STANDARDISATION OF SIZE-BASED INDICATORS FOR BROADBILL SWORDFISH IN THE INDIAN OCEAN

Natalie Dowling and Marinelle Basson
CSIRO Marine Research, Castray Esplanade
Hobart 7000, Tasmania
Australia

ABSTRACT

Information on the size distribution, for example mean length, in the catch can potentially be used as an indicator of swordfish stock status. This study looked at the standardisation of such indices particularly for spatial and seasonal effects. Standardization of size-based indices smoothed temporal trends that were evident in the nominal data, largely by accounting for the significant effect of area. Nominal peaks in the early and late 1990s were dampened, such that the standardized indices showed no overall temporal trend. GLMs indicated a strong effect of area on the size-based indices that predominated over the quarterly effects. This is to be expected from a species with size-based spatial segregation. The lack of a significant quarter effect was consistent with the lack of evidence of seasonal swordfish spawning or migrations. An increase in the inter-annual variability in the proportion of large fish since 1990 was a feature of the combined data. The increased variability was not smoothed by standardisation, and may be a feature warranting closer attention, or may simply be an artefact of lower sampling intensity. It was noted that the length-based swordfish indices did not show the pattern of decrease observed for the standardized CPUE trends in various sub-regions. These results contrasted with those from the Mediterranean Sea, where CPUE has remained stable but mean size has decreased.

INTRODUCTION

Large pelagic fisheries, such as the Indian Ocean longline fisheries for tuna and billfish, are typically data-poor in terms of fisheries-independent sampling and/or abundance surveys, with the consequence that stock status has to be indirectly inferred, whether from empirical indicators or formal stock assessment models using only fisheries dependent data. Of the main species caught on longlines in the Indian Ocean, broadbill swordfish (*Xiphias gladius*) are considered the most vulnerable to overexploitation, due to their relatively lower productivity, longer life span and hence time to mature, and their apparent higher viscosity (Campbell et al. 2003; Fonteneau and Richard 2003; Ward and Elscot 2000). Moreover, CPUE-based analyses have suggested that broadbill swordfish are almost fully exploited in longline fisheries across most oceans (IOTC 2003).

Attempts have been made to fit age-structured production models to Japanese and Taiwanese swordfish longline data in the Indian Ocean, but these have been relatively unsuccessful, largely due to a lack of contrast in, and/or contradictory catch-per-unit-effort (CPUE) indices of abundance, and a rapid increase in catch in the 1990s that could not be easily resolved by the models (Yokawa 2001; IOTC 2001). Additional problems were that swordfish were generally not a target species of the Japanese and Taiwanese longline fleets, targeting practices shifted over time, the higher degree of residency suggests multiple stocks and requires appropriate area stratification

(Yokawa, 2001; Campbell and Hobday 2003), and that there is a lack of biological knowledge about the species in the Indian Ocean.

Given the lack of feasibility of formal stock assessments for swordfish, simple indicators from fishery data are increasingly used to evaluate stock status. With the imminent introduction of Total Allowable Catch (TAC)-based management plans for the Australian domestic fishery, and the suspected vulnerability of swordfish to overfishing, there is a need to develop and test suites of stock indicators. As many different factors could be responsible for changes or trends in these indicators, it has been argued that they should ideally be standardised, in the same manner that commercial longline CPUE is standardised. If, for example, a stock is spatially disaggregated by size, changes in the timing and location of a fishery could lead to a change in the mean length in the catch that may be unrelated to a change in the underlying size distribution of the overall fishable stock.

In the face of data availability, obvious simple indicators additional to CPUE are those based on size-frequency data. Indeed, the Report of the 3rd Session of Indian Ocean Tuna Commission (IOTC) WP Billfish (2003) recommended that size-based indices for the whole fishery and by area should be considered. At high harvest rates large, old fish are generally the first to be depleted (ITOC 2003), and an absence or decrease of these fish could be reflected in the size frequency data. Monitoring size-based indices could therefore provide information on changes in the underlying population structure, as illustrated by Froese (2004) for cod stocks. We note that Punt et al (2001) found that upper percentile weight for swordfish catch in the western Pacific was a more sensitive indicator that mean weight or length; however, only length data are available from the IOTC.

In this study we develop standardised length-based indices for swordfish in the Indian Ocean, and contrast these with results from CPUE standardisations. The mean, median and upper 80th percentile length from the length-frequency data are considered. Due to the suspected higher residency of swordfish relative to the tunas, we also considered trends within sub-regions that showed patterns of decline in standardised CPUE.

This work is part of a wider study on stock status indicators, that will use simulation to investigate the robustness and sensitivity of a range of indicators, and to develop ways of combining several such indicators into a coherent framework for management decision-making. The study is addressing these issues primarily in the context of the domestic (Australian) fishery, but also in the wider context of the IOTC. Simulation work may indicate that mean length is insensitive to stock changes (see e.g. Punt et. al. 2001), and that some other measure, possibly even based on data not currently available for the IOTC fisheries, may be more reliable. Hence the current results should be viewed in this wider context as an exploration of the effects of, and need for, standardisation of indices based on existing data.

METHODS

Data

Quarterly, area-specific (on the scale of five-degree squares) lower *n*th percentiles, medians, means and upper *n*th percentiles were derived from the raw size frequency data held by the IOTC. Eye-fork length (EFL) data from the Japanese fleet was used since this contained the most records over the most number of years. We also considered the proportion of fish greater than 150cm EFL, chosen to reflect approximate size at maturity (Yabe et al. 1959; Nakano and Bayliff 1992; Di Martini 1999, Young and Drake 2002)

As with yellowfin and bigeye tuna (Basson and Dowling 2004), the similarity between annual values of mean, median, lower 20th and upper 80th percentile was such that standardisations were applied only to the mean length, and to the proportion of large fish. The proportion of small fish could also have been used as an aggregate index of recruitment, but was not considered here.

Standardisation technique

The methodology applied was analogous to that for bigeye and yellowfin tuna (Basson and Dowling 2004). General linear models were used for standardization, with time and area effects as the main covariates.

Spatial factors were considered for two reasons: 1) to account for changes in the fishing locations over time and/or 2) to account for changes in the size frequency in different areas over time. The second reason could be important for swordfish, which is now thought to have a potentially high residence time (Campbell and Hobday 2003). Different levels of fishing intensity in different areas could therefore have different effects on the mean size in the catch over time. This type of change is more likely to be observed at a relatively coarse spatial scale than a very fine spatial scale.

Incorporating environmental factors into this type of standardisation is considered inappropriate unless there is evidence of a plausible mechanism for catchability changing differentially by size under different environmental conditions. Otherwise, area or time factors should account for changes in size distribution associated with temporally or spatially varying environmental conditions (see Basson and Dowling (2004) for further detail).

Models for mean length and “proportion large”

Multiplicative models were used for mean length, with year and quarter as the main factors. The log of mean length is therefore an additive model of the relevant factors and we assume that errors are normally distributed. Several different spatial scales were considered. At the fine scale level, we used 10-degree latitude bands and the (5-degree resolution) lat-long grid positions for each quarter. On a broader scale, we considered the catch rate standardization areas (IOTC 2003) (Figure 1), with the notion that the areas were assigned on the basis of common fishery and/or other characteristics.

We also considered the Longhurst areas (Longhurst 2001), which supposedly represent "habitats” and may therefore contain fish of certain age or size classes, if distribution is driven by habitat preference.

During the exploratory phase, more complex models with main effects and interactions, for example, between year, quarter and area were fitted and compared to more parsimonious models. S-PLUS software was used and the model definitions were of the following forms:

Model type 1:glm(log(mean length) ~ year + area + quarter)

Model type 2 : glm(log(mean length) ~ year + area*quarter)

We also generated area-specific standardized size indices to enable comparison with the area-specific CPUE indices (IOTC 2003). Three areas in which Japanese CPUE had declined, and a “reference area” in which CPUE showed no temporal trend, were examined. Factors for the within-area models were year and quarter.

The 'proportion large' was fitted with a binomial model with logit link and factors were again time and the four different area definitions. The data were weighted by sample size, and the models were fitted to the subset of the data where sample size was greater than 10 (approximately the lower quartile of a summary of sample sizes across the whole data set).

Model selection

In fitting GLMs to the two indicators, the main aim is to eliminate changes due to seasonal effects or different locations of fishing, and to extract the year effects as standardized indices, rather than to determine statistically whether factors are significant. However, the goodness of fit of different models should be compared to avoid under- or over-fitting. Deviance residuals and q-q plots were used to evaluate goodness of fit, homogeneity of variance and extent of conformance to a normal distribution. Where models were nested, appropriate significance tests were used to compare them, but in the case of the binomial models, these are unlikely to be reliable because of over-dispersion. Where models were not nested, particularly where the different area-designations were used, Akaike’s information criterion (AIC) was used. The main priority, however, was to obtain the year-effects and determine whether they were sensitive to the different model formulations or variables included.

