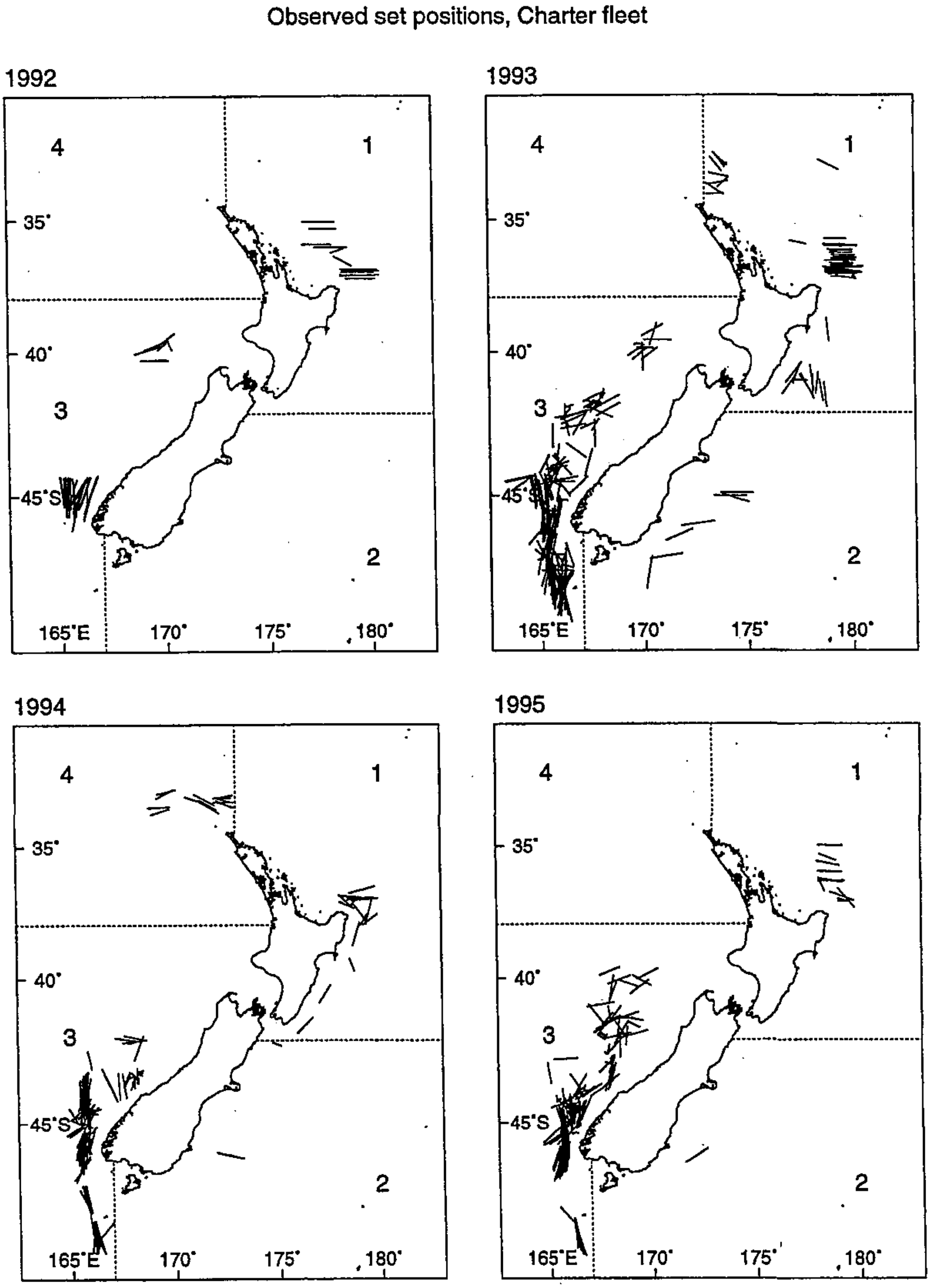
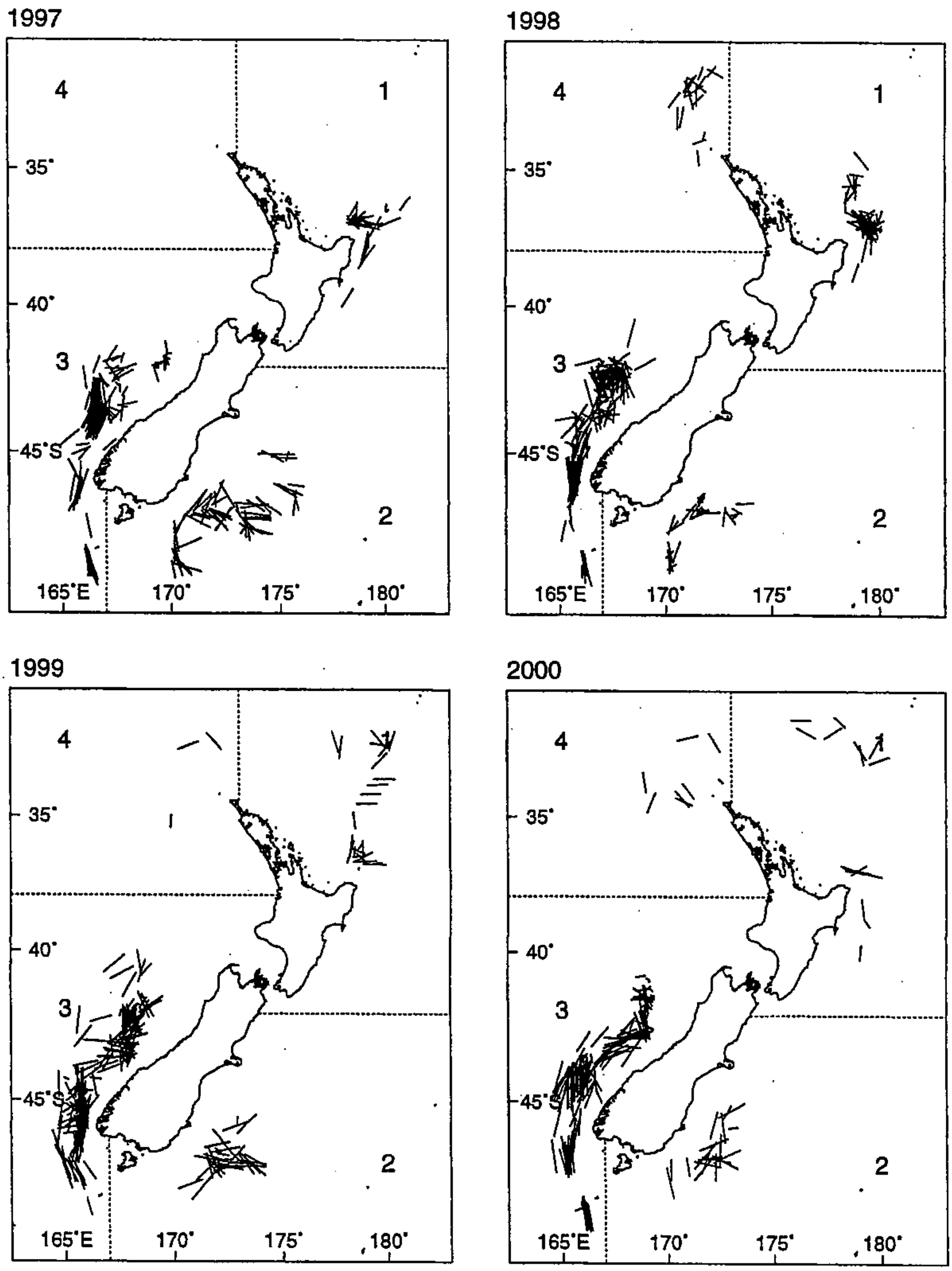


Figure 1: Observed set positions for the charter fleet, 1992–2000.

Observed set positions, Charter fleet



1997

1998

1999

2000

Figure 1 (continued).

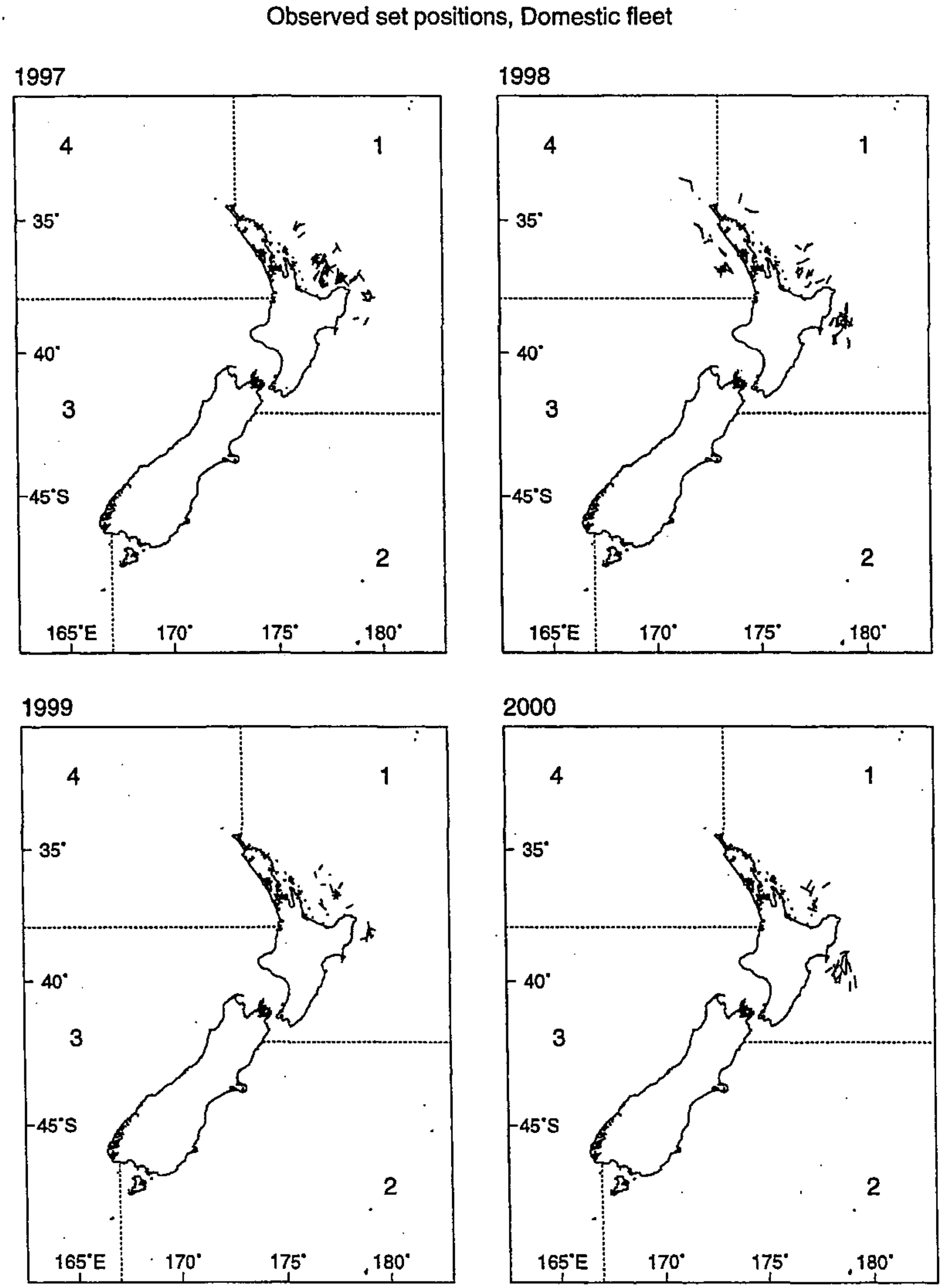


Figure 2: Observed set positions for domestic fleet, 1997–2000.

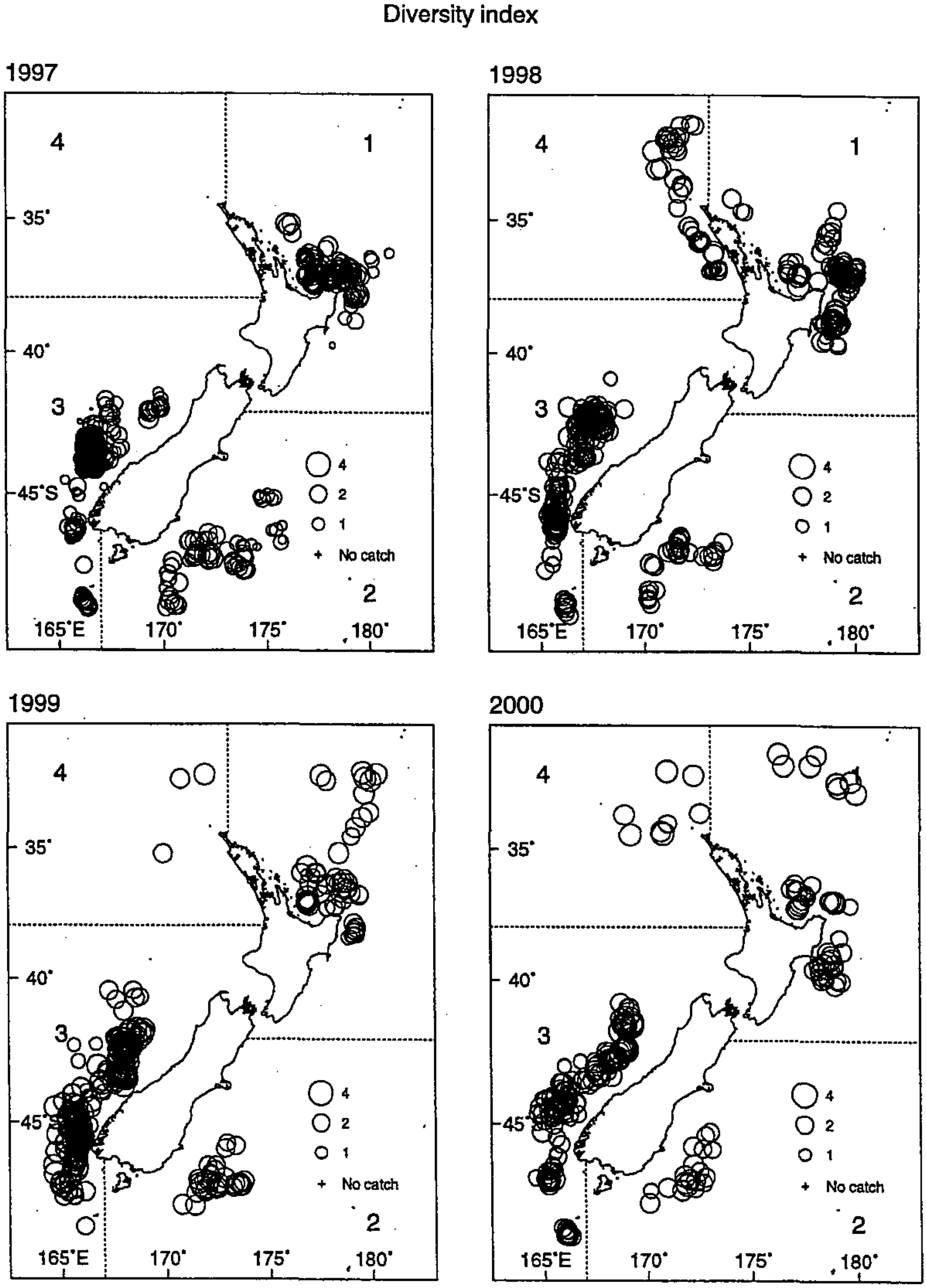


Figure 3: Diversity index for species caught on tuna longlines (charter and domestic fleets), 1997–2000.

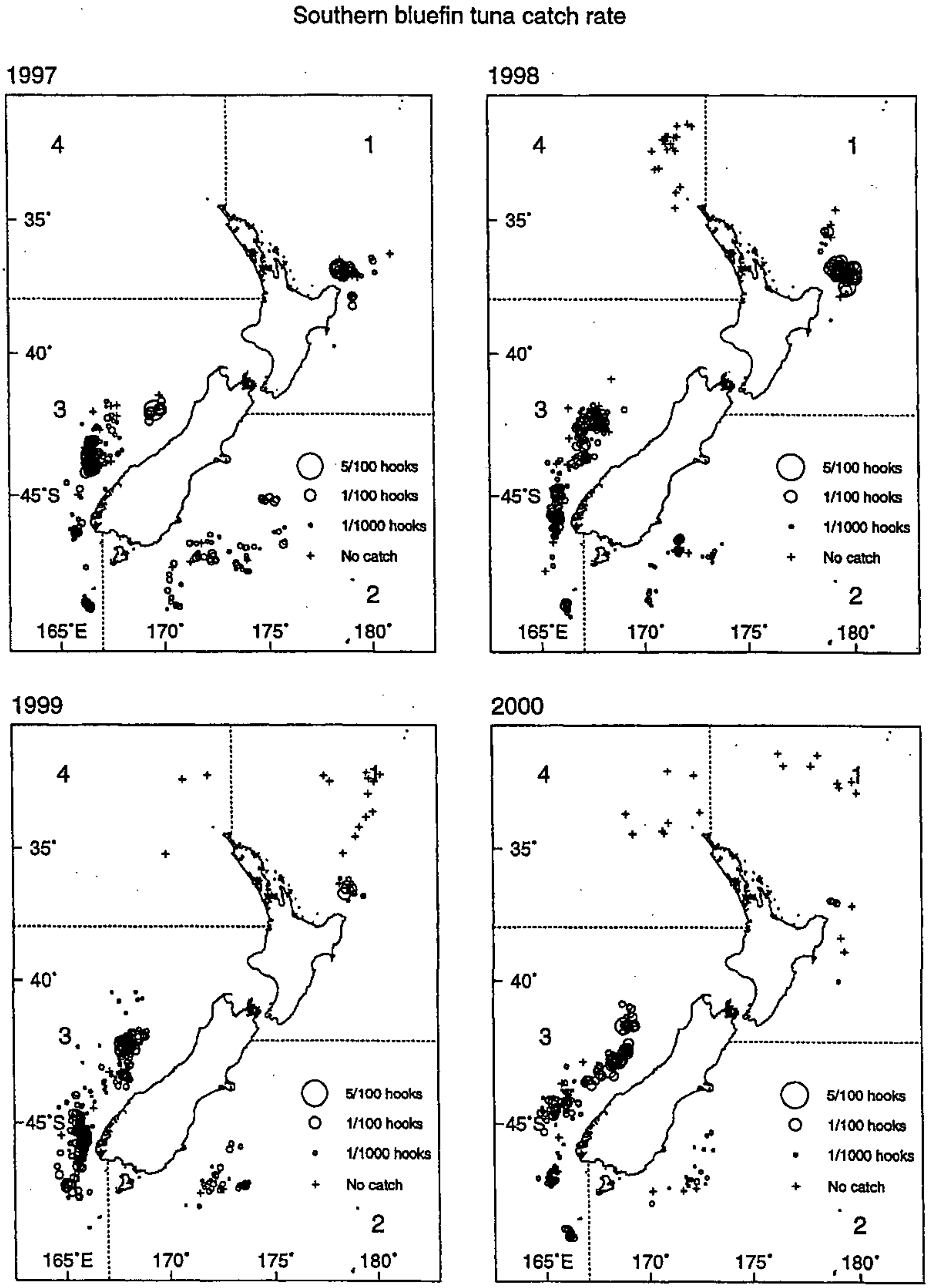


Figure 4: Southern bluefin tuna catch rates on tuna longlines (charter fleet), 1997–2000.

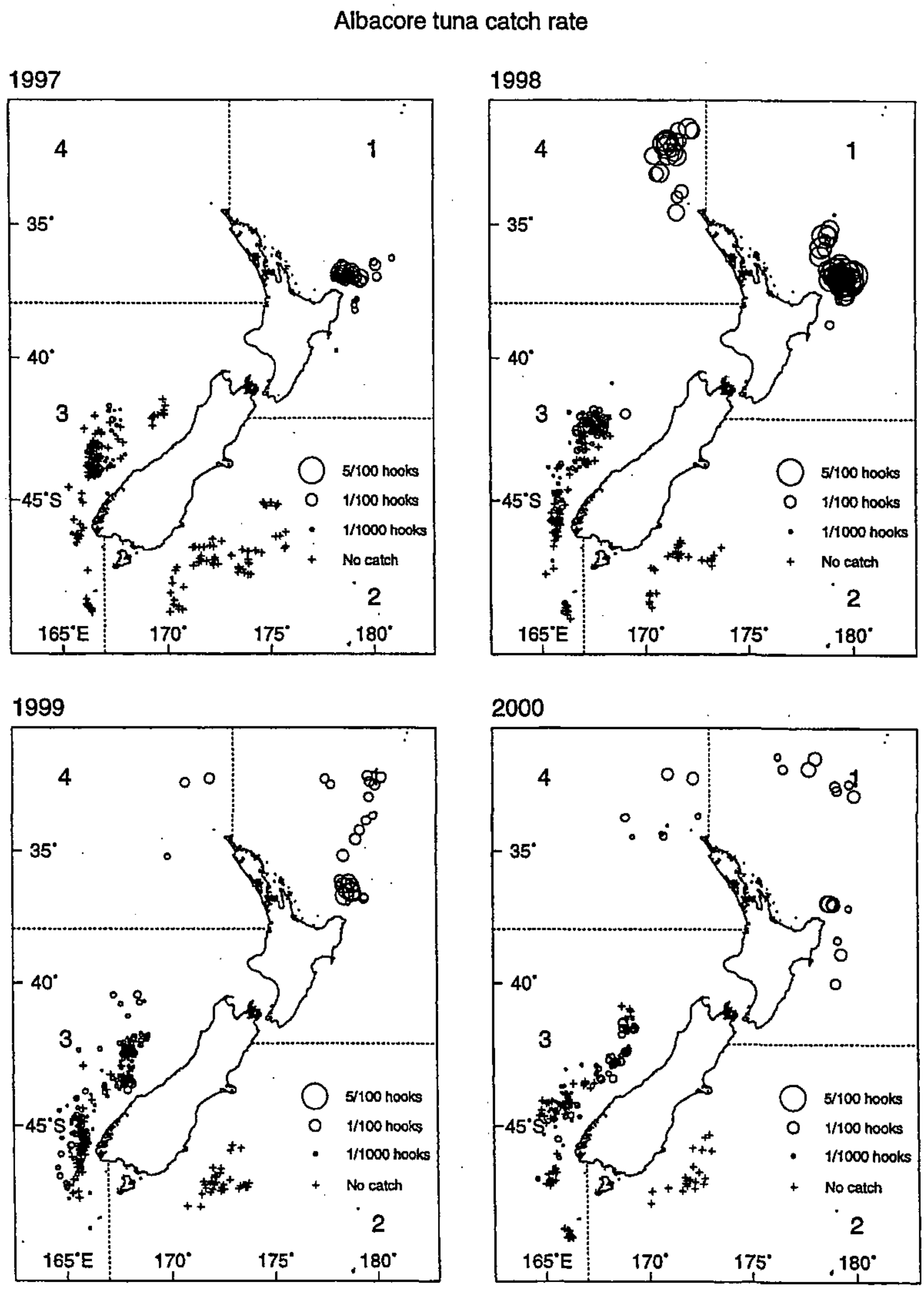


Figure 5: Albacore tuna catch rates on tuna longlines (charter fleet), 1997–2000.

