Factors that may have influenced seabird bycatch on tuna longlines in New Zealand waters, 1986–87 to 1997–98

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Abstract

Baird, S. J. & Bradford, E. 2000: Factors that may have influenced seabird bycatch on tuna longlines in New Zealand waters, 1986–87 to 1997–98. ***NIWA Technical Report 93.*** **61 p.**

The objective of this report was to investigate factors that may have influenced the levels of nonfish bycatch of associated or dependent species or protected species during tuna longline fishing operations in New Zealand waters. Data used were from the Ministry of Fisheries Scientific Observer programme for the fishing years 1986–87 to 1997–98. The Ministry of Fisheries also provided data on vessel characteristics. The observer data relate to the fishing operation, the catch, and the bycatch of seabirds. There was no provision for the collection of quantitative data relating to the abundance of birds at sea at the time sets were observed.

Data were stratified for Japanese and domestic vessels. Initial exploratory data analysis suggested that for both groups of data, fishing year, area, tori line, moon phase, sea surface temperature, and vessel might be factors that influence seabird bycatch.

The patchiness of the data in space and time, and the shape of the distribution of the observed bird catches, implied that the assumptions of the standard generalised linear model approaches would be violated. To further test the data, both the Japanese and domestic data were further organised into groups of fishing years (1986–87 to 1989–90, 1990–91 to 1992–93, and 1993–94 to 1997–98) and fishing areas (northern, southern, and western). One large domestic vessel that fished in similar waters to the Japanese vessels was considered with the Japanese vessels. The few observed sets from other large domestic vessels were ignored.

A negative binomial generalised linear model was tried, but the shape parameter could not be estimated. Significant differences were investigated for binomial and Poisson models, but these were found to be ill fitting. Consequently, several groups of data were tested in pairs mainly using randomisation tests.

Effects found to influence bird catch rate for observed Japanese vessels included area, time period, moon phase, and sea surface temperature. The use of tori lines and nightsetting did not show up as statistically significant. The domestic vessel data were all in the northern area and year group 1993–94 to 1997–98, and birds were caught on hauling as well as during setting. No significant effects due to moon phase, use of tori lines, and nightsetting were found when all the birds caught were included. When only the dead bird capture data (that is, the birds caught during setting) were considered, birds appeared more likely to be caught around the time of a full moon.

Introduction

Declines in populations of some seabirds, especially albatross species, have been shown to be directly attributable to some fisheries, especially those which use surface or bottom longlines (Weimerskirch & Jouventin 1987, Brothers 1991, Cherel *et al.* 1996). In New Zealand waters, the interaction between tuna longlines and seabirds such as albatrosses and petrels has been measured each year since the introduction of the Ministry of Fisheries Scientific Observer Programme in 1986 (Murray *et al.* 1993, Baird 1997).

Descriptions of the tuna longline fishing operations undertaken in New Zealand waters by both foreign and domestic vessels were given by Michael *et al.* (1987) and Murray *et al.* (1999), and the distribution of observer coverage and seabird bycatch was described by Baird (1997). Seabirds are hooked or tangled in the longline during the setting operation and then are pulled under and drowned. Seabirds may also be caught during hauling and these birds are generally released alive, though their survival rate is unknown. Anecdotal evidence from Ministry of Fisheries observers suggests that birds actively compete for the bait and smaller diving seabirds such as the petrels may have the baits stolen by larger seabirds such as albatrosses.

Some albatross species caught on tuna longlines in New Zealand waters were described by Harper *et al.* (1985) as usually being "surface seize [grasps prey items while floating on surface]" feeders. These include *Diomedea exulans*, *D. epomophora*, *Thalassarche melanophrys*, *T. chrysostoma*, *Phoebetria palpebrata*, *T. bulleri*, and *T. steadi*. Occasionally some species are "surface [splashes without submerging] (*T. melanophrys*, *T. chrysostoma*, *Phoebetria palpebrata*) or shallow [submerges completely but little beyond body length] plunge" feeders (*D. exulans*, *D. epomophora*, *T. chrysostoma*, *Phoebetria palpebrata*). *Thalassarche steadi*, *D. exulans*, and *T. melanophrys* have been recorded also as "pursuit plunge [pursues prey underwater]" feeders. *Thalassarche melanophrys*, *T. chrysostoma*, and *P. palpebrata* also "surface dive [submerge momentarily]". The preferred diet of all these species consists of cephalopods and fish.

Petrel species such as *Macronectes giganteus*, *M. halli*, and *Daption capense* are usually "surface seize" feeders and the latter is frequently recorded as a "surface" diver (Harper *et al.* (1985)). *Macronectes halli* and *Daption capense* are also recorded as "pursuit plunge" feeders, with a preferred diet of euphausids, cephalopods, and fish. Other petrels which have been recorded as caught on tuna longlines such as *Procellaria aequinoctialis steadi, P. westlandica, P. cinerea, Puffinus griseus,* and *Puffinus carneipes hullianus* were described as "pursuit plunge", "surface dive", and "surface seize" feeders which prefer cephalopods, fish, and euphausids.

The collection of data by observers on the numbers of different seabird species at sea around tuna longline vessels in New Zealand waters has been largely on an informal basis and there are no standardised estimates of the numbers of seabirds around the vessels during the fishing operations.

Sagar & Weimerskirch (1996) noted that southern Buller's albatrosses (*T. bulleri*) used feeding strategies similar to those of other albatross species, in that they fed along the continental shelf as well as commuted to specific feeding zones in mid-ocean areas (in February-March). The male birds kept more to the continental shelf off the west and east coasts of South Island. Walker *et al.* (1995) showed that female wandering albatrosses (*D. exulans)* from the Auckland Islands flew to the same mid-ocean area as the Buller's albatrosses.

Recent work by Waugh *et al.* (1999) showed that black-browed albatrosses (*T. melanophrys*) were primarily shelf feeders and that the birds studied spent 55% of their foraging time around their breeding location of Campbell Island, where fish was the main diet. The remainder of their time was spent on long foraging trips to the Polar Front and Antarctic Zone, where their diet consisted primarily of cephalopods, especially squid (*Martialia hyadesi*). Grey-headed albatrosses (*T. chrysostoma*) were mainly oceanic feeders, preferring to forage in the Polar Frontal Zone for squid.

Jouventin & Weimerskirch (1990) and Weimerskirch *et al.* (1997) used satellite tracking and activity recorders to show that wandering albatrosses flew to foraging areas during the day, then rested and waited for prey at night, especially on bright moonlit nights. Harper (1987) and Hedd *et al.* (1997) suggested that seabirds fed mostly during the day, though petrels are known to feed at night (Bartle 1974). Brothers *et al.* (1998) showed that fewer birds are caught on sets at night than during the day in Australian waters.

Concern about the continued bycatch of seabird species, especially those considered vulnerable or endangered, has resulted in the introduction of various measures in an attempt to mitigate the bird bycatch during tuna longline fishing operations in New Zealand waters. These include the use of tori lines and nightsetting (Murray *et al.* 1993). Some of these measures, such as the use of tori lines, have been adopted by other tuna fishing nations or organisations (Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) in 1991, Australia in 1995, Japan in August 1998). Other methods such as the use of weights on hooks and lines and bait casting machines are used by some fishers to increase the sinking rate of the line.

Despite the use of some mitigation devices, seabirds continue to be captured. The difficulty in isolating variables which may influence the rate at which seabirds are caught on longlines is compounded by the lack of data relating to the bird activity around the vessel and confounding between all the possible effects. Vessels that have similar fishing strategies and operations may have totally different rates of seabird bycatch. Furthermore, in New Zealand waters the domestic owned and operated vessels catch most birds on the haul and these birds are released alive. Seabirds caught on Japanese longlines are mostly caught during the setting operation and, therefore, are more likely to be landed dead.

Investigation of factors that may influence seabird bycatch has been undertaken in tuna longline fisheries in both hemispheres, with a worldwide focus on this interaction (Bonn Convention, Convention for the Conservation of Southern Bluefin Tuna, Food and Agriculture Organisation (CCSBT), The World Conservation Union (IUCN)).

Murray *et al.* (1993) suggested that the decrease in numbers of seabirds caught in New Zealand waters during 1991–92 might have been a result of the introduction in that year of the use of tori lines. Duckworth (1995) found that there were no statistically significant effects on seabird bycatch with factors of tori line design such as length, number of streamers, or height of attachment of tori line. He considered that the most effective tori line design should have a point of attachment less than 5 m above sea level, be at least 175 m long, and have at least 20 streamers. In his view, the more of these characteristics that a tori line had, the less likely that the fishing operation would catch birds. In fact, about half of the tori lines used during fishing operations included in the study were shown to have little or no effect (Duckworth 1995). Løkkeborg (1998) found that fewer birds (fulmars) were caught when a tori line was used and birds were caught only when strong winds were prevalent and the lines were set across the wind direction which resulted in the streamers being blown away from over the bait entry point.

In New Zealand waters, area was the most important factor in the study of effects on seabird bycatch in the tuna longline fishery data from observed Japanese vessels, with the area off the west coast of the South Island identified as an area of lower bycatch (Duckworth 1995). Area was also found to have an important effect on seabird bycatch in Australian waters, along with season and year (Klaer & Polacheck 1998).

There is a likely relationship between moon phase and seabird bycatch. Duckworth (1995) found that, for sets made at night, more seabirds were caught as the moon becomes full. In that study, when the moon was less than half full, birds were almost always caught near dawn or dusk. In Australian waters, seabird catches at night were substantially greater when the moon was on the full half-phase (Klaer & Polacheck 1998).

Frozen baits are slower to sink than thawed baits (Brothers *et al.* 1995) and therefore are potentially available for a longer time for seizure by the seabirds. Duckworth (1995) found no statistical significance in the use of frozen and thawed baits with two years of data.

Factors that relate directly to the fishing equipment, such as the type of mainline material, have also been studied. More birds were caught on lighter nylon monofilament lines than on other materials such as kuralon, nylon braided line, or tetron (polyester synthetic rope) (Brothers *et al.* 1998). Klaer & Heinemann (1998) found that rates were higher with nylon mainline in one year, but lower in the following years. However, the weighting regime of the lines or hooks is not described in either of these papers, and this may well have an effect.

The New Zealand studies by Murray *et al.* (1993) and Duckworth (1995) examined data up to 1992 and 1993 respectively. Since then there have been vast changes in the tuna longline fishery. The Japanese foreign fleet dramatically reduced its fishing effort (Baird 1997) and has not fished in New Zealand waters since 1994–95. Apart from 1995–96, Japanese vessels chartered to a New Zealand company have continued to fish in New Zealand waters, with five vessels fishing in most years during March to August. These vessels target southern bluefin tuna (*Thunnus maccoyi*) in northern and southern waters and bigeye tuna (*T. obesus*) in northern waters (Murray *et al.* 1999).

The decrease in the Japanese foreign fleet activity corresponded with an increase in domestic fishing effort, especially in waters north of 40° S, where southern bluefin and bigeye tunas, as well as albacore (*T. alalunga*) and yellowfin (*T. albacares*) tunas, are the main target species. Southern domestic effort targets southern bluefin tuna. The domestic effort in 1997–98 was three times that of the Japanese charter fleet.

As part of New Zealand's obligations to the Ecologically Related Species Working Group of the CCSBT, the Ministry of Fisheries is required to determine the factors which may influence the bycatch of seabirds in New Zealand waters. This report addresses part of Objective 3 of Ministry of Fisheries project ENV9801:

- to investigate factors that may have influenced the levels of nonfish bycatch of associated or dependent species or protected species during tuna longline fishing operations in New Zealand waters.

Data sources and treatment

Data used in this study are from the Ministry of Fisheries Scientific Observer Programme. Data for the years 1986–87 to 1997–98 were extracted from the NIWA-administered *l_line* database. The Ministry of Fisheries also provided vessel specification data for the tuna longliners observed during this period. Data are presented both for Japanese vessels (foreign and charter fleets) and for the domestic owned and operated vessels which operate quite differently in terms of area fished and fishing strategy and practice (Murray *et al.* 1999).

Since the introduction of the scientific observer programme in 1986, the collection of data has evolved to incorporate as many of the variables relating to the fishing operation and bycatch as possible. This has resulted in data sets with different categories of information and therefore limits comparability from year to year for some variables.

Scientific observers on tuna longline vessels work on their own and have observed the start of the set and the whole of the haul. The nature of the fishing operation limits the amount of data collected because it is not viable for one observer to watch the whole operation. For example, the fishing operation on Japanese vessels takes about 5.5 h to set the line, 5–6 h to soak, and about 12 h to haul (Murray *et al.* 1999). Therefore, environmental data have not been used here, because the data refer only to the start of the set. Some data, such as the bait type and snood details, were not collected in every year, but data are used where possible.

Some data reported in 1992–93 were deleted from this extract for the purposes of this study because of the consistent and extensive under-reporting by one observer (Baird *et al.* 1998, Francis *et al.* 1999). This resulted in the loss of all observed charter data for this year.

Data were extracted where the method of fishing was surface longline. This included target species (as recorded by fishing masters on Tuna Longline Catch Effort Returns (TLCER) and Catch Effort Landing Returns (CELR)) of southern bluefin, bigeye, albacore, yellowfin, and northern bluefin (*Thunnus thynnus*) tunas, and some aberrant ones such as striped marlin (*Tetrapturus audax*) and swordfish (*Xiphias gladius*). The following data were extracted for each setting operation: latitude and longitude, date, start and end times of the set and the haul, fleet, vessel length, size, power, and nationality, number of hooks set, number of birds observed caught, tori line use and type, length and height of attachment of tori line, number of streamers used, use of a bait casting machine, bait type and state (frozen or thawed), fishing speed, line feeder rate, number of snoods used per basket, snood length, and sea surface temperature.

Other variables were extrapolated from the observer data. A description of these variables is given below.

Area stratification

Murray *et al.* (1993) described five areas of tuna fishing activity in New Zealand waters and these areas have been used to estimate bird bycatch in tuna fisheries. Duckworth (1995) suggested that the southwestern area (Area 4) be divided to create an extra area (Area 6) based on evidence of a lower catch rate in the waters off the west coast of the South Island. In this study, position data were allocated to Areas 1–6 (Figure 1), as defined by Duckworth (1995).

Time of day stratification

Observers were requested to use New Zealand Standard Time (NZST) when recording the time of fishing operations. However, this has not always been adhered to, with regard to data collection on the domestic vessels, and on some occasions New Zealand Daylight Time has been used. This is only a concern for those sets which fall inside the months for which "daylight saving" occurs, and therefore affects only domestic sets during December to March. As most of the seabirds caught on domestic longlines are caught on the haul and released alive, this may have little effect on the data analysis because the haul is usually during daylight hours. However, where possible, times have been standardised to NZST.

The set and haul start times were further stratified into day, night, or twilight strata by the use of an algorithm (A. Dunn, NIWA, pers comm.) which supplied the sunrise and sunset times for a given position, date, and time of the start of a set and haul. Set start times were then allocated a "day", "night", or "twilight" category, where "twilight" refers to any set started 2 h before sunrise or 2 h after sunset. Field observations of petrels by G. Taylor (Department of Conservation, pers comm.) suggest that the peak departure time by seabirds off on foraging forays is about 1 h before sunrise and that birds return to their breeding sites in highest numbers 60–80 min after sunset. Time of capture for those birds that were landed dead was estimated after Murray *et al.* (1993).

Moon phase

The moon phase for each set was generated by the use of the method of Duffett-Smith (1990) and relates to the fraction of the lunar disc that is illuminated.

Bait type

Patterns of different bait types are used along the longline. Observers have recorded about 40 different bait types or combinations of bait type, and these were categorised into “fish”, “squid”, “lure”, and “other”. Various mackerels and pilchards make up the “fish” group. The “other” category includes “fish and lure”, “fish and squid”, and “squid and light stick”. Data were further collated into groups determined by the percentage of squid used per set. Where no squid was used, the bait pattern was nearly always all fish.

Snood data

Information on the snood patterns used has been recorded since 1987–88, with 1989–90 being the first year of complete snood records. Recording was intermittent for the next few years, and in 1992–93 snood data were recorded only for one set. Collection of these data resumed in 1993–94 and there are consistent records for the remaining years covered in this report. Observers record the number of snoods and the pattern of the snood lengths used in each basket. In some sets, the number of snoods (or the snood lengths) used per basket varied along the length of the mainline and, therefore, the mean number of snoods (and mean snood length) for each basket was used.

Mainline type

Information on the type of longline material used by different vessels was not recorded on any observer forms. However, this information has been recorded in observers' diaries or debriefing notes since 1994.

Exploratory data analysis

Data were stratified by fleet, and the number of birds observed caught per 1000 hooks was calculated for each observed set to give the bycatch rate. Mean bycatch rates were calculated as

$$\bar{x} = \sum \left(\frac{x_s}{n_s} \right) 1000 \Big/ N$$

where x_s is the number of seabirds observed caught in a set, n_s is the number of observed hooks in a set, and N is the number of observed sets. The standard error of the mean (*s.e.*) is given by

$$s.e. = \sqrt{\frac{N\sum x - (\sum x)^2}{N^2(N-1)}}$$

Where the mean catch rates of seabirds varied by more than ± 2 *s.e.*, the mean catch rates were interpreted as "substantially" different.

Japanese tuna fishery-seabird interaction: 1986–87 to 1997–98

A total of 2068 sets was observed on Japanese vessels during 1986–87 to 1997–98. This equates to 6 132 625 hooks and a total of 1171 birds observed caught. The distribution of this observer effort is shown in Figure 1.

Frequency of sets with bird captures

About 82% of all observed Japanese sets had no reported bird bycatch (Table 1). At least 69% of sets in the areas of greatest observed effort had no bycatch, and Area 6, which had the highest number of observed sets, also had the highest percentage (95%) of sets with no bycatch. This small number of sets with seabird bycatch and the spatial distribution of bird bycatch suggest difficulties in the representativeness of the bird catch rates.

***Table 1*: Observed frequency distribution of seabird capture data for observed Japanese vessels, 1986–87 to 1997–98**

No. birds	No. observed sets						
per set	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Total
0	377	55	78	302	52	824	1688
1	68	13	11	45	7	28	172
2	29	4	5	17	3	8	66
3	24	5	4	8	–	4	45
4	14	2	3	6	–	–	25
5	11	2	3	5	–	–	21
6	5	2	2	7	–	–	16
7	4	–	–	1	–	–	5
8	3	1	2	2	–	–	8
9	1	–	–	4	–	–	5
10	1	–	–	2	–	–	3
11	1	–	–	–	–	–	1
12	–	1	–	1	–	–	2
13	2	1	–	–	–	–	3
16	–	–	–	1	–	–	1
17	2	–	–	–	–	–	2
19	1	–	–	–	–	–	1
24	–	1	–	–	–	–	1
25	–	–	1	–	–	–	1
27	1	–	–	–	–	–	1
38	–	–	–	1	–	–	1
Total	544	87	109	402	62	864	2068

Fishing year

In the early years of observer coverage of this fleet, there were some substantial differences between annual catch rates (Figure 2). In years of lower observer effort, the catch rate for 1988–89 was substantially higher than that observed in 1987–88. When the number of observed sets was more even between years, such as in 1989–90 to 1991–92, when at least 430 000 hooks were observed a year, there were significant differences between mean catch rates. These years showed a decreasing trend in the number of birds reported caught per 1000 hooks, from 0.287 (*s.e.* = 0.050) in 1989–90 to 0.019 (*s.e.* = 0.009) in 1991–92 (the lowest catch rate recorded, if the small amount of observed effort in 1986–87 is ignored).

Observed fishing effort increased in 1992–93 to over 1 million hooks and then averaged about 800 000 hooks for each of the following years, except for 1995–96 when no Japanese vessels fished in New Zealand waters. Mean bycatch rates were similar for 1992–93 to 1994–95 (range 0.12–0.19 birds per 1000 hooks). The mean catch rate for 1996–97 (0.36 birds per 1000 hooks, *s.e.* = 0.07) was substantially higher than that calculated for the previous two years of effort. A slightly lower rate was observed for 1997–98.

Month

Japanese vessels were observed over the autumn-winter months of March to August (Figure 3). Observed fishing effort was greatest in May and June and catch rates for these two months were lower than for other months. The mean catch rate for May was substantially lower than for all other months, and that for June was substantially lower than for all months except for March and August which had substantially lower effort and therefore large standard errors.

Area

Japanese vessels were observed fishing in all areas during 1986–87 to 1997–98 (*see* Figure 1). The greatest amount of observed effort was in Area 6 where more than 2.6 million hooks were observed from 1986–87 to 1997–98 (Figure 4). More than 1.2 million hooks were observed in each of Areas 1 and 4, and less than 325 000 were observed in each of the remaining areas.

Mean bycatch rates for Areas 5 and 6 were substantially lower than those in other areas at less than 0.1 birds per 1000 hooks. When the areas of low effort (Areas 2, 3, and 5) are excluded, there appears to be no difference between the mean bycatch rates for Areas 1 and 4 (0.343 and 0.285 birds per 1000 hooks respectively), but there is a substantial difference between rates for these two areas and Area 6 (0.022 birds per 1000 hooks).

Annual mean bycatch rates for the areas of greatest observed effort are given in Figure 5. The high bycatch rate in Area 1 comes mainly from 1996–97 and 1997–98 fishing year effort when bycatch rates were substantially higher (1.43 and 0.72 birds per 1000 hooks respectively) than those for years of higher observed fishing effort (range of 0.02 to 0.25 birds per 1000 hooks for 1989–90 to 1992–93). There were no real differences in annual bycatch rates in either Area 4 or Area 6.

Latitude band

Data were collated by 1° latitude bands and separated into two groups: those off the east coast of New Zealand and those off the west coast. Catch rates of greater than 0.2 birds per 1000 hooks were made in latitude bands between 35° and 37° S and 45° and 48° S for eastern sets (Figure 6). Bird catch rates were generally lower off the western coasts. Where effort was in western waters south of 40°, mean catch rates were substantially lower to about 44° S (less than 0.05 birds per 1000 hooks) compared with those latitudes further south (range between about 0.1 to 0.5 birds per 1000 hooks) (Figure 7). These data correspond to the area data, such that the higher catch rates seen in the higher southern latitudes are from Area 4.

Where effort was greatest in the northern latitude bands off the east coast, between 35° and 37° S, mean catch rates were similar to those in the 46° to 48° S latitude bands off both coasts. However, it must be remembered that these data apply to different times of the year; most northern sets off the east coast were made during July and August, whereas those in the southern areas were made generally during April to June. Those northern sets off the west coast of New Zealand were usually made during January to March, whereas those off the west coast of the South Island were in April to June.

Tori line

Japanese vessels began to use tori lines as bird scaring devices in 1990–91, when about 23% of observed hooks were set with a tori line in use. The use of tori lines and/or nightsetting as mitigation devices was a requirement for Japanese vessels fishing in New Zealand waters from 1991–92. This requirement became mandatory in September 1993, as did the use of the CCAMLR design of tori line as the minimum design specification (CCAMLR 1990). In 1992–93 about 82% of hooks were set with a tori line in use and all sets observed since 1993–94 have used tori lines.

When all the data for 1986–87 to 1997–98 are combined, there is no difference between sets which used tori lines and those which did not (Figure 8). These data comprise 296 sets with no record, 334 sets with no tori line in use, and 1438 sets with a tori line. When the data are stratified by area and tori line use, there are some differences between mean catch rates of birds for those areas with the highest bycatch rates and reasonably consistent observer coverage. Area 1 had higher catch rates in years for which all sets were made using tori lines except in 1994–95; Area 4 had slightly lower catch rates when tori lines were used; and Area 6 showed little difference. Where at least 350 000 hooks were observed, and were set with a tori line in use, the mean catch rates observed for Area 1 (0.877, *s.e.* = 0.129), Area 4 (0.230, *s.e.* = 0.038), and Area 6 (0.016, *s.e.* = 0.004) were all substantially different.