RESULTS

Nominal trends and exploratory analyses

The mean lengths by area, quarter and year were highly variable. The annual averages of mean length were also very variable, ranging between about 132 and 162cm EFL. Although there appear to be increases and decreases in the annual average series, and in particular, an overall increase from 1978 to 1999, with decreases in 1995 and since 1999, these should be seen within the context of the range of the size frequency. Figure 2a shows the annual averages (over location and quarter) of the mean and of the 20th and 80th percentiles. Changes in the mean (and median) time series were small relative to the inter-percentile range. Similarly, the decrease in swordfish mean size over the last 2 years appears relatively insignificant relative to the long-term pattern, and the size range. The inter-quantile range has not changed substantially over the whole period, varying between 31 and 56cm with no systematic temporal pattern.

The pattern of the nominal time series plot for the proportion of fish >150cm EFL was similar to that of mean length (Figure 2b), as would be expected. There were increases in the proportion of large fish in the early and late 1990s to historically high levels (to greater than 70% “large” fish), followed by a decreases to the pre-1990 levels.

Exploratory analysis was undertaken to investigate the effect of alternative temporal scales and area designations on the inter-annual trends. This included comparing nominal time series broken down by quarter and area to find any obvious patterns, and comparing standardised indices across alternative models. The following points summarise the minor findings from the exploratory analyses:

- Plots of mean length (and the other candidate indicators) over time and by the different area designations did not show any clear patterns to inform model choice. Plots were generally noisy, with missing data and much inter-annual variability.

- Figure 3 shows the mean length GLM year coefficients for 5 alternative model types/area designations. For both mean length and “proportion big”, the relative pattern of the year coefficients was very similar between model types and choice of area designation. The exception was the model using the Longhurst area, which did not appear to smooth/reduce the nominal increases in mean length observed in the early and late 1990’s. The Longhurst area of the Indian South Subtropical Gyre province (Longhurst 2001) incorporates the CPUE standardization areas 5 through to 9 (Figure 1). For GLMs using the CPUE areas, area coefficients were high for area 8, intermediate for areas 7 and 9 and low for areas 5 and 6 (Figure 5c). The larger Longhurst area perhaps could not reconcile these different effects within one area and standardize for them appropriately. Finally, although models with interaction terms sometimes gave a better fit to the data, the standardised indices were essentially unchanged.

- Models using the CPUE standardisation areas generally gave lower AIC values compared to those using other area designations. Therefore, only the main effects models using the CPUE standardisation areas are subsequently considered in detail. These models were also convenient in allowing for direct comparison with standarised CPUE trends.

GLM standardisation of mean length and proportion >150cm EFL

Results are presented for mean length modelled as:

$$\text{glm}(\ \log(\text{mean length}) \sim \text{year} + \text{CPUEarea} + \text{quarter}).$$

This model has a common spatial pattern for each year and a common quarterly pattern in each year and area. The standardized indices generally showed a similar temporal trend to the nominal pattern, except that the relative increases in nominal mean length in the early and late 1990s were dampened (Figure 4a). The standardised indices for the proportion of swordfish > 150cm EFL, using the same factors as the mean length model, showed no overall increase from 1980 to the early 1990’s, as was apparent in the nominal trend (Figure 4b). Standardised values varied about consistently higher proportions than the nominal values, particularly prior to the mid 1990s. The standardisation did not smooth the increase in inter-annual variability in the proportion of large fish that was observed since 1990.

Figure 5 shows diagnostics and results for the mean length model. Residuals did not show any systematic patterns, either overall or when plotted against each set of predictor variables. The q-q plot showed that the data were almost normally distributed, with deviation mainly at the lower tail. These large negative residuals persisted in models with interactions. The area coefficients were estimated relative to CPUE area 4 because this area had high levels of sampling over the whole time period (see Table 1). Note that area 8, in the middle of the southern Indian Ocean (Figure 1), had the highest-value coefficient, but this was based on a single, 1982 sample; hence the high standard error. Area 4, encompassing Indonesia and the northeast Indian Ocean south of the Bay of Bengal (Figure 1), has the lowest-value coefficient (Figure 5c). The quarter coefficients were small in value relative to the area coefficients, indicating a lesser relative effect on mean length (by approximately an order of magnitude). The highest-value quarter coefficient was in quarter 3, and the lowest was in quarter 2 (Figure 5d). The results imply a 7cm difference between mean length in quarter 2 versus quarter 3, and a substantial 60cm difference between mean length in area 4 versus area 8.

The trends in the area coefficients reflect the size segregation by latitude that has been observed for swordfish. Spawning occurs in tropical/sub-tropical regions where surface temperatures exceed 20°C, that is, in latitudes that rarely extend north of 35N or south of 35S (Ward and Elscot 2000). Juveniles are confined to these regions for at least their first year, and migrate to higher latitudes as they grow (Campbell and Miller 1998). Females attain larger sizes than males and occupy the highest latitudes of the range (Campbell and Miller 1998). In the northern Pacific, the average size of swordfish in longline catches increases with latitude for both sexes (DeMartini 1999). This is reflected in the values of the area coefficients of the mean length model, with these being largest for the higher latitude areas (Figure 1; Figure 5c). In the Indian Ocean, the greatest concentrations of larvae have been found in the eastern Indian Ocean, off of north-western Australia and south-west of Java (Nishikawa and Ueyanagi 1974), which is consistent with the adjacent area 4 having the lowest area coefficient. Larvae have also been reported in the Mozambique Channel, and east of Madagascar (Palko et al. 1981), and in equatorial waters (Nishikawa et al. 1985). Correspondingly, area coefficients were low in areas 3, 5 and 6, which encompass the equator and Madagascar.

Residuals for the model of proportion of swordfish >150cm EFL (again fitted relative to CPUE area 4) were also reasonably homoscedastic and close to normal (Figure 6), and showed no pattern when plotted against each set of predictor variables. Area 8 had no data (due to the sample size restriction on the model), so the value of the coefficient was automatically zero, with no standard error. Of the areas for which there was data input to the model, areas 7, 9, 10 (all south of 20°S) and 1 (north of 10°N) had the highest value coefficients, and hence higher proportions of large fish, while areas 4 and 5 (the latter in the western Indian Ocean encompassing northern Madagascar) had the lowest (Figure 6c). The lowest-value quarter coefficient was in quarter 2, while quarters 3 and 4 had the highest-value coefficients. Hence large fish appear to be caught in greater proportions in the latter half of the year (Figure 6d). As with mean length, the quarterly coefficients were of an order of magnitude lower value than the area coefficients, indicating a lesser effect of quarter on the proportion of large fish in the catch, relative to area.

As with the mean length, the area coefficients for the proportion large model reflect the size-differentiated spatial distribution of swordfish. The lowest proportion of “large” fish by area was lowest in the areas for which larval concentrations are highest, while the greatest proportions of “large” fish were associated with higher latitude regions, consistent with the observation that swordfish progressively migrate towards higher latitudes as they grow.

The standard errors of the standardised indices tended to be inversely related to sample size, in numbers of fish (Figure 7). This effect was more marked when weighting by sample size was used in the models. There is therefore less relative certainty associated with the standardised trends from more recent years, and this will have an effect on how such a series is implemented as a "stock status indicator". This comment also applies to the other standardised indices presented below.

Within-area analyses

At the 3rd Session of the IOTC Working Party on Billfish (2003) catch rate standardizations were undertaken on longline data. Relatively large decreases in Japanese CPUE were noticed in areas 3, 5&6 and 7 since 1990, which coincided with the timing of an increase in catch (Figure 10). It should be noted also that areas 3 and 7 are those from which the most catches are taken (IOTC 2003). In contrast, the standardized CPUE series from area 4 showed no temporal trend with the possible exception of the last couple of years. In terms of the length-frequency data, Table 1 shows that the highest length-frequency sample sizes over the most continuous time series were also taken from areas 3, 4, 6 and 7.

To see whether similar patterns of decrease were observed using size-based indices, we constructed separate standardized indices of mean length and proportion large for areas 3, 6 and 7. Area 5 was not considered because of a lack of data. We also constructed indices for area 4, chosen as a “reference” area in which CPUE had not declined. The GLMs considered above suggested that the mean length and proportion of large fish was lowest from area 4, moderately low for areas 3 and 6, and high for area 7. It is re-iterated that these area-specific GLMs are standardizing only for the effect of quarter.

The standardized mean length indices for each area showed very similar temporal trends to the nominal patterns (Figure 8). Only the standardised trend for area 4 showed any appreciable differences in some years to nominal mean length pattern (Figure 8), as this was the only area-specific model for which quarter was a significant factor (ANOVA, $P < 0.005$), with lower-value coefficients in quarters 2 and 4 (Figure 11). Figure 8 shows that there were essentially no temporal trends in standardised (or nominal) mean length in any of these areas, except for a sharp drop in mean size in area 6 in 2000 and 2001.

Figure 9 shows the standardized and nominal proportions of swordfish greater than 150cm EFL. Again, the standardized patterns are very similar to the nominal trends, indicating that the quarterly pattern in each year is not strong. The greatest differences between the nominal and standardized values were for some years in areas 6 and 7.

None of the areas showed even vaguely similar patterns to the CPUE trends. The only consistent feature across CPUE and the proportion large indices was the peaks in the mid to late 1980s in areas 3 and 7 (Figure 9).

