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A comparison of a trawl survey index with CPUE series for hake (*Merluccius australis*) off the west coast of South Island (HAK 7)

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EXECUTIVE SUMMARY

Horn, P.L.; Ballara, S.L. (2018). A comparison of a trawl survey index with CPUE series for hake (*Merluccius australis*) off the west coast of South Island (HAK 7).

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The 2017 west coast South Island hake assessment identified major conflicts between the two relative abundance indices. An assessment model using only the research trawl survey series of relative abundance estimates indicated stock status in 2017 to be 26% B_0, while an alternative model using only a time series of catch-per-unit-effort indices (CPUE) estimated a status of 50% B_0. This report describes an investigation of the available catch statistics, and anecdotal information on any changes in hake fishing practice, in an attempt to determine whether one of the two sources of relative abundance information was more likely to represent true west coast hake abundance.

Alterantive CPUE series were produced to determine whether analyses of subsets of the 'all fleet' data could explain why the CPUE trend was different to that of the trawl survey. It was apparent that even when removing midwater trawl data, or using only fishery data from the trawl survey area, or analysing fleets with consistent fishing gear and practice, the resulting CPUE trajectories were little different to that produced for the entire fishery. The overall CPUE trend was a decline from 2000 to about 2007, followed by an increase (but sometimes with another decline after about 2012). A CPUE series intended to closely mirror the trawl survey data, by using only bottom trawl tows conducted during daylight hours from 20 July to 23 August each year, was similar to, though more variable than, the other bottom trawl CPUE series in the survey area. None of the CPUE series matched well with the research trawl survey indices. Further, anecdotal information collected during this project suggests that aspects of the fishing behaviour for hake have changed in ways that cannot easily be standardised for in CPUE analyses, therefore we conclude that it would be unwise to assume that any currently available hake CPUE series from the west coast South Island fishery is a reliable index of fish abundance.

1. INTRODUCTION

The HAK 7 (WCSI) stock was assessed in 2017 (Horn 2017). Two relative abundance series were available: a series of four research trawl surveys conducted in 2000, 2012, 2013 and 2016, and a CPUE series using observer-collected tow-by-tow data from 2001 to 2015. Previous hake assessment projects have investigated a variety of CPUE series using data since 1990, but because of known variations over time in the fishing behaviour and catch reporting behaviour relating to hake it was believed that the post-2001 observer series, incorporating catch data after the establishment of the deemed value system, was the least likely to be biased. The previous HAK 7 assessment completed in 2013 (Horn 2013) had only the first two research survey points available, and there was no apparent conflict between the survey and CPUE relative abundance series.

The 2017 assessment, however, found major conflicts between the two series (Horn 2017). The series of four comparable surveys inferred a steady decline from 2000 to 2016 (although there are no points in the series from 2001 to 2011), whilst the CPUE series declined from 2001 to about 2008 but has steadily increased since then. Consequently, assessment models using each of the two series separately produce markedly different outcomes: a current stock status of 26% B_0 when based on the surveys, or 50% B_0 when based on the CPUE.

Both abundance series have shortcomings. The survey series is sparse, has a long gap between the first and second surveys, and does not cover the entire area off WCSI where hake are known to be relatively abundant. The CPUE series is based on commercial catches which can be influenced by many factors not related to hake abundance. In particular, changes in fishing technology and in the commercial (economic) desirability of hake are not captured in the QMS effort statistics, and so cannot be standardised for in any CPUE model. It was considered desirable to further investigate the available catch statistics, and anecdotal information on any changes in hake fishing practice, in an attempt to determine whether one of the two available relative abundance series is more likely to represent true hake abundance, and therefore, which of the two assessment scenarios should be given primacy in the management of west coast hake.

This report fulfils the reporting objective of a variation to Project DEE201609 “To update the stock assessment of hake, including biomass estimates and sustainable yields”, funded by the Ministry for Primary Industries.

1.1 Abundance series used in 2017 assessment

The trawl survey and CPUE relative abundance series used in the 2017 assessment are listed in Table 1. Brief descriptions of the derivations of these series are as follows.

A combined trawl and acoustic survey by *Tangaroa* in 2000 (O’Driscoll et al. 2004) was replicated (with some modifications) in the winters of 2012, 2013 and 2016 (O’Driscoll & Ballara 2018), so a four year comparable time series was available (Table 1). The biomass estimates from the four surveys were standardised using random day-time bottom trawl stations in strata 1&2A, B, and C, and 4A, B, and C (core strata in depths 300–650 m), with stratum areas from the 2012 survey (O’Driscoll & Ballara 2018). Since the initial survey, additional shallower and deeper strata have been added, but the abundance series used in the assessment modelling related only to the core strata common to all four surveys.

A standardised CPUE series from the trawl fishery in HAK 7 was developed using data to the end of the 2014–15 fishing year (Ballara 2018). The series used observer data collected since 2001 from the winter trawl fishery primarily targeting hoki. This was the series chosen by the Deepwater Fisheries Assessment Working Group for inclusion in the most recent assessment (Horn 2017) and in the previous assessment (Horn 2013). It was believed that this series, incorporating catch data after the establishment of the deemed value system, was the least likely to be biased by changes in fishing behaviour and catch reporting behaviour (Ballara 2013).

Table 1: The relative abundance indices (and associated CVs) used in the assessment of the WCSI hake stock (from Horn 2017).

	Trawl survey		CPUE	
Year	Index	CV	Index	CV
2000	803	0.13	–	–
2001	–	–	0.95	0.04
2002	–	–	2.13	0.04
2003	–	–	0.94	0.07
2004	–	–	0.98	0.04
2005	–	–	0.80	0.04
2006	–	–	1.00	0.04
2007	–	–	0.71	0.06
2008	–	–	0.44	0.05
2009	–	–	0.36	0.06
2010	–	–	0.72	0.06
2011	–	–	1.18	0.05
2012	583	0.13	1.24	0.04
2013	331	0.17	1.35	0.03
2014	–	–	1.03	0.03
2015	–	–	1.15	0.03
2016	221	0.24	–	–

The MPD model fits to the relative abundance series, along with the estimated biomass trajectories are shown for the CPUE series in Figure 1 and the trawl survey series in Figure 2. The resulting differences between the two model runs in the biomass trajectories are marked and clearly contradictory.

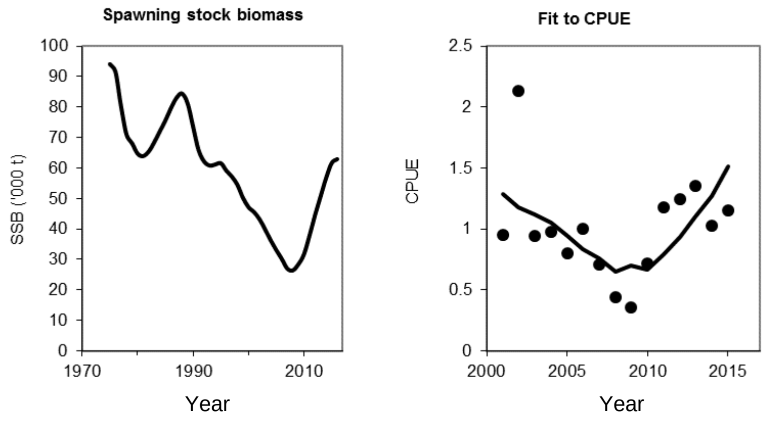


Figure 1: Estimated biomass trajectory and model fits to the trawl fishery CPUE series. Dots represent the observed relative abundance series points.

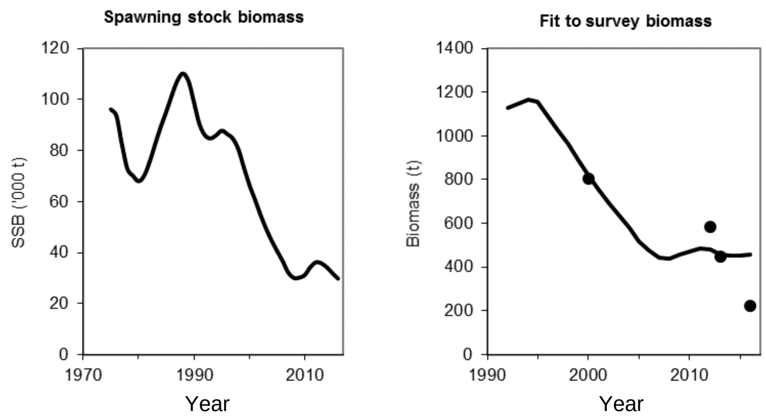


Figure 2: Estimated biomass trajectory and model fits to the trawl survey series. Dots represent the observed relative abundance series points.

The CPUE series used in previous assessment modelling had been derived using data from both bottom and midwater trawling conducted over the area of the entire WCSI hake fishery. The research trawl survey series had sampled a subset of the entire WCSI hake area, using bottom trawl only during daylight hours (Figure 3). The intent of the work described below was to determine whether CPUE series derived using sets of data more in line with the area and fishing method of the trawl survey would produce trends comparable to those of the trawl survey series.

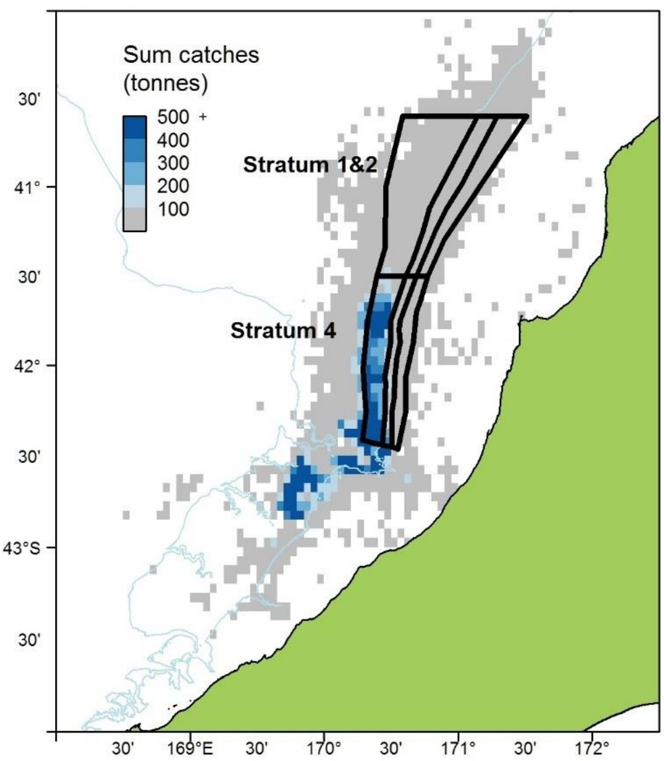


Figure 3: Density plots of all commercial hake catches from TCEPR tow-by-tow records for target hake and hoki tows from fishing years 1999–2000 to 2015–16 combined. WCSI trawl survey strata are shown for the core strata from 300–650 m for strata 1&2 and 4 (black lines). Stratum depth bands are 300–430 m, 430–500 m, and 500–650 m for both strata. The 500 m and 1000 m isobaths are also plotted (light blue lines).

2. METHODS

2.1 CPUE series

Using the QMS database, multiple CPUE series were produced to determine whether truncating the fishery area to equal the survey area, and/or removing midwater trawl tows, could explain why the CPUE trend was different to that of the trawl survey. One series aimed to most closely approximate the trawl survey data by using only bottom trawl tows conducted during daylight hours from 20 July to 23 August each year. The date range comprises the earliest and latest start and finish dates of any of the 2012, 2013 and 2016 surveys.

2.1.1 Data extraction and grooming

Catch-effort, daily processed, and landed data were extracted from the MPI catch-effort database "warehou" as extract 10800 and consist of all fishing and landing events associated with a set of fishing trips that reported a positive catch or landing of hoki, hake, or ling from fishing years 1989–90 to 2015–16. This included all fishing recorded on Trawl Catch, Effort and Processing Returns (TCEPRs); Trawl Catch Effort returns (TCERs); Catch, Effort and Landing Returns (CELRs); LCER (Lining Catch Effort Return); LTCER (Lining Trip Catch Effort Return); NCELR (Netting Catch Effort Landing Return); and included high seas versions of these forms.

Data were checked for errors, and groomed, using simple checking and imputation algorithms similar to those used by Ballara & O'Driscoll (2016). The grooming algorithms were developed in the statistical software package 'R' (R Development Core Team 2016). Individual tows were investigated and errors were corrected using median imputation for start/finish latitude or longitude, fishing method, target species, tow speed, net depth, bottom depth, wingspread, duration, and headline height for each fishing day for a vessel. Range checks were defined for the remaining attributes to identify outliers in the data. The outliers were checked and corrected if possible with mean imputation on larger ranges of data such as vessel, target species and fishing method for a year or month, or the record was removed from the dataset. Statistical areas were calculated from positions where these were available. Transposition of some data was carried out (e.g., bottom depth and depth of net). The tow-by-tow commercial catches of hake were corrected for possible misreporting, using the method of Dunn (2003).

Hake trawl data can be recorded on TCEPR, TCER, or CELR forms. TCEPR and TCER returns contain tow-by-tow data. CELR returns often amalgamate a day's fishing into a single line of data, so some of the data on individual tows may be lost (e.g., duration, towing speed, bottom depth, gear dimensions). Only TCEPR data was used in the analyses as there was found to be little difference between CPUE indices including or excluding TCER data (Ballara & Horn 2011).

TCEPR forms record tow-by-tow data and summarise the estimated catch for the top five species (by weight) for individual tows. The daily processed part of the TCEPR form contains information regarding the catch that was processed that day. The processed fish are weighed and a conversion factor (depending on processing type) allows the weight of the fish before processing (i.e., green weight) to be estimated. Trawl vessels over 28 m used TCEPR forms.

2.1.2 Variables

Variables used in the CPUE analysis are described in Table 2 and are generally similar to those used in previous analyses (e.g., Ballara 2018). CPUE indices were calculated using catch per tow for tow-by-tow data, or catch per vessel-day for daily processed data, with tow *duration* offered as an explanatory variable. *Year* was a categorical variable and defined as June–September as this is when most of the catch was taken from the WCSI. Season variables *month* and *day of year* were offered to the model. Hoki trawling uses both bottom and midwater gear, so when data from both methods were used in an analysis, *method* was offered as an explanatory variable, although midwater tows were additionally classified as either midwater trawl, or midwater trawl fished on the bottom (i.e., if recorded net depth was within 5 m of recorded bottom depth). Gear width was not used as an explanatory variable as this field in the TCEPR variously contained wingspread and doorspread measurements, and hence, headline height was the only trawl gear dimension variable offered to the model. Individual vessel details were checked for consistency each year. Tow records with no vessel identification data were excluded from further analyses. *Vessel* was incorporated into the CPUE standardisation to allow for differences in fishing power between vessels. For the estimated catch-by-tow analyses, all variables were included. For the daily processed catch analysis, *start time*, and *time mid* (mid time of tow) were not included because they were unavailable. Date was included in the processed catch run as *year* and *month*, or *day of year*.

Table 2: Description of variables used in the CPUE analysis for the estimated tow-by-tow dataset and the daily processed dataset. Continuous variables were fitted as third order polynomials except for tow duration which was offered as both third and fourth order polynomials. *, response variable.

Variable	Type	Estimated tow-by-tow catch dataset	Daily processed catch dataset
Year	Categorical	Year (June–October)	Year (June–October)
Vessel	Categorical	Unique (encrypted) vessel identification number	Unique (encrypted) vessel identification number
Statarea	Categorical	Statistical area	Main statistical area
Subarea	Categorical	Defined by fishing effort distribution and depth for a tow (see Horn 2008)	Defined by fishing effort distribution and depth for a given day (see Horn 2008)
Effort	Continuous	–	Number of tows for a given day
Primary method	Categorical	Fishing method for a tow (BT is bottom trawl; MB is midwater trawl within 5 m of the seabed; MW is midwater trawl)	Fishing method for a given day (BT is bottom trawl; MB is midwater trawl within 5 m of the seabed; MW is midwater trawl)
Tow duration	Continuous	Duration of tow (hrs)	Duration of all tows (hrs) on a given day
Tow distance	Continuous	Distance of tow	Distance of all tows on a given day
Distance2	Continuous	Distance of tow (speed in knots × duration)	Distance (as speed × duration) of all tows on a given day
Headline height	Continuous	Headline height (m) of the net for a tow	Median headline height (m) of the net on a given day
Bottom depth	Continuous	Seabed depth (m) for a tow	Median seabed depth (m) on a given day
Speed	Continuous	Vessel speed (knots) for a tow	Median vessel speed (knots) on a given day
Net depth	Continuous	Net depth (m) for a tow (depth of ground rope)	Median net depth (m) on a given day (depth of ground rope)
Vessel experience	Continuous	Number of years the vessel has been involved in the fishery	Number of years the vessel has been involved in the fishery
Twin trawl vessel	Categorical	T/F variable for a vessel that used a twin trawl in that tow	T/F variable for a vessel that has used a twin trawl that day
Catch	Continuous	Estimated green weight of hake (t) caught from a tow	Estimated green weight of hake (t) caught on a given day
Longitude	Continuous	Longitude of the vessel for a tow	Median longitude of the vessel on a given day
Latitude	Continuous	Latitude of the vessel for a tow	Median latitude of the vessel on a given day
Target species	Categorical	Target species of tow	Main target species on a given day
Date	Continuous	Date of the tow	Date the fish were processed
Month	Categorical	Month of the year	Month of the year
Dayofyear	Continuous	Day of the year, starting at 1 January	Day of the year, starting at 1 January
Time start	Continuous	Start time of tow	–
Time mid	Continuous	Mid time of tow	–
CPUE *	Continuous	Hake catch (t) per tow	Hake catch (t) per tday

2.1.3 Data selection

The data used for each CPUE analysis consisted of all records from core vessels that targeted hoki or hake. Vessels not involved in the fishery for at least two years were excluded because they provided little information for the standardisations, which could result in model over-fitting (Francis 2001). Data were investigated for level of catch and effort for different years of vessel participation in the fishery, and thus CPUE analyses were undertaken for “core” vessels only, which together reported approximately 80% of hake catches in the defined fishery and were each involved in the fishery for a significant number of years. To ensure that the data were in plausible ranges and related to vessels that had consistently targeted and caught significant landings of hake, data were accepted if all the constraints were met (Table 3). The definitions of the six initial CPUE series derived are listed in Table 4 (datasets a–f), along with the criteria used to select vessels that were responsible for about 80% of the catch. Dataset d is the series aimed to most closely approximate the trawl survey data.

As a consequence of feedback received from fishing industry representatives, two additional CPUE series were derived for two distinct fleets, i.e., Korean flagged vessels using bottom trawl to target hake, and Ukrainian flagged vessels using midwater trawl to target hoki, but with a hake bycatch (Table 4, datasets g and h). These vessel sub-sets were chosen as it was believed that, within each fleet, fishing had been carried out in a consistent way, in relatively consistent areas, and with little change in gear technology. Data constraints for these fleets are listed in Table 5 (showing where they differ from the tow-by-tow constraints for the six initial analyses in Table 3).

Table 3: CPUE data constraints for each dataset.

Data source	TCEPR daily processed	TCEPR tow-by-tow
Year range	2000–2016	2000–2016
Year definition	June–September	June–September
Statistical areas	034, 035, 036	034, 035, 036
Method	MW, MB, BT	MW, MB, BT
Target species	HOK, HAK	HOK, HAK
Core vessel selection	About 80% of catch (and see Table 4)	About 80% of catch (and see Table 4)
Catch	< 80 t	< 50 t
Bottom depth	300–900 m	300–900 m
Duration	0.2–24 hours	0.2–15 hours
Latitude	40–43.5° S	40–43.5° S
Other	Exclude days with misreported tows One vessel removed (odd behaviour) PSH tows removed (11 in 2014) Exclude days with both BT and MW trawls	Exclude days with misreported tows One vessel removed (odd behaviour) PSH tows removed (11 in 2014)

Table 4: Definitions of the data sources used in the derived CPUE series for WCSI hake.

Data set	Fishing method	Area	Catch derivation	Core vessel definition
a	BT & MW	Research survey area	Tow-by-tow	≥ 8 years vessel participation, all tows/year
b	BT & MW	Non-survey area	Tow-by-tow	≥ 8 years vessel participation, all tows/year
c	BT only	Research survey area	Tow-by-tow	≥ 8 years vessel participation, ≥ 20 tows/year
d	BT only	Research survey area	Tow-by-tow, 0800–1800 NZST 20 Jul–23 Aug	≥ 8 years vessel participation, all tows/year
e	BT only	Non-survey area	Tow-by-tow	≥ 6 years vessel participation, all tows/year
f	BT & MW	Research survey area	Daily processed	≥ 7 years vessel participation, all days/year
g	BT Korea	All WCSI	Tow-by-tow	Korean, 10 years participation in the fishery
h	MW Ukraine	All WCSI	Tow-by-tow	Ukrainian, all 7 vessels in the dataset

Table 5: CPUE data constraints for the Korean and Ukrainian fleet datasets, showing any differences to the other tow-by-tow analyses.

Data source	Korean fleet	Ukrainian fleet
Year range	2003–2016	2000–2016
Statistical areas	034, 035	034, 035
Method	BT, headline < 18 m	MW, headline ≥ 18 m
Target species	HAK	HOK
Core vessel selection	Vessels in the fishery for 10 years (7 vessels)	All 7 vessels in the dataset
Catch	< 50 t	< 25 t
Bottom depth	400–900 m	250–750 m
Vessel length	< 60 m	> 100 m
Tows outside trawl survey area	44%	72%
Catch outside trawl survey area	42%	95%

The use of daily processed catch from the TCEPR processing summaries to estimate catch and derive CPUE indices was developed to account for changes over time in the recording of the top five species on the top of the TCEPR by Phillips (2005). CPUE indices were derived from daily processed catch reported on the TCEPR processing summaries as done in the past (e.g., Ballara 2013, 2015). Total daily processed catch was calculated from the daily processing summaries of the TCEPR forms and merged with the combined tow-by-tow data. Tow-by-tow commercial catches of hake were combined into vessel-day summary records. Catch data from the daily processing summaries for a vessel-day were excluded from further analyses if the vessel-day was identified as having a misreported catch in any of its associated tow-by-tow data. Days with both bottom and midwater tows were excluded from the analysis. The variable vessel-day from the combined tow-by-tow data and the daily processing summary was used to link the data for various variables. The location and depth of fishing were defined as the median value of these variables for the day's fishing for a particular vessel from all of its individual tows. Target species associated with the daily processed catch data is not reported, hence target species was defined as the most common target species specified in the tow-by-tow data. Vessel-days that targeted either hake or hoki on any tow but did not process any hake were considered to be a zero day. Both hake and hoki target tows were selected, as hake form a significant and important bycatch of the more dominant hoki fishery.

