ICES Journal of Marine Science, 2025, Vol. 82, Issue 10, fsaf182
https://doi.org/10.1093/icesjms/fsaf182
Received: 28 April 2025; **revised:** 12 September 2025; **accepted:** 15 September 2025
Original Article

Abundance indices for black marlin (*Istiompax indica*) derived from 50 years of diarized daily catch-effort data from the charter fishery off the Great Barrier Reef, Australia

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Abstract

The capture of a 1000-pound black marlin off the northern Great Barrier Reef (GBR), Australia, in September 1966 initiated the rapid development of a recreational charter fishery that has operated every year since. The fishery has a distinct 2.5-month-long season, covers the same area off the outer edge of the GBR, specifically targets black marlin and has used essentially similar fishing methods through its history. For the first three decades of the fishery, there was no mandatory logbook requirement. Fortuitously, a study conducted in the late 1990s found that some charter captains and crew had kept detailed personal diaries or logs of daily catch and effort, including zero-catch days since the beginning of the fishery. The earlier study analysed CPUE data extracted from such records for the period 1970 through 1997. Here, we present an extension of this analysis with the addition of new daily records spanning 1998–2023. Nominal CPUE for the early period showed high but highly variable values at the beginning of the series, then a declining trend towards the late 1990s. Standardized CPUE since the early 2000s then showed a gradual increase to match that recorded in the early 1970s. Factors having a significant effect on CPUE were Southern Oscillation index, moon phase, meridional current velocity and direction, month, latitude, and captain. The results demonstrate that long-term personal, unbiased daily fishing records may be used to demonstrate fluctuations in stocks, in this case recording a decline and recovery of black marlin CPUE that may not have been possible from other data sources.

Keywords: black marlin; *Istiompax indica*; recreational charter fishery; long-term CPUE; standardized CPUE

Introduction

A recreational charter fishery targeting black marlin (*Istiompax indica*) has operated off the outer Great Barrier Reef, Australia, since the late 1960s (Goadby 1970, Pepperell 2010). The fishery has long been famous for its high strike rate (number of marlin hooked per day) and reputation for encountering marlin of over 1000 lb (Pepperell and Joyce 2006, Joyce 2020), attracting anglers from around the world and generating considerable economic income for the region (Coopers and Lybrand 1996).

The season, area fished, and basic methods used in the black marlin charter fishery have been remarkably consistent through over 50 years of its operation. The black marlin has been the sole target species for the duration of the fishery. The breaking strain of lines used is normally 60 kg, or less often, 37 kg (both defined as 'heavy tackle' and conforming to standards set by the International Game Fish Association (IGFA) (https://igfa.org/international-angling-rules). Stout rods with roller line guides are paired with large, overhead reels with lever drag systems. By far the most common baiting system has always been to troll two dead fish baits, a smaller one rigged to imitate a swimming fish, and a large one rigged to create a splashing effect. Lures are used to a far lesser extent than bait, usually when travelling over distances, or if fishing well beyond the outer reef edge.

In the southwestern Pacific, considerable numbers of black marlin, blue marlin (*Makaira nigricans*) and striped marlin (*Kajikia audax*) are all caught as incidental bycatch of commercial longline and purse seine fisheries (Pepperell 2014). However, only the striped marlin has been the focus of stock assessments. The most recent assessment for that species determined that the stock is likely overfished, and undergoing overfishing (Castillo-Jordan et al. 2024). In contrast, no stock assessment for black marlin has ever been carried out for southwestern Pacific, primarily because of the relatively low commercial value of the species. The production of an abundance index may help to support development of a stock assessment for black marlin.

Retrospective assessment of catch history has been showed to be useful to support development of abundance indices in recreational fisheries for which no formal monitoring has been in place. This has included archived newspaper and magazine reports and/or photographs of catches (McClenachan 2009; Parsons et al. 2009, Mal et al. 2014, Thurstan et al. 2018), fishing competition records (Boucek et al. 2023, Gledhill et al. 2015, Pita and Freire 2014, Pepperell et al. 2011), diaries of catches (Conron et al. 2018), fishing club annual reports and tag and release data (Pepperell 1992, Gartside et al. 1999, Pepperell et al. 2011, Guillemin et al. 2025) and oral history from long-term recreational fishers (Saenz-Arroyo et al. 2005, Parsons et al. 2009, Thurstan et al. 2018, Boucek et al. 2023). However, many of these studies lack detail regarding fishing effort, specific locations and zero-catch days making standardization a challenge.

A study was undertaken in the late 1990s to attempt to retrospectively quantify and analyse the catch per unit of fishing effort (CPUE) of this fishery since its origins (Campbell et al. 2003). At the time, there was no mandatory logbook in place to monitor catches or CPUE in the fishery, but the authors became aware that some captains and deckhands had been recording daily catch information for their own use in personal diaries, notebooks and logs over many seasons. Through word-of-mouth and cooperation with fishers developed over years of liaison by one of the authors (JP), a number of longstanding captains allowed access to their personal archives for an analysis of the variability of black marlin relative abundance and sustainability of the fishery from 1970 to 1997. The data contained in the personal catch and effort records used in this study provide detailed unbiased information that allowed standardization, including fishing effort, specific locations, and zero-catch days. The resultant study was able to compute annual indices of abundance of black marlin, demonstrating the value of such latent or cryptic data. Importantly, that study was also able to explore possible effects on CPUE of environmental factors such as sea-surface temperature, current velocity and moon phase (Campbell et al. 2003).

Since that study, a mandatory logbook for charter fishing off the State of Queensland had been introduced in 1996. However, that logbook was primarily designed to record gross weights of retained catches of reef fishes rather than individual numbers of offshore pelagic species being voluntarily released. Spot checks of retained catches are made by field compliance officers and evaluated against logbook records on site. While the logbook might in theory be useful for providing some estimates of catch per unit effort (CPUE) in the black marlin charter fishery, because the fishery is almost 100% catch and release, it is difficult to verify the released component. In addition, the Queensland Charter Fishing Logbook is not designed to record the proportion of targeted fishing effort for black marlin, simply recording days when marlin were caught, but not days when marlin were targeted but none were encountered or caught.

In contrast, the daily data recorded in captains' and deckhands' personal diaries and logs provide full information on every individual fish, whether captured or released, and also records all 'zero' contact days when targeting marlin. It was therefore decided to extend the Campbell et al. (2003) study by collecting as many personal fishing records as possible covering the period since that study (1998–2023) and to combine both sets of data for a unique analysis of over 50 continuous years of CPUE in the fishery. As before, effects of environmental influences on CPUE were investigated, extended over a further 25 years, and expanded to include several important additional environmental variables, global monitoring of which did not commence until the mid-1990s.

Materials and methods

Personal diary and logbook data

Using a number of sources, including personal contacts, the Black Marlin Blog (https://www.blackmarlinblog.com/), and social media profiles of captains and crew, a comprehensive list of potential active fishers was compiled, focusing on long-term participants in the charter fishery. As many as possible were contacted and asked if they had ever kept diaries, logs or notebooks during any heavy tackle seasons from 1998 to 2022, or even before that period, and if so, would they be willing to share these for the study of long-term catch rates in the fishery. It was stressed that all data would be treated confidentially.

Diaries, notebooks, and logs, that were physically received were, with permission, photographed page by page, then relevant data extracted and entered on a master spreadsheet. In addition to provision of physical material, one long-term captain provided his own digitally entered data, and one long-term deckhand manually transferred his data to hard-copy spreadsheets that were then digitally entered.

For the earlier period, 1970 to 1997, collection of personal diary and logbook records had followed a similar method (see Campbell et al. 2003). The digitized data from that period had been archived and were available for this study but original diaries were not. While collecting data for the current study, additional diaries kept by some captains and deckhands prior to 1998 were received, which added significantly to the original data for the earlier period. The combined dataset provided detailed information on daily fishing activity for black marlin, which allowed catch statistics and catch-per-unit-effort (CPUE) to be calculated for the fishery.

Catch and effort statistics

Daily catch records provided by captains and deckhands allowed a variety of interactions per day of black marlin to be determined. These were the number of fish raised (i.e. fish observed following trolled baits or lures), the number of strikes (also called bites), the number of fish hooked, and the number of fish caught (composed of fish tagged, released without a tag, and landed). Assuming that all of the interactions were recorded, the hierarchy of these records meant that the number of fish raised should always be equal or greater than the number of strikes, the number of strikes should be equal to or greater than the number hooked, and the number of fish hooked should be equal to or greater than the number caught. However, given the individual nature of record keeping, some of these interaction types were not always recorded by each captain or deckhand. Therefore, the minimum number of fish raised, struck, or hooked was determined from the other fields reported (e.g. number raised equalled the number of strikes when not recorded). However, for the purposes of CPUE analyses, only the numbers of fish caught were used given that these data required no interpolation.

Annual fishing statistics were determined for: (i) number of days fished, (ii) the number of fish reported by each interaction type, (iii) the nominal daily CPUE for each interaction type, (iv) the percentage of zero interaction days (i.e. no strikes, hookups, or catches), and (v) the number of individual captains and fishing records (days) provided for each year (season). Spatial effort was aggregated to a decadal scale to examine how fishing locations may have changed throughout the entire time series. Most daily records provided a fishing location, nearly always as named known reefs or occasionally other features such as banks or ridges. During the course of any given fishing day, it was normal for captains to record the span of reefs that were fished, for example, Number 1 to Number 5 Ribbon Reefs, Linden Bank to Opal Reef, and so on. In these instances, we nominated a single location as the site for that day's fishing activity, usually an intermediate point within the range. Using that reef or feature name, the latitude and longitude were accessed using the `gisaimsr` R package from the Australian Institute of Marine Science (Barneche and Logan 2024). If no location nor latitude and longitude were provided, then the position of that fishing event could not be determined.