Tori line characteristics

Observers report on the compliance of fishers to the CCAMLR tori line design. The percentage of sets with tori lines with at least the CCAMLR specifications increased from 94% in 1993–94 to 100% in 1997–98. Despite this ruling there are marked differences in the designs of the tori lines. Tori lines varied in length from 15 to 260 m (Figure 9), and 60% of sets had 150 m tori lines. Birds were caught on sets with tori lines which ranged from 68 to 260 m. Tori lines longer than 125 m were used on sets which caught more than three birds per 1000 hooks.

The height at which the tori line is attached varies from 4 to 15 m above the water. Birds were caught on sets with tori line heights throughout this range. The relationships between the tori line length and height of attachment and the number of streamers used are shown in Figures 10 and 11. The number of streamers used ranged from 0 to 87, but 89% of sets with tori lines had between 3 and 10 streamers. There appears to be no real difference in bird catch rates observed for this subset of the data (Figure 12).

Time of day

From 1986–87 to 1997–98 there has been a change from setting throughout the 24-hour period, as is seen in the observer data for the earlier years, to setting at night (Figure 13). Since the 1990–91 fishing year Japanese vessels have been starting their setting operations in darkness. For recent years, most set start times were between 1800 and 0400 h for observed Japanese vessels. This trend was particularly evident in the observed data for 1996–97 and 1997–98. Hence most sets were made during the hours of darkness. However, with the average set duration of 5.39 h, sets need to begin before midnight to finish before twilight and sunrise. Seabirds were caught throughout the day in earlier years, but as setting has taken place in darkness, the estimated time of capture of dead birds has also generally been during the hours of darkness (Figure 14).

The distribution of bycatch rates over 24 h in relation to the time of the start of sets is shown by area in Figure 15. Birds were caught on sets throughout the 24 h, but predominantly on those that began at night. The spread of catch rates in Area 1 where fewer than 3 birds per 1000 hooks were reported was reasonably uniform for sets started between about 1600 and 0400 h. Both these times include sets that would have traversed twilight hours. The highest bird catches in this area were from sets that began between 1900 and 2300 h. In Area 4, a peak in catch rates was seen in sets with start times between 2000 and 2200 h, and there were some higher catch rates observed for morning sets. The low catch rates in Area 6 were reasonably evenly spread throughout the day and night, though the highest catch rates were seen during day sets and those which began around 2000–2200 h (which in more recent years has been the start time for most sets).

In areas where there was less observer coverage there were no obvious patterns, but in Area 2 several of the highest rates were from day sets (which represents earlier data when setting took place throughout the day). In Area 5, where there was very little bycatch, birds were caught only in sets that began in the early morning. The highest catch rates seen in Area 3 were also from the early morning sets.

When the data were grouped into day, night, and twilight categories for all years of observer data, 92% of the sets started during hours of darkness, about 5% during daylight, and the remaining 3% were begun during the twilight hours.

Moon phase

Japanese vessels fishing in New Zealand waters generally set each day and therefore fish during all phases of the moon. Observer coverage, especially in the last few years, has been high on these vessels and, therefore, data for observed sets also cover all phases. It appears that in most years seabirds were caught more often on nights around a full moon than at any other time (Figure 16). In most areas, birds were caught on sets throughout the range of the moon phase, with occasional peaks at new and full moon. In Area 1 higher catch rates were reported for sets made around a full moon, whereas lower catch rates (fewer than 4 birds per 1000 hooks) were spread throughout the moon phase.

Sea surface temperature

There were two peaks in the distribution of observed Japanese tuna longline effort by sea surface temperature — one at about 12–13 °C and a smaller one at 15–16 °C (Figure 17). These peaks represent the different northern and southern sea surface temperatures for the months of observed effort — in the northern areas effort was concentrated around the 15–20 °C band (represented by observed effort in January to March and July and August) and in the southern areas most effort was around 10–15 °C, depending on the latitude (for April to June).

The number of seabirds caught per 1000 hooks varied greatly within the half-degree strata; for example, for the category of 12.0–12.4 °C, the numbers of birds caught per 1000 hooks ranged from 0 to 12, with a mean value of about 0.25. The seabird bycatch rates were substantially lower in waters of temperatures between 12.5 and 14.0 °C (which equate to average temperatures in Area 3 during June, Area 4 during May and June, and Area 6 during April to July) compared with rates seen in 15.5–17.0 °C waters. The latter temperature range represents fishing activity in Area 1 during May to August and Area 2 during June and July. The lower bycatch rates observed for temperatures over 17.5 °C represent the observed effort in Area 5 during June to August.

Vessel

During 1986–87 to 1997–98, observers were placed on 30 Japanese longliners. Of these vessels, 18 were observed in only one year, 5 in two years, 2 in three years, 1 in four years, and 4 in six years. The observer coverage and mean bycatch rates for the individual vessels over these years are shown in Figure 18.

When the data for the five vessels with the most observer coverage are compared, one vessel has a substantially higher bycatch rate than the other four. A closer look at the data shows differences in bird bycatch rates between the vessels within each fishing year, with some substantial differences for vessels fishing in the same areas in similar months.

Vessel characteristics

Observed Japanese vessels had the following specifications: length range 43–57 m (average of 54 m), weight range 199–619 GRT (average of 458 GRT), and engine range 520–1205 kW (average of 673 kW). There was little difference between mean bird catch rates for the various length, weight, or power ranges of the observed Japanese vessels.

The speed at which vessels set their lines ranged from about 5 to 13 kn., with an average of 10 kn. Of the 1995 observed longlines for which speed at setting was recorded, 93% were set at 9–11.9 kn. The mean number of seabirds caught per 1000 hooks for longlines set at 9–9.9 kn. (n = 443 sets) and 10–10.9 kn. (n = 971) were similar at 0.19 (*s.e.* = 0.04) and 0.13 (*s.e.* = 0.02) respectively, but there was a substantial difference between those set at 10–10.9 kn. and those at 11–11.9 kn. (n = 442, 0.28 birds per 1000 hooks, *s.e.* = 0.04).

The line feeder rate ranged from 4.9 to 9.7 $m.s^{-1}$ (average of 6.9). About 98% of observed longlines (hooks) were set with a line feeder rate of between 6.0 and 7.9 $m.s^{-1}$. For the ranges 6.0–6.4 (n = 186 sets), 6.5–6.9 (n = 600), and 7.0–7.5 $m.s^{-1}$ (n = 1001), the mean bycatch rates were very similar; for example, the bird bycatch rate for the latter category was 0.21 birds caught per 1000 hooks (*s.e.* = 0.02). However, the mean bycatch rate for sets for which the line was fed out at 7.5 kn. or faster (n = 198 sets) was substantially lower at 0.078 birds per 1000 hooks (*s.e.* = 0.016).

Set duration

About 97% of the observed Japanese sets were between 4 and 7 h long, with about 75% being between 5 and 6 h in duration, 13% between 4 and 5 h, and 10% between 6 and 7 h (Figure 19). Birds were caught in all categories of set duration.

Mainline type

Historically, Japanese vessels have used kuralon as the mainline material. However, observer information shows that in 1994–95 vessels used either kuralon or a mixture of kuralon and a braided line made from eight strands of clear nylon monofilament. Of the sets observed in 1996–97 and 1997–98, just over 50% used this nylon multifilament line (Table 2).

***Table 2*: Number of observed Japanese vessels (and number of observed sets) for the mainline material* used during tuna fishing operations in New Zealand waters, by fishing year since 1993–94**

Fishing year	Kuralon	Nylon multifilament	Mix	No record
1993–94			1 (29 sets)	6 (214 sets)
1994–95	3 (97 sets)	1 (36 sets)	3 (119 sets)	
1996–97	2 (119 sets)	5 (127 sets)		
1997–98	2 (132 sets)	3 (178 sets)		

* Mix category consisted generally of kuralon and the nylon multifilament line.

Use of bait-casting machines

The use of bait-casting machines (BCMs) was not recorded by scientific observers until 1993–94. During the subsequent years, the percentage of observed sets which used a BCM increased from 29% in 1993–94 to 40% in 1994–95, 86% in 1996–97, and 94% in 1997–98. For 1993–94 to 1997–98, 65% of the 1075 sets observed used BCMs. There was no difference between the bird catch rates for sets that used BCMs (n = 379 sets, 0.196 birds per 1000 hooks, *s.e.* = 0.028) and those that did not (n = 696 sets, 0.216 birds per 1000 hooks, *s.e.* = 0.031).

During the early years of BCM use, sets that used a BCM had substantially lower bycatch rates than those that did not (Figure 20). However, as the use of BCMs increased, there was no difference between categories in the 1996–97 and 1997–98 fishing years.

Bait

Information on whether bait was frozen or thawed was not collected by observers until 1991–92. The use of thawed baits has increased from about 80% of bait used in years up to 1994–95 to about 92% in 1996–97 and 1997–98: 195 sets used frozen bait, 1397 used thawed bait, and there were no records for 476 sets.

The type of bait used was grouped into categories based on the percentage of squid. There were no substantial differences in the bird bycatch rates for sets with thawed (n = 1397, 0.18 birds per 1000 hooks, *s.e.* = 0.02) or frozen bait (n = 195, 0.27 birds per 1000 hooks, *s.e.* = 0.07) or for sets with different percentages of squid used in the baskets.

Snood data

The snood data represented 1625 observed Japanese sets. The number of snoods used ranged from 5 to 10 per basket: bird bycatch rates were highest when sets used 6 snoods per basket (Figure 21), which accounted for 50% of the snoods used. Most of the remaining sets used 7–8 snoods (26%) or 9–10 snoods per basket (22%). High catch rates were recorded for sets with these numbers of snoods. The average lengths of snoods used by observed Japanese vessels ranged from about 31 to 42 m, with 84% of snoods used being between 35 and 40 m long. The largest range was seen for baskets of 6 snoods (Figure 22). Birds were caught throughout the range of snood lengths (Figure 23).

Domestic tuna fishery-seabird interaction: 1991–92 to 1997–98

Scientific observers have been placed on domestic owned and operated tuna longline vessels since 1992. A total of 535 sets (752 483 hooks) was observed between 1991–92 and 1997–98 and 190 birds were reported caught on domestic longlines. The distribution of observer effort is shown in Figure 24.

Frequency of sets with bird captures

About 80% of observed domestic sets between 1991–92 and 1997–98 had no reported bird bycatch (Table 3). Of the 109 sets with bird bycatch, 105 caught three or fewer birds. Area 1 had the greatest number of sets with bird bycatch and this area accounted for the few captures of four or more birds per set.

***Table 3*: Observed frequency distribution of seabird capture for observed domestic vessels, 1990–91 to 1997–98**

No. birds							No. observed sets
per set	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Total
0	123	37	36	54	65	111	426
1	38	8	–	9	7	4	66
2	15	4	–	4	3	1	27
3	8	1	–	1	1	1	12
4	1	–	–	–	–	–	1
5	–	–	–	–	–	–	–
6	1	–	–	–	–	–	1
7	–	–	–	–	–	–	–
8	–	–	–	–	–	–	–
9	–	–	–	–	–	–	–
10	1	–	–	–	–	–	1
11	1	–	–	–	–	–	1
Total	188	50	36	68	76	117	535

Fishing year

The early years of observer coverage of domestic tuna longline vessels amounted to only 16 sets (19 525 hooks) in 1991–92 and none in 1992–93. It was not until 1994–95 that observer coverage in this fishery increased (Figure 25).

Since 1994–95 at least 152 980 hooks have been observed each year. This represented about 8.5% of all sets made (TLCER data) in 1994–95, 9% in 1995–96, 12% in 1996–97, and 6.6% in 1997–98 (this year included CELR data). The number of birds reported caught per 1000 hooks increased each fishing year to a peak in 1996–97, but decreased in the following year. The bycatch rates for 1994–95 (0.14 birds per 1000 hooks, *s.e.* = 0.04) and 1995–96 (0.23, *s.e.* 0.05) were similar, but there was a substantial difference between these two years and the catch rate calculated for 1996–97 (0.74, *s.e.* = 0.13). The bird catch rate for 1997–98 was within 2 standard errors of those for other fishing years.

Month

Domestic vessels were observed throughout the year. Most observed effort was in the autumn (April-June). Bycatch rates were lowest for these months (Figure 26) and that for April was substantially different from those for March and May. However, the month fished was closely related to the area fished, in that vessels were observed in Areas 1, 2, and 5 during the January-February, mainly in the southern areas during March-June, and in Area 1 in July.

Area

The distribution of the observed effort, including those sets that caught birds, is shown in Figure 27. About 29% of observed hooks were in Area 6, 24% in Area 1, 18% in Area 4, 13% in Area 3, and the remainder in Areas 2 and 5. Birds were reported caught from all areas except Area 3 for which there was observer coverage only in 1996–97. The highest mean bycatch rate was calculated for Area 1, and this was substantially higher than that for all areas other than Area 2. Mean bird bycatch rates in the southern areas were generally lower, with those for Area 3 (no bird bycatch) and Area 6 being substantially lower than for all other areas.

When the area data are compared for each fishing year, wide variations in effort are apparent between years (Figure 27). For some years in which at least 150 000 hooks were observed over all areas, bycatch rates showed significant differences. For example, in 1995–96, the area with the most observed effort was Area 6 and the bycatch rate of 0.016 birds per 1000 hooks (*s.e.* = 0.016) was substantially lower than that for other areas with comparable effort. A similar low rate was observed in 1996–97 (0.036 birds per 1000 hooks, *s.e.* = 0.022), and this was substantially different from that observed in Area 1 (1.23, *s.e.* = 0.22). These two areas accounted for 90% of all observed effort in 1996–97. No hooks were observed in Area 6 in 1997–98, and only 6% of the total observed hooks for this year were in Area 1. This resulted in large standard errors about the mean catch rate. However, mean catch rates for the northern areas, apart from Area 5, were substantially higher than those in all other areas. About 50% of the 1997–98 observed effort was in Area 3 and no birds were reported caught from this area.

Latitude band

Most sets observed off the east coast of New Zealand were started between latitudes 36° and 38° S and between 46° and 47° S. All the bird bycatch for these sets came from the northern latitudes where the smaller domestic vessels fished. There appears to be a higher mean bird bycatch rate observed for hooks set between 37° and 38° S (1.2 birds per 1000 hooks, *s.e.* = 0.2) (Figure 28): this equates to the Area 1 observed effort.

Very few hooks were observed off the west coast of New Zealand at latitudes north of 40° S, and no bird captures were reported for these latitudes (Figure 29). The observer effort here was too small to compare bird bycatch rates with those at the same latitudes off the east coast. However, where there was observer effort in the southern latitudes, birds were observed caught off the west coast whereas none were observed off the east coast. The mean bird catch rate for 46° S was substantially higher for sets made off the west coast.

Tori line

Tori lines were recorded as used on 76% of all sets, which equates to 86% of all observed hooks. When the mean catch rates for hooks set with a tori line in place were compared with those set without, there was a substantial difference in the mean bird bycatch rates (Figure 30). Where tori lines were used, a mean bird bycatch rate of 0.268 (*s.e.* = 0.044) birds per 100 hooks was observed compared with 0.861 birds per 1000 hooks (*s.e.* = 0.156) when no tori line was used. When these data were stratified by area, there were differences between areas (Figure 31). Domestic vessels that were observed fishing in the southern areas (the larger ex-Japanese vessels) used tori lines all the time in Area 3 and Area 4 and on all but three sets in Area 6. Although there was not much observed effort in Area 2, this was the only northern area to show a substantial difference between the mean bird bycatch rates for tori line use.

Tori line characteristics

Where a tori line was used, 86% of observed hooks were set with a tori line with designed to CCAMLR standards. Tori line length was recorded for 74% (*n* = 396) of observed sets (84% of observed hooks). The lengths of tori lines used on observed domestic vessels ranged from 60 to 220 m, and 55% of observed sets used tori lines of 150–175 m (Figure 32). Mean bird bycatch rates were similar for all groups, though the mean number of birds caught per 1000 hooks when tori lines between 200 and 225 m long (*n* = 84 sets) were in use was substantially lower than the mean number caught for sets with 150–175 m tori lines (*n* = 219 sets).

The height at which tori lines were attached ranged from 3 to 10 m above sea level. The relationship between tori line length and height of attachment is shown in Figure 33. There are no differences between sets with or without bird bycatch. The number of streamers used on the tori lines ranged from 0 to 20 (Figure 34). There is no relationship between the number of birds caught and the number of streamers used (Figure 35).

Time of day

Start times of observed domestic sets (Figure 36) followed a similar pattern to those seen for the Japanese sets, and most sets in recent years were made during the hours of darkness. Birds which were landed dead were generally caught within 5 h either side of midnight (Figure 37). However, most birds caught on observed domestic vessels were released alive and therefore were caught during hauling, which generally started between 0500 and 1600 h.

Moon phase

In years when at least 150 000 hooks were observed, sets have been observed through all phases of the moon (Figure 38). Sets that caught birds appear to follow a similar distribution, though it seems that more birds were caught in sets around the time of a full moon in 1995–96 and 1996–97, whereas in 1997–98 birds were more likely to be caught on nights around a new moon. When the data were stratified by area, mean bird bycatch rates were reasonably constant throughout the moon phases in all areas except Area 5, which appeared to have slightly higher catch rates around a full moon and a new moon.

Sea surface temperature

Sea surface temperatures recorded by observers in Area 3 (March-April), Area 4 (March-May), and Area 6 (April-August) ranged between 11 and 16 °C, with the peak of observed effort in waters of 13–14.5 °C (Figure 39). This peak represented sets in Areas 4 and 6. Mean bird bycatch rates in these areas were very similar and were substantially lower than those at sea surface temperatures of 20–22 °C. The smaller peak of activity around 18 °C represents the observed effort in Area 1 (June-September), Area 2 (May), and Area 5 (June-July). The second peak of observed effort was around 20–22 °C; these data represented sets made in Area 1 (December-April), Area 2 (February-March), and Area 5 (December). The highest temperatures were recorded for Area 5 sets observed during January and February.

Vessel

During 1991–92 to 1997–98, observers were placed on 17 different domestic owned and operated vessels. The number of sets observed on these vessels ranged from 2 to 137, corresponding to a range of 1224 to 350 651 hooks. One of these vessels was observed in three different years, 7 in two years, and 9 were observed in one year. Mean bird bycatch rates for these vessels varied greatly, as did the amount of observed effort (Figure 40).

Vessel characteristics

The domestic owned and operated vessels varied greatly in size and area fished. The observed vessels ranged from 11.8 to 53.6 m in length, 12 to 344 GRT in weight, and 138 to 970 kW in power. The average number of hooks set per observed set for each vessel ranged from 612 to 2560. Of the 17 vessels that have been observed since 1991–92, 13 were observed only in the northern areas and 2 were observed only in southern areas: the remaining 2 vessels were observed in both areas.

The domestic vessels were grouped by their length and weight characteristics into four categories (Table 4). The vessel lengths and weights for each category are well defined, but there is marked overlap between "A" and "B" vessels for power. The speed at which the vessels set the line ranged from 3.5 to 10.5 kn.; however, the average speeds recorded for observed sets were similar and ranged from 7.0 kn. for sets by "A" vessels to 7.8 kn. for "B" vessel sets. Similarly, the average line feeder rates ranged from 4.6 $m.s^{-1}$ for "A" and "B" vessel sets to 5.4 $m.s^{-1}$ for "C" vessel sets.

Vessels in categories "A" and "B" fished exclusively in the northern areas. About 67% of observed sets made by "A" vessels were in Area 1, 31% in Area 2, and the remainder in Area 5. For "B" vessels, the observed effort was equally spread between Areas 1 and 2. Although category "C" and "D" vessels were observed in northern and southern areas, most of their observed effort was in the southern areas.

About 72% of category “C” vessels’ observed effort was in Areas 4 and 6, and 81% of “D” vessels’ observed effort was in Areas 3, 4, and 6.

The mean bird bycatch rate for the smallest vessels (category “A”) was substantially higher than that for all the other categories (Figure 41), and the bycatch rate for category “B” was substantially higher than that for “C” and “D” vessels: the last two categories had similar rates.

***Table 4*: Data for observed domestic vessel categories**

Characteristic	A	B	C	D
Length range (m)	11.8–17.8	18.8 -23.3	32.0–36.6	53.4–53.6
Weight range (t)	12.0–50.0	53.0–86.0	140.0–206.0	344.0–344.9
Power range (kW)	122.9–395.0	149.1–372.2	370.0–500.0	970
Speed range (kn.)	4.0–9.4.	3.5–9.6	6.1–8.6	5.0–6.5
Line feeder range (m.s^{-1})	2.9–5.5	3.2–5.6	4.2–6.5	5.0–6.5
Average no. hooks	823	936	1 237	2312
No. vessels	8	4	3	2
No. sets	152	97	116	170
No. hooks	125 139	90 769	143 444	393 131
Area fished	1, 2, 5	1, 5	1, 2, 4, 5, 6	1, 3, 4, 5, 6

Set duration

Observed domestic sets were from 1 to 6 h long, and the average set duration was about 4 h. The two peaks in set duration shown in Figure 42, at about 2–3 h and 4–5 h, were representative of the fishing effort by the different sizes of domestic vessels. The longer sets were generally made in the southern areas where the larger domestic vessels were observed. Where birds were landed dead, it was assumed that they were caught on the set. The peaks in the number of birds caught per 1000 hooks were similar to those for the number of observed sets for each set duration group.

Haul duration

The time taken to haul a longline on observed domestic vessels varied from about 1 to 21 h (Figure 43). About 44% of observed sets had hauls 5–8 h long. These haul times represented vessels fishing in the northern areas, whereas the longer haul times of about 10 h were generally from vessels observed fishing in Areas 3, 4, and 6. Where birds were caught and released alive it was assumed that they were caught on the haul. Higher bird bycatch rates were observed on shorter hauls.

Mainline type

All observed domestic vessels used monofilament mainline.

Bait

Of the 535 observed domestic sets, 96% used thawed bait and the remainder used frozen bait. About 42% of sets used bait patterns with at least 50% of baits in a basket being squid. Fish was the predominant bait used in other sets. Mean bird bycatch rates in observed sets that used at least 75%

squid appear to be substantially higher than those in which less squid was used (Figure 44). Smaller vessels observed fishing in Areas 1 and 2 tended to use a higher percentage of squid, with 67% of sets baited with at least 75% squid. Vessels in Area 5 used all four groups of bait, whereas those fishing in Area 3 used less than 25% squid and those in Areas 4 and 6 used less than 50% squid.

Snood data

The number of snoods used per basket on observed domestic longlines ranged from 2 to 25. The highest bird bycatch rates were recorded when between 16 and 24 snoods were used (this range represented 18.5% of the sets) and when between 8 and 16 snoods were used (about 62% of all observed sets) (Figure 45). Snoods used on observed domestic longlines ranged between 6 and 20 m in length, with longer snoods (10–20 m) used on sets with less than 15 snoods to a basket and shorter snoods (5–10 m) used in baskets of more than 15 snoods. It appeared that higher bird catch rates were observed when shorter snoods were used (Figure 46).

Fitting models to the seabird capture data and testing for significance

Choosing the model

The tender specified that the main model to be fitted would be a Generalised Linear Model (GLM) with a negative binomial error distribution. This error distribution was suggested to help overcome the over-dispersion noted when using Poisson models for similar data (Venables & Ripley 1994). A negative binomial distribution fits quite well the overall distribution of the number of times a particular count of birds caught per set was observed.

