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Use of charter boat data to infer the annual availability of black marlin, *Makaira indica*, to the recreational fishery off Cairns, Australia

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Abstract. Catch data, recorded in daily diaries kept by the captains of charter boats in the recreational fishery that targets black marlin (*Makaira indica*) in the Cairns/Lizard Island region off north-eastern Australia, were used to calculate annual indices of fishing success (catch per day). Generalized Linear Models were used to investigate factors likely to influence catch rates, such as captain, area fished, water temperature, moon phase and the strength and direction of prevailing currents. Despite a high degree of inter-annual variability in the catch, results indicate that there has been a long-term decline of between 20–30% in estimated availability between 1970 and 1997. Models fitted to the data for the period 1987–1996 indicate that several environmental factors can have a significant influence on availability in any given year, with higher catch rates occurring close to a half moon and associated with water temperatures around 26.0–26.5°C. Catch rates for the period 1980–1997 were also found to be negatively correlated with longline effort levels within the inshore region close to the recreational fishery, though this correlation was not found to be significant.

Extra keywords: game fishery, longliner, recreational catch rates.

Introduction

The recreational fishery that targets black marlin (*Makaira indica*) in the Cairns/Lizard Island region off north-eastern Australia (hereafter referred to as 'the Cairns region') is world renowned, with many world record-breaking fish having been caught there (Goadby 1998; IGFA 2001). Game fishers from around the world are lured to the region, not only in the hope of hooking a 'thousand pounder' (large females associated with the spawning and pre-spawning aggregations that occur during the spring months), but because of the high strike rates obtained. In response to the potential for capturing giant black marlin in these waters (the first black marlin weighing more than 1000 lb (455 kg) was caught off Cairns in 1966) a 'fleet' of charter boats was developed in Cairns in the late 1960s and early 1970s. Due to the marked seasonal nature of the fishery (September–December) the size of the charter fleet has varied over time, but is believed to average about 20–30 boats in any season.

The potential to catch black marlin in the Cairns region was first realized when Japanese longliners began fishing in the Coral Sea region in the early 1950s. From October to December, black marlin, by weight, comprised more than half the catch (Williams *et al.*1993). Following the declaration of the Australian Fishing Zone (AFZ) in 1979, a number of restrictions were placed on the operations of Japanese longliners fishing off eastern Australia. Although many of these restrictions were intended to reduce interaction with the expanding domestic tuna longline fishery, the restrictions off northern Queensland were specifically directed at reducing the perceived negative impact of the Japanese fishery on the recreational fishery for black marlin in this region. In particular, two large areas were permanently closed to Japanese vessels in 1980 and 1990 (Fig. 1). The combined closed areas total approximately 172 000 square kilometres and are now known as Area E. Since 1986, Japanese longliners fishing within the AFZ also agreed to a voluntary code to release all black or blue marlin alive at the time of retrieval. A detailed summary of these arrangements is given by Caton and Ward (1996). Japanese longlining ceased within the AFZ in 1997.

Since 1987, an Australian commercial longline fishery operating out of Cairns has also been developed, targeting yellowfin and bigeye tunas, and more recently broadbill swordfish. This fishery underwent considerable expansion during the 1990s. To date, thirteen permits have been granted that allow vessels to operate within Area E, though in recent years only 8 or 9 vessels have operated within this zone.

Based on tagging data (Squire and Neilson 1983; Pepperell 1990) and a recent genetic study (Falterman 2000), it is currently believed that the black marlin that occur in the Pacific Ocean comprise a single stock. However, despite the well-developed recreational fishery for black marlin in the Cairns and greater Pacific regions, and the

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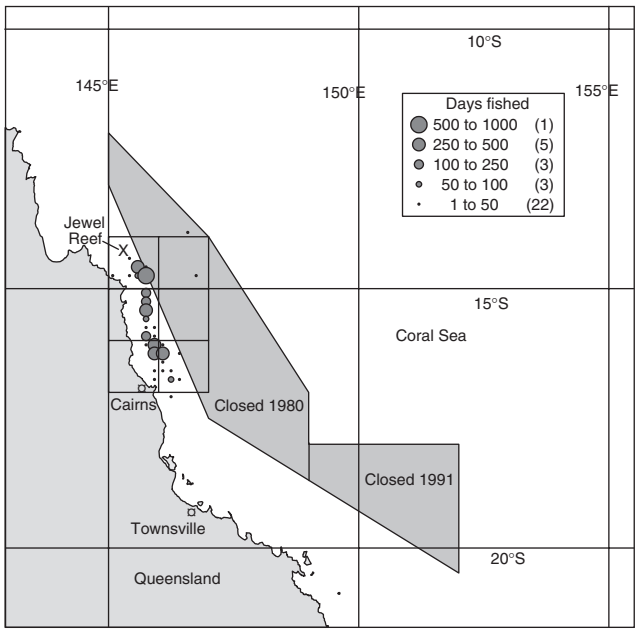

Fig. 1. Map showing the region known as Area E off the north-eastern Queensland coast. The dates indicate the years in which each section of Area E was closed to Japanese longliners. The location of the recreational fishing effort based on the data collected from charter boat fleet is also shown, stratified by the number of fishing days and aggregated by ten minutes of latitude and longitude.

long-term catch of black marlin by commercial longliners, annual indices of stock size for black marlin are not well developed. Data from recreational fisheries are not readily available, and data from longline fisheries are usually difficult to interpret because black marlin are not a target species of these fisheries and, therefore, changes in catch rates may be due to factors independent of stock abundance (e.g. setting deeper longlines, exclusion from areas of high black marlin abundance). Nevertheless, assessment of status of the black marlin stock in the Pacific, together with understanding the nature of interactions between commercial and recreational fisheries, concerns both anglers and fishery managers confronted with the long-term viability of the fisheries (Campbell *et al.* 1996).