While this method of determining locations fished was applied for data covering 1998–2022, the archived digital positional data from 1970 to 1997 had already been converted to co-ordinates (with the actual named locations not saved). These co-ordinates for any given reef or feature coincided with those converted for the latter years. A map of reef locations is provided in Fig. 1. These locations were used to link available environmental variables to fishing events at the finest available resolutions. When multiple reef locations were listed and a single location nominated, the distance between these reefs was often less than the spatial resolution of the available environmental data. Therefore, the same environmental data would have been associated with each fishing record even if a different reef was nominated on a given day.

Environmental variables

A suite of environmental variables was selected to test for potential effects on CPUE of black marlin through time. These variables were accessed from a variety of online sources. Monthly variables such as Southern Oscillation Index (SOI) using the Troup Index (Troup 1965) and total monthly rainfall were accessed from the Queensland government (https://www.longpaddock.qld.gov.au/soi/soi-data-files/) and from the Bureau of Meteorology (BOM) weather radar at Cairns Airport, respectively. Moon phase as percentage illumination was accessed using the `lunar` R package (Lazaridis 2022) and joined to catch records using the fishing date. Sea surface temperature (SST) in degrees Celsius and meridional geostrophic velocity anomalies (ms^{-1}) on a daily scale at a resolution of 0.1° were accessed from the BRAN2020 dataset (Chamberlain et al. 2021) from 1993 onwards (Supplementary Fig. S1). A similar dataset for SST was available from NOAA from 1981 onwards. However, this dataset had a coarser resolution with a 0.25° scale. Initially, this was accessed for 1981–1992 in order to further extend the SST time series. However, comparison of equivalent daily SST measurements from BRAN2020 and NOAA demonstrated inconsistencies that prevented these datasets from being combined. Ultimately, the BRAN2020 data was used given its finer resolution and sufficient 30-year coverage (1993–2022). Fishing records were joined to SST and meridional velocity data by rounding their latitude and longitude to the nearest grid centroid of the BRAN2020 data. This rounding was performed such that exact locations were shifted to the northeast of a reef structure. This was done to avoid locations situated on tops of reefs, rather than outside the reef in oceanic water, where marlin fishing always occurs.

Chlorophyll-a was accessed as 8-day composites at a 0.04° scale from the NASA Aqua MODIS dataset from 1997 to 2021 (https://modis.gsfc.nasa.gov/data/dataprod/chlor_a.php). However, these data were sparse for many daily observations over the area examined. Chlorophyll-a could not be joined to many fishing records and this variable was subsequently dropped from the analysis. A time series of environmental variables and the percentage of fishing records that could be attributed to each variable is shown in Supplementary Fig. S2. Incomplete coverage occurs for SST and meridional velocity when a latitude and longitude are not recorded for a given fishing event.

CPUE standardization

While all data were used for nominal CPUE calculations, data from captains who fished fewer than 20 days across all years were dropped from the CPUE standardization. CPUE standardization was performed to determine the effect of environmental and catchability variables on CPUE and estimate a relative index of abundance that may be used to infer stock status. For this analysis, the number of fish caught per boat-day was used as the dependent variable. Month, year, captain, and boat were treated as factors. Latitude, monthly total rainfall, SOI, SST, moon phase (% illumination), and meridional velocity were treated as continuous variables. Standardization was applied from 1993 to 2023 to maximize the number of environmental variables, and records that could be associated with them, to be included (Supplementary Fig. S2). Comparisons between standardized and nominal CPUE were made by centring both series on a mean of one.

Captain was used as a random effect in the final model to account for the CPUE of each captain representing their own random sample. Generalized linear mixed effects models (GLMMs) were used to determine the linear and non-linear relationships of predictor variables. Splines were used for any environmental variable whose univariate relationship was non-linear, as determined through LOESS smoothers. This included SST, SOI, monthly rainfall, and moon phase (Supplementary Fig. S3). Given that catch was recorded as the number of fish (which can include zeros), only count data error structures such as the Poisson and negative binomial distributions were considered in the GLMM approach. This represents that CPUE data were strictly positive integers or zero. All models were fitted using the `glmmTMB` R package (Brooks et al. 2017) with the `s()` function from the `mgcv` R package (Wood 2011) used to apply splines. The addition of splines to within `glmmTMB` extends a generalized linear mixed effect model (GLMM) so that it is similar to a generalized additive mixed effect model (GAMM). Modelling workflow was improved by using the glmmTMB package since it can handle different model structures such as random effects and splines, which normally need different R packages depending on model formulation. This allows more thorough examination of model structures and formats using a single package and central framework.

Model diagnostics were examined using the `performance` R package (Lüdecke et al. 2021) to ensure the models were appropriately fitted. These diagnostics included visualization of residuals and posterior predictive checks to ensure that the model error structures were appropriate. Models fit with a Poisson distribution were over-dispersed and displayed zero inflation. Therefore, a negative binomial distribution was used in the final model to account for both effects, as demonstrated by the model diagnostics. Variance inflation factors (VIF) were

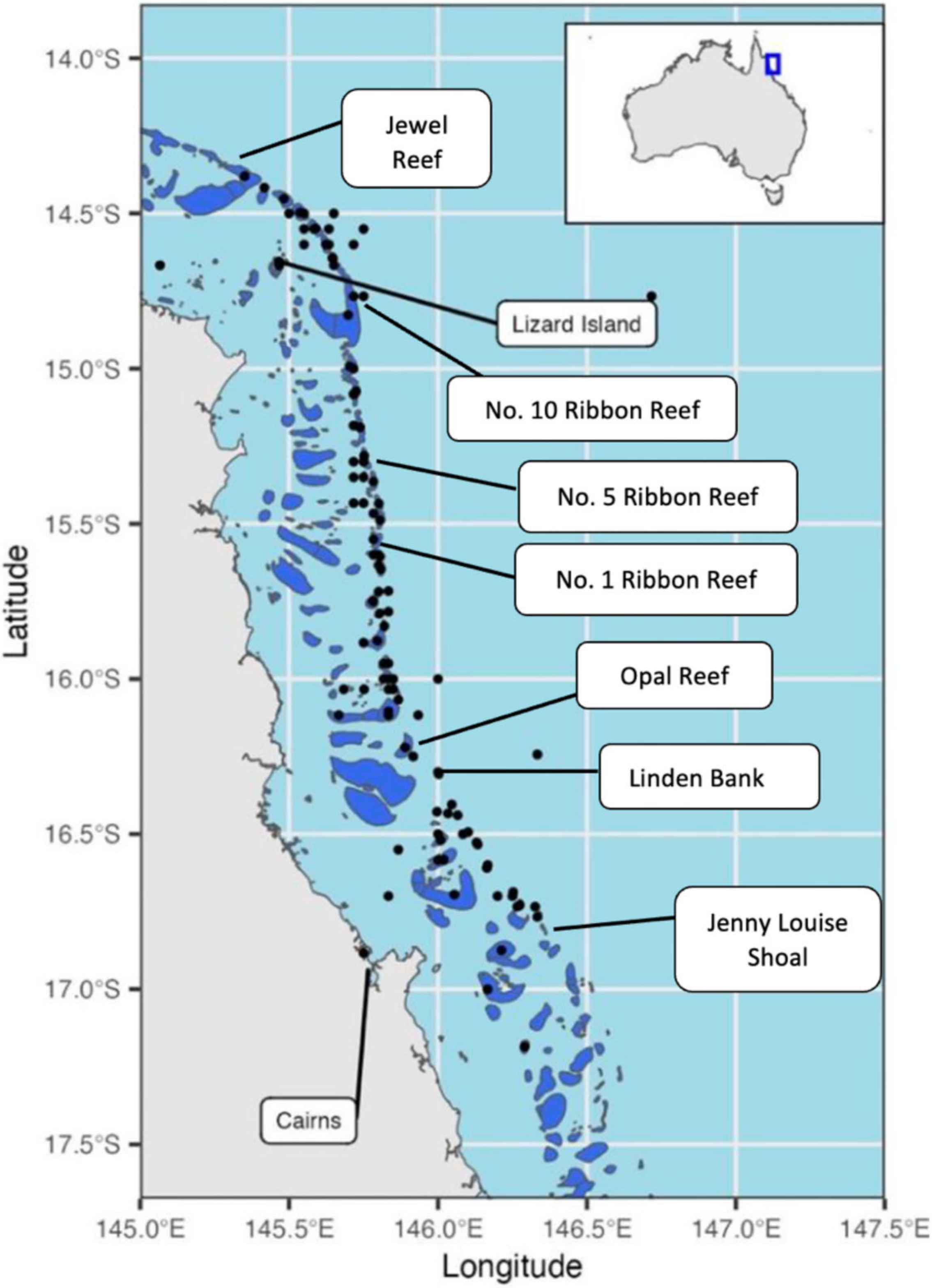

Figure 1. Reported black marlin fishing locations (black circles) from charter fishery diaries and logs. Names of reefs corresponded with those available from the `gisaimsr` R package. If no names were used, then fishing location represents the latitude and longitude provided in the diaries.

used to determine if any variables were collinear, which occurred for boat and captain and was addressed by dropping the former as a predictor variable. Captain was selected over boat as a predictor variable, as some captains fished across several vessels. The logbook data provided was also based on the catch and effort data of captains, rather than vessel, leading to this variable providing a greater representation of fishing activity.