2.1.4 The model

Annual unstandardised (raw) CPUE indices were calculated as the mean of catch per tow (kg) for tow-by-tow data, or catch (kg) per vessel-day for daily processed data. All series used the lognormal distribution for the positive catch model. A binomial model based on the presence/absence of hake in each data set was also calculated, with the two models combined using the delta-lognormal method to provide the final series (Vignaux 1994). Estimates of relative year effects were obtained from a stepwise multiple regression method, where the data were fitted using a normal model having log transformed non-zero catch-effort data. A forward stepwise multiple-regression fitting algorithm (Chambers & Hastie 1991) implemented in the R statistical programming language (R Development Core Team 2016) was used to fit all models. The algorithm generates a final regression model iteratively and used the year term as the initial or base model in all cases. The reduction in residual deviance (denoted r2) was calculated for each single term added to the base model. The term that resulted in the greatest reduction in the residual deviance was then added to the base model, where the change was at least 1%. The algorithm was then repeated, updating the base model, until no more terms were added. A stopping rule of 1% change in residual deviance was used because this results in a relatively parsimonious model with moderate explanatory power. Alternative stopping rules or error structures were not investigated.

Model fits to the lognormal component of the combined model were investigated using standard residual diagnostics. For each model, a plot of residuals against fitted values and a plot of residuals against quantiles of the standard normal distribution were produced to check for departures from the regression assumptions of homoscedasticity and normality of errors in log-space (i.e., log-normal errors). For the binomial component, model fits were investigated visually using randomised quantile residuals (Dunn & Smyth 1996). Randomised quantile residuals are based on the idea of inverting the estimated distribution function for each observation to obtain exactly standard normal residuals. For discrete distributions, such as the binomial, some randomisation was introduced to produce continuous normal residuals.

Predictor variables were either categorical or continuous. The variable *year* was treated as a categorical value so that the regression coefficients of each year could vary independently within the model. The relative year effects calculated from the regression coefficients represent the change in CPUE through time, all other effects having been taken into account, and represents a possible index of abundance. *Year* was standardised to the first year of the data series. Year indices were standardised to the mean and were presented in canonical form (Francis 1999). Potential continuous variables were modelled as third-order polynomials, although a fourth-order polynomial was also offered for duration. Interaction terms with method were used as there was more than one fishing method in the dataset. *Vessel* was incorporated into the CPUE standardisation to allow for differences in fishing ability between vessels. The CVs represent the ratio of the standard error to the CPUE index. The 95% confidence intervals were also calculated for each index.

Unstandardised CPUE was also derived for each year from the available datasets. The annual indices were calculated as the mean of the individual daily catch (kg) for trawl processed data, or catch per tow (kg) for tow-by-tow data.

The model predictors for each selected variable were plotted, with all other model predictors fixed. These fixed values were chosen to be 'typical' values (see Francis (2001) for further discussion of this method). If different fixed values were chosen, the absolute values on the plotted *y*-axis would change but the trend would be unchanged.

The influence of each variable accepted into the lognormal models was described by coefficient–distribution–influence (CDI) plots (Bentley et al. 2012). These plots show the combined effect of (a) the expected log catch for each level of the variable (model coefficients) and (b) the distribution of the levels of the variable in each year, and therefore describe the influence that the variable has on the unstandardised CPUE and that is accounted for by the standardisation.

2.2 Information on changes to fishing practice

Attempts were made to establish whether the fleet or fishing behaviour of the main participants in the HAK 7 trawl fishery had changed since about 2010. This information was derived by directly querying fishing industry participants (i.e., fleet managers, skippers). The participants were asked if they were aware of any changes in fleet or fishing behaviour, or in the behaviour of fish, that might have influenced the size or frequency of catches from this fishery in the last 8–10 years. In particular:

- Were vessels instructed to try to avoid, or conversely to target, hake?
- Were there changes in fishing gear or technology that made it more/less likely that hake would be caught?
- Were there changes in trawling behaviour that made it more/less likely that hake would be caught?
- Have skippers perceived any changes in the behaviour or distribution of hake off WCSI?

The information sought aimed to investigate fishery changes that are not recorded in any way on TCEPR forms, but that might have influenced hake catches. The information received was reported in a way that maintains anonymity of respondents and companies; it simply comprises a summary list of changes or potential influences that have occurred.

3. RESULTS

3.1 CPUE analyses

CPUE series for trawl-caught hake from the initial six datasets described in Table 4 are presented below. None of these series is the same as that used in the previous stock assessment; that series is shown in Table 1 and Figure 1. Data summaries, characterisation data, and CPUE analysis details and diagnostics are shown in Appendix A. For each standardised CPUE analysis, the estimated catch of hake, number of tows (tow-by-tow data) or vessel-days (daily processed data), proportion of zero catches, the number of vessels involved, and unstandardised CPUE by year for the initial and core datasets are given in Appendix A, Table A1, with CPUE indices in Table A2. Fishery characterisation data are shown in Figure A2. For each CPUE analysis, catch and effort data (Figure A3), unstandardised and standardised CPUE trajectories (Figure A4), the effects of adding additional variables (Figure A5), comparisons of lognormal, binomial, and delta lognormal trajectories (Figure A6) are also presented. Diagnostics for each CPUE series comprise effect and influence plots (Figure A7), expected variable effects (Figure A8), and residual plots (Figures A9 and A10).

The variables retained in each model are listed in Table 6, and the CPUE series are illustrated (and can be compared to the trawl survey series) in Figure 4. The final lognormal models explained a relatively high proportion of the variance (i.e., at least 55%, and up to 71%). The retained variables exhibited many similarities across the six models (Table 6). Duration was included in all except the daily processed catch model, and was the most important variable in all the bottom trawl tow-by-tow analyses. There was a reasonably strong vessel effect in all analyses, and bottom depth, target species and locational variables were also retained in most analyses. In the binomial models, depth of net was consistently the most important variable, with the vessel effect and positional variables also retained in all models (Table 6). The binomial models all explained at least 27% of the variance.

The four CPUE series that were produced using catch and effort data from the trawl survey area only (datasets a, c, d & f) all exhibit the same general shape, i.e., a decline from 2000 to about 2007, followed by an increase to a plateau from 2011 to 2013, and a subsequent decline but with the 2014 point being notably depressed (Figure 4). The series intended to most closely resemble the trawl survey data (i.e., dataset d) is more spiky than the other three owing to fewer data (see Figure A4), with high values in 2011 and 2015. However, this series and the other three datasets from the trawl survey area do not match well with the research trawl survey index (Figure 4). It could be argued that the two bottom and midwater trawl series in the survey area (datasets a & f) have declining trends from 2012 to 2016 that match the research survey decline over the same period. The CPUE series produced using catch and effort data from the non-survey area (datasets b & e) also exhibit the same general shape, i.e., a decline from 2000 to 2008, followed by an increase, but to a lower level than at the start of the series (Figure 4). These two series differ from the survey area CPUEs in that they do not exhibit the high plateau from 2011 to 2013. They also do not match the research trawl survey index series (Figure 4).

Table 6: Variables retained in order of decreasing explanatory value by each model for each dataset, with the corresponding total r^2 value. Alphabetic table identifiers (a–f) relate to the dataset identifier in Table 4. BT, bottom trawl; MW, midwater trawl.

Lognormal		Binomial	
Variable	r^2	**Variable**	r^2
(a) TCEPR tow-by-tow, BT or MW, survey area			
Year	4.02	Year	2.28
Depth of bottom	40.23	Depth of net	30.84
Vessel	50.49	Vessel	33.96
Target species	55.18	Latitude	36.02
Latitude	57.81		
Mid time of tow	59.14		
Method : Duration	62.82		
Method : Headline height	64.15		
(b) TCEPR tow-by-tow, BT or MW, non-survey area			
Year	4.04	Year	1.94
Vessel	40.34	Depth of net	17.71
Target species	48.59	Vessel	24.23
Depth of net	51.41	Latitude	25.39
Method : Duration	54.75	Method : Duration	27.26
(c) TCEPR tow-by-tow, BT, survey area			
Year	3.37	Year	5.08
Duration	45.88	Depth of bottom	30.79
Longitude	55.41	Day of year	32.95
Vessel	61.08	Latitude	34.19
Target species	63.43	Vessel	35.45
Mid time of tow	65.55		
Depth of bottom	67.84		
Day of year	68.84		
(d): TCEPR tow-by-tow, BT, survey area, day time, survey date range			
Year	8.92	Year	10.45
Duration	51.90	Depth of net	24.70
Longitude	62.71	Vessel	27.83
Vessel	67.95	Longitude	29.36
Target species	70.06		
Depth of bottom	71.17		
(e) TCEPR tow-by-tow, BT, non-survey area			
Year	5.87	Year	4.93
Duration	40.21	Longitude	24.31
Target species	47.48	Depth of net	34.23
Longitude	51.08	Vessel	38.71
Vessel	54.59	Target species	39.94
Mid time of tow	55.82		
(f) TCEPR daily processed, BT, survey area			
Year	6.60	Year	5.33
Depth of bottom	52.97	Depth of net	21.95
Day of year	59.45	Day of year	24.67
Vessel	61.75	Vessel	27.63
Distance2	63.76	Statistical area	29.31
Statistical area	65.42	Duration	30.49

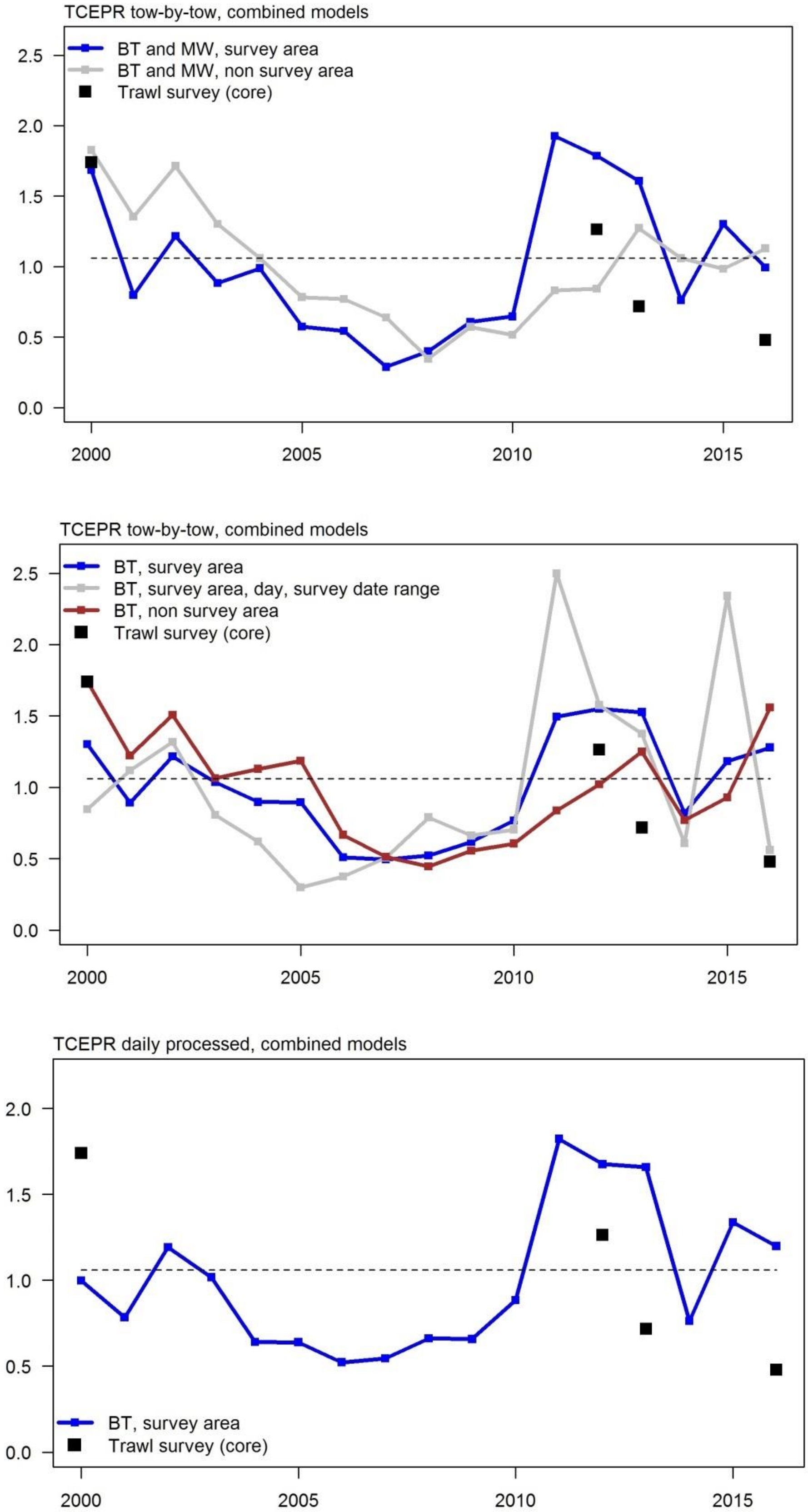


Figure 4: Comparisons of indices from the six initial datasets (datasets a–f in Table 4), and the research trawl survey series. All series are scaled to have a mean of 1 (shown by the horizontal dashed line).

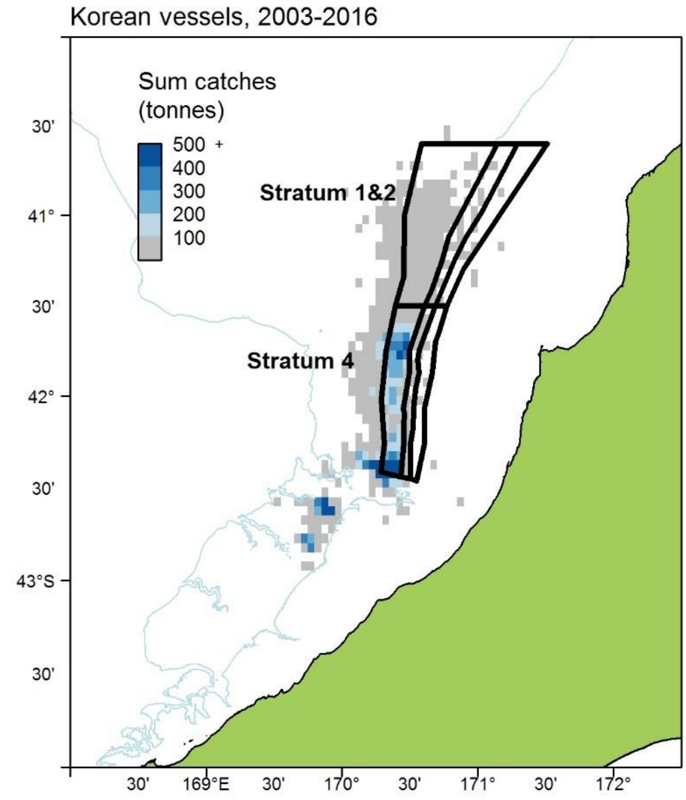
Additional CPUE series were derived from hake catches taken by the Korean and Ukrainian fleets. As well as the differences in the fishing methodology (targeting hake with bottom trawl by the Korean fleet, and targeting hoki with midwater gear by the Ukrainian fleet), there were also marked differences in areas fished (Figure 5). Over half of the Korean catch and effort was in the trawl survey area, with most deeper than 500 m, whereas most of the Ukrainian effort and almost all of its catch was outside the trawl survey area and concentrated to the south and west of the Hokitika Trench (Table 5).

The variables retained in the two models are listed in Table 7. Duration was moderately important in all models, but most particularly in the Korean binomial analysis. Year explained more variance than any other variable in both the lognormal models, but the start time of the tow and tow duration were also very influential in the Korean analysis. Depth of net was influential in the Ukrainian analyses; for a fleet targeting hoki, the chances of catching hake will generally be greater in deeper tows (e.g., see Figures A7a and A7b). The vessel effect in these analyses was important, but less so than in the previous 'all fleet' analyses, as might be expected given that the vessel and gear characteristics were generally consistent within each of the Korean and Ukrainian fleets.

The two CPUE series are illustrated in Figure 6. The apparent trends were very similar to those presented previously (see Figure 4) for the 'all fleets' series.

Table 7: Variables retained in order of decreasing explanatory value by each model for the Korean and Ukrainian fleet datasets, with the corresponding total r^2 value. Alphabetic table identifiers (g–h) relate to the dataset identifier in Table 4. BT, bottom trawl; MW, midwater trawl.

Lognormal		**Binomial**	
Variable	r^2	**Variable**	r^2
(g) TCEPR tow-by-tow, BT, Korean, HAK target			
Year	15.33	Year	7.31
Start time of tow	29.03	Duration	26.83
Duration	38.09	Depth of bottom	33.80
Vessel	43.12	Vessel	39.54
Longitude	45.49	Day of year	44.55
Day of year	46.70	Distance	45.67
(h) TCEPR tow-by-tow, MW, Ukraine, HOK target			
Year	15.86	Year	5.87
Depth of net	19.17	Latitude	17.99
Duration	22.70	Depth of net	22.24
Latitude	25.71	Vessel	25.61
Vessel	28.51	Duration	26.82



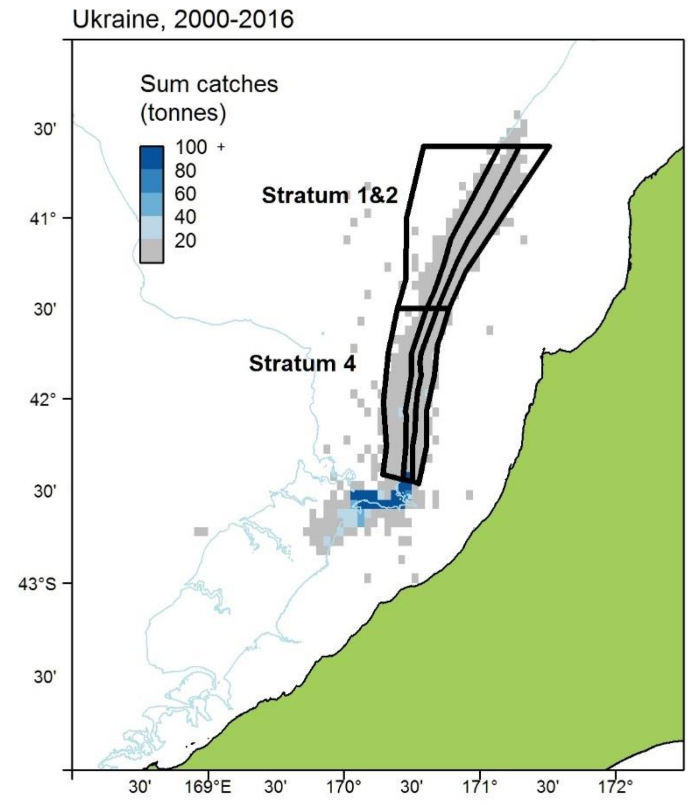
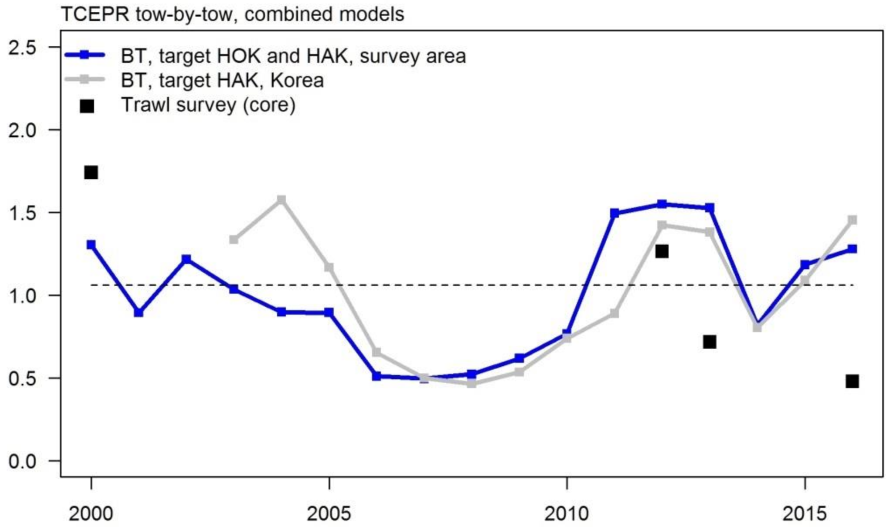


Figure 5: Density plots of hake catches by the Korean and Ukrainian fleets during the periods covered by the CPUE analyses of these fleets. The trawl survey stratum boundaries are also shown (black lines, see Figure 3 for descriptions), as are the 500 m and 1000 m isobaths (light blue lines).



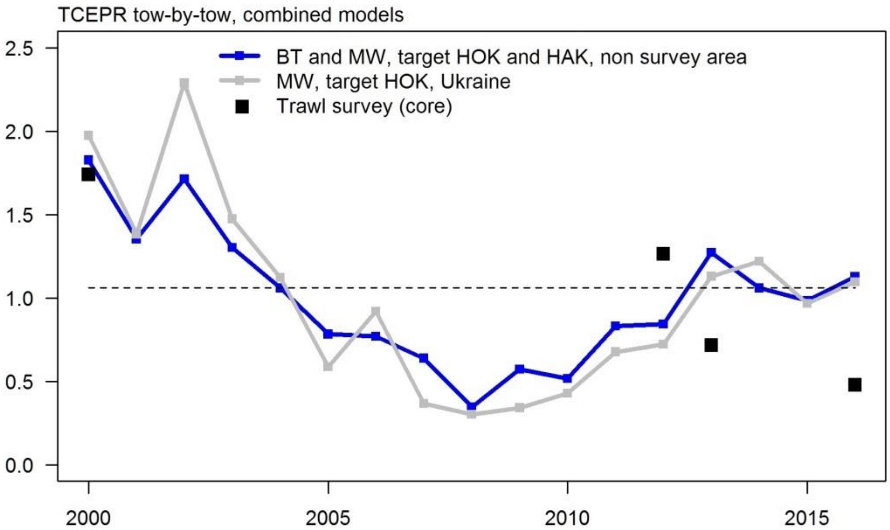


Figure 6: Upper panel — CPUE series for the Korean bottom trawl fleet and dataset c (bottom trawl, survey area). Lower panel — CPUE series for the Ukrainian midwater trawl fleet and dataset a (bottom and midwater trawl, non-survey area). The research trawl survey series is also plotted on both panels. All series are scaled to have a mean of 1 (shown by the horizontal dashed line).