Given the limitations and/or lack of commercial data, it is believed that, under appropriate circumstances, catch rates derived from localized recreational fisheries could be used to successfully monitor the status of tuna and billfish stocks (Palko *et al.* 1987; Squire 1987; Cramer and Turner 1994; Brown 1995). Perhaps the longest running survey of this type is the Pacific Billfish Angler Survey, presently run by the US National Marine Fisheries Service (NOAA 2000). This survey, which commenced in 1969, is based on fishers voluntarily returning a postcard-type information sheet on which they provide basic catch and effort data on their fishing activities. The black marlin fishery off Cairns has always been included in this survey. However, due to the unstructured

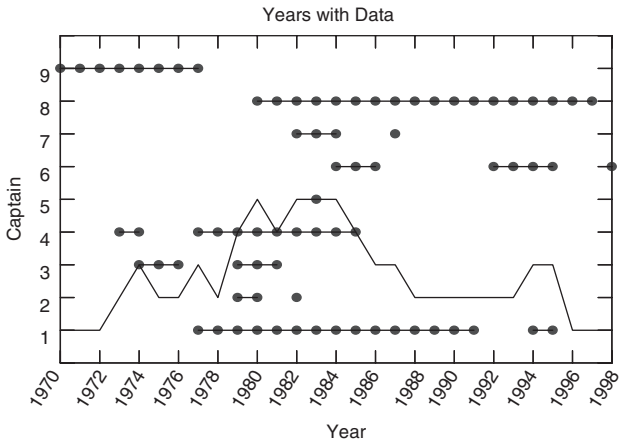

Fig. 2. Years in which data were collected from each of the nine charter boat captains who made their data available to the project. The line indicates the total number of captains supplying data for a given year.

and voluntary nature of this survey, and the small number of angler days from Australia (only 110 in 1999), the interpretation of catch rate variations is not a straightforward process. In order to help overcome some of these problems with interpretation, we have developed indices of black marlin availability in the Cairns region, based on data collected from the charter boats operating in this region. These indices have been standardized to account for a number of features that could influence catch rates (e.g. captain, area fished, water temperature, moon phase and the strength and direction of prevailing currents). This was done in an attempt to understand some of the factors that may influence the changes in availability of black marlin to the recreational fishery from year to year, and to obtain a more accurate index of annual availability.

Materials and methods

Data from personal diaries

A structured logbook program has never been implemented for the recreational fishery in the Cairns region. However, it was found that daily diaries detailing days fished and catch data had been kept by a number of the captains of charter boats operating in the region. The catch data recorded in these diaries, together with the number of days fished, were used to calculate annual indices of fishing success (catch per day) of black marlin in this fishery. The collection of personal diaries was undertaken during 1998–1999. Data were obtained from nine charter boat captains covering 4022 fishing days over the 29-year period between 1970 and 1998. The individual years for which data were supplied are shown in Fig. 2. The number of years of data from any individual captain varied between 1 and 18 years, with a mean of around 8.5 years. The total number of fishing days in any given month were recorded as follows: August (8), September (608), October (1917), November (1428) and December (55). A list of the data extracted from the diaries and the number of non-null data records for each variable are displayed in Table 1.

The fishing locations of the 3667 data records that have corresponding latitude and longitude information are shown in Fig. 1. The positions are aggregated by 10 minutes of latitude and longitude. Apart from a few records (which are possibly in error) all fishing has occurred within four one degree squares of latitude and longitude.

Table 1. Details of the charter boat data indicating the number of non-null records and number of fish with recorded weights and fight-times

Data Type	Number of records	Number of fish
Captain	4022	
Vessel	4022	
Date	4022	
Latitude	3667	
Longitude	3667	
Water temperature	204	
Wind speed	2256	
Wind direction	2261	
Sea state	1394	
Number of fish raised	3661	12 181
Number of strikes	1691	3572[A]
Number of fish hooked	3864	6153
Number of fish caught & retained	2952	539
Number of fish tagged & released	3728	3121
Number of fish released, not tagged	82	43
Capture weight		335
Estimated tagged weight		1863
Fight time		104

[A]Strikes are often not recorded separately.

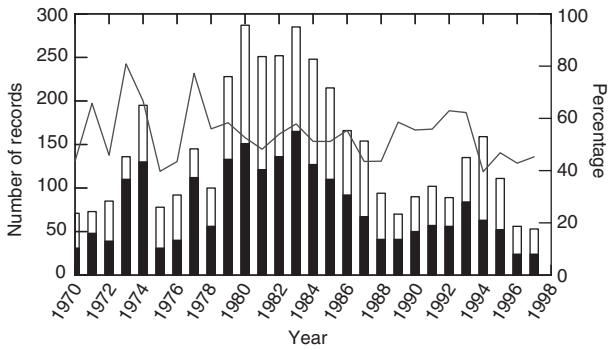

Fig. 3. Histogram of the number of catch records (corresponding to days fished) by year. Also shown are the number of days where a non-zero catch was obtained (shown in black) and the percentage of days fished each year where a catch was obtained (shown by the line).

Definition of catch and catch-per-day

As indicated in Table 1, the number of fish observed or 'contacted' in a fishing day by a given boat were recorded in several ways: (*i*) the number of fish raised (i.e. observed to be following the bait); (*ii*) the number of strikes; (*iii*) the number of fish hooked; and (*iv*) the number caught (composed of those fish **caught** and retained, **tagged** and released and **released** without tagging). However, the number of fish within the first three categories was not always recorded. For example, there are 3864 records indicating the number of fish hooked, but fewer records (3661) indicating the number of fish raised, and even fewer records for the number of strikes. Consequently, we define the 'total catch' associated with a days fishing to be the total number of fish caught, tagged or released without tagging. The number of days fished each year, together with the number of days with a recorded catch, are shown in Fig. 3.

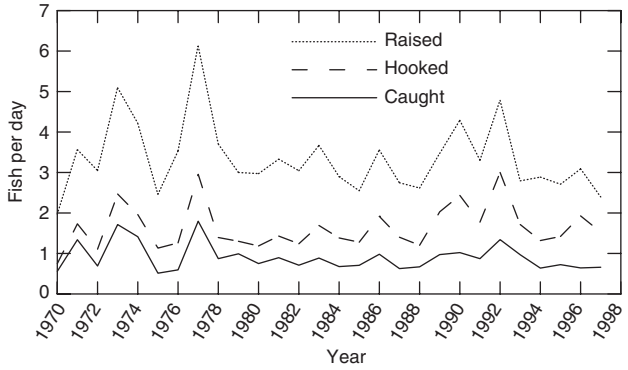

Fig. 4. Mean number of black marlin raised, hooked and caught per day by year.