The proportion of "large" fish caught in area 3 showed the highest inter-annual variability of the four areas, with the "proportion large" varying between about 90% and less than 5%(Figure 9a) In area 4, the "proportion large" ranged within 15% and 70%. (Figure 9b). Overall, the proportion of large fish was generally lower (in area 4) relative to the other areas, consistent with the low-value coefficient for this area from the main model (Figure 6c). In area 6, between 1970 and 1992, the proportion of large fish was relatively constant (between 30% and 60%), but has varied much more since 1990. The proportion dropped to less than 20% in 1992 and subsequently peaked above 70% in 1993 and 1994 (Figure 9c). Finally, the proportion of large fish in area 7 showed high inter-annual variability. With the exception of 1983 and 1984, the proportion was greater than 50% (Figure 9d). This is consistent with the result that area 7 had one of the highest-value coefficients in the main model (Figure 6c).

Trends in the quarterly coefficients for the area-specific mean length and proportion large models were not particularly consistent across areas, with area 4 showing the most difference (Figure 11). This could be interpreted that there is an interaction effect between area and season (i.e. that the effect of season is different for each area). It should be recalled that areas 3 and 4 straddle both hemispheres, while areas 6 and 10 are in the southern hemisphere, such that a quarter of the year corresponds to opposite seasons for each hemisphere, so perhaps the inconsistencies should be expected. However, the inclusion of an area-quarter interaction in the main GLMs for mean length and "proportion large" was not statistically significant at the 5% level although it was at the 10% level for the mean length model (ANOVA; P = 0.068) (note also that quarter as a main effect was marginally insignificant in the mean length model; P=0.057). Moreover, the inclusion of an interaction term had a negligible effect on the values of the year coefficients (see Figure 3 as an example for the mean length model).

DISCUSSION

As with bigeye and yellowfin tuna (Basson and Dowling 2004), the results presented here for swordfish show that it is possible to standardise the mean length and other similar indices reasonably successfully. In particular, and as opposed to bigeye and yellowfin standardisations, which showed little difference to the nominal patterns, the standardization of size-based indices for swordfish smoothed temporal trends that were evident in the nominal data, largely by accounting for the significant effect of area. Standardization of swordfish mean length and proportion "large" tended to dampen nominal peaks in the early and late 1990s, such that the standardized trends showed no overall temporal trend. While mean length did not appear to be a sensitive or reliable indicator for bigeye or yellowfin tuna (Basson and Dowling 2004), simple yield per recruit analysis indicates that the largest change in mean length as fishing mortality increases is likely to occur for slow growing species. This suggests that mean length may be a poor stock status indicator for yellowfin, which is relatively fast growing, but it could be reasonable for a species like swordfish. However, selectivity patterns can also influence mean length and render it misleading, particularly if selectivity patterns change over time.

The GLMs indicated a strong effect of area on the size-based indices that predominated over the quarterly effects. This is to be expected from a species with higher residency, and, more particularly, size-based spatial segregation, where fish migrate to progressively higher latitudes as they grow, and larval concentrations are highest about the equator and in specific regions. The lack of a significant quarter effect is possibly also unsurprising, since there is no evidence of seasonal spawning or migrations for swordfish (Ward and Elscot 2000).

An increase in the inter-annual variability in the proportion of large fish since 1990 was a feature of the combined data, and of the temporal trends from CPUE standardisation areas 4 and 6. Simultaneously, it was noted that the greatest increases in catch did not occur in areas 4 and 6, but rather in areas 3 and 7 (Figure 10). The increased variability was not smoothed by standardisation, and may be a feature warranting closer attention (e.g. sample size issues or differences in sex ratio, given that females grow to larger sizes than males (Ward and Elscot 2000)). Typically, a continuous decline in the value of a stock status indicator over a time series alerts decision makers to potential problems, but the onset of, or an increase in instability could be of equal concern. That the increase in variability occurred in areas with lower increases in catch may suggest that closer attention needs to be paid to more marginal areas of the fishery, though it could simply be an artefact of lower sampling intensity.

The standardization process yields useful by-products: most importantly, estimates of standard error that are likely to be more robust than direct estimates from the raw data. When implementing such an index in a monitoring framework the standard errors would play a strong role in assessing whether change in indices are substantial enough to warrant management action. The increase in standard errors when sample sizes decreases was noted, and would have to be taken into account when implementing such indices into a monitoring or management framework.

The standardisation also allows for the integration of data in a statistical framework and for 'like with like' comparisons in different areas or in the same area in different quarters. The standardisation can reduce the effects of 'noise' in the data. This does not mean that careful scrutiny of the detailed data is unnecessary. Particularly when changes are observed, there would be a need to try to understand why and where those changes are occurring.

Since swordfish are often caught together with bigeye tuna, there is value in comparing the standardized size-based indices for the two species. Referring to Basson and Dowling (2004), the trends in standardized mean length for bigeye tuna showed no similarity to those for swordfish, and the only similarity in the “proportion large” indices was a peak occurring in the mid 1990s. Quarterly coefficients for mean length showed opposing patterns, with bigeye having the lowest quarterly coefficient in quarter 3, which yielded the highest value coefficient for swordfish.

The length-based swordfish indices did not show the pattern of decrease observed for the standardized CPUE trends in areas 3, 6 and 7. There are many possible explanations for this observation, and it is not currently feasible to say which mechanism(s) may be operating. It may, for example, suggest that standardised CPUE is a more sensitive stock status indicator, or that the abundance of all sizes reflected in the CPUE is changing in a similar way, so that means size remains relatively constant. Areas with CPUE declines could be areas with slow replenishment times. With few new recruits coming in to these areas, CPUE could decline while the size of the catch could remain relatively constant. Indeed, area 4, the "reference" area showing no apparent decline in CPUE, had the lowest mean length coefficient value and one of the lowest proportion "large" coefficients, and lies close to an identified area of high larval concentration. Area 4 could thus be seen as a recruitment area that is thereby less likely to show declines in catch rates relative to other heavily fished areas.

It is interesting to note that the findings for standardized CPUE and size-based indices for the Indian Ocean contrast with those from the Mediterranean Sea, where CPUE has remained stable but mean size has decreased. This combination of indicator trends could perhaps have more serious biological implications than what is observed in the Indian Ocean, since it hints towards hyperdepletion, whereby an aggregating stock or highly efficient fleet allows catch rates to be maintained despite declines in overall abundance. Additionally, a decrease in mean size despite constant catch rates has potential implications for reproduction and recruitment, since fecundity is positively related to size.

ACKNOWLEDGEMENTS

This work was supported by funding from the Australian Fisheries Research Development Corporation (project 2003/042) and CSIRO. We thank the IOTC Secretariat, Miguel Herrera in particular, for assistance with the data and for prompt responses to our questions. Any misinterpretations of the data are entirely our fault.

REFERENCES

Basson, M. and Dowling, N. (2004). Standardisation of size-based indicators for bigeye and yellowfin tuna in the Indian Ocean. IOTC-2004-WPTT-XX

Campbell, R.A. and Hobday, A. (2003). Swordfish-Environment-Seamount-Fishery Interactions off eastern Australia. Report to the Australian Fisheries Management Authority, Canberra, Australia.

Campbell, R.A. and Miller, R.J. (eds.) (1998). Fishery Assessment Report 1997: Eastern Tuna and Billfish Fishery. Australian Fisheries Management Authority, Canberra, Australia.

Campbell, R.A., Basson, M. and Dowling, N. (2003). Review and analysis of information for determination of Total Allowable Catches and decision rules for the Southern and Western Tuna and Billfish Fishery. Report to the Australian Fisheries Management Authority, Canberra.

DeMartini, E. (1999) Size at maturity and related reproductive biology. Pp. 161-169 in DeNardo, G.T. (ed.) Proceedings of the Second International Symposium on Swordfish in the Pacific Ocean. Southwest Fisheries Science Centre Administrative Report NOAA-TM-NMFS-SWFSC-263. National Marine Fisheries Service, Honolulu.

Fonteneau, A. and Richard, N. (2003). Relationship between catch, effort, CPUE and local abundance for non-target species, such as billfishes, caught by Indian Ocean longline fisheries. Marine and Freshwater Research 54: 383-392.

Froese, R. (2004). Keep it simple: three indicators to deal with overfishing. Fish and Fisheries 5(1): 86-91.

Indian Ocean Tuna Commission (2003). Report of the 3rd Session of the IOTC Working Party on Billfish. Perth, Australia, November 10-12, 2003

Indian Ocean Tuna Commission (2001). Report of the 2nd Session of the IOTC Working Party on Billfish, St. Gilles, La Reunion, November 5-8, 2001

Internation Commission for the Conservation of Atlantic Tunas (2003). Report of the 2003 ICCAT Mediterranean Swordfish Stock Assessment Session. Col. Vol. Sci. Pap. ICCAT 56(3):

Longhurst, A.R. (2001). Ecological geography of the sea. Academic Press, San Francisco, California.