A multi-model approach using model selection was performed using the dredge() function from the MuMIn R package (Bartoń 2024). This function was applied to the full model with all variables included (except 'boat') as well as each possible combination of model terms (256 models in total). Akaike information criterion with a low sample size bias adjustment (AICc) was used to determine the best-fitting model. Any alternative models with an AICc more than two points greater than the best-fitting model were deemed to be a poorer-fitting model (Burnham and Anderson 2001). The best-fitting model was re-checked for model diagnostics prior to its acceptance. The visreg R package (Breheny and Burchett 2017) was used to examine the marginal effects of the environmental and catchability variables from the best-fitting model, as well as to create the standardized index of abundance (with standard error) based on the model coefficient of the 'year' variable.

Results

Spatial distribution of fishing effort

The spatial distribution of fishing effort as derived from daily records in diaries and logs was remarkably similar over time, with fishing events spread across similar regions and higher occurrences in similar areas through each of five decades (Fig. 2). As points of reference on this figure, the larger cluster of fishing effort in the northern part of the fishery is located mainly off the northern section of Number 10 Ribbon Reef, while the cluster in the south centres on waters around Linden Bank, Opal Ridge and off Opal Reef. In addition to these clusters, it is clear that the fishery operates right along the outer edge of the Great Barrier Reef from east of Cairns in the south (Jenny Louise Shoal) to north–northwest of Lizard Island in the north (Jewel Reef), a span of approximately 280 km.

Catch data statistics

Daily catch data were obtained from personal diaries, logbooks, and notebooks representing 51 captains and 66 boats. Season summary catch data were also obtained from two of the captains included in these tallies while captaining an additional four boats. Figure 3 shows the number of seasons and daily records per season attributable to each captain. Data were received from 13 captains spanning one to three seasons, 16 captains spanning five seasons or more, 9 captains spanning 10 seasons or more, and 3 captains spanning 20 seasons or more.

In most cases, data are from captains' own diaries or logs, but in others, the diaries were contributed by deckhands, some of whom worked on multiple boats operated by different captains over multiple seasons. In a small number of instances, diaries were received from both the captain and the deckhand of a given boat covering the same days fished. These were found to be close matches, but as a protocol, we used only the captain's records in such cases.

Campbell et al. (2003) collected personal diaries tallying to 4022 fishing days from 1970 through 1997. The present study added a further 1186 days to that period, and 5553 days for the period 1998 through 2023. This resulted in data from a total of 11 613 days of black marlin fishing, which were suitable for calculations of nominal CPUE. Of those, 852 days were sourced from summary data provided by two captains who tallied days fished and catches for some seasons, and could thus be incorporated for calculations of annual nominal CPUE. The remaining 10 761 daily records were suitable for use in CPUE standardization (Table 1).

The number of captains who contributed data in any given season varied through time, peaking at 13 in 2000, with an average of 3.96 for 1970–1997, 5.37 for 1998–2023, and 4.72 over the entire time period (Fig. 3). The numbers of days targeting marlin recorded each season are shown in Fig. 4. The average number of days per season for the entire time series was 214.2 days (range: 49–377 days). The percentage of zero-catch days varied over time but had a relatively stable trend, typically falling between 30% and 60% of days over the 53-year period (Fig. 4).

The average number of black marlin caught per year recorded in the diaries and logs received was 186 for 1970–1997, 222 for 1998–2023, and just under 200 for the whole period. Regarding the representativeness of these subsamples, the total number of black marlin tagged and released each season in the early years of the fishery is a reliable estimate of total numbers caught by the fleet since it is known that the great majority of released fish were tagged at the time. Squire and Nielsen (1983) reported numbers tagged by the charter fleet under the US-based NOAA cooperative tagging program for 1970–1978, while Pepperell (1990) reported numbers tagged under the New South Wales gamefish tagging program for 1974–1986. Combining these, during that 17-year period, the average number of black marlin tagged per season was 527. Adding numbers caught and weighed each year (Cairns Game Fishing Club annual reports, R. Joyce unpublished data) brings the average number of fish caught per season to 600 (range: 157–933). For this same period, the collected diaries recorded an average of 178 fish caught per season, or 29.7% of actual numbers recorded as tagged and/or weighed.

More recently, a long-standing blog commenting on activity in the fishery in real time provided another source of comparison of sampled data to the fleet as a whole (https://www.blackmarlinblog.com/). During six seasons between 2008 and 2018, when season highlights of boats' activities were mentioned, identified boats in our sample ranged between 15.4% and 40% (mean 24.7%) of all boats mentioned in the blog.

Daily interactions with black marlin showed substantial variability across years (Supplementary Fig. S4). The mean number of annual fish interactions per boat per day from 1970 to 2023 was 2.5 fish raised per day, 1.9 strikes per day, 1.3 fish hooked per day and 0.9 fish caught per day (Fig. 5). The patterns in number of fish struck, hooked, and caught were similar within years. However, this may be a reporting effect where missing information for a particular interaction type meant that a minimum number was considered based on the reported information for a given fishing event.

Nominal CPUE of fish caught, as opposed to other interaction categories, also varied through time but was most variable in the 1970s when both the lowest CPUE (0.5 fish caught per day in 1975) and highest CPUE (2.0 fish caught per day in 1973) occurred (Fig. 5). There was a general and slight declining trend from the beginning of the time series until the early 2000s. From that point, CPUE had a slight increasing trend. The CPUE in 2023 (1.6 fish caught/day) was the third highest on record and the highest for 49 years (Fig. 5). However, this is derived from a small number of fishing days (49) from one captain and must be treated cautiously.

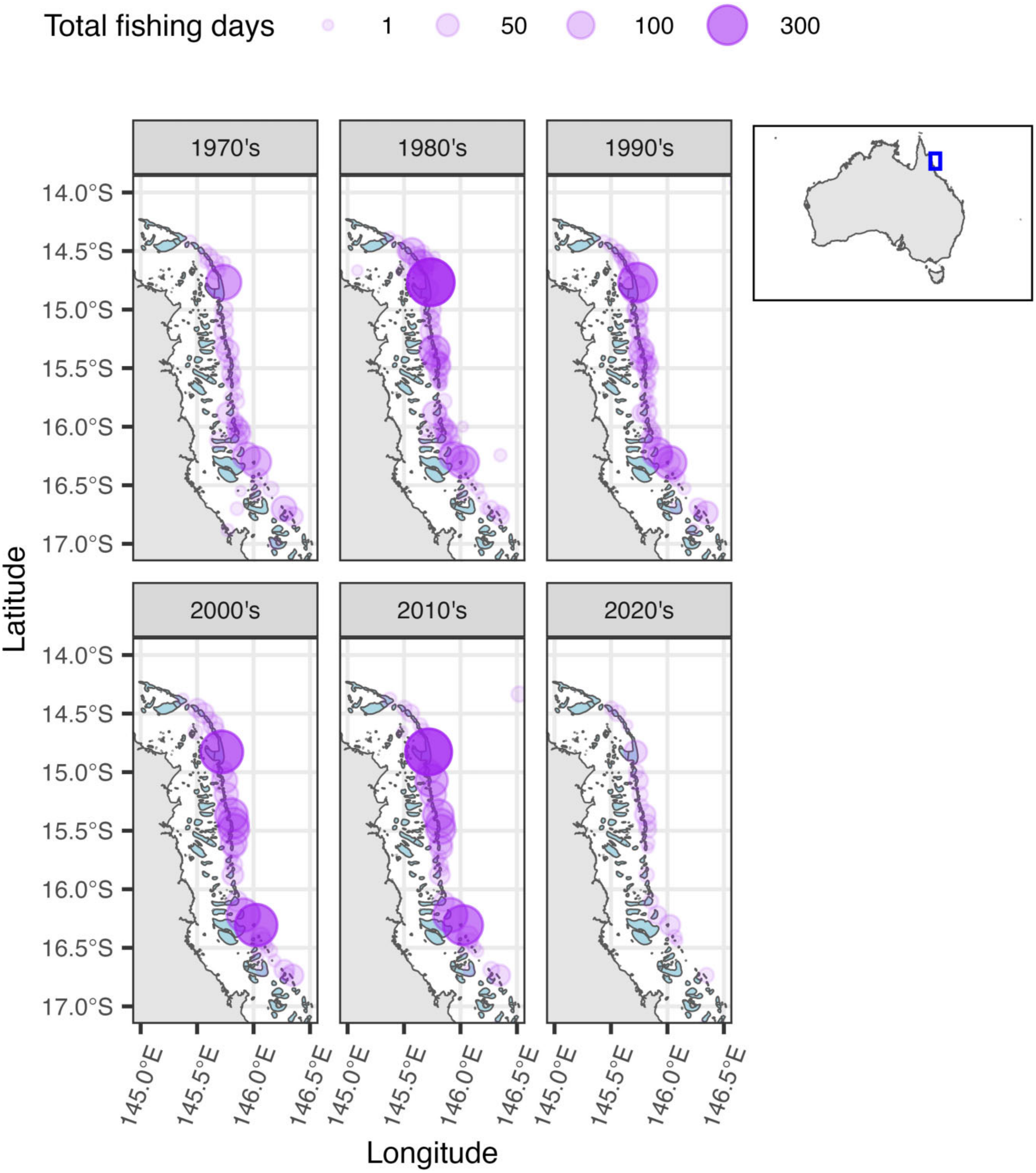

Figure 2. Plots of spatial fishing effort for black marlin for each decade. The size of the purple circles indicates the total number of daily fishing records in that location each decade. Note that only 3 years of data are available in the 2020s, hence fewer fishing days recorded.