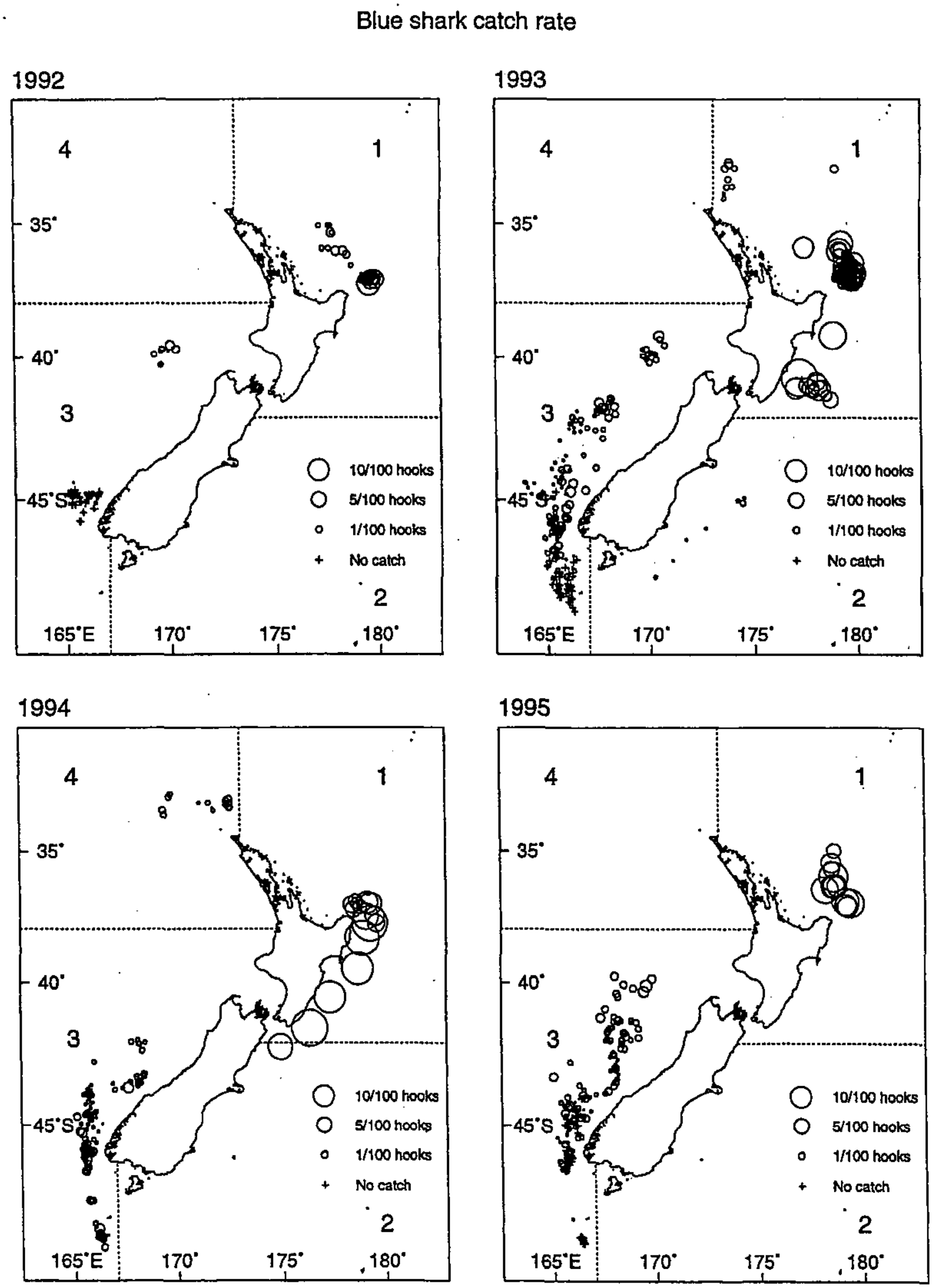


Figure 6: Blue shark catch rates on tuna longlines (charter fleet), 1992–2000.

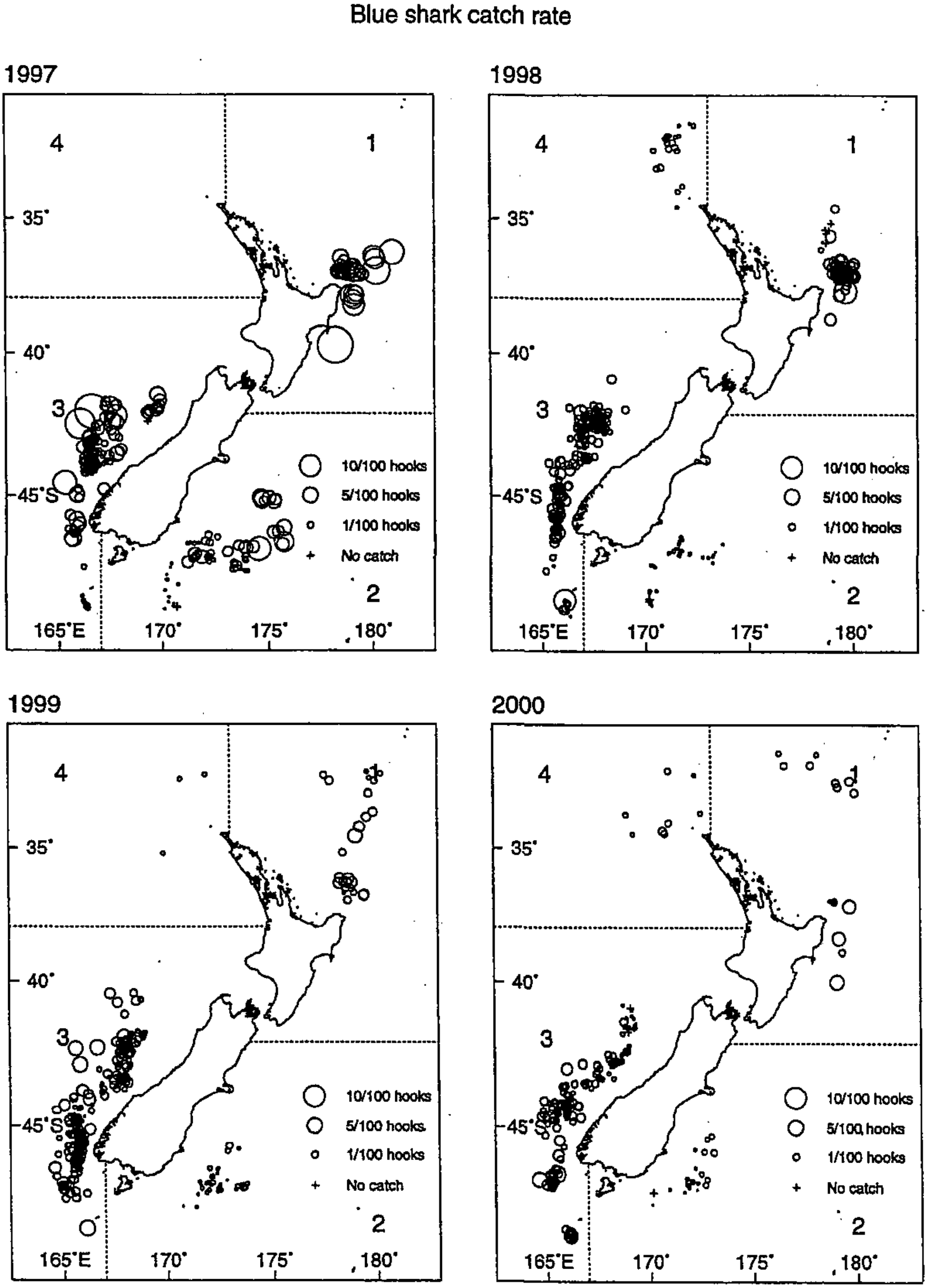

Blue shark catch rate

Figure 6 (continued).

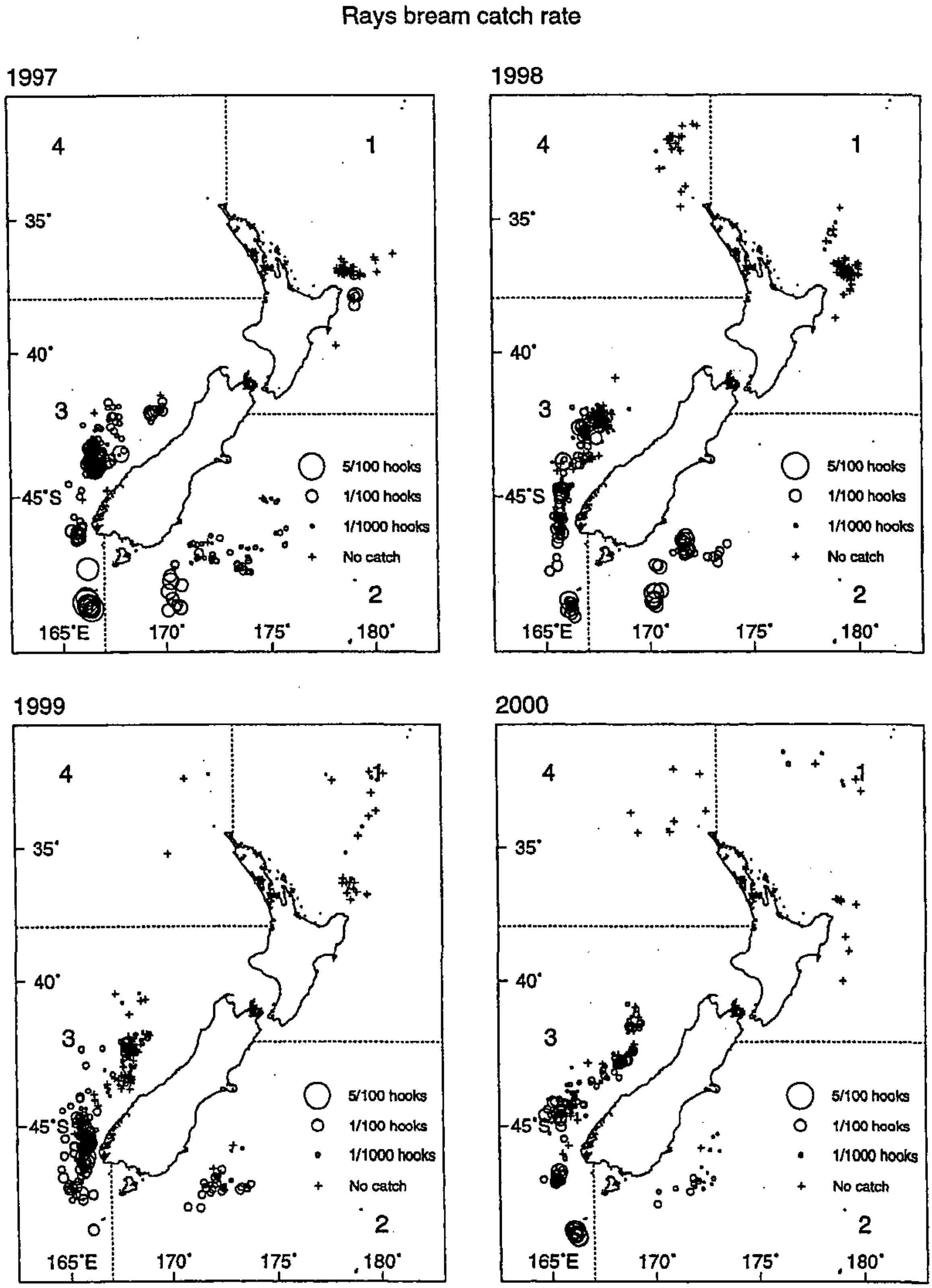


Figure 7: Ray's bream catch rates on tuna longlines (charter fleet), 1997–2000.

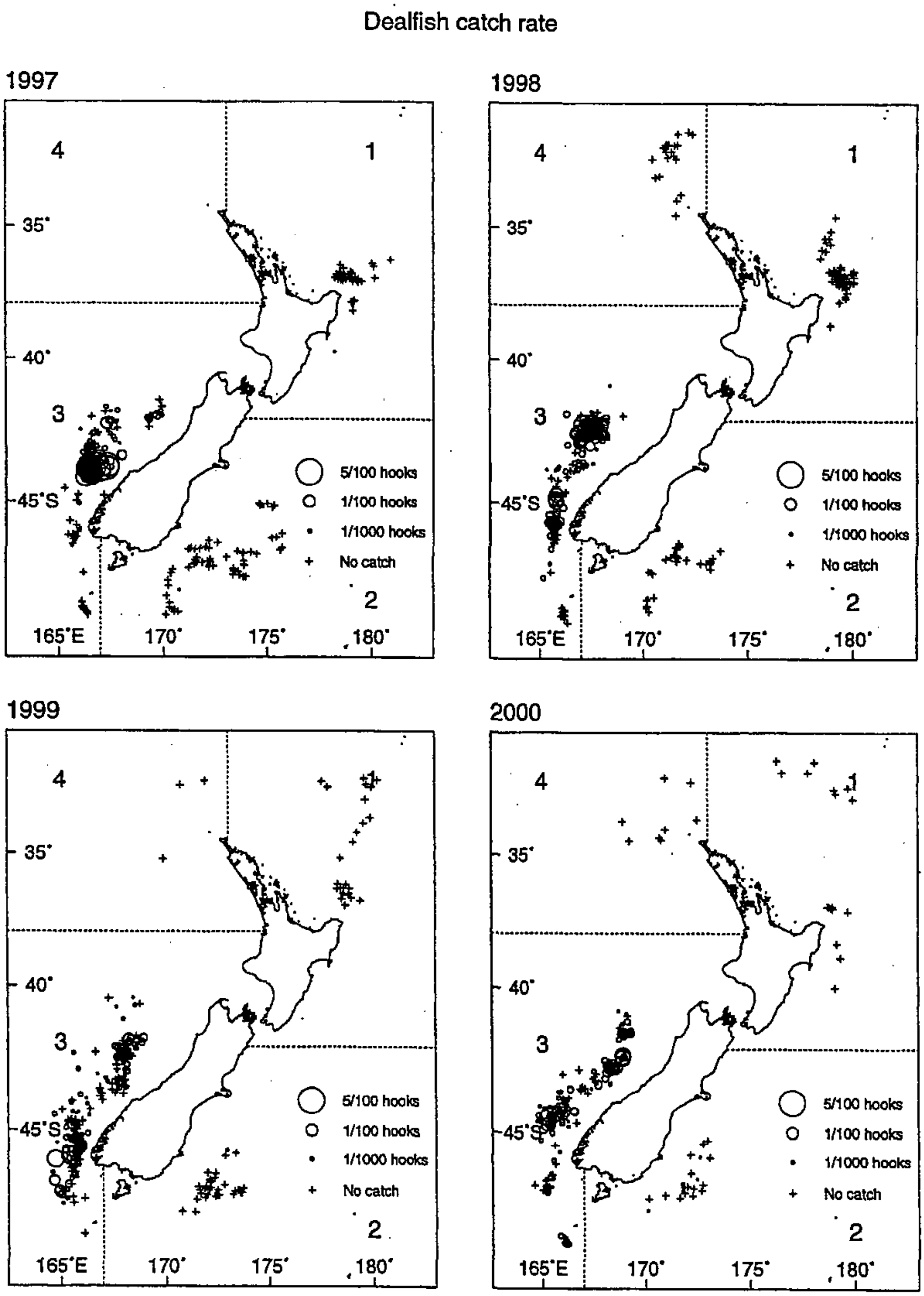


Figure 8: Dealfish catch rates on tuna longlines (charter fleet), 1997–2000.

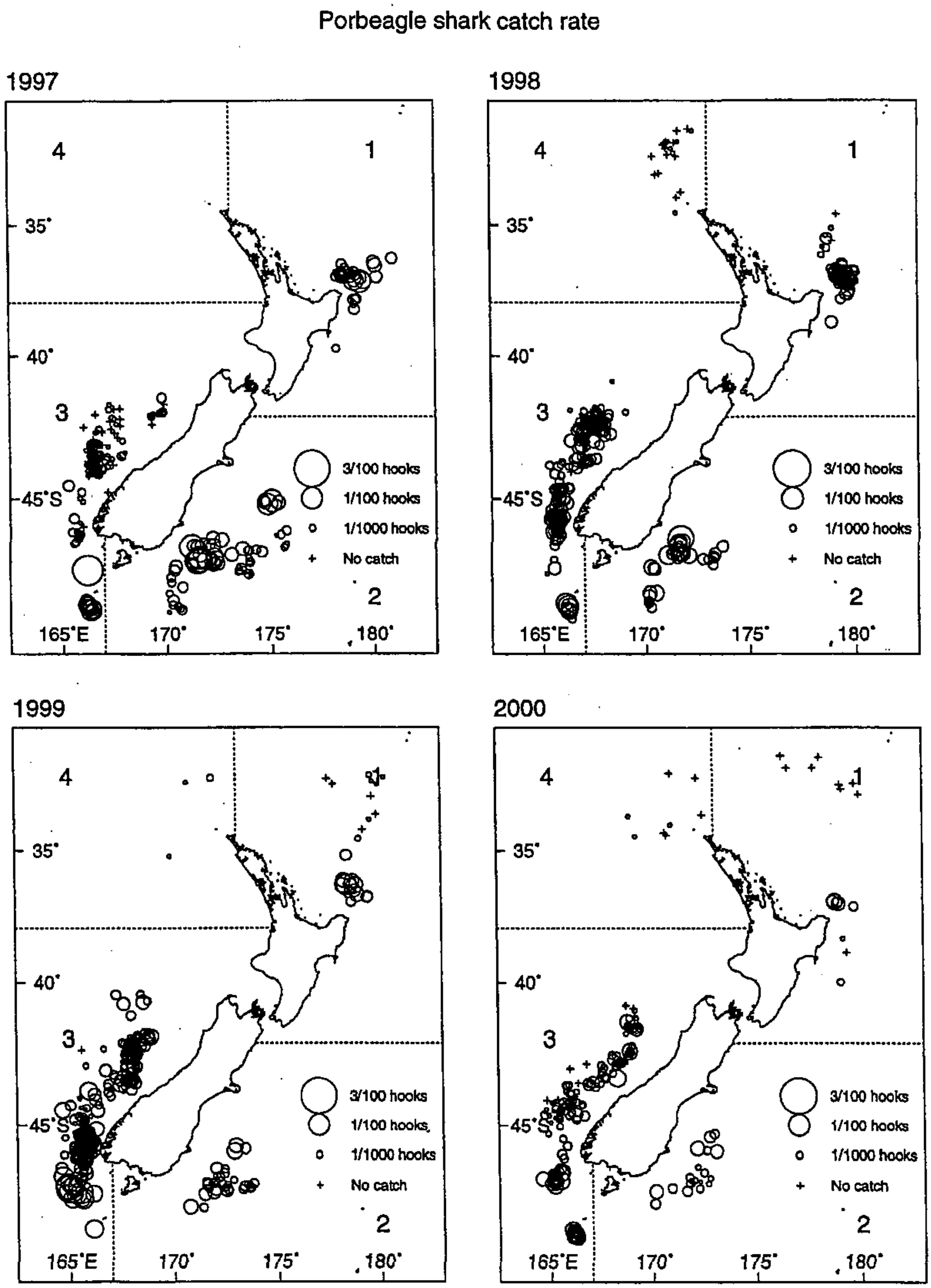


Figure 9: Porbeagle shark catch rates on tuna longlines (charter fleet), 1997–2000.

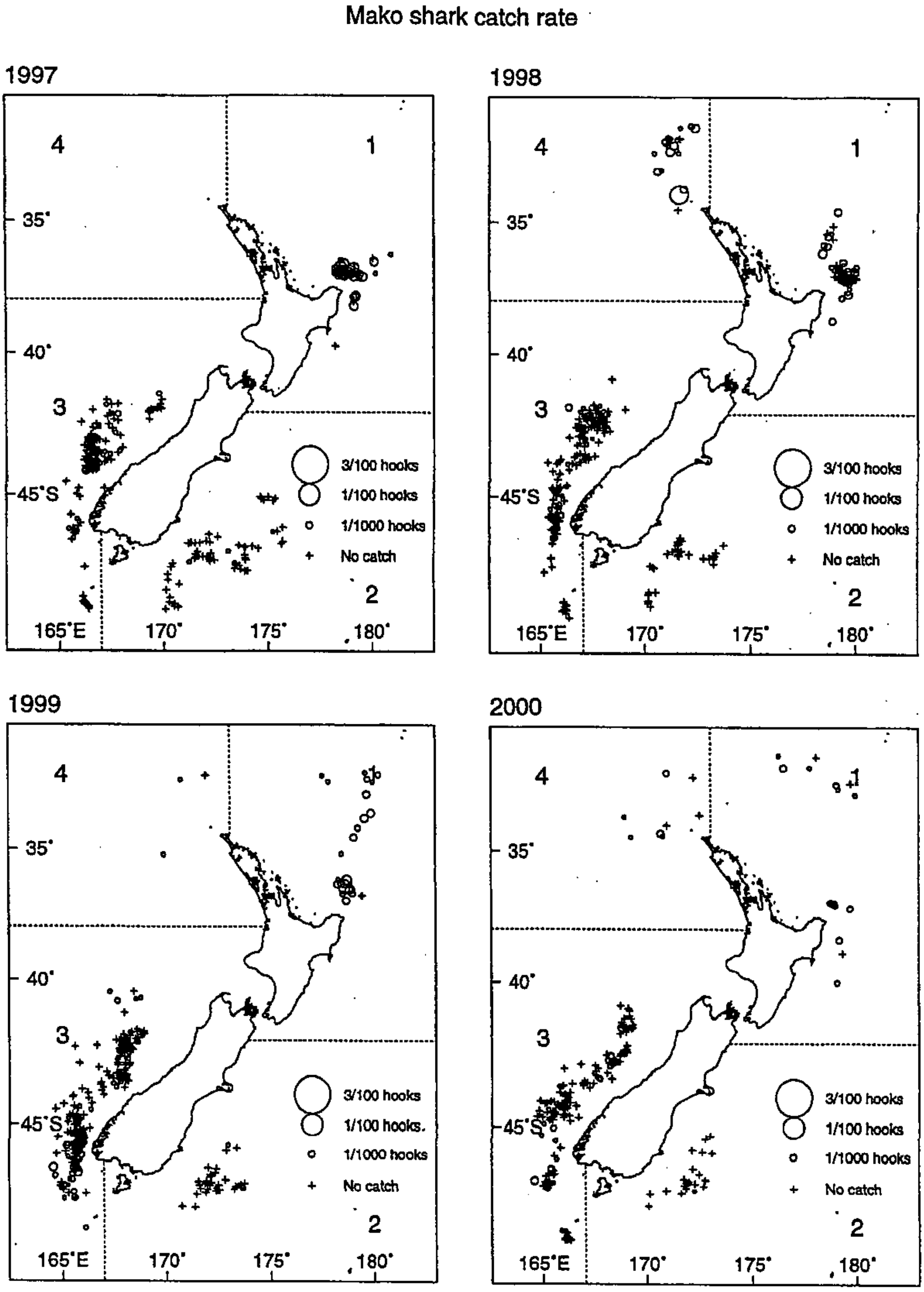


Figure 10: Mako shark catch rates on tuna longlines (charter fleet), 1997–2000.