3.2 CPUE summary

Multiple CPUE series using QMS data since 2000 were produced to determine whether analyses of subsets of the 'all fleet' data could explain why the CPUE trend was different to that of the trawl survey. It was apparent that even when removing midwater trawl data, or restricting the fishery area to be the same as the trawl survey area, or analysing separate fleets with consistent fishing gear and practice, the shapes of the resulting CPUE trajectories (either lognormal or combined indices) showed little difference to that produced for the entire fishery by Ballara (2018). The overall trend was a decline from 2000 to about 2007, followed by an increase (and sometimes with another decline after 2013). There were slight differences between series derived from the trawl survey area as opposed to the non-survey area. The trawl survey area CPUE series exhibit a decline from 2000 to about 2007, followed by an increase to a plateau from 2011 to 2013, and a subsequent decline but with the 2014 point being notably depressed. The CPUE series produced for the non-survey area exhibit a decline from 2000 to 2008, followed by an increase. The non-survey area series do not exhibit the high plateau from 2011 to 2013.

The series intended to most closely mirror the trawl survey data by using only bottom trawl tows conducted during daylight hours from 20 July to 23 August each year was similar to, though more spiky than, the other bottom trawl CPUE series in the survey area. The analyses using data from single fleets were also little different to similar 'all fleet' series. The analysis using daily processed data in the survey area (which should have accounted for any changes in search times associated with targeting hake) was little different to the comparable tow-by-tow series. None of the CPUE series match well with the entire research trawl survey series.

It was apparent that the plots showing the influence of particular variables (i.e., target species, net depth or bottom depth, and tow duration) on unstandardised CPUE by fishing year had trends similar to the CPUE series (Figures A7a–A7f). In general, from about 2005 to 2010 there was more hake targeting, in deeper waters, with longer tow duration, than either earlier or later in the series, and these characteristics had a strong influence on hake CPUE, and resulted in lower CPUE indices.

3.3 Changes to fishing practice

The following is a list of comments related to whether the fleet or fishing behaviour of the main participants in the HAK 7 trawl fishery had changed in ways that might have influenced the size or frequency of hake catches from this fishery in the last 8–10 years.

<u>Fleets and gear</u>

- The New Zealand flagged fleet has been more variable (in terms of vessel characteristics, gear, and behaviour) than some of the foreign flagged fleets. The Korean and Ukrainian fleets were identified as groups of vessels that had fished and behaved relatively consistently over the last 10 years.
- At the start of this investigation period, but more particularly before it (i.e., before 2008), hake was regularly targeted by Russian/Ukrainian, Japanese, Korean and Polish fleets southwest of the Hokitika Trench in depths of about 700 m. Since 2008, hake targeting in that area has been conducted almost exclusively by the Korean fleet, probably because they have a lower cost structure than other fleets, and the catch rates of hake there are too low for other vessels/fleets to target it economically.
- Some vessels have sporadically 're-examined' this hake target area since 2008, but have not stayed for long because the availability of hake was still deemed insufficient to be economically viable.
- Some vessels targeting hoki were directed to avoid areas where the Korean fleet was fishing (thus reducing their chance of taking a significant hake bycatch).
- Some vessels targeting hoki were directed to shift to a different fishing area if their percentage hake bycatch was deemed to be higher than the company desired.
- In some years, some vessels stayed longer in the squid fishery, thus arriving later for the hoki target fishery.
- In general, there was little indication of any major changes in technology (i.e., fishing gear or electronics) that would have markedly altered CPUE.
- Changes in net technology have been related primarily to materials used (i.e., lighter twine sizes). No comments were received as to whether this might alter CPUE.

<u>Hake behaviour</u>

- The depth distribution of hake varied between years: in some years they were more abundant in deeper waters, in others there were more hake shallower, particularly close to the Hokitika Trench at the end of the hoki season. In some years it was considered possible that much of the hake population was inside the 25 n.mile line south of the Trench.

- The extent of hoki-hake mixing varied between years, producing different proportions of hake bycatch when targeting hoki.
- In years (or times of the year) when hoki were relatively less abundant there was likely to be more targeting for hake, and proportionately more hake bycatch (but note that the reported target species was not always the actual target).
- The hake in the Hokitika Trench area changed noticeably from being consistently abundant up to 2007 to being relatively sparse since 2008.
- When hake are schooled up for spawning they are relatively easy to catch if you can find them. So, catch rates per tow can usually be maintained if you are targeting hake, but search times will vary.
- Hake can exhibit highly defined temporal and geographical occurrence, e.g., being readily available to bottom trawl in the early afternoon, but much less abundant in bottom trawl catches at the same location at other times of the day.

<u>Economics</u>

- The global financial crisis around 2008 resulted in the value per kilogram of hake fillets decreasing to become approximately equal to the value of hoki fillets (Spain had previously been a major market for hake taken by the NZ flagged fleet.). Hence, there was less incentive to catch or target hake. Consequently, vessels that might previously have stayed on the west coast to catch hoki and hake in September (when the relative abundance of hoki was declining as they returned to their non-spawning grounds) were more likely to leave for the east coast where they could still catch reasonable catches of hoki in the Pegasus Canyon area. Also, vessels that might previously have appreciated hake for the premium price it provided might now try to avoid the species as it was more efficient to process (i.e., fillet) the consistent sized hoki. [But note that prices for exported hake appear to have troughed around 2012–14 (not 2008), and that in all but one year since 2008, Spain was still New Zealand's most lucrative export market for hake products (https://www.seafoodnewzealand.org.nz/publications/export-information/).]
- In more recent years, the market for hake has recovered somewhat.
- The global financial crisis did not impact the Korean fleet as their hake catch was predominantly consumed in Korea (and the fleet also had relatively low costs).

4. DISCUSSION

Many previous assessments of the HAK 7 (west coast South Island) stock have been problematic because there were no reliable indices of relative abundance (Dunn 2004, Horn 2011). While CPUE series have been produced previously (e.g., Ballara & Horn 2011) the trends in these series have generally not been plausible, and it was concluded that catch rates of hake off WCSI were influenced more by fisher behaviour than by abundance of the species. An assessment in 2013 (Horn 2013) differed from previous assessments in that it included a CPUE series that was considered by the Deepwater Fisheries Assessment Working Group to be reliable, and as well as two comparable trawl biomass estimates from surveys that had covered a large proportion of the likely hake habitat off WCSI. That assessment was accepted by the Working Group.

Subsequently, two additional points were added to the research survey series, but an updated assessment found that there was a marked conflict between the CPUE and trawl survey relative abundance indices (Horn 2017). The assessment was indicative of a stock that was steadily fished down for 20 years from about 1990. However, the current stock status and the likely biomass trajectory since 2010 were very uncertain. The two relative abundance series used in this assessment indicated markedly different levels of virgin spawning biomass (i.e., 125 000 t for CPUE, and less than 60 000 t for the trawl survey) and markedly different trends in recent biomass (Horn 2017). Consequently, there were two conflicting assessment models available for consideration, one implying no sustainability issues, and the other indicating that the stock will more likely than not be below 20% B_0 by 2021. There was a clear need to try to determine which of the two relative abundance series is most accurate, and therefore, which of the two assessment scenarios should be used to inform the management of hake off WCSI.

The analysis presented here examined subsets of the catch and effort data used to produce the CPUE indices for the stock assessment (Horn 2017). The aim was to produce new CPUE series using data that were more comparable to the research trawl survey, i.e., bottom trawl catches from the survey area. It was clear that CPUE was similar when using commercial catch data from inside or outside the survey area, and when excluding or using midwater trawl data. Although there was variation between the CPUE series produced, they all exhibited a general trend of a decline from 2000 to about 2006–2008, followed by a subsequent increase, sometimes with marked adjacent-year variation. Additional CPUE series estimated using only data from distinct fleets (i.e., Ukrainian midwater trawl hoki target, Korean bottom trawl hake target) also produced series with the same general trends. None of the new CPUE series matched well with all four data points in the research biomass series. For the two series using midwater and bottom trawl data from the survey area (tow-by-tow or daily processed), a decline from 2012 to 2016 did match reasonably closely with the decline indicated by the three trawl survey indices during the same period. In conclusion, however, the conflict between the research trawl survey biomass series and the CPUE series was not resolved.

It is apparent that the WCSI hake fishery is quite complex, and that over time there have been marked changes in the structure of the fleets catching hake, and in the appeal of hake as either a target or bycatch species. It is also known that there have been past issues regarding the accurate reporting of hake catches from that area (Dunn 2003). The feedback from fishing industry representatives makes it clear that fleet behaviour, in terms of targeting and/or avoidance of hake has been very variable over the last 10 years. There is also some anecdotal indication, however, that hake behaviour varies between years, and it appears likely that a marked change in the distribution pattern of hake occurred around 2007–08. Changes in hake behaviour could markedly influence CPUE (particularly if it involved the movement of hake to or from areas where the bulk of the fleet could not or did not fish). The CPUE standardisations suggest a temporary change in target species (and, probably as a consequence, a change in depth and longitude) around 2006–07, but it appeared to return to 'normal' around 2009–10 (see Figure A7a–f). The possible change in hake distribution may have been at least partially responsible for the targeting changes around 2007. A conscious attempt by a proportion of the fleet to avoid hake bycatch could also bias CPUE downward. So while some of factors noted by fishing industry representatives to have varied over the time of this CPUE update should have been accounted for by the standardisation processes in the analyses, it is clear that others would not have been accounted for.

It is generally assumed that there is a proportional relationship between standardised CPUE and fish abundance. However, if fish behaviour changes in ways that make them more or less available to the fishery (i.e., changes related to depth, distribution, or their mixing with hoki), this will not be accounted for in the standardisation. Also, if a bycatch species (i.e., hake) is actively avoided by individual vessels during some (but not all) portions of the fishery, then using such data in a CPUE analysis will bias the series. It is also known that hake spawn off WCSI at least during June to October, possibly with a peak in September (Horn 2017), and that aggregations of spawning hake do occur. At these times and at known aggregation locations, hake will be more available and hence more easily targeted, and therefore the indices from such aggregations may have a hyperstable relationship between CPUE and abundance. Search time is seldom able to be incorporated in analyses of CPUE from commercial fishery data, and it cannot be incorporated here for hake (although the analysis using daily processed data should have gone some way towards accounting for search time when hake was the true target). Consequently, a CPUE series for hake based either on background by-catches of hake, or on catches from spawning aggregations, should be treated with caution. It is concluded, therefore, that it would be unwise to assume that any currently available hake CPUE series from the WCSI fishery is a reliable index of fish abundance.

While it appears very likely that hake fishery CPUE is an unsatisfactory index of abundance, we can not conclude at present that the trawl survey series does provide a satisfactory index. The shortcomings of the survey series have been described above: it is sparse, has a long gap between the first and second surveys, and does not cover the entire area off WCSI where hake are known to be relatively abundant. Similar trawl surveys elsewhere have, however, been shown to produce very useful abundance index series for hake, even when the numbers of hake caught in individual surveys are relatively small (e.g., the Chatham Rise hake stock is well indexed by the summer trawl survey series (Horn 2017)). Given the size and value of the WCSI hake fishery, there is a sound argument therefore for continuing the WCSI survey series, at least in the medium term, to enable a better evaluation of its efficacy.

5. ACKNOWLEDGMENTS

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APPENDIX A: DATA AND DIAGNOSTICS FOR THE CPUE ANALYSES

Table A1: Summary of data for all and core vessels included in the CPUE datasets, by year. Data include: number of unique vessels fishing (No. vessels), number of tow records (trawl tow-by-tow data) or number of vessel-days (daily processed data) (Effort), proportion of tows (trawl tow-by-tow data) or vessel-days (daily processed data) that caught zero catch (Prop. zeros), estimated catch (Catch), and unstandardised CPUE (CPUE). Alphabetic table identifiers (a–f) relate to the dataset identifier in Table 4. BT, bottom trawl; MW, midwater trawl.

(a) TCEPR tow-by-tow, BT or MW, survey area

	All vessels					Core vessels				
Fishing year	No. vessels	Catch	Effort	Prop. zeros	CPUE	No. vessels	Catch	Effort	Prop. zeros	CPUE
2000	44	2 021.1	1 668	0.59	1.21	24	1 626.7	1 070	0.56	1.52
2001	47	1 123.3	1 544	0.51	0.73	25	882.4	939	0.48	0.94
2002	42	1 483.3	1 403	0.53	1.06	26	1 135.0	881	0.52	1.29
2003	39	2 062.8	1 588	0.55	1.30	26	1 439.8	1 051	0.57	1.37
2004	37	1 870.9	1 029	0.54	1.82	25	1 547.5	751	0.54	2.06
2005	31	1 233.0	549	0.61	2.25	23	1 138.9	449	0.60	2.54
2006	32	3 366.8	901	0.47	3.74	27	3 121.9	819	0.44	3.81
2007	28	439.5	362	0.70	1.21	25	423.9	333	0.70	1.27
2008	24	1 041.7	691	0.45	1.51	22	994.2	647	0.46	1.54
2009	23	2 690.4	602	0.47	4.47	22	2 679.4	583	0.47	4.60
2010	27	1 838.4	777	0.56	2.37	22	1 711.4	731	0.56	2.34
2011	25	2 166.7	1 361	0.35	1.59	22	2 041.1	1 305	0.36	1.56
2012	28	3 054.9	1 134	0.44	2.69	20	2 891.7	1 014	0.36	2.85
2013	24	3 120.4	962	0.48	3.24	19	3 058.2	913	0.43	3.35
2014	24	1 442.5	831	0.62	1.74	18	1 426.9	774	0.59	1.84
2015	25	3 301.6	1 164	0.53	2.84	18	3 153.8	1 057	0.49	2.98
2016	23	1 207.5	706	0.68	1.71	16	1 195.7	626	0.65	1.91

(b) TCEPR tow-by-tow, BT or MW, non-survey area

	All vessels					Core vessels				
Fishing year	No. vessels	Catch	Effort	Prop. zeros	CPUE	No. vessels	Catch	Effort	Prop. zeros	CPUE
2000	49	4 030.9	2 020	0.33	2	26	3 152.2	1 451	0.32	2.17
2001	61	6 131.3	2 944	0.41	2.08	29	5 073.0	2 064	0.38	2.46
2002	55	5 441.4	2 771	0.36	1.96	29	4 768.6	2 013	0.34	2.37
2003	50	4 458.4	2 472	0.34	1.80	29	3 705.2	1 943	0.32	1.91
2004	50	4 946.5	2 613	0.35	1.89	29	4 652.7	2 214	0.24	2.10
2005	34	5 378.9	1 704	0.37	3.16	26	4 413.4	1 372	0.36	3.22
2006	35	2 578.5	1 620	0.31	1.59	29	2 459.9	1 523	0.29	1.62
2007	31	4 363.1	966	0.28	4.52	28	4 200.5	927	0.26	4.53
2008	25	1 270.2	734	0.26	1.73	23	1 260.7	715	0.26	1.76
2009	23	1 297.6	560	0.15	2.32	22	1 290.3	556	0.15	2.32
2010	25	246.2	340	0.34	0.72	21	245.8	339	0.32	0.73
2011	25	902.1	556	0.37	1.62	24	899.3	551	0.37	1.63
2012	30	936.6	626	0.47	1.50	24	911.2	559	0.46	1.63
2013	26	1 853.8	991	0.27	1.87	23	1 840.1	955	0.26	1.93
2014	25	1 788.5	1 226	0.24	1.46	21	1 718.3	1 095	0.22	1.57
2015	28	1 772.5	1 453	0.26	1.22	21	1 730.5	1 294	0.21	1.34
2016	26	1 320.9	1 588	0.23	0.83	18	1 203.6	1 265	0.17	0.95

(c) TCEPR tow-by-tow, BT, survey area

	All vessels					Core vessels				
Fishing year	No. vessels	Catch	Effort	Prop. zeros	CPUE	No. vessels	Catch	Effort	Prop. zeros	CPUE
2000	29	810.6	706	0.42	1.15	9	509.7	365	0.28	1.40
2001	33	789.6	984	0.33	0.80	12	557.0	531	0.27	1.05
2002	32	1 340.9	1 153	0.37	1.16	13	865.6	613	0.35	1.41
2003	34	1 610.9	1 199	0.36	1.34	10	921.5	555	0.34	1.66
2004	30	1 097.4	580	0.54	1.89	11	529.8	303	0.58	1.75
2005	24	1 183.1	449	0.55	2.63	6	937.9	216	0.41	4.34
2006	23	1 507.2	657	0.46	2.29	10	1 363.7	499	0.39	2.73
2007	20	415.7	314	0.50	1.32	7	337.7	214	0.29	1.58
2008	16	984.2	624	0.29	1.58	9	780.5	453	0.22	1.72
2009	16	633.4	438	0.24	1.45	10	551.7	350	0.22	1.58
2010	20	1 754.6	664	0.31	2.64	10	1 569.4	567	0.26	2.77
2011	18	2 107.4	1 046	0.14	2.01	12	1 796.4	897	0.14	2.00
2012	21	3 032.2	1 018	0.26	2.98	14	2 769.9	863	0.20	3.21
2013	17	2 960.8	751	0.31	3.94	12	2 868.1	703	0.23	4.08
2014	16	1 336.0	651	0.39	2.05	11	1 320.4	586	0.32	2.25
2015	17	3 078.2	886	0.31	3.47	12	3 005.8	832	0.28	3.61
2016	18	1 191.0	625	0.56	1.91	11	1 174.7	556	0.53	2.11

(d) TCEPR tow-by-tow, BT, survey area, day time, survey date range

	All vessels					Core vessels				
Fishing year	No. vessels	Catch	Effort	Prop. zeros	CPUE	No. vessels	Catch	Effort	Prop. zeros	CPUE
2000	16	60.8	165	0.56	0.37	10	30.3	84	0.52	0.36
2001	22	159.5	356	0.34	0.45	11	90.9	196	0.29	0.46
2002	30	459.2	539	0.40	0.85	15	322.8	306	0.36	1.05
2003	33	149.7	399	0.47	0.38	14	78.6	190	0.46	0.41
2004	24	416.0	136	0.62	3.06	12	158.2	81	0.63	1.95
2005	22	131.4	103	0.75	1.28	13	92.0	58	0.80	1.59
2006	20	261.6	156	0.54	1.68	14	252.5	127	0.51	1.99
2007	17	85.4	76	0.61	1.12	11	65.7	67	0.53	0.98
2008	14	175.6	120	0.27	1.46	11	159.8	103	0.20	1.55
2009	15	209.3	157	0.23	1.33	14	204.2	150	0.18	1.36
2010	18	311.7	199	0.39	1.57	15	306.0	197	0.37	1.55
2011	17	717.4	293	0.17	2.45	16	666.0	281	0.18	2.37
2012	18	652.5	346	0.33	1.89	15	629.2	314	0.26	2.00
2013	16	385.8	241	0.47	1.60	12	371.8	223	0.37	1.67
2014	16	427.8	155	0.60	2.76	12	423.1	143	0.57	2.96
2015	17	1 868.6	364	0.25	5.13	12	1 803.3	322	0.23	5.60
2016	17	144.4	177	0.72	0.82	11	141.7	157	0.69	0.90

(e) TCEPR tow-by-tow, BT, non-survey area

	All vessels					Core vessels				
Fishing year	No. vessels	Catch	Effort	Prop. zeros	CPUE	No. vessels	Catch	Effort	Prop. zeros	CPUE
2000	26	918.2	484	0.13	1.90	16	856.0	419	0.11	2.04
2001	28	897.6	698	0.20	1.29	18	683.3	477	0.14	1.43
2002	30	1 744.5	952	0.09	1.83	19	1 566.2	748	0.07	2.09
2003	37	2 106.7	1 059	0.13	1.99	20	1 595.8	807	0.11	1.98
2004	28	2 483.5	689	0.14	3.60	18	2 301.0	643	0.13	3.58
2005	21	1 759.5	549	0.09	3.20	15	1 435.3	471	0.07	3.05
2006	23	1 201.2	638	0.18	1.88	18	1 081.1	573	0.18	1.89
2007	19	715.4	351	0.19	2.04	16	647.8	325	0.20	1.99
2008	16	1 198.1	436	0.05	2.75	13	1 188.6	417	0.04	2.85
2009	16	837.9	337	0.03	2.49	15	832.8	335	0.03	2.49
2010	16	185.8	79	0.13	2.35	14	185.4	78	0.11	2.38
2011	14	824.4	256	0.02	3.22	14	822.0	255	0.02	3.22
2012	19	737.7	212	0.09	3.48	16	717.8	202	0.05	3.55
2013	17	1 186.9	284	0.09	4.18	13	1 176.1	262	0.07	4.49
2014	14	1 248.5	398	0.07	3.14	12	1 244.5	377	0.04	3.30
2015	16	1 349.1	453	0.05	2.98	12	1 340.3	442	0.03	3.03
2016	16	765.4	240	0.13	3.19	11	758.0	229	0.07	3.31

(f) TCEPR daily processed, BT, survey area

	All vessels					Core vessels				
Fishing year	No. vessels	Catch	Effort	Prop. zeros	CPUE	No. vessels	Catch	Effort	Prop. zeros	CPUE
2000	28	781.6	342	0.05	2.29	17	641.4	228	0.04	2.81
2001	33	695.8	429	0.05	1.62	19	563.7	282	0.02	2.00
2002	29	1 497.7	523	0.10	2.86	18	1 209.8	373	0.08	3.24
2003	32	1 471.4	598	0.04	2.46	18	1 290.5	453	0.04	2.85
2004	26	890.1	423	0.10	2.10	19	678.0	359	0.10	1.89
2005	24	1 167.3	401	0.09	2.91	19	1 113.5	354	0.09	3.15
2006	23	1 419.8	501	0.12	2.83	20	1 405.4	484	0.12	2.90
2007	19	430.9	204	0.19	2.11	17	423.4	199	0.18	2.13
2008	15	864.8	333	0.02	2.60	15	864.8	333	0.02	2.60
2009	16	621.2	202	0.03	3.08	16	621.2	202	0.03	3.08
2010	19	1 563.8	366	0.06	4.27	17	1 547.7	361	0.05	4.29
2011	18	1 990.2	464	0.02	4.29	17	1 986.9	461	0.02	4.31
2012	21	2 524.6	483	0.03	5.23	17	2 466.3	463	0.03	5.33
2013	17	2 413.3	392	0.03	6.16	14	2 370.7	371	0.03	6.39
2014	15	1 124.0	333	0.06	3.38	13	1 118.1	326	0.06	3.43
2015	16	2 910.0	434	0.05	6.71	13	2 874.7	423	0.05	6.80
2016	16	839.7	410	0.08	2.05	12	828.5	386	0.07	2.15

Table A2: Lognormal, binomial, and delta lognormal (combined) standardised CPUE indices (with CVs to 2 decimal places). Alphabetic table identifiers (a–f) relate to the dataset identifier in Table 4. BT, bottom trawl; MW, midwater trawl.