The annual CPUE of each captain varied with most averaging just under one fish per day (Fig. 6). Six out of forty captains had upper 95% confidence intervals that reached 3 fish per day, indicating their ability to attain high catches during some years. Once captains with low total numbers of fishing days (<10) were excluded from consideration, none achieved an overall average catch of more than two fish per day (Fig. 6).

CPUE standardization

The best-fitting model according to AICc omitted monthly rainfall and SST but kept all other variables (Table 2). No alternative models had AICc results within two points (ΔAICc) of the best-fitting model. The marginal effects of this model (i.e. the relative effect of each variable when all others are held constant) demonstrated distinct effects between fishing variables such as month, fishing latitude, and captain. Latitude had a positive linear trend, indicating higher CPUE at

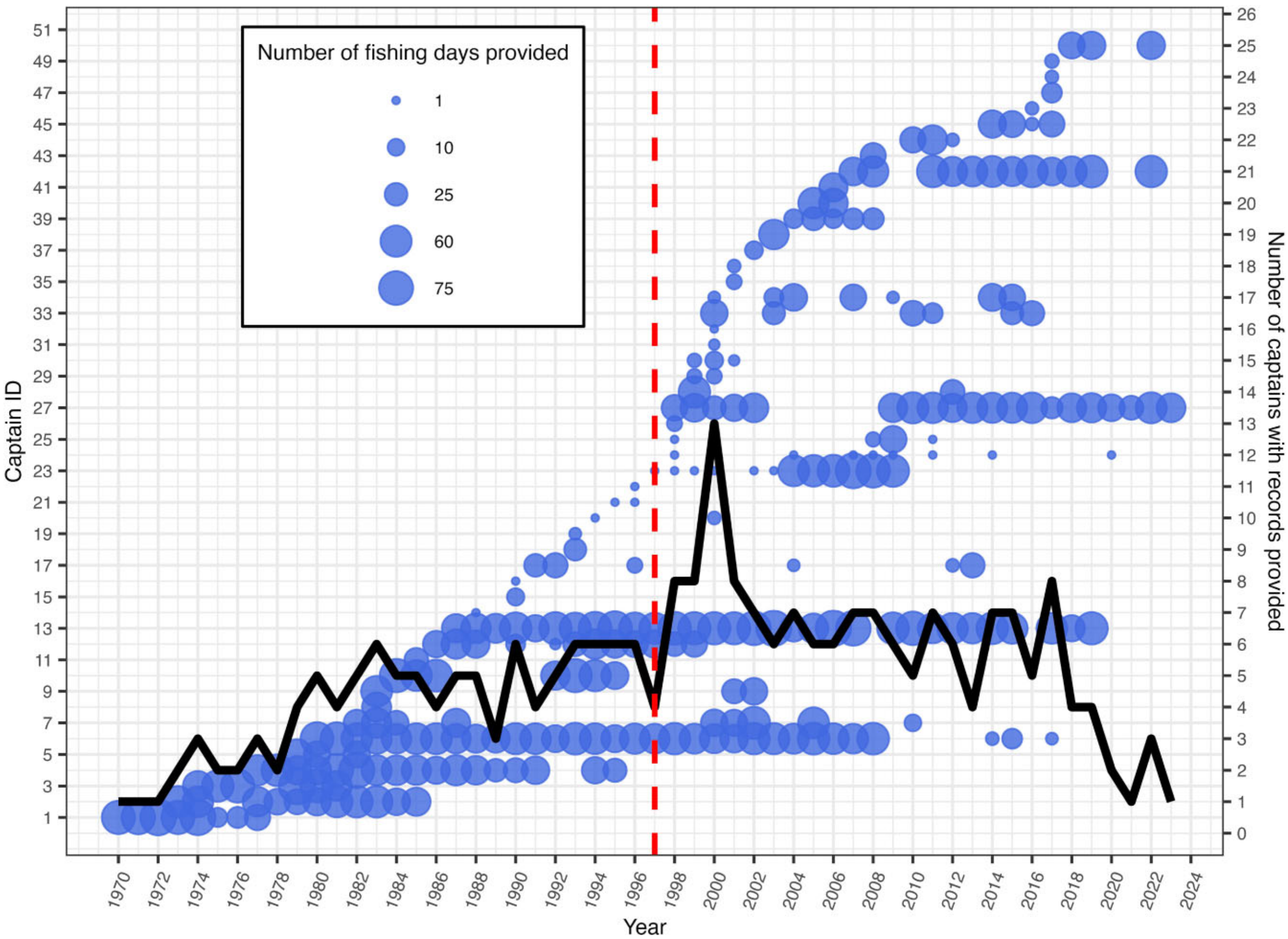

Figure 3. The number of captains represented in personal diary/logbook data each year (season), ranked by the year that they first provided records. The size of the blue circles indicates the number of fishing days provided each season. The solid line and the right-hand axis indicate the number of captains represented in records each year. The dotted line indicates the periods covered by the Campbell et al. (2003) study (to the left of the line) and the current study (to the right of the line).

Table 1. Statistics of the numbers of boats, diarists, captains, and total fishing days covered by the diaries, notebooks, and logbooks received.

Period	Boats	Diarists	Captains	Days
1970–1997 Daily records original study	18	10	9	4 022
1970–1997 New daily records	37	12	20	1 186
1970–1997 Season summaries	1	1	1	40
1998–2022 Daily records	40	13	31	5 553
1998–2022 Season summaries	6	2	2	812
1970–2022 Daily records	66	23	51	10 761
1970–2022 Season summaries	6	2	2	852
1970–2022 Totals	66	23	51	11 613

Overall number of captains and boats represented is greater than number of diarists due to some deckhand keeping diaries on multiple boats. Most records extracted were on a daily basis, although two captains also provided some season summaries of total days fished and catches of marlin, but not daily catches for those seasons.

the northern extent of the fishery (Fig. 7d). The fishing season in each year extended from September to December with the highest CPUE occurring in October and November, following which CPUE declined in December (Fig. 7b). The model estimates demonstrated there was not a significant difference between the effects of September and December factor levels on CPUE (Table 3). This is likely due to the lower number of fishing days that occurred in December and a greater level of CPUE variability estimated for this factor level in the model (Fig. 7b; Fig. 8) Many captains had similar marginal effects on CPUE, although variation existed with some captains having higher or lower effects on CPUE than the broader group. This result corresponds with the nominal CPUE calculated for each captain (Figs 6 and 7f).

Three environmental variables had distinct effects on CPUE. Meridional velocity had a linear trend with CPUE increasing with the strength of northwards currents (i.e. positive values of geostrophic velocity anomalies) (Fig. 7a). Moon phase had a non-linear relationship with higher CPUE during a half moon and approximately 30%–40% lower during new or full moons (Fig. 7e). Lastly, SOI had a strongly non-linear relationship with the lowest CPUE occurring during El Niño

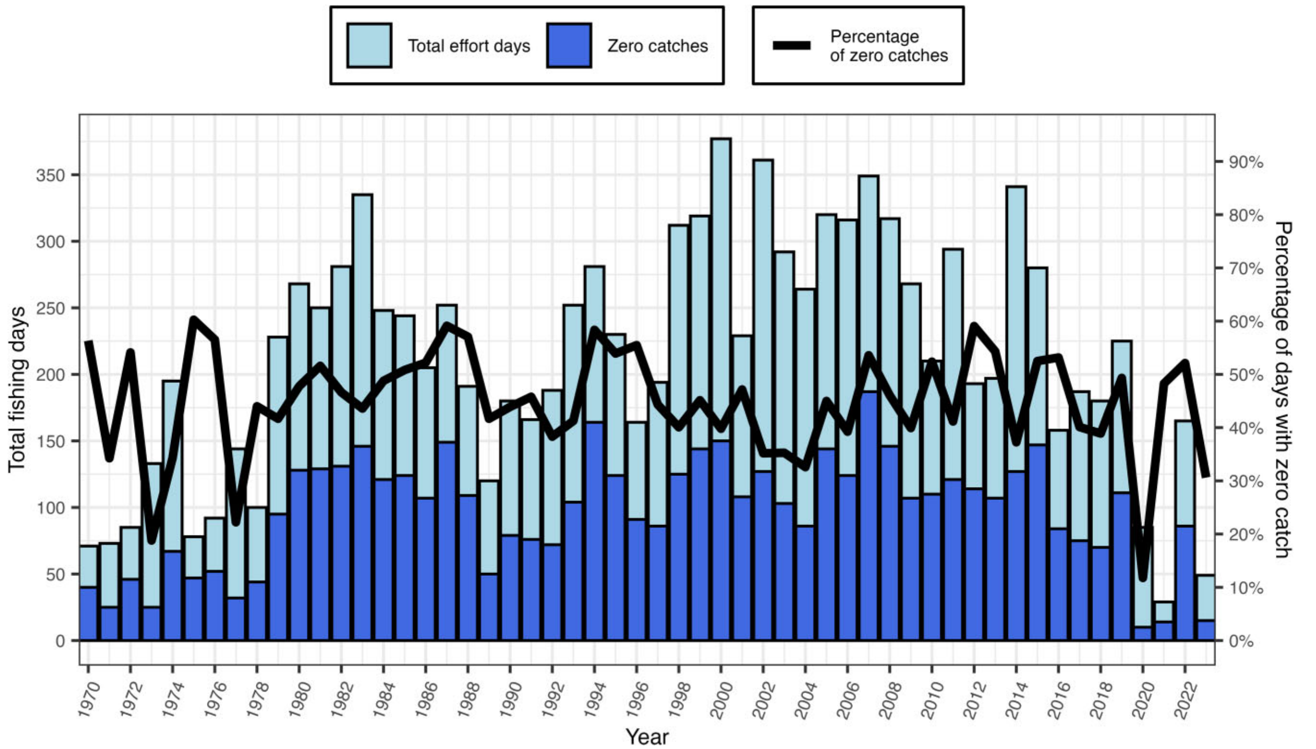

Figure 4. Annual reported fishing effort (boat days targeting black marlin) grouped by zero and non-zero catch days. The percentage of zero catch days is shown by the black line and the right-hand axis.