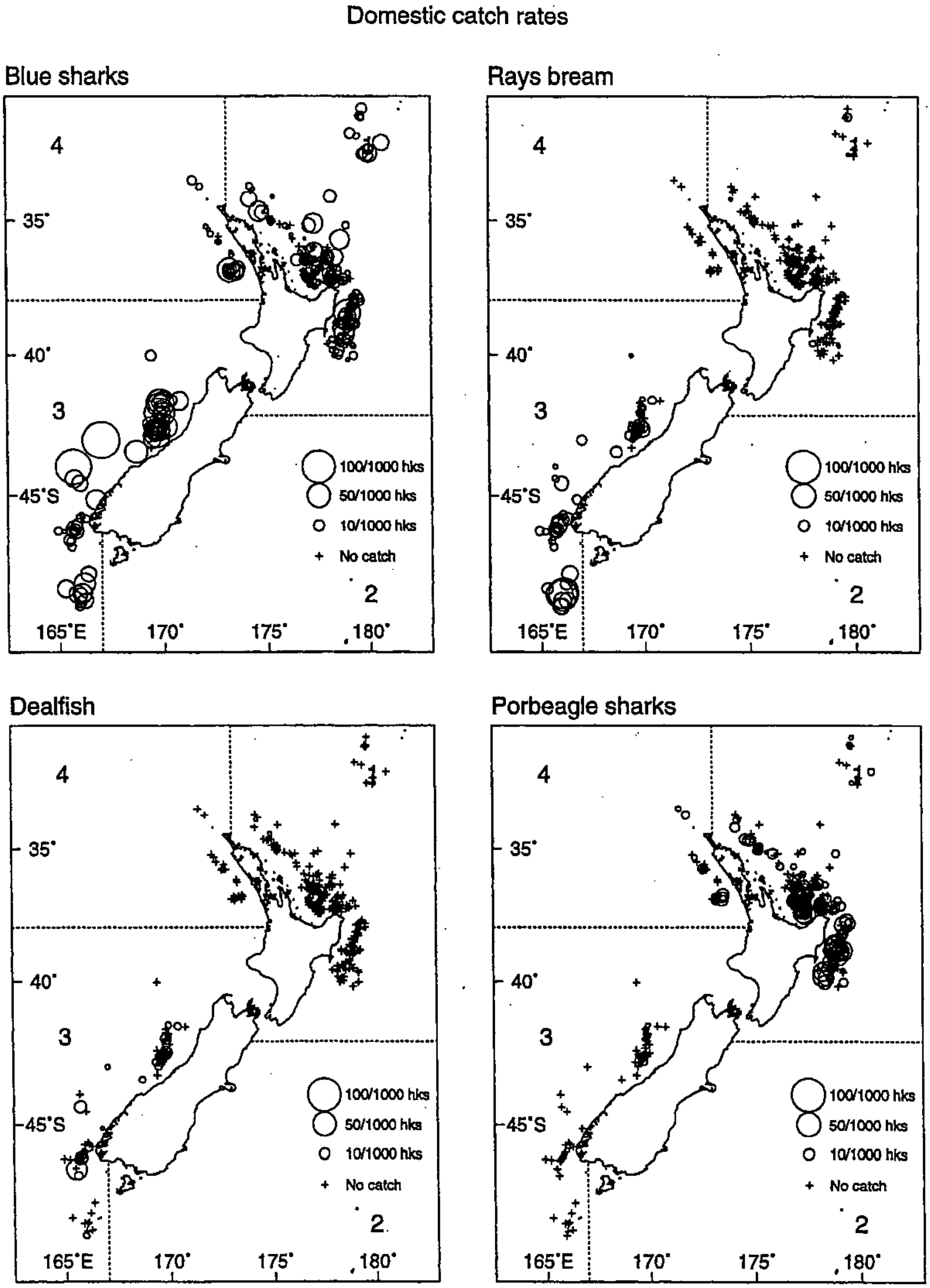


Figure 11: Blue shark, Ray's bream, dealfish, and porbeagle shark catch rates on tuna longlines (domestic fleet), all years together.

Swordfish catch rate, Charter

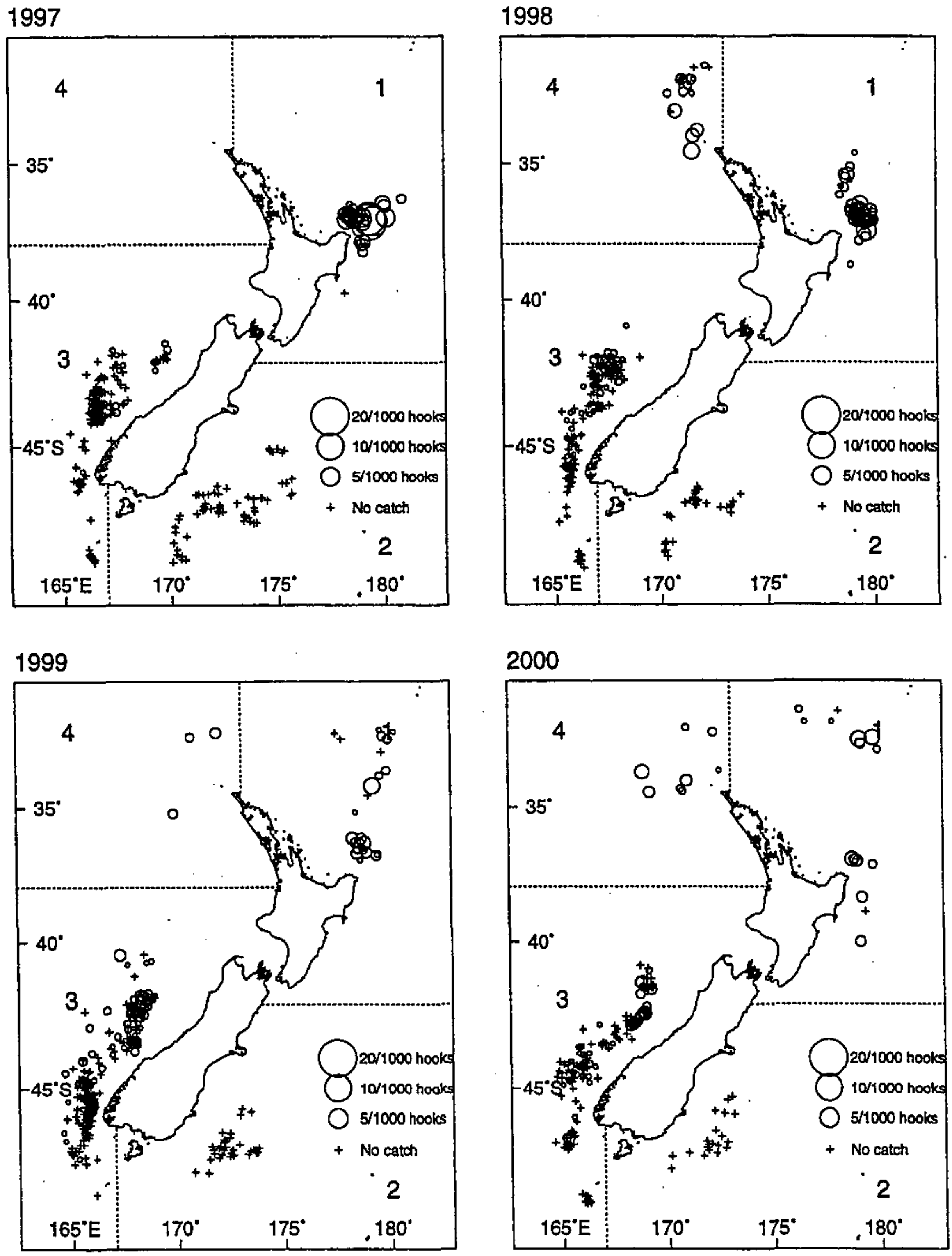


Figure 12: Swordfish catch rates on tuna longlines (charter fleet), 1997–2000.

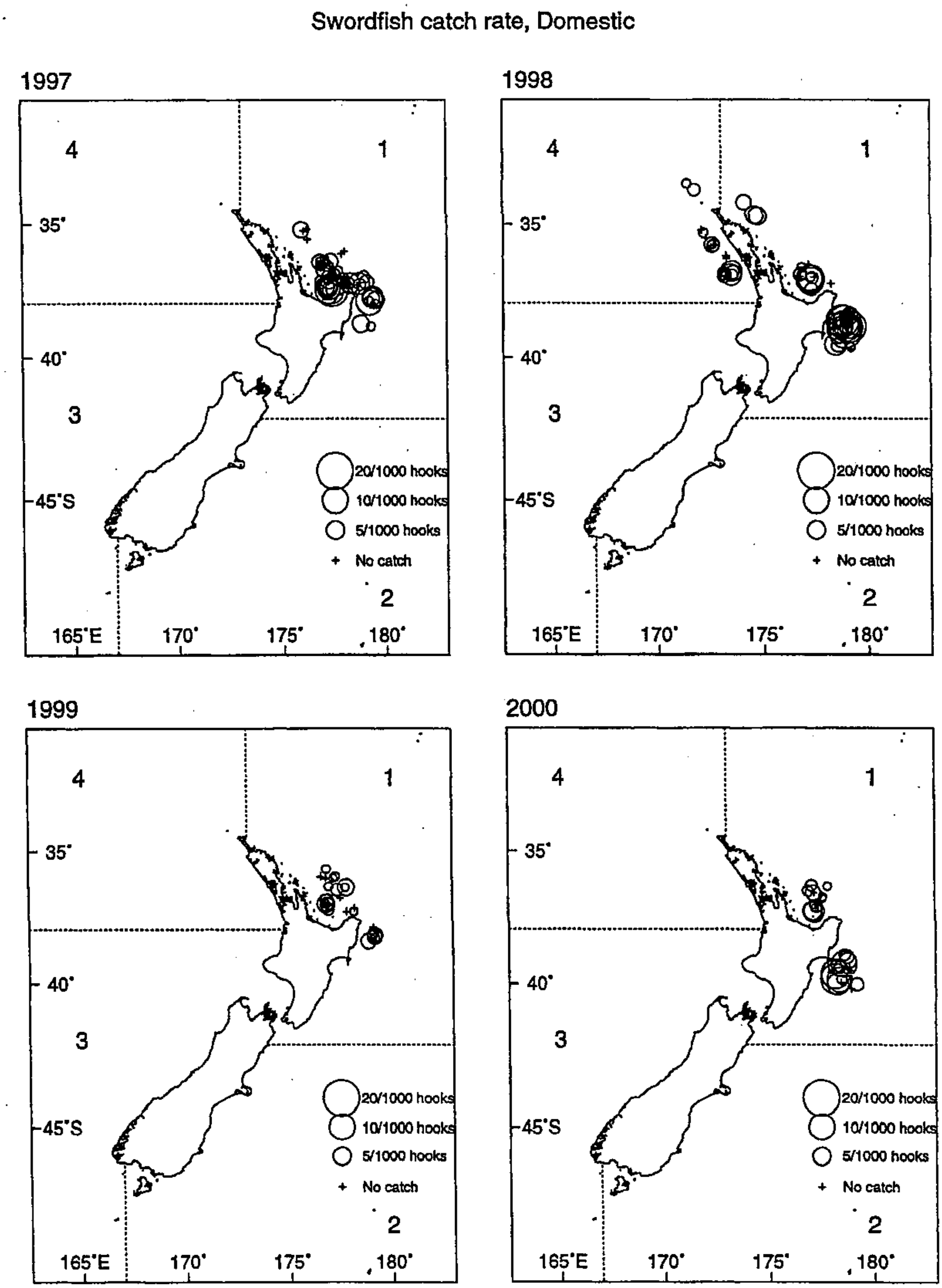


Figure 13: Swordfish catch rates on tuna longlines (domestic fleet), 1997–2000.

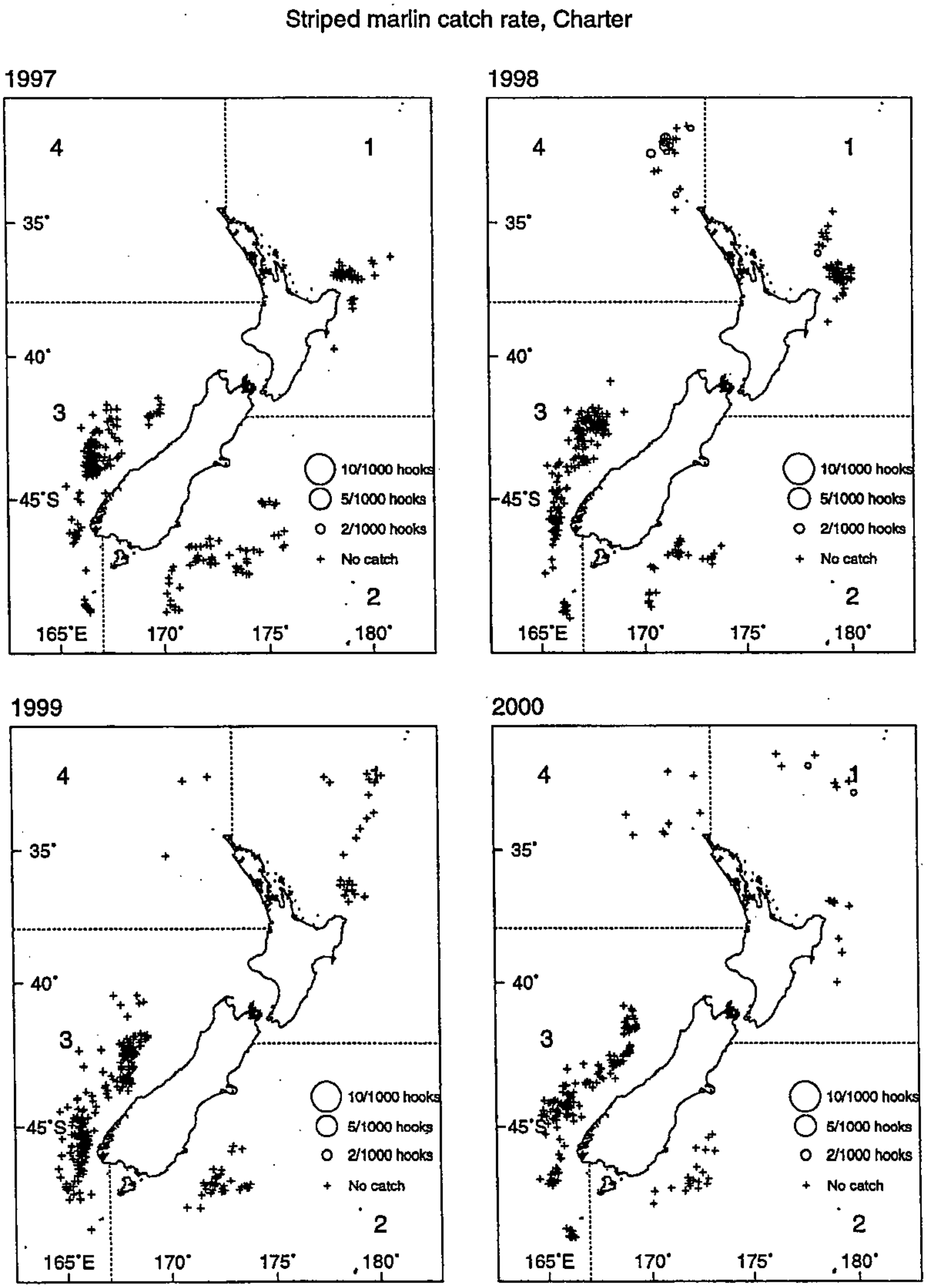


Figure 14: Striped marlin rates on tuna longlines (charter fleet), 1997–2000.

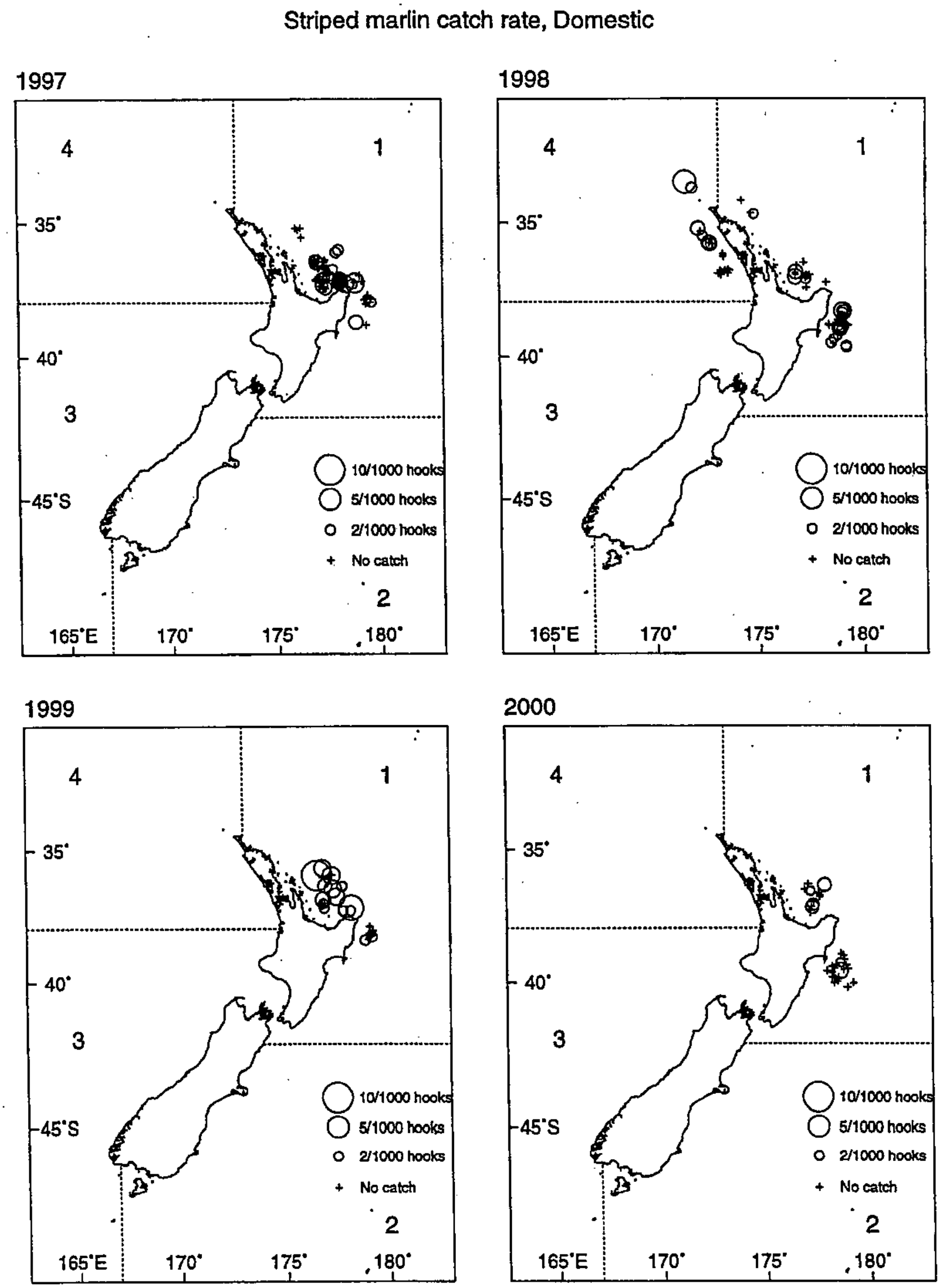
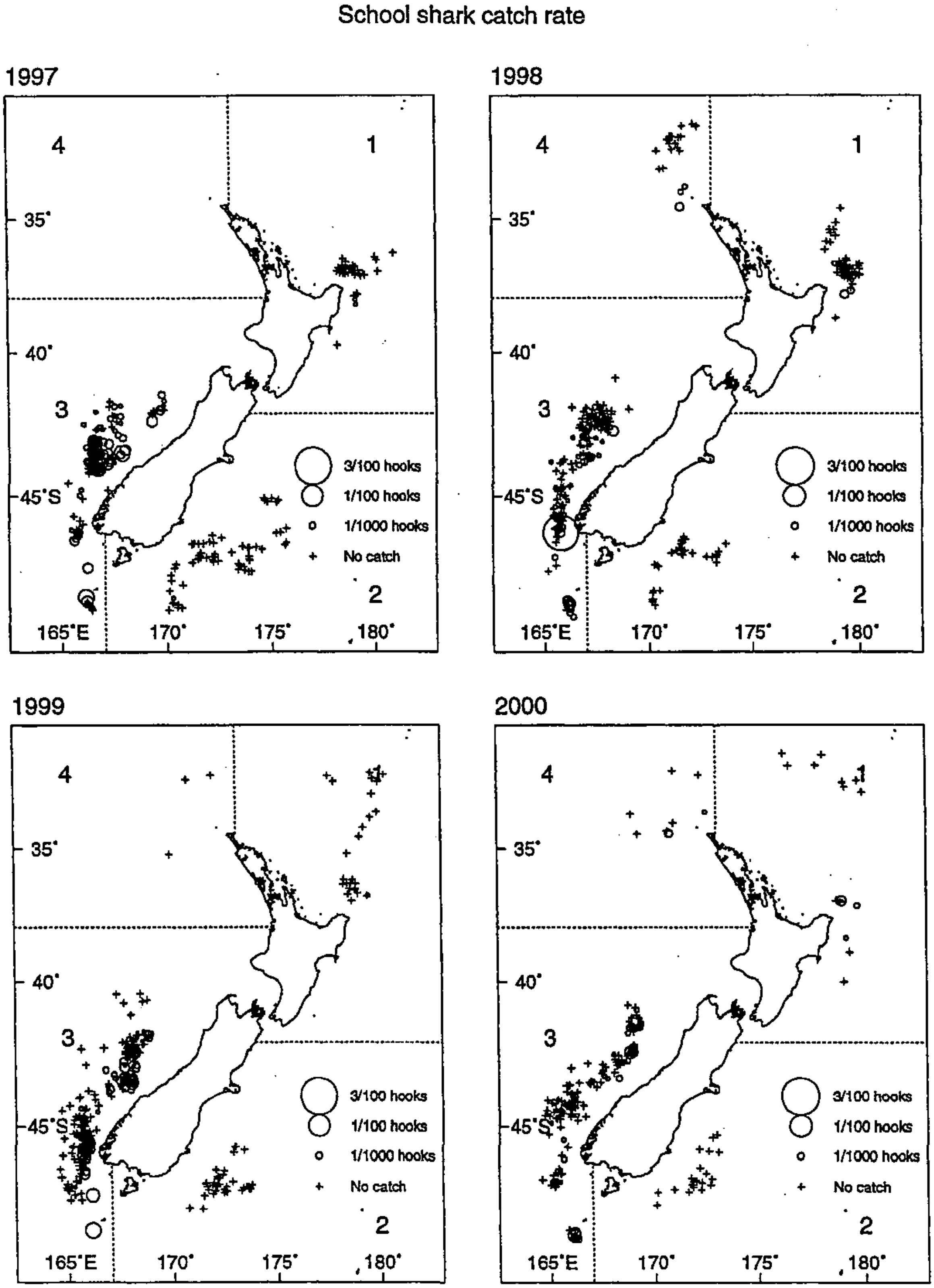


Figure 15: Striped marlin catch rates on tuna longlines (domestic fleet), 1997–2000.