(a) TCEPR tow-by-tow, BT or MW, survey area

	Lognormal		Binomial		Delta lognormal	
Year	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**
2000	1.74	0.03	0.59	0.00	1.68	0.03
2001	0.96	0.03	0.51	0.00	0.80	0.03
2002	1.39	0.03	0.54	0.00	1.22	0.03
2003	1.00	0.03	0.54	0.00	0.88	0.03
2004	1.24	0.04	0.49	0.00	0.99	0.04
2005	0.90	0.05	0.39	0.00	0.57	0.05
2006	0.83	0.04	0.40	0.00	0.54	0.04
2007	0.55	0.05	0.32	0.00	0.29	0.05
2008	0.50	0.04	0.49	0.00	0.40	0.04
2009	0.79	0.04	0.47	0.00	0.61	0.04
2010	0.80	0.04	0.49	0.00	0.65	0.04
2011	1.18	0.03	1.00	0.00	1.93	0.03
2012	1.34	0.03	0.82	0.00	1.79	0.03
2013	1.34	0.03	0.74	0.00	1.61	0.03
2014	0.86	0.04	0.54	0.00	0.76	0.04
2015	1.11	0.03	0.72	0.00	1.30	0.03
2016	1.32	0.04	0.46	0.00	0.99	0.04

(b) TCEPR tow-by-tow, BT or MW, non-survey area

	Lognormal		Binomial		Delta lognormal	
Year	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**
2000	1.94	0.03	0.84	0.00	1.83	0.03
2001	1.54	0.02	0.79	0.00	1.35	0.02
2002	1.86	0.02	0.82	0.00	1.71	0.02
2003	1.40	0.02	0.83	0.00	1.30	0.02
2004	1.07	0.02	0.89	0.00	1.06	0.02
2005	0.96	0.03	0.73	0.00	0.78	0.03
2006	0.89	0.03	0.77	0.00	0.77	0.03
2007	0.84	0.03	0.68	0.00	0.64	0.03
2008	0.44	0.04	0.70	0.00	0.35	0.04
2009	0.62	0.04	0.82	0.00	0.57	0.04
2010	0.59	0.05	0.78	0.00	0.52	0.05
2011	0.86	0.04	0.86	0.00	0.83	0.04
2012	1.00	0.04	0.75	0.00	0.84	0.04
2013	1.28	0.03	0.89	0.00	1.27	0.03
2014	1.00	0.03	0.95	0.00	1.06	0.03
2015	0.93	0.03	0.95	0.00	0.98	0.03
2016	1.01	0.03	1.00	0.00	1.13	0.03

(c) TCEPR tow-by-tow, BT, survey area

	Lognormal		Binomial		Delta lognormal	
Year	Index	CV	Index	CV	Index	CV
2000	1.24	0.05	0.90	0.00	1.30	0.05
2001	0.92	0.04	0.83	0.00	0.89	0.04
2002	1.28	0.04	0.81	0.00	1.22	0.04
2003	1.02	0.04	0.87	0.00	1.04	0.04
2004	1.16	0.06	0.66	0.00	0.90	0.06
2005	1.23	0.07	0.62	0.00	0.89	0.07
2006	0.69	0.04	0.63	0.00	0.51	0.04
2007	0.57	0.07	0.74	0.00	0.49	0.07
2008	0.57	0.05	0.78	0.00	0.52	0.05
2009	0.67	0.05	0.79	0.00	0.62	0.05
2010	0.82	0.04	0.80	0.00	0.77	0.04
2011	1.28	0.03	1.00	0.00	1.49	0.03
2012	1.42	0.03	0.93	0.00	1.55	0.03
2013	1.42	0.04	0.92	0.00	1.53	0.04
2014	0.84	0.04	0.83	0.00	0.82	0.04
2015	1.16	0.04	0.87	0.00	1.18	0.04
2016	1.51	0.04	0.73	0.00	1.28	0.04

(d) TCEPR tow-by-tow, BT, survey area, day time, survey date range

	Lognormal		Binomial		Delta lognormal	
Year	Index	CV	Index	CV	Index	CV
2000	1.06	0.11	0.59	0.00	0.85	0.11
2001	1.07	0.07	0.77	0.00	1.12	0.07
2002	1.37	0.06	0.71	0.00	1.32	0.06
2003	0.83	0.07	0.72	0.00	0.81	0.07
2004	1.02	0.11	0.45	0.00	0.62	0.11
2005	0.82	0.13	0.27	0.00	0.30	0.13
2006	0.62	0.09	0.44	0.00	0.37	0.09
2007	0.70	0.12	0.53	0.00	0.51	0.12
2008	0.75	0.10	0.78	0.00	0.79	0.10
2009	0.71	0.08	0.69	0.00	0.66	0.08
2010	0.81	0.07	0.64	0.00	0.70	0.07
2011	1.84	0.06	1.00	0.00	2.50	0.06
2012	1.34	0.06	0.87	0.00	1.58	0.06
2013	1.29	0.07	0.79	0.00	1.38	0.07
2014	0.87	0.08	0.51	0.00	0.61	0.08
2015	1.95	0.06	0.88	0.00	2.34	0.06
2016	0.91	0.08	0.45	0.00	0.56	0.08

(e) TCEPR tow-by-tow, BT, non-survey area

	Lognormal		Binomial		Delta lognormal	
Year	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**
2000	1.88	0.05	0.98	0.00	1.74	0.05
2001	1.33	0.05	0.97	0.00	1.22	0.05
2002	1.62	0.04	0.98	0.00	1.51	0.04
2003	1.13	0.04	0.99	0.00	1.06	0.04
2004	1.22	0.04	0.97	0.00	1.13	0.04
2005	1.29	0.05	0.97	0.00	1.19	0.05
2006	0.73	0.04	0.96	0.00	0.67	0.04
2007	0.59	0.06	0.91	0.00	0.51	0.06
2008	0.50	0.05	0.94	0.00	0.44	0.05
2009	0.59	0.06	0.99	0.00	0.55	0.06
2010	0.65	0.11	0.98	0.00	0.61	0.11
2011	0.88	0.06	1.00	0.00	0.84	0.06
2012	1.08	0.07	0.99	0.00	1.02	0.07
2013	1.34	0.06	0.98	0.00	1.25	0.06
2014	0.82	0.05	0.99	0.00	0.77	0.05
2015	0.98	0.05	1.00	0.00	0.93	0.05
2016	1.66	0.07	0.99	0.00	1.56	0.07

(f) TCEPR daily processed, BT, survey area

	Lognormal		Binomial		Delta lognormal	
Year	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**
2000	1.07	0.06	0.97	0.00	1.00	0.06
2001	0.83	0.06	0.98	0.00	0.78	0.06
2002	1.33	0.05	0.93	0.00	1.19	0.05
2003	1.08	0.05	0.98	0.00	1.02	0.05
2004	0.71	0.05	0.94	0.00	0.64	0.05
2005	0.71	0.06	0.93	0.00	0.64	0.06
2006	0.61	0.05	0.89	0.00	0.52	0.05
2007	0.63	0.07	0.90	0.00	0.55	0.07
2008	0.70	0.05	0.98	0.00	0.66	0.05
2009	0.73	0.07	0.93	0.00	0.66	0.07
2010	0.94	0.05	0.98	0.00	0.88	0.05
2011	1.89	0.05	1.00	0.00	1.82	0.05
2012	1.75	0.05	0.99	0.00	1.68	0.05
2013	1.74	0.05	0.99	0.00	1.66	0.05
2014	0.81	0.05	0.98	0.00	0.76	0.05
2015	1.41	0.05	0.98	0.00	1.34	0.05
2016	1.26	0.05	0.99	0.00	1.20	0.05

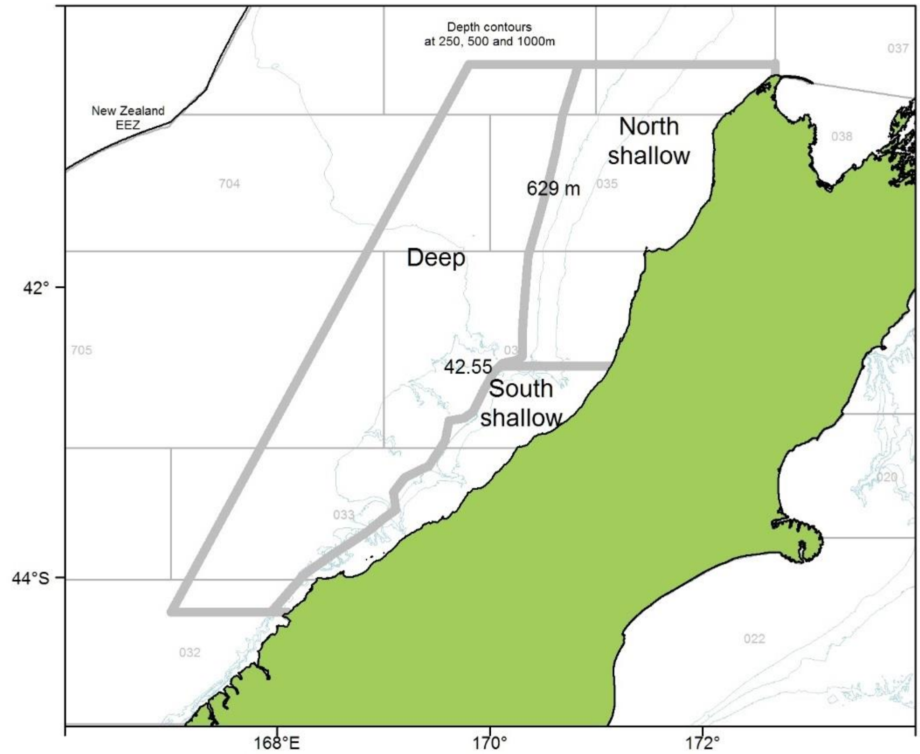


Figure A1: Location and boundaries of the three WCSI sub-areas used in this analysis: Deep (at least 530 m deep); North shallow (less than 530 m deep, north of 42.55° S); South shallow (less than 530 m deep, south of 42.55° S).

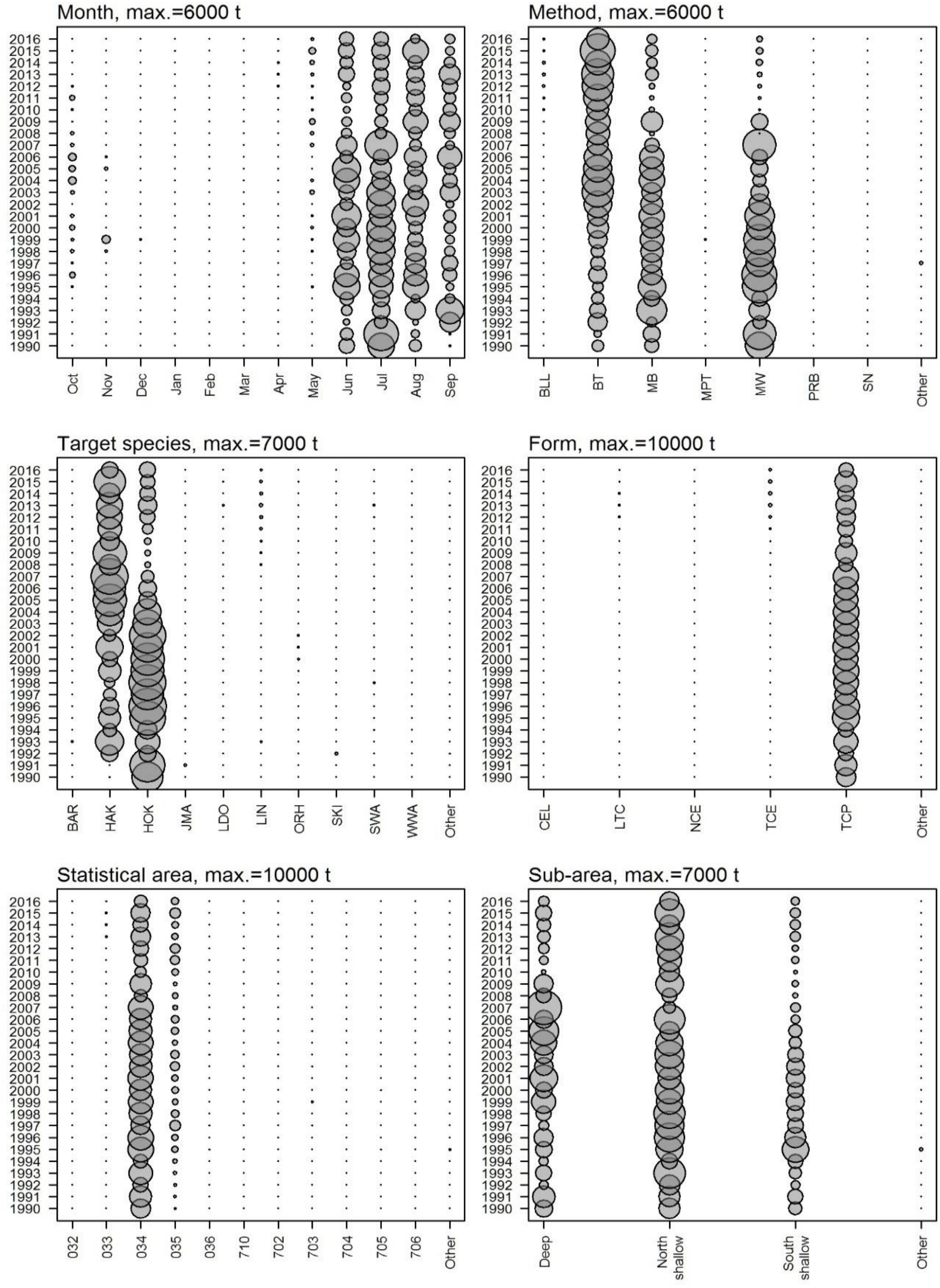


Figure A2: Distribution of WCSI hake effort by month, statistical area, method, target species, form type, and sub-area, by fishing year since 1989–90 (1990). Circle size is proportional to catch; maximum circle size is indicated on the top of each plot. Statistical areas and sub-areas are defined in Figure A1. Form types: CEL, Catch, Effort, Landing Return; LTC, Lining Trip Catch, Effort return; NCE, Net Catch Effort Return; TCE, Trawl, Catch, Effort Return; TCP, Trawl, Catch, Effort, and Processing Return. Method definitions: BLL, bottom longlining; BT, bottom trawl; MB, midwater trawl within 5 m of the bottom; MPT: midwater pair trawl; MW, midwater trawl; SN, set net; PRB, bottom trawl precision seafood harvesting. Species codes: BAR, barracouta; HAK, hake; HOK, hoki; JMA, jack mackerels; LDO, lookdown dory; LIN, ling; ORH, orange roughy; SKI, gemfish; SWA, silver warehou; WWA, white warehou.

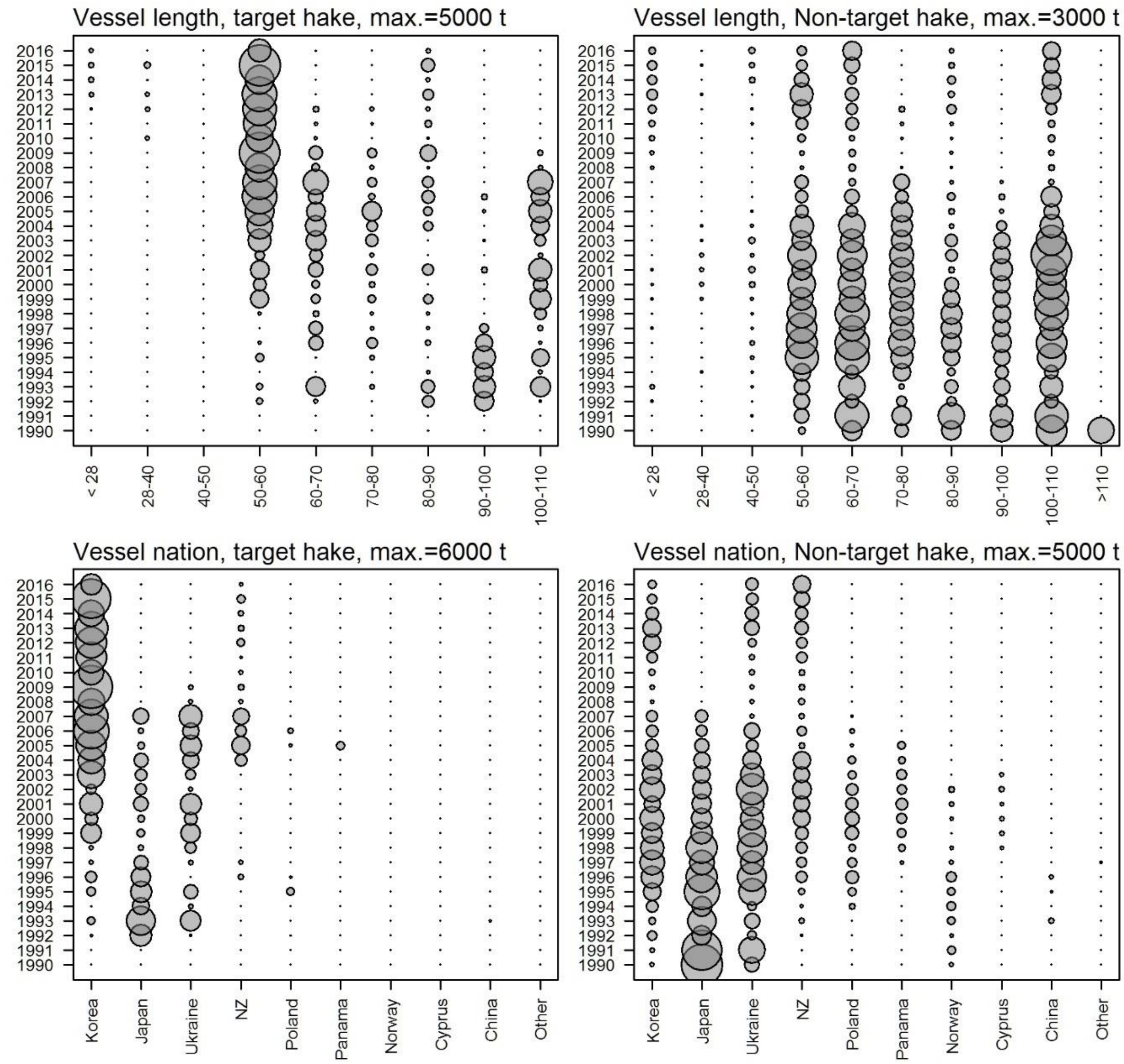
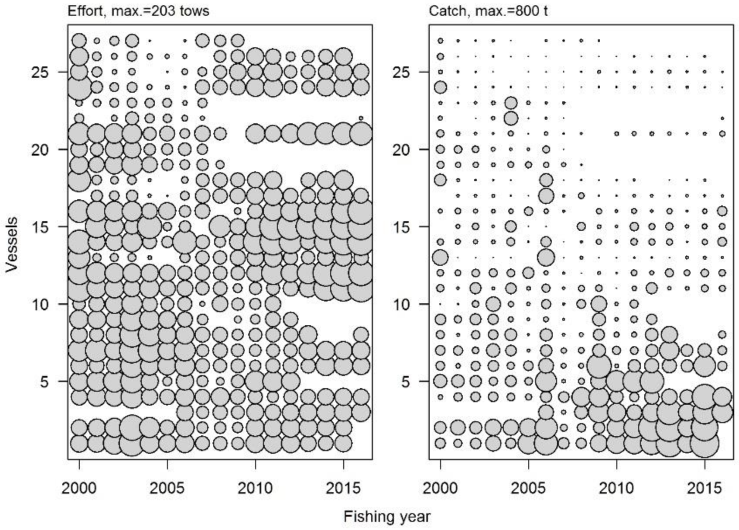
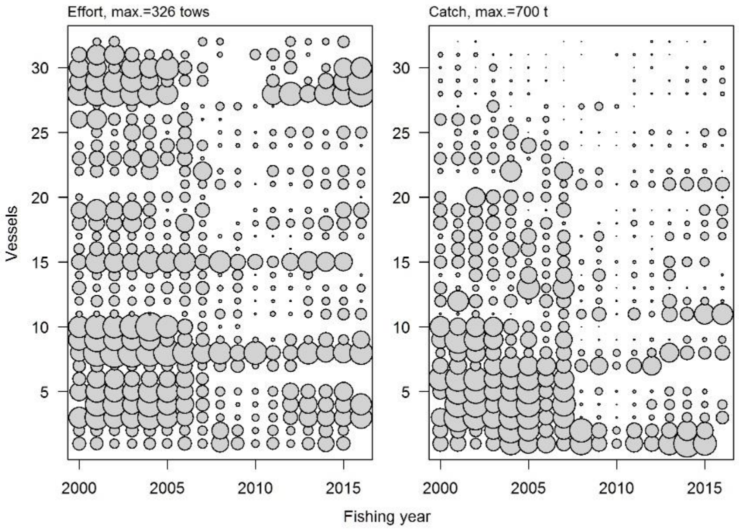


Figure A2 continued: Distribution of WCSI target and non-target hake catch by vessel length and nationality, by fishing year since 1989–90 (1990). Circle size is proportional to catch; maximum circle size is indicated on the top of each plot.

