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Standardised CPUE indices for swordfish (*Xiphias gladius*) from the New Zealand tuna longline fishery, 1993 to 2012

New Zealand Fisheries Assessment Report 2013/46.

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Catch per unit effort (CPUE) indices for swordfish (*Xiphias gladius*) in the New Zealand surface longline fishery were updated to include fishery data from the five years since the previous analysis, for use as relative abundance indices in a revised south Pacific-wide swordfish stock assessment model being assembled by the Western and Central Pacific Fisheries Commission (WCPFC).

Examination of changes in the fishery data (including the use of light sticks, depth of the longline, and timing of fishing around hours of darkness and with respect to the fullness of the moon) showed that targeting of swordfish has effectively been increasing over time, particularly since 2004 when targeting became legal after the introduction of swordfish into the Quota Management System (QMS).

Generalised Additive Models (GAMs) assuming a quasi-poisson error distribution were applied to commercial catch-effort data and remote-sensed environmental variables to produce three alternative CPUE series: **all-data**, based on data from 1993 to 2012 and all vessels in the fishery; **core-vessel**, based on a core set of vessels and the more recent fishery, 1998 to 2012; and **late-series**, based on the core set of vessels and the period subsequent to the introduction of swordfish into the QMS, i.e., 2005 to 2012.

Each model showed an increase in CPUE as the fraction of the longline soak-time occurring in darkness increased. Recorded target species in the all-data model, and rate of light stick usage in the late-series model were also significant.

The indices of the updated models followed a similar temporal pattern to each other and to those of the earlier analyses for the overlapping years, indicating a decline in CPUE between 1993 and 2004, followed by a small increase to 2007. For the subsequent period, 2004 to 2012, the revised models all showed a continuation of this increasing CPUE, reaching a level higher than that of any previous year in the series.

Although it was suspected that changes in operational procedures affecting swordfish catch rates were at least partly responsible for the recent increase in CPUE, it was not possible to determine whether these changes were sufficiently accounted for by the model variables and therefore to have confidence in the use of the year-effects as relative abundance indices.

1. INTRODUCTION

Swordfish are a highly migratory species, widespread in the Pacific Ocean from at least 50° N to 50° S in the western Pacific Ocean (Unwin et al. 2006). Although the New Zealand region forms only a small part of the species range, studies have indicated that the Pacific Ocean population is genetically structured (Chow et al. 1997, Reeb et al. 2000) and that fish may be resident in New Zealand for long periods and return to a limited home ground after seasonal migrations (Beckett 1974). A study of the Australian swordfish longline fishery showed that high catch rates were maintained only by continually extending the fishing grounds, therefore indicating that local depletion is possible and that measurement of local abundance has particular relevance to the local population.

The commercial catch of swordfish (*Xiphias gladius*) in New Zealand is taken in the surface longline fishery. It is either specifically targeted or caught as bycatch when targeting bigeye tuna (*Thunnus obesus*) and, to a lesser extent, southern bluefin tuna (*Thunnus maccoyii*). Swordfish have been caught around much of New Zealand and the adjacent high seas areas but most of the historical catch has come from north of 40º S (Ministry for Primary Industries 2012). Swordfish catches are greatest in the first and second quarters of the year, lower in the third quarter, and lowest in the fourth quarter (Griggs & Richardson, 2005).

Swordfish were introduced into the New Zealand Quota Management System (QMS) in October 2004 under a single Quota Management Area (QMA) and with an annual Total Allowable Commercial Catch (TACC) of 885 t, which has remained unchanged. Before then targeting of swordfish was prohibited, although retention of swordfish caught as bycatch in other target fisheries was permitted. Swordfish can be legally discarded under the provisions of Schedule 6 of the Fisheries Act (1996) if there is a chance they will survive, if it is done immediately, and if they are small (less than 1.25 m long). However, most of the catch (90–100%) is retained in most years (Griggs & Baird 2013).

Swordfish have certain behavioural characteristics which can be taken advantage of by longline fishers to increase the likelihood of capture. One of these is their crepuscular diving behaviour. Swordfish move into surface waters at dusk and remain there during the hours of darkness, returning to deeper water (below 600 m and as deep as 900 m) at dawn and staying there during daylight hours (Carey & Robison, 1981) except for occasional excursions to the surface—especially for larger fish (Holdsworth et al. 2010). Another is that catch rates of swordfish are known to be better when there is a bright moon (e.g., Bigelow et al. 1999). This influence of light on swordfish behaviour is recognised by fishers, and catch rates can be increased by attaching luminescent light sticks at intervals along the longline. Although the use of light sticks in the New Zealand tuna longline fishery pre-dates the introduction of swordfish into the QMS (to attract some tuna species to the lines if not swordfish) this information was not recorded on catch-effort forms until 2003.

Foreign Licensed Japanese longliners began catching swordfish in New Zealand in the late 1970s but, beginning in 1990–91, this fleet was largely replaced by a domestic fleet which grew rapidly in numbers through the 1990s and has subsequently dominated effort and landings in the northern longline fishery. The fleet now has two components, Foreign Charter Vessels (FCVs) and domestically owned and operated vessels (Davies & Griggs 2013). The FCV fleet (and before that Foreign Licenced Vessels) fished predominantly for southern bluefin tuna off the west and south of the South Island, whereas the northern fishery (north of about 42° S) has been dominated by the domestic fleet. The CPUE analysis presented here is limited to the northern fishery, in which most of the swordfish catch is taken.

Swordfish landings were lowest during the transition between the Foreign Licensed and domestic fleets, with less than 100 t per year landed between 1992–93 and 1994–95 (Ministry for Primary Industries 2012) but then increased rapidly after 1994–95 to peak at over 1000 t in 2000–01. Landings subsequently declined to 400–600 t in the mid to late 2000s, but increased again to a level of about 700 t in 2010–11 and 2011–12.

Management of swordfish throughout the western and central Pacific Ocean (WCPO) is the responsibility of the Western and Central Pacific Fisheries Commission (WCPFC). A decision was made at the Commission's 8th Regular Session in 2012 to update the swordfish stock assessment for the south west and south central Pacific Ocean for the 2013 Scientific Committee Meeting. This work is primarily being carried out by scientists of the Secretariat of the Pacific Community (SPC) in New Caledonia, but some of the model input data analyses, such as CPUE indices, are undertaken individually by country scientists of WCPFC member nations. This research was presented to the SPC pre-assessment workshop in Noumea, New Caledonia in April 2013.

The first comprehensive analysis of swordfish CPUE (Unwin et al. 2006) used Catch Effort Returns from the tuna longline fishery to generate standardised CPUE indices by year and quarter. This study incorporated bathymetric and remote-sensed sea surface temperature (SST) and ocean colour (Chl-a) data with operational data in a Generalised Additive Model (GAM)-based regression using a quasi-poisson error distribution to deal with the large number of zero catch records. A cross-validation method resulted in a model comprising a large number of variables, with a strong influence on CPUE suggested for longitude, recent fishing activity levels, soak time, night fraction, SST, and bottom depth. This showed CPUE with a strong seasonal fluctuation but generally rising during the development of the domestic fishery, reaching a peak which endured through the late 1990s and early 2000s then declining to levels approximately average for the series as a whole in 2003 and 2004.

This study was later updated (Unwin et al. 2009), but with a focus on the more fully developed domestic fishery (the years 1998 to 2007) and a core set of experienced vessels. The variability was dominated by a seasonal effect but also showed CPUE declining gradually to a low point in 2003 and 2004, followed by increasing values to the end of the series.

This report addresses the Ministry for Primary Industries project SEA2012/16: "New Zealand contributions to the Pacific swordfish stock assessment". The single objective of this project was to "Develop a CPUE analysis for South Pacific swordfish caught in New Zealand Fisheries".

2. METHODS

2.1 Fishery location

The tuna longline fishery is widely distributed around New Zealand, apart from waters off the east coast of the South Island. The CPUE analysis presented here is based on fishing effort recorded from within the New Zealand EEZ and north of a line at 36° S on the west coast and 42° S on the east coast (Figure 1). This excludes part of the west coast North Island fishery and all of the southern bluefin tuna fishery off the South Island west coast, and is consistent with previous CPUE analyses for this fishery (Unwin et al. 2006, 2009). These excluded areas account for about 10% of the total estimated swordfish catch between 1993 and 2012.