School shark catch rate

1997

1998

1999

2000

Figure 16: School shark catch rates on tuna longlines (charter fleet), 1997–2000.

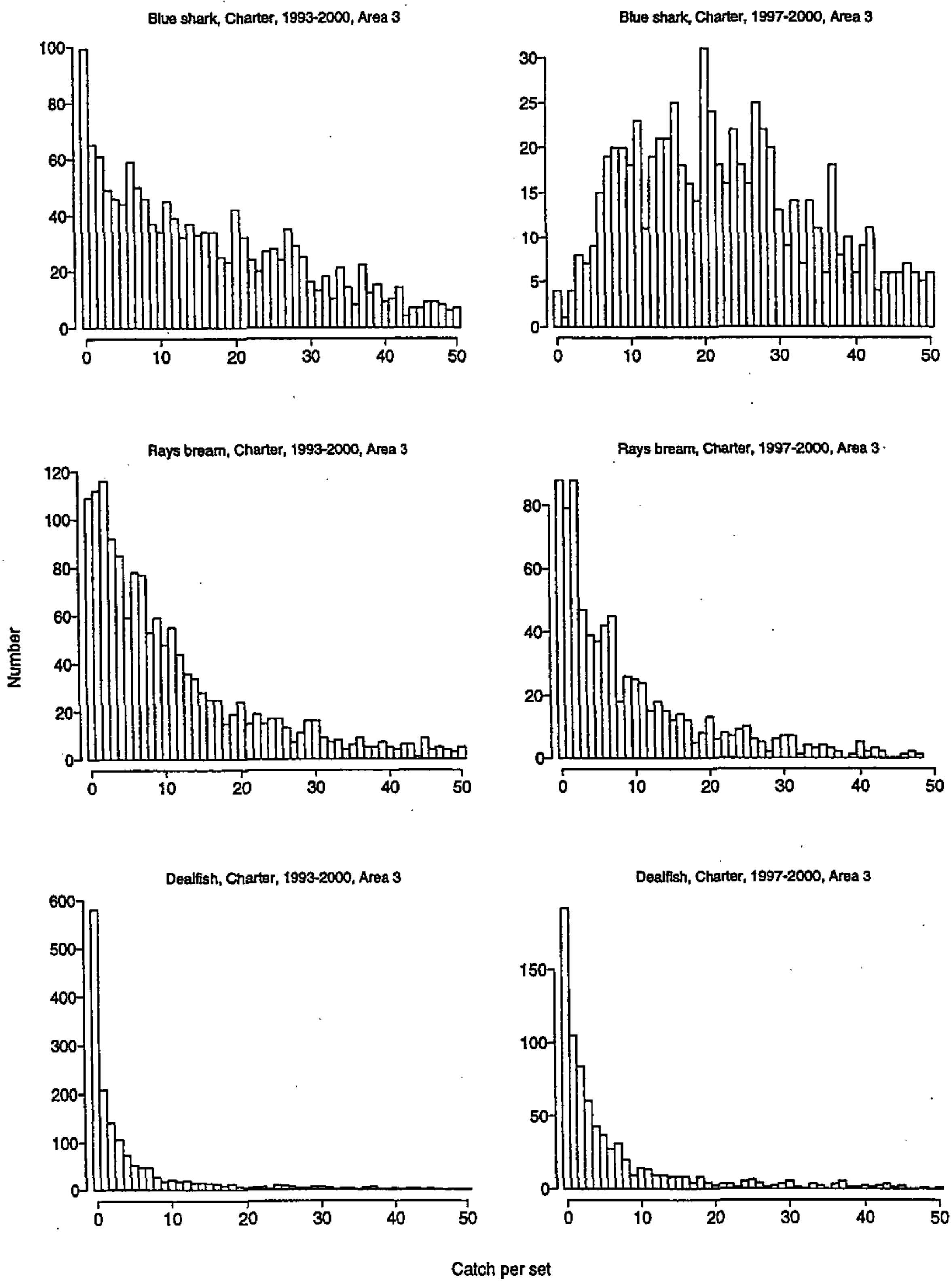


Figure 17: Catch per set distributions for blue sharks, Ray's bream, and dealfish from the charter fleet in Area 3. Catch per set of more than 50 is not shown for convenience but does occur (especially for blue sharks).

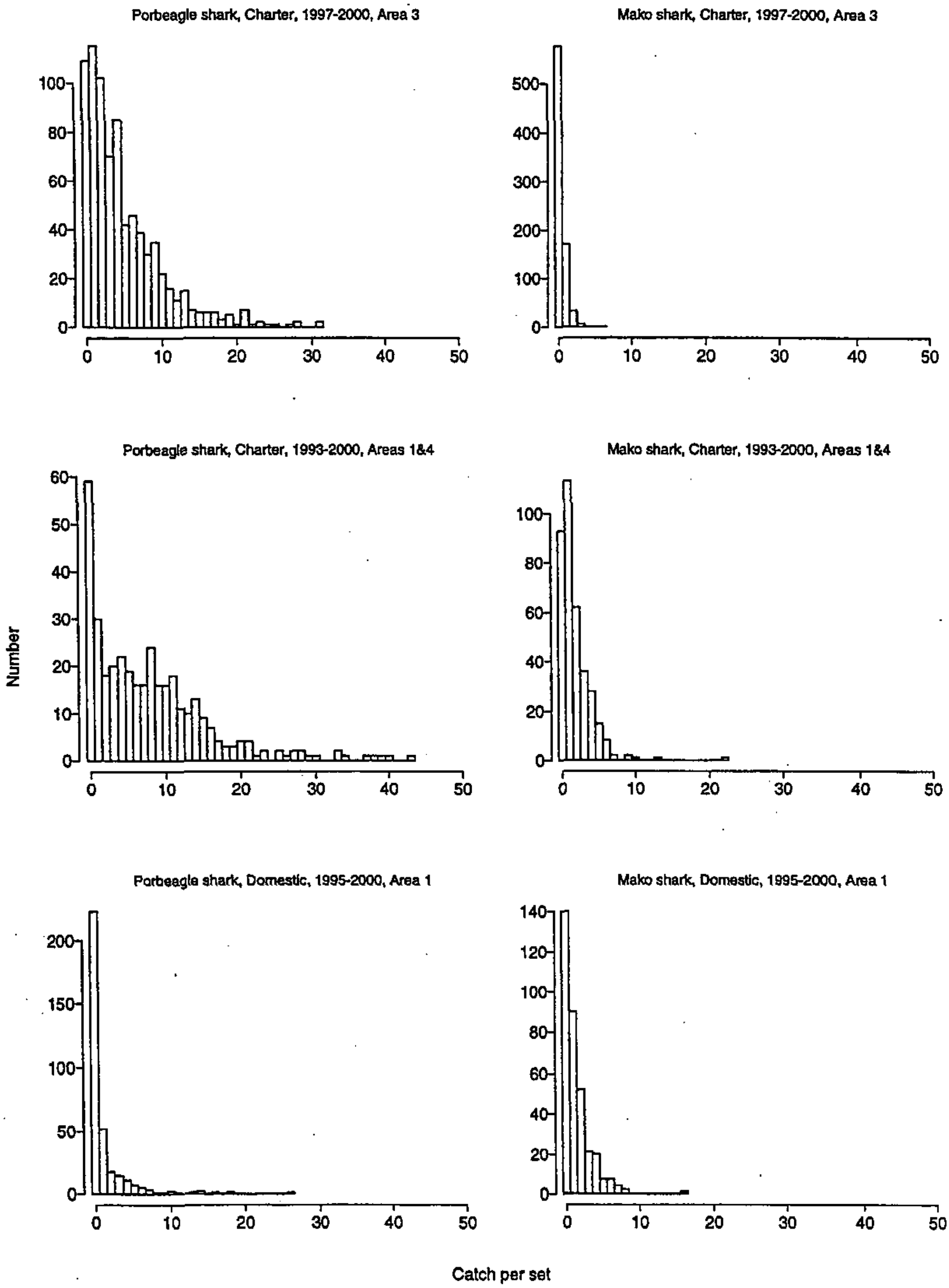


Figure 18: Catch per set for porbeagle and mako sharks.

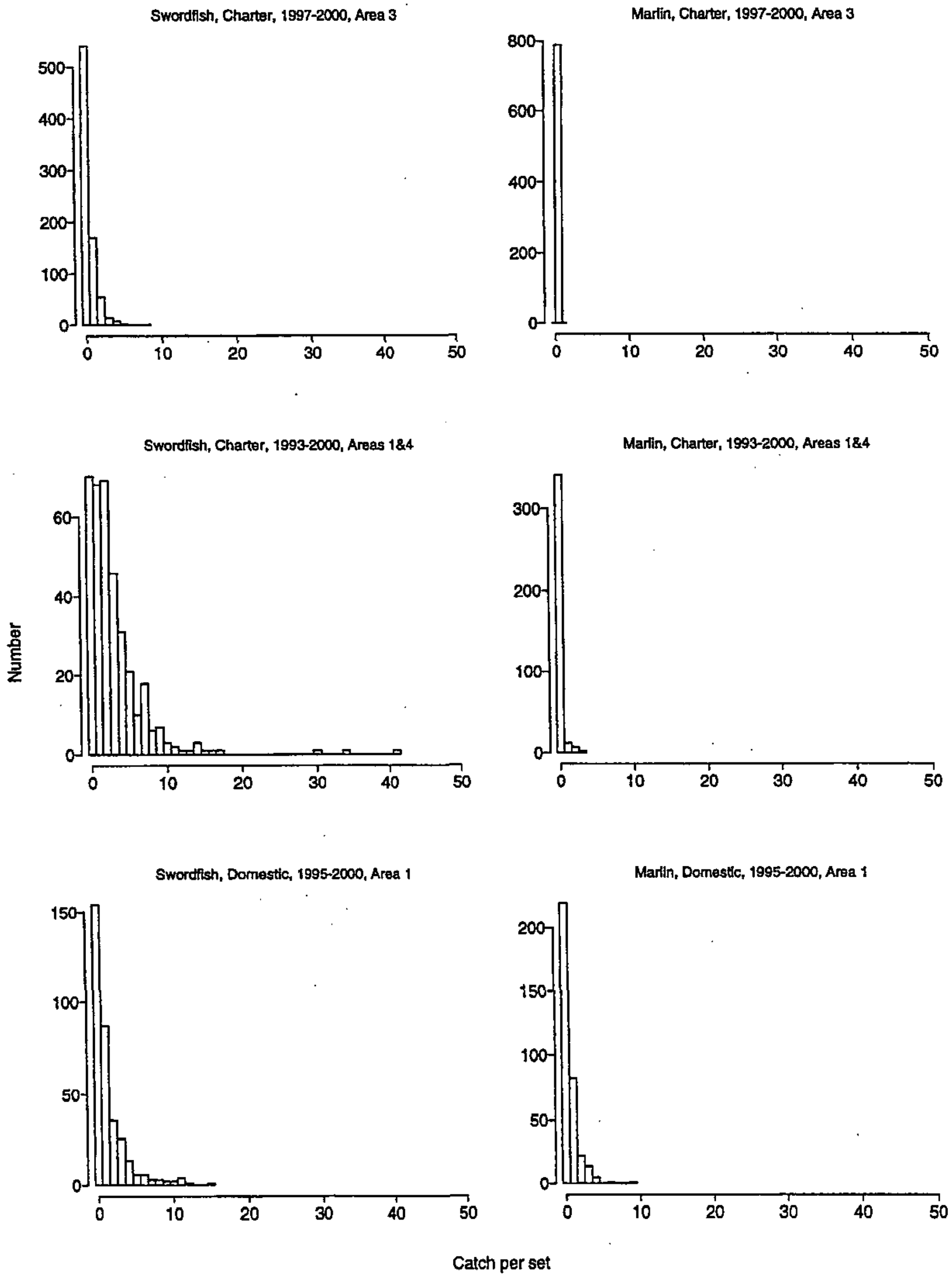


Figure 19: Catch per set for broadbill swordfish and striped marlin.

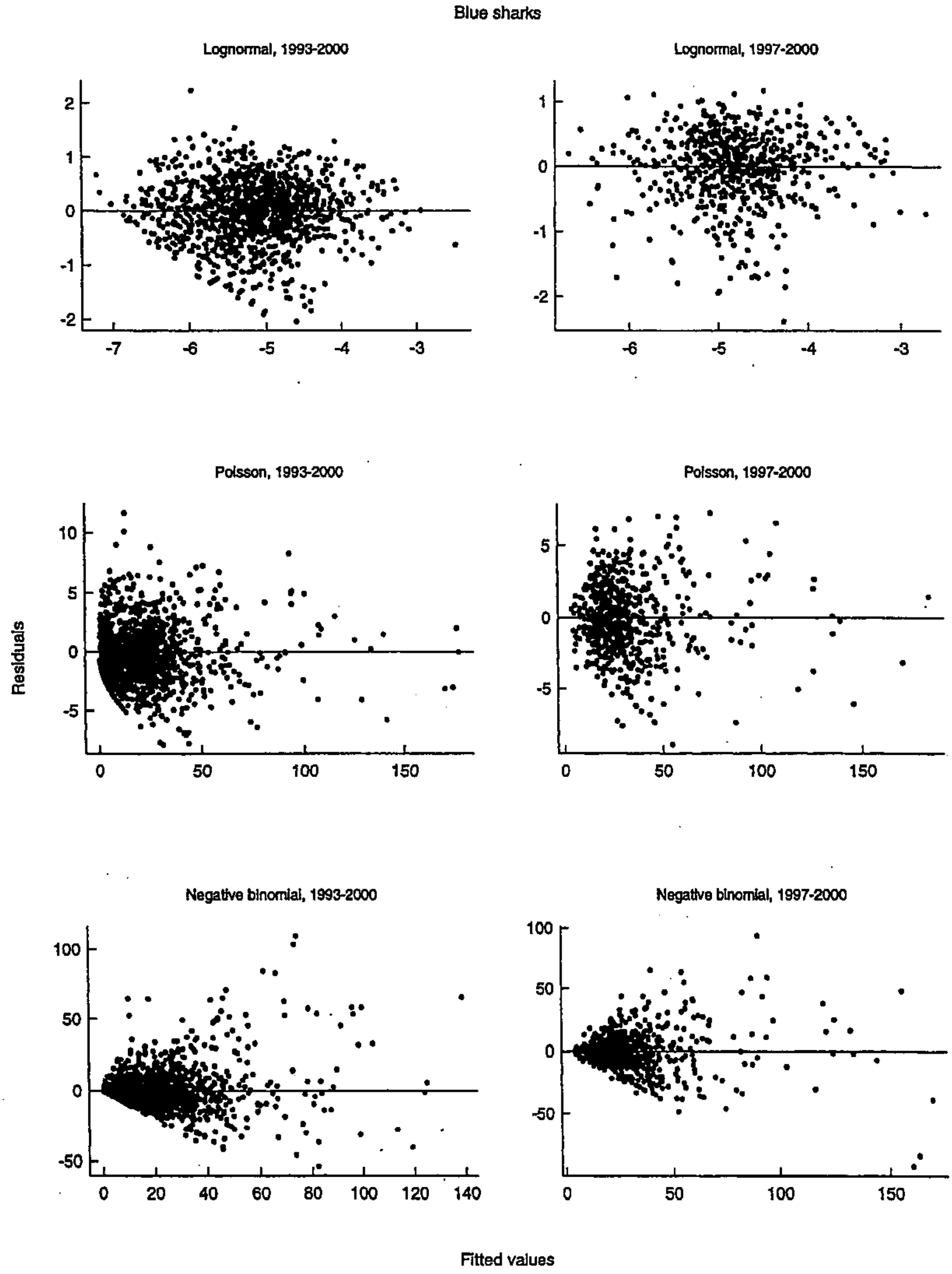


Figure 20: Plots of residuals versus fitted values for blue shark models, charter fleet, Area 3.

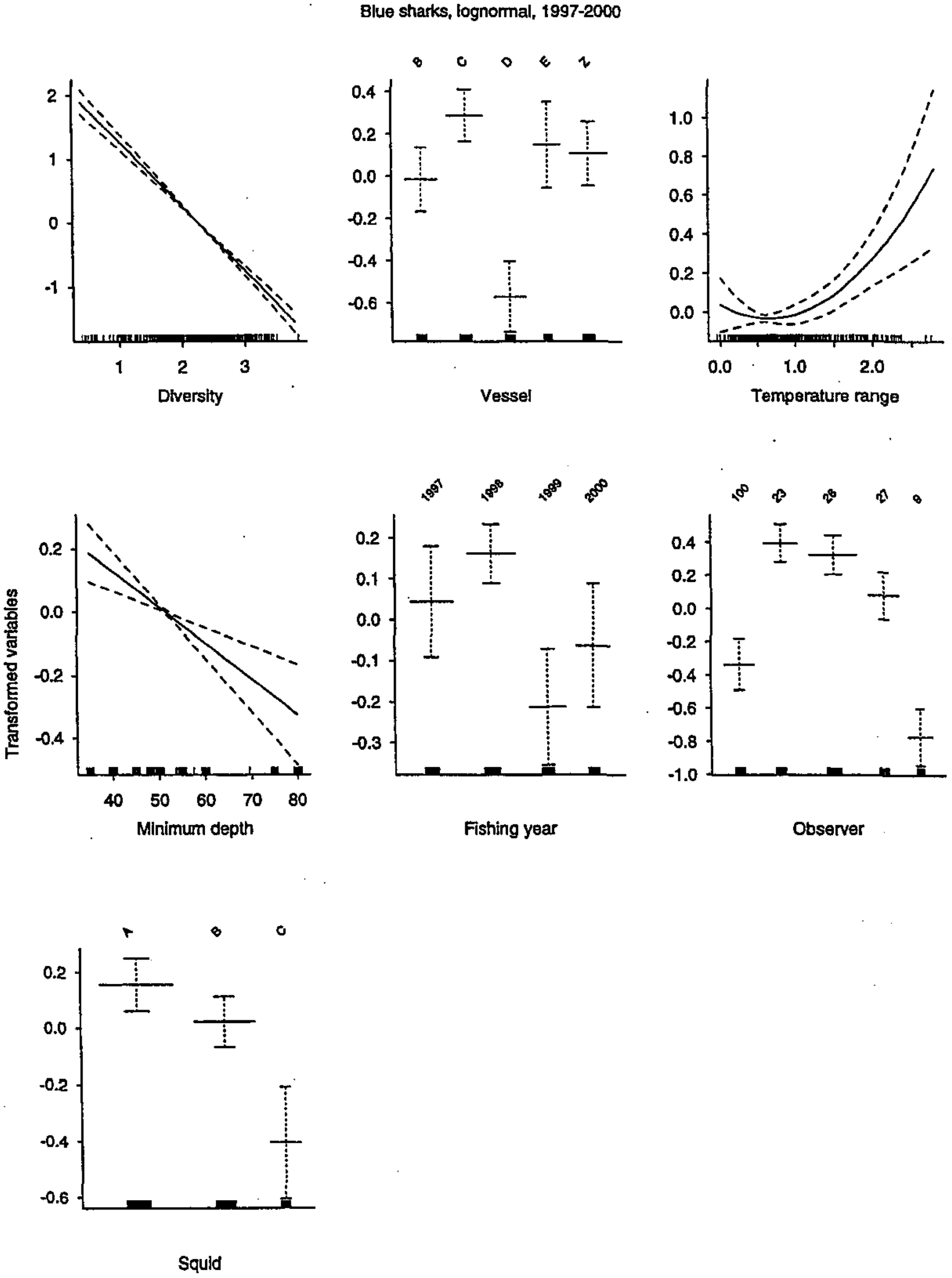


Figure 21: Fits of predictor variables for the lognormal model from 1997–2000 for blue sharks, charter fleet, Area 3. A, B, C represent increasing proportions of squid bait. The data plotted on the y scales have been log transformed and have the mean removed. Where appropriate they include the polynomial transformation used.