(a) TCEPR tow-by-tow, BT or MW, survey area



(b) TCEPR tow-by-tow, BT or MW, non-survey area



(c) TCEPR tow-by-tow, BT, survey area

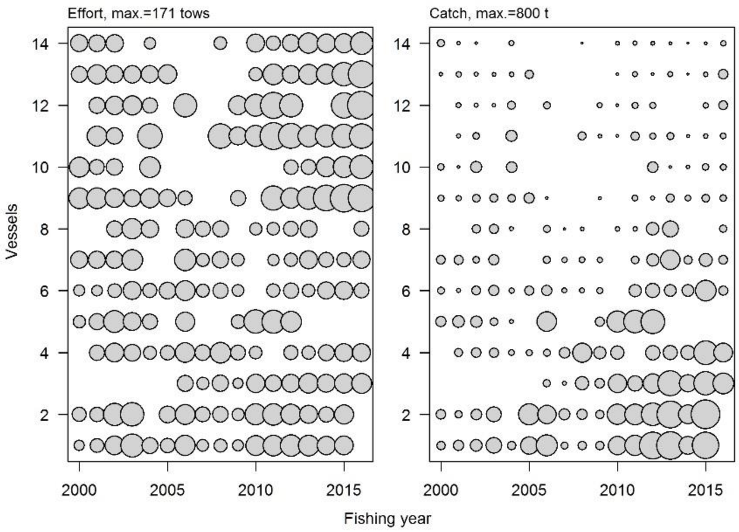
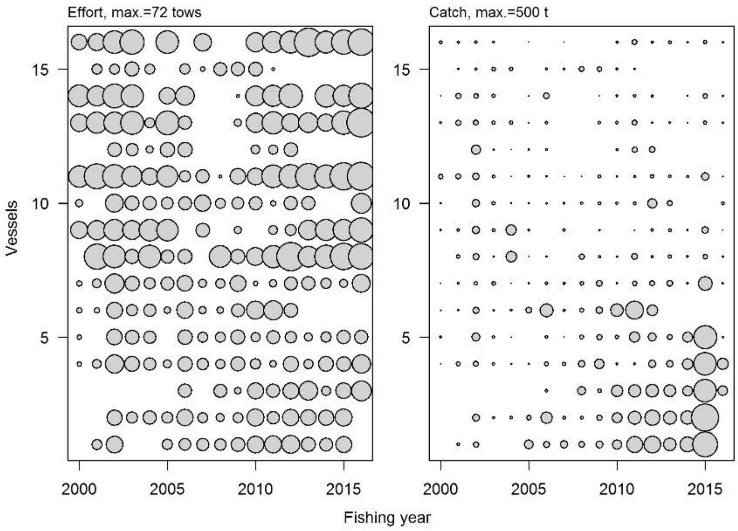
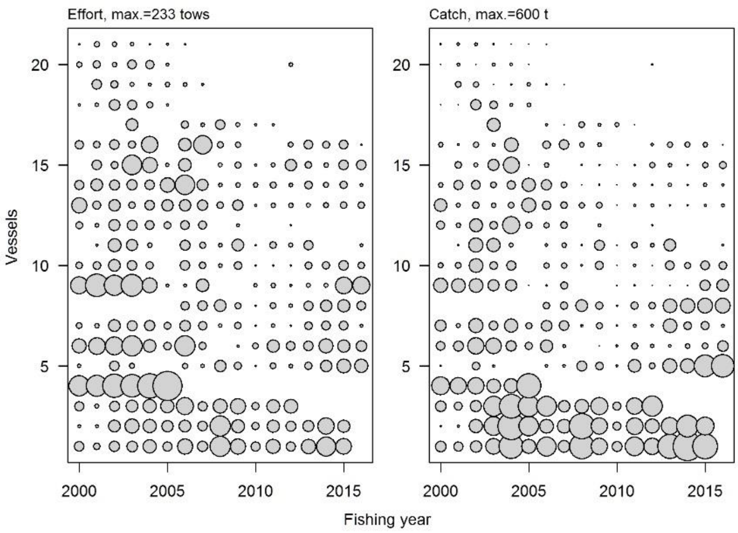


Figure A3: Trawl fishing effort and catches (where circle area is proportional to the effort or catch) by fishing year (June–September) for individual vessels (denoted anonymously by number on the *y*-axis) in the WCSI 'core' CPUE analyses.

(d) TCEPR tow-by-tow, BT, survey area, day time, survey date range



(e) TCEPR tow-by-tow, BT non-survey area



(f) TCEPR daily processed, BT, survey area

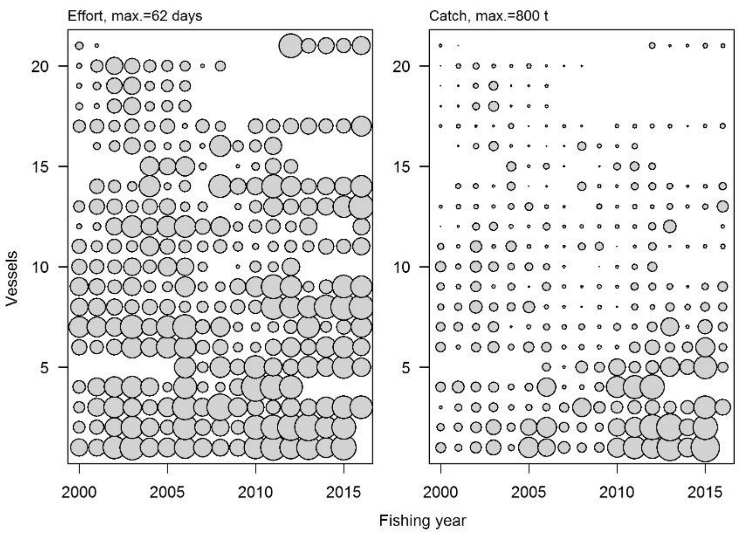


Figure A3 continued.

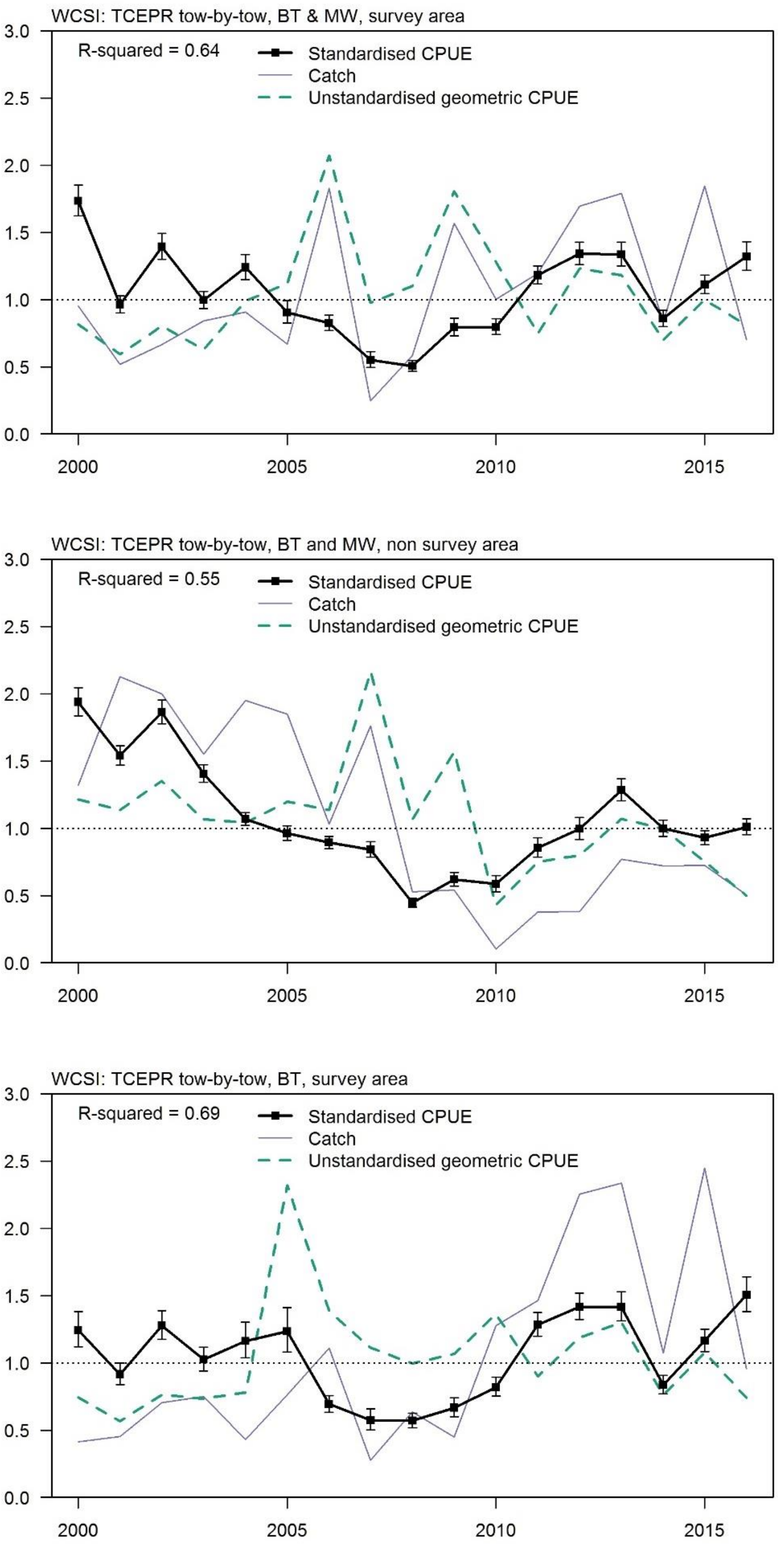
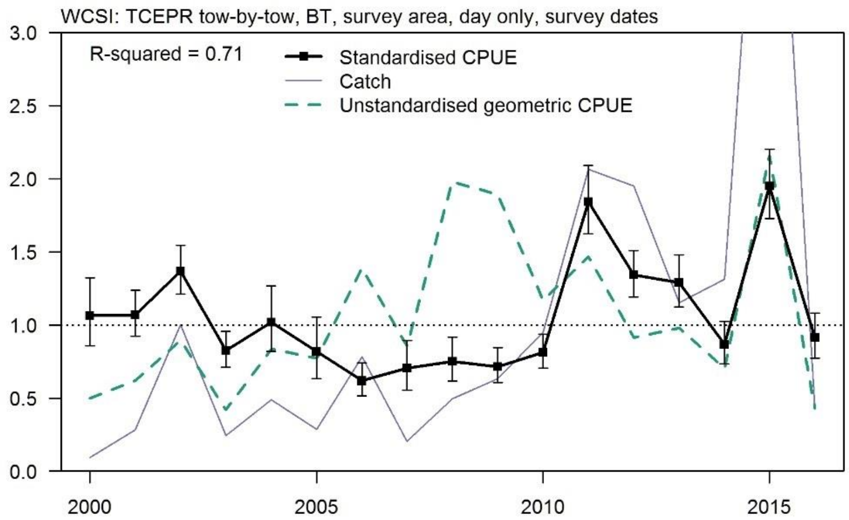
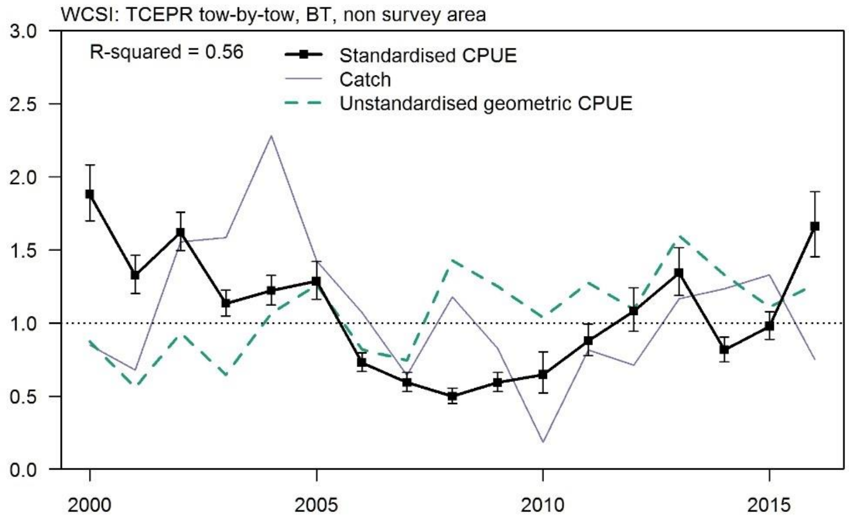


Figure A4: Unstandardised and standardized CPUE indices from the WCSI lognormal models (bars indicate 95% confidence intervals), and total catch of hake from WCSI, with all series scaled to have a mean of 1 (shown by the horizontal dotted line). Year defined as June–September.





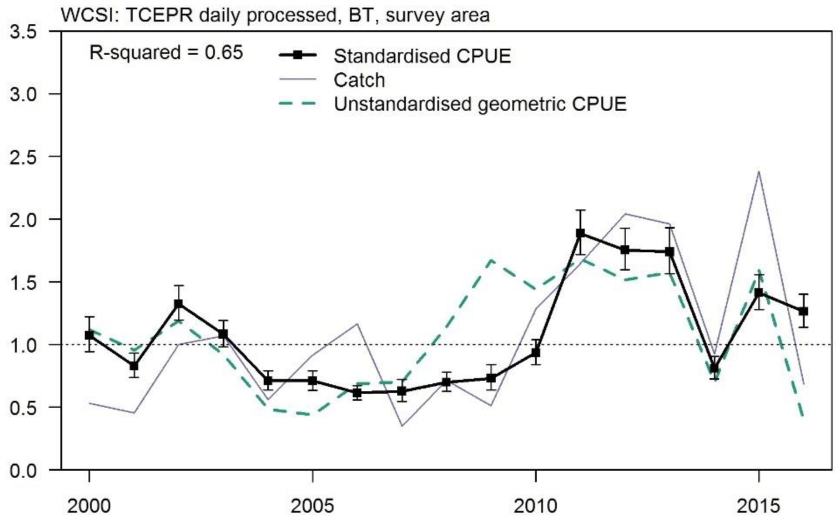
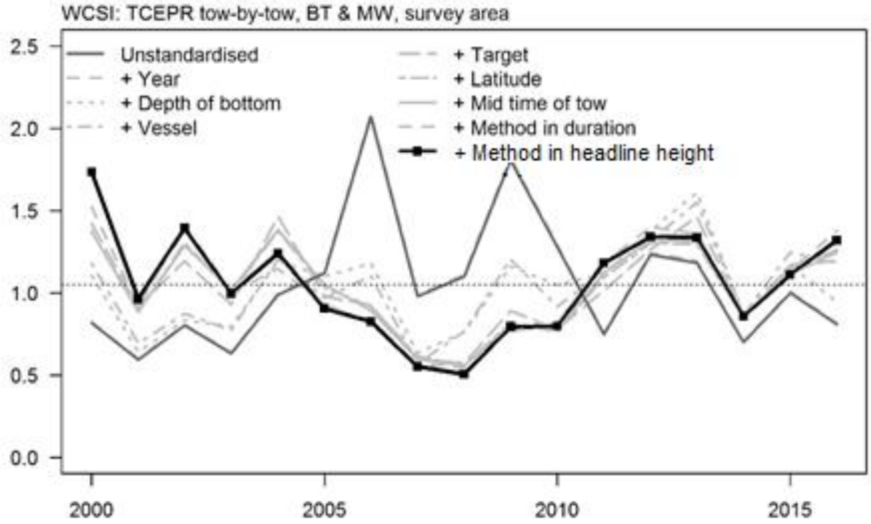
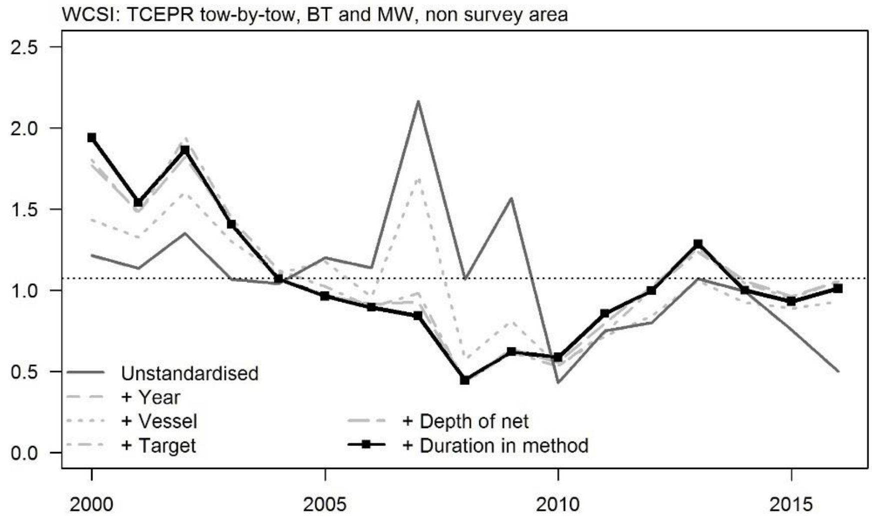


Figure A4 continued.





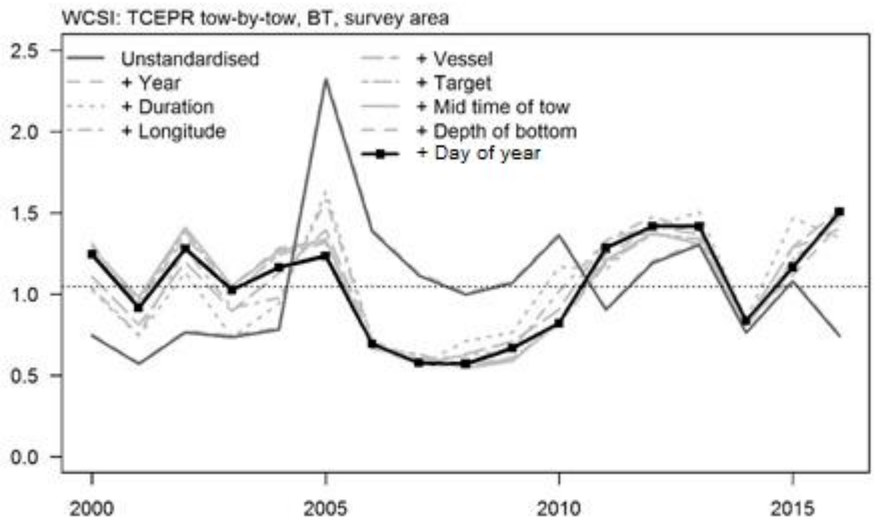


Figure A5: Standardised CPUE indices from the WCSI lognormal model showing the effect of addition of variables. All series are scaled to have a mean of 1 (shown by the horizontal dotted line). Year defined as June–September.

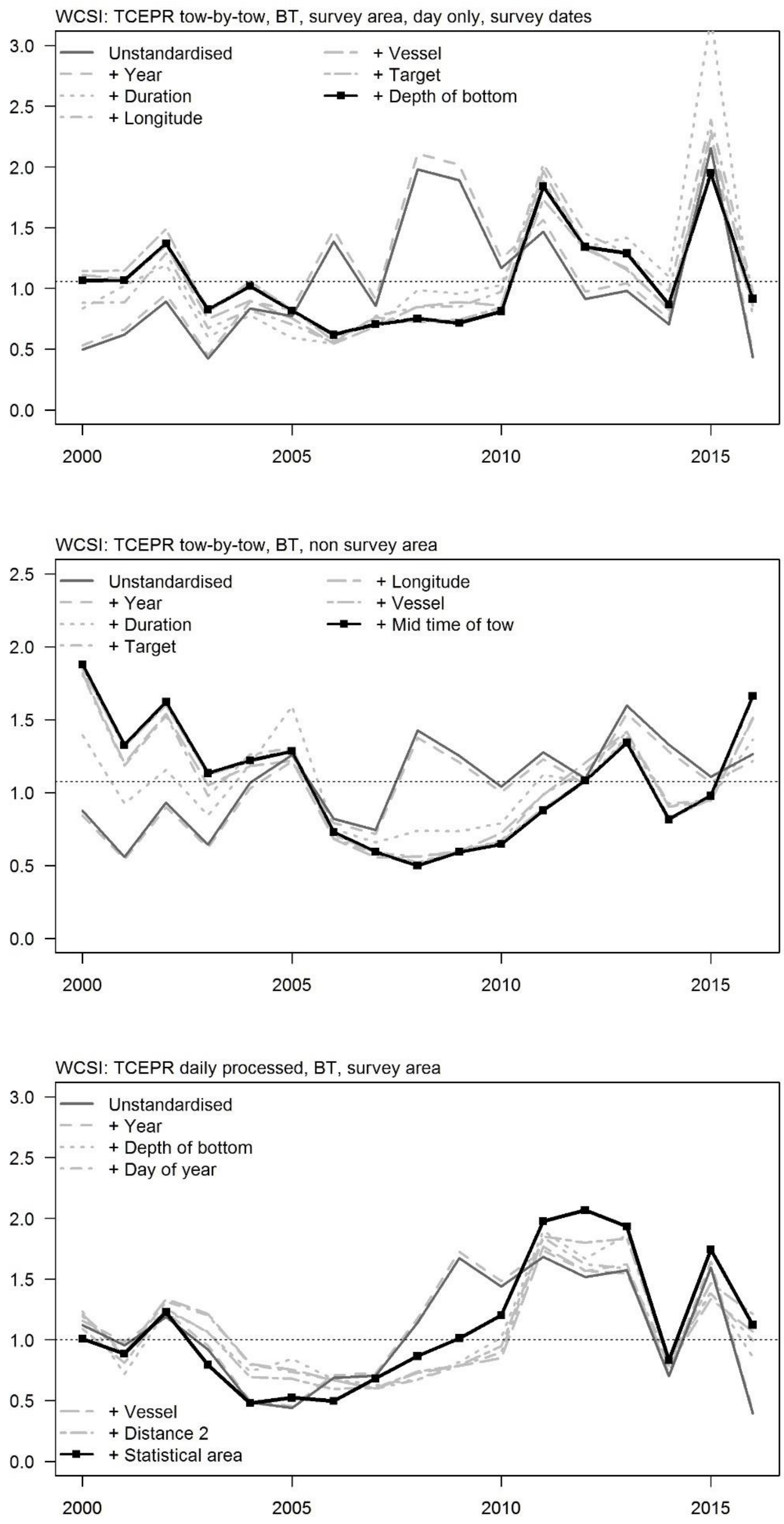


Figure A5 continued.