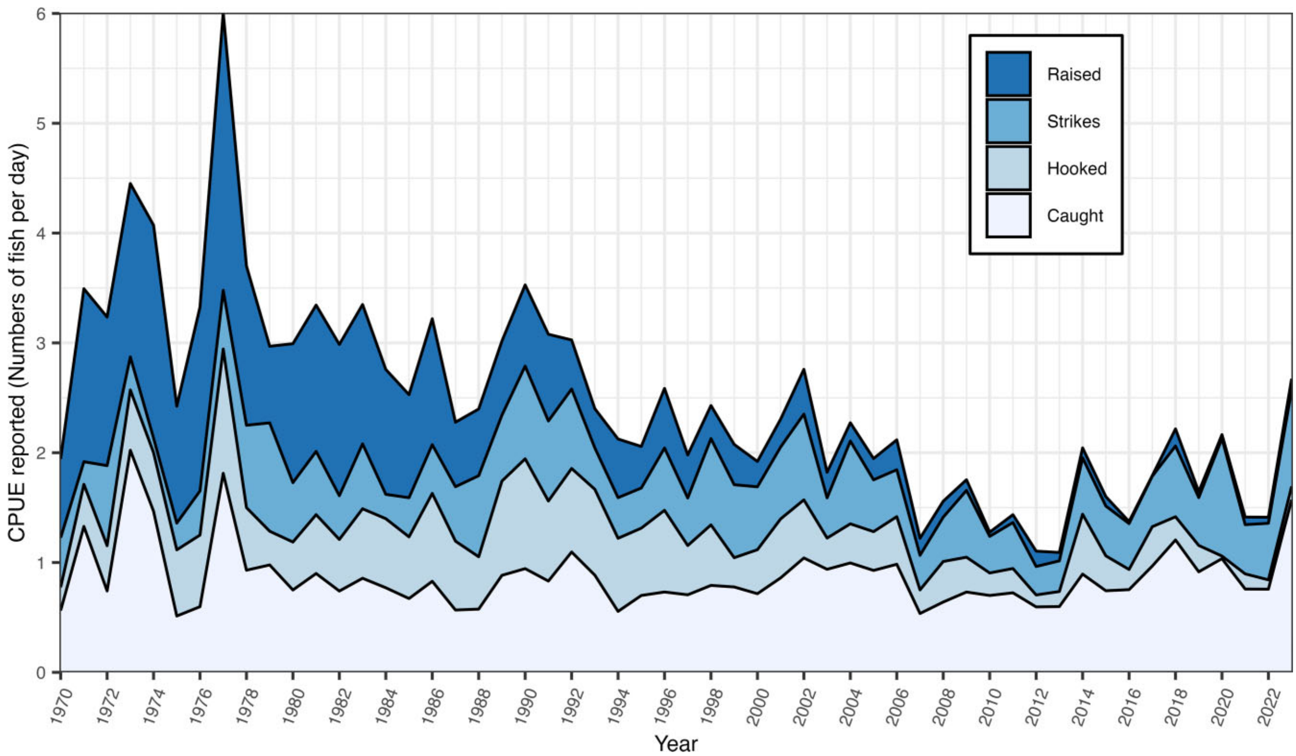

Figure 5. Nominal catch per unit effort (CPUE) of each interaction type. Note that not all diarists recorded each category of interaction for each fish encountered, but all diarists did record the number caught.

events (SOI lower than -7) and highest during La Niña events (SOI greater than 7; Fig. 7c). Between these values, there was a non-monotonic relationship between CPUE and SOI with a peak occurring at negative SOI values occurring just after to the onset of El Niño events and a low point that occurred just before the onset of La Niña events (Fig. 7c).

Sea surface temperature (SST) was not included in the final model based on AICc (Table 1). Interestingly, when the

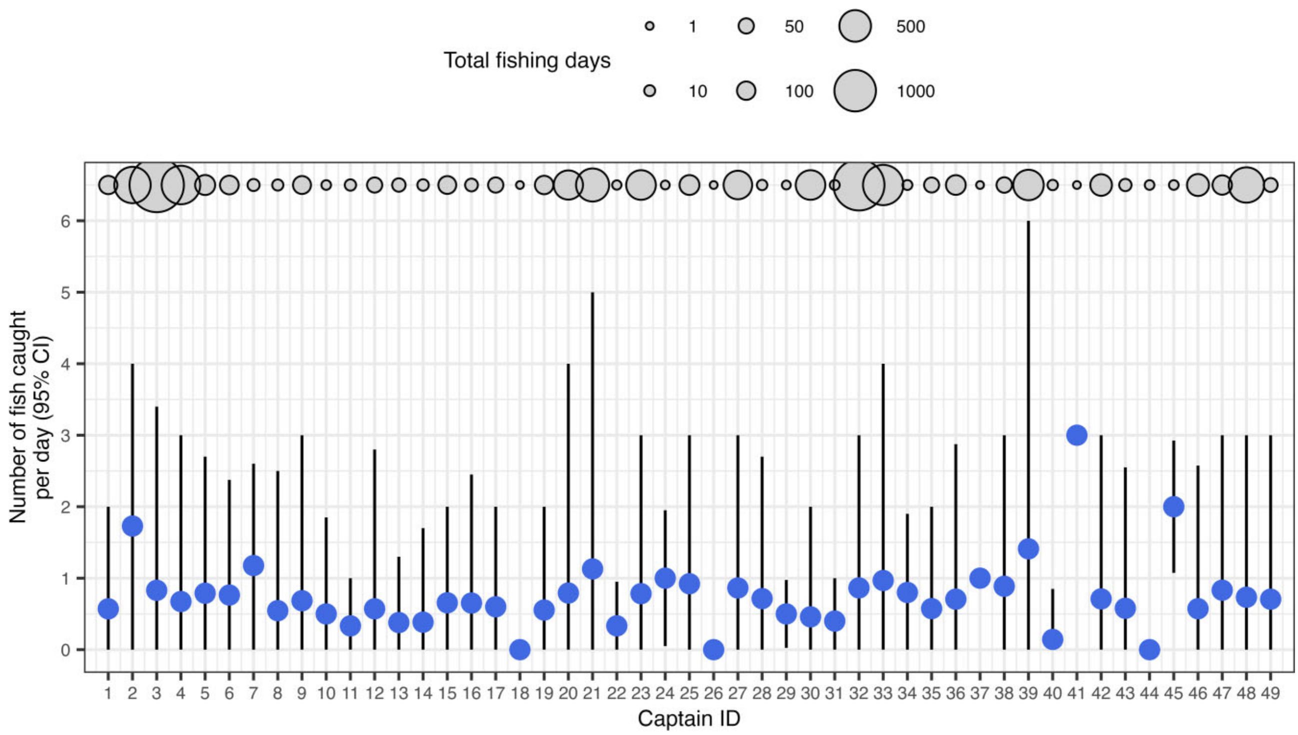

Figure 6. Average annual nominal CPUE (± 95 confidence intervals) for each captain (points with black bars representing the mean). The number of fishing days (i.e. records) provided by each captain is shown as bubbles at the top of the figure. Captains with a point but no crossbars only contributed one record.

Table 2. Model selection results for the CPUE GLMM.

Model rank	Model terms	df	AICc	ΔAICc	Weight
1	$CPUE_{N.caught}$ ~ Year + Month + s(SOI) + Latitude + Meridional.velocity + s(Moon_illumination) + (1|Captain)	42	12 220.5	0	0.47
2	$CPUE_{N.caught}$ ~ Year + Month + s(Rainfall) + s(SOI) +Latitude + Meridional.velocity + s(Moon_illumination) + (1|Captain)	44	12 223.2	2.56	0.12
3	$CPUE_{N.caught}$ ~ Year + Month + s(SST) + s(SOI) +Latitude + Meridional.velocity + s(Moon_illumination) + (1|Captain)	44	12 223.3	2.78	0.12
4	$CPUE_{N.caught}$ ~ Year + Month + Latitude + Meridional.velocity + s(Moon_illumination) + (1|Captain)	40	12 223.3	2.99	0.12
5	$CPUE_{N.caught}$ ~ Year + Month + Latitude + Meridional.velocity + s(SST) + s(Moon_illumination) + (1|Captain)	42	12 224.7	3.82	0.06
Full model	$CPUE_{N.caught}$ ~ Year + Month + s(Rainfall) + s(SOI) + Latitude + Meridional.velocity + s(SST) + s(Moon_illumination) + (1|Captain)	46	12 225.9	5.4	0.03

The five best-performing models of the 256 model candidates are presented, along with the results of the full model. The model rankings are determined by the model with the lowest AICc. Any models with ΔAICc >2 are considered to be outperformed.

marginal effects were examined for models that included SST, this variable became linear with a flat slope, despite the univariate relationship with CPUE being non-linear and appearing significant (Supplementary Fig. S3). Further interrogation of the independent variables showed a strong relationship between month and SST, as well as a weak relationship with latitude band (Fig. 8). Therefore, given that CPUE was lowest in September and December and highest in