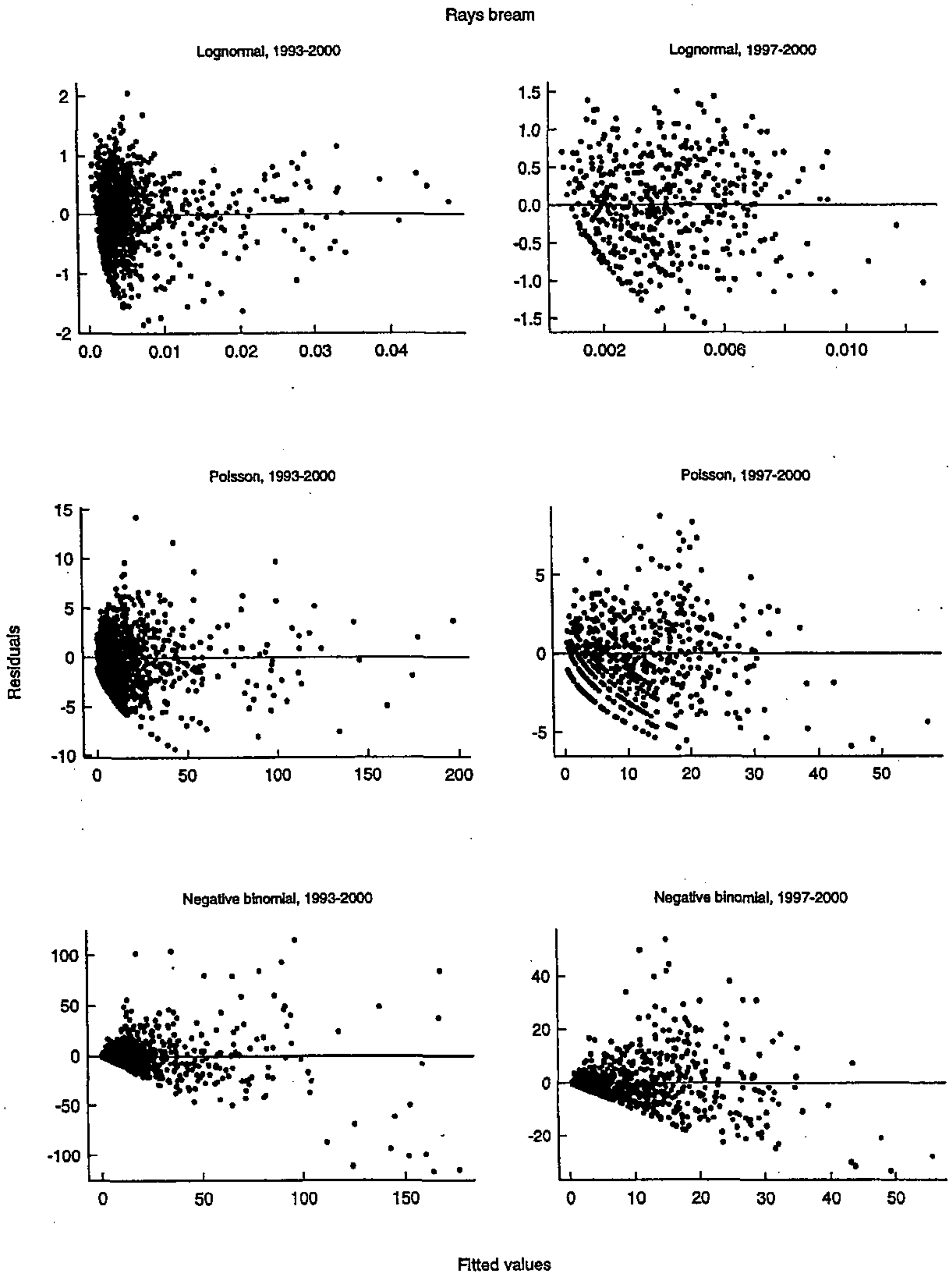


Figure 22: Plots of residuals versus fitted values for Ray's bream models, charter fleet, Area 3.

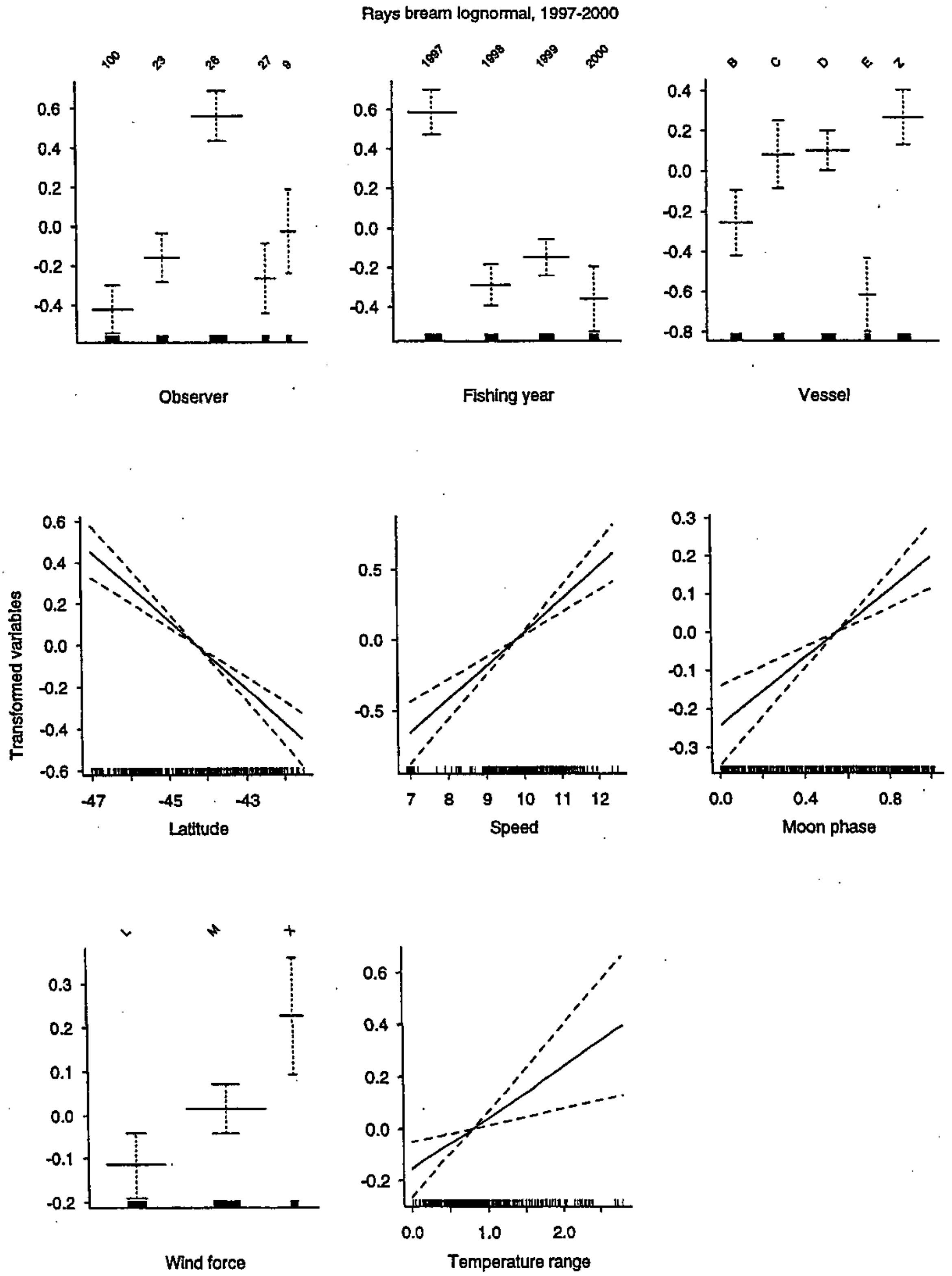


Figure 23: As for Figure 21 but showing fits of predictor variables for the lognormal model from 1997–2000 for Ray's bream, charter fleet, Area 3. L, M, and X represent increasing wind force.

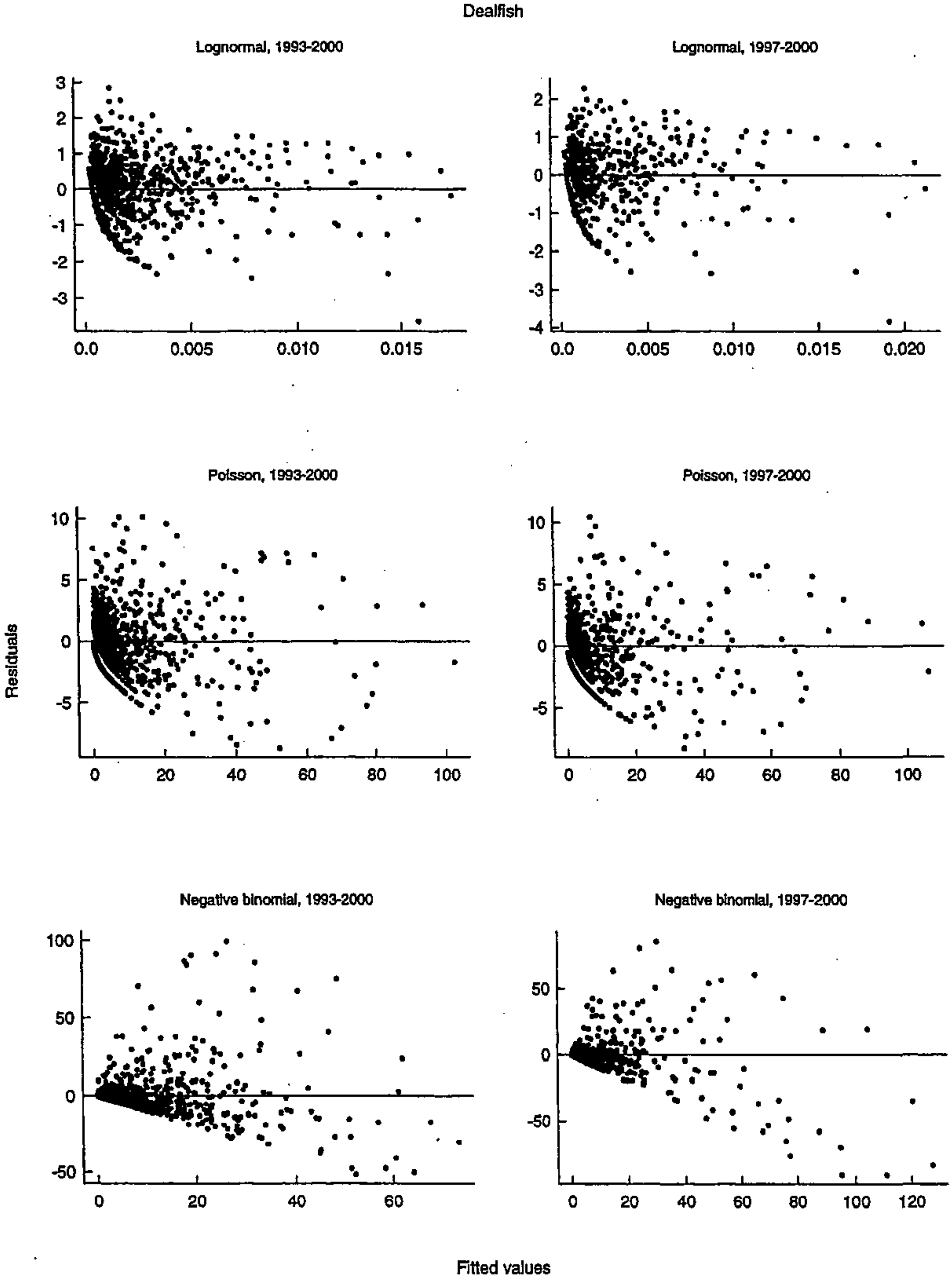


Figure 24: Plots of residuals versus fitted values for dealfish models, charter fleet, Area 3.

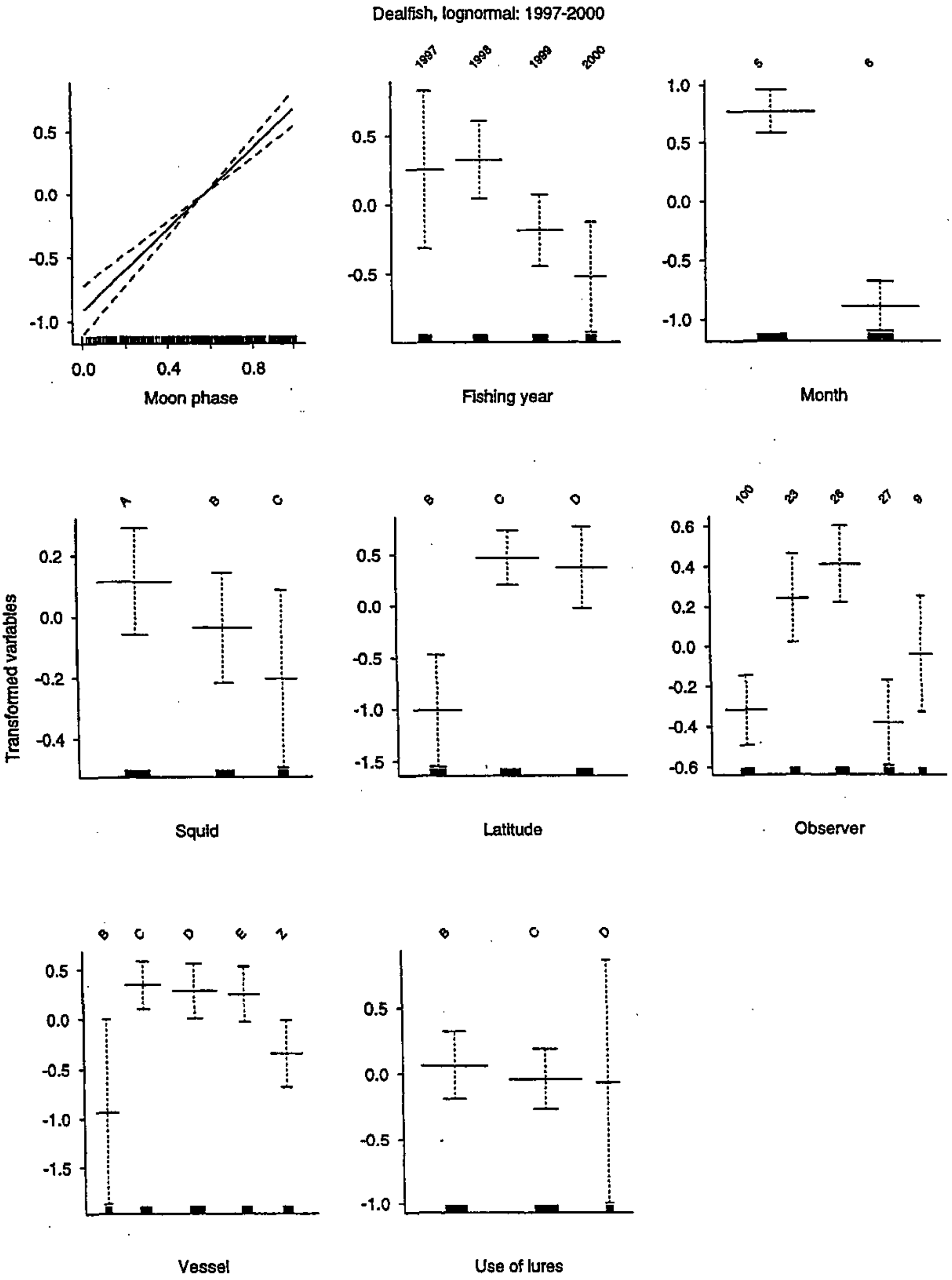


Figure 25: As for Figure 21 but showing fits of predictor variables for the lognormal model from 1997–2000 for dealfish, charter fleet, Area 3. A, B, C represent increasing amounts of squid bait. B, C, D distinguish the latitude bands, B being the most southerly. B, C, D represent increasing numbers of lures used.

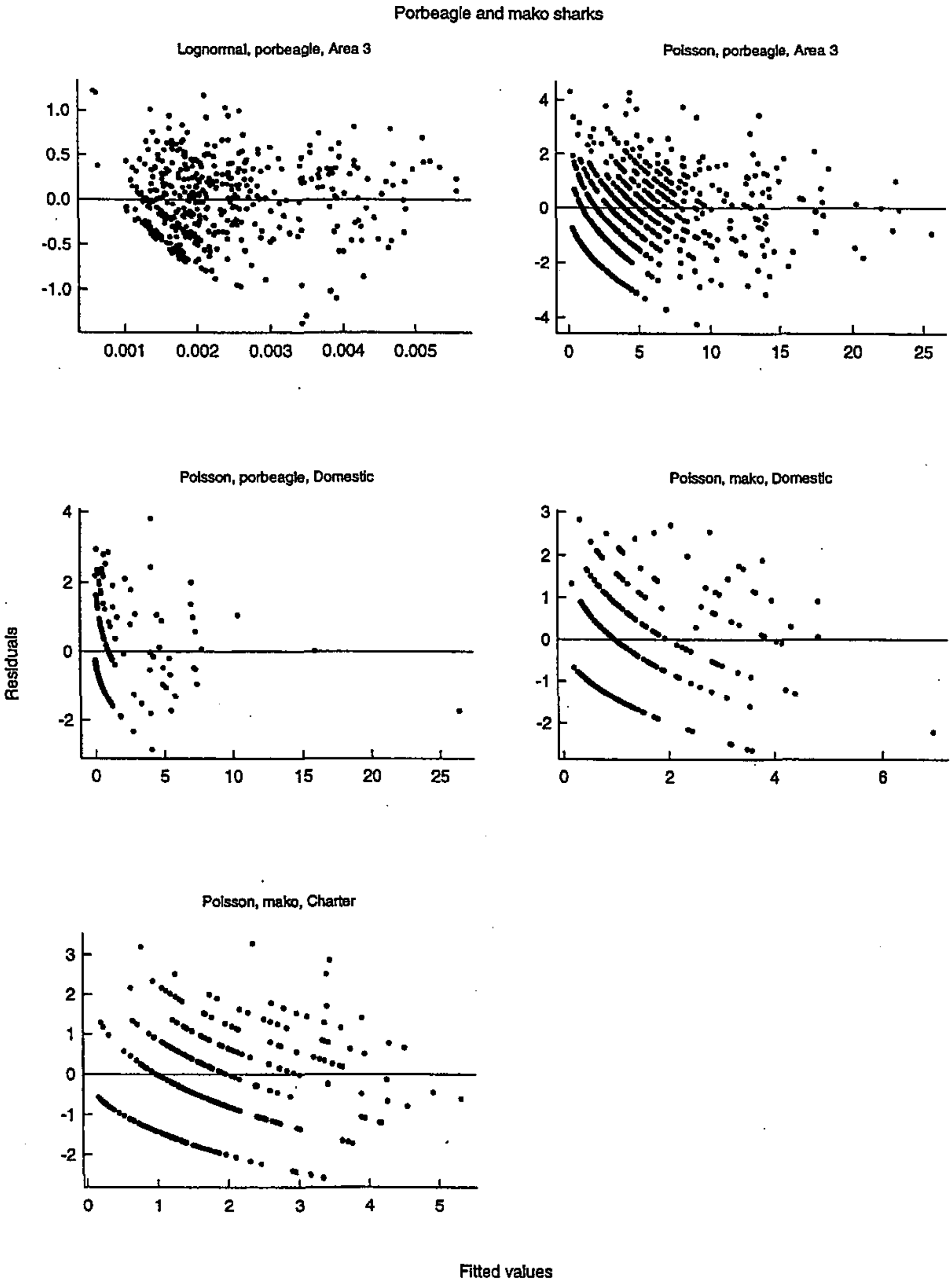


Figure 26: Plots of residuals versus fitted values for porbeagle and mako shark models,

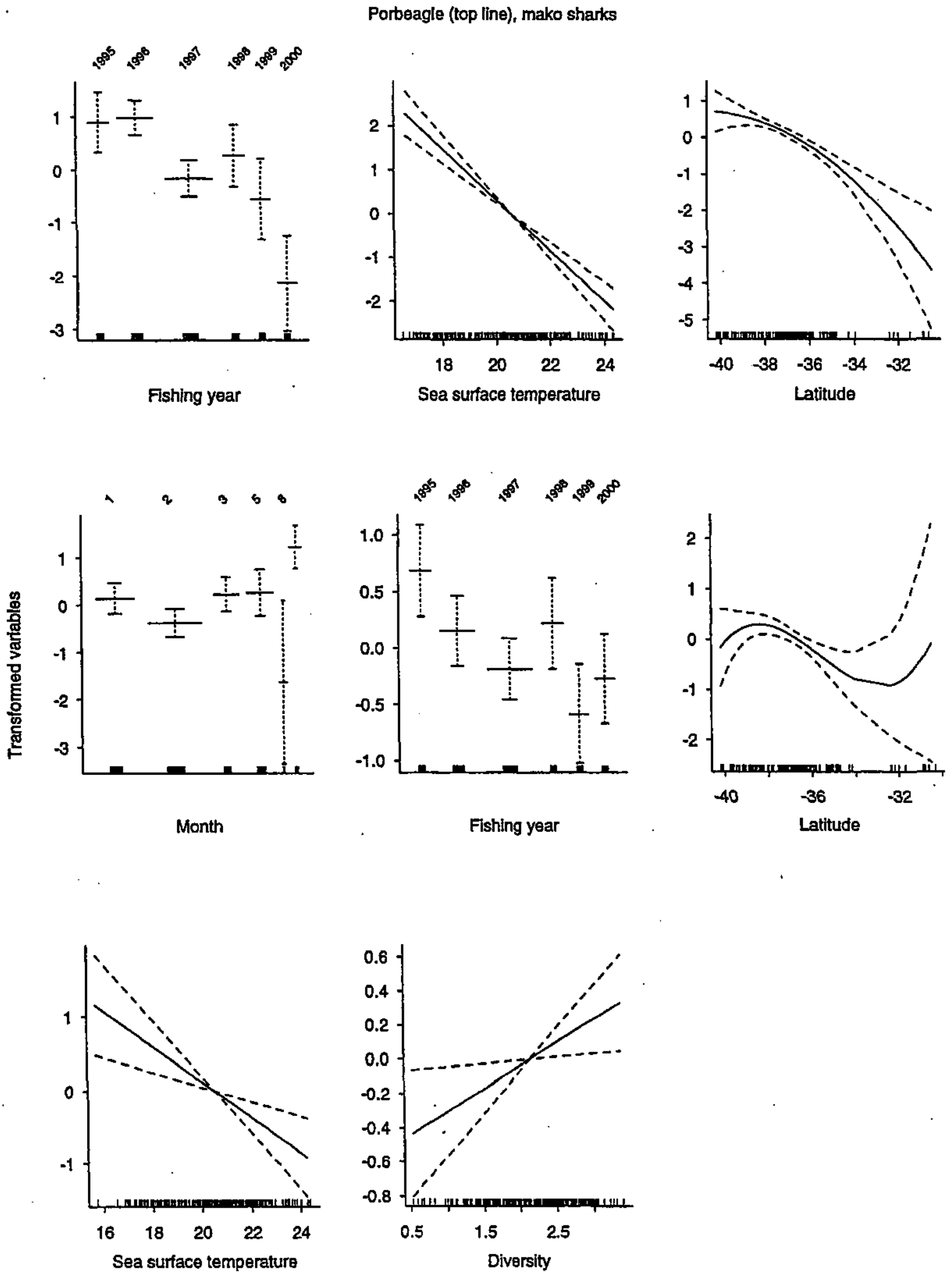


Figure 27: As for Figure 21 but showing fits of predictor variables for the Poisson models for porbeagle and mako sharks, domestic fleet, Area 1.