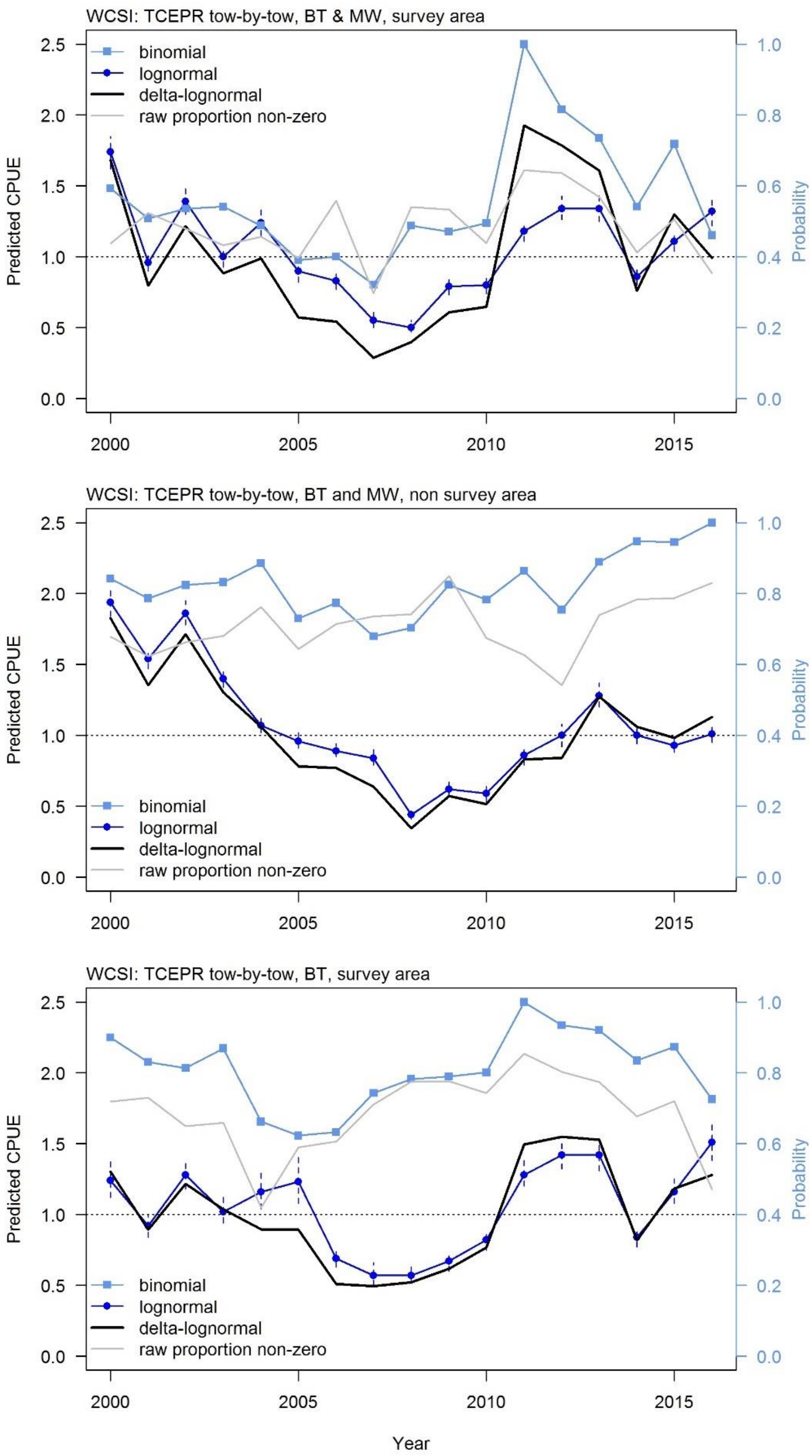


Figure A6: Standardised predicted CPUE indices from the lognormal, binomial and combined (delta-lognormal) model for each fishery. Bars indicate 95% confidence intervals. Year defined as June–September. The horizontal dotted line shows the mean of the combined series. The probability scale relates to the binomial and raw proportion non-zero series.

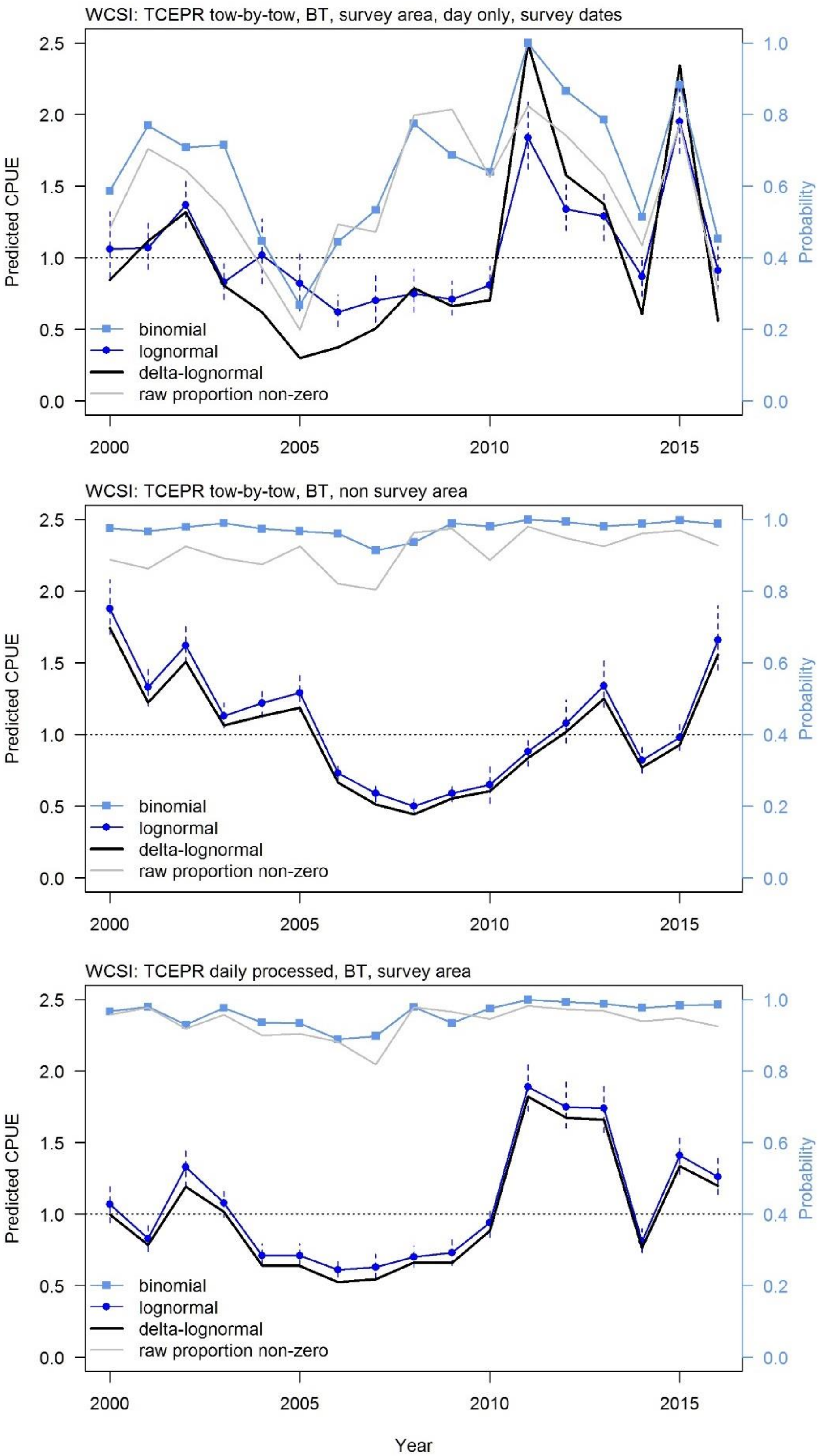


Figure A6 continued.

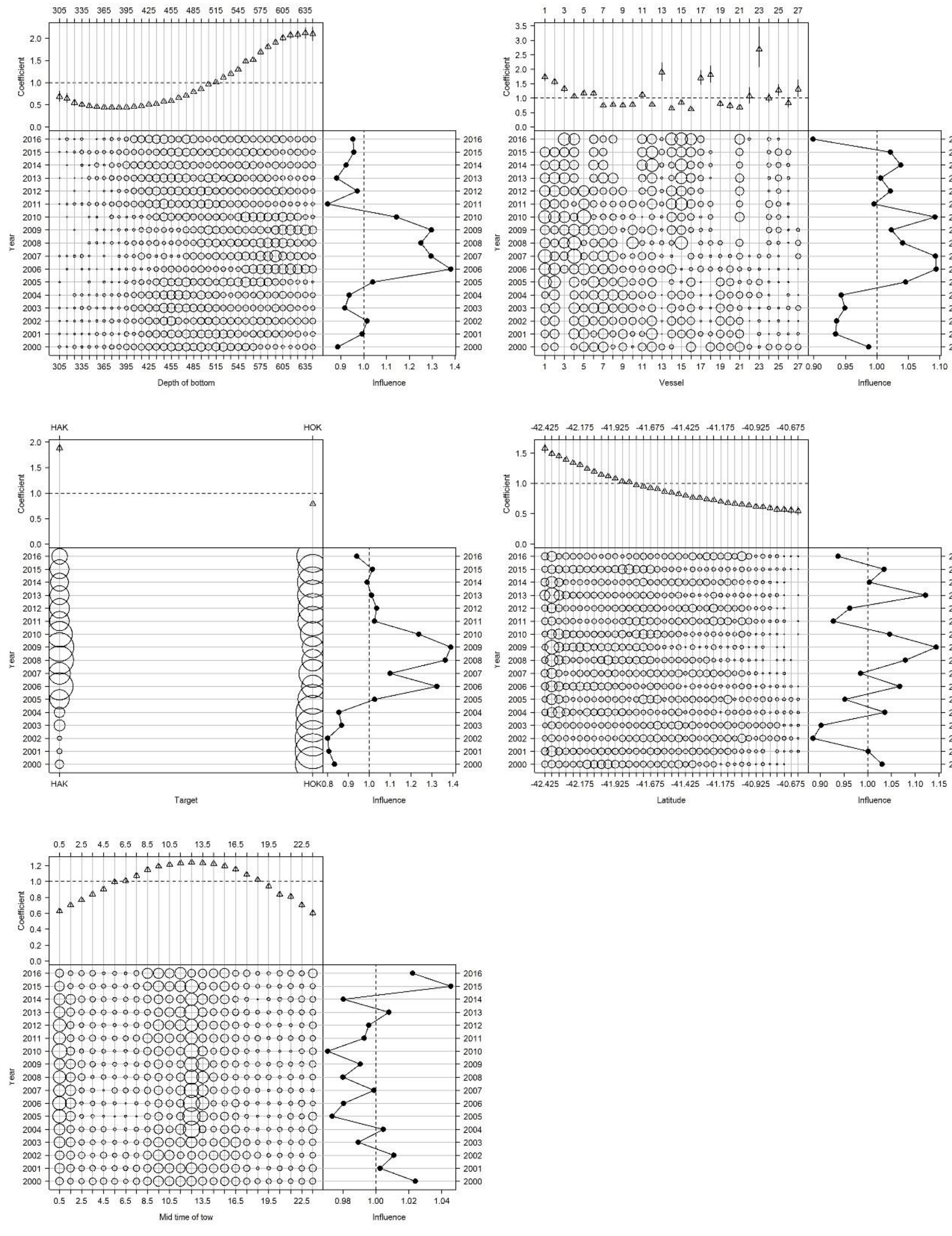


Figure A7a: Effect and influence of non-interaction term variables in WCSI TCEPR tow-by-tow, BT or MW, survey area core vessel lognormal model. Top: relative effect by level of each variable. Bottom left: relative distribution of each variable by fishing year. Bottom right: influence of variable on unstandardised CPUE by fishing year.

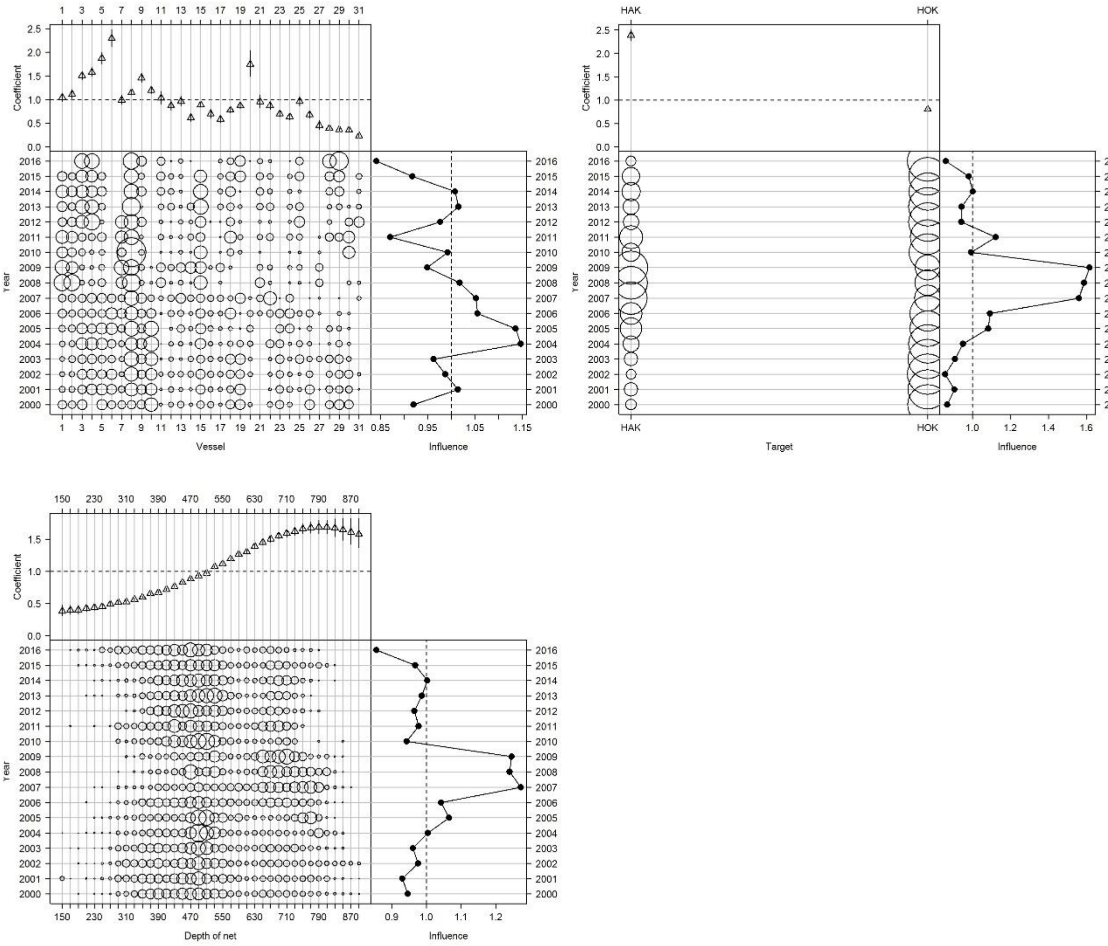


Figure A7b: Effect and influence of non-interaction term variables in the WCSI TCEPR tow-by-tow, BT or MW, non-survey area core vessel lognormal model. Top: relative effect by level of each variable. Bottom left: relative distribution of each variable by fishing year. Bottom right: influence of variable on unstandardised CPUE by fishing year.

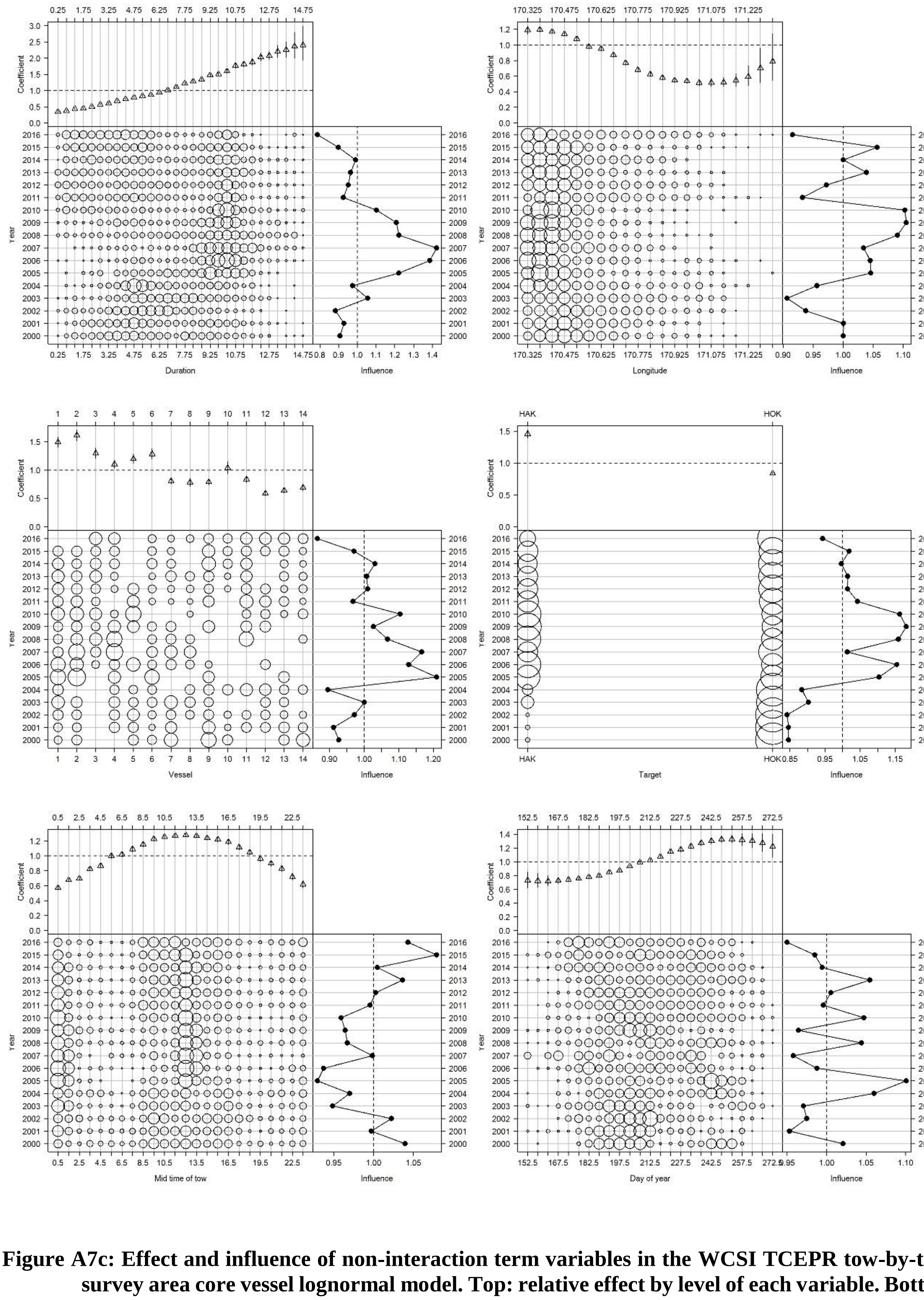


Figure A7c: Effect and influence of non-interaction term variables in the WCSI TCEPR tow-by-tow, BT, survey area core vessel lognormal model. Top: relative effect by level of each variable. Bottom left: relative distribution of each variable by fishing year. Bottom right: influence of variable on unstandardised CPUE by fishing year.

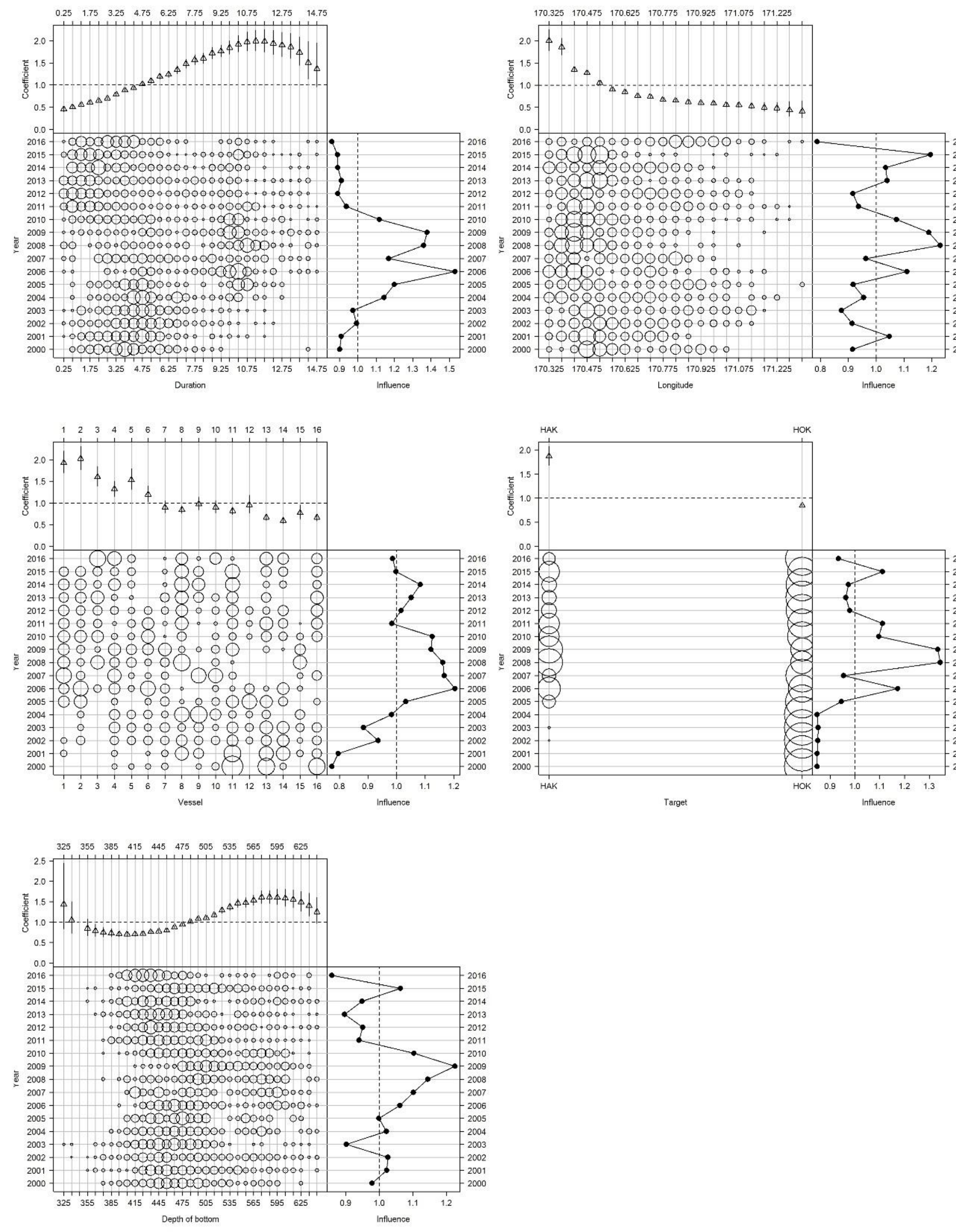


Figure A7d: Effect and influence of non-interaction term variables in the WCSI TCEPR tow-by-tow, BT, survey area, day time, survey date range core vessel lognormal model. Top: relative effect by level of each variable. Bottom left: relative distribution of each variable by fishing year. Bottom right: influence of variable on unstandardised CPUE by fishing year.