However, when using the negative binomial error distribution in a GLM there are two parameters to be fitted, and the bird capture data are such that the fitting process does not converge. This probably arises because the bird count distributions are extreme cases of the distribution with a high fraction of sets with no bird captures and occasional extremely large values. Also, the count distributions do not appear to have the same shape in the various areas and at different times.

The relatively small number of sets which caught birds, especially in recent years, led to the choice of a binomial model (such that a set did or did not catch birds) as the basic model. Pairwise testing of differences between groups of data was used when looking for effects that might be significant because there are numerous interactions in the explanatory variables. The Poisson error distribution was also considered, once it was noticed that the over-dispersion decreased as the amount of variance explained increased, that is, the model fit was improved. Appendix 1 gives some mathematical details on these models.

In principle, the binomial models could be used as part of a combined model. The other part would come from models that explain the bird catches (excluding all sets which did not catch birds). The latter part of the calculation would be based on little information and has not been attempted. The nature of the combined model to be used would also need to be explored.

The use of a multinomial model[1] (multiple logistic regression model) was investigated. Here instead of describing the bird capture distribution as (0, many) as in the binomial model, it can be described as (0,1, ..., many). These models converged in a small number of steps. The disadvantage was that each extra number allowed in the distribution added another set of variables and the Akaike Information Criterion (Akaike 1974, Venables & Ripley 1994) rapidly became larger. These models are not discussed further as it is not clear at this stage how to assess the multinomial model fits and how to decide whether they help in the interpretation of the bird capture data.

The bird capture data presented other problems when attempting to fit any of these models. The aim of the modelling is to show what factors influence bird catch rates and, incidentally, the effectiveness or otherwise of mitigation devices which have been introduced. To distinguish effects due to mitigation measures from those due to year, area, and other factors, it is necessary to model the underlying effects caused by differences in the fishery in different areas at different times. Furthermore, it would be useful to be able to include factors that describe bird numbers and behaviour, but no quantitative information of this type exists. Investigation of the pattern of observations suggested that there would be interaction terms between the areas and years (time), and that the domestic and Japanese (foreign and charter fleets) vessels fished differently.

The ideas behind using GLMs are closely related to those underlying the theory of experimental design. In properly designed experiments, all potential effects have roughly the same number of repetitions and the total number of measurements can be used in the determination of the error. In unbalanced designs, interaction terms in the explanatory variables can give undesired results for groups of data where there are no (or few) observations (Hearn & Bradford 1996).

Catch rate distributions from recreational fishing have a similar form to the seabird capture data, though the fraction of unsuccessful trips, p_0, is smaller. Bradford & Francis (1999) showed that the sample size required to detect decreases (increases) in a catch rate of 50% (100%) with reasonable certainty increased as p_0 increased and was about 250 when p_0 was greater than 0.65. Catch rates in the snapper and kahawai target recreational fisheries were used. Values of p_0 did not go above 0.8 in those data. In this work, p_0 could be considered as the fraction of successful trips, that is, those that did not catch birds. Particularly in recent years, the values of p_0 are high (over 0.9 in some areas). When p_0 becomes high (that is, when few sets catch birds), the mean catch rate per set (or per 1000 hooks) becomes small, unless there are several abnormally high bird catches, and tends to have high error.

Grouping the data

If individual years and the six areas are considered to give "data cells", many cells are empty and some are poorly represented. Also, different trends in catch rate over time are seen in some of the areas, that is, time-area interactions will occur in any regression models used. To minimise the problems arising from the lack of balance in the data they were grouped so that each cell contained at least 100 observations (as far as practicable). These groups are defined below.

Observations from two types of vessels were considered in separate models:

1. *Japanese*: all the foreign and charter vessel data, and data from one large domestic vessel which fished in a similar way and in similar areas to the Japanese vessels;
2. *Domestic*: the domestic vessels with length less than 30 m which were observed after 1994–95.

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[1] The multinomial model was implemented using the function ***multinom*** in the S-PLUS© library nnet (neural net). This library solves problems using neural nets and was written by Professor Brian Ripley, University of Oxford. The library is available via the Internet and through later editions of Venables & Ripley (1994). The permission to use this function is gratefully acknowledged.

A few observed sets on domestic vessels that were over 30 m in length but fished with longlines substantially shorter than the Japanese vessels have been excluded. There appeared to be nothing atypical about the bird captures by these vessels.

Three time periods were considered.

1. *Y1*: 1986–87 to 1989–90 when no bird capture mitigation measures were in place;
2. *Y2*: from 1990–91 to 1992–93 when some vessels used bird mitigation measures;
3. *Y3*: from 1993–94 onwards when bird mitigation measures were required. All the observations for the domestic (as defined above) vessels are in this period.

The six areas (*see* Figure 1) were amalgamated into three areas that appeared to have roughly similar bird capture probabilities:

1. *A1*: the northern area comprised Areas 1, 2, and 5. All domestic vessels fish in this area.
2. *A3*: the southern area comprised Areas 3 and 4;
3. *A6*: the area comprised Area 6.

Notation

A higher (lower) catch rate implies that the fraction of sets not catching birds is lower (higher) and the means of the numbers of birds caught per set and per 1000 hooks are higher (lower).

Testing strategy

Binomial and Poisson GLMs of increasing complexity were applied to the bird capture data. These models were generally ill fitting, explaining a small percentage of the original deviance, and the Poisson models were over-dispersed. Both models suggested where significant differences might lie, but the significance level was dubious.

To investigate where significant changes have occurred, the sets were divided into groups determined by the terms included in the GLMs. The data in each (relevant) pair of these groups were tested for significant difference. The tests carried out were for the difference of the two values of p_0 (the fraction of sets that did not catch birds) involved and for the differences in mean number of birds per set and mean number of birds per 1000 hooks.

The large sample test for difference in success probabilities for binomial data (Larsen & Marx 1986) was used to test whether the two values of p_0 were different. A two-sided randomisation test (Manly 1991) was used to test for differences in mean number of birds per set and mean number of birds per 1000 hooks. In this test, the magnitude of the observed difference was compared with the magnitude of the changes in the two means after assigning 4999 random re-orderings of the individual catch rates into two groups (representing the data being tested). The number of times the magnitude of the observed change was exceeded gave the p-value. Means were estimated as averages of the individual set values.

The number of birds caught per 1000 hooks is the "catch rate" used in the exploratory data section. The significance level of the various apparent differences shown there could be tested as done here, if the group size was large enough. Variables considered potentially important are tested below. Examples of variables used are time period, area, whether tori lines were used, whether sets were made at night, moon phase, sea surface temperature, and interaction terms between several of these variables. Those for which it seemed unlikely that significant results could be obtained were ignored. Examples of variables ignored are the individual vessels, the structure of tori lines, the details of bait type and how it was deployed, and the set duration. The confidence intervals used in the exploratory data section are approximate. The true confidence intervals for the means of catch rate distributions like those for the seabird bycatch data are difficult to determine analytically and some form of randomisation is required.

Tabulation of results

The results for each section are presented in sets of three tables (a, b, and c).

(a) contains the percentage of deviance explained and the dispersion from models with binomial and Poisson error distributions and the explanatory variable used. The deviance explained in the binomial models is generally low though the dispersion is close to 1. The Poisson models are better fitting than the binomial models in terms of the percentage deviance explained, but the dispersion is always substantially greater than 1. It is quite common for an interaction term to explain more of the deviance than the individual main effects in regression models.

(b) contains the results of tests for differences in the values of p_0 (fraction of sets where birds were not caught). The values of p_0 are obtained for the data sets identified by the two group labels. To help identify the pattern of changes, the last column of the table gives the sign of the change; "+" signifies an increase in p_0 and is a desirable change. The p values for the large sample binomial tests that are significant at the 5% level are given in italics. The significance levels should be regarded with caution, particularly those between 0.01 and 0.05, because the data could contain undetected biases.

(c) contains the results of tests for differences in the values of the mean number of birds caught per set (*MS*) and the mean number of birds caught per 1000 hooks (*MH*). The same data sets are used as in (b). The sign of the change is included; "–" signifies a desirable change. If p_0 increases, then fewer of the sets caught birds and generally the mean numbers of birds caught decrease (but a large catch in one set can distort this result). So, for example, when looking for an "improvement" after a mitigation measure is introduced, the expected change should have a positive sign for the change in p_0 and negative signs for the change in mean numbers of birds caught. Again, the p values for the two-sided randomisation tests that are significant at the 5% level are given in italics.

Fishery models (Japanese vessels)

The results from the models used to explain effects that underlie any explanation of bird capture mitigation for the Japanese vessels are given in Tables 5a, 5b, and 5c. These models used time period, area, and their interaction as potential predictor variables. The change over time appears small, the difference between areas seems greater, and there appears to be an interaction between time period and area.

The groups used were for the different time periods (*Y1*, *Y2*, and *Y3*), the areas (*A1*, *A3*, and *A6*) and several combinations of time period and area. Only combinations thought to be meaningful were tested. That is, the area differences within each time period and the time period differences for each area (*see* Tables 5b and 5c and Figure 47). It is left to the reader to list the nine time period-area groups, the 35 possible pairs of groups that could be tested for differences, and hence, to find the list of tests not documented. The reasons for not doing these tests should become apparent.

These results show that bird catches in *Y1* were significantly higher than in both the later time periods. Bird catches in *Y2* and *Y3* were much the same, though *Y3* could have had higher catches than *Y2*. Area *A6* had significantly lower bird catches than both Areas *A1* and *A3*, overall and in each separate time period. Area *A1* may have had lower bird catches than Area *A3* overall.

There was no difference between the bird catches in Areas *A1* and *A3* in *Y1*; in *Y2*, the p_0 values are the same, but the mean catches were greater in Area *A3* than Area *A1*; in *Y3* bird catches were greater in Area *A1*. In Area *A1*, bird catches reduced from *Y1* to *Y2*, but increased again between *Y2* and *Y3* and were greater in *Y3* than *Y1*, though not all variables changed were significant in the latter case. In Area *A3*, the changes in variables were not significant except that more sets caught birds in *Y1*. In Area *A6*, bird catches were higher in *Y1* and stayed much the same in *Y2* and *Y3*.

Some of the results above are of concern because there has not been a consistent improvement in bird catch rate over the time that various bird catch mitigation measures were introduced.

Bird catch in relation to mitigation measures (Japanese vessels)

The data for the Japanese vessels were then restricted to *Y2* and *Y3* and the effectiveness of the bird mitigation measures investigated. The few sets where the information about tori use was unknown were ignored. Sets were divided into *night* and *other*. *Night* was taken to be from 2 h after sunset to 2 h before sunrise; a long twilight period was allowed. Any sets where part of the set was outside the night period were classed as *other*. These definitions were used to get a sufficient number of sets into the *other* category because in recent years few sets have been made totally during the day (Figure 48). Strictly, the setting time should be divided into a night part and a day part. The small aggregate time of daylight setting means that getting unequivocal results proving that the bird catches were greater during the day would be difficult. Figure 14 shows that Japanese vessels caught most birds during the night (because most of the setting was done then (*see* Figure 13)).

Table 6a and Figure 47 contain results for when the model included tori use and nightsetting. Including both effects did not explain substantially more deviance than had already been explained by the time period and area interaction.

The test results showing the effectiveness of the main mitigation method are given in Tables 6a, 6b, and 6c. All sets used tori lines in *Y3*. During *Y2* in Area *A1*, and to lesser extent in Area *A6*, more birds were caught when tori lines were used than when they were not. The use of tori lines in Area *A3* led to no significant change. In Area *A1*, nightsetting led to significantly lower bird catches in *Y2*, but higher catches in *Y3*; bird catches were higher in *Y3* than *Y2* irrespective of setting time. In Area *A3*, all nightsetting was not significantly different from setting partially during the day in both *Y2* and *Y3*; nor was there any change for nightsetting, and partial day setting between the time periods. In Area *A6*, nightsetting gave lower bird catches than partial nightsetting in both time periods; nightsetting was slightly worse in *Y3* than *Y2*.

These results are disturbing in that the data suggest that the mitigation measures have not been successful. They suggest mitigation measures were probably effective in Area *A6* where bird captures have always been low, had little effect in Area *A3*, and to be generally detrimental in Area *A1*. The data may not be adequate to test the success or otherwise of these measures. The Japanese vessels have complied with both the use of tori lines (of approved design) and nightsetting. Sets have started earlier, and proportionately more sets took place wholly during the night in *Y3* than *Y2*.

Table 5a**: Deviance explained (Dev explnd) and dispersion for binomial and Poisson error distribution models using Japanese vessels. The response variable in the binomial model was whether birds were not caught during a set, and in the Poisson model was the number of birds caught in a set**

	Binomial		Poisson	
Explanatory variables	Dev explnd (%)	Dispersion	Dev explnd (%)	Dispersion
YR	2.5	1.0012	2.2	7.5068
AREA	10.8	0.9774	16.7	4.9343
*YR * AREA*	13.0	1.0028	22.9	4.1781

Table 5b**: Results of testing the difference in the values of p_0 (fraction of sets when birds were not caught) for Group* 1 and Group 2 of data presented in Table 5a. *N* is the number of points in the group and Sign is the sign of the change**

		Group 1		Group2			
Group 1	Group 2	*N*	p_0	*N*	p_0	*p*	Sign
Y1	*Y2*	281	0.655	699	0.847	*0.000*	+
Y1	*Y3*	281	0.655	1 212	0.844	*0.000*	+
Y2	*Y3*	699	0.847	1 212	0.844	0.434	–
A1	*A3*	680	0.693	583	0.762	*0.003*	+
A1	*A6*	680	0.693	929	0.952	*0.000*	+
A3	*A6*	583	0.762	929	0.952	*0.000*	+
Y1;A1	*Y1;A3*	165	0.618	72	0.625	0.460	+
Y1;A1	*Y1;A6*	165	0.618	44	0.841	*0.003*	+
Y1;A3	*Y1;A6*	72	0.625	44	0.841	*0.007*	+
Y2;A1	*Y2;A3*	332	0.789	119	0.790	0.493	+
Y2;A1	*Y2;A6*	332	0.789	248	0.952	*0.000*	+
Y2;A3	*Y2;A6*	119	0.790	248	0.952	*0.000*	+
Y3;A1	*Y3;A3*	183	0.585	392	0.778	*0.000*	+
Y3;A1	*Y3;A6*	183	0.585	637	0.959	*0.000*	+
Y3;A3	*Y3;A6*	392	0.778	637	0.959	*0.000*	+
Y1;A1	*Y2;A1*	165	0.618	332	0.789	*0.000*	+
Y1;A1	*Y3;A1*	165	0.618	183	0.585	0.262	–
Y2;A1	*Y3;A1*	332	0.789	183	0.585	*0.000*	–
Y1;A3	*Y2;A3*	72	0.625	119	0.790	*0.007*	+
Y1;A3	*Y3;A3*	72	0.625	392	0.778	*0.003*	+
Y2;A3	*Y3;A3*	119	0.790	392	0.778	0.392	–
Y1;A6	*Y2;A6*	44	0.841	248	0.952	*0.003*	+
Y1;A6	*Y3;A6*	44	0.841	637	0.959	*0.000*	+
Y2;A6	*Y3;A6*	248	0.952	637	0.959	0.309	+

* *Y1; A1* is data from Area *A1* in *Y1*, *etc.*

***Table 5c*: Results of testing the difference of mean number of birds per set (MS) and mean number of birds per 1000 hooks (MH) for Group* 1 and Group 2 of data in Table 5a**

				Birds per set				Birds per 1000 hooks	
Group 1	Group 2	MS 1	MS 2	*p*	Sign	MH 1	MH 2	*p*	Sign
Y1	*Y2*	0.954	0.369	*0.000*	–	0.334	0.126	*0.000*	–
Y1	*Y3*	0.954	0.549	*0.004*	–	0.334	0.192	*0.005*	–
Y2	*Y3*	0.369	0.549	*0.050*	+	0.126	0.192	*0.032*	+
A1	*A3*	0.975	0.796	0.221	–	0.344	0.272	0.152	–
A1	*A6*	0.975	0.069	*0.000*	–	0.344	0.024	*0.000*	–
A3	*A6*	0.796	0.069	*0.000*	–	0.272	0.024	*0.000*	–
Y1;A1	*Y1;A3*	1.127	0.958	0.659	–	0.395	0.332	0.629	–
Y1;A1	*Y1;A6*	1.127	0.295	*0.042*	–	0.395	0.109	*0.044*	–
Y1;A3	*Y1;A6*	0.958	0.295	*0.029*	–	0.332	0.109	*0.035*	–
Y2;A1	*Y2;A3*	0.380	0.992	*0.005*	+	0.134	0.326	*0.013*	+
Y2;A1	*Y2;A6*	0.380	0.056	*0.000*	–	0.134	0.019	*0.000*	–
Y2;A3	*Y2;A6*	0.992	0.056	*0.000*	–	0.326	0.019	*0.000*	–
Y3;A1	*Y3;A3*	1.918	0.707	*0.000*	–	0.679	0.244	*0.000*	–
Y3;A1	*Y3;A6*	1.918	0.058	*0.000*	–	0.679	0.020	*0.000*	–
Y3;A3	*Y3;A6*	0.707	0.058	*0.000*	–	0.244	0.020	*0.000*	–
Y1;A1	*Y2;A1*	1.127	0.380	*0.000*	–	0.395	0.134	*0.000*	–
Y1;A1	*Y3;A1*	1.127	1.918	*0.023*	+	0.395	0.679	*0.018*	+
Y2;A1	*Y3;A1*	0.380	1.918	*0.000*	+	0.134	0.679	*0.000*	+
Y1;A3	*Y2;A3*	0.958	0.992	0.972	+	0.332	0.326	0.984	–
Y1;A3	*Y3;A3*	0.958	0.707	0.347	–	0.332	0.244	0.339	–
Y2;A3	*Y3;A3*	0.992	0.707	0.315	–	0.326	0.244	0.400	–
Y1;A6	*Y2;A6*	0.295	0.056	*0.001*	–	0.109	0.019	*0.000*	–
Y1;A6	*Y3;A6*	0.295	0.058	*0.001*	–	0.109	0.020	*0.001*	–
Y2;A6	*Y3;A6*	0.056	0.058	1.000	+	0.019	0.020	0.837	+

* *Y1; A1* is data from Area *A1* in *Y1*, *etc.*

***Table 6a*: Deviance explained (Dev explnd) and dispersion for binomial and Poisson error distribution models using Japanese vessels and including mitigation measures used by the Japanese vessels. The response variable in the binomial model was whether birds were not caught during a set, and in the Poisson model was the number of birds caught in a set**

		Binomial		Poisson
Explanatory variables*	Dev explnd (%)	Dispersion	Dev explnd (%)	Dispersion
*YR*AREA + TU*	13.7	0.9883	25.2	4.2378
*YR*AREA + DN*	12.6	0.9946	24.9	4.0607
*YR*AREA + TU*DN*	13.7	0.9916	25.6	4.0802

* *TU* is tori lines used *yes* or *no*; *DN* is all of the set was during the night or all or part of the set was during the day.

***Table 6b*: Results of testing the difference in the values of p_0 (fraction of sets when birds were not caught) for Group* 1 and Group 2 of data presented in Table 6a, investigating mitigation measures as used by the Japanese vessels**

		Group 1		Group 2			
Group 1	Group 2	*N*	p_0	*N*	p_0	*p*	Sign
Y2;A1;TN	*Y2;A1;TY*	192	0.870	140	0.679	*0.000*	–
Y2;A3;TN	*Y2;A3;TY*	45	0.800	74	0.784	0.417	–
Y2;A6;TN	*Y2;A6;TY*	97	0.990	149	0.926	*0.012*	–
Y2;A1;TY	*Y3;A1;TY*	140	0.679	183	0.585	*0.042*	–
Y2;A3;TY	*Y3;A3;TY*	74	0.784	391	0.777	0.452	–
Y2;A6;TY	*Y3;A6;TY*	149	0.926	637	0.959	*0.043*	+
Y2;A1;NT	*Y2;A1;DY*	159	0.893	173	0.694	*0.000*	–
Y2;A3;NT	*Y2;A3;DY*	45	0.733	74	0.824	0.119	+
Y2;A6;NT	*Y2;A6;DY*	71	0.986	175	0.937	*0.054*	–
Y3;A1;NT	*Y3;A1;DY*	111	0.459	72	0.778	*0.000*	+
Y3;A3;NT	*Y3;A3;DY*	258	0.779	133	0.774	0.458	–
Y3;A6;NT	*Y3;A6;DY*	521	0.965	116	0.931	*0.045*	–
Y2;A1;NT	*Y3;A1;NT*	159	0.893	111	0.459	*0.000*	–
Y2;A3;NT	*Y3;A3;NT*	45	0.733	258	0.779	0.250	+
Y2;A6;NT	*Y3;A6;NT*	71	0.986	521	0.965	0.179	–
Y2;A1;DY	*Y3;A1;DY*	173	0.694	72	0.778	*0.091*	+
Y2;A3;DY	*Y3;A3;DY*	74	0.824	133	0.774	0.198	–
Y2;A6;DY	*Y3;A6;DY*	175	0.937	116	0.931	0.418	–

* *TN*, *TY* is tori lines not used, used; *NT*, *DY* is all setting during the night, some or all setting during the day.

***Table 6c*: Results of testing the difference of mean number of birds per set (MS) and mean number of birds per 1000 hooks (MH) for Group* 1 and Group 2 of data in Table 6a, investigating mitigation measures as used by the Japanese vessels**

		Birds per set				Birds per 1000 hooks			
Group 1	Group 2	MS 1	MS 2	*p*	Sign	MH 1	MH 2	*p*	Sign
Y2;A1;TN	*Y2;A1;TY*	0.177	0.657	*0.000*	+	0.062	0.234	*0.000*	+
Y2;A3;TN	*Y2;A3;TY*	1.289	0.811	0.664	–	0.422	0.268	0.657	–
Y2;A6;TN	*Y2;A6;TY*	0.010	0.087	*0.029*	+	0.004	0.029	*0.035*	+
Y2;A1;TY	*Y3;A1;TY*	0.657	1.918	*0.000*	+	0.234	0.679	*0.000*	+
Y2;A3;TY	*Y3;A3;TY*	0.811	0.708	0.731	–	0.268	0.245	0.802	–
Y2;A6;TY	*Y3;A6;TY*	0.087	0.058	0.311	–	0.029	0.020	0.440	–
Y2;A1;NT	*Y2;A1;DY*	0.189	0.555	*0.000*	+	0.068	0.196	*0.001*	+
Y2;A3;NT	*Y2;A3;DY*	1.600	0.622	0.225	–	0.524	0.206	0.218	–
Y2;A6;NT	*Y2;A6;DY*	0.014	0.074	0.113	+	0.004	0.025	0.072	+
Y3;A1;NT	*Y3;A1;DY*	2.468	1.069	*0.011*	–	0.862	0.397	*0.017*	–
Y3;A3;NT	*Y3;A3;DY*	0.612	0.895	0.217	+	0.205	0.321	0.139	+
Y3;A6;NT	*Y3;A6;DY*	0.052	0.086	0.332	+	0.017	0.034	0.167	+
Y2;A1;NT	*Y3;A1;NT*	0.189	2.468	*0.000*	+	0.068	0.862	*0.000*	+
Y2;A3;NT	*Y3;A3;NT*	1.600	0.612	*0.037*	–	0.524	0.205	*0.039*	–
Y2;A6;NT	*Y3;A6;NT*	0.014	0.052	0.396	+	0.004	0.017	0.292	+
Y2;A1;DY	*Y3;A1;DY*	0.555	1.069	*0.040*	+	0.196	0.397	*0.026*	+
Y2;A3;DY	*Y3;A3;DY*	0.622	0.895	0.505	+	0.206	0.321	0.406	+
Y2;A6;DY	*Y3;A6;DY*	0.074	0.086	0.859	+	0.025	0.034	0.657	+

* *TN*, *TY* is tori lines not used, used; *NT*, *DY* is all setting during the night, some or all setting during the day.