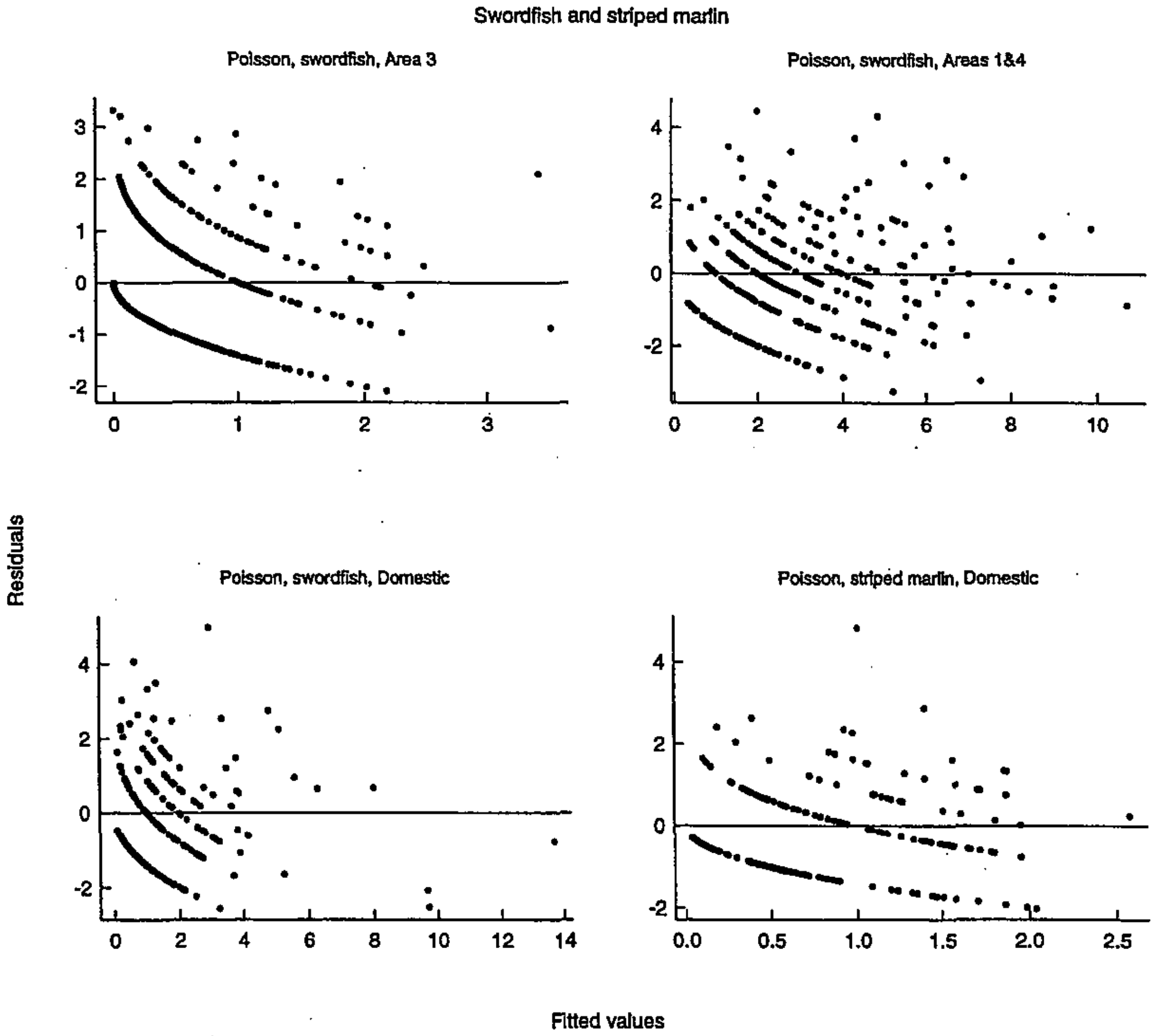


Figure 28: Plots of residuals versus fitted values for swordfish and striped marlin models.

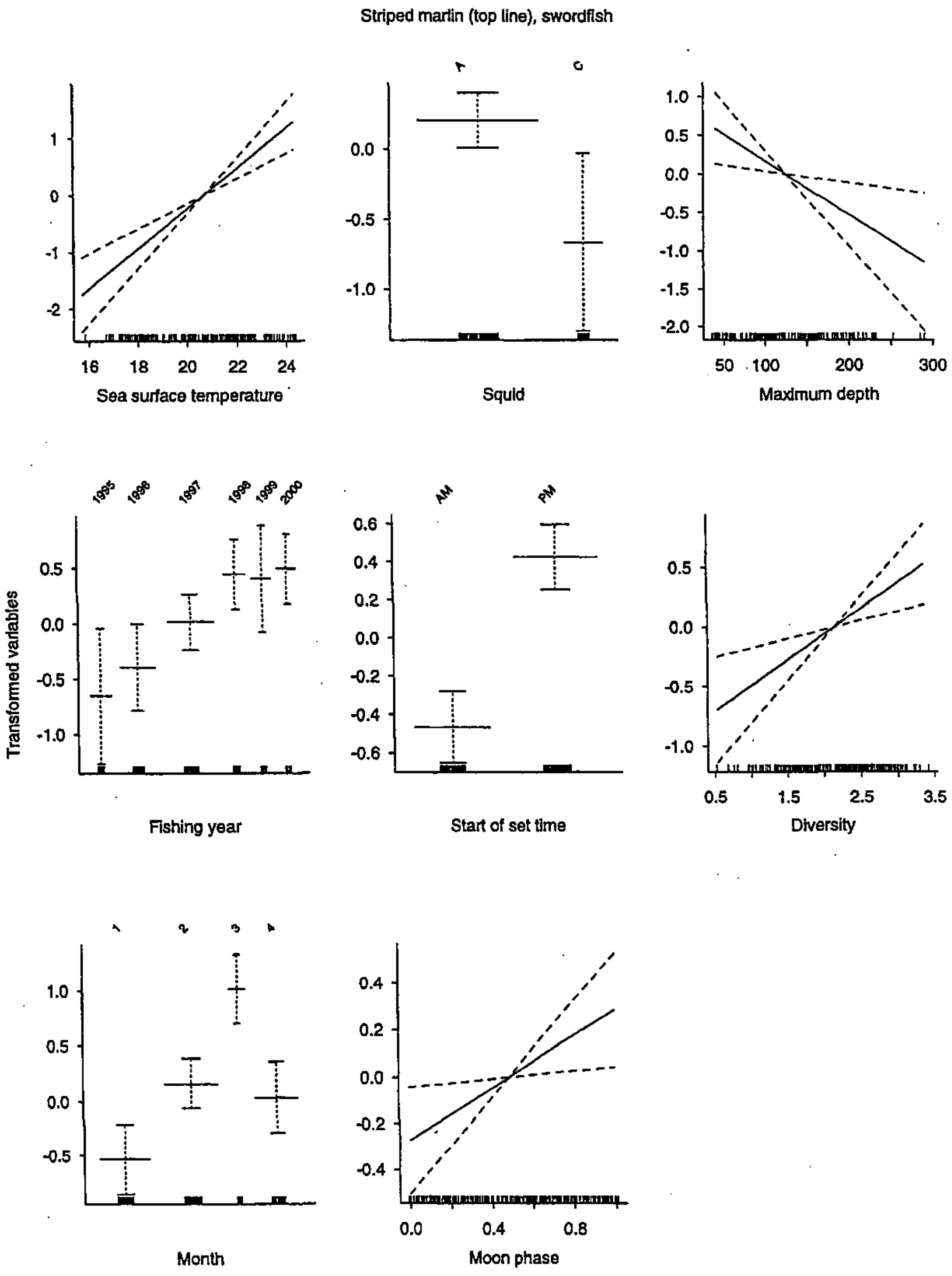


Figure 29: As for Figure 21 but showing fits of predictor variables for the Poisson models for striped marlin and swordfish, domestic fleet, Area 1. A represents up to 50% squid bait, B more than this.

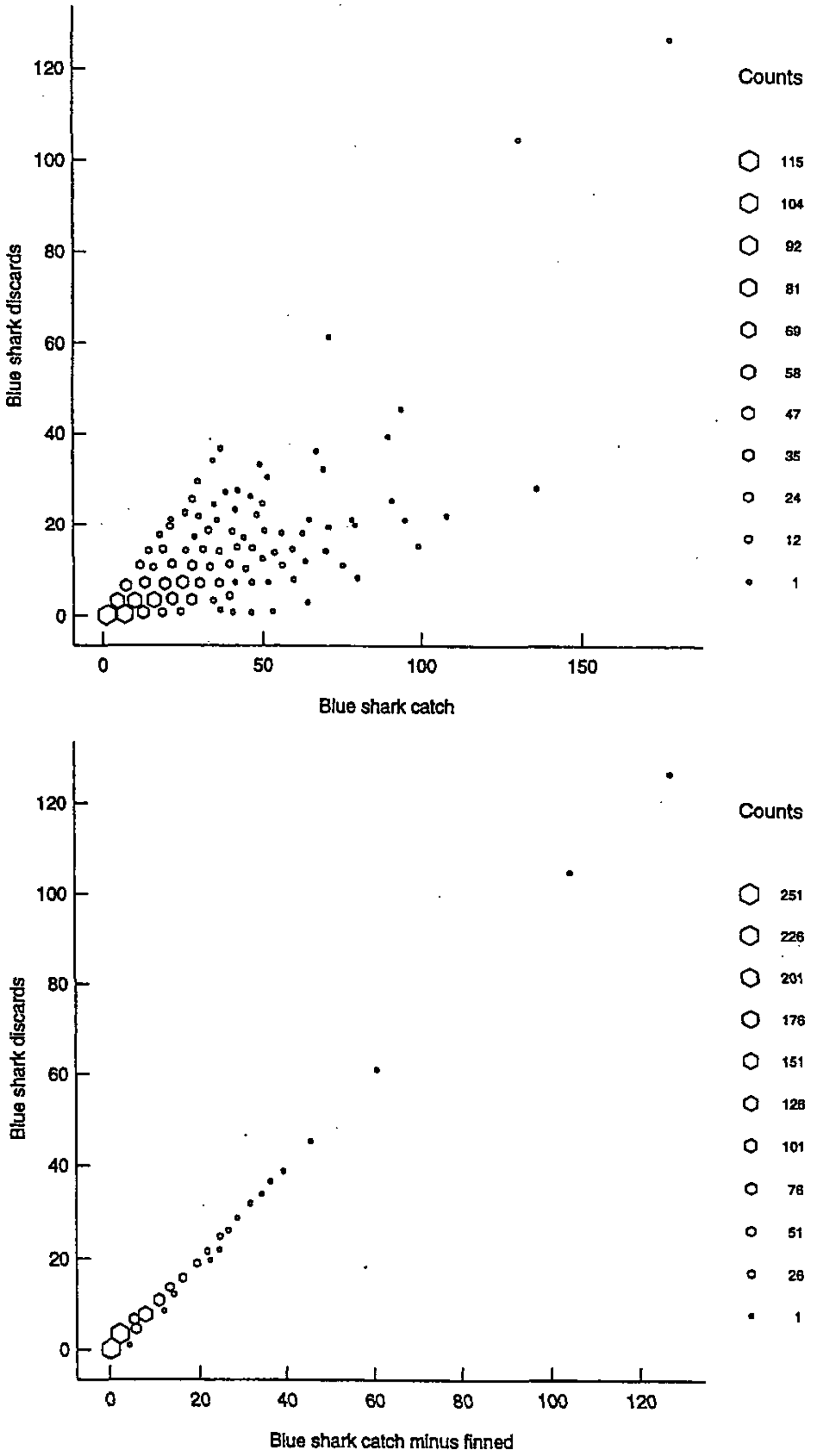


Figure 30: Blue shark catch discards versus catch and discards versus catch minus finned in Area 3 by charter fleet, 1992–2000. Sets where information about the fate of at least 90% of blue sharks caught was known were used.

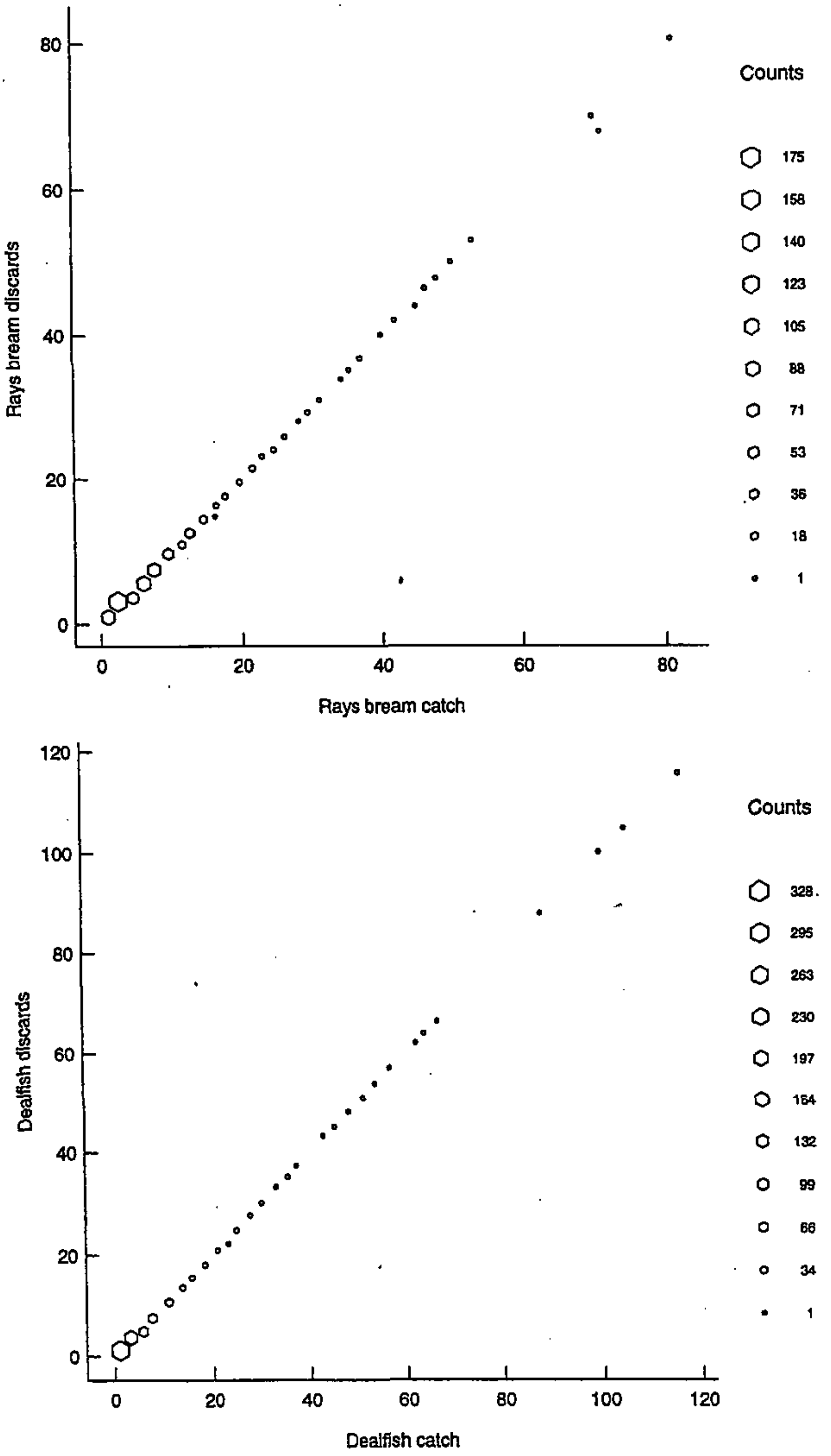


Figure 31: Ray's bream catch discards versus catch and dealfish discards versus catch in Area 3 by the charter fleet, 1992–2000. Sets where information about the fate of at least 90% of the species caught was known were used.

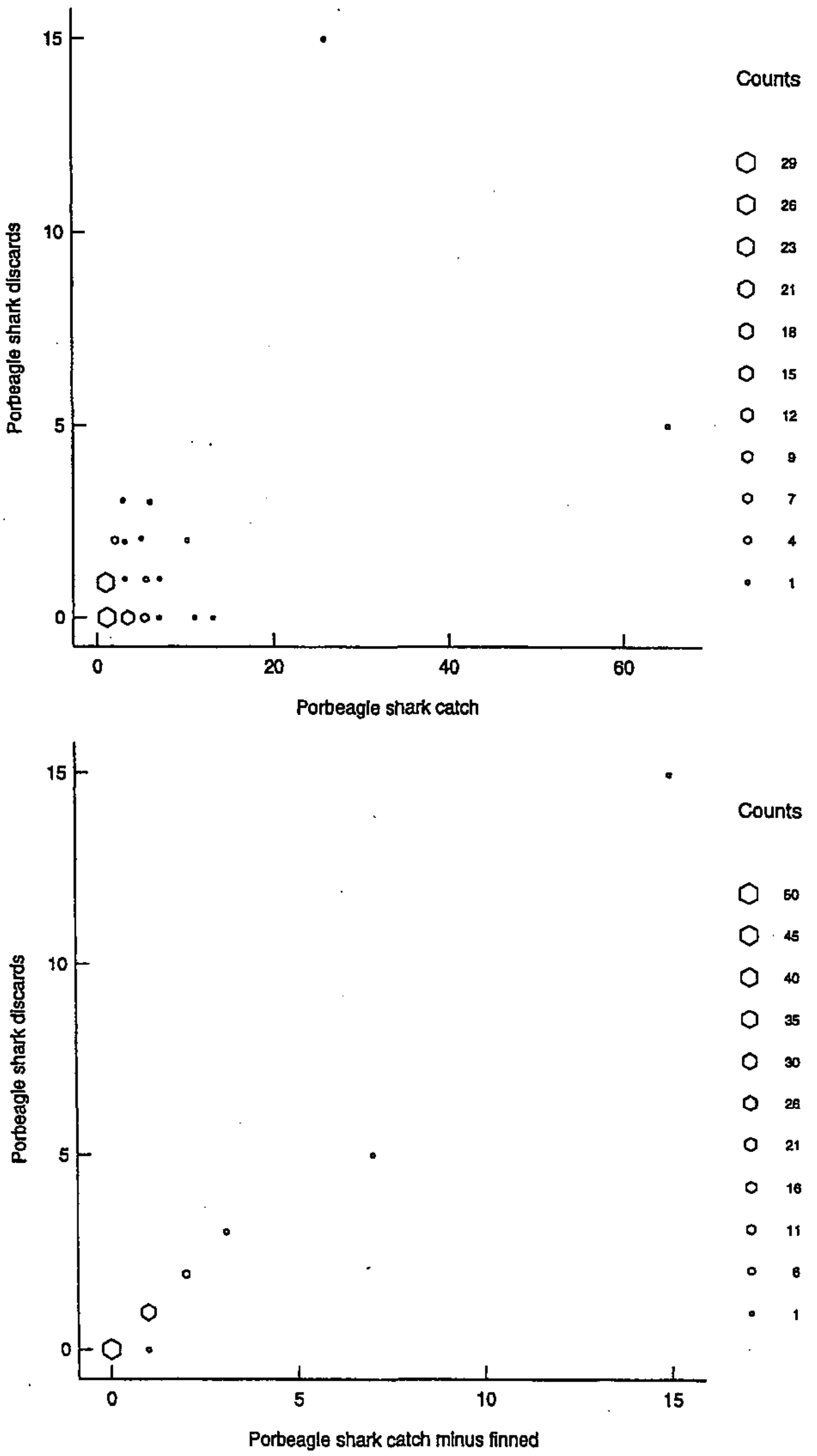


Figure 32: Porbeagle shark catch discards versus catch and discards versus catch minus finned in Areas 1 & 4 by the domestic fleet, 1995–2000. Data where information about the fate of at least 90 % of porbeagle sharks caught on a set was known were used.