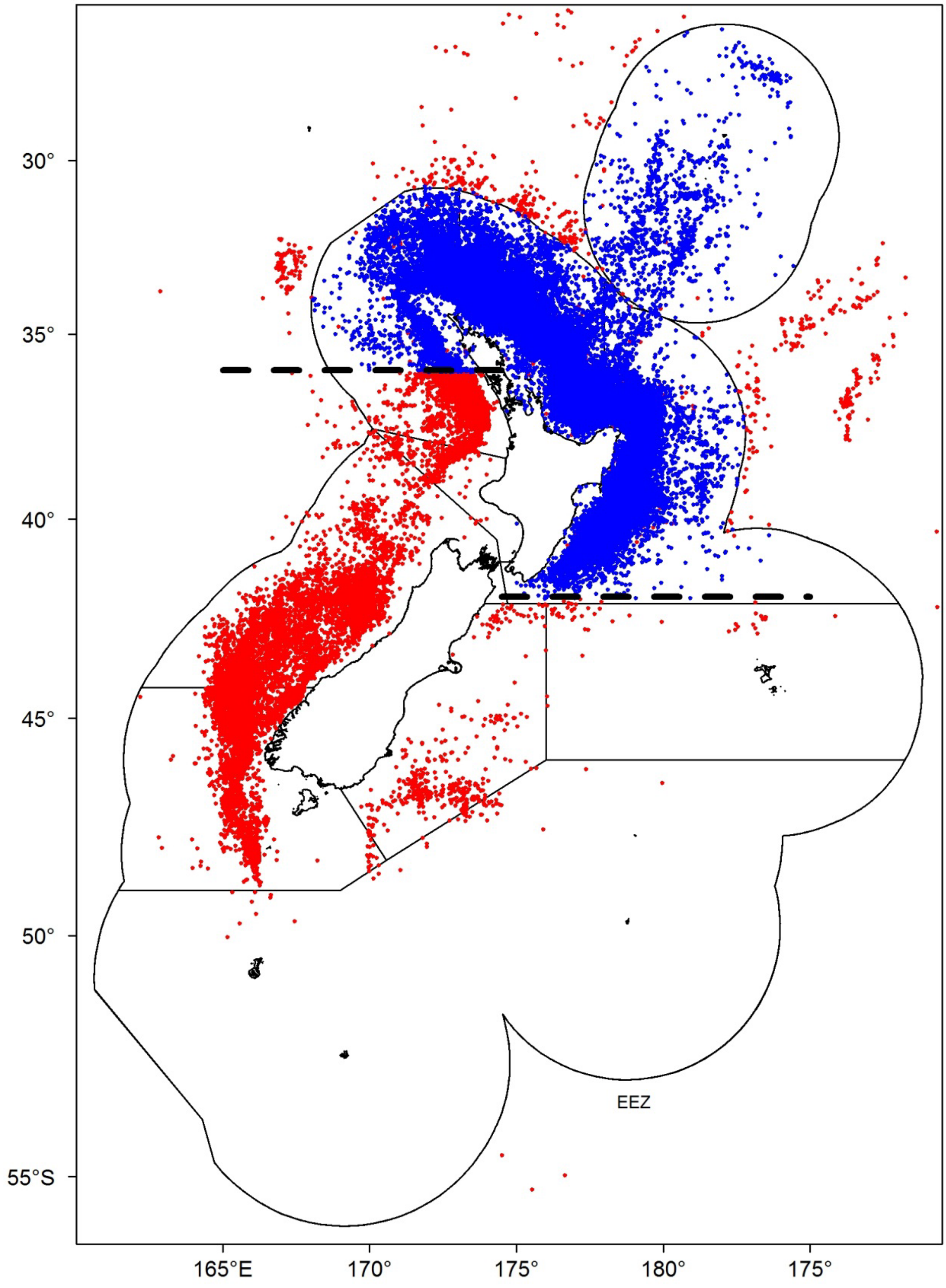

Figure 1: All reported commercial tuna longline sets (start positions) for 1 January 1993 to 30 December 2012. Sets used for the present analysis were limited to those plotted in blue, i.e., lying within the EEZ and north of the dashed lines at 42° S (off the east coast) and 36° S (off the west coast).

2.2 Data Sources

Set by set catch-effort data from the New Zealand tuna longline fishery are recorded on Tuna Longline Catch Effort Returns (TLCERs) and Catch, Effort and Landing Returns (CELRs) and transferred to the MPI database *warehou*. The data recorded on these forms includes the location, date, and other operational variables (e.g., number of hooks, hooks per basket, line length), and the catch (both number of fish and total weight) of all fish species landed. A set of edited and groomed data derived from this database is also stored in the database *tuna* administered by NIWA (Wei 2004). All data from the northern longline fishery, as defined above, covering the period 1 January 1993 to 30 December 2012 were extracted from *tuna* and subjected to a further set of error-checking procedures.

Hook numbers considered to be errors were checked and corrected where possible. Corrections were made to hook numbers of 268 records. Records considered to be errors were those where hook number was missing, low, high, less than the number of baskets, or clearly entered in the wrong field. Each record was checked against the recorded hook numbers for the sets on the same trip immediately before and after that on which the error occurred. These were used to assign a corrected hook number where possible, or hook number was moved or swapped where it had clearly been recorded in the wrong field, e.g., where hook number was transposed with basket number or line length. Some records had hook numbers with one digit too many (e.g., 500 was recorded as 5000) or too few (e.g., 500 was recorded as 50) which may have been data entry errors. In several cases these corrections also resulted in a correction to basket number or line length, but hook number was the main focus of error-checking, given its importance for CPUE analysis.

Corrections were made to 13 records with latitude/longitude errors. These errors included some where latitude and longitude had been transposed, and others where the decimal point was out of place. Corrections to these were made only after comparing the revised set position with those for records on the same trip from immediately before and after that where the error occurred. Unknown vessel nationality was corrected for 22 records which were known to be from New Zealand vessels.

After grooming and removal of missing values for predictor variables, 63 203 records were available for the CPUE analysis.

2.3 Environmental data

In addition to the operational data available from the catch-effort records, a set of independent environmental variables with potential for influencing swordfish distribution and local abundance were obtained for the analysis: estimated SST, SST anomaly, Sea Surface Height (SSH), and current velocity variables at the start position and date of each set.

The SST estimates used were based on the Reynold's Optimum Interpolation Sea Surface Temperature Analysis (Reynolds & Smith 1994, Reynolds et al. 2002). This analysis is produced daily on a one-quarter degree grid and incorporates in situ and satellite SSTs in addition to SST values simulated from known sea ice cover. Before the analysis is computed, the satellite data are adjusted for biases using the method of Reynolds (1988) and Reynolds & Marsico (1993). The bias correction improves the large scale accuracy of the Optimum Interpolation. The SST value for each set was determined by finding the nearest SST data point to the start position for the same day. The one-quarter degree SST grid provided a resolution of approximately 25 km. SST anomaly is essentially the difference between the estimated SST and the mean SST for the location and time of year.

The SSH values for the start of each set were determined using a web-based product (http://www.aviso.oceanobs.com/en/altimetry.html) which is the reference version of the Maps of Absolute Dynamic Topography (MADT) dataset. This is a spatially analysed combination of 10-day repeat measurements of sea surface height anomaly with the Mean Dynamic Topography (the part of mean SSH due to permanent currents, corresponding to the mean SSH minus the geoid). SSH is related to the integrated density of the water through the entire depth of the ocean - because less dense (warm, less salty) water stands taller than more dense (cold, saltier) water. The nature of ocean variability around New Zealand means that almost all of the variability in SSH results from changes in temperature. Thus, highs in SSH correspond to areas with higher mean temperatures and vice versa.

The slopes in the sea surface due to variability in SSH result in currents that run along the lines of constant height (in the same way that winds flow along isobars in weather maps) which means that the estimates of SSH can also be used to supply estimates of the surface current field. In this study, the magnitude of the current at the start of each set was estimated from the SSH data.

The SSH and current velocity data have resolutions of about 20–30 km latitude, 30 km longitude, and 7 days. Estimates for these values at the start of each set were determined from the nearest data point to the set location, on the nearest day.

2.4 CPUE analysis

The CPUE analysis for the New Zealand domestic longline fishery for swordfish was updated using the five years of additional data available since the last analysis (Unwin et al. 2009). The CPUE models constructed were based on set-by-set operational data (63 203 records) using a quarterly time step over the period 1 January 1993 to 30 December 2012. The analysis was limited spatially to sets within the New Zealand EEZ, and north of 36° S west of the North Island and 42° S east of the North Island (see Figure 1). This area excludes the mainly FCV fleet fishery targeting southern bluefin tuna off the west coast of the South Island, but accounts for about 90% of the total New Zealand catch of swordfish during the 20-year period.

In addition to the independently derived environmental variables described above, a set of variables with a potential influence on swordfish CPUE were selected or derived from the operational records for consideration in the CPUE model (Table 1). Target species was configured as a categorical variable with four levels; ALB (albacore tuna, *Thunnus alalunga*), BIG (bigeye tuna), STN (southern bluefin tuna), and OTHER. Swordfish was included in OTHER because swordfish targeting has been inconsistently recorded due to the targeting prohibition prior to 2004. Time at start of set (TSOS) was adjusted to represent the nearest hour relative to midnight, a useful reference point with an essentially night-time fishery. Recent effort (n10d50k), was calculated for each set to quantify the level of local fishing effort. This was defined as the number of longline sets within a 50 km radius of the set (based on the start of set location) during the previous 10 days. Although the number of hooks per basket (HksBask) is a potentially useful variable, because in general more hooks per basket (i.e., between floats) equates to deeper fishing, additional floats are sometimes added when targeting swordfish and these are not recorded on catch-effort forms. Moon phase (the fraction of the illumination provided by a full moon) was calculated from an astronomical algorithm (Meeus 1991).