Nakano, H. and Bayliff, W.H. (1992). A review of the Japanese longline fishery for tunas and billfishes in the eastern Pacific Ocean, 1981-87. Inter-American Tropical Tuna Commission Bulletin 20(5): 183-355.

Nishikawa, Y. and Ueyanagi, S. (1974). The distribution of the larvae of swordfish, *Xiphias gladius*, in the Indian and Pacific Oceans. pp. 261-264 in Shomura, R.S. and Williams, F. (eds.) Proceedings of the International Billfish Symposium held Kailua-Kona, Hawaii, 9-12 August 1972. Part 2. Review and contributed papers. NOAA Technical Report, NMFS SSRF-675.

Nishikawa, Y., Honma, M., Ueyanagi, S. and Kikawa, S. (1985). Average distribution of larvae of oceanic species of scombrid fishes, 1956-1981. Far Seas Fisheries Research Laboratory, Shimizu. S. Series 12.

Palko, B.J., Beardsley, G.L. and Richards, W.J. (1981). Synopsis of the biology of the swordfish, *Xiphias gladius* Linnaeus. United States Department of Commerce, NOAA Technical Report NMFS Circular 441 (FAO Fisheries Synopsis No. 127).

Punt, A.E., Campbell, R. and A.D.M. Smith. 2001. Evaluating empirical indicators and reference points for fisheries management: Application to the broadbill swordfish fishery off Eastern Australia. *Mar. Freshwater Res*. 52: 819-832.

Ward, P. and Elscot, S. (2000). Broadbill swordfish: status of world fisheries. Bureau of Rural Sciences, Canberra, 208pp.

Yokawa, K. (2001). Problems in swordfish stock assessment in the Indian Ocean. WPM01-09 IOTC Proceedings no. 4. pp 232-233.

Yabe, H., Ueyanagi, S., Kikawam S, and Watanabe, H. (1959). Study of the life history of the sword-fish,, *Xiphias gladius* Linnaeus. Nankai Reg.Fish. Res. Lab. Rep. 10: 107-150.

Young, J. and Drake, A. (2002). Reproductive dynamics of broadbill swordfish (*Xiphias gladius*) in the domestic longline fishery off eastern Australia. FRDC Project 1999/108 Final Report.

Table 1: The total number of length-frequency sampled fish, by year and CPUE standardization area, normalized by the approximate number of 5-degree squares in that area.

YEAR	CPUE STANDARDISATION AREA									
	1	2	3	4	5	6	7	8	9	10
	APPROXIMATE NUMBER OF 5-DEGREE SQUARES									
	12	10	26	28	14	14	23	6	14	20
1970	NA	59.80	3.62	12.14	NA	27.79	0.04	NA	NA	NA
1971	NA	3.20	6.08	8.68	NA	18.14	NA	NA	5.00	0.45
1972	NA	9.90	0.42	12.00	NA	18.14	NA	NA	1.50	NA
1973	NA	NA	1.15	8.79	1.21	14.00	NA	NA	NA	NA
1974	NA	0.50	NA	15.04	NA	21.64	NA	NA	1.43	NA
1975	NA	5.30	1.31	8.39	2.14	31.21	0.04	NA	0.07	NA
1976	7.08	2.80	0.04	6.57	0.36	48.07	0.04	NA	NA	NA
1977	1.83	NA	12.50	7.68	NA	41.07	0.04	NA	3.21	NA
1978	NA	2.40	2.35	7.61	NA	40.71	1.26	NA	10.07	NA
1979	2.92	8.30	1.42	9.36	0.07	61.57	0.17	NA	1.43	NA
1980	NA	NA	2.88	10.14	NA	72.86	NA	NA	NA	NA
1981	NA	0.50	2.73	12.14	0.29	94.64	0.48	NA	NA	NA
1982	NA	12.50	10.81	9.50	1.57	89.07	NA	0.17	0.71	NA
1983	NA	14.90	4.73	9.71	0.14	72.29	4.43	NA	0.64	0.25
1984	NA	4.80	9.00	6.21	1.21	62.21	38.48	NA	NA	NA
1985	NA	19.00	4.54	7.36	0.14	79.36	20.65	NA	NA	NA
1986	NA	19.90	8.08	4.61	0.50	60.79	10.70	NA	NA	NA
1987	0.50	13.90	11.96	5.46	0.71	38.50	2.65	NA	NA	NA
1988	0.42	17.60	15.81	6.25	NA	26.57	11.78	NA	0.57	0.25
1989	NA	13.70	1.42	5.36	NA	20.50	32.87	NA	0.07	2.20
1990	NA	13.30	4.00	4.21	NA	20.93	44.74	NA	NA	NA
1991	NA	NA	1.00	3.61	NA	14.93	34.04	NA	1.93	8.75
1992	NA	3.60	0.77	0.86	NA	6.14	14.83	NA	2.00	2.30
1993	NA	NA	NA	1.07	NA	3.29	39.39	NA	2.36	NA
1994	NA	NA	2.27	0.86	0.36	1.00	41.57	NA	NA	NA
1995	NA	2.70	4.23	1.61	NA	1.93	45.17	NA	NA	NA
1996	NA	0.30	1.65	2.04	NA	2.36	22.35	NA	0.21	0.20
1997	NA	NA	4.19	0.43	NA	3.93	37.13	NA	NA	NA
1998	NA	1.80	5.54	1.32	NA	1.29	33.39	NA	0.07	NA
1999	NA	0.20	NA	1.04	NA	NA	16.70	NA	NA	NA
2000	NA	1.80	2.08	1.75	2.71	0.43	13.65	NA	NA	NA
2001	NA	0.20	NA	0.14	NA	0.29	15.17	NA	NA	NA
2002	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

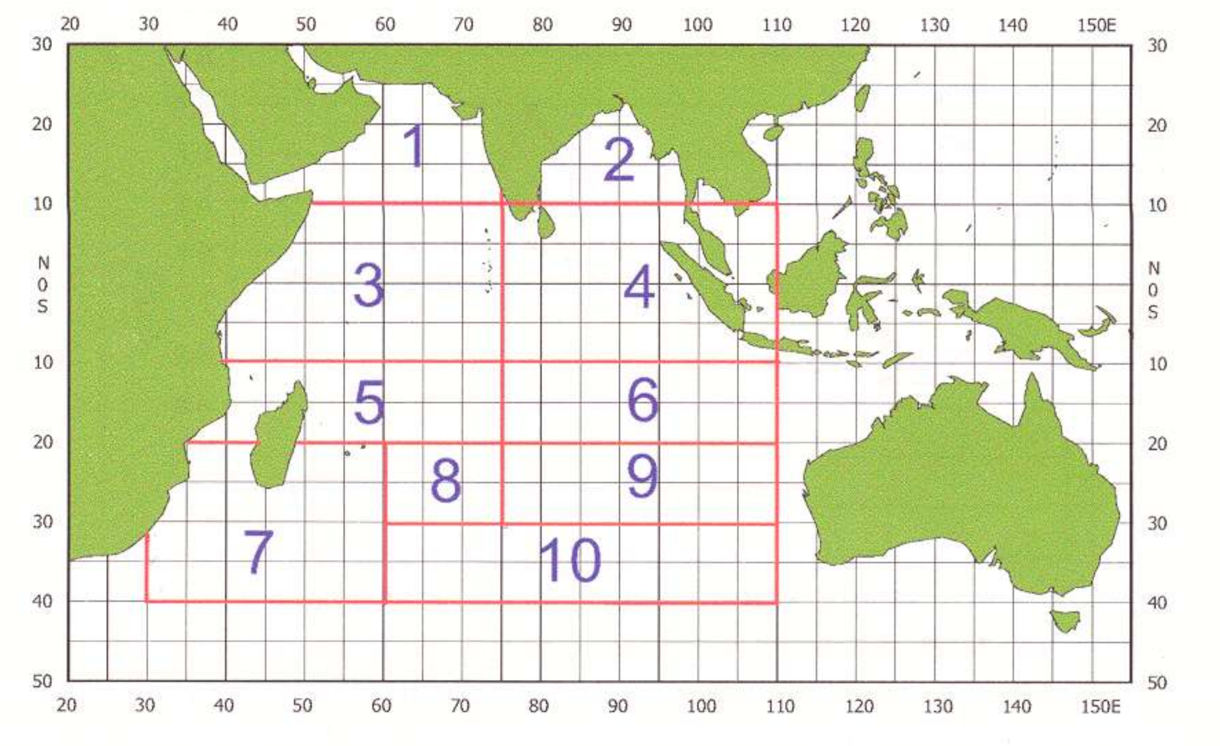


Figure 1: The areas used for standardization of broadbill swordfish longline CPUE (Report of 3rd Session IOTC WP Billfish, 2003)