Further models (Japanese vessels)

In previous modelling of the seabird capture data, factors such as moon phase (or intensity) and sea surface temperature have been considered as explanatory variables (for example, Duckworth 1995). Several additional models were run containing these factors (Table 7a).

***Table 7a*: Deviance explained (Dev explnd) and dispersion for binomial and Poisson error distribution models using Japanese vessels, including mitigation measures and other explanatory variables. The response variable in the binomial model was whether birds were not caught during a set, and in the Poisson model was the number of birds caught in a set**

	Binomial		Poisson	
Explanatory variables	Dev explnd (%)	Dispersion	Dev explnd (%)	Dispersion
*YR*AREA*DN*	15.4	1.0000	27.6	3.7564
*YR*AREA*DN + TU*	16.1	0.9827	28.1	3.8217
*YR*AREA*DN + TU + moonph*	23.6	1.0474	42.0	2.8347
*YR*AREA*DN + TU * DN*moonph*	24.4	1.0463	42.6	2.7449
*YR*AREA*DN + TU * DN*moonph + sst*	24.5	1.0542	43.0	2.7087
*YR*AREA*DN + TU * DN*moonph + poly(sst,4)*	25.3	1.0387	44.9	2.5782
*YR*AREA*TU*	14.0	0.9939	26.3	3.8853
*YR*AREA*TU + moonph*	21.4	1.1803	40.6	2.9617
*YR*AREA*TU + DN*moonph*	21.8	1.1082	41.3	2.8631
*YR*AREA*TU + DN*moonph + sst*	22.0	1.1286	41.8	2.8565
*YR*AREA*TU + DN*moonph + poly(sst,4)*	23.3	1.0867	43.9	2.6531

* *TU* is tori lines used *yes* or *no*; *DN* is all of the set was during the night or all or part of the set was during the day; *moonph* is moon phase; *sst* is sea surface temperature.

The effect of sea surface temperature appeared to be small. The normal ranges of sea surface temperature in Areas *A1*, *A3*, and *A6* are different and more or less distinct. Thus sea surface temperature is primarily an area effect. High order polynomials were presumably trying to mimic the distribution of sea surface temperatures observed (*see* Figure 17).

The inclusion of moon phase made a large difference, presumably because the extra light at night allowed the birds to see the baits. Including an interaction between the moon phase and the night or partial night effect added little explanatory power, presumably because most setting was done during the night. The brightness of the moon may be dimmed by cloud cover, but information on cloud cover was recorded only at the start of the set and consequently could not be considered as covering the whole setting period.

To examine the effect of moon phase further, the sets were divided into two groups defined as *light* and *dark*. *Light* was defined as periods when the moon phase was greater than 0.8 (80% or more of the lunar disc was illuminated). The effects of any part of the set being during the day were excluded. This split resulted in about a third of the sets occurring on light nights. The differences in bird catch rates between setting on light and dark nights were large and higher catch rates occurred during the light nights. The differences were very significant in Areas *A1* and *A2* in *Y2* and *Y3*; in Area *A6*, the differences between setting on light and dark nights were smaller, mainly because the overall bird catches were smaller in this area (Tables 7b and 7c, *see* Figure 48). The only significant changes between *Y2* and *Y3* occurred in Area *A1* where the bird catches were higher during both light and dark sets.

***Table 7b*: Results of testing the difference in the values of p_0 (fraction of sets when birds were not caught) for Group* 1 and Group 2 of data in Table 7a, investigating the effect of moon phase, for Japanese vessels**

		Group 1		Group 2			
Group 1	Group 2	*N*	p_0	*N*	p_0	*p*	Sign
Y2-A1-LT	*Y2-A1-DK*	119	0.664	213	0.859	*0.000*	+
Y2-A3-LT	*Y2-A3-DK*	38	0.553	81	0.901	*0.000*	+
Y2-A6-LT	*Y2-A6-DK*	85	0.918	161	0.969	*0.038*	+
Y3-A1-LT	*Y3-A1-DK*	62	0.323	121	0.719	*0.000*	+
Y3-A3-LT	*Y3-A3-DK*	120	0.583	271	0.863	*0.000*	+
Y3-A6-LT	*Y3-A6-DK*	200	0.935	437	0.970	*0.018*	+
Y2-A1-LT	*Y3-A1-LT*	119	0.664	62	0.323	*0.000*	–
Y2-A3-LT	*Y3-A3-LT*	38	0.553	120	0.583	0.369	+
Y2-A6-LT	*Y3-A6-LT*	85	0.918	200	0.935	0.309	+
Y2-A1-DK	*Y3-A1-DK*	213	0.859	121	0.719	*0.001*	–
Y2-A3-DK	*Y3-A3-DK*	81	0.901	271	0.863	0.181	–
Y2-A6-DK	*Y3-A6-DK*	161	0.969	437	0.970	0.467	+

* *LT, DK* is *light* (moon phase > 0.8) or *dark* (other sets).

***Table 7c*: Results of testing the difference of mean number of birds per set (MS) and mean number of birds per 1000 hooks (MH) for Group* 1 and Group 2 of data in Table 7a, investigating the effect of moon phase, for the Japanese vessels**

		Birds per set				Birds per 1000 hooks			
Group 1	Group 2	MS 1	MS 2	*p*	Sign	MH 1	MH 2	*p*	Sign
Y2-A1-LT	*Y2-A1-DK*	0.613	0.249	*0.001*	–	0.215	0.089	*0.000*	–
Y2-A3-LT	*Y2-A3-DK*	2.711	0.185	*0.000*	–	0.890	0.062	*0.000*	–
Y2-A6-LT	*Y2-A6-DK*	0.106	0.031	*0.044*	–	0.036	0.010	*0.021*	–
Y3-A1-LT	*Y3-A1-DK*	3.323	1.198	*0.000*	–	1.144	0.441	*0.000*	–
Y3-A3-LT	*Y3-A3-DK*	1.667	0.284	*0.000*	–	0.575	0.098	*0.000*	–
Y3-A6-LT	*Y3-A6-DK*	0.095	0.041	*0.050*	–	0.031	0.016	0.147	–
Y2-A1-LT	*Y3-A1-LT*	0.613	3.323	*0.000*	+	0.215	1.144	*0.000*	+
Y2-A3-LT	*Y3-A3-LT*	2.711	1.667	0.189	–	0.890	0.575	0.262	–
Y2-A6-LT	*Y3-A6-LT*	0.106	0.095	0.865	–	0.036	0.031	0.752	–
Y2-A1-DK	*Y3-A1-DK*	0.249	1.198	*0.000*	+	0.089	0.441	*0.000*	+
Y2-A3-DK	*Y3-A3-DK*	0.185	0.284	0.458	+	0.062	0.098	0.385	+
Y2-A6-DK	*Y3-A6-DK*	0.031	0.041	0.730	+	0.010	0.016	0.595	+

* *LT, DK* is *light* (moon phase > 0.8) or *dark* (other sets).

Whether or not the large domestic vessel was included with the Japanese vessels made little difference to the significance levels in the tests, though the values of p_o and the mean catch rates in Areas *A3* and *A6* in *Y3* were changed. The main difference in catch rates occurred in Area *A3* where the domestic vessel had lower bird catch rates than the Japanese vessels, so the Area *A3* results showed a worse bird catch rate when this vessel was excluded. Sets made totally in the dark had significantly lower bird catch rates in Area *A6* in *Y3* when this vessel was excluded.

Fishery models (domestic vessels)

Bird catch in relation to mitigation measures and other factors (domestic vessels)

The domestic vessels considered here all fished in Area *A1*, in *Y3*, so there was no spatial or temporal part in the models used to explain the variance in the bird capture rate. Many of the birds caught on the domestic vessels were caught on the haul, rather than during setting, and were released alive. A set of models was run using all bird captures (dead or alive) and again using those birds that had been returned for identification (dead).

The results from several models that include mitigation measures, moon phase, and sea surface temperature in several combinations similar to those used for the Japanese vessels for all bird captures and for those returned for identification are given in Table 8a. It should be clear that the mitigation measures did little to explain the variance in bird catch. The sea surface temperature effect occurred because the values of sea surface temperature were mainly within a limited range, with all the sets made within a localised area.

Table 8a: **Deviance explained (Dev explnd) and dispersion for binomial and Poisson error distribution models using domestic vessels, including mitigation measures and other explanatory variables. The response variable in the binomial model was whether birds were not caught during a set, and in the Poisson model was the number of birds caught in a set**

	Binomial		Poisson	
Explanatory variables*	Dev explnd (%)	Dispersion	Dev explnd (%)	Dispersion
All birds recorded as caught				
DN	0.00	1.0081	0.10	2.6581
TU	0.50	1.0080	0.00	2.6716
*DN * TU*	0.60	1.0162	0.80	2.5430
*DN * TU + moonph*	0.80	1.0203	1.20	2.5338
DN TU * moonph*	2.00	1.0322	2.60	2.4382
*DN * TU * moonph + poly(sst,3)*	3.50	1.0610	10.20	2.2343
All birds returned dead				
DN	1.80	0.9926	3.40	1.2402
TU	0.90	0.9965	1.00	1.3123
*DN * TU*	2.70	1.0153	4.20	1.2900
*DN * TU + moonph*	3.70	1.0010	7.00	1.1504
DN TU * moonph*	5.80	1.0700	8.70	1.2279
*DN * TU * moonph + poly(sst,3)*	10.60	1.0753	14.90	1.1791

* *TU* is tori lines used *yes* or *no*; *DN* is all of the set was during the night or all or part of the set was during the day; *moonph* is moon phase; *sst* is sea surface temperature.

The pairwise test results in Tables 8b and 8c perhaps show a little more. The apparent significant result that there was a higher catch rate of all birds when the setting was done in the dark part of the lunar cycle is probably spurious because some of these birds were caught during hauling. For just those dead birds that were returned for identification, there was no significant difference in catch rates whether or not tori lines were used. Bird catch rates tended to be higher when the setting took place partly in daylight, and catch rates were higher when the set was made in the *light* part of the moon phase. These domestic vessels mainly used lines with less than 1000 hooks, so the mean catch per set is lower than the mean catch per 1000 hooks.

Table 8b: **Results of testing the difference in the values of p_0 (fraction of sets when birds were not caught) for Group* 1 and Group 2 of data in Table 8a, investigating the effect of moon phase, for domestic vessels**

		Group 1		Group 2			
Group 1	Group 2	*N*	p_0	*N*	p_0	*p*	Sign
All birds recorded as caught							
TN	*TY*	120	0.700	129	0.628	0.115	–
NT	*DY*	143	0.671	106	0.651	0.368	–
LT	*DK*	77	0.688	172	0.651	0.283	–
All birds returned dead							
TN	*TY*	120	0.933	129	0.891	0.122	–
NT	*DY*	143	0.937	106	0.877	0.050	–
LT	*DK*	77	0.870	172	0.930	0.061	+

* *TN*, *TY* is tori lines not used, used; *NT*, *DY* is all of the set took place during the night, other; *LT*, *DK* is *light* (moon phase > 0.8) or *dark* (other sets).

Table 8c: **Results of testing the difference of mean number of birds per set (MS) and mean number of birds per 1000 hooks (MH) for Group* 1 and Group 2 of data in Table 8a, investigating the effect of moon phase, for the domestic vessels**

		Birds per set				Birds per 1000 hooks			
Group 1	Group 2	MS 1	MS 2	*p*	Sign	MH 1	MH 2	*p*	Sign
All birds recorded as caught									
TN	*TY*	0.617	0.605	0.851	–	0.857	0.697	0.354	–
NT	*DY*	0.587	0.642	0.633	+	0.800	0.739	0.893	–
LT	*DK*	0.429	0.692	0.124	+	0.580	0.861	0.164	+
All birds returned dead									
TN	*TY*	0.083	0.132	0.339	+	0.110	0.153	0.458	+
NT	*DY*	0.070	0.160	0.069	+	0.092	0.187	0.109	+
LT	*DK*	0.182	0.076	0.048	–	0.210	0.098	0.071	–

* *TN*, *TY* is tori lines not used, used; *NT*, *DY is* all of the set took place during the night, other; *LT*, *DK* is *light* (moon phase > 0.8) or *dark* (other sets).

Discussion

This report has examined some factors that might influence the capture of seabirds during tuna longline fishing operations. The analysis showed factors such as area, year, use of tori lines, time of day, moon phase, and sea surface temperature were likely to show significant differences in bycatch rate. Furthermore, the exploratory analyses showed that it was unlikely that there were any significant differences arising from the details of the tori line design, from the type and state of the bait used, or from how the bait was deployed.

Much effort has been expended since 1991 to reduce the bycatch of seabirds by tuna longliners operating in New Zealand waters with the use of nightsetting and tori lines. The observed fishing vessels have generally complied with mandatory measures, but this exploratory analysis has not shown conclusively that the mitigation measures have been successful. For example, data from Area 1 have shown that the use of tori lines does not necessarily lower the rate of bird bycatch. However, there is a lack of knowledge and information about other possibly confounding variables, such as the abundance of birds around the vessels at the time of fishing in a given year and environmental factors which may affect the mitigating effect of tori lines. The seabird bycatch data are further confounded because the fishing patterns and observer coverage vary from year to year and the fraction of observed sets in an area is not constant (*see* Figures 4 and 5, for example).

Seabird bycatch rates vary with year, position, and fishing practice, and therefore we need to be aware of interaction terms in any models used to examine the reasons for variation in the bycatch rate. The shape of the distributions of seabird bycatch (that is, a large number of zero catch rates followed by an exponential-like decline in catch rate) poses technical problems, mainly concerned with the determination of the confidence interval around the mean. One consequence is that large sample sizes (at least 100) for any subdivision of the data can be tested against another. (Bradford & Francis 1999 discussed the similar problem that arises with recreational fishing catch rates.) The standard approaches to GLMs give ill determined models, convergence failure, or possibly both.

Because of these concerns, the data were organised into a form so that statistical tests could be performed upon a sufficient number of sets. Hence, the observed sets were divided into groups that were reasonably large and covered the main time periods (1986–87 to 1989–90, 1990–91 to 1992–93, and 1993–94 to 1997–98), fishing areas (northern, southern, and western), and fleet (Japanese longliners, including one large domestic vessel, and smaller domestic longliners).

To avoid spurious results, no attempt was made to test differences that might arise when the number of sets in a "group" was small. So, for example, no test were made on the effectiveness of particular types of tori lines because nearly all the tori lines used complied with CCAMLR standards. Also, once the vessels involved had been divided into two groups with roughly similar operating power, no further account was taken of differences between vessels because the number of observed sets on some vessels was small.

The differences in bird bycatch rate in these northern, southern, and western areas were apparent, with different time trends in different area groupings (*see* Figure 47). Sets made around the time of a full moon were more likely to catch birds than those made at other times, particularly in the northern and southern areas. This, of course, is the time when tuna catch rates are believed to be highest.

Sea surface temperature appears to have some influence on the seabird bycatch rate, but this term in the GLMs seems to be mainly picking up the normal range of sea surface temperatures in an area at the time the fishing took place and is confounded with area-season effects.

It could not be shown that the use of tori lines and/or nightsetting gave a consistently statistically significant reduction in seabird bycatch rate. For some Japanese vessels, an apparently higher bird bycatch rate occurred in some areas when tori lines were used than when they were not. Also, apparently little change in bird bycatch rate occurred when sets were made completely during the night compared with those made wholly or partly during the day. In an Australian study, Brothers *et al.* (1998) showed that bird bycatch rates were higher for sets that used a tori line for all the 1991–95 data, but when the data were stratified by area and season there appeared to be lower rates for those sets that used a tori line. This might be related to the higher use of tori lines in areas with high bycatch.

Duckworth (1995) primarily used data from the middle time period used here. He found the same area differences and some influence of moon phase on the bird catch rate. The other factors that he used as predictor variables were rejected here as being inappropriate (because they were recorded only at the start of the set) or leading to too small a group size to give statistically reliable results (given the nature of the data and the general ill fit of GLMs to this kind of data).

One difference between the bird bycatch rates of the Japanese and domestic fleets is that for the Japanese fleet essentially all birds were caught during the setting part of the fishing operation, but for the domestic small vessel fleet many of the birds were caught during the haul. The requirement of nightsetting means that hauling will usually be done during the day when several bird species are actively foraging for food (Harper 1987, Hedd *et al.* 1997).

Acknowledgments

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References

Akaike, H. 1974: The analysis of unbalanced cross-classification (with discussion). *Journal of the Royal Statistical Society A 141*: 195–223.

Baird, S.J. 1997: Report on the incidental capture of nonfish species during fishing operations in New Zealand waters. (Unpublished report prepared for the Ministry of Fisheries, September 1997, as part of ENV9701). 15 p + appendices.

Baird, S.J., Francis, M.P., Griggs, L., & Dean, H. 1998: Annual review of bycatch in southern bluefin tuna and related tuna longline fisheries in New Zealand 200 n. mile Exclusive Economic Zone. CCSBT-ERS/9806/31. (Unpublished summary report prepared for the Third Meeting of the CCSBT Ecologically Related Species Working Group, Tokyo, 9–13 June 1998.) [Draft report held in NIWA library, Wellington.]

Bartle, J.A. 1974: Seabirds of eastern Cook Strait, New Zealand, in autumn. *Notornis 21*: 135–166.

Bradford, E. & Francis, R.I.C.C. 1999: Power to detect changes in recreational harvest rates. New Zealand Fisheries Assessment Research Document. 99/6. 23 p.

Brothers, N. 1991: Albatross mortality and associated bait loss in Japanese longline fishery in the Southern Ocean. *Biological Conservation 55*: 255–268.

Brothers, N., Foster, A., & Robertson, G. 1995: The influence of bait quality on the sink rate of bait used in the Japanese longline tuna fishing industry: an experimental approach. *CCAMLR Science 2*: 123–129.

Brothers, N., Gales, R., & Reid, T. 1998: The influences of environmental variables and mitigation measures on seabird catch rates in the Japanese tuna longline fishery within the Australian Fishing Zone, 1991–95. CCSBT-ERS/9806/17. (Unpublished paper presented at CCSBT ERS meeting held June 1998, Tokyo.) 29 p.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) 1990: Report of the Ninth Meeting of the Commission. CCAMLR, Hobart.

Chambers, J.M. & Hastie, T.J. (Eds.) 1992: Statistical models in S. Wadsworth & Brooks/Cole Advanced Books & Software, Pacific Grove, California. 608 p.

Cherel, Y., Weimerskirch, H., & Duhamel, G. 1996: Interactions between longline vessels and seabirds in Kerguelen waters and a method to reduce seabird mortality. *Biological Conservation 75*: 63–70.

Duckworth, K. (1995): Analyses of factors which influence seabird bycatch in the Japanese southern bluefin tuna longline fishery in New Zealand waters, 1989–93. N.Z. Fisheries Assessment Research Document 95/26. 58 p. [Draft report held in NIWA library, Wellington.]

Duffett-Smith, P. 1990: Astronomy with your Personal Computer. Second edition. Cambridge University Press, Cambridge. 258 p.

Francis, M.P., Griggs, L.H., Baird, S.J., Murray, T.E., & Dean, H.A. 1999: Fish bycatch in New Zealand tuna longline fisheries. *NIWA Technical Report 55*. 70 p.

Harper, P., Croxall, J.P., & Cooper, J. 1985: A guide to foraging methods used by marine birds in Antarctic and subantarctic seas. *SCAR/SCOR/IABO/ACMRR Biomass Handbook 24*. 20 p. + appendices.

Harper, P.C. 1987: Feeding behaviour and other notes on 20 species of procellariiformes at sea. *Notornis 34(3)*: 169–192.

Hedd, A., Gales, R., Brothers, N., & Robertson, G. 1997: Diving behaviour of shy albatrosses (*Diomedea cauta*) in Tasmania: initial findings and dive recorder assessment. *Ibis 139*: 452–460.

Hearn, W. & Bradford, E. 1996: Absent values in generalised linear models containing interaction terms. (Note to CCSBT workshop on SBT CPUE and VPA, January 1996, Hobart.)

Johnston, N.L., Kotz, S., & Kemp, A.W. 1992: Univariate discrete distributions. Second edition. John Wiley & Sons, Inc. New York. 565 p.

Jouventin, P. & Weimerskirch, H. 1990: Satellite tracking of wandering albatrosses. *Nature 343*: 746–748.

Klaer, N. & Heinemann, D. 1998: Japanese longline seabird bycatch in the Australian Fishing Zone, April 1997-March 1998. CCSBT-ERS/9806/24. (Document provided to the CCSBT ERS meeting, June 1998, Tokyo.) 9 p.

Klaer, N. & Polacheck, T. 1998: The influence of environmental factors and mitigation measures on by-catch rates of seabirds by Japanese longline fishing vessels in the Australian region. CCSBT-ERS/9806/25. (Document provided to the CCSBT ERS meeting, June 1998, Tokyo.) 17 p.

Larsen, R.J. & Marx, M.L. 1986: An introduction to mathematical statistics and its applications. Second edition. Prentice-Hall International, Inc. Englewood Cliffs, New Jersey. 630 p.

Løkkeborg, S. 1998: Seabird by-catch and bait loss in longlining using different setting methods. *ICES Journal of Marine Science 55*: 145–149.

Manly, B.F.J. 1991: Randomisation and Monte Carlo methods in biology. Chapman and Hall. London. 281 p.

McCullagh, P. & Nelder, J.A. 1989: Generalised linear models. Second edition. Chapman & Hall. London. 511 p.

Michael, K.P., Jones, J.B., & Bailey, K.N. 1987: Report of observer trips on Japanese southern bluefin tuna longliners off East Cape, June-July 1987. N.Z. Fisheries Research Centre Internal Report No. 80. 36 p. [Draft report held in NIWA library, Wellington.]

Murray, T.E., Bartle, J.A., Kalish, S.R., & Taylor, P.R. 1993: Incidental capture of seabirds by Japanese southern bluefin tuna longline vessels in New Zealand waters, 1988–1992. *Bird Conservation International 3*: 181–210.

Murray, T.E., Richardson, K., Dean, H., & Griggs, L. 1999: New Zealand tuna fisheries with reference to stock status and swordfish bycatch. (Unpublished report prepared for the Ministry of Fisheries as part of TUN9701.) 126 p.

Sagar, P.M. & Weimerskirch, H. 1996: Satellite tracking of southern Buller's albatrosses from The Snares, New Zealand. *The Condor 98*: 649–652.

Venables, W.N. & Ripley, B.D. 1994: Modern applied statistics with S-Plus. Springer-Verlag. New York. 462 p.

Walker, K., Elliott, D., Nicholls, D.M., & Dilks, P. 1995: Satellite tracking of wandering albatross (*Diomedea exulans*) from the Auckland Islands: preliminary results. *Notornis 42*: 127–137.

Waugh, S.M., Weimerskirch, Y., Cherel, Y., Shankar, U., Prince, P.A., & Sagar, P.M. 1999: Exploitation of the marine environment by two sympatric albatrosses in the Pacific Southern Ocean. *Marine Ecology Progress Series 177*: 243–254.

Weimerskirch, H. & Jouventin, P. 1987: Population dynamics of the Wandering Albatross, *Diomedea exulans*, of the Crozet Islands: causes and consequences of the population decline. *Oikos 49*: 315–322.