Table 1: Variables used in the swordfish CPUE models

Dependent variable (code in brackets)	
CPUE	Number of fish per 1000 hooks (rounded to the nearest whole number).
Categorical variables	
Year-quarter (*YR_qtr*)	Calendar year and quarter, Jan–Mar = 1, etc.; all-data model, 80 levels, core-data model, 60 levels, late-series model, 32 levels.
Target species (*targCAT*)	Albacore (ALB), bigeye (BIG), southern bluefin (STN), other (OTHER); 4 levels.
Time at start of set (*TSOS*)	Nearest hour relative to midnight (-11 to +12), 24 levels.
Vessel (*Vessel_ID*)	Coded vessel registration number (all-data model, 275 levels; core-data and late-series models, 21 levels).
Core (*Core*)	All-data model only; experienced vessels (see text);
Isbig (*Isbig*)	All-data model only; big or small vessel, based on mean longline length, 2 levels >80 km and < 80 km.
Continuous variables	
Latitude (*Lat_S*)	Latitude (in decimal degrees) at start of set.
Longitude (*Long_S*)	Longitude (in decimal degrees) at start of set.
Current effort (*n10d50k*)	Number of sets within 50 km during the previous 10 days.
Soak-time (*soaktime*)	Hours from start of set to start of haul.
Hooks per basket (*HksBask*)	The number of hooks per basket (i.e. between floats)
Moon phase (*moonbright*)	The fraction of the illumination provided by a full moon (0–1).
Day length (*daylength*)	Length of day (sunrise to sunset, hours)
Night fraction (*nightfrac*)	Fraction of the set (soaktime) during the hours of darkness.
Sea surface temperature (*SST*)	Estimated from remotely sensed data – see text (°C).
SST anomaly (*SSTanom*)	Estimated from remotely sensed data – see text (°C).
Sea surface height (*SSH*)	Estimated from remotely sensed data – see text (metres).
Current speed (*CRNTspd*)	Derived from SSH – see text ($cm.s^{-1}$)
Light stick rate (*NLS_rate*)	Number of light sticks per 1000 hooks (late-series model only)
Squid bait % (*Bait_Squid_pct*)	Percentage of hooks baited with squid (late-series model only).

Following the methodology of Unwin et al. (2009), a GAM model was used to allow smoothed fits of model covariates, and the quasi-poisson error distribution was used to deal with the large number of zero catches and over-dispersion of the data relative to the poisson distribution (Maunder & Punt 2004). The poisson distribution is particularly useful for this type of fishery (where catches are recorded in numbers of fish rather than weights) because it models integer values and explicitly allows for zero counts. Predictors were accepted into the model based on the increase in R^2 they provided; only predictors increasing R^2 by 1% or more were accepted. A core set of experienced vessels was identified, using similar criteria to those of Unwin et al. (2009). Core vessels were defined as those which had fished in ten or more years between 1998 and 2012, including one of the most recent two years. This set of core vessels excluded 92% of all vessels and 60% of the total swordfish catch for the 1998–2012 period. There was considerable overlap of vessels across years in the core dataset, ensuring that year-effects in models using this dataset would be properly linked. Five of the 21 core vessels had fished in each year from 1998 to 2012, and all of the 11 vessels fishing in the first two years of this period were still fishing in the last two years (Figure 2).

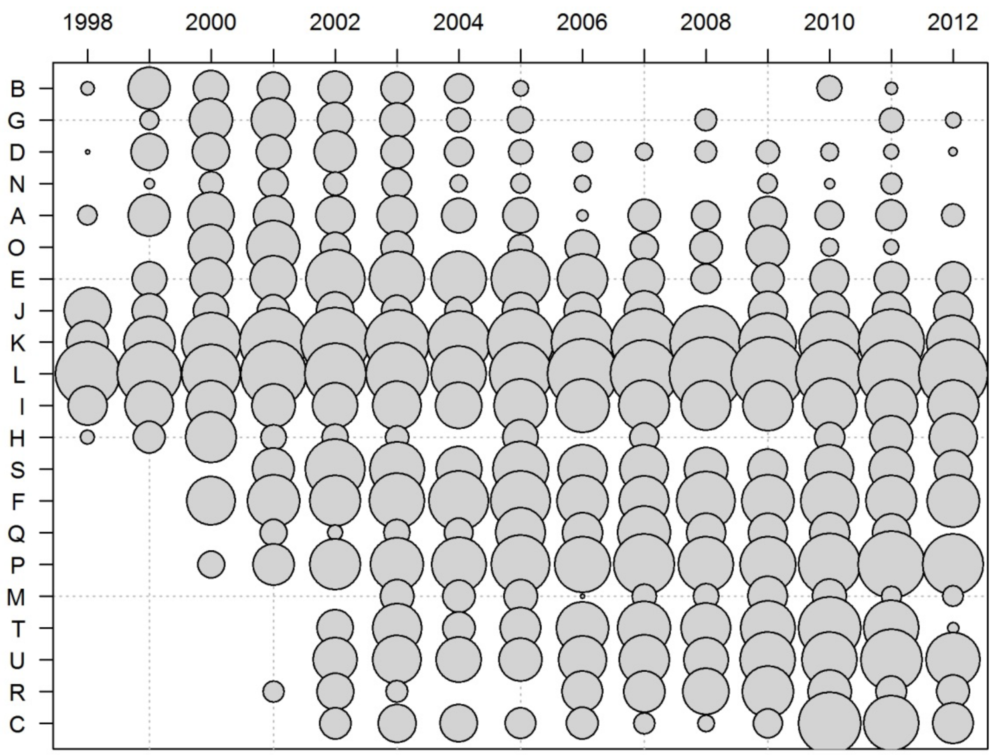

Figure 2: Bubble plot showing the relative effort (number of sets) in each year by each of the 21 core vessels. The area of the circles is proportional to the number of sets. Vessels are ordered from top to bottom by the average of the year associated with each of their records.

Three models were constructed: all-data, based on the years 1993 to 2012 and all vessels in the fishery; core-vessel, based on the core set of vessels and the more recent fishery, 1998 to 2012; and late-series, based on the core set of vessels and the period subsequent to the introduction of swordfish into the QMS and for which information on light stick usage and bait type was available for each set, i.e., 2005 to 2012.

3. RESULTS

3.1 Changes in species composition and targeting

The main species caught in the study region during 1993 to 2012 have been albacore tuna, followed by swordfish, blue shark (*Prionace glauca*), bigeye tuna, and southern bluefin tuna (Table 2). The relative catches of these species have changed substantially over time, however, with the initial dominance of albacore in the catch (51–67% of the total between 1993 and 1999) being gradually displaced by increased catches of swordfish and blue shark, so that since 2007 these three species have accounted for a similar fraction of the total catch.

Table 2: Annual catch by species (%) in the northern New Zealand tuna longline fishery.

	Albacore tuna	Swordfish	Blue shark	Bigeye tuna	Southern Bluefin tuna	Mako	Yellowfin tuna	Other	Striped marlin	Butterfly tuna	Pacific Bluefin tuna	Skipjack tuna	Blue marlin	Black marlin
1993	52	11	3	9	18	3	1	0	0	2	0	0	0	0
1994	67	9	5	8	1	2	4	2	0	0	0	0	0	0
1995	60	7	7	7	1	3	12	2	1	0	0	0	0	0
1996	58	10	4	7	2	1	12	4	1	0	0	0	0	0
1997	53	11	8	9	6	3	8	2	0	0	0	0	0	0
1998	56	12	6	12	5	2	3	2	0	0	0	0	0	0
1999	51	16	6	12	6	2	3	2	1	0	0	0	0	0
2000	40	21	7	14	6	3	3	4	1	0	0	0	0	0
2001	46	18	7	12	4	3	3	5	1	1	0	0	0	0
2002	55	17	7	5	5	2	1	6	0	1	1	0	0	0
2003	59	13	8	5	6	3	1	4	0	0	1	0	0	0
2004	40	19	15	8	6	4	1	5	2	0	1	0	0	0
2005	33	16	15	11	13	3	2	3	2	1	1	0	0	0
2006	25	29	18	10	7	4	1	2	1	1	1	0	0	0
2007	18	21	23	14	13	5	2	2	1	1	0	0	0	0
2008	22	27	18	13	8	4	1	2	2	1	1	0	0	0
2009	25	22	18	15	9	4	0	2	2	1	1	0	0	0
2010	24	25	23	7	11	5	0	2	1	1	0	0	0	0
2011	16	30	22	8	12	5	0	3	2	0	1	0	0	0
2012	11	24	34	7	14	5	0	2	1	0	1	0	0	0

The main target species in this fishery has been bigeye tuna (Figure 3), this species accounting for about 60–80% of all sets during 1993–2012. In most years the next most targeted species was southern bluefin tuna. The fraction of sets targeting this species steadily increased since 1995 and accounted for about 20–40% of all sets since 2002. Targeting of other species (mainly albacore, Pacific bluefin tuna (*Thunnus orientalis*), and yellowfin tuna (*T. albacares*)) accounted for a further 10–20% of sets in most years until targeting of swordfish became legal in 2004 after which it dropped to almost zero. Despite this change in the regulations, recorded targeting of swordfish has stayed at low levels, generally at about 5%.

In addition to swordfish, bigeye tuna, southern bluefin tuna, Pacific bluefin tuna, yellowfin tuna, blue shark, and mako shark (*Isurus oxyrinchus*) were all introduced into the QMS in 2004 and this is likely to have had an influence on the subsequent relative levels of targeting and catch of all these species.