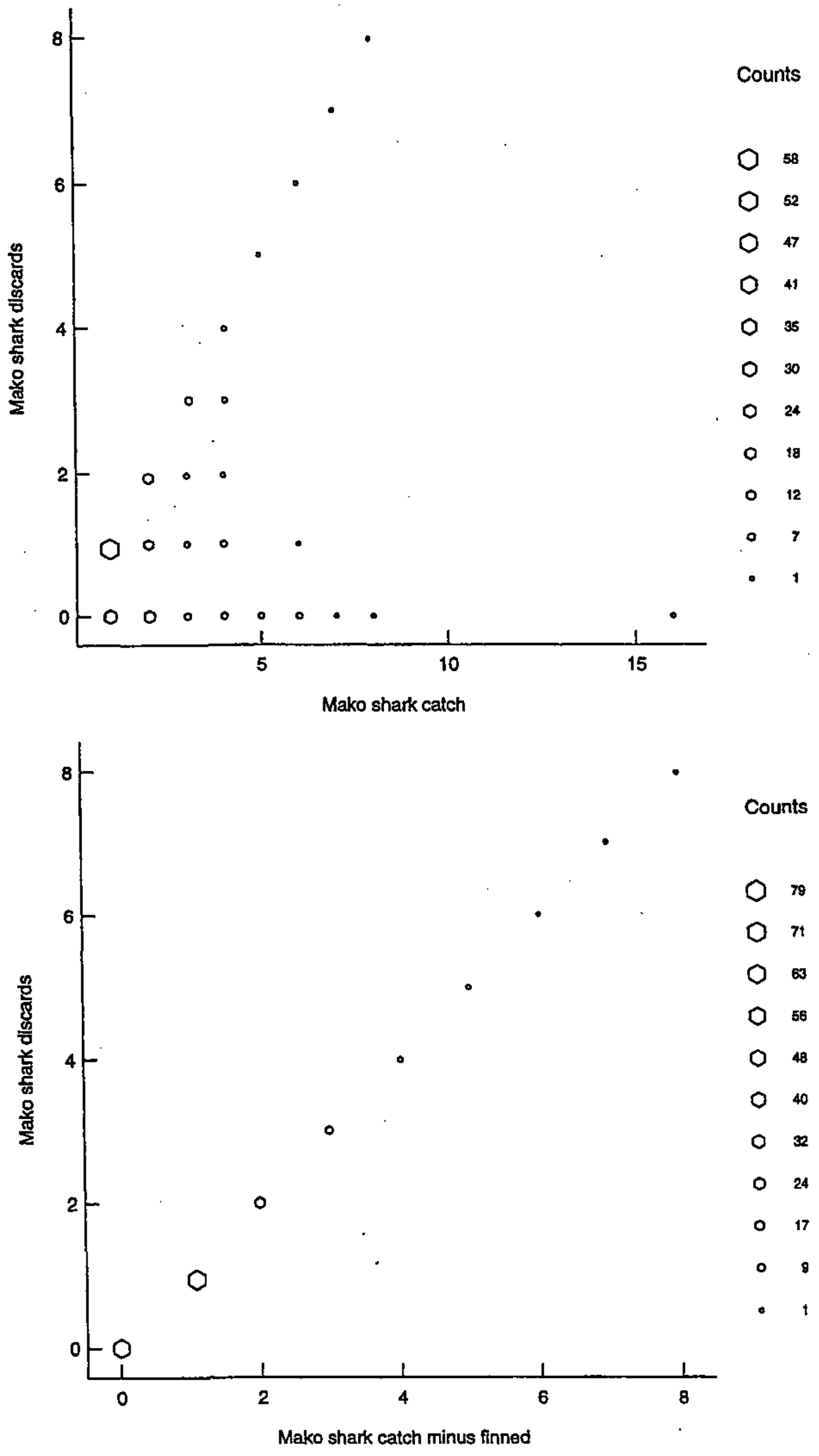


Figure 33: Mako shark catch discards versus catch and discards versus catch minus finned in Areas 1 & 4 by the domestic fleet, 1995–2000. Data where information about the fate of at least 90% of mako sharks caught on a set was known were used.

Appendix 1:

Representativeness of observer coverage in 1998–99 and 1999–2000

This appendix examines whether the observer coverage of the tuna fleet in New Zealand waters in 1998–99 and 1999–2000 was representative of the commercial effort. The charter and domestic fleets are considered separately. For these purposes, a large domestic vessel that normally fishes alongside the charter vessels was considered to belong to the charter fleet.

The two variables that best encapsulate the temporal and spatial variation of the fishery are time and latitude. Time was taken as the day on which the set started. The east-west differences were distinguished by using separate plots for the east and west coasts of New Zealand. The east and west of the country were separated using the divisions defined for estimating sea bird capture by the tuna longline fishery. Areas 1 and 2 extend from east of the QMA 1/QMA 9 boundary at longitude 172°02.8' E around the eastern southern coasts of New Zealand to a line at longitude 167° E. Areas 3 and 4 extends westwards between the same lines.

Formal definitions of the two fleets and four Areas are given in the report to which this section is appended.

The commercial effort data came from the Ministry of Fisheries TLCER database. The start of set positions were provided to the nearest tenth of a degree. Some sets far outside the New Zealand EEZ were removed as being erroneous. A few sets by the domestic fleet were apparently on land (these have not been removed), and probably some sets that were given as being west of 180° were in fact east of this line. Such errors will make little difference to the discussion, especially if the latitude is correct. The small amount of domestic tuna effort recorded on CELR forms was ignored. Observer data came from the l_line database administered by NIWA for the Ministry of Fisheries and latitudes have been rounded to the nearest tenth of a degree for comparison.

Methods

Maps of start of set positions of commercial and observed sets are presented for both fleets in 1998–99 and 1999–2000.

The method of comparing the observed effort and total effort for the charter fleet closely follows that used by Doonan (1999, 2000) and Bradford (2000). The numbers of thousands of hooks set per tenth of a degree of latitude in Areas 1 and 2 were calculated for both the observed and total effort and then these curves smoothed using the constraint that the area under both curves was the same. The latitude used was the start of set latitude. This procedure was repeated for Areas 3 and 4, and using days instead of latitude. The observer coverage of the charter fleet was high (greater than 90%) in 1998–99 and 1998–99 and the interest here is in any mismatches between the observer effort and total effort.

The observer coverage for the domestic fleet was low (less than 1%) in 1998–99 and 1999–2000 and a modified method that did not smooth the data was used as it was judged desirable to use a method that clearly showed the low as well as the non-representative coverage of the domestic fishery. For the domestic fleet, the commercial and observed effort (in thousands of hooks) were plotted against start of set latitude (in tenths of a degree) and day in the fishing year for the 1998–99 and 1999–2000 fishing years. Data were restricted to those from Areas 1 and 4 and consequently small amount of domestic commercial effort in southern latitudes was ignored. Small discrepancies between the start of set positions and the start of set day are possible due to the different methods of recording of the data and would be less noticeable if the data were smoothed.

Results

The observer coverage of the charter fleet was high and gave a good representation of the effort (Figures A1–A5) though some small portions of the data without observer coverage are apparent, especially in the eastern areas (Figures A1, A2, A4). Sometimes, the observer on the charter vessels carried out other duties or missed a small proportion of the hooks. The large domestic vessel had no observer in the 1999–2000 fishing year.

The low observer coverage of the domestic fleet (less than 1% in both years) gives a poor representation of the commercial effort in both space and time (Figures A6–A10). There was no observer coverage of the domestic effort on the west coast of the North Island (Area 4) in either year. The poor observer coverage of the domestic tuna fleet has been apparent for some years and a target of 10% observer coverage has been set for the 2000–2001 fishing year.

Most of the domestic effort took place within 100 nautical miles of the coast, and the plots of effort against time suggest the vessels made short trips, possibly returning to port for the weekend.

The different spatial and temporal fishing patterns of the charter and domestic tuna fleets are clearly apparent when Figures A1–A5 are compared with Figures A6–A10.

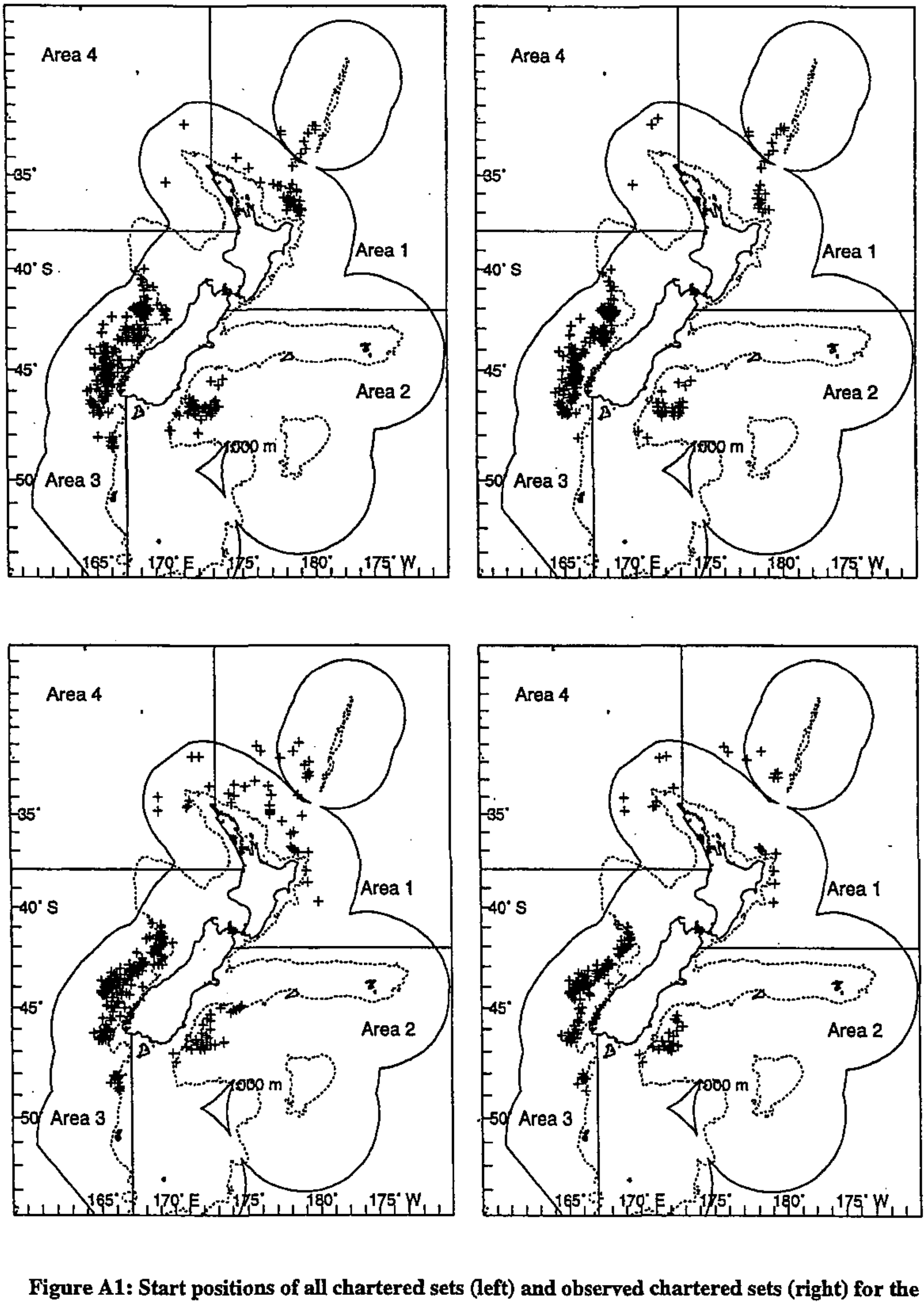


Figure A1: Start positions of all chartered sets (left) and observed chartered sets (right) for the tuna longline fishery in 1998–99 (top) and 1999–2000 (bottom).

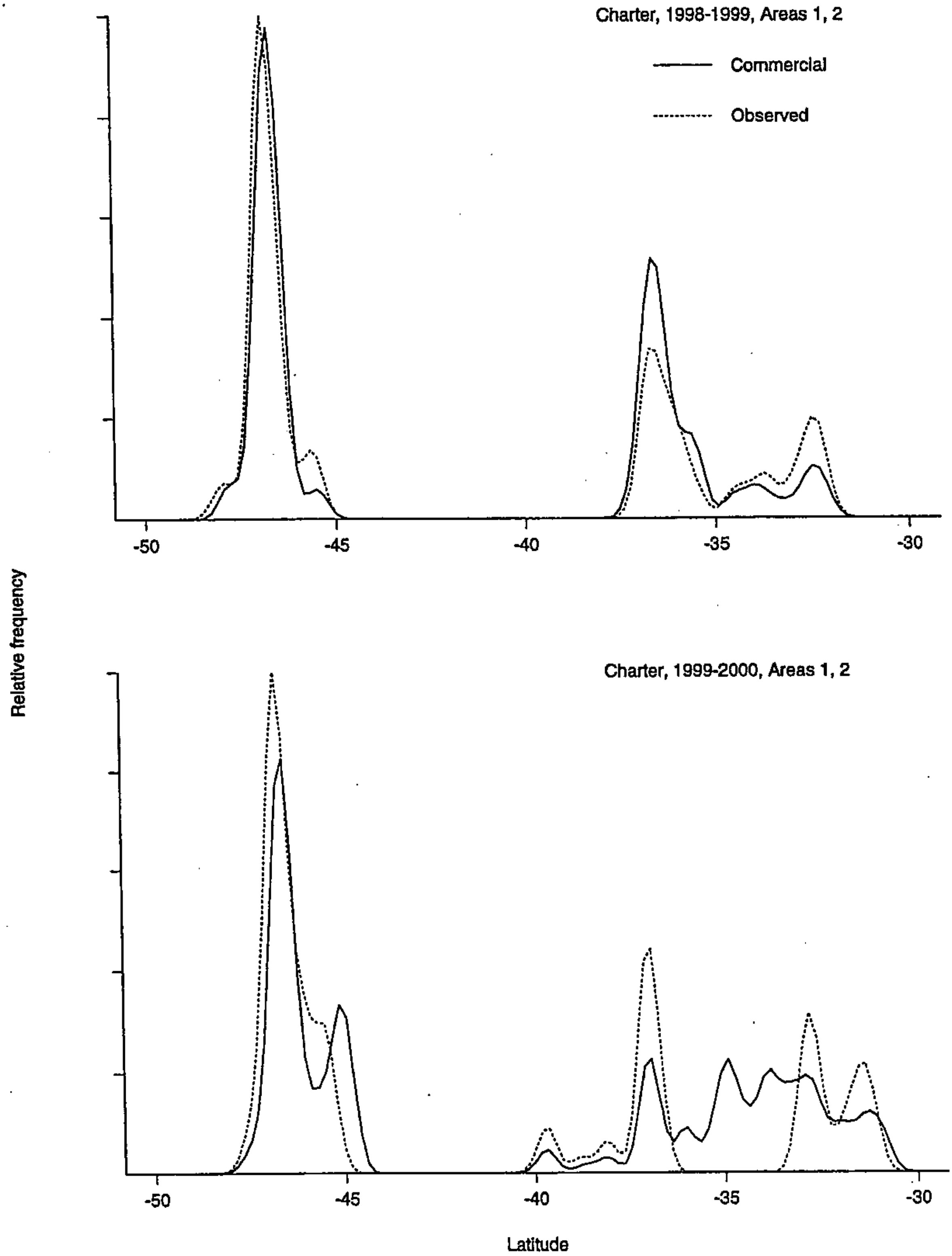


Figure A2: Total and observed effort by the charter fleet on the east coast of New Zealand by latitude in 1998–99 and 1999–2000.

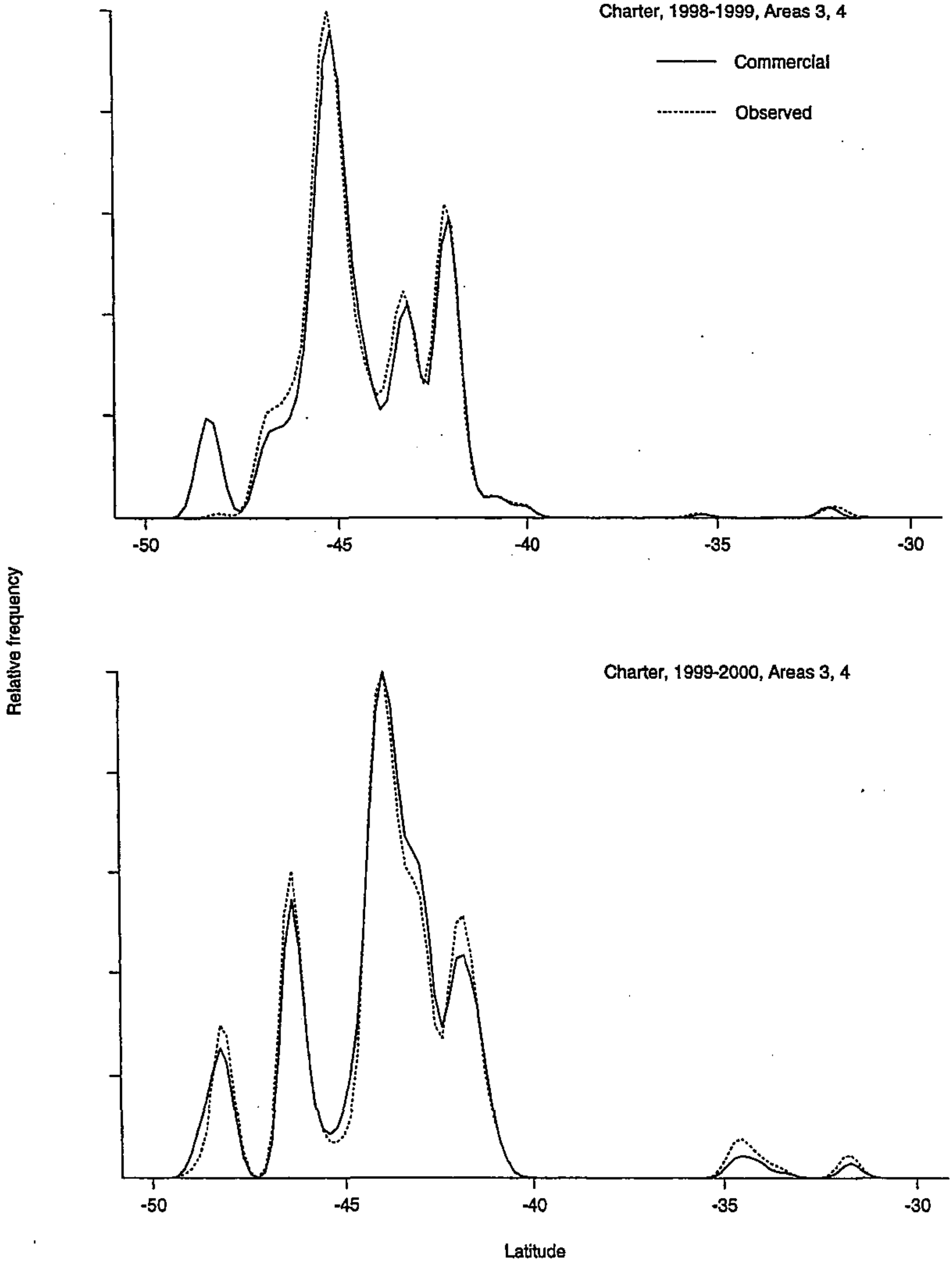


Figure A3: Total and observed effort by the charter fleet on the west coast of New Zealand by latitude in 1998–99 and 1999–2000.

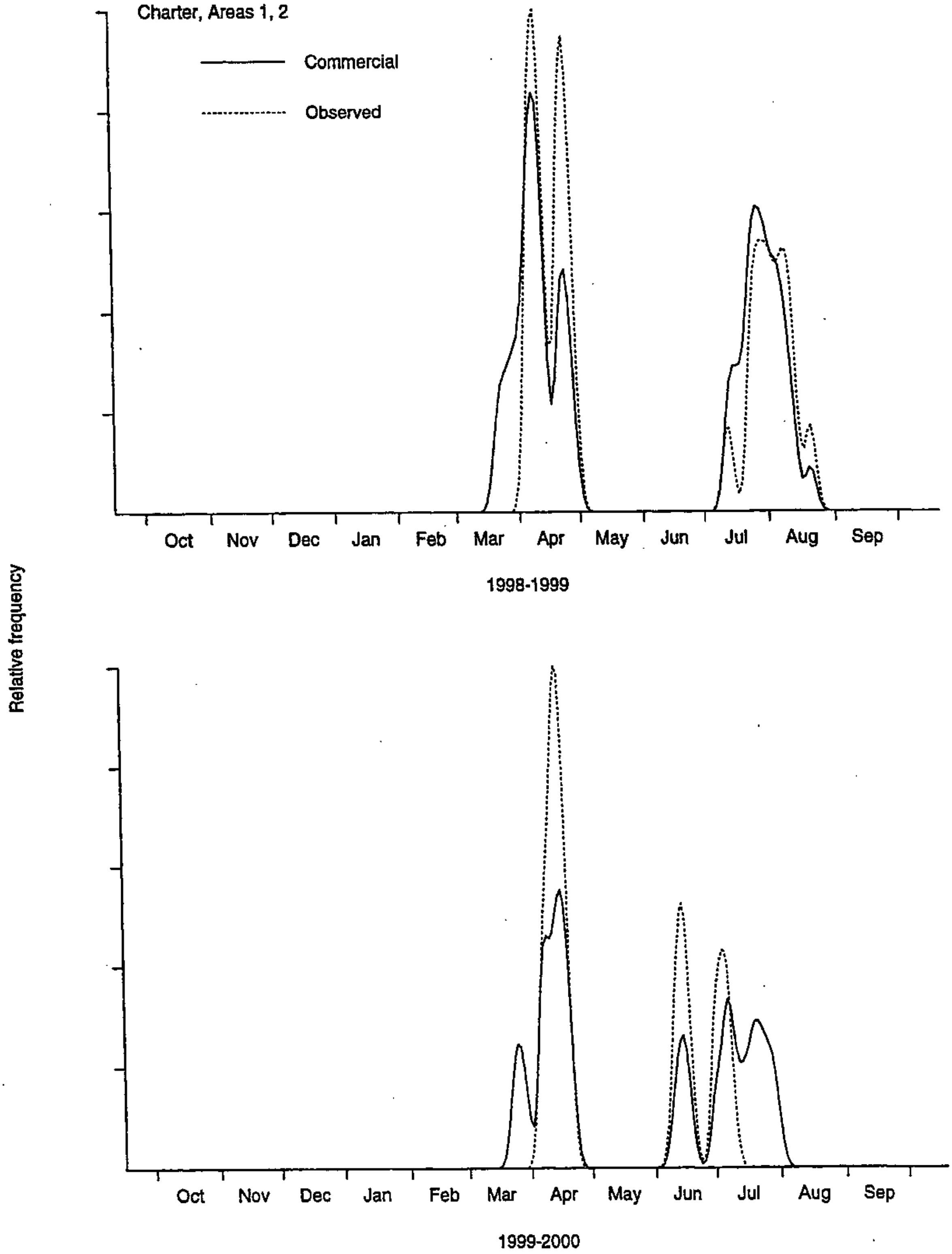


Figure A4: Total and observed effort by the charter fleet on the east coast of New Zealand by time of year in 1998–99 and 1999–2000.