Weimerskirch, H., Wilson, R.P., & Lys, P. 1997: Activity pattern of foraging in the wandering albatross: a marine predator with two modes of prey searching. *Marine Ecology Progress Series 151*: 245–254.

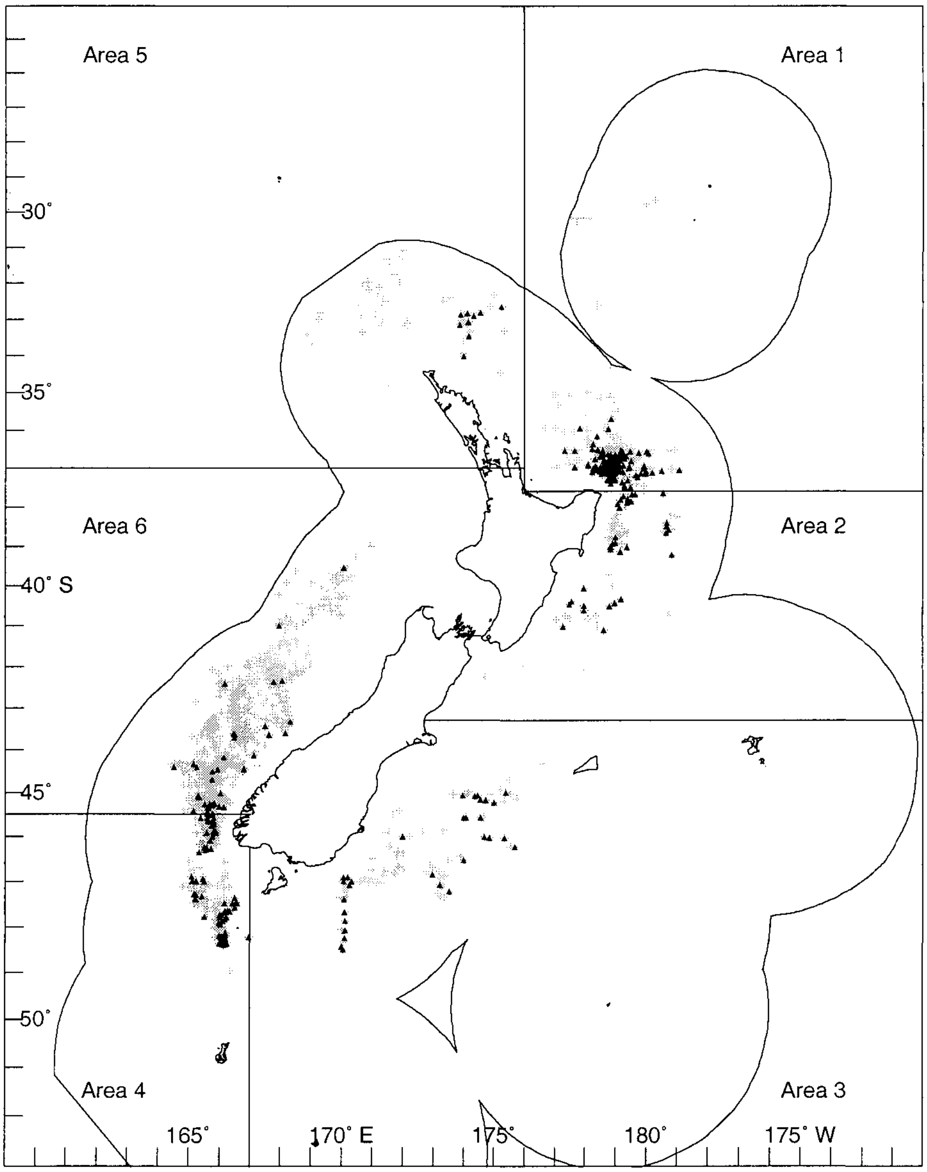


Figure 1: **Start positions of observed Japanese sets (+), including those with bird bycatch (▲), for fishing years 1986–87 to 1997–98.**

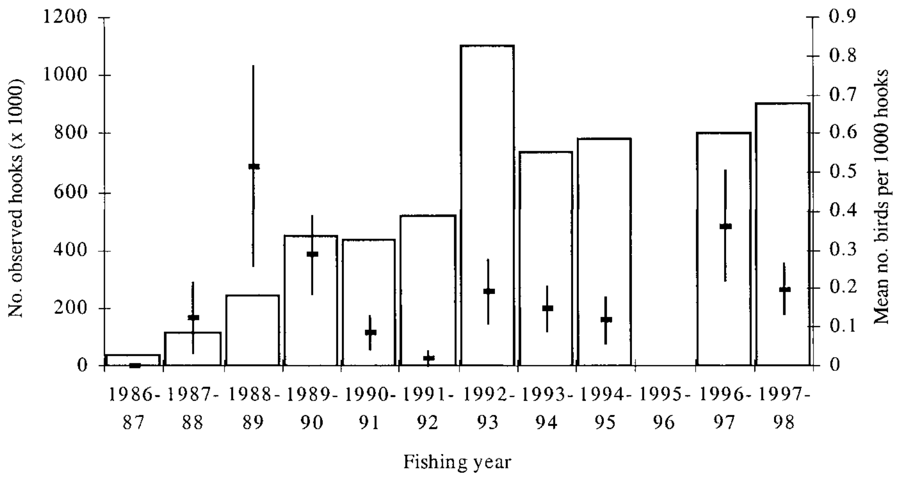


Figure 2: **Number of observed Japanese hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) by fishing year.**

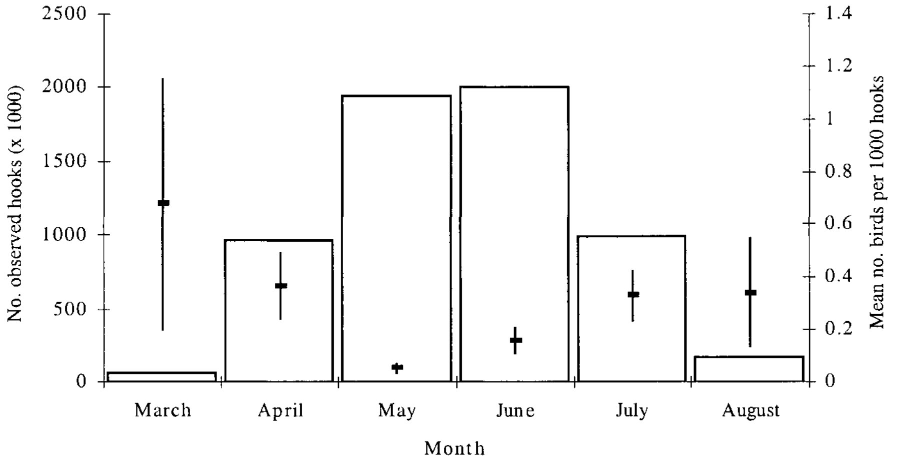


Figure 3: **Number of observed Japanese hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) by month, for 1986–87 to 1997–98.**

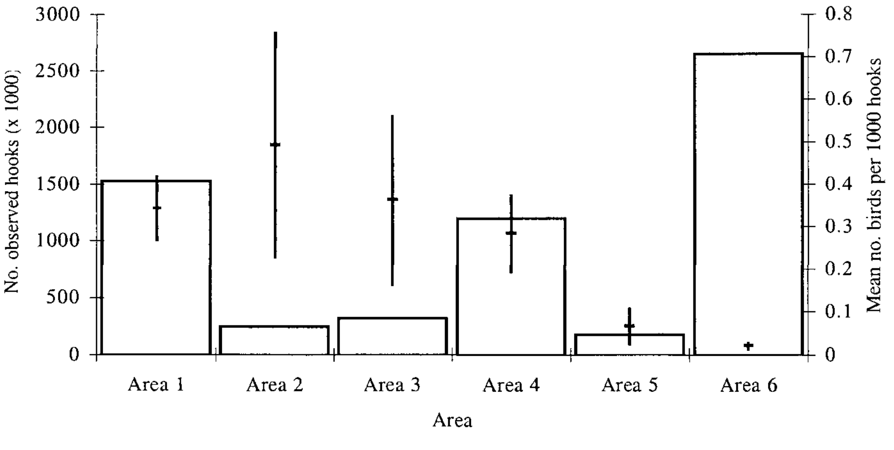


Figure 4: **Number of observed Japanese hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) by area, for 1986–87 to 1997–98.**

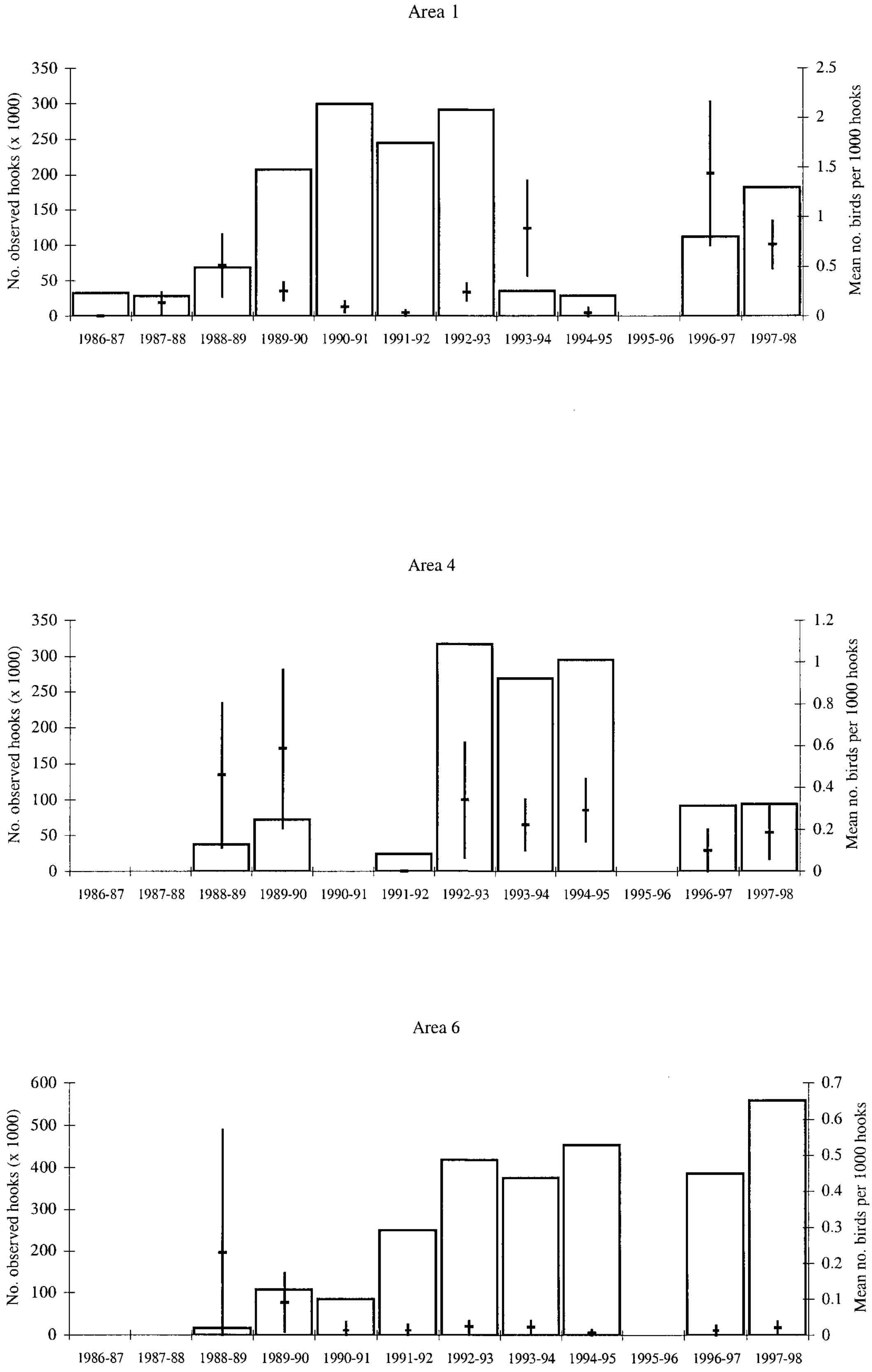


***Figure 5*: Number of observed hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) for Japanese vessels fishing in Area 1, Area 4, and Area 6, by fishing year.**

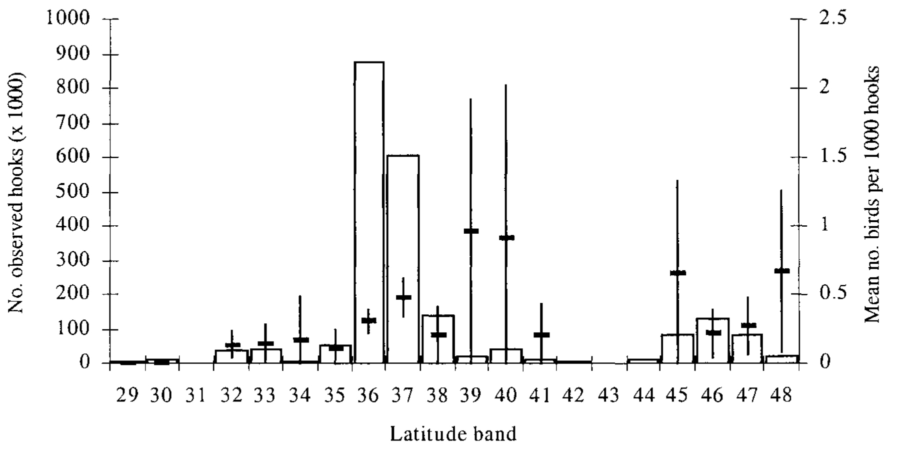


Figure 6: **Number of observed hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) for observed Japanese longlines, by latitude band (° S) for east coast sets.**

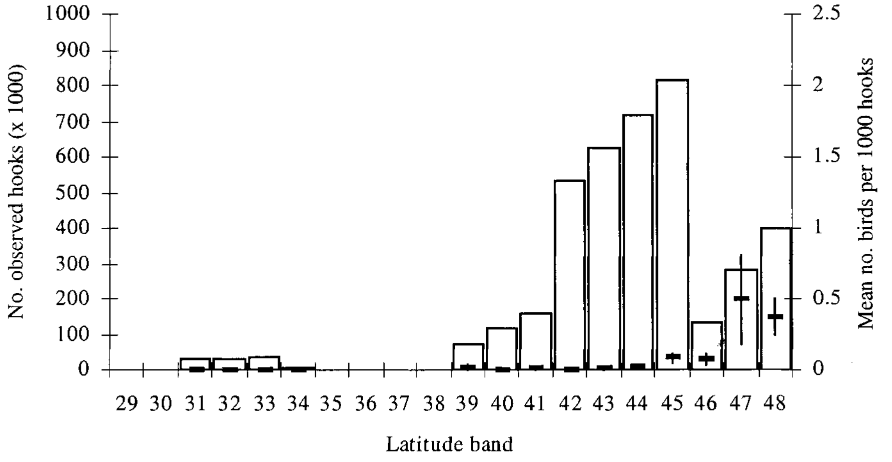


Figure 7: **Number of observed hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) for observed Japanese longlines, by latitude band (° S) for west coast sets.**

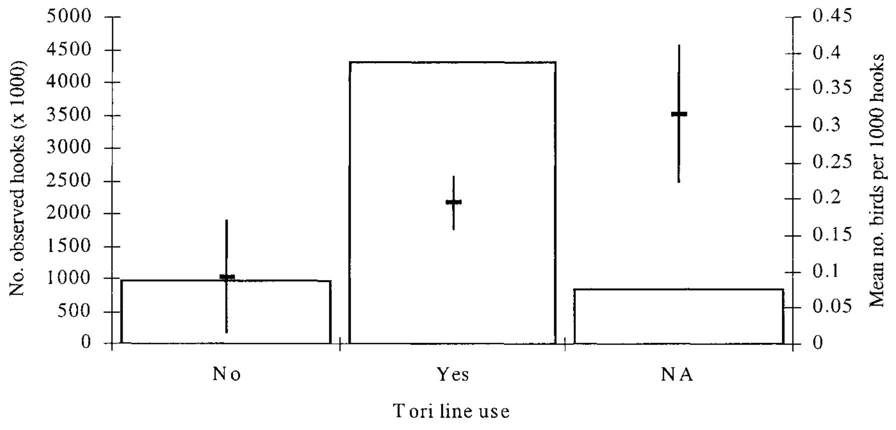


Figure 8: **Number of observed Japanese hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) for all years combined, by tori pole use (NA means no record was made).**

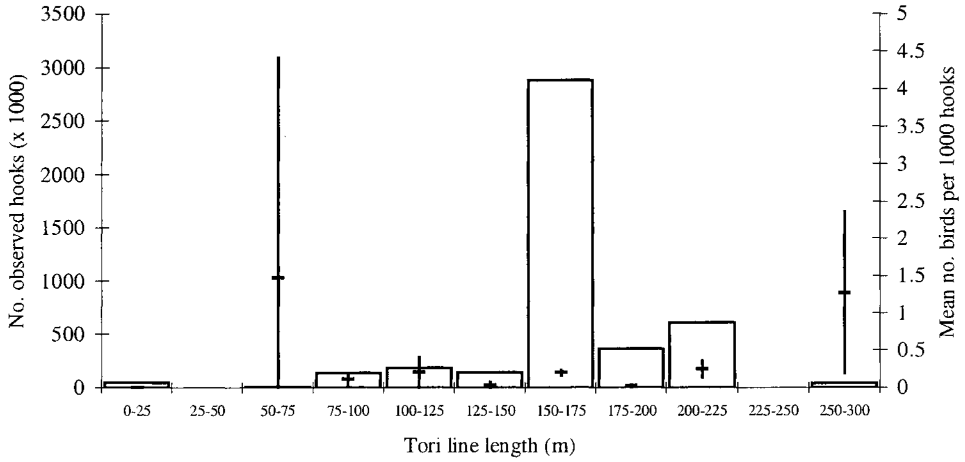


Figure 9: **Number of observed Japanese hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) by tori line length.**

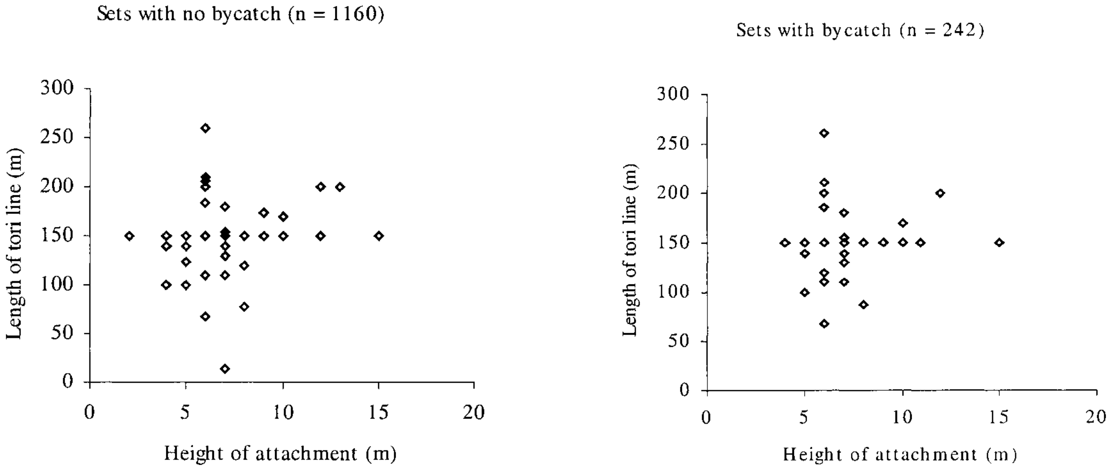


Figure 10: **Relationship between tori line length and the height of attachment above sea level for observed Japanese vessels.**

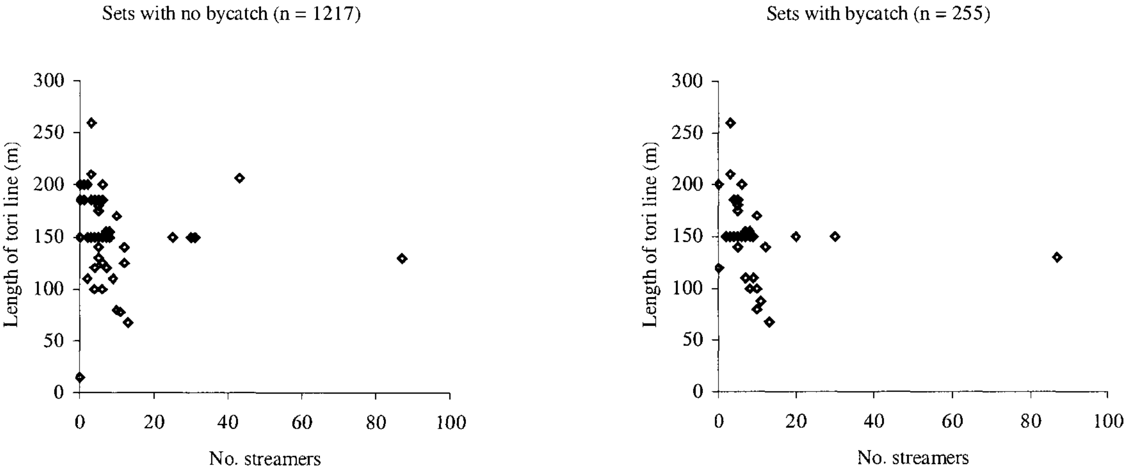


Figure 11: **Relationship between tori line length and number of streamers for observed Japanese sets.**

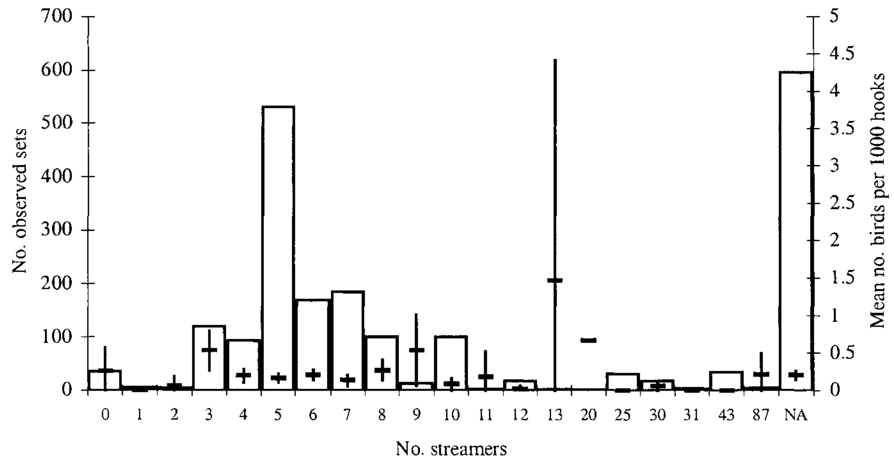


Figure 12: **Number of observed sets (histogram) and mean bird bycatch rates (± 2 *s.e.*) for observed Japanese sets by number of streamers on the tori line (*n* = 1438).**