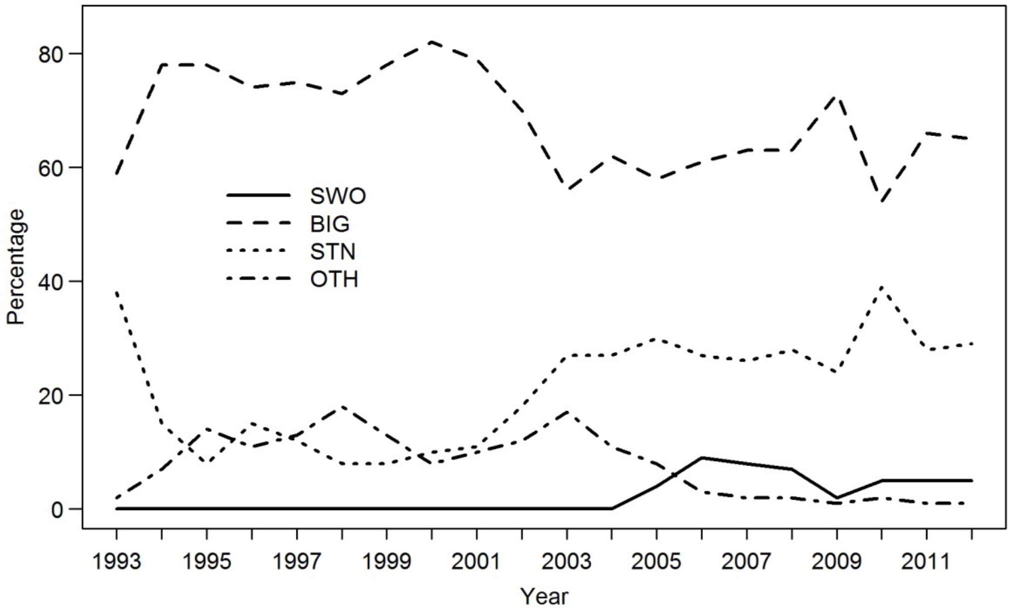

Figure 3: Changes in recorded target species in the northern New Zealand tuna longline fishery.

The annual catch of swordfish followed the pattern of increasing and then decreasing annual effort through the 1990s and into the 2000s, leading to relatively constant nominal catch rates, but after 2005 effort levelled out at about 2 million hooks per year while catch increased from about 4000 fish in 2005 to over 10 000 fish in the most recent three years (Figure 4). A peak of effort in the fishery occurred in 2002, when the fleet had grown to over 140 vessels deploying over 7000 sets and about 8.5 million hooks—to achieve an annual catch of about 12 000 fish. A similar level of catch was achieved in 2012 from less than 2 million hooks set by 36 vessels.

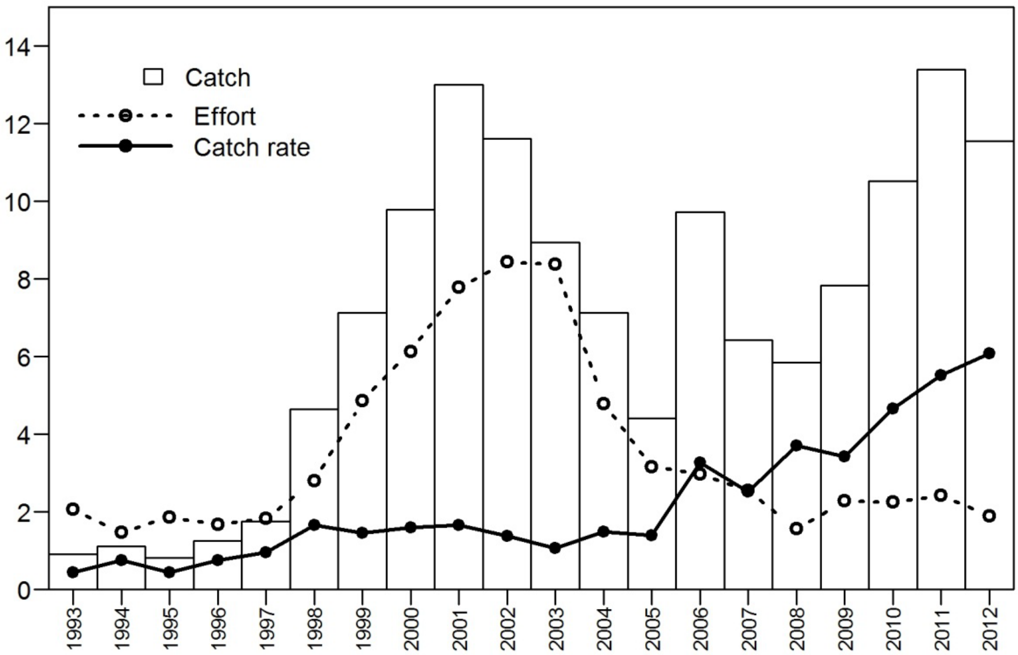

Figure 4: Annual swordfish catch (thousands of fish), effort (millions of hooks), and catch rate (number of swordfish per thousand hooks) in the northern New Zealand tuna longline fishery.

3.2 Examination of operational and environmental variables

Plots of the mean latitude and longitude of longline set start positions revealed some annual variability in the location of the fishery (assuming that the distribution of set directions was not substantially different between years). In particular the fishery was centred considerably further south in some years, especially 2003 and 2004, but no persistent trends were identified (Figure 5). The overall latitudinal range of the annual fishery centre of effort for the period was about 150 km and the longitudinal range about 110 km.

Fishing effort became more focussed over time on the full phase of the lunar cycle, especially after 2004 when swordfish targeting became legal. The moon fullness associated with fishing operations increased from about 48–52% full before 2004 to about 54–56% full since.

Soak-time steadily increased during the development of the domestic fleet in the 1990s, from less than 10 h in 1993 to 14–15 h since 2000. Soak-time is strongly correlated with longline length which has also increased over time, from 30–35 km at the beginning of the period to 40–45 km since 2003 (the outlier at the left of the plot in the bottom panel is due to the presence of several large Japanese vessels which subsequently left the fishery).

Another change in fishing behaviour that would be expected to increase catch rates of swordfish is the shift of set start times to earlier in the evening and the associated increase in the fraction of the soak-time during the hours of darkness. In 1993–1995 the mean set start time was an hour or two after midnight and the night fraction about 40%; by 2010 the mean set start time was about 2 hours before midnight and the night fraction about 55%.

The fleet fished in slightly warmer waters in the first few years than in subsequent years (a feature which could be related to seasonal differences in effort between years) but there is no trend in SST after about 2000, during which time the fishery became centred on surface waters with a temperature of about 18–18.5 °C. Changes are more apparent in SSH, essentially a measure of the thermal energy of the entire water column at the start position of the set, with this value generally increasing over time and, for the most recent eight years, showing some correlation with latitude.

The percentage of sets with zero catch of swordfish has declined linearly over time, from about 70–80% in the first few years to about 10% in the last two years. This may indicate a steady increase in the effective targeting of swordfish over time, an increase in reporting of swordfish catch, or an increase in abundance.

Mean swordfish weight (derived from the total recorded weight and number of fish on each set) decreased in a similar way to zero catch percentage, with the mean weight of swordfish dropping from about 55 kg in 1993 to about 35 kg by 2012.