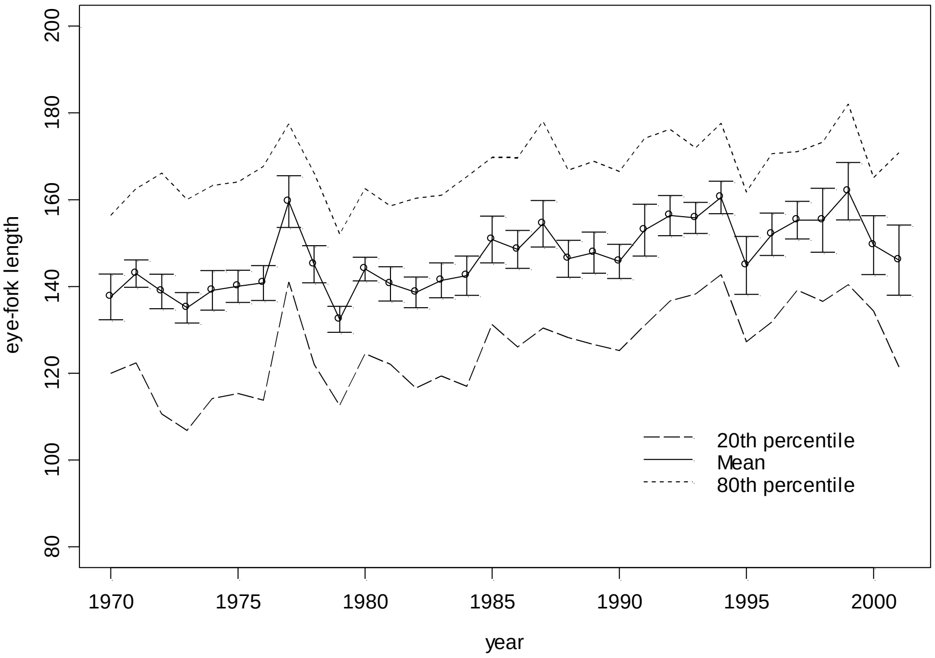
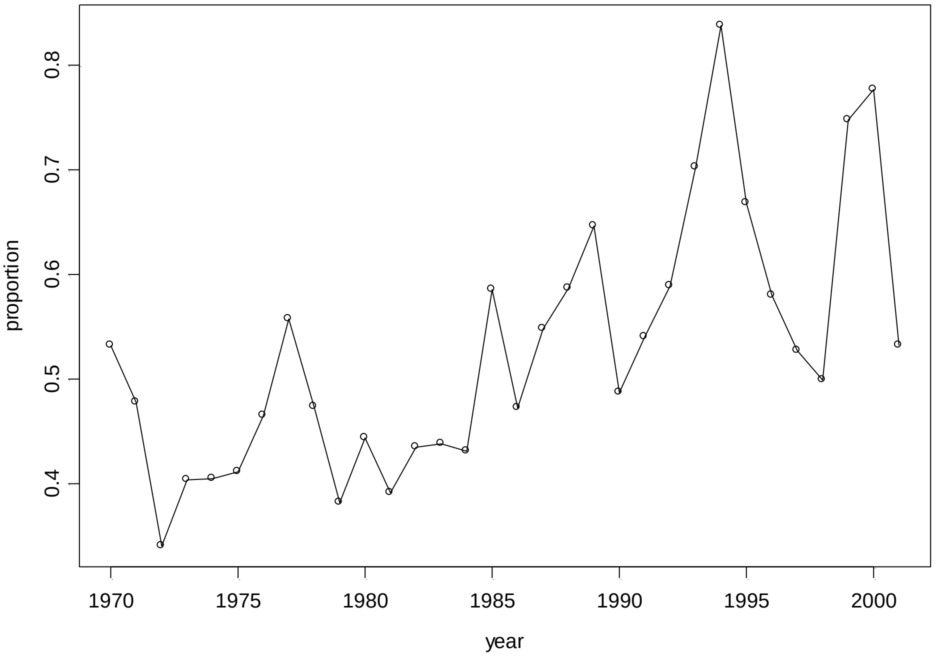


Figure 2a: Japanese longline annual averages of mean length and average 20th & 80th percentiles (FL in cm) for the whole of the IO. Error bars are ±1 standard error (s.e.).
Figure 2b: Japanese longline annual proportion >150cm EFL (EFL in cm) for the whole of the IO.



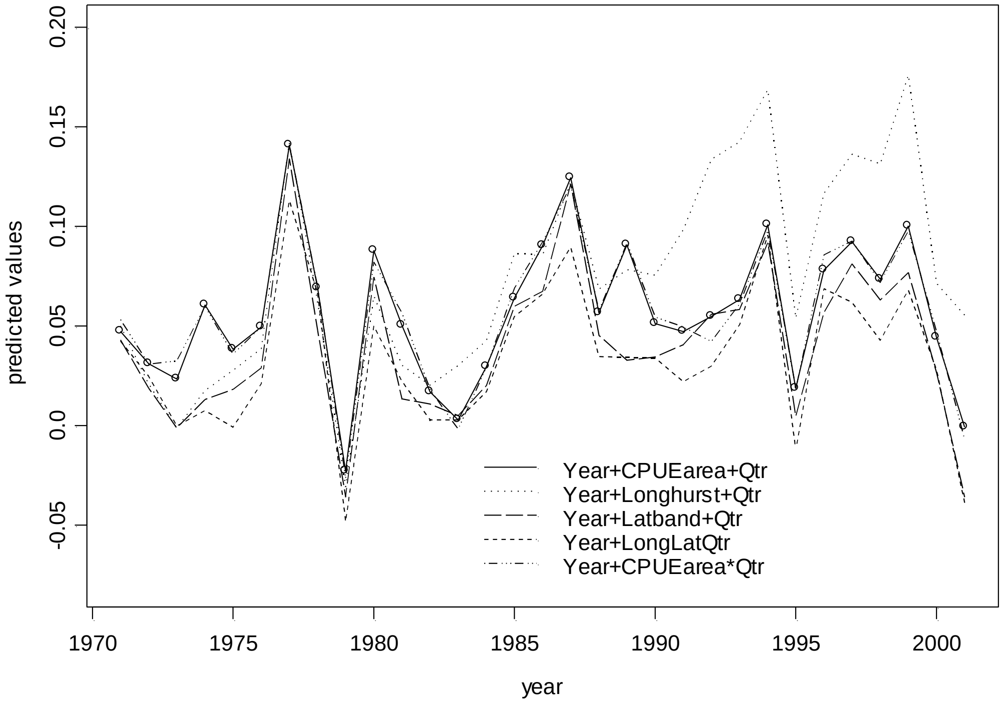


Figure 3: Japanese longline year coefficients overlaid for GLMs of log(mean length) as a function of i) Year + CPUEarea + Quarter, ii) Year + Longhurst + Quarter, iii) Year + Latitude band + Quarter, iv) Year + LongLatQtr, v) Year + CPUEarea*Quarter.