Table 2. Mean annual catch rates of black marlin (and standard deviations) in the charter fishery off Cairns/Lizard Island

	1970s	1980s	1990s	All years
Number of years	10	10	8	28
Raised-per-day	3.67 (1.23)	3.09 (0.40)	3.28 (0.83)	3.35 (0.89)
Hooked-per-day	1.61 (0.68)	1.48 (0.30)	1.89 (0.57)	1.64 (0.54)
Catch-per-day	1.05 (0.49)	0.79 (0.13)	0.86 (0.25)	0.90 (0.25)

A comparison of the annual trend in the catch-per-boat-per-day in the fishery with the trends in the number of fish raised-per-boat-per-day and the number of fish hooked-per-boat-per-day is shown in Fig. 4. Only those daily records where the number of fish raised and hooked were recorded together with the total catch were used (3558 records). The means of the annual rates over the 28-year period shown are 3.35 fish raised per day, 1.64 fish hooked per day and 0.90 fish caught per day. The mean annual rates for each decade are shown in Table 2. All three mean rates were lowest in the 1980s, whereas the number of fish raised-per-day and the catch-per-day were highest in the 1970s, and the number of fish hooked-per-day was highest in the 1990s. The reason for this difference remains unknown. However, based on a paired *t*-test there is no statistical difference in the mean rates across the three decades for any of the three observations. The inability to discern significant changes in the rates across the three decades, despite apparent differences in the means, may be due to the relatively high variances in these rates, particularly in the 1970s and 1990s when the number of daily catch records was relatively small. Alternatively, observed differences between the means may be relatively unimportant and biologically meaningless.

Factors influencing catch-per-day

A number of factors can influence the catch obtained during a fishing day. These include the general availability of fish to the charter boat fleet, together with the fishing power (catchability) of the fleet. Availability, itself influenced by the prevailing oceanographic and environmental conditions as well as the propensity of the fish to bite, will vary between year and month and between the different areas of the fishery. Catchability, on the other hand, will be dependent on factors such as the gear being used and the skill of the fishers. The catch rates in the fishery are, therefore, seen as being a function of a number of variables:

$$C/E = f(Y,M,A,G,S,Env)$$

where Y is the associated year, M is the month, A is the area fished, G is the gear type, S is the skill of the fisher and Env is a composite of environmental and oceanographic conditions.

The oceanographic factors that influence the availability of black marlin to the charter boats are likely to operate on several scales. First, large-scale spatial and temporal oceanic circulation patterns in the Coral Sea are likely to influence the movement patterns of black marlin into and out of the region. Second, smaller-scale oceanographic patterns may influence local movement patterns and residence times of the black marlin on the fishing grounds. As the fleet fishes in a relatively small region along the outer edge of the Great Barrier Reef, relatively small-scale spatial shifts in the location of the preferred oceanographic habitat of the black marlin may significantly influence contact with fish, and therefore catch rates. To account for the influence of large-scale oceanographic effects we examined monthly mean 1-degree sea-surface temperatures (SST, Reynolds and Smith 1994) together with the monthly value of the Southern Oscillation Index (SOI) – often used as a measure of the strength of the El Nino-Southern Oscillation that influences global weather patterns. To account for small-scale differences in oceanographic conditions, *in situ* hourly current strength and water temperature data recorded at Jewel Reef (14°20′6″ S, 145°20′6″ E) were examined (Steinberg 1999). Several environmental variables were also recorded in some of the diaries at the time of fishing, but as the amount of information recorded was generally low and of unknown quality, these data were not used.

General linear models

We used Generalized Linear Models (Crosbie and Hinch 1985; McCullagh and Nelder 1989) to estimate the influence of the factors listed in the previous section on the observed catch-per-day. As is commonly assumed with the analysis of catch rate data (Gavaris 1980; Allen and Punsley 1984), this approach assumes that the explanatory variables have an additive error structure. Due to the unavailability of data for some of the environmental factors for the entire time series of catch data, two sets of analyses were completed for two different time periods.

For the period 1971–1998, the linear predictor used to model the data was assumed to be of the form:

$$\mathrm{Log}(C/E) = I + Y + M + Y.M + A + S + Moon \qquad (1)$$

where, together with the terms defined previously, I is a constant intercept term, *Moon* is the phase of the moon and $Y.M$ refers to the interaction between year and month factors. The area effects, A, refer to each of the four main one-degree squares of latitude and longitude where the majority of the fishing took place (cf. Fig. 1) and the captain of the boat was taken as a proxy for the effect of fishing skill. All effects were fitted as categorical variables. Due to aliasing, the inclusion of the $Y.M$ term precluded the use of monthly SOI effect. Further interactions were not investigated because there were insufficient data to support their inclusion.

For the period 1987–1996, the linear predictor used to model the data was assumed to be of the form:

$$\mathrm{Log}(C/E) = I + Y + M + A + S + Moon + SOI_M \qquad (2)$$
$$+ SST_A + \sum (Env + Env^2)$$

where, in addition to the terms in the previous model, *Env* refers to each of the following variables (all based on data recorded at Jewel Reef):

- *WTEMP* = average *in situ* water temperature
- *SPEED* = average *in situ* current speed
- *NORTHSP* = average northern component of current velocity
- *EASTSP* = average eastern component of current velocity
- *NETSP* = average net current speed
- *NDAYS* = percentage of days in a month with a mean northerly current flow
- *EDAYS* = percentage of days in a month with a mean easterly current flow

Note that the last two effects were only fitted to the aggregate monthly data (see below). No $Y.M$ interaction term was included as this term is aliased with some of the other environmental effects. However, in order to minimize the loss of statistical fit of the model to the data due the non-inclusion of this term, the model was only fitted to the data for October and November. This excludes the highly aberrant catch rate observed in September 1990, which made a significant contribution to the $Y.M$ term in the model fitted to the first time series. Indeed, one of the objectives here was to understand the influence of prevailing environmental conditions on catch rates, rather than explaining changes in catch rates through statistical factors only.

In order to explore the appropriateness of different assumed error structures, two statistical models were chosen for the analysis during each period. The first assumed that the catch during a given period has a Poisson distribution (SAS 1993). This model allows the inclusion of the zero catch information in the data since zero is a legitimate response value from a Poisson distribution. The second model fitted the data in a two-stage process, often called a delta-lognormal model (Lo *et al.*1992). In the first stage, the probability of success (i.e. of obtaining a catch) during a given period was modelled using the binomial distribution, whereas in the second stage, the size of the catch during a given period (given that at least one fish is caught) was modelled using a normal distribution. In all models a log link was used to relate the mean of the dependent variable to a linear combination of the factors deemed to influence either the probability of a successful catch or the size of the catch. Further details are given in Campbell *et al.* (2000).