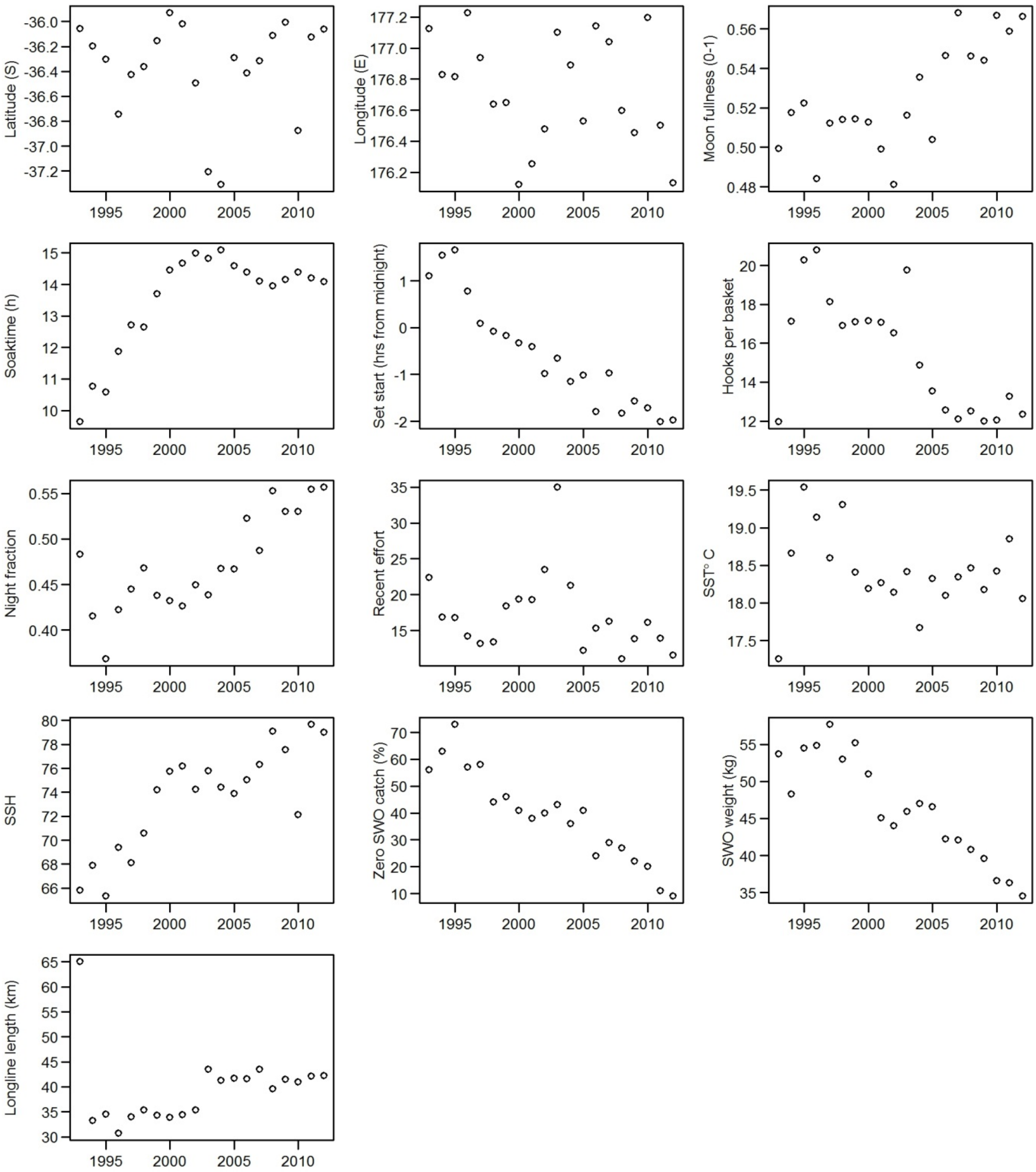

Figure 5: Changes in recorded and derived operational variables and independently estimated environmental variables associated with the longline sets used in the CPUE analyses. Except for zero SWO catch, the points in the plots indicate annual means.

3.3 CPUE models

3.3.1 Core-vessel model

The regression analysis based on the core-vessel dataset produced a model in which about a third of the variability in swordfish catch rates is explained by the time-step variable *YR_qtr*. The model accepted three additional variables: *nightfrac*, *Vessel_ID*, and *SST*, together providing a model with relatively high explanatory power (R^2 = 44%). The contribution to the model R^2 of the next variable selected in the stepwise procedure, *SSTanom*, was insufficient for selection into the model (Table 3).

Table 3: Core-vessel model: standardised CPUE model results for the New Zealand longline swordfish fishery, using the core dataset. See Table 1 for a description of the predictors. Predictors in grey did not meet the selection criteria for inclusion in the model.

Predictor	Degrees of freedom	Deviance	Residual degrees of freedom	Residual deviance	R^2
YR_qtr			18 727	-119.7	0.339
nightfrac	-1	-1.927	18 726	-121.6	0.412
Vessel_ID	-20	-39.981	18 706	-161.6	0.431
SST	-1	-1.990	18 705	-163.6	0.441
SSTanom	-1	-1.994	18 704	-165.6	0.447

The year-quarter index shows a strong similarity to the index from the previous study (Unwin et al. 2009) for the overlapping years. The strong seasonal fluctuation seen in that study, with generally higher CPUE in the first two quarters of each year, is repeated in the current model and continues for the years following the end of the earlier series. CPUE over time, disregarding seasonal fluctuation, shows a slow decrease between 1998 and 2003, followed by a steady increase (and an increase in the seasonal variability) through to 2012 (Figure 6, Appendix 1).

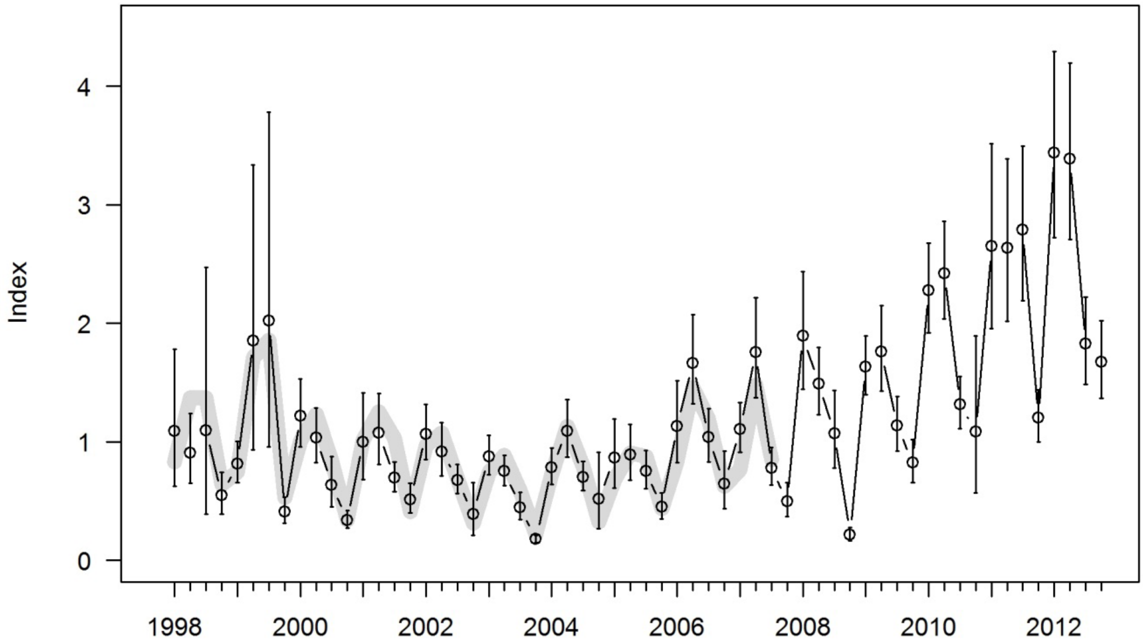

Figure 6: Core-vessel model: standardised CPUE indices by year-quarter using a GAM model with a quasi-poisson error function. Error bars represent 95% CIs based on a bootstrap process giving equal weight to each vessel. The grey line shows the CPUE indices used in the previous assessment (from Unwin et al. 2009), scaled so as to have the same mean as the indices for the equivalent period in the updated series.

The influence of night fraction on CPUE in this model is considerable (Figure 7). CPUE increases strongly as more of the soak time falls within the hours of darkness, so that CPUE for sets 80–100% during night hours is about four times the CPUE for sets 0–20% during night hours.

There are substantial differences in CPUE between the 21 vessels used in this model; CPUE for the best performing vessels is nearly two times that for the worst performing vessels.

Surface water temperature also has an influence in this model, with higher CPUE associated with increasing SST. At low values of SST, where there are little data, CPUE is not well determined but across the main range of SST values associated with the fishery (about 16–22° C) CPUE approximately doubles.