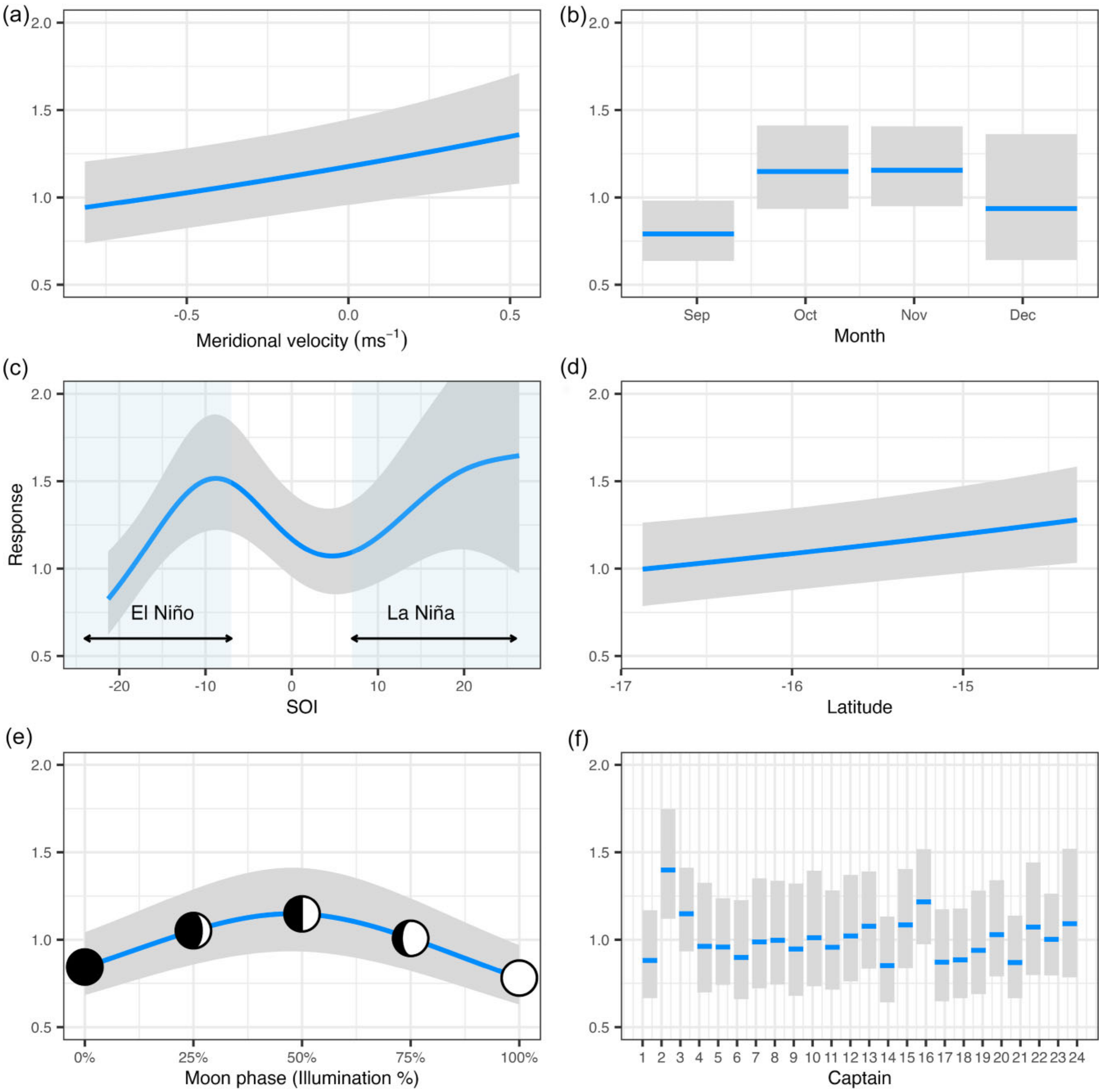

Figure 7. The marginal effect sizes of environmental variables (left column) and catchability variables (right column). The line represents the model estimate of each predictor variable on the response ($CPUE_{number.caught}$) when all other variables were held constant. The shading represents the standard error of those estimates. Variables with crossbars (Month (d) and Captain (f)) were treated as factors in the GLMM, while all other variables were continuous. The Captain IDs displayed for that variablem(f) do not relate to those of Fig. 3 to maintain anonymity. All variables are centred on a mean of 1 to allow for direct comparisons between them.

Table 3. Model estimates of the CPUE GLMM for the fixed effects with 'Year' excluded due to the number of levels.

Variable	Estimate	Standard error	Z Statistic	*P* value
Intercept	2.94	1.61	1.97	**0.04**
Latitude	1.10	0.04	2.82	**<0.01**
Month 10	1.45	0.09	5.74	**<0.01**
Month 11	1.46	0.10	5.82	**<0.01**
Month 12	1.18	0.21	0.94	0.33
Meridional.velocity	1.31	0.12	3.07	**0.00**
s(Moon_illumination)	0.94	0.03	-2.03	**0.04**
s(SOI)	1.48	0.18	3.30	**<0.01**

The estimates and standard errors are on the natural scale and provided for the continuous variables (latitude and Meridional velocity), month as a factor and the continuous variables fit using splines (SOI and moon illumination). The month of September is not presented as it is represented by the Intercept. Variables were considered significant according to $\alpha = 0.05$ and *P*-values in bold indicate significance at this threshold.

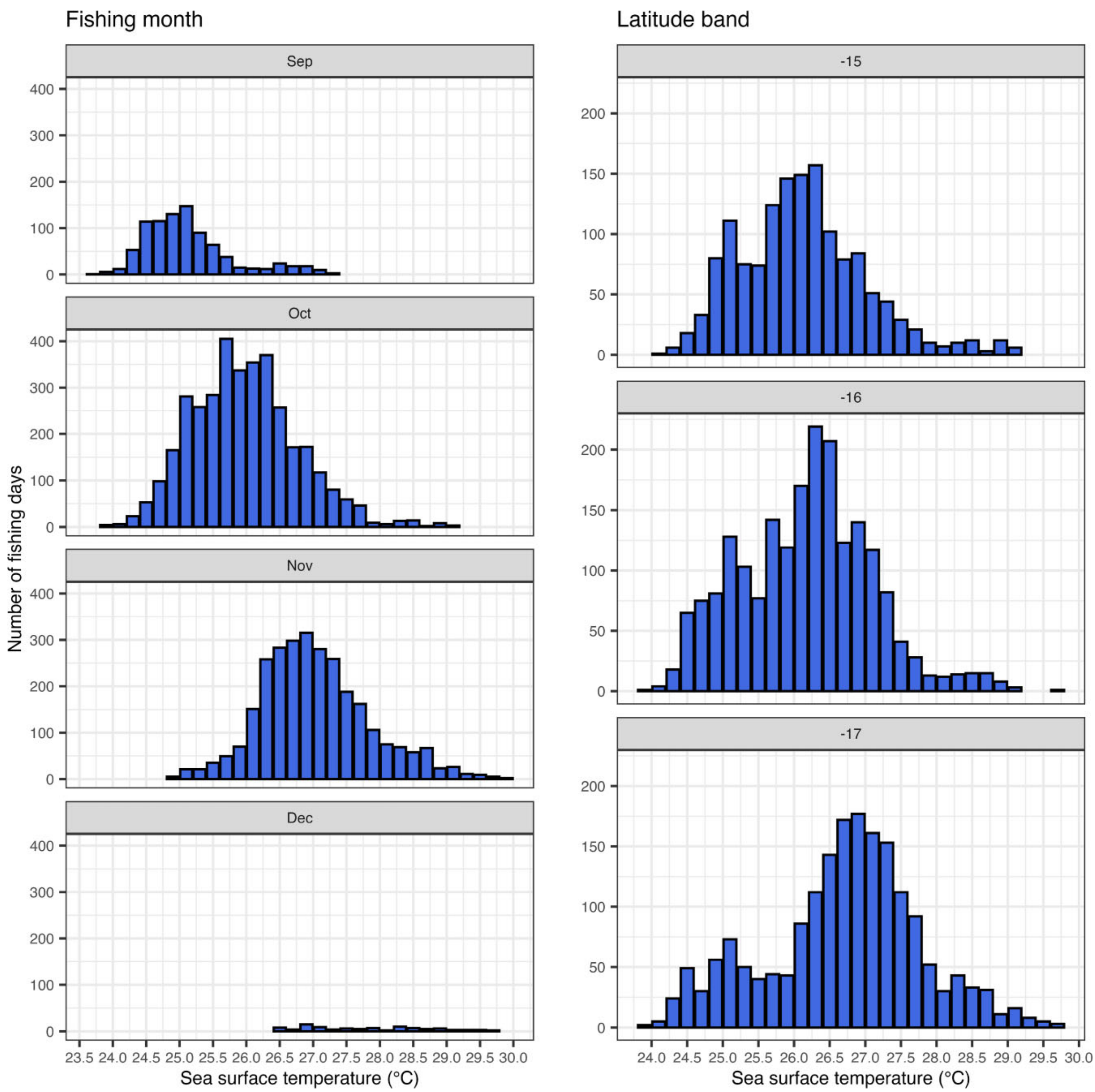

Figure 8. Histograms of sea surface temperature (°C) of daily records lumped for all years and grouped by month (left) and latitude (°N) band (right).

October and November, it appears that the initial non-linearity determined for SST was actually an effect of fishing month (Supplementary Fig. S3, Fig. 7b, Fig. 9). Therefore, SST was not included in the best-fitting model with this variation in CPUE attributed to month and, to a lesser extent, latitude band (Fig. 8).