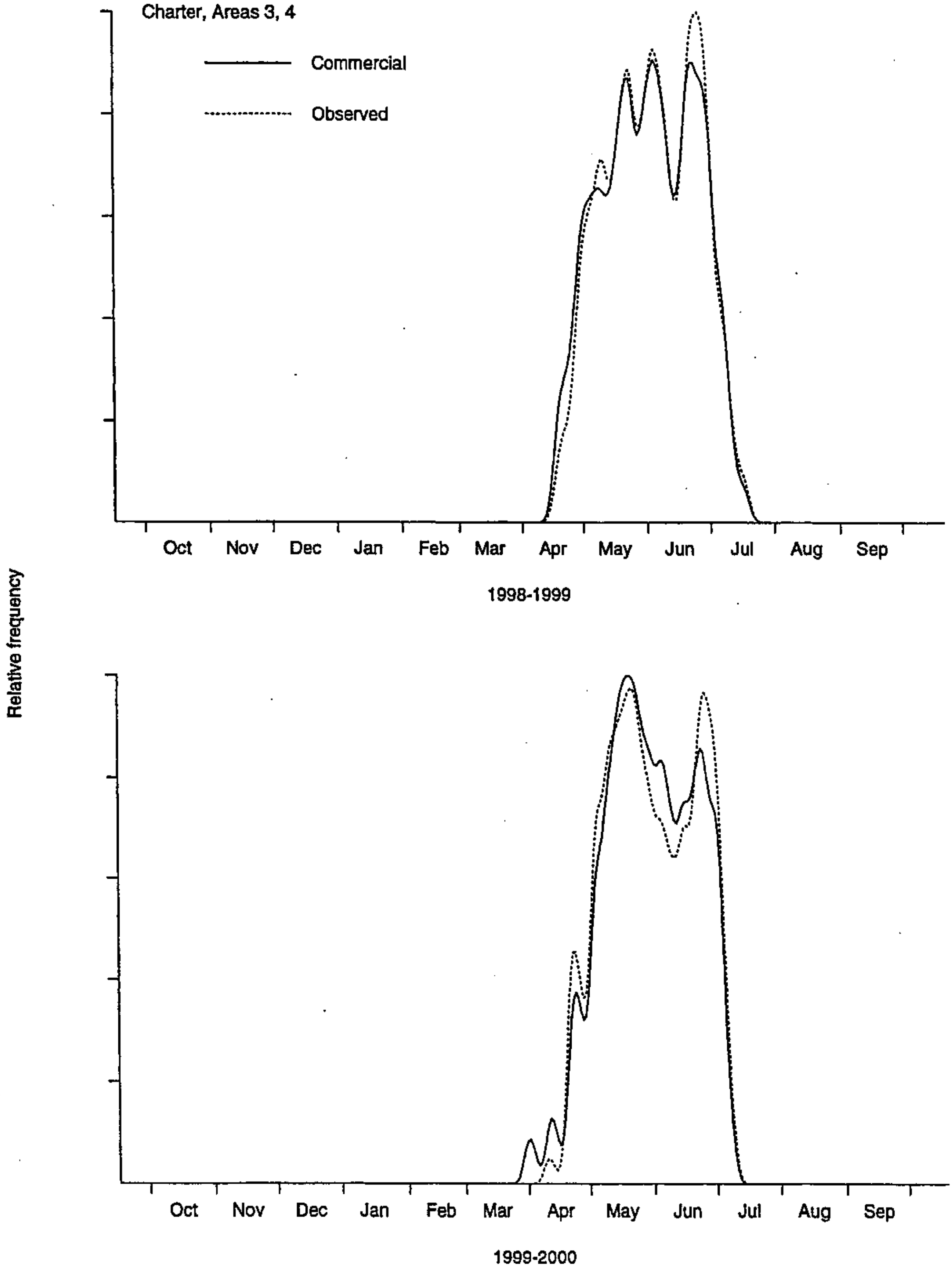


Figure A5: Total and observed effort by the charter fleet on the west coast of New Zealand by time of year in 1998–99 and 1999–2000.

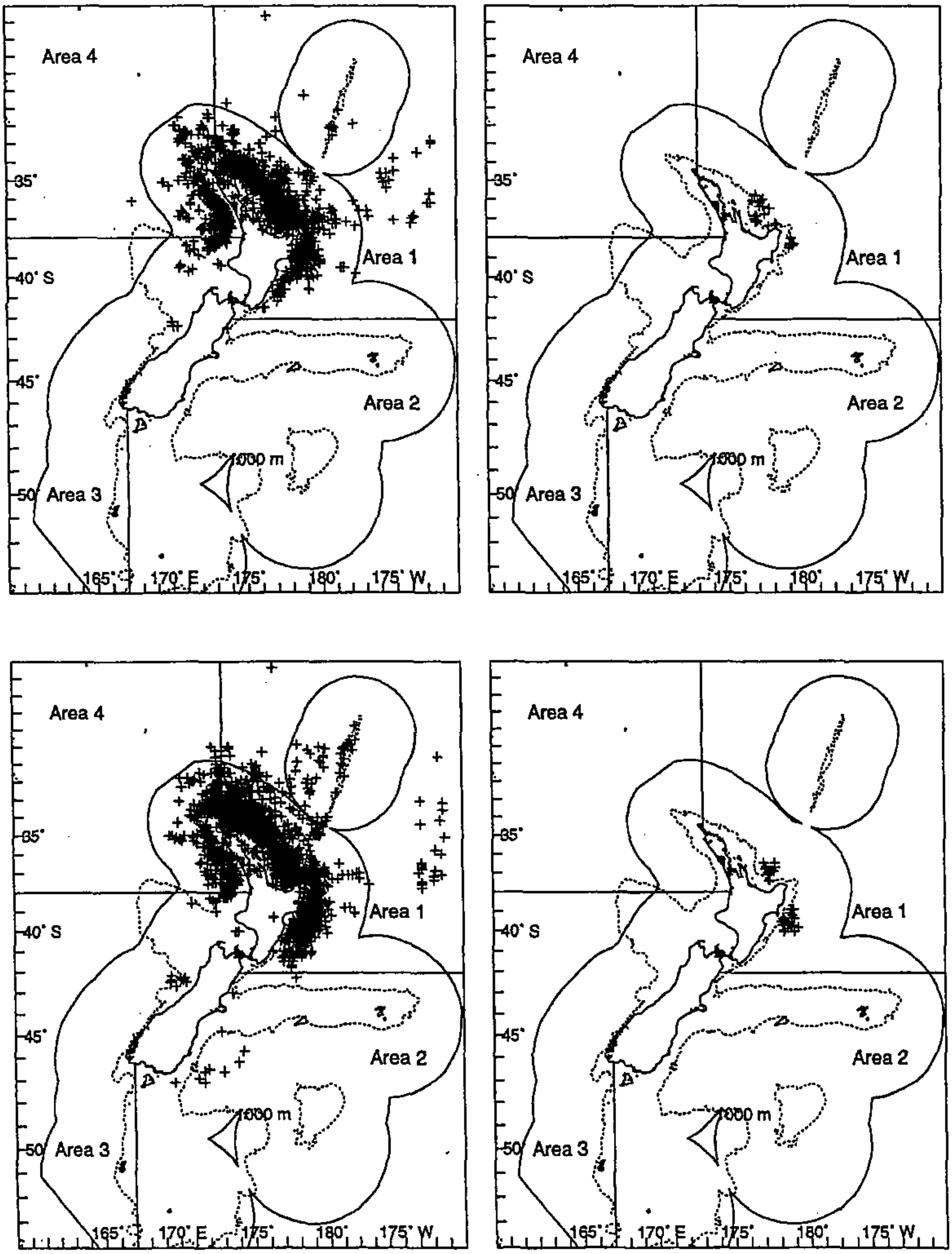


Figure A6: Start positions of all domestic sets (left) and observed domestic sets (right) for tuna longline fishery in 1998–99 (top) and 1999–2000 (bottom).

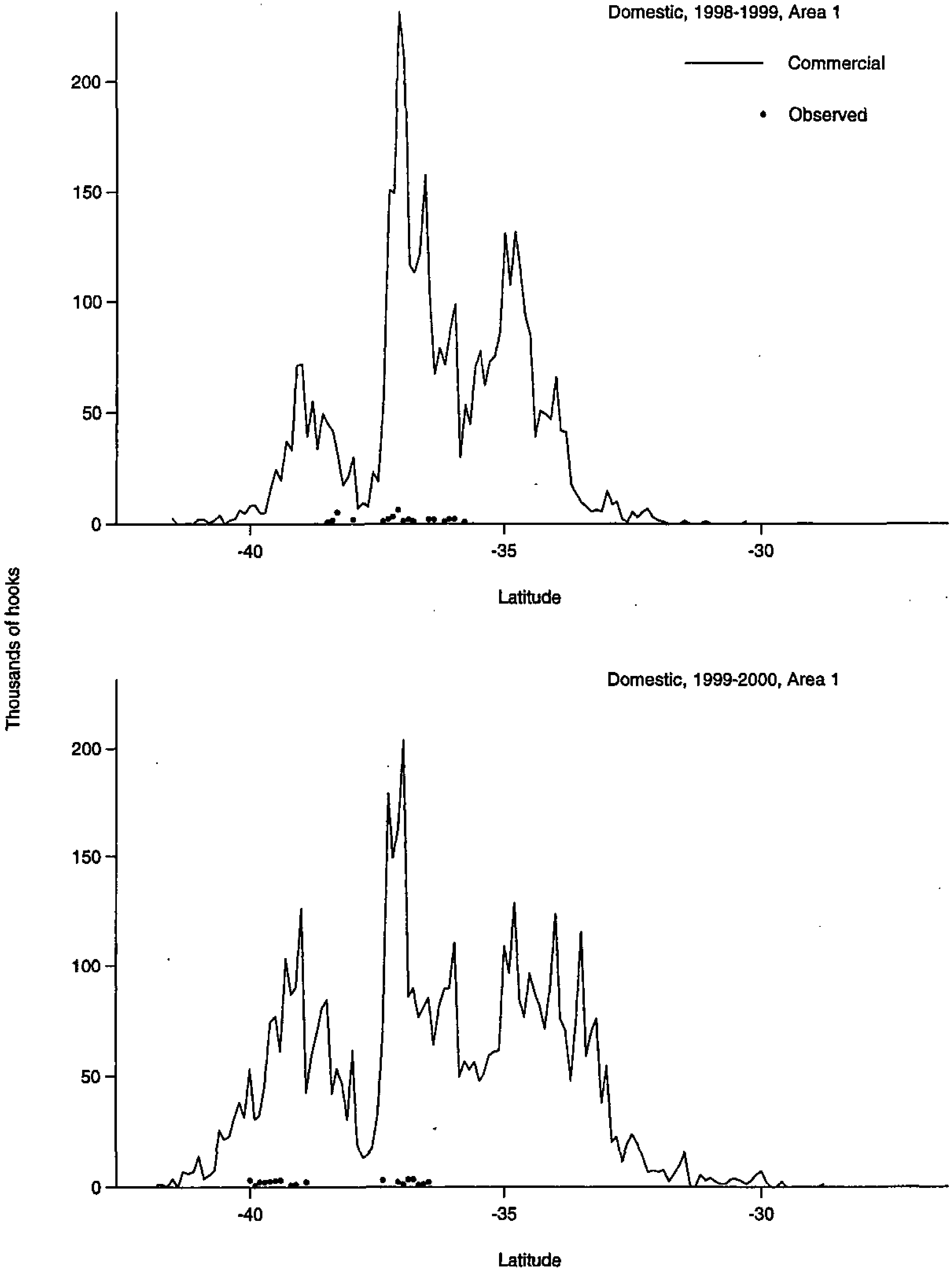


Figure A7: Total and observed effort by the domestic fleet on the east coast of New Zealand by latitude in 1998–99 and 1999–2000.

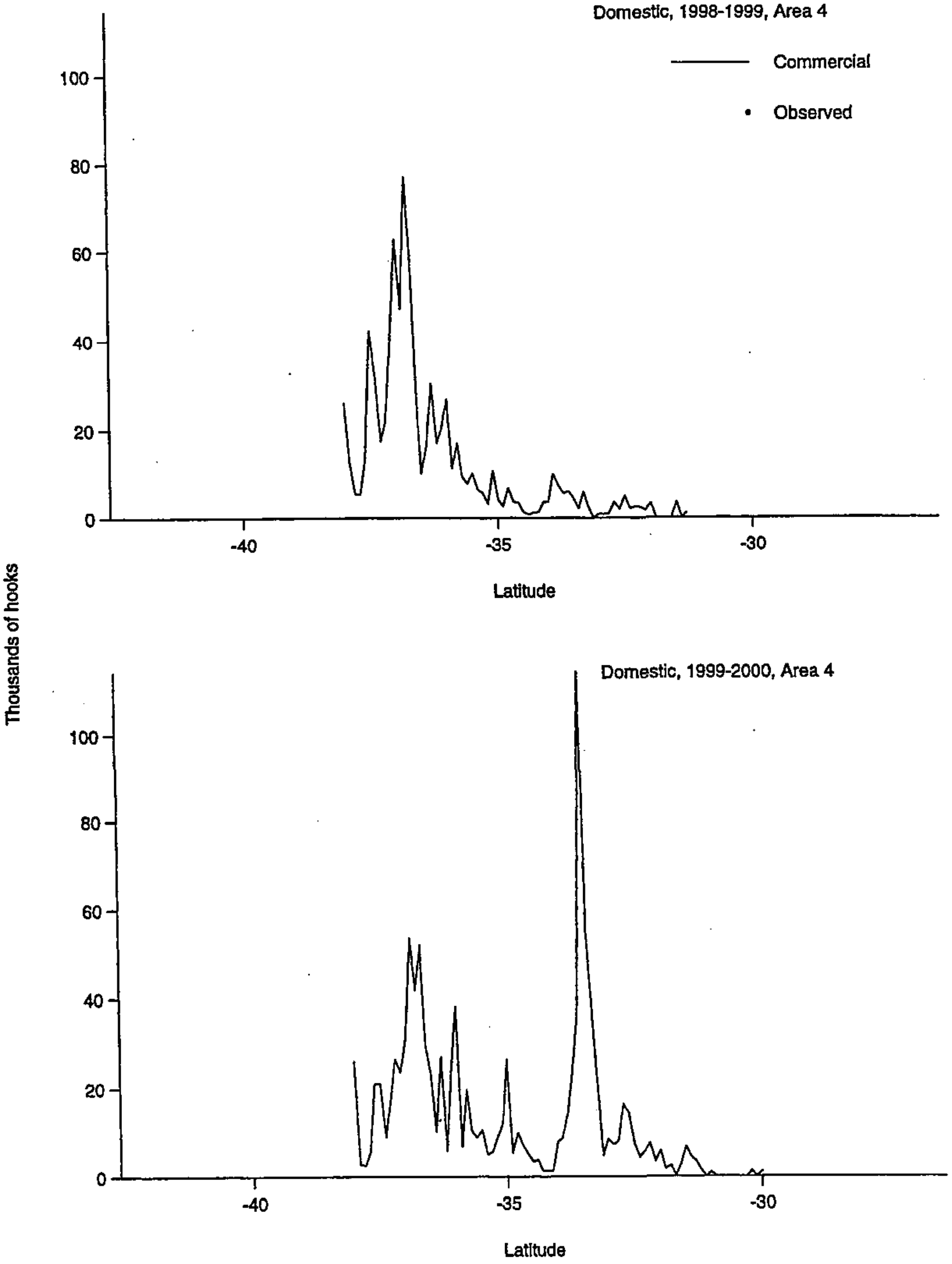


Figure A8: Total effort by the domestic fleet on the west coast of New Zealand by latitude in 1998–99 and 1999–2000. There was no observed effort in this Area in these years.

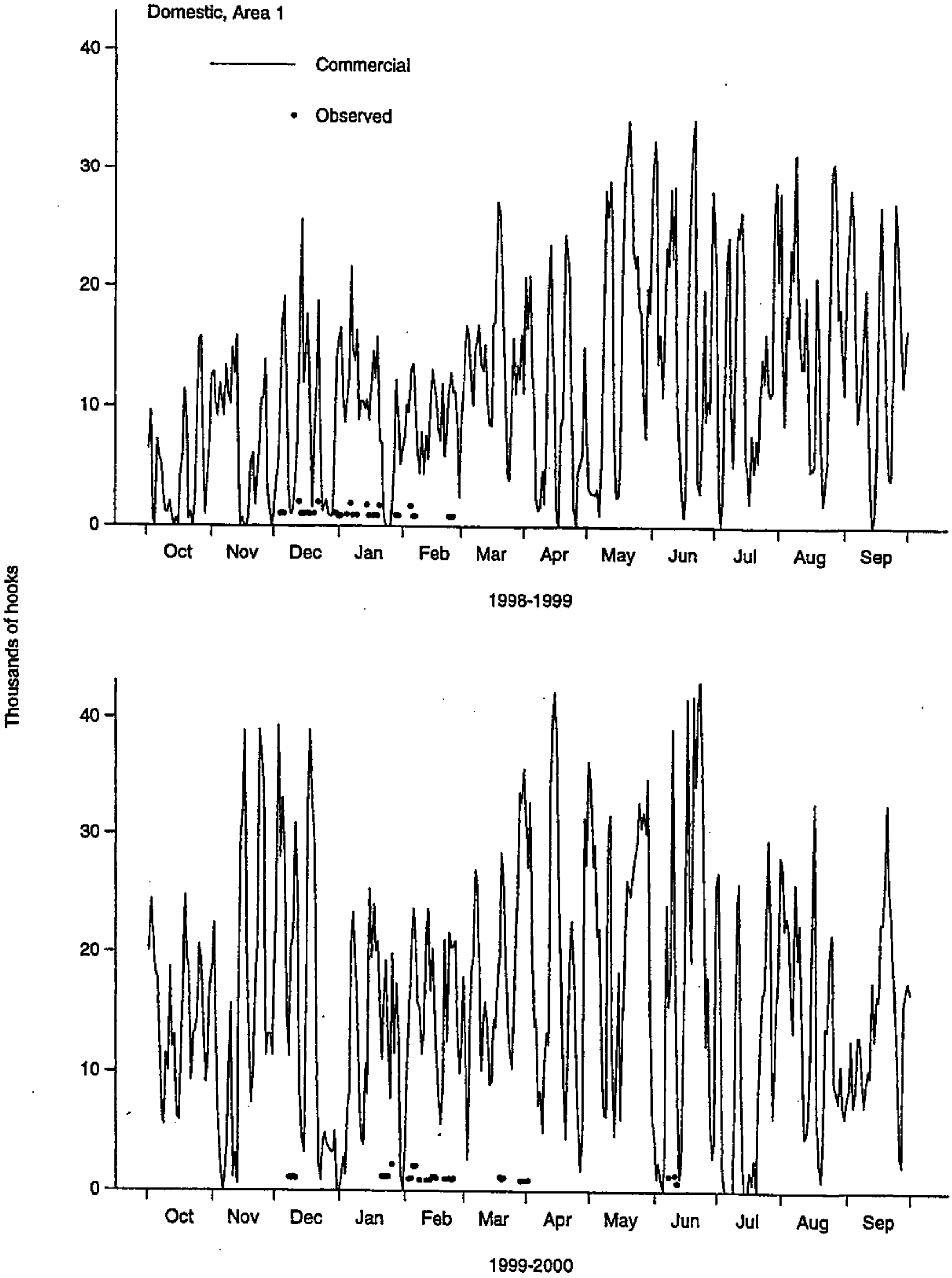


Figure A9: Total and observed effort by the domestic fleet on the east coast of New Zealand by time of year in 1998–1999 and 1999–2000.

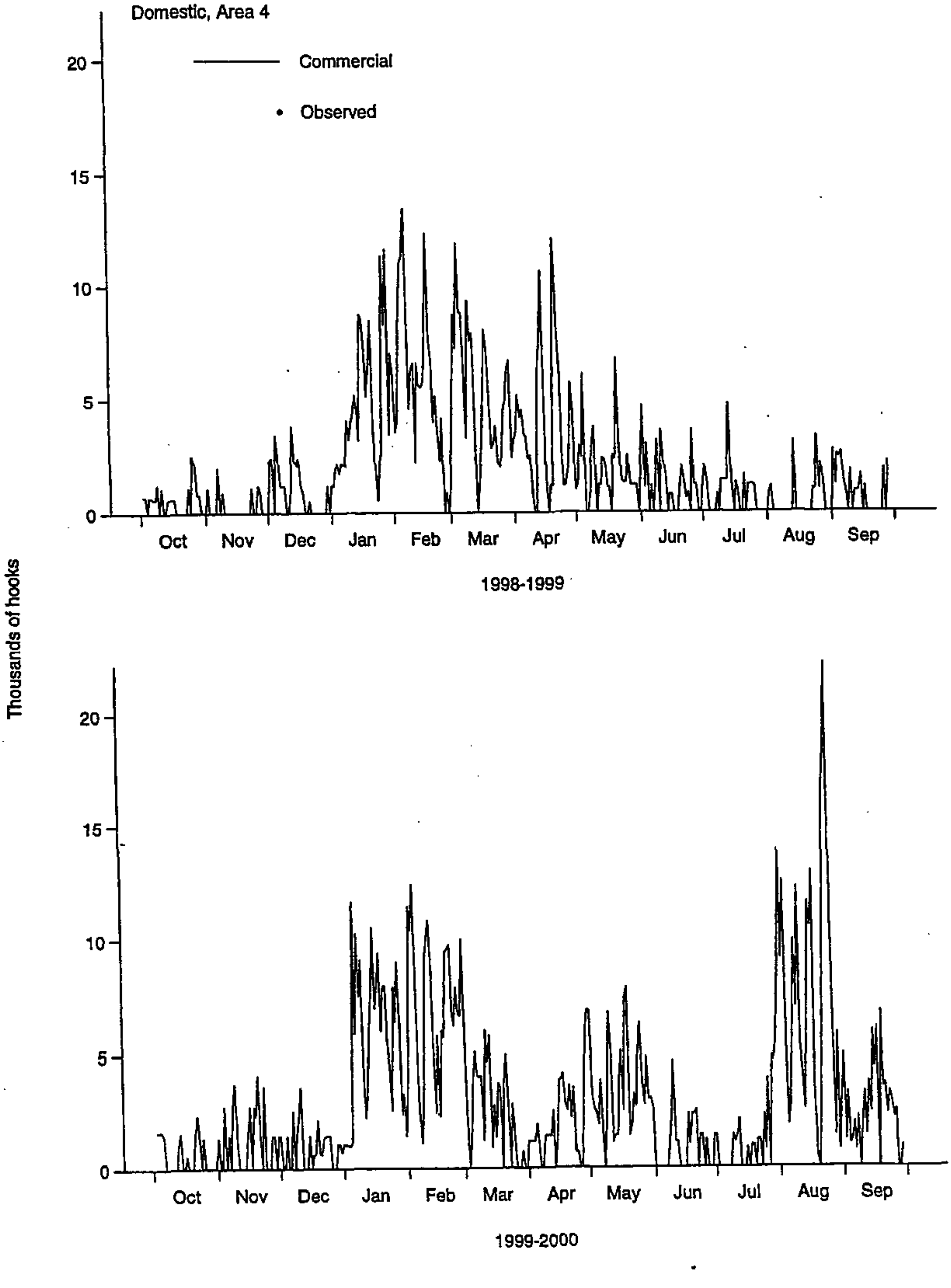


Figure A10: Total effort by the Domestic fleet on the west coast of New Zealand by time of year in 1998–99 and 1999–2000. There was no observed effort in this area in these years.