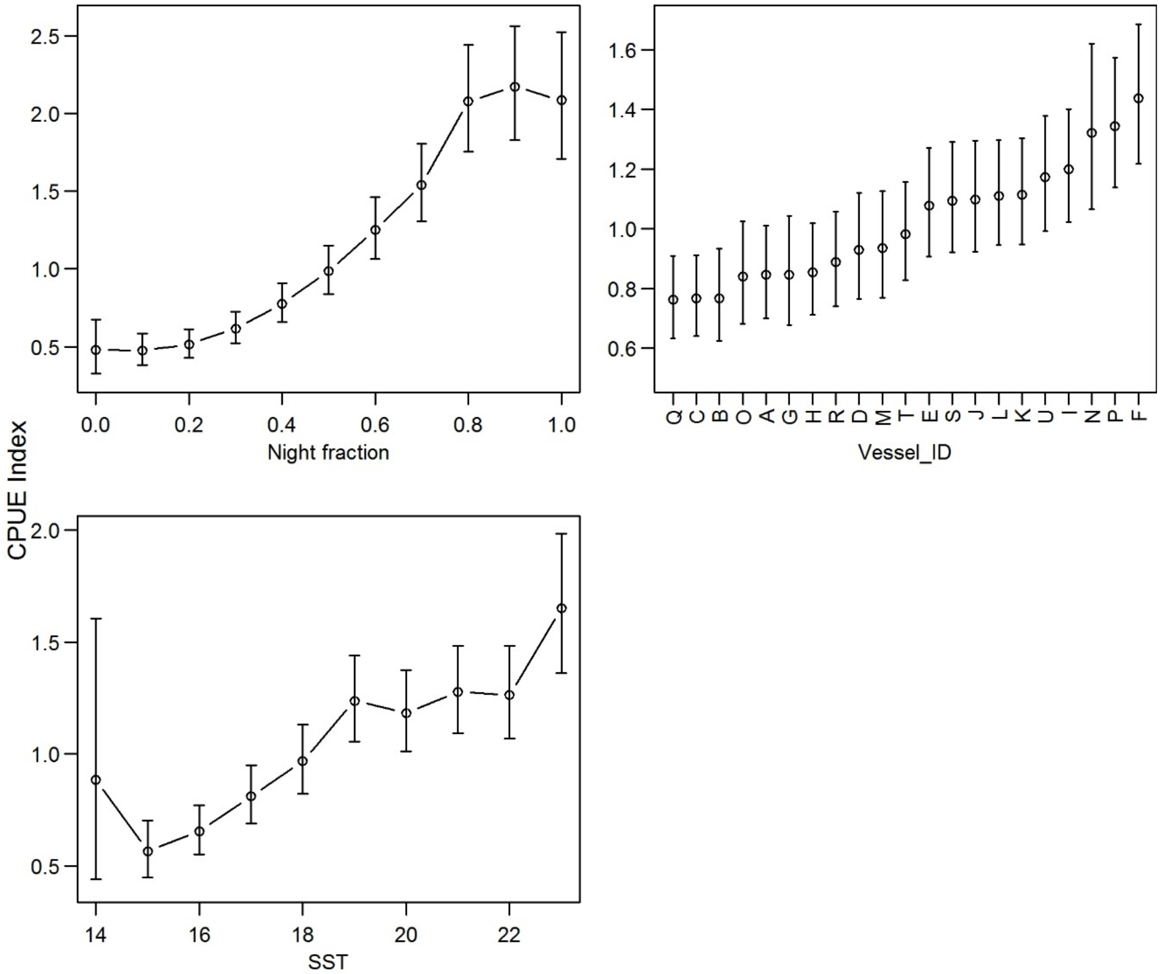

Figure 7: Core-vessel model: model fits to explanatory variables. In the top right panel vessels are ordered by efficiency from lowest to highest. Error bars show +/- 2x the model standard errors.

The overall pattern of changing CPUE over time is determined by the year-quarter effect, with the additional variables adding only subtle modifications to the index (Figure 8). The strong seasonal variation is tempered slightly by the inclusion of the first additional variable, *nightfrac*, especially in the second half of the series. The influence of this effect on the index is enhanced by the overall change in night fraction from year to year, as seen above in Figure 5. The next variable to be added, *Vessel_ID*, has almost no discernible effect on the series despite having a significant influence in the model. This is because although there are significant differences in catch rates between vessels, the relative effort of each vessel between years is relatively stable (see Figure 2), especially because the data set has been limited to a core set of vessels. In contrast to this, the last variable to be added, SST, again strongly tempers the seasonal variability in the model and has much more influence on the index than vessel, despite having lower explanatory power in the model. This influence, again, is due to the level of annual variability in the spread of effort across the range of surface water temperatures.

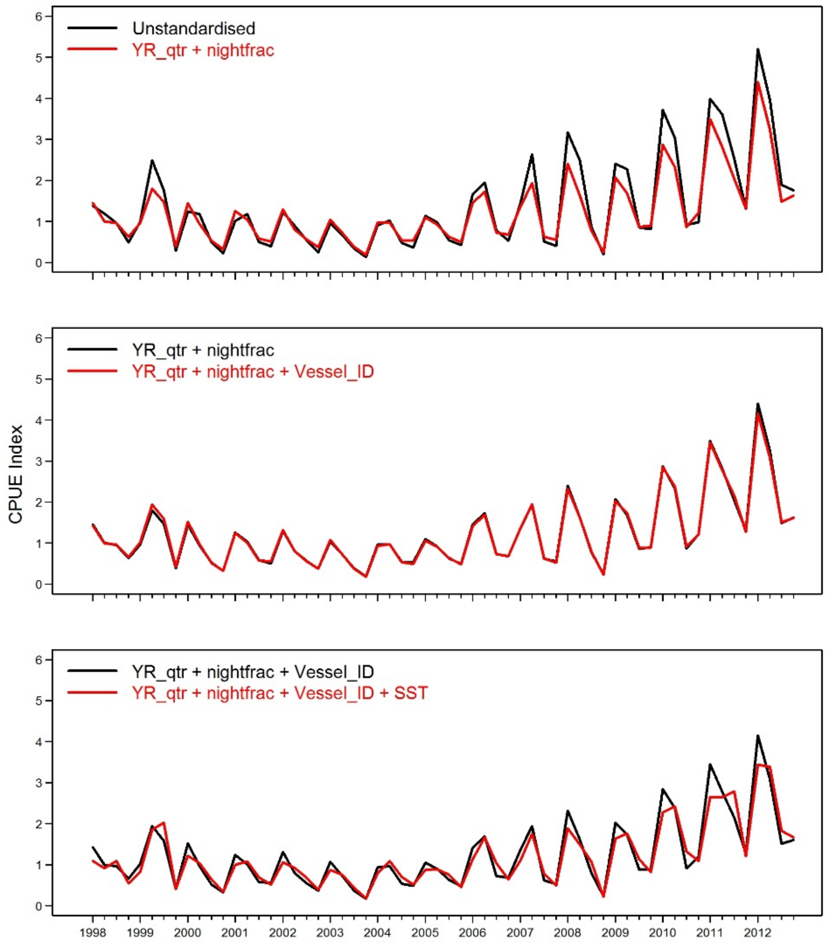

Figure 8: Core-vessel model: step plot showing the effect on the CPUE index as each variable is added to the model. The top panel shows the unstandardized index (with *YR_qtr* as the only model variable) and the first additional variable (*nightfrac*) plotted on top. Successive panels repeat the overplotted series from the previous panel and add the series from the next additional variable.

3.3.2 Late-series model

The regression analysis based on the late-series dataset produced a model with the same first additional variable, *nightfrac*, as for the core dataset model. In this case, however, only one further variable was accepted, *NLS_rate* (light-stick rate). The next variable selected in the step-wise procedure, target (*targCAT*), fell marginally short of the criteria for inclusion in the model; notably *Vessel_ID* was not included in this model (Table 4). Although the explanatory power of *YR_qtr* is slightly less than in the core dataset model, *nightfrac* has a relatively greater influence and *NLS_rate* explains a further 6% of the variability, leading to a model with slightly greater explanatory power (46%) than the core dataset model.

Table 4: Late-series model: standardised CPUE model results for the New Zealand longline swordfish fishery, using data from core vessels and the period 2005–2012. See Table 1 for a description of the predictors. Predictors in grey did not meet the selection criteria for inclusion in the model.

Predictor	Degrees of freedom	Deviance	Residual degrees of freedom	Residual deviance	R^2
YR_qtr			10 871	-63.7	0.299
nightfrac	-1	-1.902	10 870	-65.6	0.397
NLS_rate	-1	-1.938	10 869	-67.5	0.459
targCAT	-3	-5.990	10 866	-73.5	0.468

The year-quarter index shows the same general pattern as the comparative period of the core-vessel model, with only small differences, mainly in the later part of the series. Although seasonal variability is high, the same trend of gradually increasing CPUE is apparent throughout the period (Figure 9, Appendix 1).

The relationship between CPUE and night-fraction in this model is also similar to that shown in the core-vessel model, with a steady increase in predicted CPUE across the entire range of possible values, and an even more pronounced difference in CPUE between sets mostly during the day and sets mostly during the night.

The influence of light sticks on swordfish CPUE in the model is as expected, with steadily increasing CPUE with increasing rate of light stick usage up to about 450–500 light sticks per 1000 hooks. The CPUE at this upper end of light stick usage was over three times that for when no light sticks were used.