The year effect variable and its standard error were used to infer an index of abundance from the CPUE data (Fig. 9). The standardized index closely matches the nominal CPUE when the two are overlaid over corresponding years. Use of a LOESS smoother fit to the nominal CPUE data demonstrates the overall trend in abundance within considerable inter-annual variability. This demonstrates the declining CPUE that occurred from 1970 through to the late 1990s prior to an increasing trend occurring from this point until 2023 (Figs 5, 9).

Discussion

Structured diary systems have been used to measure catch and effort in some recreational fisheries, both small scale (e.g. Conron et al. 2018, Holdsworth and Saul 2019) and large scale (e.g. Henry and Lyle 2003). However, those were pre-designed and relied on recruitment of anglers to the survey and regular formal contact with volunteer diarists to interview them regarding fishing effort and catches. In the case of the present study, it is entirely fortuitous that captains and crew kept their own personal daily records of interactions and catches of black marlin in a well-defined fishery, in many cases spanning multiple seasons. It is also fortunate that diarists recorded their daily data in a similar manner, recording dates and locations of fishing together with interactions with the single target species (black marlin) in a well-understood

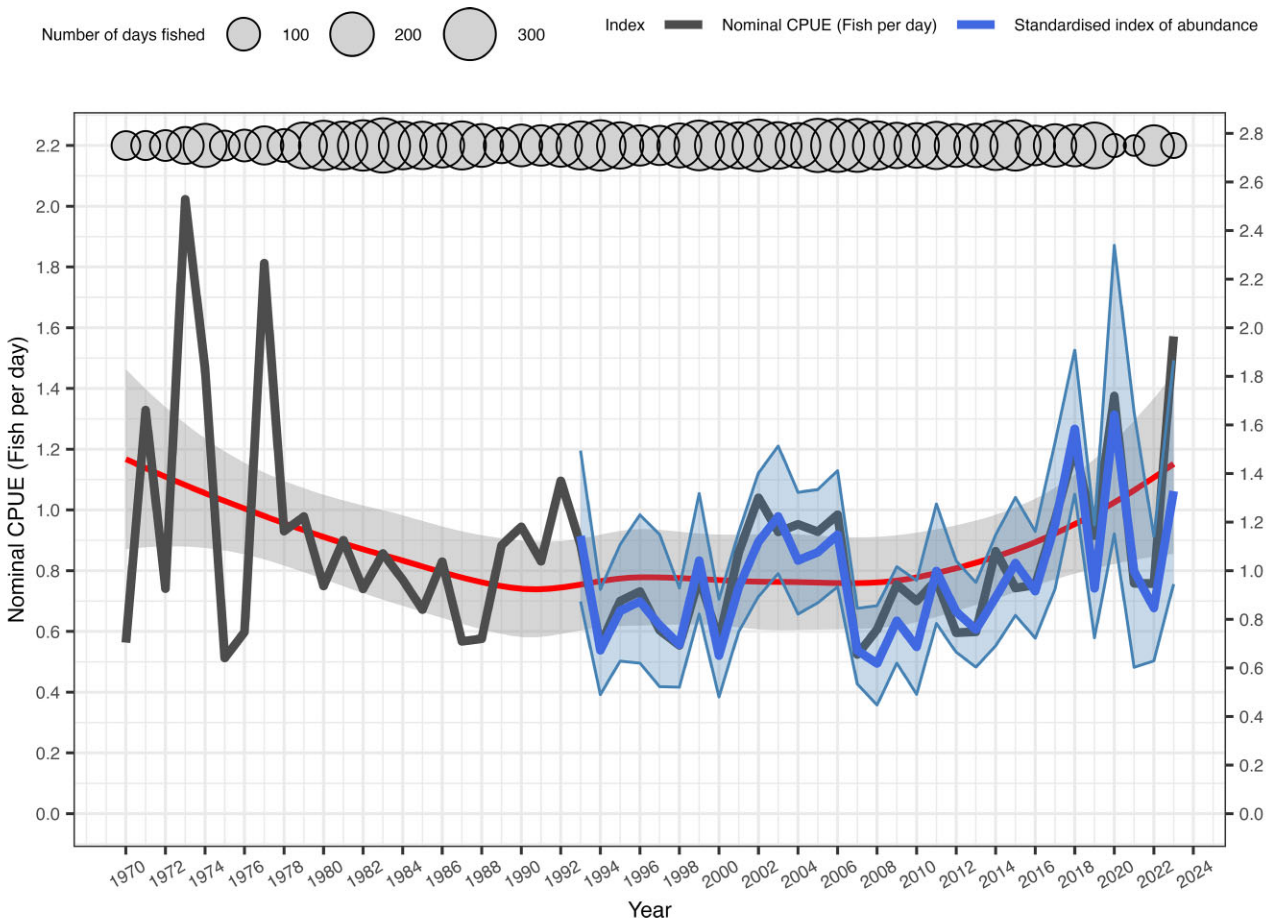

Figure 9. The nominal CPUE (black line) and standardized CPUE (blue line) for black marlin from 1970 to 2023. The grey circles above the plot show the number of fishing days per year. The standardized CPUE with its standard error (blue shading) has been centred on the nominal CPUE for comparability (right-hand axis). A LOESS smoother (red line and grey shading) has been fitted to the nominal CPUE as a trend line.

shorthand system. The diaries, notebooks and logs examined for this study were maintained for personal purposes, and as such, can be considered free from any biases that might otherwise be the case for mandatory logbook systems. These data were sourced from a large number of highly active fishers, many of whom had long continuous careers in the fishery, covering many successive seasons. In CPUE analyses, these participants provide the most valuable information with less active members of the fleet often being dropped through data filtering rules. Therefore, the representativeness of these data means that they can be used to provide valuable a standardized index of abundance.

CPUE analysis

The standardized CPUE closely fit the nominal CPUE (Fig. 9), giving confidence that nominal CPUE calculated by Campbell et al. (2003) for the period before many environmental parameters were available was a reasonable proxy for an abundance index. The results indicate high interannual variability of CPUE, particularly during the early 1970s. Nominal and standardized CPUE then showed a decline to the mid/late 1990s (as suggested by captains at the time), continuing at relatively low levels in the present study until 2001. There then followed 6 years of relatively high catch rates (near 1.0 fish per day), a marked drop to the second lowest rate in 2008, and then a variable but steady average increase to the end of the series in 2023. These results indicate, with caveats below, that personal fishing records may be used to demonstrate fluctuations in stocks, in this case recording a decline and recovery that may not be able to be determined from other data. If there was a low degree of variability within the nominal CPUE data, then this may demonstrate precise trends in population abundance. However, the abrupt fluctuations in different years (such as those during the 1970s) suggest that a large amount of variability remained unaccounted for in the nominal CPUE data.

The fishery coincides with an annual aggregation of black marlin, long suspected of being a spawning aggregation (Howard and Ueyanagi 1965, Nakamura 1975, 1985) and more recently shown to be the case (Domeier and Speare 2012). Given the broad size distribution of black marlin caught in this fishery (70–650 kg; Pepperell 1990), it is clear that multiple year classes of fish are present on the grounds each year rather than single modal cohorts. In that case, the expectation would be for less fluctuation in year-to-year abundance than that seen in the data, even if there is year-to-year variability in recruitment. Recaptures of tagged fish on the spawning grounds after multiples of 12 monthly intervals indicate at least some level of annual philopatry (Squire and Neilsen 1983, Pepperell 1990, Domeier and Speare 2012), but the question remains as to the representativeness of the indices of abundance of fish on the spawning grounds to the entire stock. Given there are no other known sites for aggregations of adult black marlin of this magnitude in the southern Pacific, it is a reasonable working assumption that the long-term trends in the index of abundance shown here may reflect trends in the overall stock over time.

In any case, given the level of variability remaining in the index of abundance derived from the standardized CPUE, the results of this analysis are especially useful for understanding the environmental and fleet dynamic effects (month, latitude, and captain) on CPUE. However, accounting for these factors did not ultimately affect the standardized CPUE time series, suggesting that nominal CPUE has a strong signal from the overall abundance trends. This demonstrates that the longer period can be considered as an index of abundance since a lack of environmental variables from the earlier era (1970–1992) is unlikely to have led to a substantially different trend if standardization were possible for those years. This result, therefore, increases the usefulness of the logbook data collected from these captains over this extended period, as it allows a longer time series of abundance information to be considered.

Environmental influences on catch rates

Reinforcing the results of the previous study (Campbell et al. 2003), moon phase had a strong effect on CPUE over the entire time series, with higher catch rates occurring on the half-moons compared with new and full moons (Fig. 7e). The possible reason for this effect, as suggested in Campbell et al. (2003) is that tidal movement is greatest on ‘spring tides’, around new and full moons, causing greater volumes of water to flow out on ebb tides from the GBR lagoon through the relatively narrow reef passes. This means that, on spring ebb tides, plankton-rich ‘green’ water, and post-rain lower salinity water extends well out to sea from the reef edge. The general consensus among captains is that black marlin tend to avoid such coloured water, preferring clearer, blue oceanic water.

Other studies on the effects of moon phase on catches of marlin species have produced equivocal results. Lowry et al. (2007) found that recreational catch rates of black marlin increased to a peak between full moon and the last quarter; however, their data were derived from tournaments off southeastern Australia, where black marlin encountered are juveniles (<100 kg) occurring inside the continental shelf break. Shimose et al. (2013) found that diurnal catches of blue marlin in a commercial troll fishery off Yonaguni, Japan significantly increased around the full moon. These studies speculated on possible effects of lunar illumination on feeding behaviour, whereas Ortega-Garcia et al. (2008) found no effect of moon phase on catch rates in a recreational fishery for striped marlin off Baja California. Our finding of higher CPUEs on half-moons would support the tidal hypothesis rather than possible effects of lunar illumination.