The models were also fitted to both daily and aggregated monthly catch data. Only the data for the months of September, October and November were used, as there were too few data for the other months. In total there were 3580 daily records (including 1609 zero catch records) and 542 monthly records (including 83 zero catch records). For the daily analysis, the catch rate is the catch per boat per day (since the unit of effort was taken to be a fishing day). For the monthly analysis, the mean catch rate was taken to be the total catch taken by a boat during a month divided by the total number of days the boat fished during that month. When modelling the size of the non-zero catch rate for a month, the catch rate was taken to be the total catch for that month divided by the total number of non-zero catch days for that month (i.e. the mean catch rate on the days a catch was attained). Note, for the monthly analysis the *Moon* effect in the models above refers to the mean phase of the moon for the days fished and was fitted as a covariate (with a quadratic term).

Calculation of index of annual availability

After fitting each model, a standardized index of apparent availability of black marlin to the charter fleet in any year and month was calculated as follows:

$$Index(Y,M) = \exp(I + Y + M + Y.M)$$

For those models that included the $Y.M$ term, different indices were calculated for each month and then the average of the monthly indices was taken to obtain a single index for each year. In order to compare the index based on the daily data with that based on the monthly data, the former index was scaled so that the average of the two indices over the time series were equal.

Relation between recreational catch rates and longline effort

In order to investigate the possibility of a direct temporal interaction between the recreational and longline fleets, we calculated a Pearson's correlation coefficient (ρ) between the time series of longline effort and the standardized index of black marlin availability. The correlation was calculated using longline effort within two separate regions. The first region encompasses that part of the Coral Sea bounded by 10–20°S and 145–155°E, whereas the second region is the smaller inshore region coincident with the recreational fishery itself and bounded by 14–17°S

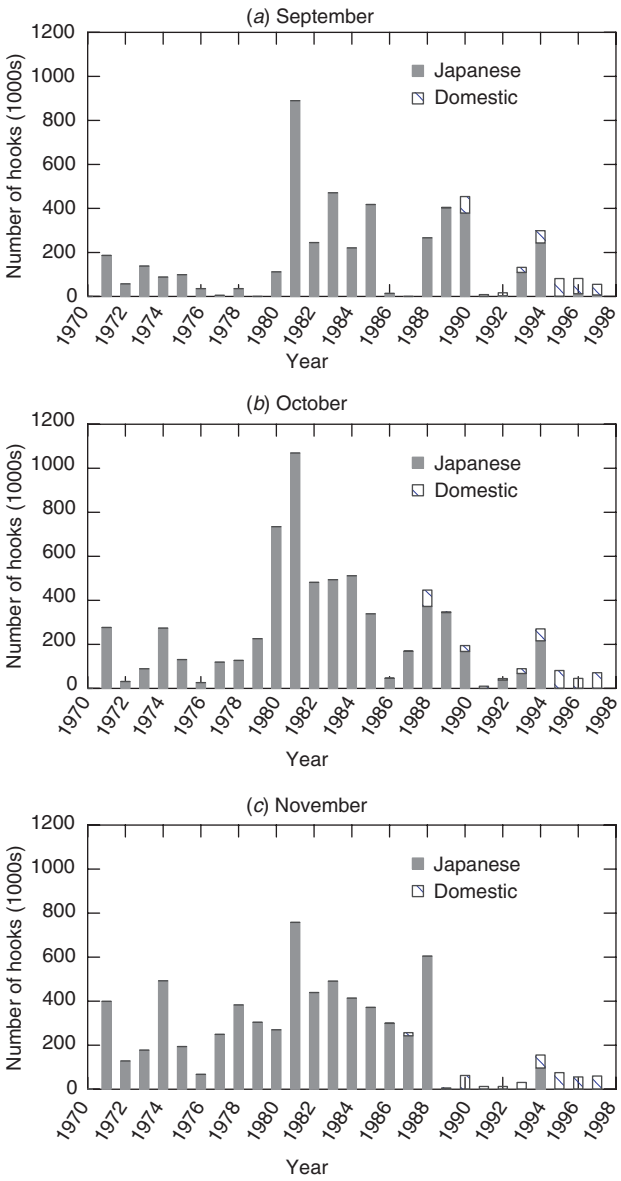

Fig. 5. Japanese and Australian longline effort within the four 5-degree squares within the Coral Sea bounded by 10–20°S and 145–155°E (cf. Fig. 1).

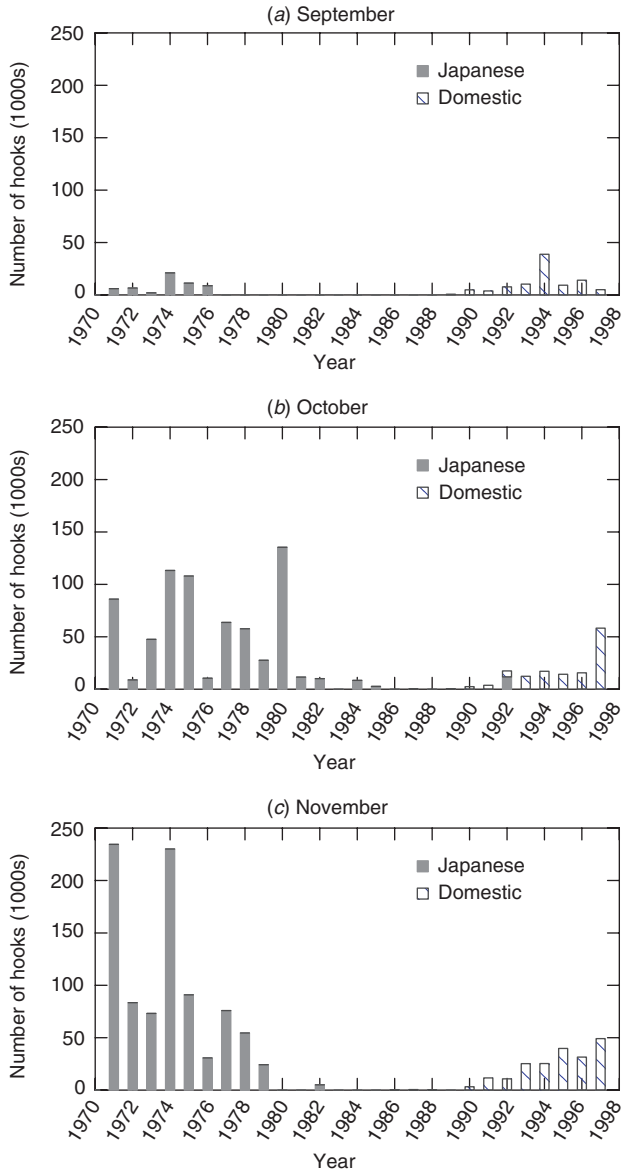

Fig. 6. Japanese and Australian longline effort within the six 1-degree squares bounded by 14–17°S and 145–147°E (cf. Fig. 1).

and 145–147°E. (cf. Fig. 1). The total Japanese and domestic Australian longline effort within these two regions is shown in Figs 5 and 6.