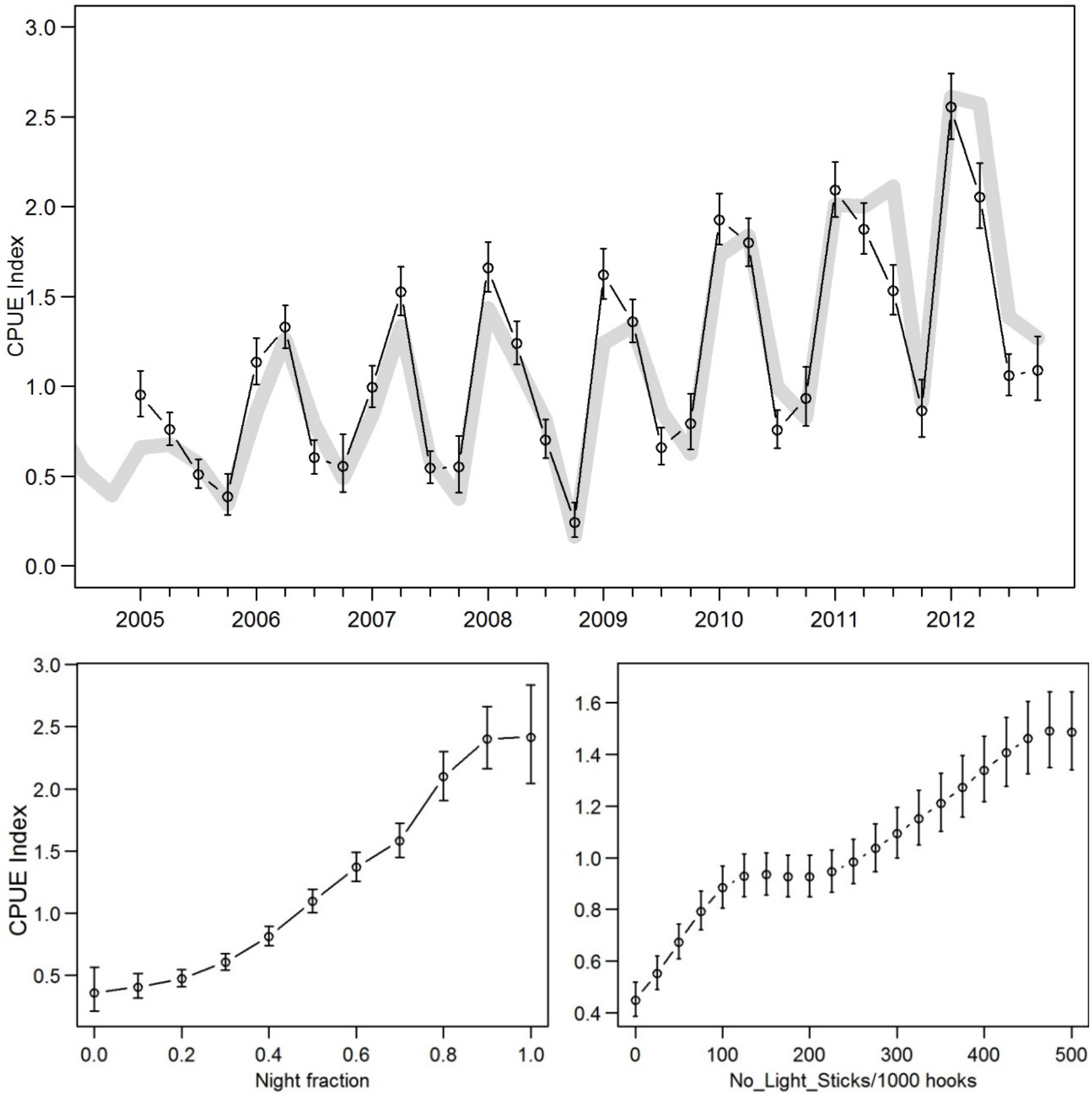

Figure 9: Late-series model: standardised CPUE indices and fits to the other model variables using a GAM regression with a quasi-poisson error function, and data from core vessels and the period 2005–2012. Error bars represent +/- 2x the model standard errors. The grey line in the top panel shows the CPUE indices from the core-vessel model, scaled so that the indices for the period equivalent to the late-series has the same mean as the late-series (see Figure 6).

3.3.3 All-data model

The all-data model uses data from all vessels in the dataset and from all years since the development of the domestic fishery, i.e., 1993 to 2012. This repeats the all-years model of Unwin et al. 2009, with the addition of data from the five subsequent years of the fishery. To take into account the effect of vessel experience on CPUE this model was offered the variable *core* (differentiating between core and non-core vessels) and, as a further alternative to *Vessel_ID*, the variable *isbig* (differentiating between large and small vessels) (see Table 1).

The first additional variable accepted into the all-data model, *nightfrac*, is the same as for the core-vessel and late-series models. The only other additional variable accepted into this model was *targCAT*; the next variable in the stepwise procedure, *HksBask* (the number of hooks per basket – a proxy for hook depth), did not add sufficient explanatory power to be accepted (Table 5). The model explains about 38% of the variability in the data, slightly less than in the other two models.

Table 5: All-data model: standardised CPUE model results for the New Zealand longline swordfish fishery, using data from all vessels and the period 1993–2012. See Table 1 for a description of the predictors. Predictors in grey did not meet the selection criteria for inclusion in the model.

Predictor	Degrees of freedom	Deviance	Residual degrees of freedom	Residual deviance	R^2
YR_qtr			63 123	-159.7	0.284
nightfrac	-1	-1.929	63 122	-161.7	0.355
targCAT	-3	-5.985	63 119	-167.6	0.371
HksBask	-1	-1.995	63 118	-169.6	0.376

The year-quarter index closely matches that of the equivalent model in Unwin et al. (2009) for the overlapping years, with the main difference being that some of the peak values (first and second quarter) are greater in the updated series, especially for the middle and later years of the earlier series. The all-data model shows CPUE initially increasing as the domestic fishery developed through the 1990s, and for later years agrees with the patterns seen in the core-vessel and late-series models, i.e., decreasing values through the early 2000s to a low point centred at about 2003 followed by strongly fluctuating but generally increasing values through to 2012 (Figure 10, Appendix 1).

The influence of night-fraction on CPUE in this model is also similar to that seen in the other two models, except that there is a slight decrease in CPUE for sets fishing more than 90% during darkness, although such sets are uncommon (less than 3% of all sets) and the model may not estimate well for these values.

The model predictions for the four target categories shows the highest CPUE for the OTHER target category (mainly swordfish, yellowfin tuna, and Pacific bluefin tuna); the lowest CPUE is associated with targeting southern bluefin tuna, possibly because this fishery is centred more towards the southern and eastern edge of the region—away from the core area of high swordfish catch rates. Predicted CPUE for the other two target species categories, albacore tuna and bigeye tuna, are similar to each other and intermediate in value.

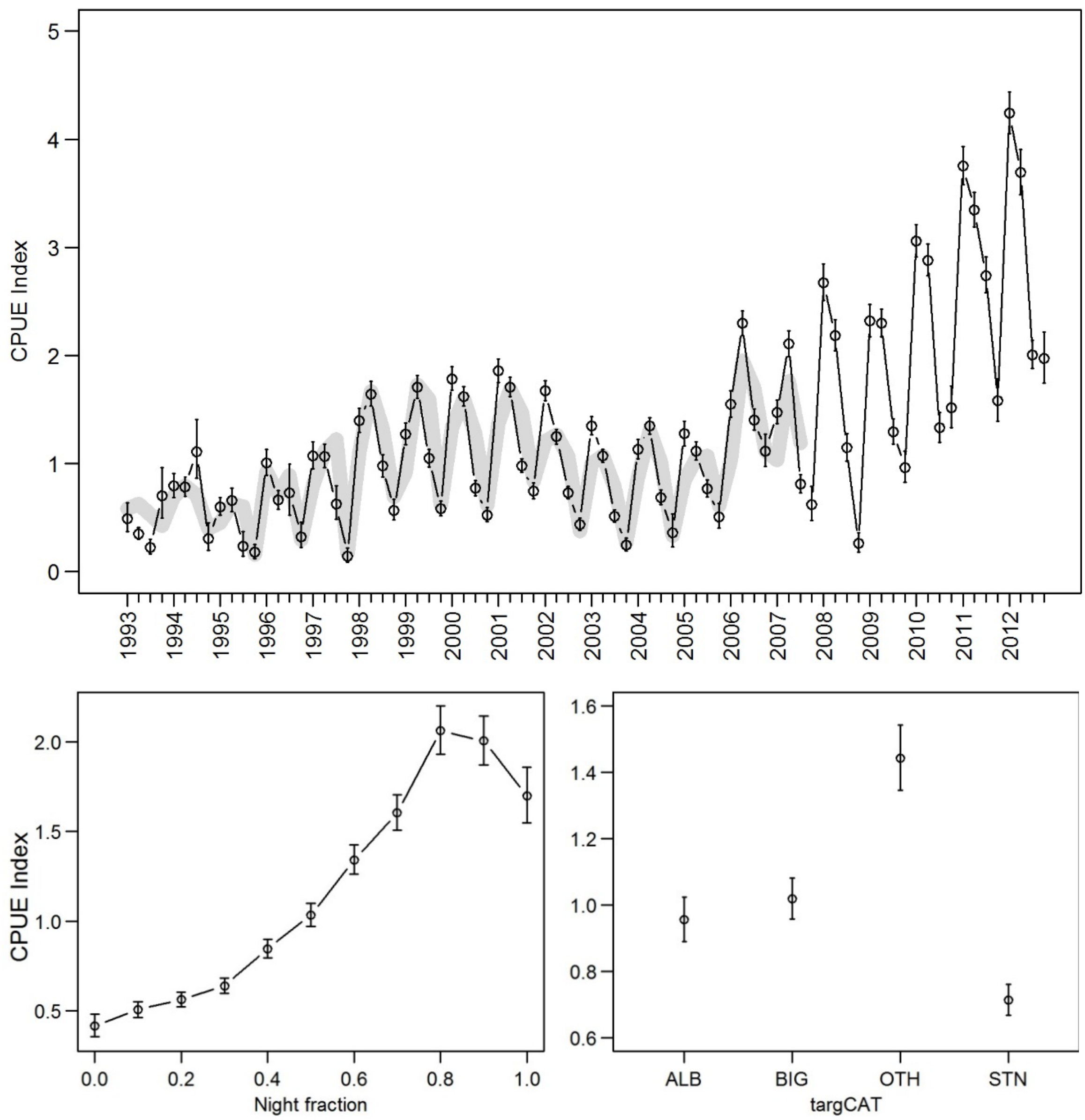

Figure 10: All-data model: standardised CPUE indices and fits to the other model variables using a GAM model with a quasi-poisson error function, and data from all vessels and the period 1993–2012. Error bars represent +/- 2x the model standard errors. The grey line in the top panel shows the CPUE indices from the equivalent model of Unwin et al. 2009, scaled so as to have the same mean as the indices for the equivalent period in the updated series.