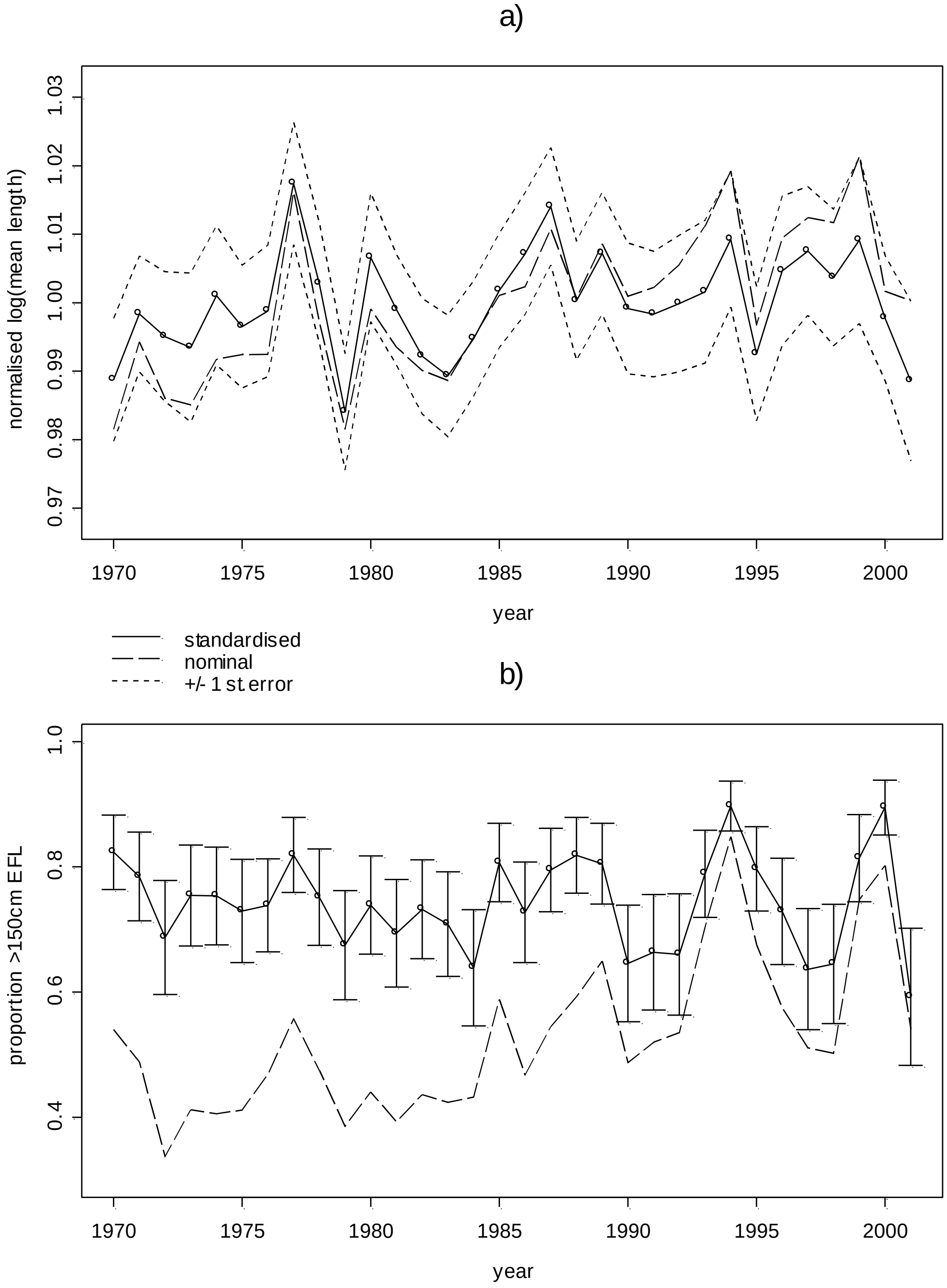


Figure 4: Japanese longline time series of a) standardized and nominal swordfish mean length indices on the log scale, normalized using the mean values over the time series, and b) standardized and nominal indices for proportion of swordfish >150cm EFL. Error bars are ±1 s.e.

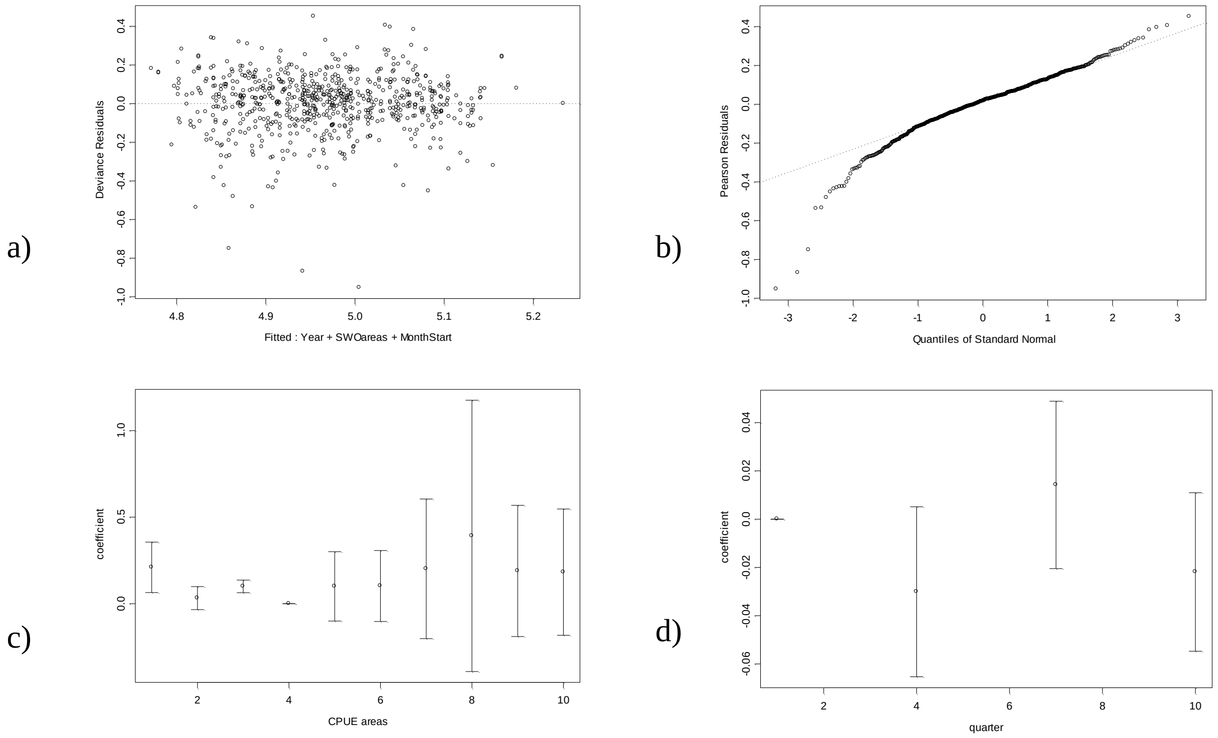


Figure 5: Japanese Longline. Plots of a) deviance residuals vs. fitted values, b) Pearson residuals vs. quantiles of standard normal, c) CPUE area coefficients, relative to area 4, and d) quarter coefficients relative to quarter 1, for the mean length main effects GLM (model coefficients relative to CPUE area 4). Error bars are ±1 s.e.

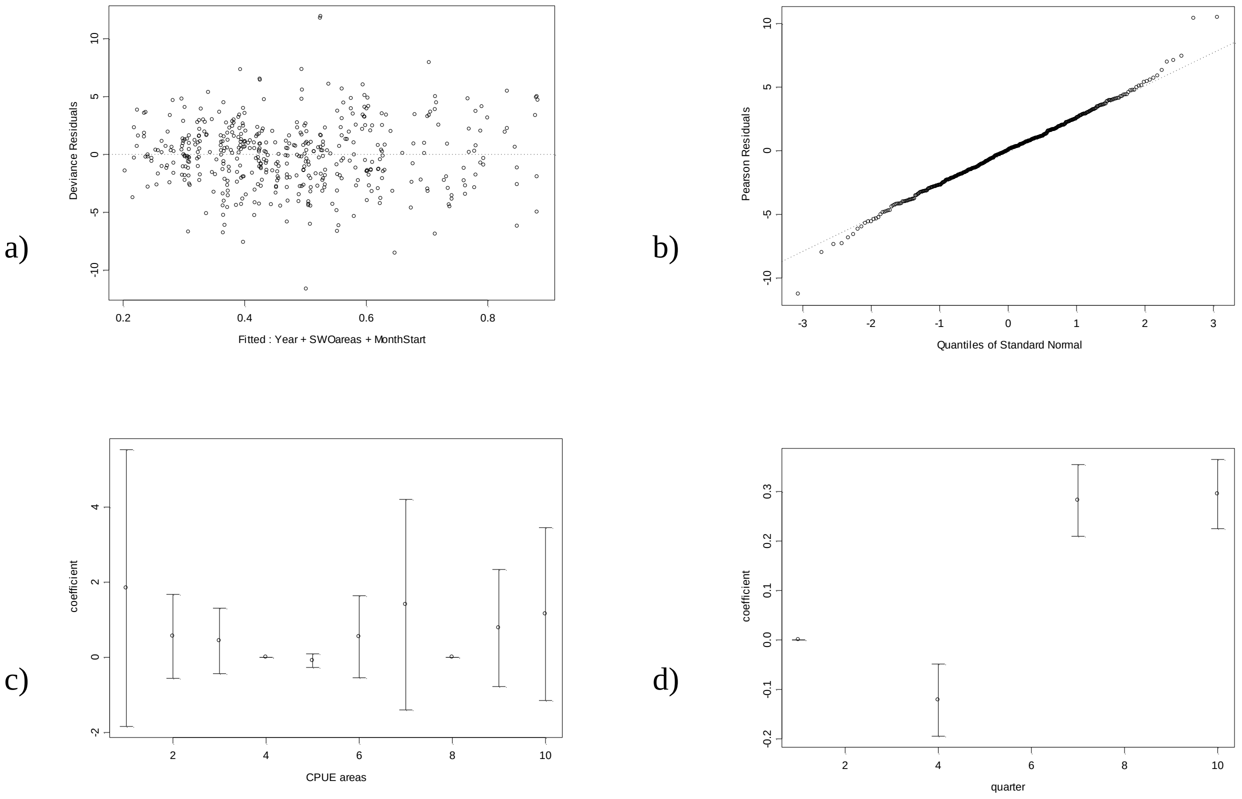


Figure 6: Japanese Longline. Plots of a) deviance residuals vs. fitted values, b) Pearson residuals vs. quantiles of standard normal, c) CPUE area coefficients relative to area 4, and d) quarter coefficients relative to quarter 1, for the GLM of proportion of swordfish >150cm EFL (model coefficients relative to CPUE area 4). Error bars are ±1 s.e.