Results

Annual indices: 1971–1997

The annual indices associated with fitting the Poisson model to both the daily and aggregated monthly data are shown in Fig. 7*a*. The nominal catch-per-day is also shown for comparison. All terms fitted were found to be significant at the 1% level. Both models gave a reasonable fit to the model assumptions, but the result for the daily data indicated a more satisfactory fit ($Pr < W$ is 0.70 using the Shapiro–Wilks test of normality, but is rejected at the 0.10 level using the Kolmogorov test of normality for the monthly data). Nevertheless, the resulting indices based on the two sets of data are very similar.

The Binomial model was fitted to the monthly aggregated data, with the number of successful catch days used as the binomial random variable and the binomial number of trials parameter being equal to the number of days fished in the month. Again, all terms fitted were found to be significant at the 1% level. The normal probability plot for the residuals (not shown) indicated a small degree of non-linearity ($Pr < W$ is 0.007 using the Shapiro–Wilks test of normality). The Normal model was used to fit the mean catch rates

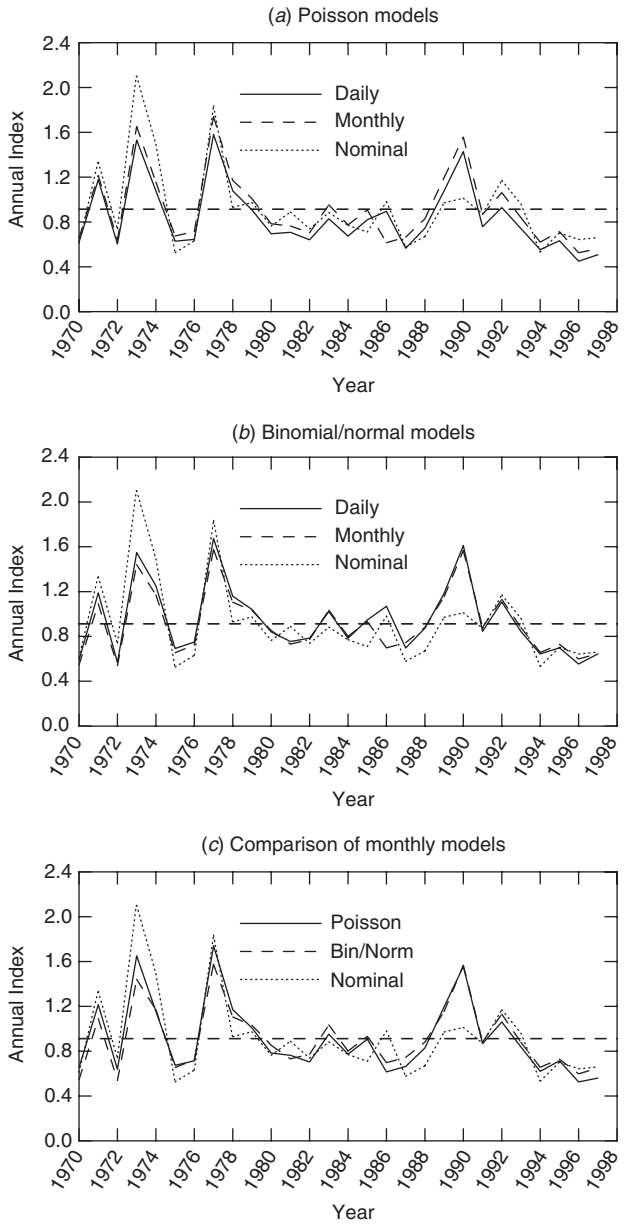

Fig. 7. Annual indices of black marlin availability to the charter boat fishery off northern Queensland based on (*a*) the Poisson model, (*b*) the Binomial/Normal model fitted to both daily and monthly data, and (*c*) a comparison of the result for both models, based on the monthly data. The nominal catch-per-day is also shown in each figure. The horizontal dashed line indicates the mean of the monthly Poisson index over all years.

on successful fishing days. The model was fitted to both the monthly ($Pr < W = 0.04$) and daily data ($Pr < W = 0.0001$). The resulting indices after combining the results of the Binomial model with the two results from the Normal model are shown in Fig. 7*b*.

A comparison of the annual indices based on the monthly results is shown in Fig. 7*c*. As the interaction between year and

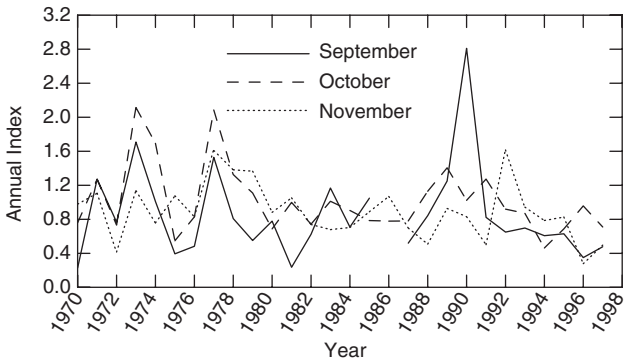

Fig. 8. Comparison of the annual indices of black marlin availability for the months September, October and November.

month was found to be significant within each model (indicating that the annual pattern of indices is different between months) annual indices for each month are also displayed in Fig. 8. As the results for the various models were very similar only the results for the Poisson model are shown.