Previous CPUE analyses for the fishery (Campbell et al. 2003) found a relationship between SST and CPUE. This demonstrated that in November, CPUE increased with SST up to approximately 26.5°C after which CPUE declined. However, in the present study CPUE did not have a significant relationship with SST. The initial inclusion of SST in the full model demonstrated a weak linear relationship with CPUE, rather than the parabolic one determined by Campbell et al. (2003). This occurred as SST increased linearly with month of the year when temperatures increased over the fishing season (September to December). However, as the fishing season ends in December when CPUE decreases (as seen here and in Campbell et al. 2003), the GLMM in the present study attributed this decline in CPUE to the late stage in the season, rather than higher SST. Similarly, SST was linearly correlated with latitude, where CPUE increased as fishing occurred further north. Therefore, the model again detected a weaker SST effect given that stronger effects were estimated for month and latitude.

Other studies have inferred effects of SST on movements of black marlin. Domeier and Speare (2012) analysed SST data from popup satellite archival tags (PSATs) deployed on black marlin by charter boats off the GBR. They found that tagged fish tended to remain within the northern half of what they termed the Great Barrier Reef Environment (GBRE)—a much larger area than the charter fishing grounds—during October and November, but then dispersed southward with SSTs of 26–27°C SST. The mean SST experienced by PSAT-tagged fish within the GBRE was 25.6°C in October, 26.4°C in November and 27.4°C in December. Similarly, Williams et al. (2017) found SST and mixed layer depth to be associated with the vertical habitat use of black marlin off the Great Barrier Reef. It was shown that greater times were spent at depth when SST was in the range of 26–28°C.

Hill et al. (2015), using release positions of 18 717 black marlin tagged by recreational fishers between 1998 and 2013 off eastern Australia, found a southerly shift in the geometric mean of modelled ideal black marlin habitat occurring at a rate of 88.2 km per decade. However, sea surface temperature (SST) was only a minor (4%) contributor to the model of suitable habitat. There is little doubt that the fishing grounds off the GBR would undergo changes in SST through the time period of this study (53 years); however, there was not one season in which black marlin failed to aggregate in the region.

We found a strong non-linear relationship between CPUE and Southern Oscillation Index (SOI) with highest catch rates occurring during La Niña events and lowest during El Niño events. A possible explanation for this is that eastward-flowing currents in the western Pacific are strongest during El Niño conditions, which may influence the movements of black marlin onto and away from the spawning grounds in the northwestern Coral Sea. Hill et al. (2015) found that interannual variability of black marlin preferred habitat correlated with ENSO events, with presumed ideal habitat extending up to ~300 km further south during La Niña events. However, a key difference between Hill et al. (2015) and this study was their focus on sub-adult fish, rather than adults that would have predominantly contributed to the records in this study. In the eastern Pacific Ocean, Farchadi et al. (2018) found that during La Niña events, habitat suitability of both black and blue marlin extended well offshore along the equator, whereas during El Niño events, suitable habitat shifted nearshore to more northern and southern waters of the eastern Pacific Ocean. They further found that the strength of ENSO events had a strong influence on shifting the distribution of both marlin species closer or farther from the coast, which may be one aspect of the effect found in this study.

Current strength and velocity

CPUE was higher when currents flowed from south to north, and with stronger currents in that direction. It is not clear why this should be so, but it might be speculated that it would be disadvantageous for the tropical larvae of black marlin to be swept well to the south into unsuitable habitat. The only black marlin larvae sampled off eastern Australia have been found in tropical latitudes off the GBR (Ueyanagai 1960, Nakamura 1975, Leis et al. 1987, Domeier and Speare 2012). Another factor may be prevailing 'trade' winds, which are predominantly from the southeast during the black marlin season. Such persistent winds drive surface currents and increase turbulence at the surface. Rough conditions are thought to bring the black marlin to the surface to feed, as observed by specialist Taiwanese harpoon fishers (W. Chiang, pers. comm.) and captains in the charter fishery (L. Wright, P. Bristow, pers. comm.).

Changes in fishing gear and techniques through time

In any fishery, especially over a long period of time, changes in fishing gear, technology and expertise may increase the efficiency of targeting and catching the prime target species. This is just as true for commercial fisheries (Bishop 2006) as it is for recreational fisheries (Cooke et al. 2021). For these reasons, when the timings of such changes are able to be documented, catch rates may be standardized to allow for such increases in effective effort and thus derive more realistic indices of abundance (Hoyle et al. 2014, Hoyle et al. 2024). Care needs to be taken, however, to account for technical and methodological changes in the fishery that are not captured by logbook data alone (Bishop et al. 2008).

Having noted above the consistency in basic gear and methods used in this fishery over its long history, a number of important changes have occurred over time. These include type of hook used, number of baits trolled, and use of electronic equipment, including GPS, chart plotters and sonar. These are described in detail in the Supplementary Materials.

Attempting to accurately document such changes through time, so that standardization of CPUE with respect to gear and techniques could be attempted, is a difficult task and outside the scope of the present study. It would be difficult to establish the extent of these changes through the fishery, and to define the time periods when these occurred. Such a study may be possible with the help of long-term captains and crew of this fishery, and a scoping study is therefore recommended to determine likelihood of success of such an undertaking. As a general comment, at least some of the identified changes are likely to have enhanced fishing efficiency, and therefore help explain to an uncertain degree the increase in catch rates in the fishery since the mid-2000s.

Potential for stock assessment

While the stock structure of black marlin in the Pacific is not fully understood, recent evidence points to the increasing likelihood of the existence of at least two stocks. Black marlin tagged off eastern Australia have been recaptured widely throughout the Pacific Ocean (Pepperell 1990, Ortiz et al. 2003, Domeier and Speare 2012). Such broad dispersal led to assumptions of a panmictic Pacific stock. However, the confirmation of the presence of distinct black marlin spawning grounds in the northwestern Coral Sea (Domeier and Speare 2012) and the south China Sea (Sun et al. 2015) along with the identification of a separate Indian Ocean stock (Williams et al. 2015) together with global genetics evidence (Williams 2018), strongly support the existence of at least two separate stocks of black marlin in the Pacific Ocean, one in the northern Pacific and one in the southern Pacific. With confidence in this evidence, a stock assessment for black marlin for this region is strongly recommended, an assessment that should benefit substantially from the present study.

Conclusions

Following similar methods to the study of Campbell et al. (2003), the present study was successful in expanding the collection and utilization of daily records of black marlin fishing effort and catch that had been recorded in diary or note form for personal use by charter captains and deckhands. These data yielded nominal CPUE from 1970 to 2023, standardized CPUE from 1993 to 2023, serving as an abundance index. While annual CPUE in the fishery has fluctuated over time, data from the most recent 17 years show a continuing increase of the abundance index, likely indicating the stock to be in a sustainable state. However, it is also likely that adoption of new gear and techniques in the fishery over its history has contributed to this increase in standardized CPUE, but to what extent is unknown. It is recommended that the results of this work, which provides a relative index of abundance of black marlin over five decades, be used for input into any stock assessments of this important species that may be undertaken in the future.

Acknowledgements

We are most grateful to the Ocean Health Foundation, the Cairns Professional Game Fishing Association, the Game Fishing Association of Australia and the Queensland Game Fishing Association for funding this work.

Sincere thanks to the following Captains and crew who kindly provided access to their personal diaries, notebooks and logs: Ben Bright, Peter Bristow, Simon Carosi, Brad Craft, Barry Cross, Jim Dalling, Bill Edwards, Greg Edwards, Luke Fallon, Dean Ford, Gordon Hallam, Darren Haydon, Dennis Hayes, Col Grimes, Bob Jones, Noel Jones, Tim Richardson, Bill Spooner, Dennis Wallace, Laurie Wright.

Kelly Dalling-Fallon canvassed many captains and deckhands and provided contact details to the lead author. We also thank her for entering data from diaries of Captain Luke Fallon covering 19 black marlin seasons between 1998 and 2023 and for maintaining blackmarlinblog.com.

Special thanks are due to Holly Moore, daughter of the late Captain Bill Billson, for allowing access to her father's remarkably detailed diaries, covering consecutive black marlin fishing seasons from 1987 through 2019. Also to Col Grimes who provided daily records for black marlin fishing seasons from 1983 through 2022 while working as deckhand on 24 boats under 24 captains. Thanks also for insights into changes in fishing gear and methods through time to Laurie Wright, Ben Bright, Tim Simpson and Col Grimes.

Lastly, thanks to Laura Smith and Jessica Bolin for providing R code for accessing environmental data from online databases.

Author contributions

Jonathan Smart (Data curation [supporting], Formal analysis [lead], Methodology [equal], Writing – original draft [supporting], Writing – review & editing [supporting]), Barrett W. Wolfe (Formal analysis [supporting], Methodology [supporting], Writing – original draft [supporting], Writing – review

& editing [supporting]), Samuel M. Williams (Methodology [supporting], Validation [supporting], Writing – original draft [supporting], Writing – review & editing [supporting])

Supplementary data

Supplementary data is available at *ICES Journal of Marine Science* online.

Conflict of interest: None declared.

Data availability

The data underlying this article were provided by third parties. Data will be shared on request to the corresponding author with permission of these third parties.

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Handling editor: Kieran Hyder