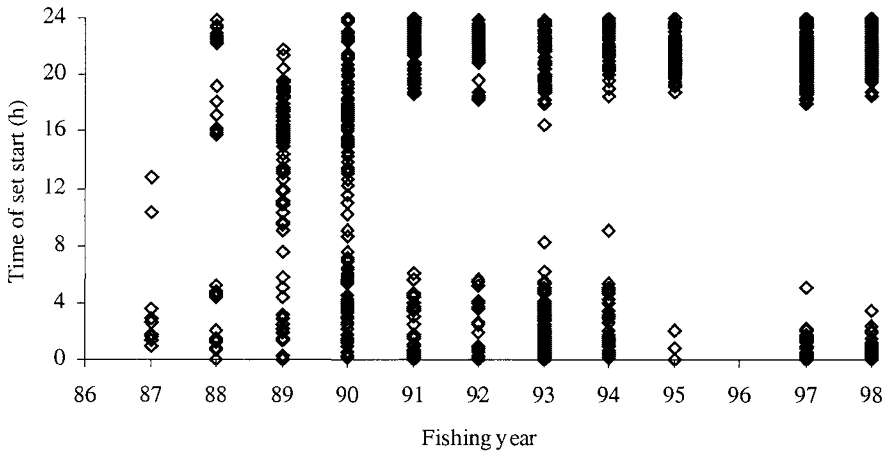


Figure 13: **Start times of observed Japanese sets, 1986–87 to 1997–98.**

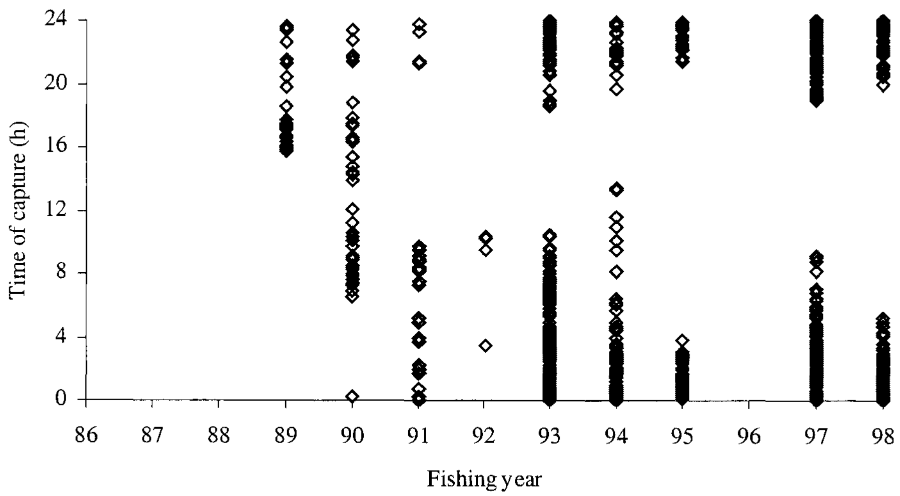


Figure 14: **Time of capture of dead birds (*n* = 925) caught on observed Japanese sets, by fishing year.**

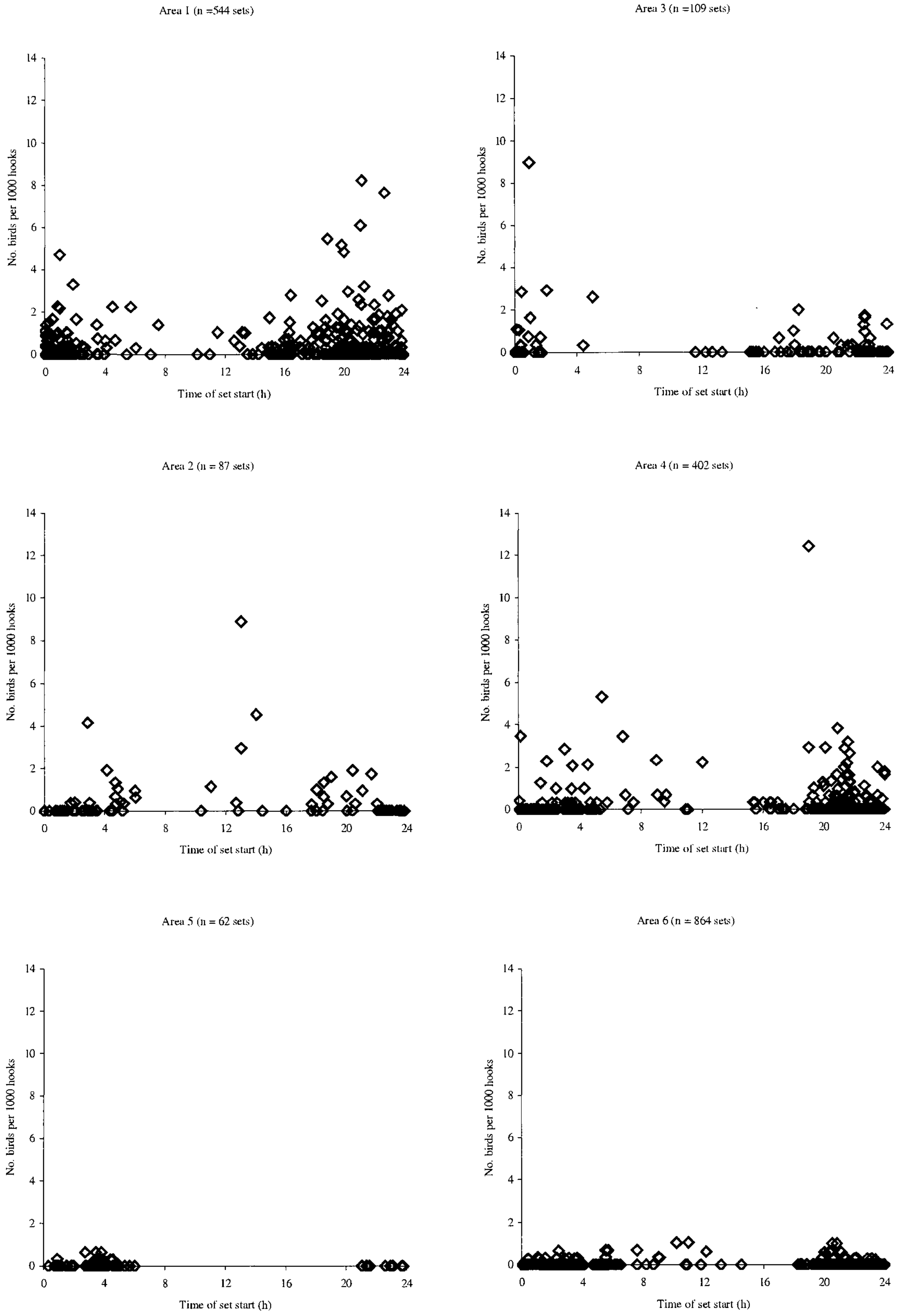


Figure 15: **Number of birds per 1000 hooks for set start times for observed Japanese sets, by Areas 1–6, 1986–87 to 1997–98.**

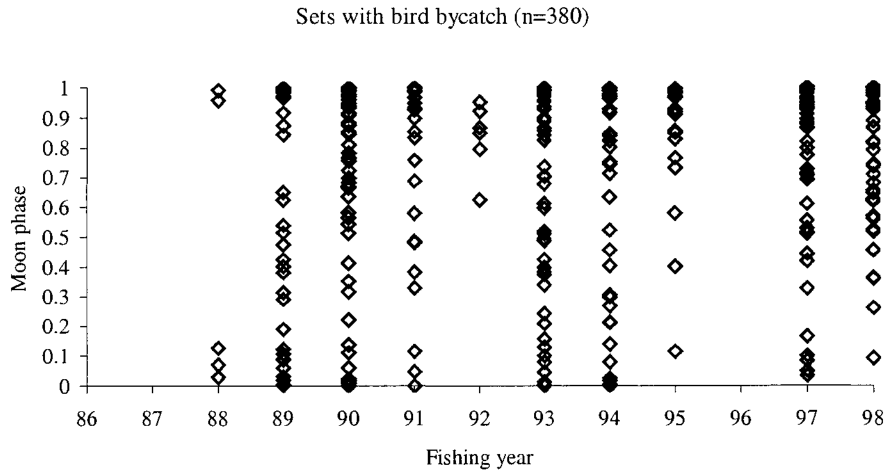


***Figure 16*: Moon phases for observed Japanese sets, by fishing year.**

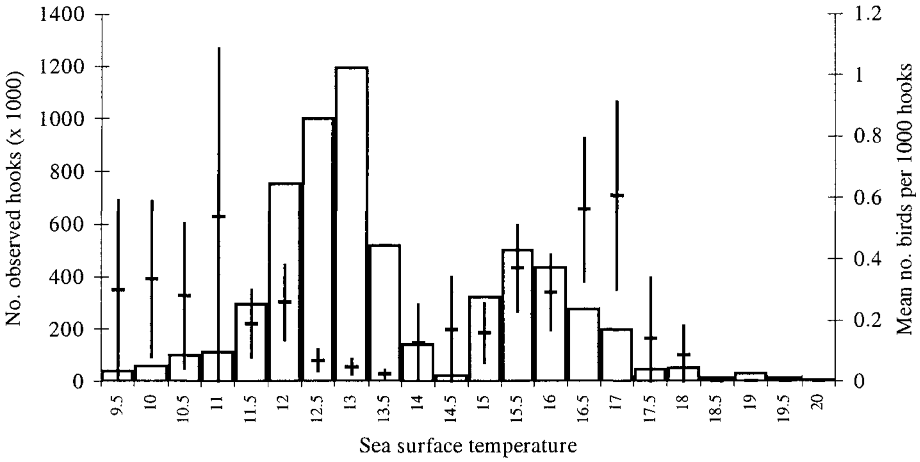


***Figure 17*:Number of observed Japanese hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) by sea surface temperature (°C).**

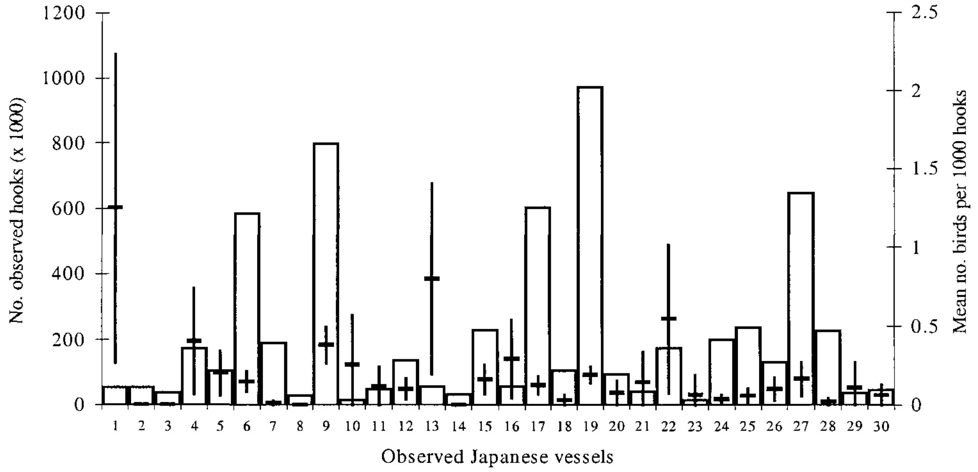


***Figure 18*: Number of observed hooks (histogram) and mean bird bycatch rates (± 2 *s.e.*) for individual observed Japanese vessels, 1986–87 to 1997–98.**

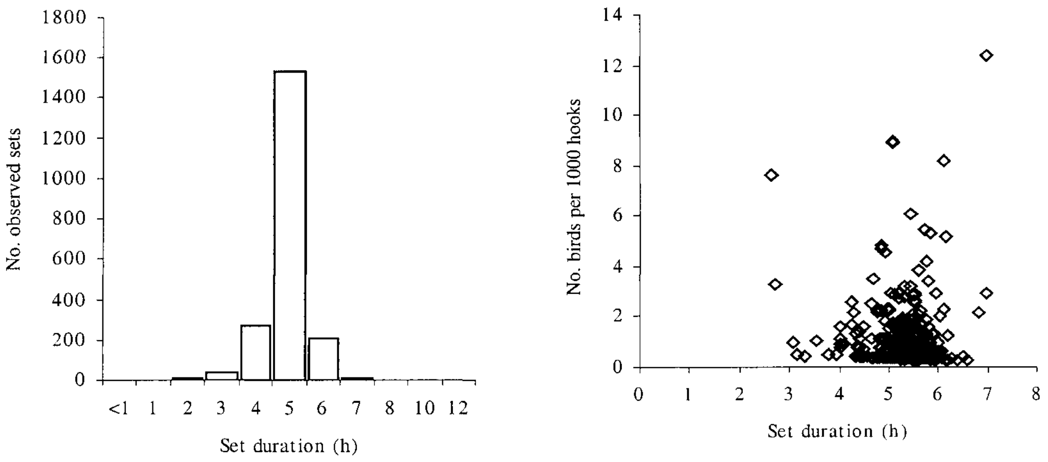


Figure 19: **Distribution of observed Japanese sets (*n* = 2068) and number of birds per 1000 hooks for those sets with bycatch (*n* = 380), by set duration.**

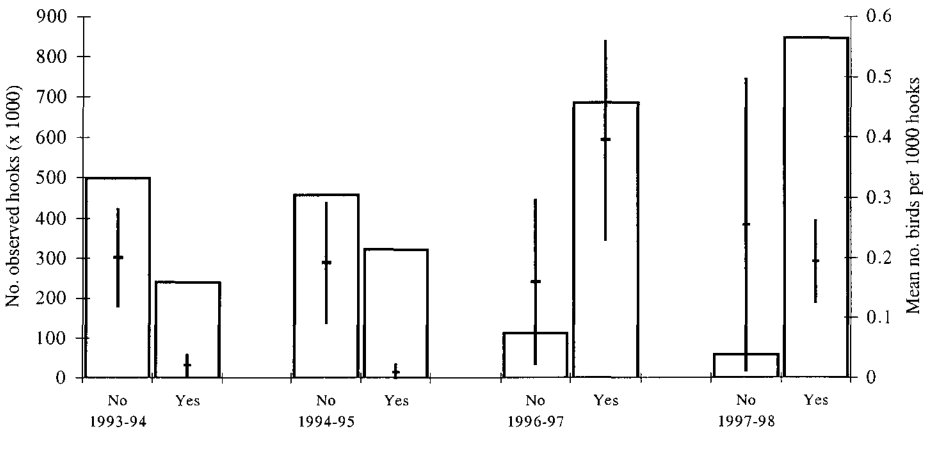


Figure 20: **Number of observed Japanese hooks (histogram) and mean bycatch rates (± 2 *s.e.*), by use of bait casting machines, 1993–94 to 1997–98.**

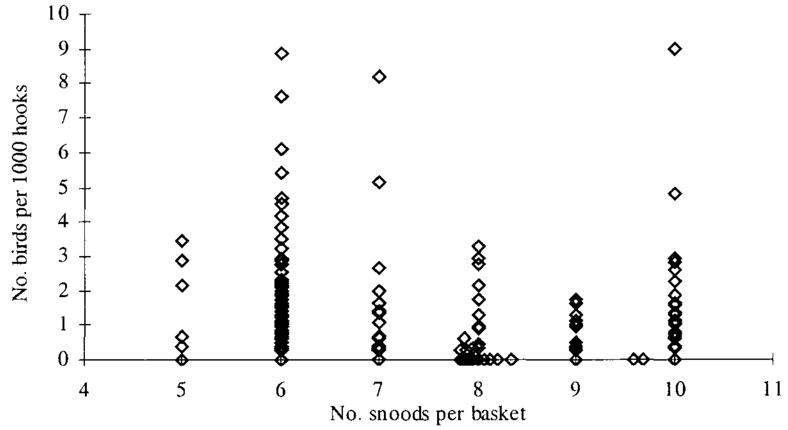


Figure 21: **Number of birds per 1000 hooks for mean number of snoods used per basket on observed Japanese longlines.**

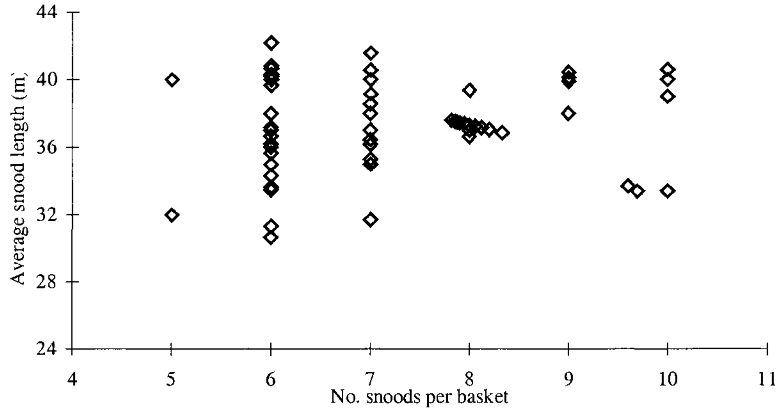


Figure 22: **Average snood lengths used for the number of snoods used per basket on observed Japanese longlines.**

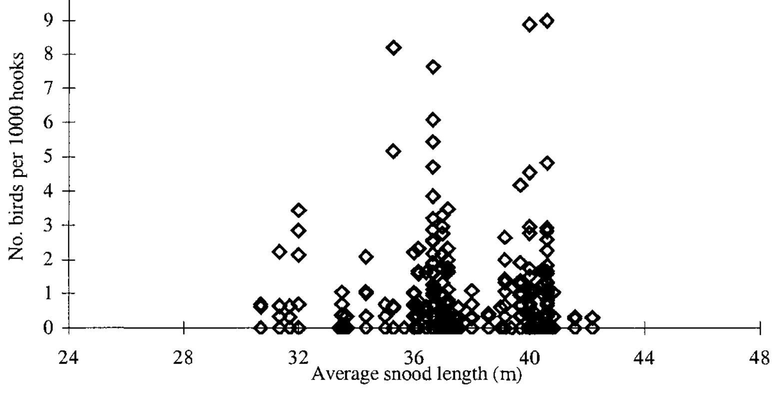


Figure 23: **Number of birds per 1000 hooks for average snood lengths used on observed Japanese longlines.**

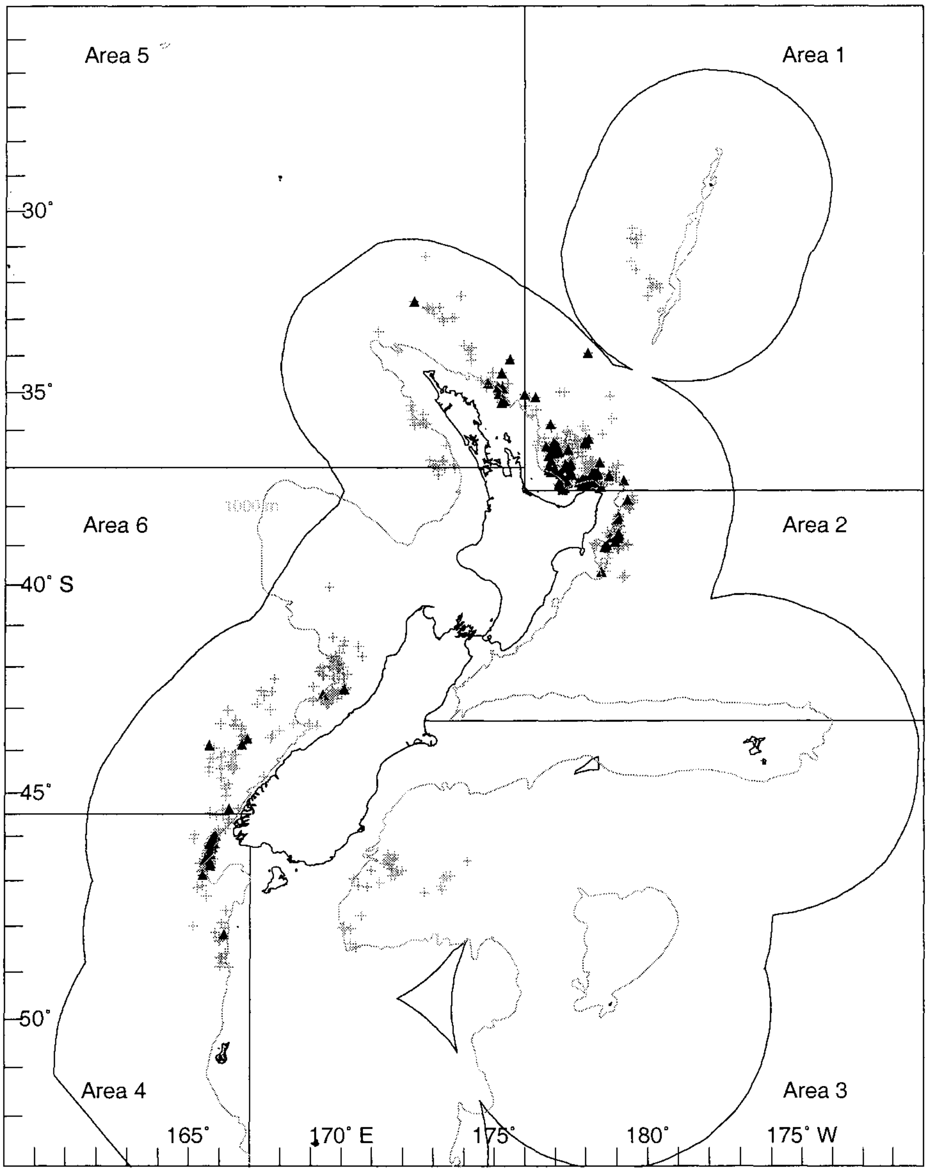


Figure 24: **Start positions of observed domestic sets (+), including those which caught birds (▲), by Areas 1–6, 1991–92 to 1997–98.**

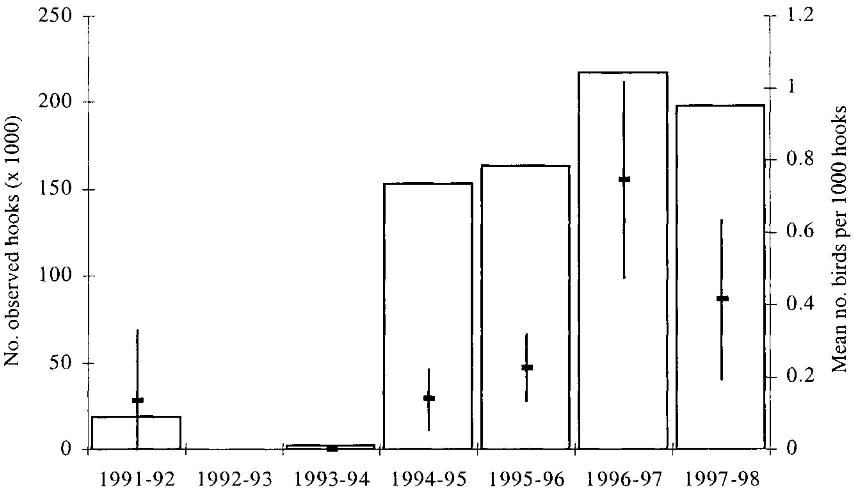


***Figure 25*: Number of observed domestic hooks (histogram) and mean bird bycatch rate (± 2 *s.e.*), by fishing year.**

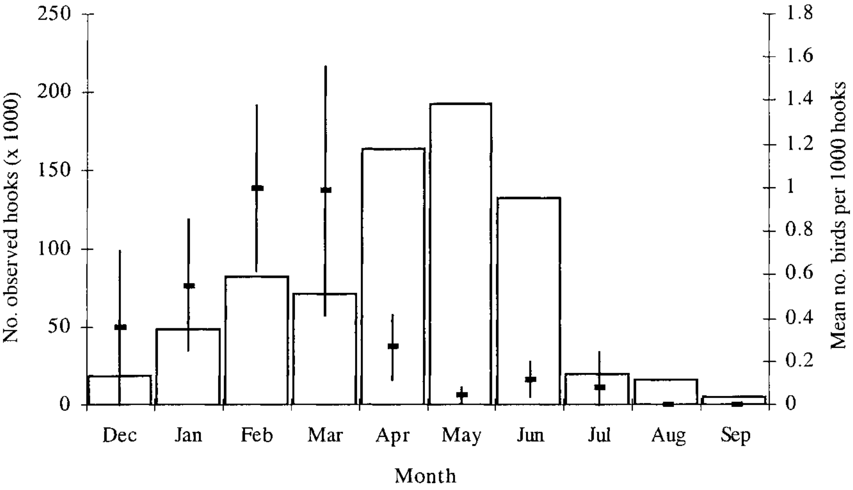


***Figure 26*: Number of observed domestic hooks (histogram) and bird bycatch rate (± 2 *s.e.*), by month for 1991–92 to 1997–98.**