Several features are apparent in these results:

- The time series of the index for each year is similar for the two statistical models.
- All results display a high degree of inter-annual variability, though this variability appears to be greatest in the 1970s. This may simply be a reflection of the sample sizes, as the years with the smallest degree of inter-annual variability (1980–1985) correspond to the years with the most data (cf. Fig. 3). On the other hand, the inter-annual variability during the 1990s is smaller than that seen in the 1970s though the amount of data is similar for both decades.
- The index is unusually high in 1990. Reference to Fig. 8 indicates that this is due to an anomalously high catch rate observed in September of that year.
- The index since 1993 for all months is below the historical mean. This indicates that the availability of black marlin to the recreational fishery has been lower than the annual average over the past thirty years, though there were periods during the 1980s when the index was also below this average.
- The index for both statistical models indicates that the availability of black marlin was lower during 1996 and 1997 than during the previous two years, though this decline is estimated to have been greater for the Poisson model.

In order to investigate the fourth point more fully, the average (and standard error) of each index for each month during each decade is listed in Table 3. Due to the high value for September 1990 the means have been calculated separately for the period 1991–1997. Averaged over the entire 28-year period, catch rates have generally been highest in October (index = 1.02) and lowest in September (index = 0.85). Apart from the influence of the high catch rate in September 1990, for each month and model the mean index is highest in the

Table 3. Mean value (with standard error, s.e.) of the monthly index of black marlin availability during each of the indicated periods

Model	Period	September		October		November	
		Mean	s.e.	Mean	s.e.	Mean	s.e.
Poisson	1970s	0.875	0.157	1.246	0.178	1.065	0.109
	1980s	0.797	0.108	0.922	0.070	0.815	0.057
	1990s	0.880	0.280	0.863	0.087	0.785	0.143
	1991–1997	0.605	0.058	0.840	0.097	0.778	0.164
	1971–1997	0.851	0.103	1.021	0.077	0.896	0.062
Binomial/	1970s	0.829	0.132	1.131	0.141	1.003	0.114
Normal	1980s	0.817	0.091	0.974	0.065	0.871	0.059
	1990s	0.915	0.269	0.944	0.083	0.792	0.122
	1991–1997	0.650	0.052	0.932	0.095	0.785	0.141
	1971–1997	0.851	0.094	1.021	0.060	0.896	0.058

1970s and lowest in the 1990s, indicating a general decline in catch rates over these three decades. Excluding 1990, the decrease in catch rates over this period is greater for the Poisson model, being 31%, 33% and 27% for September, October and November respectively (and 30% overall). For the Binomial/Normal model the declines are 22%, 18% and 22% respectively (and 20% overall). Furthermore, for the month of September, the majority of change over the 28-year period is seen to have occurred between the 1980s and the 1990s, whereas for October and November, the majority of the change occurred between the 1970s and 1980s. It should be noted, however, that due to the relatively large inter-annual variation in the annual indices (and the corresponding high standard errors), few of these decadal differences in mean indices are statistically significant. Using a paired t-test, for the Poisson model the observed declines between the 1970s and 1990s are significant at the 5% level only for October, with the declines over this period for the other two months being significant only at the 10% level. The decline between the 1970s and 1980s during November is also significant at the 5% level, whereas the decline between the 1980s and 1990s during September is significant at the 10% level (also being the only significant result for the Binomial/Normal model).

Annual indices 1987–1996

Annual indices based on both the Poisson and Binomial/Normal models are compared in Fig. 9. As expected, the exclusion of the data for September has greatly reduced the index value for 1990. However, the overall amount of inter-annual variation in catch rates has also decreased, indicating that some of the variation in catch rates between years has been accounted for by the environmental factors included in the model. Both results indicate a decline in catch rates, and based on the fitting of a simple regression line through each series, the decline over the ten-year period is 25% and 40% respectively. Nevertheless, these declines are not statistically significant. However, if one excludes the low value at the start of the time series, the trend for the Binomial/Normal is found to be significant at the 10% level.

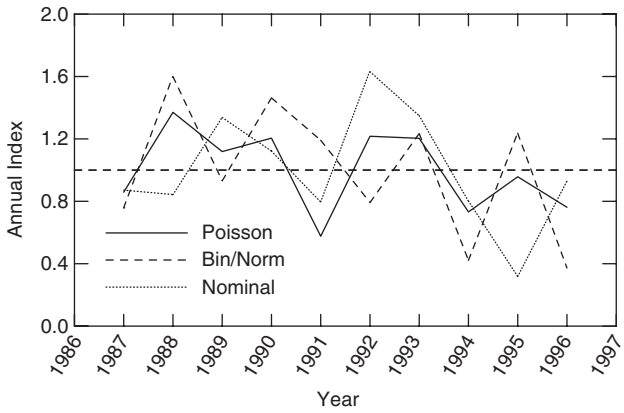

Fig. 9. Comparison of annual indices of black marlin availability based on fitting the monthly aggregated data to both the Poisson and the Binomial/Normal models that included environmental factors. The nominal index is also shown.

Influence of environmental factors

The phase of the moon was found to be a significant factor influencing catch rates in each of the models fitted to the data for the period 1971–1997. The result based on the Poisson model fitted to the daily data is shown in Fig. 10 and indicates that the highest catch rates are obtained near a half-moon and that catch rates decrease by around 30% as both a new and full moon are approached. The results for each of the models fitted to the monthly data are also shown in Fig. 10. The result for the Poisson model closely approximates a curve-of-best-fit to the daily result, indicating that the two results closely agree. The difference between the Binomial and Normal model results indicates that the phase of the moon has a greater influence on the likelihood of achieving at least one catch during the day rather than on the total number of fish caught. Similar results were obtained for the models fitted to the data for the period 1987–1996.

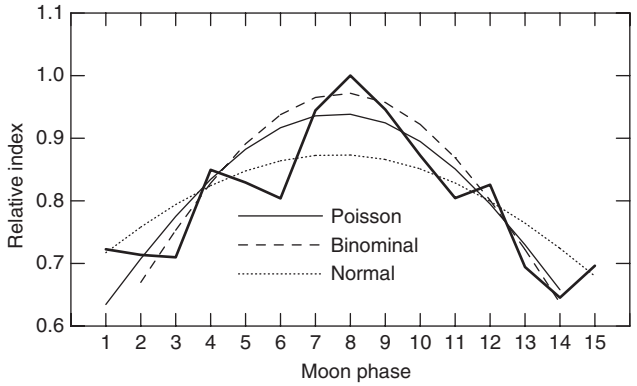

Fig. 10. Influence of the daily moon phase on black marlin catch rates (thick line). The size of the effect is relative to that of a half-moon (phase = 8). Note, a full moon is denoted by phase = 15 and a new moon is denoted by phase = 1. Also shown (thin and dashed lines) are the results from each model where the Moon effect was fitted as a covariate (with a quadratic term) to the monthly aggregate data.