4. DISCUSSION

It was anticipated that the additional variables available for the late-series model known to be associated with higher catch rates of swordfish (i.e., rate of light-stick usage and squid bait percentage), in addition to the number of hooks per basket and moon fullness used in the other models, may have provided a better measure of the level of targeting of swordfish than the recorded target species, and thus help to explain the recent increase in catch rates seen in the other models. Although light stick usage was accepted into the late-series model, there was little difference in the relative values of the indices for the overlapping years of all three models, supporting the conclusion of Unwin et al. (2009) that these variables are likely to be adequately accounted for in the model by other variables, including the year-effect. The increase in catch rate due to changes in targeting behaviour can be hidden in the year-effect if the effect of these variables is relatively constant within a year, but changes stepwise as the years go by. Although examination of these variables did not reveal any obvious stepwise patterns, they may exist at a lower level.

The increasing index seen in each of the models after 2004 (when targeting of swordfish became legal) may be due to a combination of factors including: increased targeting of swordfish (not properly declared in catch-effort reporting and not fully accounted for by the available model variables such as night-fraction, moon fullness, and light-stick usage that provide a proxy for targeting); decreasing occurrence of zero catches; and a real increase in swordfish abundance—especially small fish. The relative influence of each of these factors is unknown but this pattern of increasing CPUE was found to be persistent across all models, including trial log-normal models (not shown here) which tested both ignoring or adding a small catch to records with zero catches—and it seems possible that an increase in numbers of swordfish in the region is at least partially responsible for the observed increase in CPUE. However, a potential explanation for increasing catch rates and decreasing fish size since the early 2000s is that the effectiveness of light sticks may be size-related; if small swordfish were more attracted to light sticks than larger fish then the increasing light stick usage over the last 10 years or so would result in an increase in catch per hook independent of changes in abundance of swordfish.

This lack of certainty regarding the usefulness of these CPUE series as indices of swordfish abundance in the New Zealand region is compounded by their conflict with the other CPUE series for the south Pacific region, based on data from the Japanese and EU longline fleets, neither of which indicate a significant increase in CPUE in recent years (Nick Davies, SPC, Noumea, unpublished data). Because of this, the SPC pre-assessment workshop recommended that these indices not be used for the reference case in the current south Pacific swordfish stock assessment model but to include the all-data series as a sensitivity analysis with low relative weight.

The workshop made the following suggestions for future analyses of swordfish CPUE in the New Zealand domestic tuna longline fishery:

- Explore delta/lognormal models to deal with the large number of zero catches. Although delta models can suffer from the flaw that fishing events with zero catch of the species in question may be fundamentally different to positive catch events (e.g., they may have suffered from some operational problem that is not captured by the catch-effort recording system or not have been recorded at all if the total catch was zero), they may be more appropriate in this fishery (compared to, e.g., a trawl fishery) where differences in operational variables between sets are well recorded and sets with zero catches of all species are far less frequent.

- Trial the use of spatial categorical variables to account for the improvement over time in fishers' ability to target areas of high swordfish catch as the fishery changed from a bycatch fishery to a target fishery.

- Model aggregation effects by including number of hooks per unit of longline length as a variable in the model. The degree to which swordfish aggregate has the potential to affect CPUE as measured by catch per numbers of hooks when there is variability in the distance between hooks and therefore in the availability of bait to aggregated fish on a section of the longline.

- Investigate influence of changes in hook type on CPUE using observer data to determine the extent and timing of the introduction of circle hooks into the core vessels of the fleet.

- Examine the effect of distance to the nearest seamount on CPUE. Swordfish are known to aggregate around seamounts and historical tagging studies have shown a high degree of fidelity to home grounds (Beckett 1974). Of particular interest would be to determine whether there is any evidence of individual or serial depletion of seamount swordfish populations.

- Trial models using different criteria for defining core vessels to account for the effect (in the current models) of vessels leaving the fishery in recent years; for example by restricting the analysis to a smaller core-fleet which had fished in all years in the series.

5. ACKNOWLEDGMENTS

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APPENDIX 1

Model indices and CVs. For the core-vessel series CVs are calculated by a bootstrapping procedure; for the late series and all-data series CVs are based on the model standard errors.

	Core-vessel		Late-series		All-data	
Year-quarter	Index	CV	Index	CV	Index	CV
1993_01	—	—	—	—	0.49	0.14
1993_02	—	—	—	—	0.35	0.09
1993_03	—	—	—	—	0.22	0.14
1993_04	—	—	—	—	0.70	0.17
1994_01	—	—	—	—	0.79	0.08
1994_02	—	—	—	—	0.78	0.06
1994_03	—	—	—	—	1.11	0.13
1994_04	—	—	—	—	0.30	0.20
1995_01	—	—	—	—	0.60	0.07
1995_02	—	—	—	—	0.66	0.08
1995_03	—	—	—	—	0.23	0.26
1995_04	—	—	—	—	0.18	0.17
1996_01	—	—	—	—	1.01	0.06
1996_02	—	—	—	—	0.66	0.06
1996_03	—	—	—	—	0.73	0.16
1996_04	—	—	—	—	0.32	0.19
1997_01	—	—	—	—	1.07	0.06
1997_02	—	—	—	—	1.07	0.05
1997_03	—	—	—	—	0.62	0.13
1997_04	—	—	—	—	0.14	0.21
1998_01	1.09	0.27	—	—	1.40	0.04
1998_02	0.91	0.16	—	—	1.64	0.04
1998_03	1.09	0.49	—	—	0.98	0.05
1998_04	0.55	0.16	—	—	0.57	0.09
1999_01	0.82	0.11	—	—	1.27	0.04
1999_02	1.86	0.33	—	—	1.71	0.03
1999_03	2.02	0.35	—	—	1.05	0.04
1999_04	0.41	0.13	—	—	0.58	0.05
2000_01	1.22	0.12	—	—	1.78	0.03
2000_02	1.04	0.11	—	—	1.62	0.02
2000_03	0.64	0.17	—	—	0.77	0.04
2000_04	0.34	0.11	—	—	0.52	0.06
2001_01	1.00	0.18	—	—	1.86	0.03
2001_02	1.08	0.14	—	—	1.71	0.02
2001_03	0.70	0.09	—	—	0.98	0.03
2001_04	0.51	0.12	—	—	0.75	0.05
2002_01	1.06	0.11	—	—	1.67	0.03
2002_02	0.92	0.12	—	—	1.25	0.02
2002_03	0.68	0.09	—	—	0.73	0.04
2002_04	0.39	0.29	—	—	0.44	0.07
2003_01	0.88	0.10	—	—	1.35	0.03
2003_02	0.75	0.09	—	—	1.07	0.03
2003_03	0.45	0.13	—	—	0.51	0.06
2003_04	0.18	0.08	—	—	0.25	0.12
2004_01	0.78	0.10	—	—	1.13	0.04
2004_02	1.09	0.11	—	—	1.35	0.03
2004_03	0.70	0.09	—	—	0.68	0.04
2004_04	0.52	0.31	—	—	0.36	0.22
2005_01	0.87	0.17	0.95	0.06	1.27	0.05
2005_02	0.89	0.13	0.76	0.07	1.11	0.04

APPENDIX 1 —*continued*

	Core-vessel		Late-series		All-data	
Year-quarter	Index	CV	Index	CV	Index	CV
2005_03	0.75	0.11	0.51	0.08	0.77	0.05
2005_04	0.45	0.12	0.39	0.15	0.51	0.12
2006_01	1.13	0.15	1.13	0.05	1.55	0.04
2006_02	1.66	0.11	1.33	0.05	2.30	0.03
2006_03	1.04	0.11	0.60	0.08	1.40	0.04
2006_04	0.65	0.19	0.55	0.15	1.12	0.06
2007_01	1.11	0.10	0.99	0.06	1.47	0.04
2007_02	1.76	0.12	1.53	0.05	2.11	0.03
2007_03	0.78	0.10	0.54	0.07	0.81	0.05
2007_04	0.50	0.15	0.55	0.15	0.62	0.13
2008_01	1.89	0.13	1.66	0.04	2.67	0.03
2008_02	1.49	0.10	1.24	0.05	2.18	0.03
2008_03	1.07	0.15	0.70	0.07	1.14	0.05
2008_04	0.22	0.13	0.24	0.21	0.26	0.19
2009_01	1.63	0.08	1.62	0.04	2.32	0.03
2009_02	1.76	0.10	1.36	0.04	2.30	0.03
2009_03	1.14	0.10	0.66	0.08	1.29	0.05
2009_04	0.82	0.11	0.79	0.10	0.96	0.07
2010_01	2.28	0.08	1.93	0.04	3.06	0.02
2010_02	2.42	0.09	1.80	0.04	2.88	0.02
2010_03	1.32	0.08	0.76	0.07	1.33	0.05
2010_04	1.09	0.31	0.93	0.09	1.51	0.07
2011_01	2.65	0.15	2.09	0.04	3.75	0.02
2011_02	2.64	0.13	1.87	0.04	3.35	0.02
2011_03	2.79	0.12	1.53	0.05	2.74	0.03
2011_04	1.20	0.09	0.87	0.09	1.58	0.06
2012_01	3.44	0.11	2.55	0.04	4.24	0.02
2012_02	3.39	0.11	2.05	0.04	3.69	0.03
2012_03	1.83	0.10	1.06	0.06	2.01	0.03
2012_04	1.67	0.10	1.09	0.08	1.97	0.06