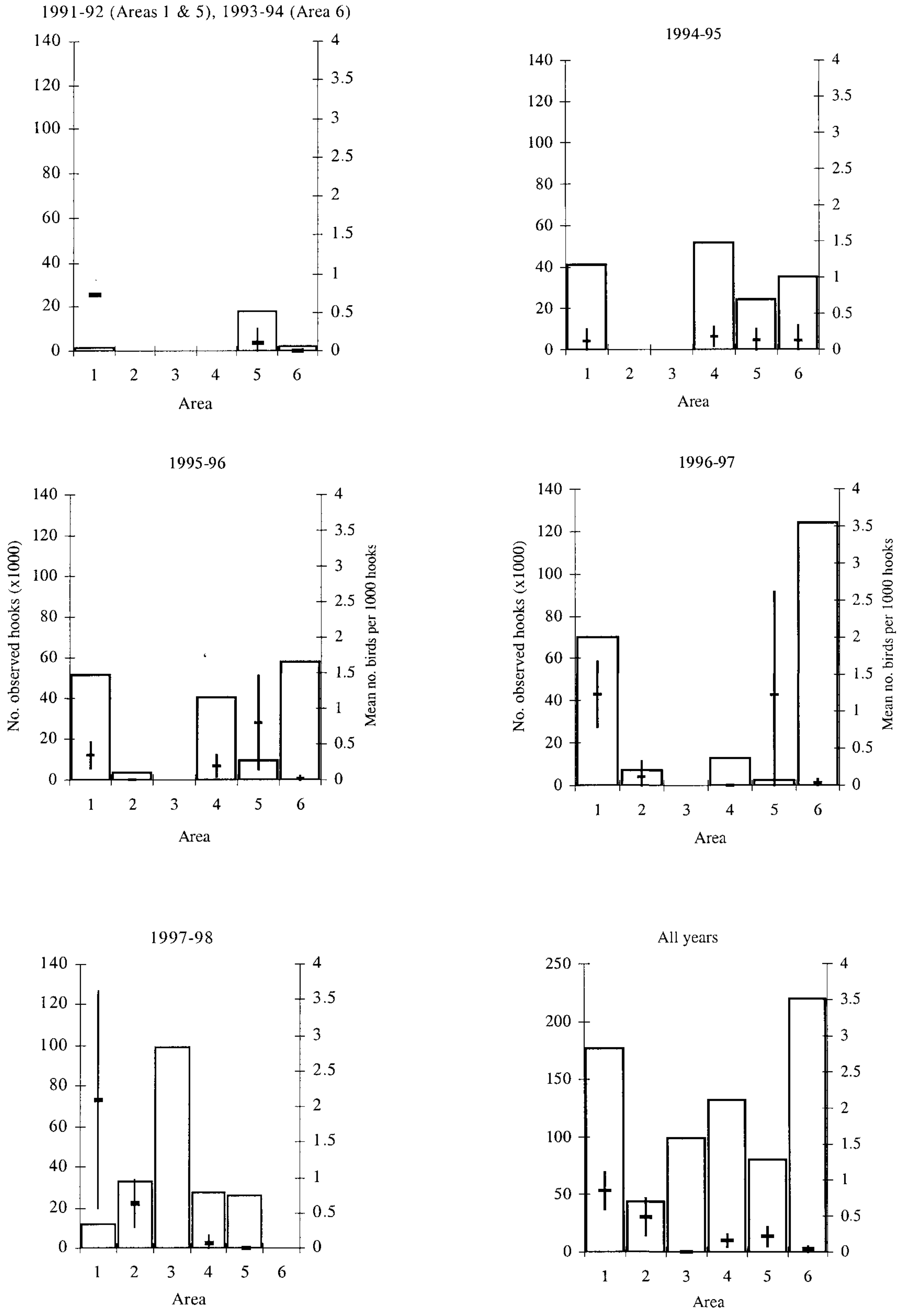


Figure 27: **Number of observed domestic hooks (histogram) and mean bird bycatch rate (± 2 *s.e.*), by Areas 1–6 for fishing years 1991–92 to 1997–98.**

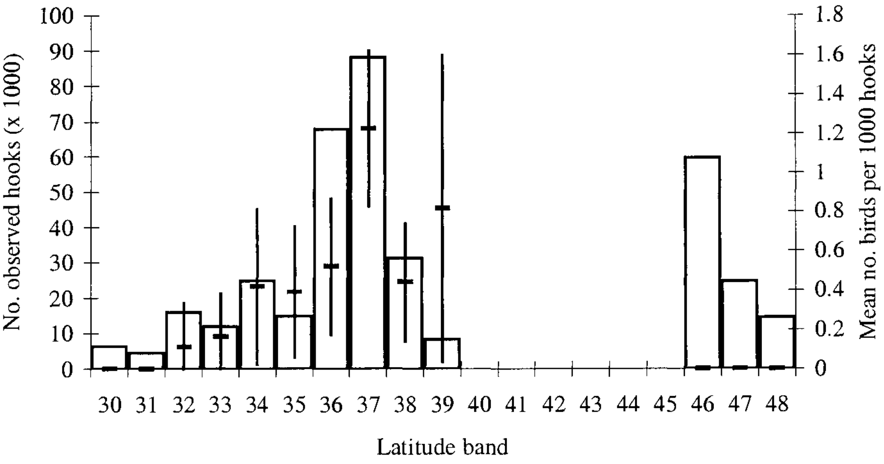


Figure 28: **Number of observed domestic hooks (histogram) and mean bird bycatch rate (± 2 *s.e.*), by 1° latitude bands, for sets made off the east coast, 1991–92 to 1997–98.**

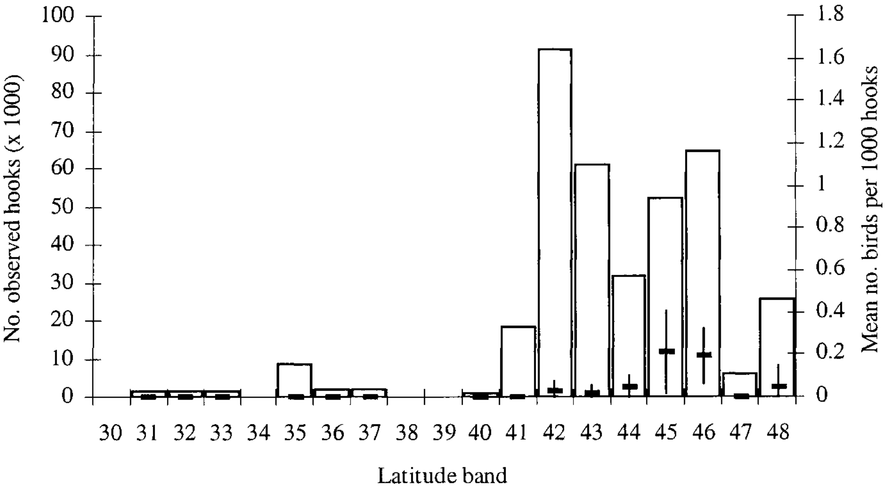


Figure 29: **Number of observed domestic hooks (histogram) and mean bird bycatch rate (± 2 *s.e.*), by 1° latitude bands, for sets made off the west coast, 1991–92 to 1997–98.**

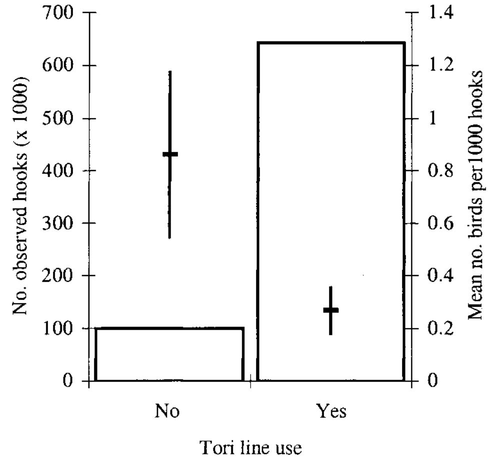


Figure 30: **Number of observed domestic hooks (histogram) and mean bird bycatch rate (± 2 *s.e.*), for tori line use (note: there was 1 set of 1380 hooks for which there was no record of tori line use).**

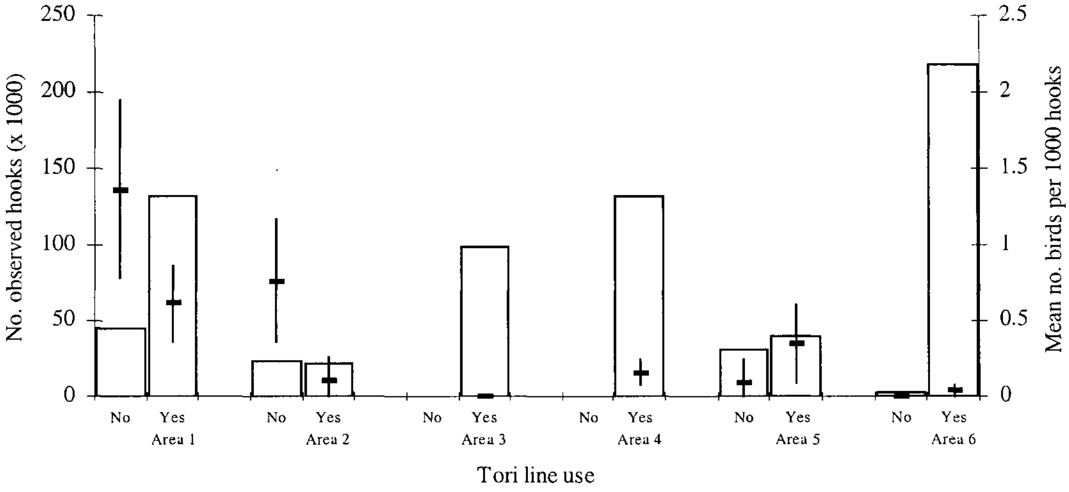


***Figure 31*:** **Number of observed domestic hooks (histogram) and mean bird bycatch rate (± 2 *s.e.*) for tori line use, by area, for 1991–92 to 1997–98.**

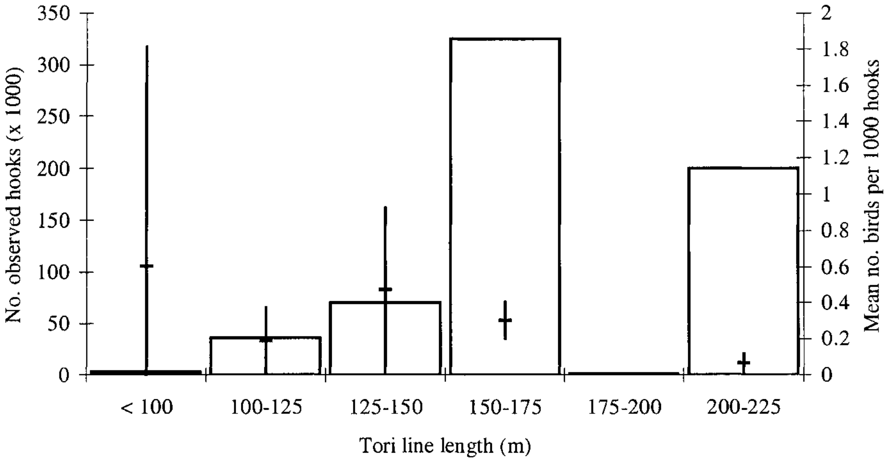
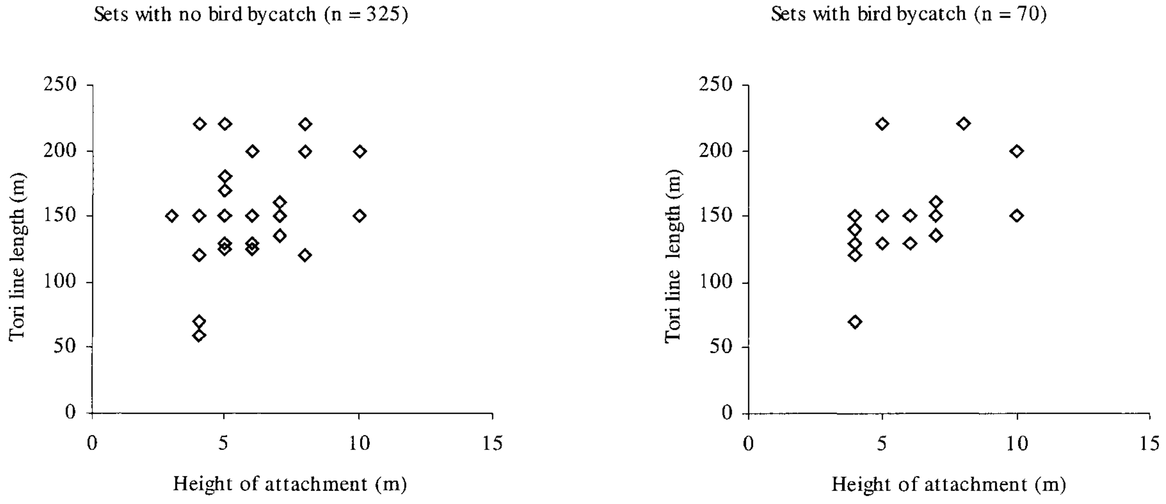


***Figure 32*:** **Number of observed hooks (histogram) and mean bird bycatch rate (± 2 *s.e.*) for tori line lengths of domestic vessels.**


Sets with no bird bycatch (n = 325)

Sets with bird bycatch (n = 70)

***Figure 33*:** **Relationship between tori line length and the height of attachment above sea level for observed domestic vessels.**

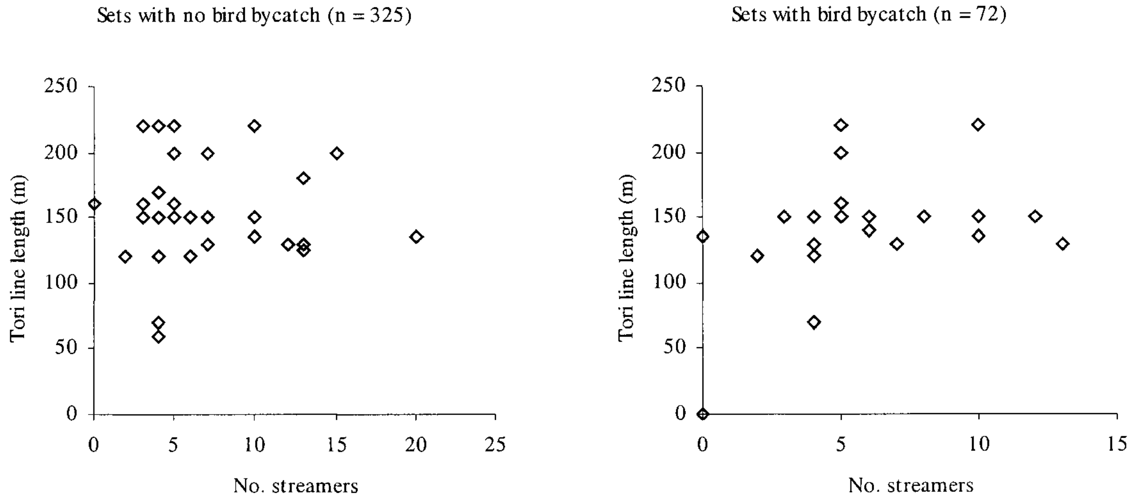


Figure 34: **Relationship between tori line length and number of streamers for observed domestic sets.**

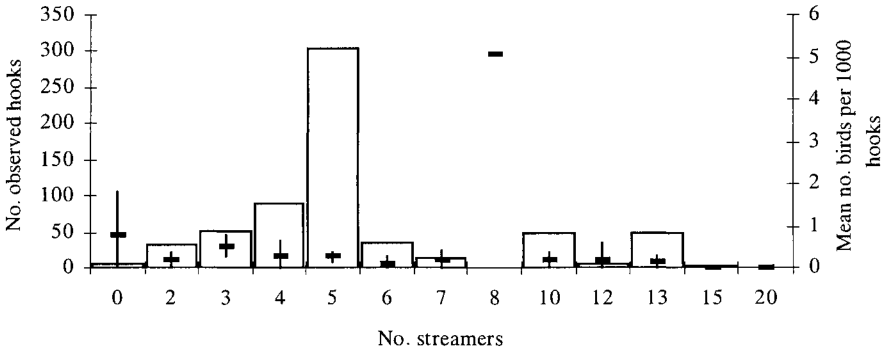


Figure 35: **Number of observed sets (histogram) and mean bird bycatch rate (± 2 *s.e.*) for observed domestic sets by number of streamers (n = 396).**

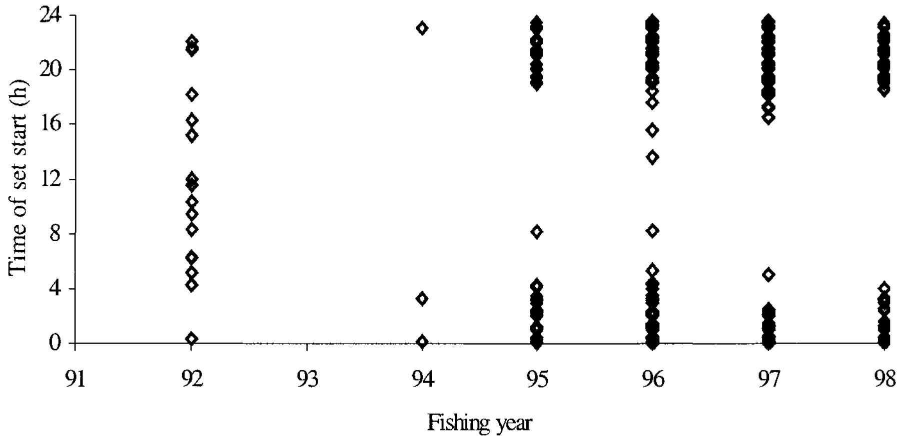


Figure 36: **Start times of observed domestic sets, 1991–92 to 1997–98.**

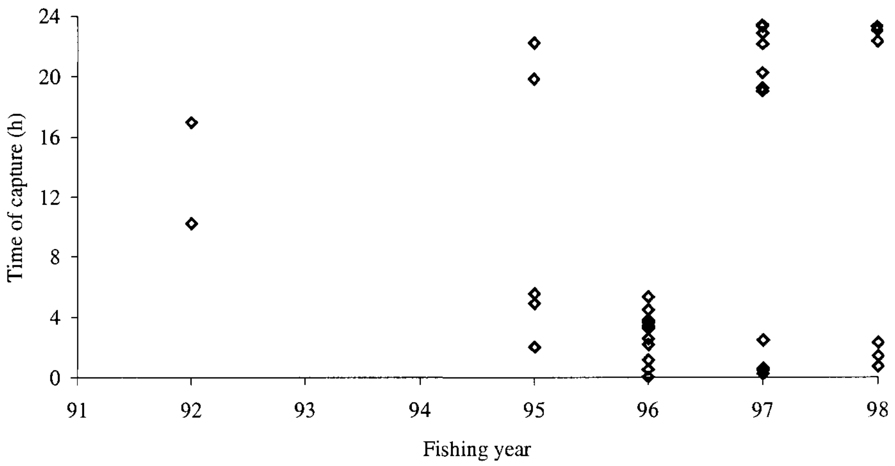


***Figure 37*: Time of capture of dead birds (*n* = 38) caught on observed domestic sets, 1991–92 to 1997–98.**

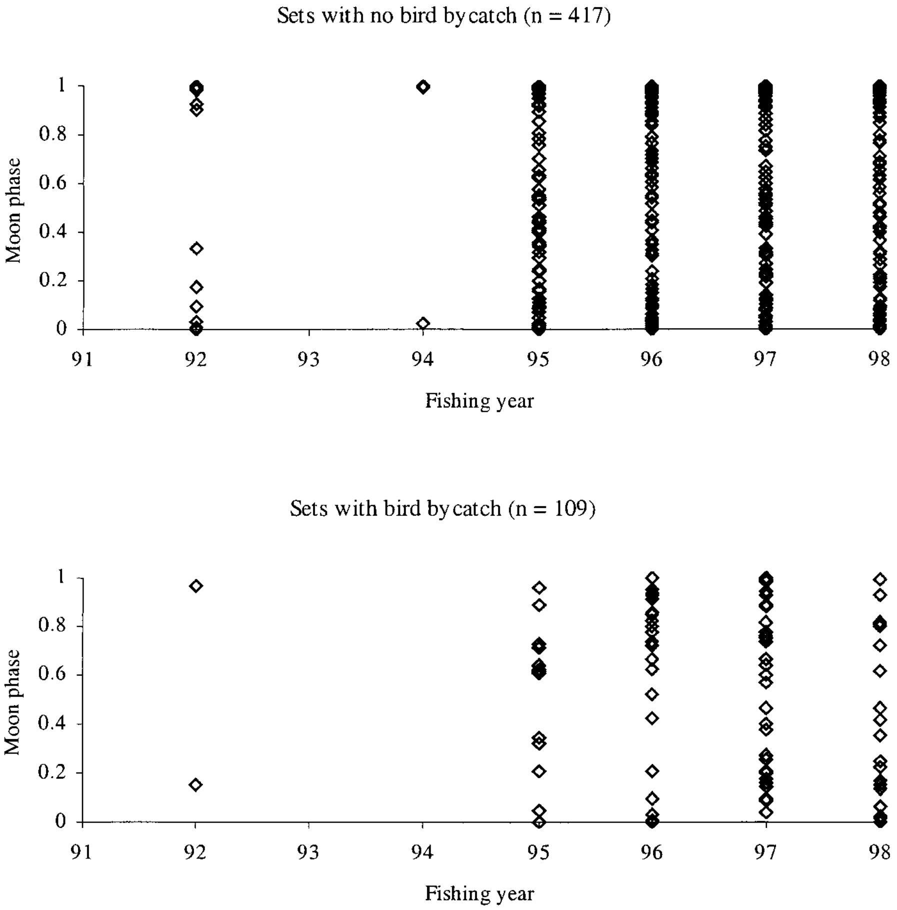


***Figure 38*: Moon phases for observed domestic sets, by fishing year.**

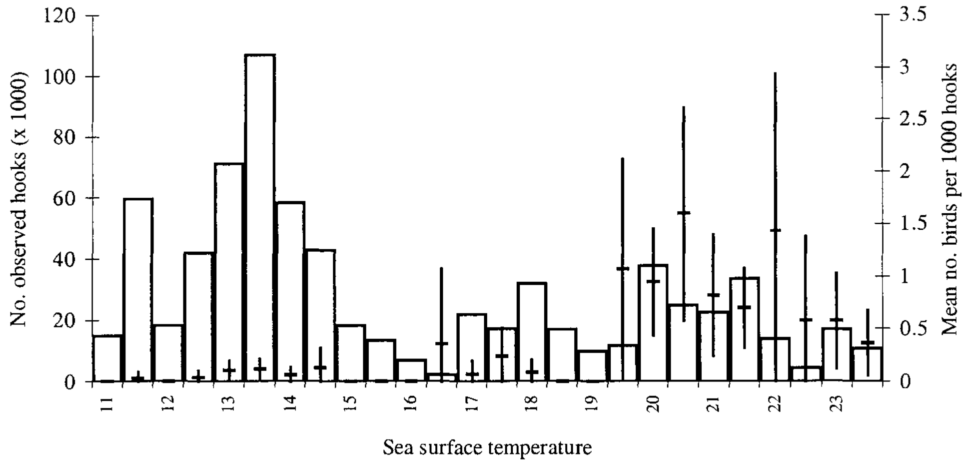


Figure 39: **Number of observed domestic hooks (histogram) and mean bird bycatch rate (±2 *s.e.*) by sea surface temperature.**