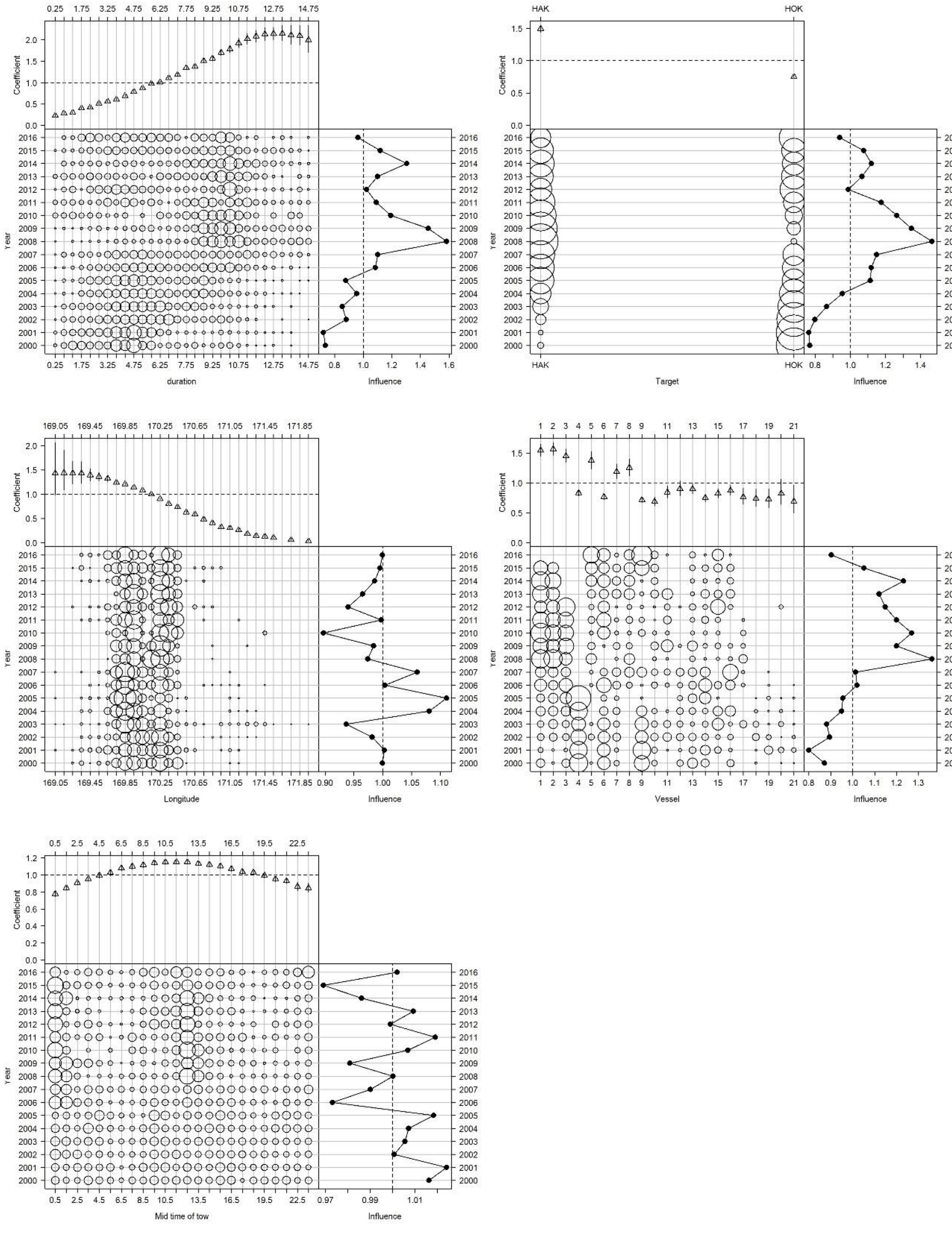


Figure A7e: Effect and influence of non-interaction term variables in the WCSI TCEPR tow-by-tow, BT non-survey area core vessel lognormal model. Top: relative effect by level of each variable. Bottom left: relative distribution of each variable by fishing year. Bottom right: influence of variable on unstandardised CPUE by fishing year.

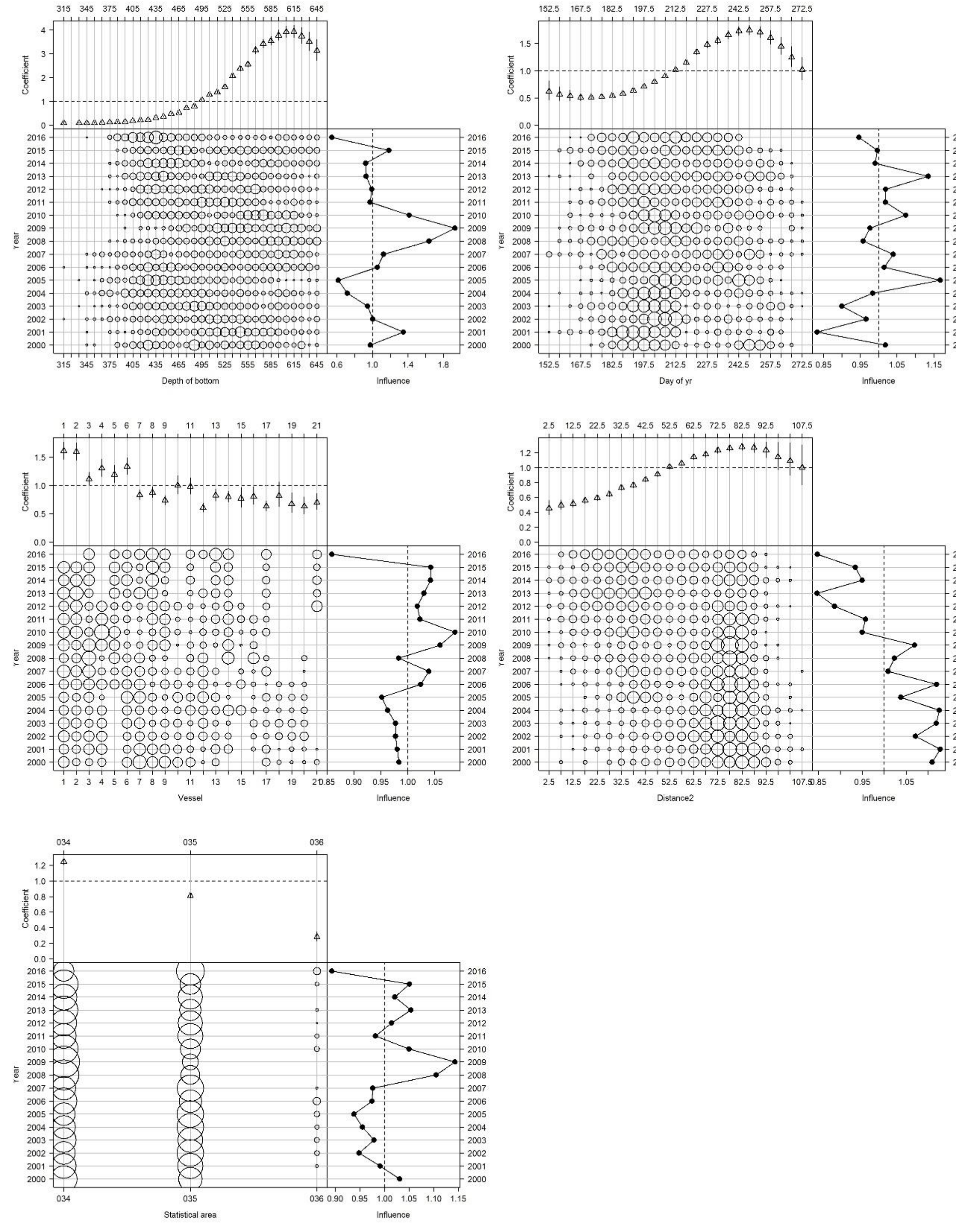


Figure A7f: Effect and influence of non-interaction term variables in the WCSI TCEPR daily processed, BT, survey area core vessel lognormal model. Top: relative effect by level of each variable. Bottom left: relative distribution of each variable by fishing year. Bottom right: influence of variable on unstandardised CPUE by fishing year.

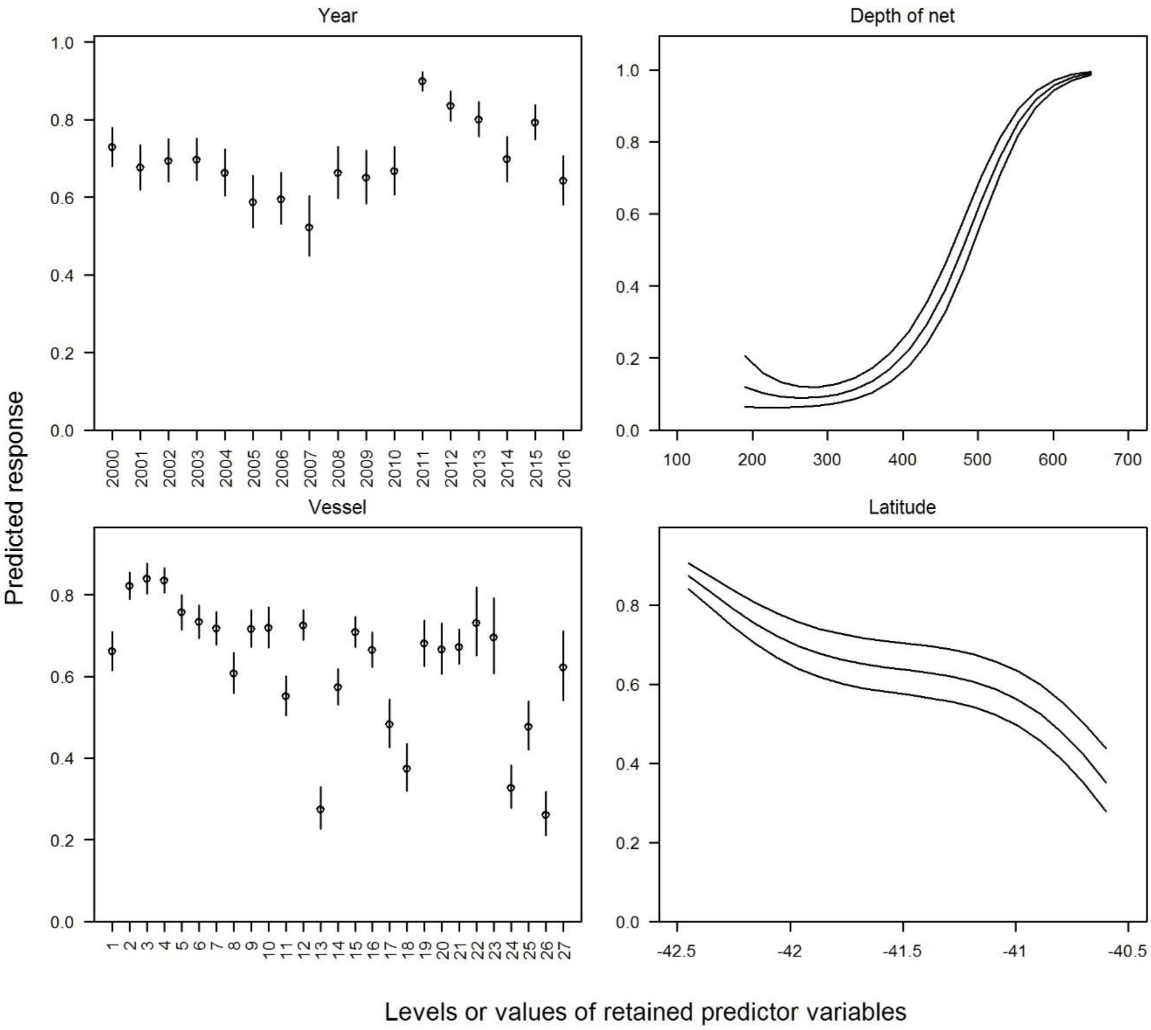


Figure A8a: Expected variable effects for variables selected into the CPUE binomial model for the WCSI TCEPR tow-by-tow, BT or MW, survey area core vessel fishery, 2000–2016. The 95% confidence intervals are shown as bars for categorical variables and as upper and lower lines for continuous variables.

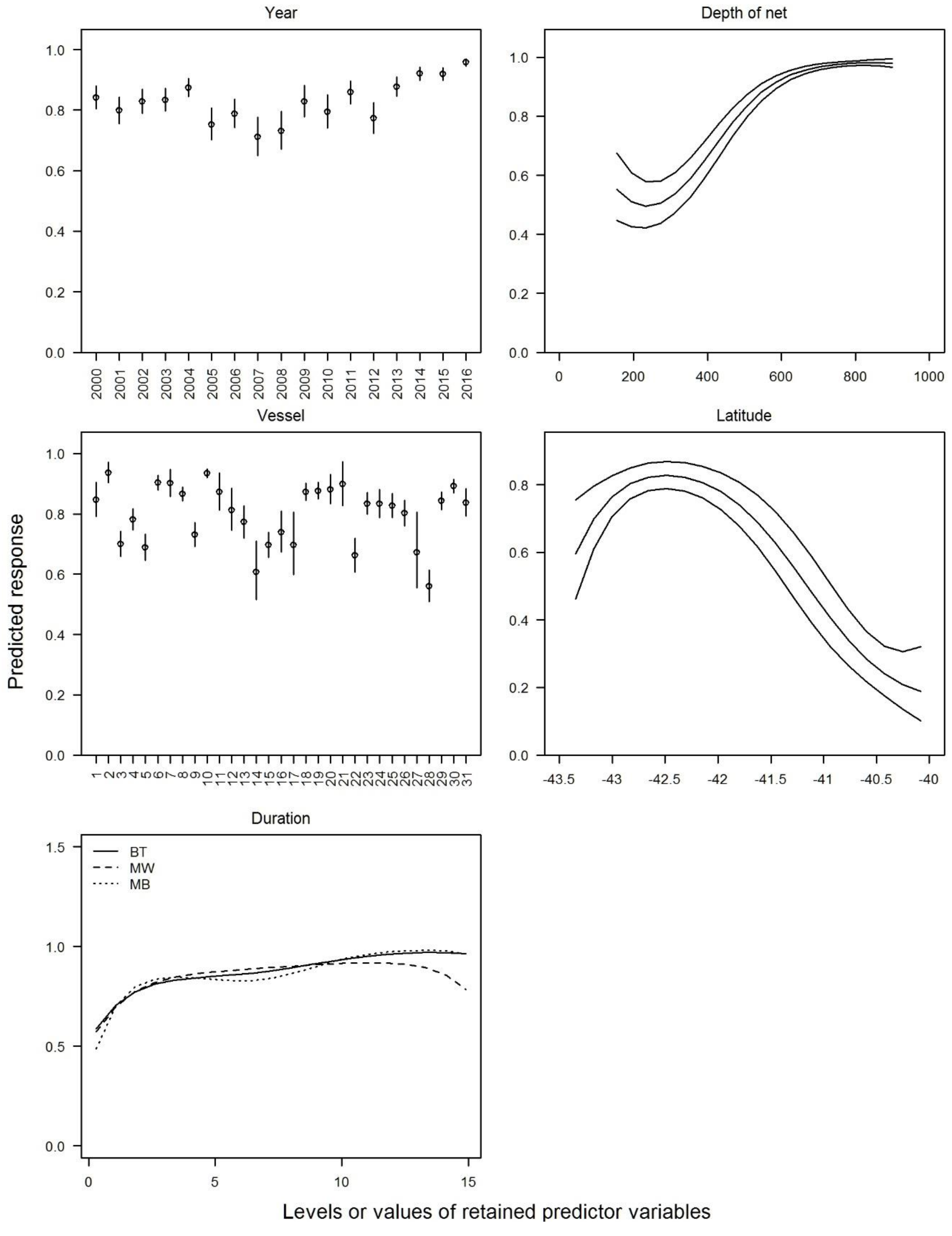


Figure A8b: Expected variable effects for variables selected into the CPUE binomial model for the WCSI TCEPR tow-by-tow, BT or MW, non-survey area core vessel fishery, 2000–2016. The 95% confidence intervals are shown as bars for categorical variables and as upper and lower lines for continuous variables.

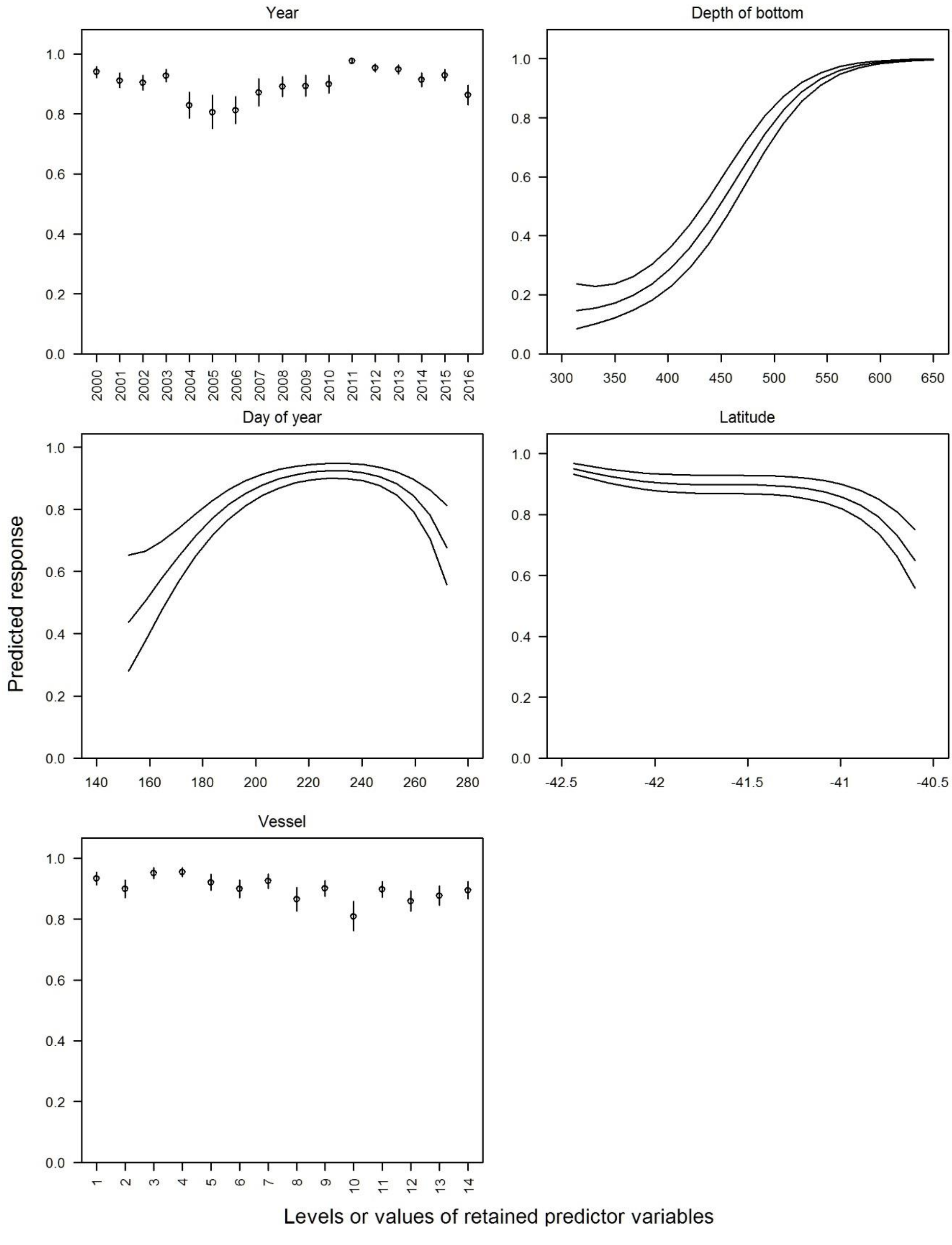


Figure A8c: Expected variable effects for variables selected into the CPUE binomial model for the WCSI TCEPR tow-by-tow, BT, survey area core vessel fishery, 2000–2016. The 95% confidence intervals are shown as bars for categorical variables and as upper and lower lines for continuous variables.

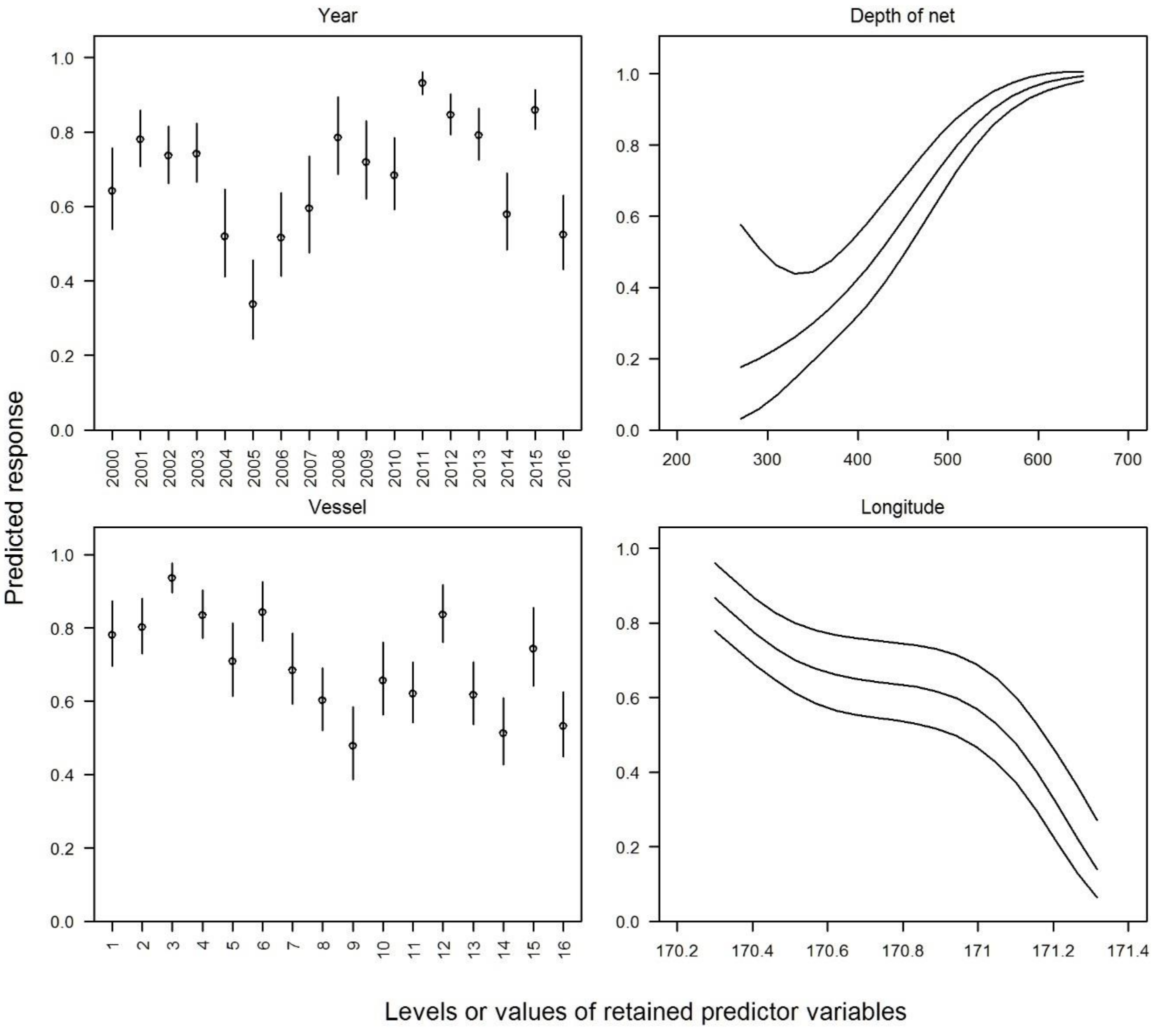


Figure A8d: Expected variable effects for variables selected into the CPUE binomial model for the WCSI TCEPR tow-by-tow, BT, survey area, day time, survey date range core vessel fishery, 2000–2016. The 95% confidence intervals are shown as bars for categorical variables and as upper and lower lines for continuous variables.