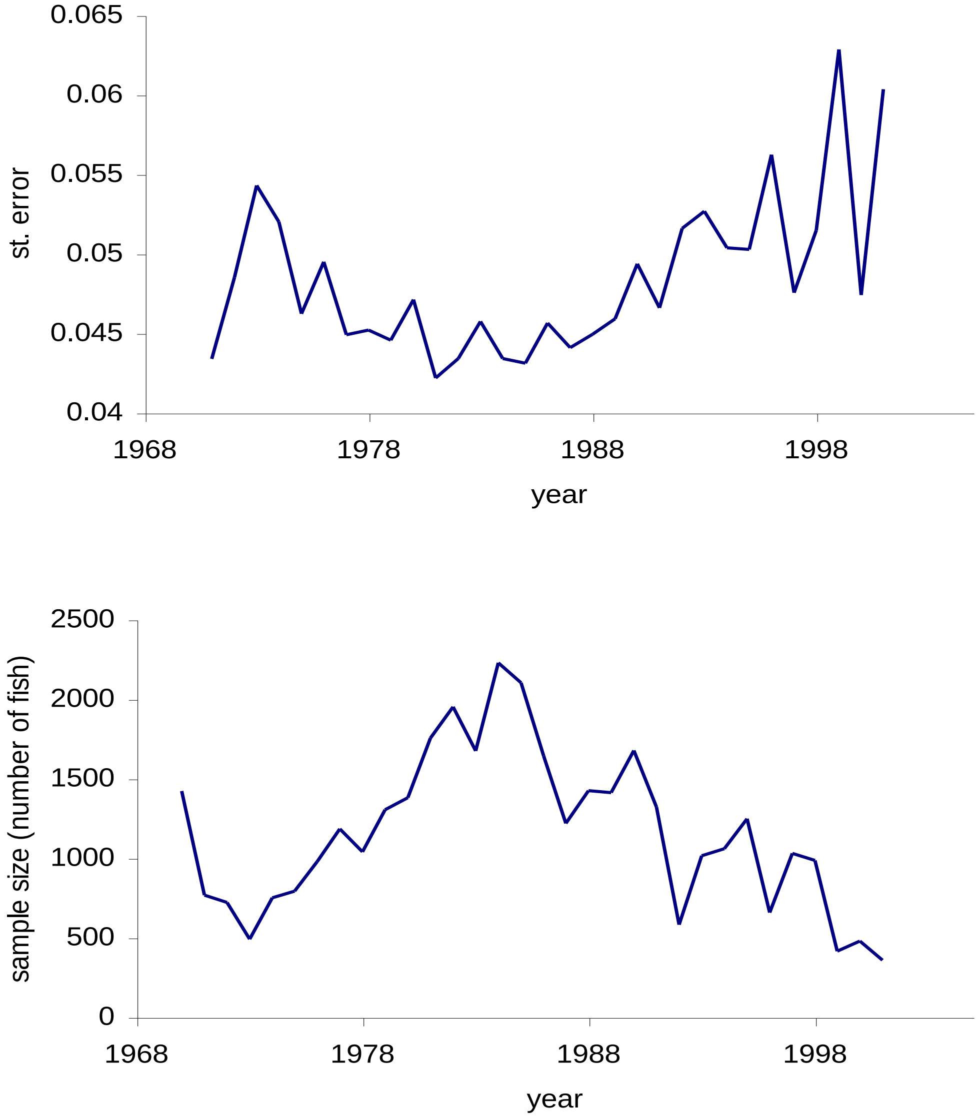


Figure 7: Japanese longline. a) standard errors associated with standardized indices for mean length and b) annual total sample sizes (numbers of fish) used in calculating mean length.

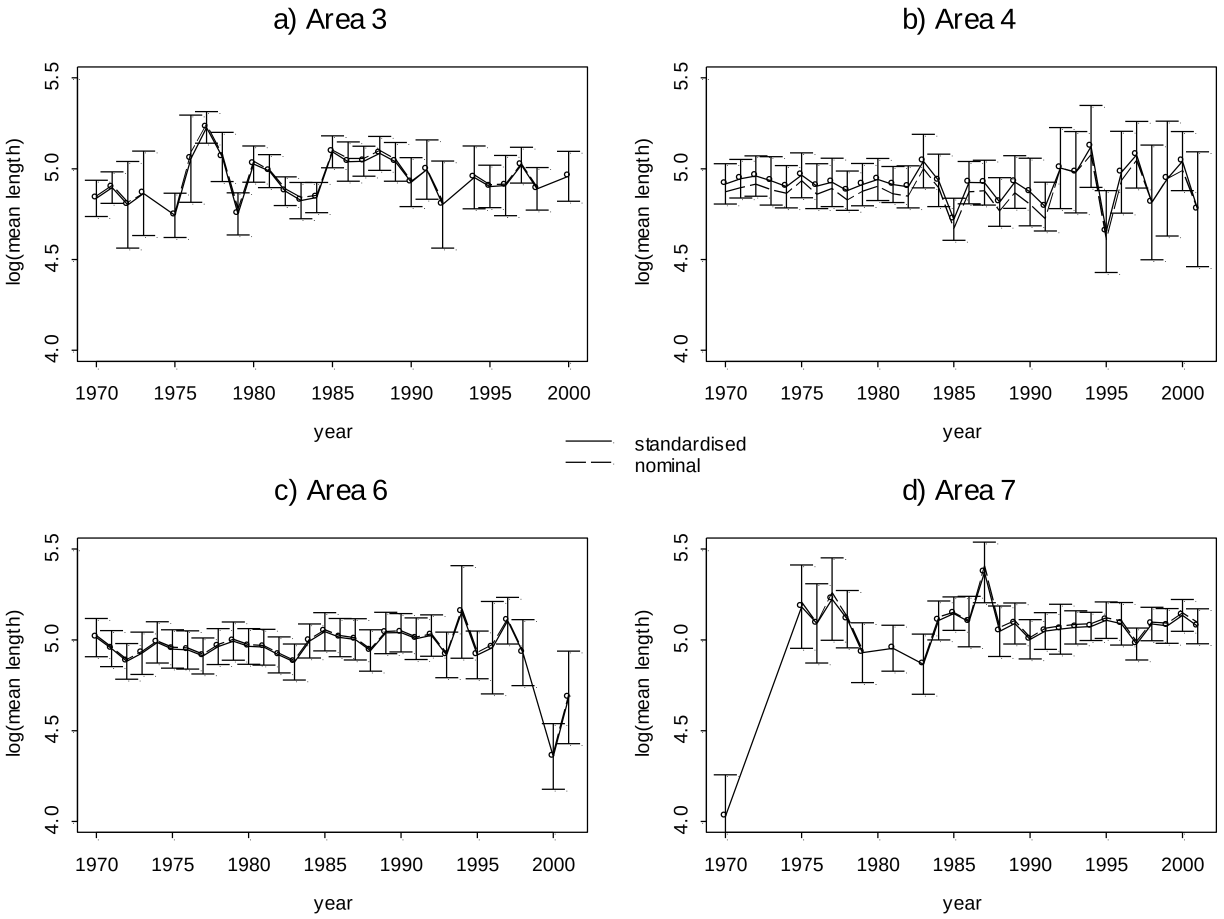


Figure 8: Japanese longline time series of standardized and nominal swordfish mean length indices on the log scale, for a) CPUE standardization area 3, b) CPUE standardization area 4, c) CPUE standardization area 6, d) CPUE standardization area 7. Error bars are ±1 s.e.