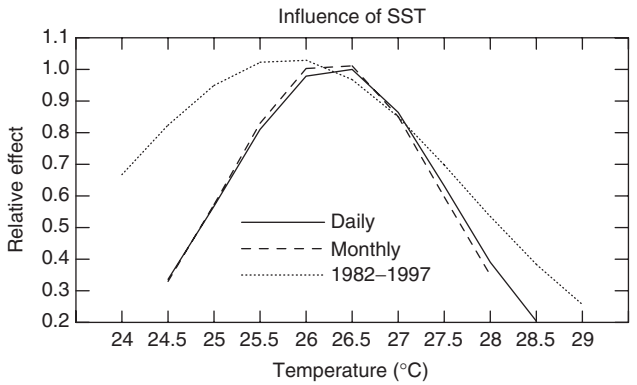

Fig. 11. Relative influence sea-surface temperature, *SST*, on catch rates of black marlin inferred from fitting the Poisson model to each of the data sets described in the text.

Anecdotal observations support the above result that fishing was better away from the full and new moons. One of the reasons suggested is the fact that the biggest tides are around the full and new moons. The big tides produce 'green water' and on an outgoing tide this dirty water will extend up to three miles off the outer reefs. Black marlin are believed to avoid this green water and on these days the fishing success decreases (B. Edwards, personal communication).

Of the environmental factors fitted to the data for the period 1987–1996, only *SST* was significant in all the models fitted, whereas *SOI* was not found to be significant in any model. Based on the results from fitting the Poisson model, the relative influence *SST* on catch rates is shown in Fig. 11. The results for the different data sets are very similar, and indicate that catch rates are greatest for sea-surface temperatures near 26.0–26.5°C. Again, this result agrees well with anecdotal reports (B. Edwards personal communication) and a separate analysis of data from a regular tournament, the Lizard Island Black Marlin Classic, between 1991 and 1999 (P. Speare, unpublished data), which also indicates that the best fishing coincides with waters temperatures in the range 25.5–26.5°C. Catch rates are predicted to decrease 30–40% when temperatures are one-degree lower (~25°C) or higher (~27.5°C) than the optimum. This result helps explain the large difference between the nominal and standardized indices for 1995 seen in Fig. 9. The average *SST* associated with each of the catch observations in the daily data set during 1995 was 27.9°C, the highest for the years shown. Each of the models therefore accounts for the relatively low catches in this year as being a result of the high prevailing sea-surface temperatures. Also, Fig. 11 displays the relative influence of *SST,* estimated when the model is fitted to the data for the period 1982–1997 with only *Moon* and *SST* as covariates (Note, monthly *SST* data have been available since 1982, but the current meter data have only been available since 1987). This result is slightly different from the previous results, inferring that high temperatures have a larger influence on catch rates than low temperatures.

Table 4. Value of Pearson's correlation coefficient, ρ, between the time-series of monthly longline effort and standardised catch rates of black marlin in the recreational fishery for the period 1980–1997.
Note: *n* refers to the number of data points in the time series

Model	Month	*n*	Coral Sea	Inshore
Poisson	September	18	0.25	−0.15
	October	18	0.08	−0.35
	November	18	−0.04	−0.30
	Total Period	18	0.05	−0.44
Binomial/Normal	September	18	0.26	−0.14
	October	18	0.01	−0.25
	November	18	−0.01	−0.38
	Total Period	18	0.02	−0.42

Of the various factors summarizing aspects of the water currents around Jewel Reef, only three (current speed, its northern component, and the proportion of days having an easterly current direction) were found to have a significant influence on catch rates. However, there was little consistency between which factors were significant across the various models. This inconsistency may be due to spurious results, due to the small data sets used in some instances. A full discussion of these results is given in Campbell *et al.* (2000).

Relationship between recreational catch rates and longline effort

The values of Pearson's correlation coefficient between the individual time series of longline effort and indices of black marlin availability, based on the analysis of daily data, are given in Table 4. As the large inter-annual variability observed in the catch rate data before 1980 may have unduly influenced the results, the correlation was calculated for the years 1980–1997 only. Apart from the result for September, the

correlation between catch rates of black marlin in the recreational fishery and effort in the larger spatial region in the Coral Sea was very small. On the other hand, a consistent negative correlation between the level of inshore longline effort and recreational catch rates was found. This indicates a general decrease in catch rates with an increase in longline effort in this region. However, the relationship is not significant with $\rho_{crit(0.05)} = 0.468$. Furthermore, the greatest value of ρ^2, which is a measure of the proportion of the variance in the observed recreational catch rates that can be attributed to its linear regression on the amount of inshore longline fishing, is only 19%.

Discussion

The analyses presented above use catch and effort data from the charter boat fleet operating in the Cairns/Lizard Island region off north-eastern Australia to infer temporal changes in the availability of black marlin to this fishery. The results of the models fitted to the data for the period 1970–1997 indicate that there has been a long-term decline of between 20–30% in the catch rates of black marlin for the charter fishery. Conversely, the results of models fitted to the data for the 1987–1996 period do not indicate a significant long-term decline in catch rates, but do suggest that environmental conditions can have a significant influence on catch rates in any given year. In particular, seasonal variations in sea-surface temperature seem to explain some of the inter-annual variations in catch rates.

The reason for the association between availability and water temperature presently remains unknown; however, variations in water temperatures are likely to influence the spatial distribution of black marlin in the region. As the recreational fishery is confined to the edge of the outer reefs of the Great Barrier Reef, relatively small shifts in the spatial distribution of the black marlin, to regions further offshore, could unduly influence catch rates. This would also help explain the relatively high inter-annual variability observed in the catch rates, which cannot be related to annual changes in overall stock size. Anecdotal reports from longliners operating further offshore in recent years indicate higher black marlin abundance than in the inshore regions and lend some support to this hypothesis. Indeed, during the 1998 season, when catch rates inshore were poor, domestic longliners in the region cooperated with the charter boat operators in helping to identify better areas to fish. Longer term studies of the movements of black marlin in the Coral Sea region, together with verified data from the domestic longliners, are needed to determine the validity of such a hypothesis (Pepperell and Davis 1999; Davis *et al.* 1999).