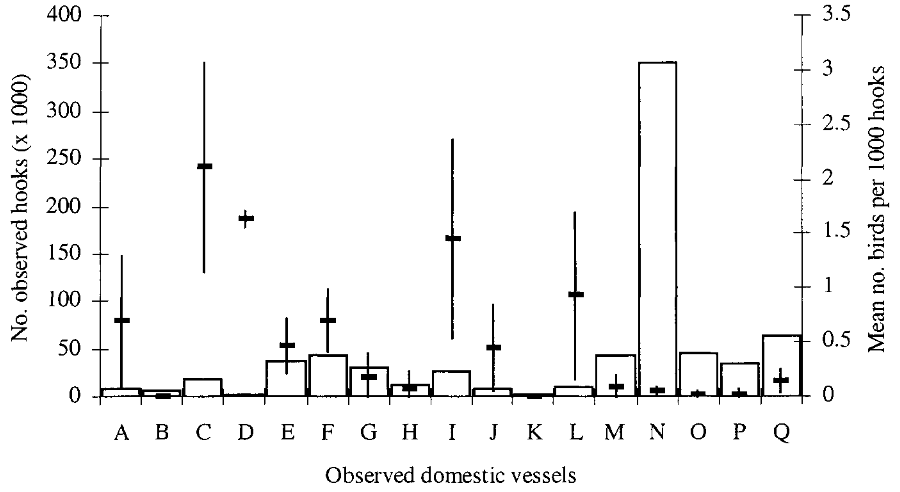


Figure 40: **Number of observed hooks (histogram) and mean bird bycatch rate (± 2 *s.e.*) for individual observed domestic vessels, 1991–92 to 1997–98.**

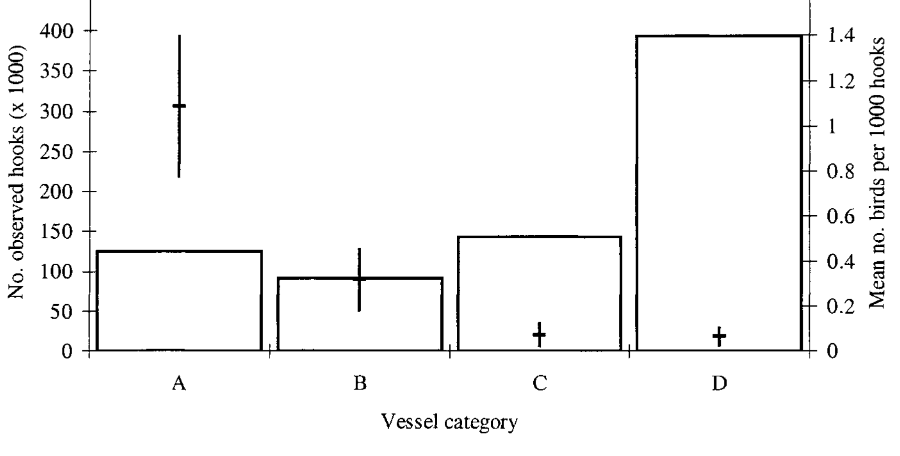


Figure 41: **Number of observed hooks (histogram) and mean bird bycatch rate (± 2 *s.e.*) for domestic vessel categories (*see* Table 4).**

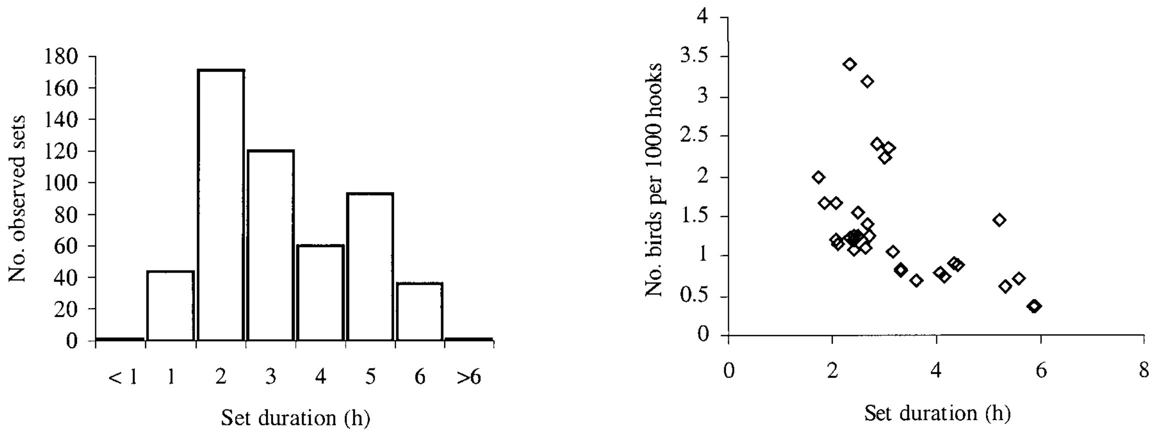


Figure 42: **Distribution of observed domestic sets (*n* = 526) and the number of birds per 1000 hooks for those sets which caught dead birds (*n* = 32), by set duration.**

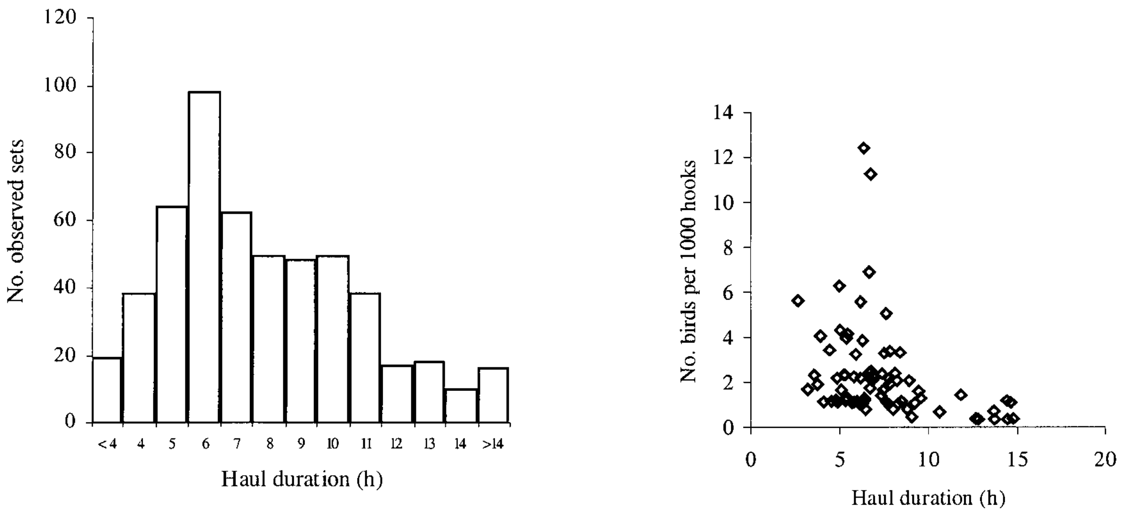


Figure 43: **Distribution of observed domestic sets (*n* = 526) and the number of birds per 1000 hooks for those sets for which birds were caught and released alive (*n* = 79), by haul duration.**

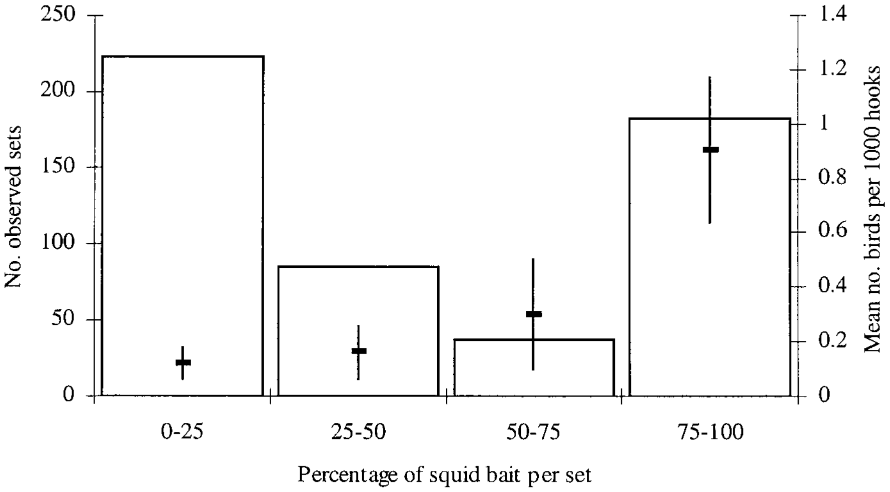


Figure 44: **Number of observed sets (histogram) and mean bird bycatch rate (± 2 *s.e.*) by bait type, for observed domestic vessels.**

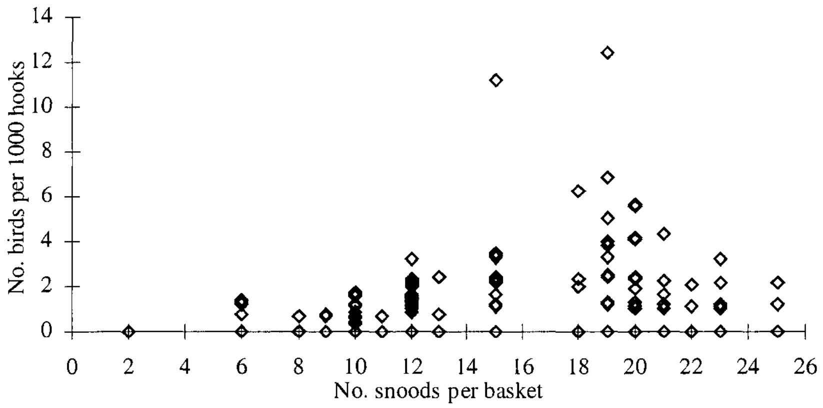


Figure 45: **Number of birds per 1000 hooks for mean number of snoods used per basket on observed domestic longlines.**

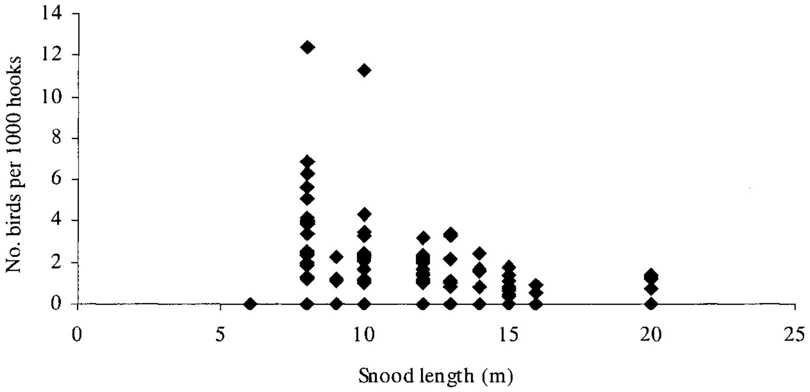


Figure 46: **Number of birds per 1000 hooks for snood lengths used on observed domestic longlines.**

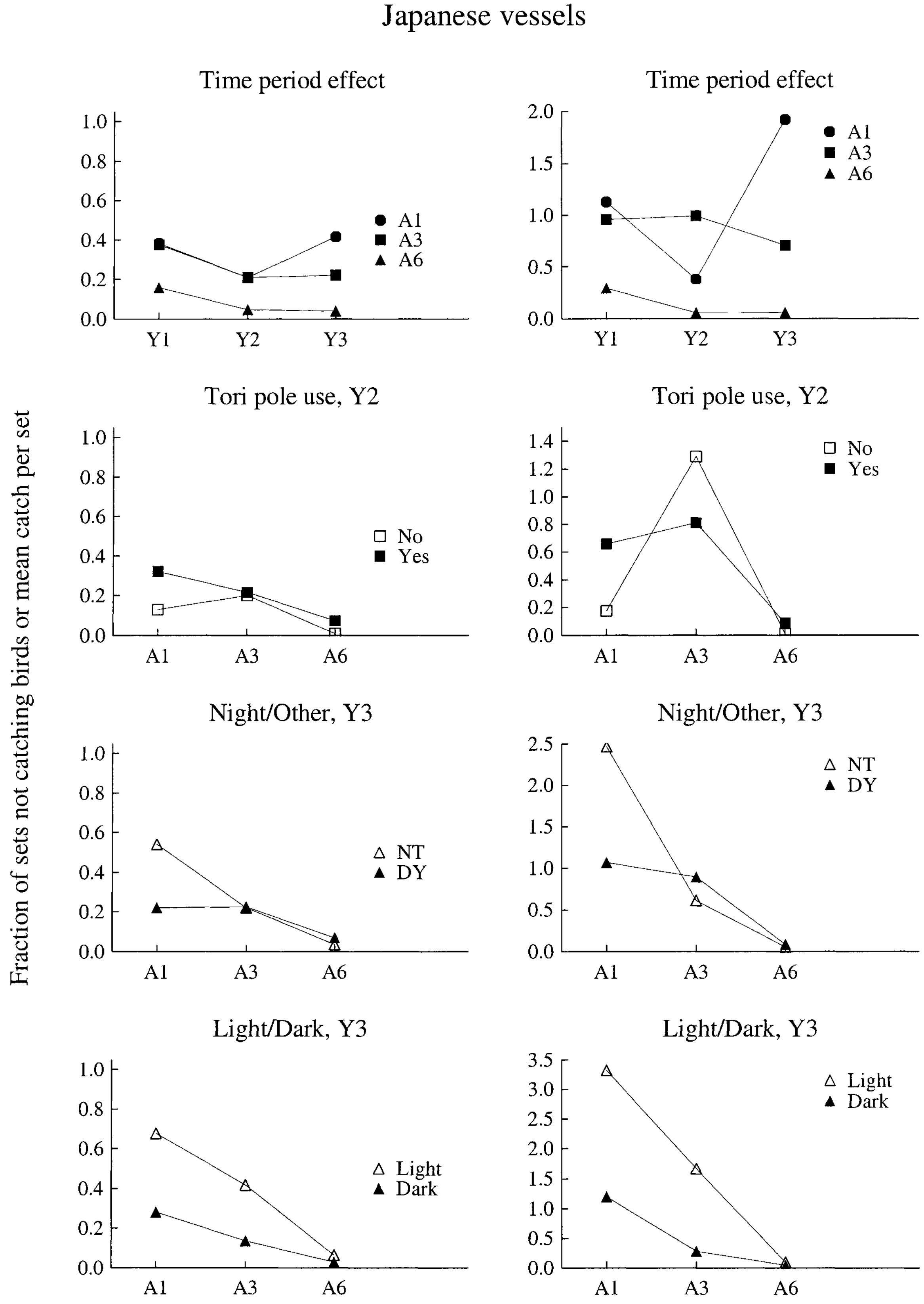


***Figure 47*: Fraction of sets catching birds, 1–p_0 (left column) and the mean bird catch per set (right column). Results are given for each time period *Y1*, *Y2*, and *Y3* or each area *A1*, *A2*, and *A6*, under the conditions indicated on the plot.**

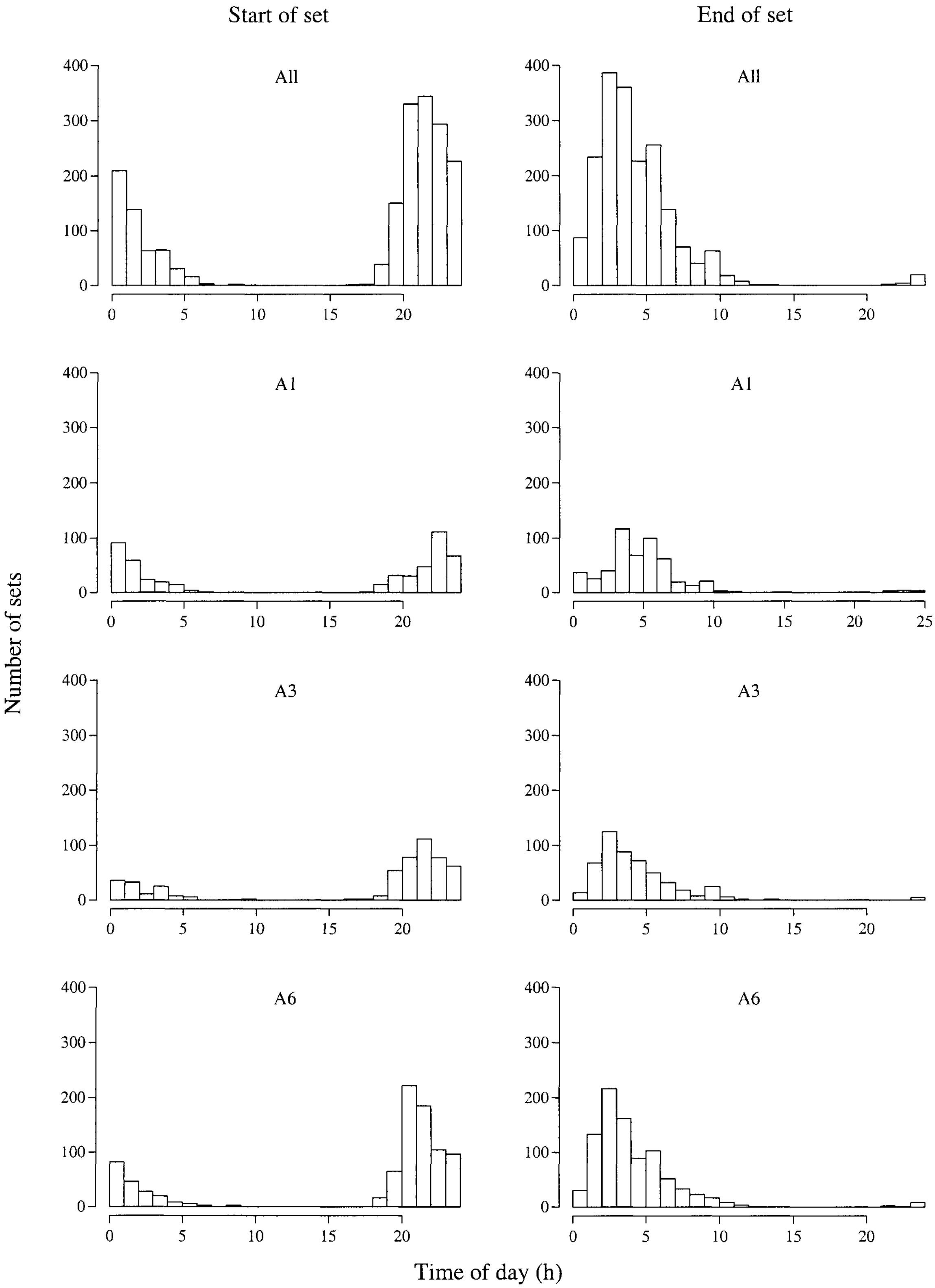


***Figure 48*: Start and finish times of sets made by Japanese vessels.**

Appendix 1: Generalised linear models for count data

These notes have been compiled using material in Venables & Ripley (1994), McCullagh & Nelder (1989), Johnston *et al.* (1992), and Chambers & Hastie (1992).

Mathematical outline

A generalised linear model may be described by the following assumptions.

- There is a response, y, observed independently at fixed values of stimulus variables $x_1, ..., x_p$.
- The stimulus variables may influence the distribution of y only through a single linear function called the *linear predictor* $\eta = \beta_1 x_1 + \ldots + \beta_p x_p$.
- The distribution of y has density of the form $f(y_i; \theta_i, \varphi) = \exp[A_i\{y_i\theta_i - \gamma(\theta_i)\}/\varphi + \tau(y_i\varphi/A_i)]$, where φ is a *scale parameter* (possibly known), A_i is a known prior weight, and the parameter θ_i controls the distribution of y_i. γ is the cumulant function.
- The mean, μ, is a smooth invertible function of the linear predictor: $\mu = m(\eta)$, $\eta = m^{-1}(\mu) = \ell(\mu)$. The inverse function, $\ell(.)$, is called the *link function.* θ is also an invertible function of μ.

Poisson

For a Poission distribution of a discrete random variable Y with mean μ we have, $\log f(y) = y \log \mu - \mu - \log(y!)$ so $\theta = \log \mu$, $\varphi = 1$, and $\gamma(\theta) = \mu = e^{\theta}$. The variance function, $V(\mu) = \mu$. The usual link function is log. The range of y is $0, 1, \ldots, \infty$.

Binomial

For a binomial distribution with a fixed number of trials n and parameter p we take the response to be $y = x/n$ where n is the number of "successes". The density is

$$\log f(y) = x \log \frac{p}{1-p} + n \log(1-p) + \log\left(\frac{n!}{x!(n-x)!}\right)$$

so we take $A_i = n_i$, $\varphi = 1$, θ to be the logit transform of p, $\theta = \log\big(p/(1-p)\big)$, and

$$\gamma(\theta) = -\log(1-p) = \log(1+e^{\theta}), \quad \mu = e^{\theta}/(1+e^{\theta}), \text{ and } V(\mu) = \mu(1-\mu).$$

The ratio $p/(1-p)$ is called the odds ratio and this is what is estimated in logistic regression (or a generalised linear regression using the binomial distribution with a logit link function). The range of y is $(0, 1, \ldots, n)/n$.

Negative binomial

The negative binomial can arise from a two-stage model for the distribution of a discrete random variable Y. We suppose there is an unobserved random variable E having a gamma distribution $\text{gamma}(\theta)/\theta$, that is, with mean 1 and variance $1/\theta$. Then, conditionally on E, Y is Poisson with mean μE. Thus,

$$Y|E \sim \text{Poisson}(\mu E)\,,\quad \theta E \sim \text{gamma}(\theta)\,.$$

The marginal distribution of Y is then negative binomial with mean, variance, and probability function given by

$$E(Y) = \mu\,,\qquad V(\mu) = \mu + \mu^2/\theta\,,\qquad f_Y(y;\theta,\mu) = \frac{\Gamma(\theta+y)\mu^y\theta^\theta}{\Gamma(\theta)y!(\mu+\theta)^{\theta+y}}\,.$$

If we assume $\theta = k\mu$ where k is a positive constant, then $V(\mu) = (1+1/k)\mu$. In all cases, the variance is greater than the mean. The range of y is $0,1,\ldots,\infty$.

There are several equivalent ways of expressing the probability function associated with the negative binomial distribution. It should be apparent from the expression above that there could be estimation problems when using the negative binomial distribution and the parameter θ has to be estimated from the data.

What is loosely called "overdispersed Poisson data" has variance greater than the mean and if this is the case, the negative binomial distribution may be appropriate.

Dispersion

The dispersion is defined to be 1 for the binomial and Poisson distributions. For many data sets this is not so. An estimate of the dispersion is calculated as the sum-of-squares of the Pearson residuals divided by the degrees of freedom. The Pearson residuals are defined by

$$r_i^P = \frac{y_i - \hat{\mu}_i}{\sqrt{V(\hat{\mu}_i)}}$$

and their sum-of-squares

$$X^2 = \sum_{i=1}^{n} \frac{(y_i - \hat{\mu}_i)^2}{V(\hat{\mu}_i)}$$

is the chi-squared statistic. Thus the dispersion is X^2/ν where ν is the degrees of freedom.