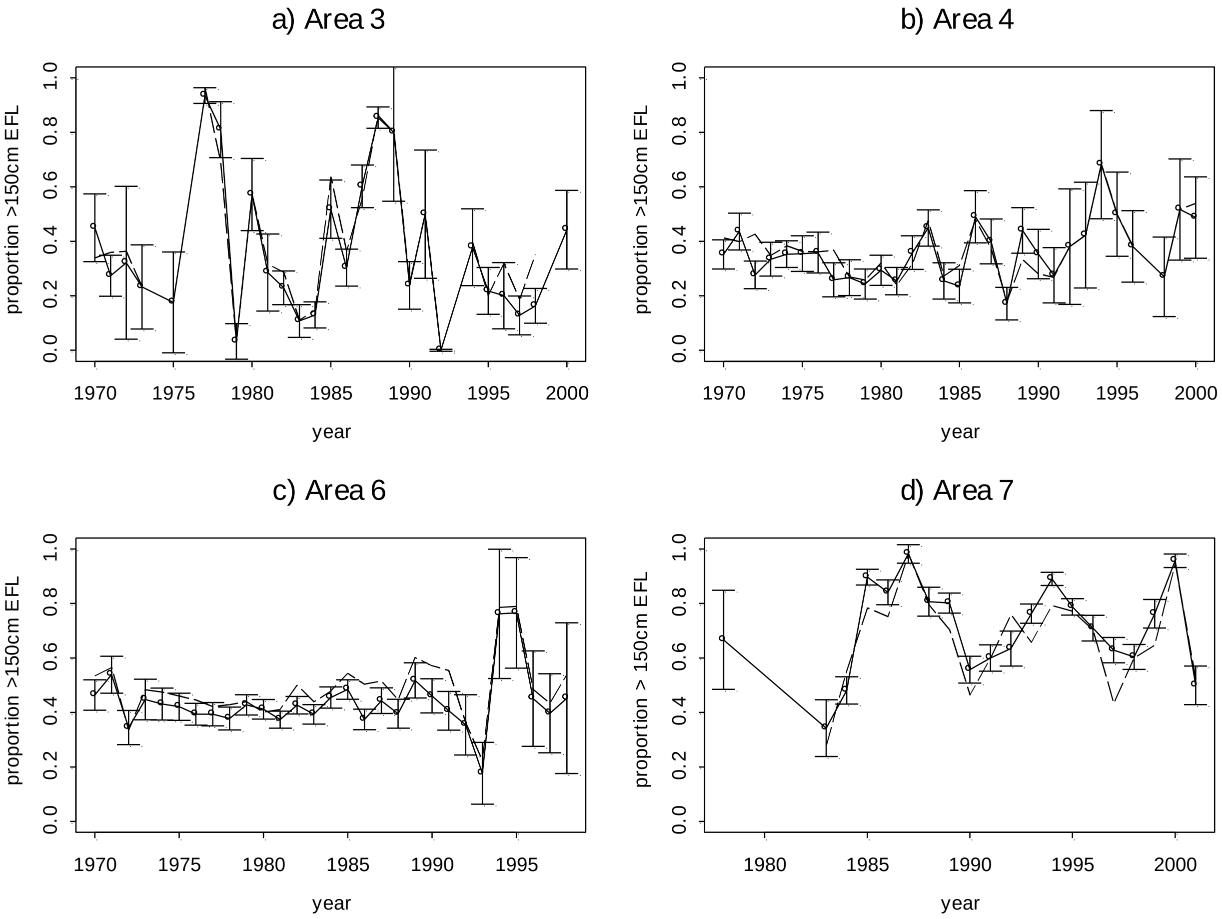


Figure 9: Japanese longline time series of standardized and nominal indices for proportion of swordfish >150cm EFL, for a) CPUE standardization area 3, b) CPUE standardization area 4, c) CPUE standardization area 6, d) CPUE standardization area 7. Error bars are ±1 s.e.

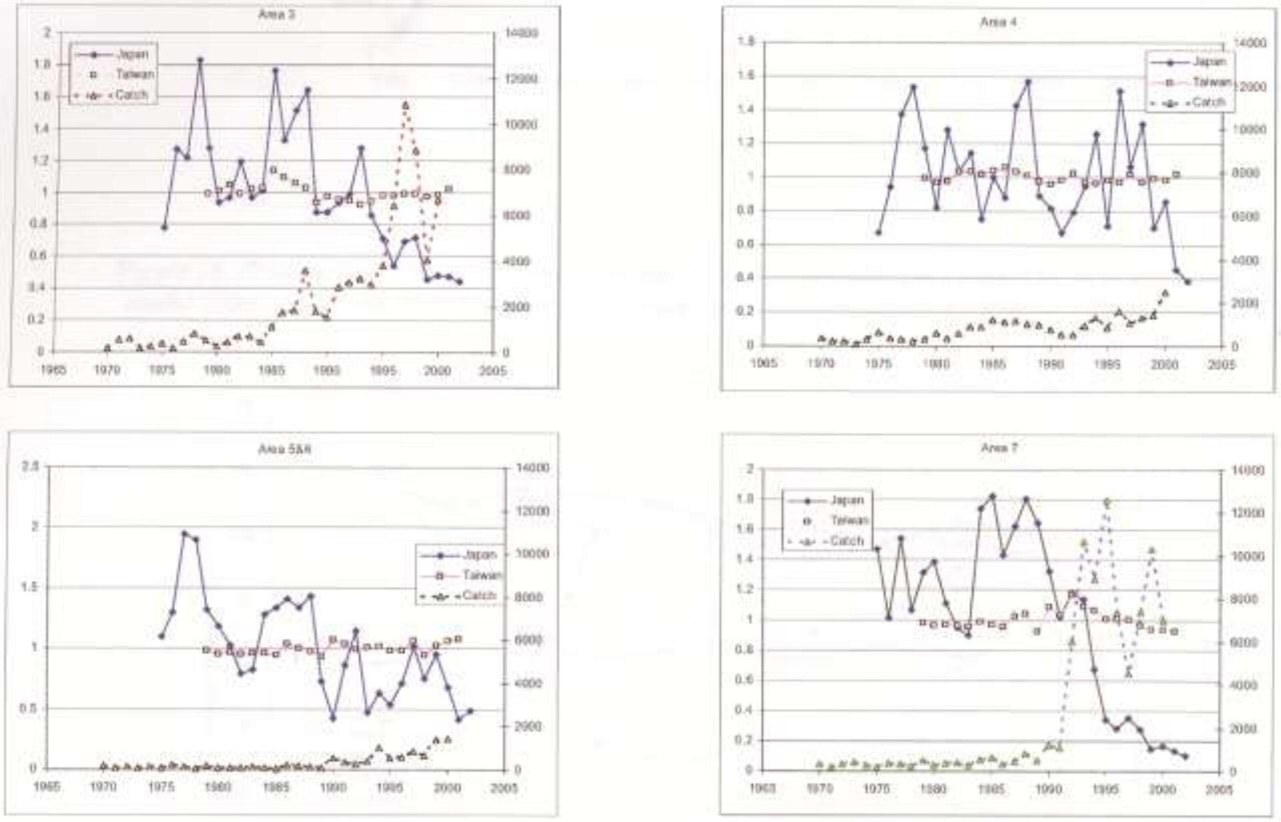


Figure 10: Standardised CPUE indices for areas 3, 4, 5&6 and 7, from the Report of the 3rd Session of the IOTC Working Party on Billfish, 2003.

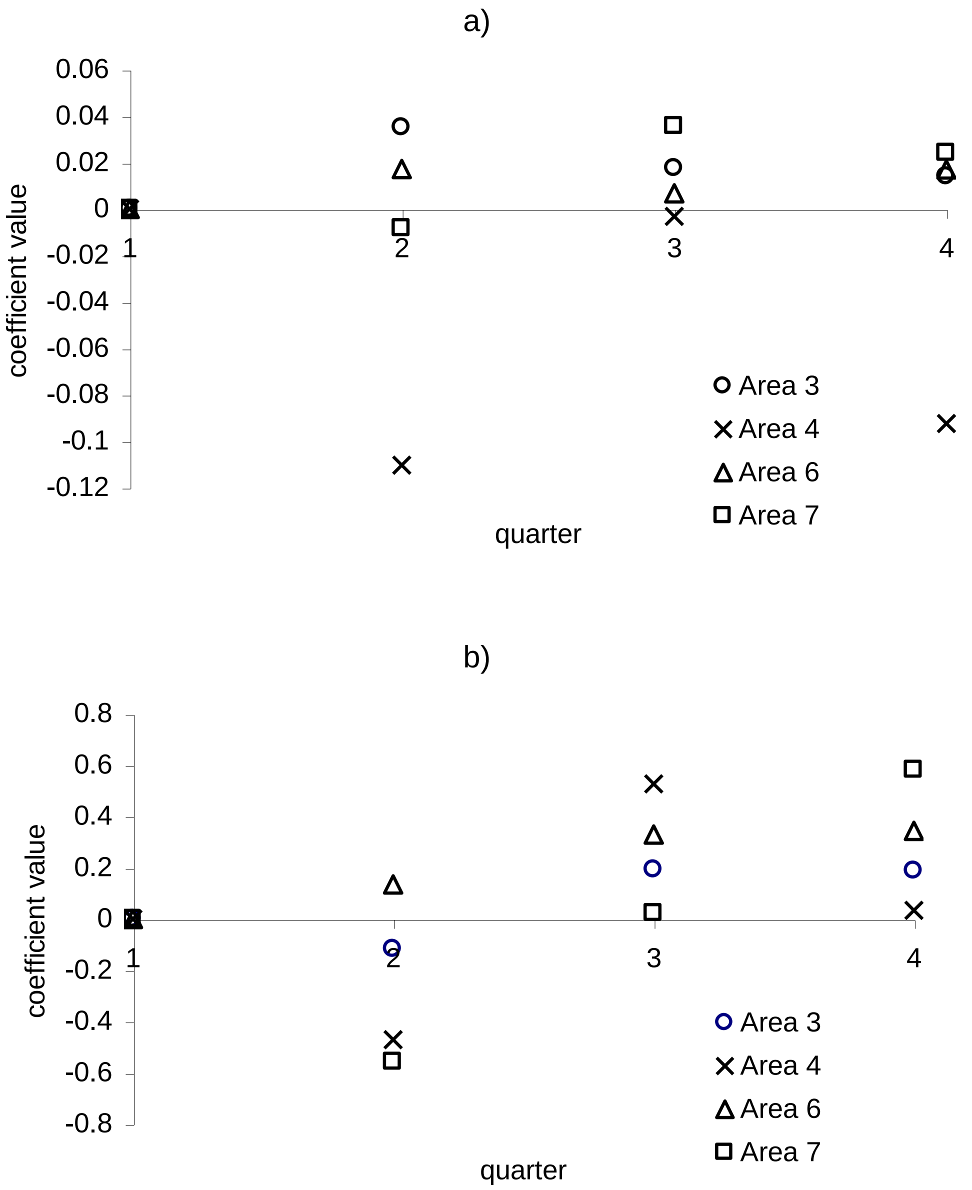


Figure 11: Quarterly coefficients for the area-specific GLMS undertaken for a) mean length and b) proportion of fish > 150cm EFL