Declines in recreational catch rates were only weakly correlated with increases in longline effort within the inshore region close to the recreational fishery. The poor relationship between longline effort and recreational catch rates is also made apparent by the absence of significant changes in catch rates after the two spatial closures imposed on the Japanese longliners. The first closure took place in 1980 and, as seen in Fig. 6, resulted in a significant reduction in longline fishing effort in the region within close proximity to the recreational fishery (particularly for October and November). There is, however, no corresponding increase in catch rates in the recreational fishery after this time. After 1980 the level of longline effort within the larger offshore region increased (cf. Fig. 5), but dropped significantly after the second spatial closure in 1991 (particularly in November). Again, there is no corresponding increase in catch rates in the recreational fishery after this time. However, the decrease in Japanese longline effort after this time is to some extent offset by the increase in domestic Australian effort, particularly in the closer inshore region.

Although the above results and observations seem to preclude a direct temporal interaction between the recreational and longline fisheries, this does not necessarily rule out a more indirect temporal interaction. Longlining has been a major activity in the Pacific since the 1950s, and the present levels of longline effort in the Pacific remain high. Although black marlin is generally not a targeted species, the annual catch of black marlin by longliners in the western-central Pacific is estimated to have ranged between 730 and 2000 tonnes since 1980 (Williams *et al.*1999). As black marlin are generally believed to be a long lived species, the stock may be more susceptible to overfishing at what, for shorter lived species, may be seen as only moderate catch levels. If past catches throughout the Pacific region have led to a long-term decline in the population size of black marlin, then this could explain the long-term decline in recreational catch rates. However, until stock assessments for black marlin in this region are undertaken this remains speculative.

The results obtained in this paper can be compared with two previous attempts to monitor the status of black marlin, based on analysis of recreational data off Cairns. The first is the annual catch per day obtained from the Pacific Billfish Angler Survey (PBAS, NOAA 2000) and the second index is based on the analysis of tagging data for this fishery, collected by the Fisheries Research Institute (FRI, Matthews and Thompson 1999; Campbell *et al.*1996). These indices are compared in Fig. 12, with the two indices based on the Poisson analyses of the monthly data. All indices have a number of features in common. First, the two indices for the early 1970s are very similar, displaying large inter-annual variability in fishing success with catch rates averaging around one fish per day, but peaking at historical high levels of around 1.6 fish per day. Second, all indices indicate a relatively high catch per day in 1977 followed by a period of declining annual catch rates until 1981/1982. Third, catch rates during the period 1982 to 1986 were relatively stable. However, there are also a number of differences. First, after 1975 the Poi-all index fluctuates around 0.8 fish per day, whereas the PBAS

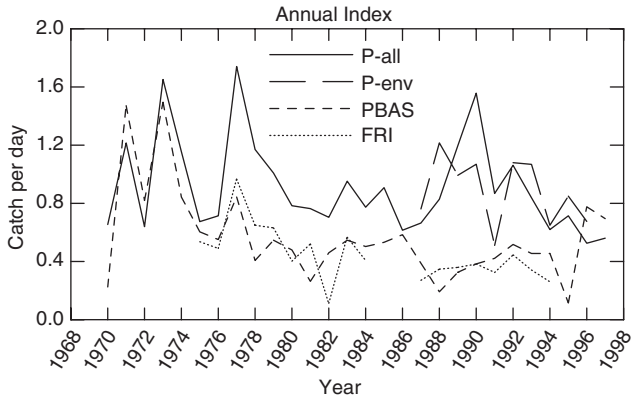

Fig. 12. Comparison of various annual indices of recreational fishing success for black marlin in the Cairns/Lizard island fishery off north-eastern Queensland, Australia. Catch per day = number of fish caught per day.

index declines appreciably to around half this value. Second, the PSAB index indicates a decline in catch rates between 1986 and 1988, whereas the Poisson based indices show an increase. Third, the FRI index indicates relatively stable catch rates between 1987 and 1994, whereas the two Poisson based indices display large inter-annual variation. Reasons for these differences remain uncertain but are most likely due to differences in the underlying data and the manner in which the index has been calculated. However, these differences suggest that the decline seen in the PBAS index after 1975 may not be related to the stock status of black marlin.

In the absence of a more definitive stock assessment of black marlin in the Pacific, it is likely that recreational fishers will continue to interpret catch rates in their fisheries in terms of stock status. However, in order to overcome the present uncertainties inherent in such interpretations, further effort needs to be made to reduce current limitations in each of the above indices. Most important in this regard is the need to obtain more data. Each of the indices presented in Fig. 12 is based on only a small sub-sample of the fishing effort, and it remains difficult to ascertain how representative the data are in each case. In order to overcome biases that may enter calculations due to small samples, it is important that data be collected from as large a component of the fishery as is possible. The analyses would also be enhanced through a more accurate measure of fishing effort. Towards this end, information should be collected on the number of hours spent fishing each day, together with information on the introduction of new fishing gears and techniques that can improve the efficiency of fishing operations, and increase catch rates. Indeed, if there have been increases in fishing efficiency over time due to the adoption of technological changes, then these changes could mask greater declines in catch rates than those reported above. In many commercial fisheries, logbooks are designed to capture much of this information, together with the basic catch and effort data. This type of information would also prove extremely useful in any logbook introduced into recreational fisheries (Pepperell and Henry 1997).

Finally, catch rates from localized recreational fisheries can be used to monitor stock status only under certain conditions. One important assumption is that migration patterns are relatively constant from year to year, and that sampling is intensive enough so that inter-annual variability is reasonably small. If migration patterns are not constant, then one would need to obtain data from different parts of the stock's range in order to produce a reliable annual index. The results reported here are based on data from only a single region and suggest that migration patterns vary in response to water temperature. Consequently, the resulting indices refer only to the relative annual availability of black marlin in the Cairns region. Nevertheless, one could argue that although the index in any year may be unduly biased as an index of overall stock status, these biases will average out over a long time series and, as such, one can still infer an overall trend in stock status. If this hypothesis is accepted, then the above results indicate that between 1970 and 1997 there was a decline in the size of the black marlin stock in the Pacific of around 20–30%.

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