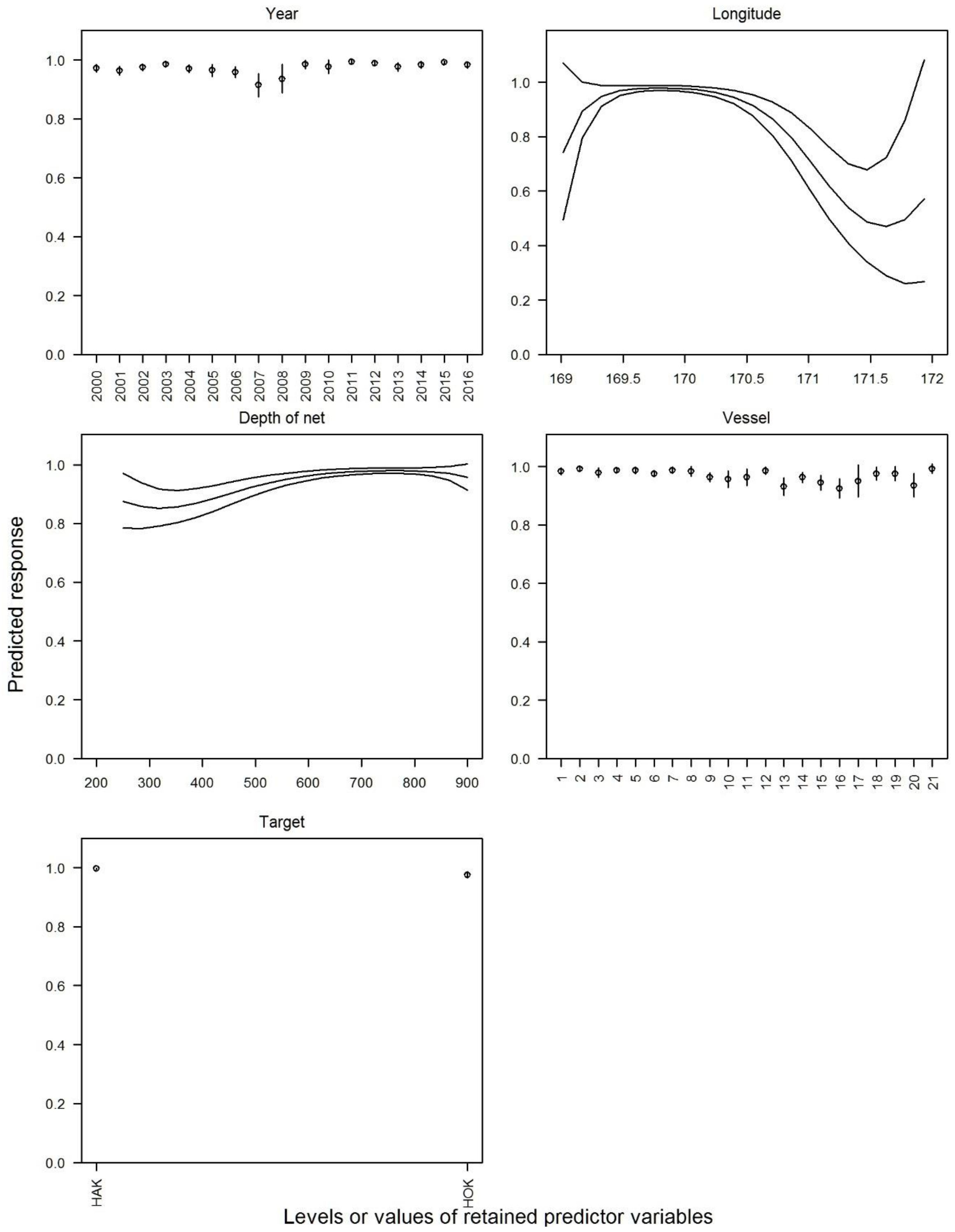


Figure A8e: Expected variable effects for variables selected into the CPUE binomial model for the WCSI TCEPR tow-by-tow, BT non-survey area core vessel fishery, 2000–2016. The 95% confidence intervals are shown as bars for categorical variables and as upper and lower lines for continuous variables.

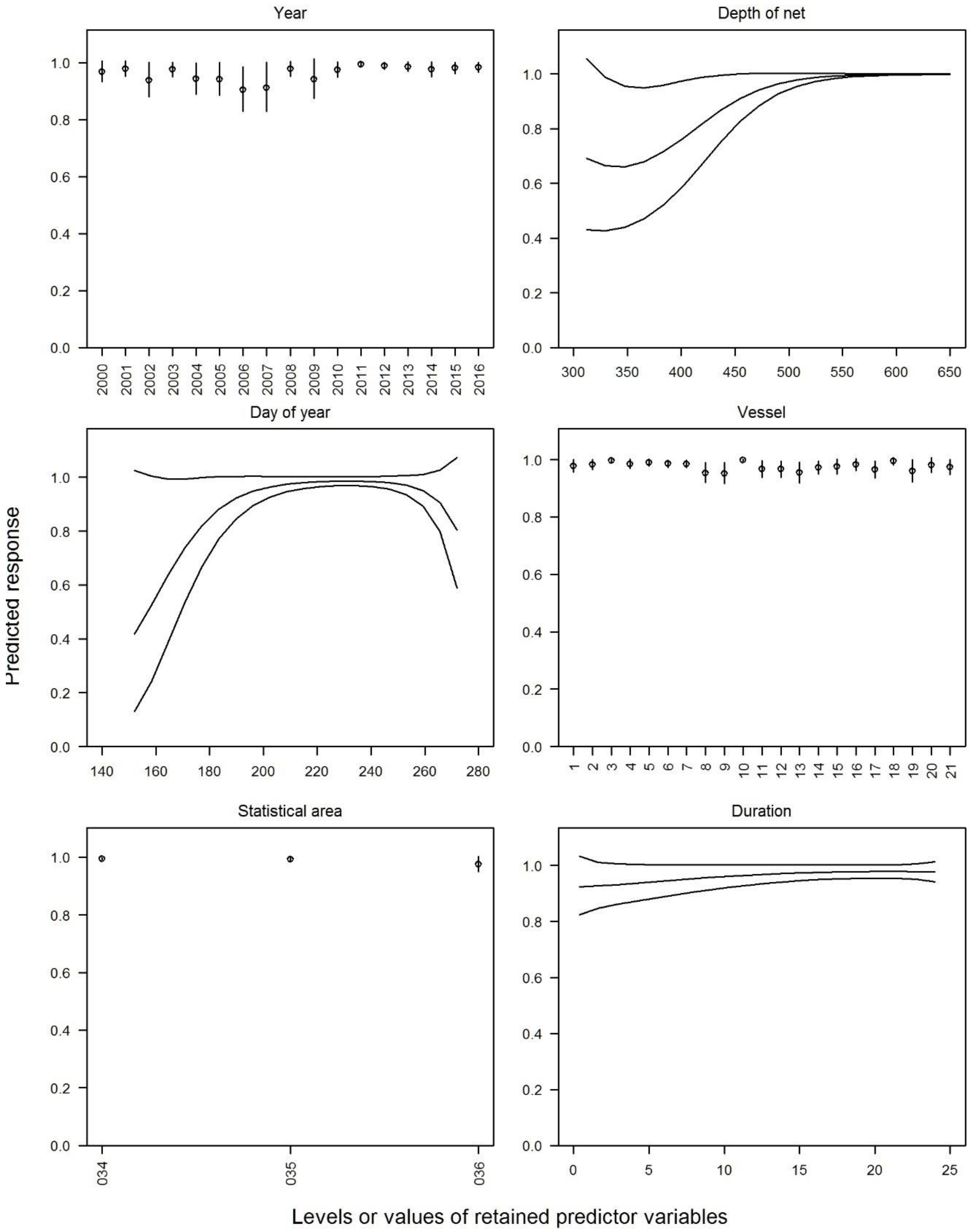
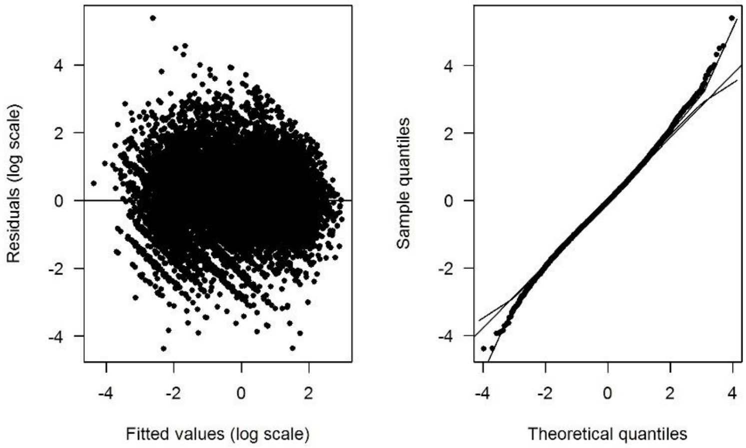
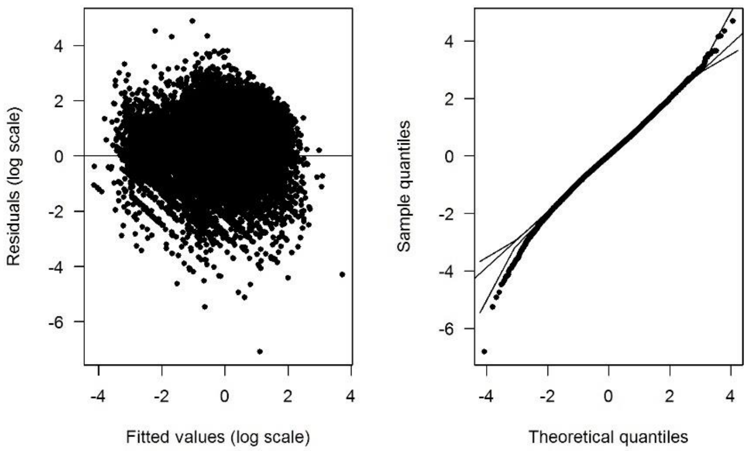


Figure A8f: Expected variable effects for variables selected into the CPUE binomial model for the WCSI TCEPR daily processed, BT, survey area core vessel fishery, 2000–2016. The 95% confidence intervals are shown as bars for categorical variables and as upper and lower lines for continuous variables.

(a) TCEPR tow-by-tow, BT or MW, survey area



(b) TCEPR tow-by-tow, BT or MW, non-survey area



(c) TCEPR tow-by-tow, BT, survey area

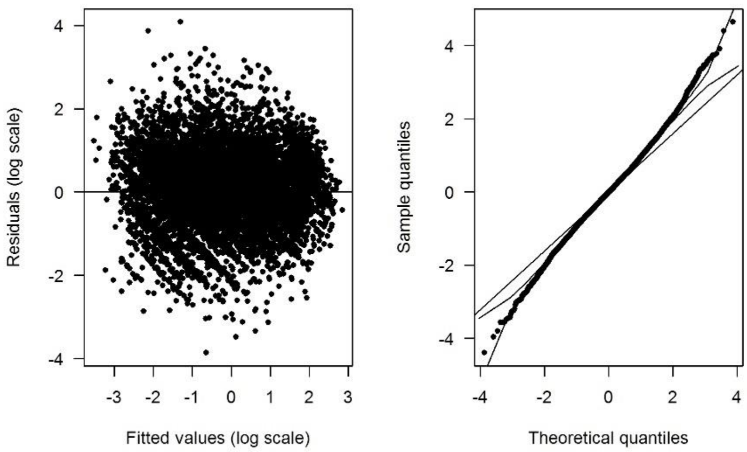
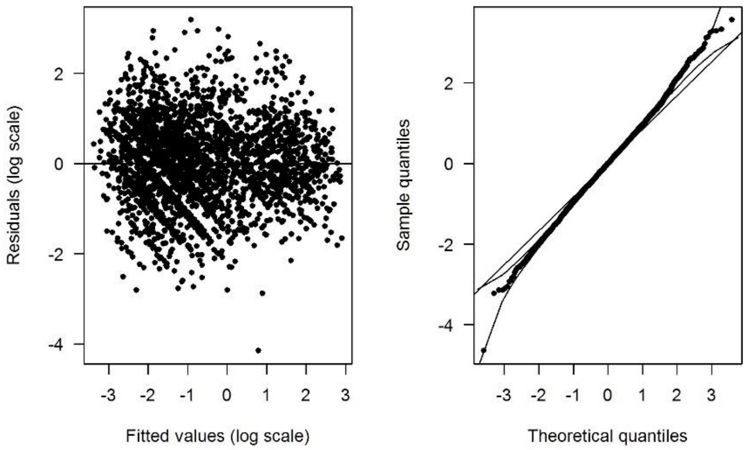
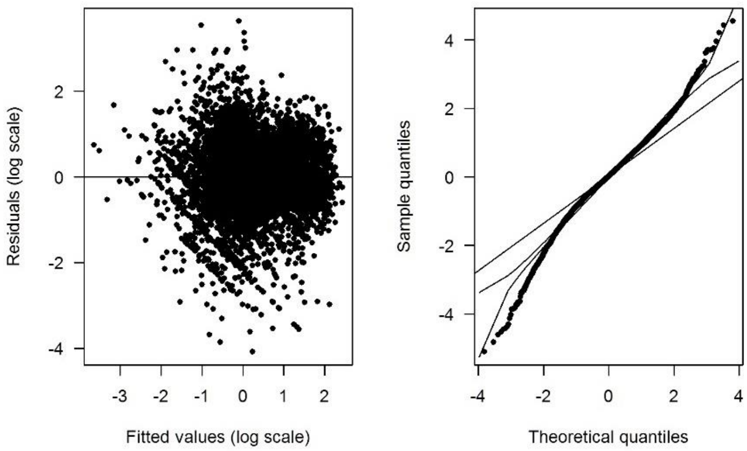


Figure A9: Diagnostic residual plots for the lognormal CPUE models.

(d) TCEPR tow-by-tow, BT, survey area, day time, survey date range



(e) TCEPR tow-by-tow, BT non-survey area



(f) TCEPR daily processed, BT, survey area

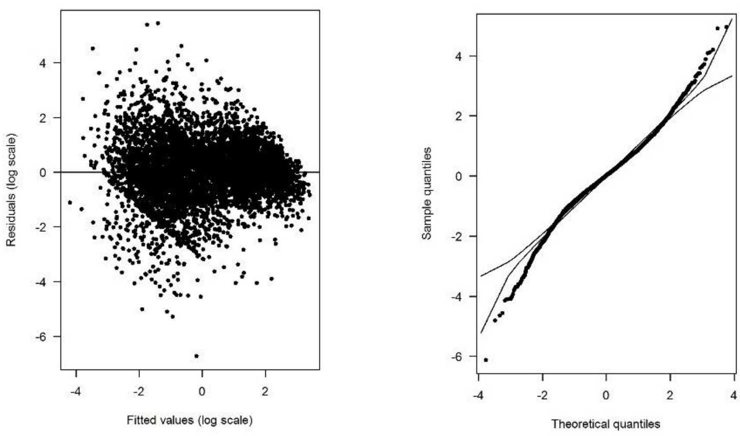
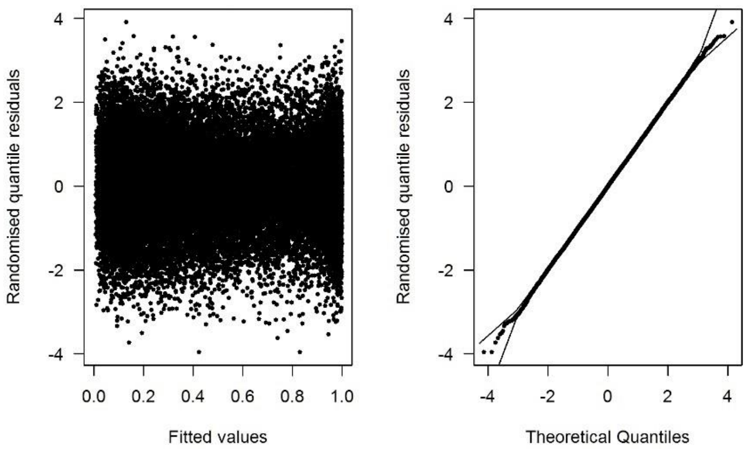
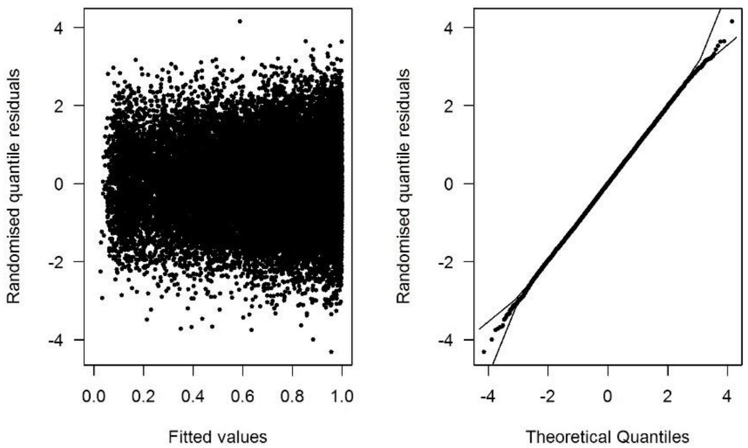


Figure A9 continued.

(a) TCEPR tow-by-tow, BT or MW, survey area



(b) TCEPR tow-by-tow, BT or MW, non-survey area



(c) TCEPR tow-by-tow, BT, survey area

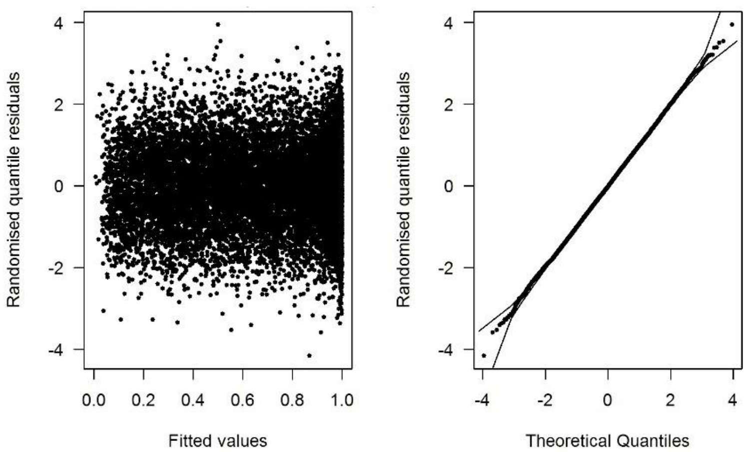
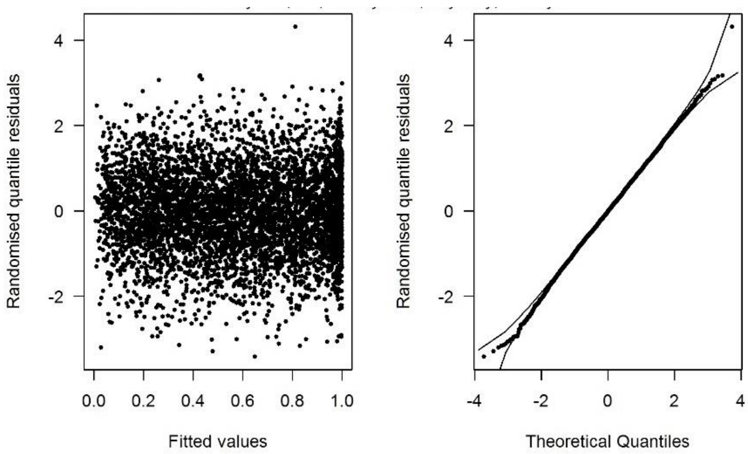
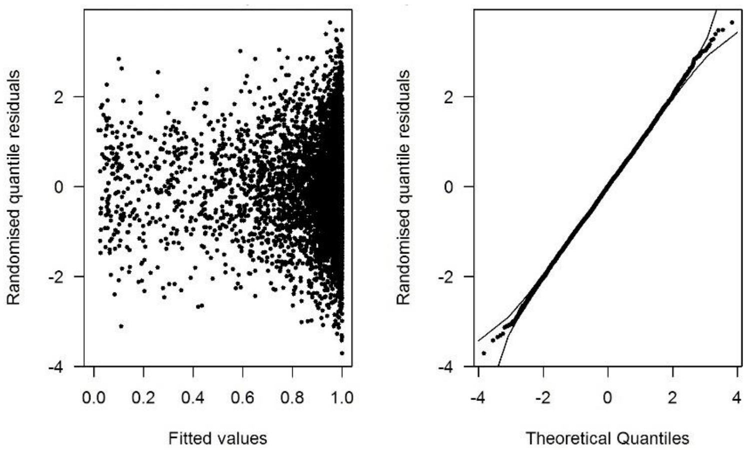


Figure A10: Diagnostic residual plots for the binomial CPUE models.

(d) TCEPR tow-by-tow, BT, survey area, day time, survey date range



(e) TCEPR tow-by-tow, BT non-survey area



(f) TCEPR daily processed, BT, survey area

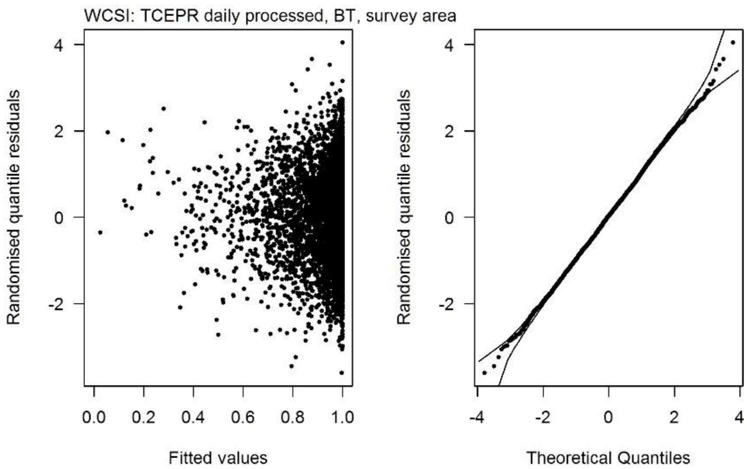


Figure A10 continued.