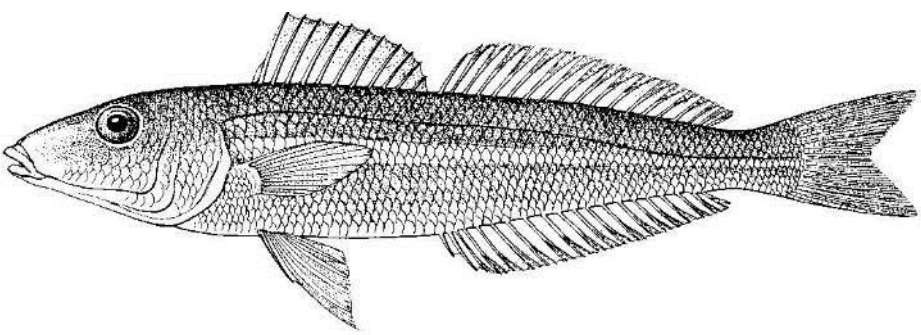
Stout Whiting Fishery

Queensland Total Allowable Catch for 2016



Species: *Sillago robusta*

Queensland Government

This publication has been compiled by MF O'Neill and GM Leigh of Agri-Science Queensland, Department of Agriculture and Fisheries.

Summary

In Queensland, stout whiting are fished by Danish seine and fish otter-trawl methods between Sandy Cape and the Queensland-New South Wales border. The fishery is currently identified by a T_4 symbol and is operated by two primary quota holders.

Since 1997, T_4 management has been informed by annual stock assessments in order to determine a total allowable commercial catch (TACC) quota. The TACC is assessed before the start of each fishing year using statistical methodologies. This includes evaluation of trends in fish catch-rates and catch-at-age frequencies against management reference points. The T_4 stout whiting TACC for 2014 was adjusted down to 1150 t as a result of elevated estimates of fishing mortality and remained unchanged in 2015 (2013 TACC = 1350 t quota).

Two T_4 vessels fished for stout whiting in the 2015 fishing year, harvesting 663 t from Queensland waters. Annual T_4 landings of stout whiting averaged about 713 t for the fishing years 2013–2015, with a maximum harvest in the last 10 fishing years of 1140 t and a maximum historical harvest of 2400 t in the 1995.

Stout whiting catch rates from both Queensland and New South Wales were analysed for all vessels, areas and fishing gears. The 2015 catch rate index was equal to 0.85, down 15% compared to the 2010–2015 fishing year average (reference point =1).

The stout whiting fish length and otolith weight frequencies indicated larger and older fish in the calendar year 2014. This data was translated to show improved measures of fish survival at about 38% per year and near the reference point of about 41%.

Together, the stout whiting catch rate and survival indicators show the fishery was sustainable. Earlier population modelling conducted for the year 2013 also suggested the stock was sustainable, but the estimate was only marginally above the biomass for maximum sustainable yield. Irrespective, reasons for reduced catch rates should be examined further and interpreted with precaution, particularly given the TACC has been under-caught in many years.

For setting of the 2016 TACC, alternate analyses and reference points were compared to address data uncertainties and provide options for quota change. The results were dependent on the stock indicator and harvest procedure used. Uncertainty in all TACC estimates should be considered as they were sensitive to the data inputs and assumptions.

For the 2016 T_4 fishing year, upper levels of harvest should be limited to 1000–1100 t following procedure equation 1, with target levels of harvest at 750–850 t for procedure equation 2. Use of these estimates to set TACC will depend on management and industry intentions.

Contents

Introduction

This fishery assessment report describes the commercial stout whiting fishery operating along Australia's east coast (Figure 1). The report was prepared to inform Fisheries Queensland (Department of Agriculture and Fisheries) and Queensland T_4 licence holders on the 2015 fishing year stock status, including a recommendation on the total allowable commercial catch (TACC) measured in tonnes for the 2016 calendar year in Queensland waters.

In Queensland, stout whiting (*Sillago robusta*) are caught by Danish seine and fish otter-trawl methods between Sandy Cape and the Queensland-New South Wales border. The Queensland fishing sector is identified by a T_4 symbol and currently operated by two licenced vessels. The stout whiting T_4 sector is managed by limiting vessel participants and TACC between water depths of 20–50 fathoms. The T_4 sector is managed and monitored separately to the trawl-whiting (stout and eastern school whiting) vessels operating in New South Wales (T_{NSW}). The T_4 sector is also managed separately to the much larger otter-trawl sectors that target eastern king prawns along Australia's east coast.

Otter trawlers targeting eastern king prawns in Queensland are not licenced to keep or record any stout whiting that are caught as by-catch. The magnitude of the stout whiting by-catch mortality across southern Queensland and Northern New South Wales waters in unknown through time. Historically, this by-catch mortality may have been quite significant given the amount of prawn fishing effort in shallow waters less than 50 fathoms depth (O'Neill, Leigh *et al.* 2014). Preliminary estimates of stout whiting discards range 1000–2000 t in the years 2002–2004 (unpublished data and analyses; MF O'Neill, GM Leigh and A J Courtney). The uncertainty and lack of data on stout whiting discards from the prawn fleet impacts on setting T_4 harvest allocations and confounds signals in the fishery indicators.

The T_4 stout whiting harvest landings has an annual gross value of around AUD3 million depending on export market prices and the value of the AUD currency. Stout whiting are primarily exported overseas for processing (such as butterfly fillets) in south-east Asia. Some processed product are imported back to Australia for domestic sale, however, the quantity and where the product is sold is generally unknown.

Fisheries Queensland has monitored harvests taken by the T_4 stout whiting sector since the development of management in 1991. Harvest and effort statistics are recorded in logbooks for each vessel's daily catch operation. Commercial fishers also provide Fisheries Queensland with two box-samples of fish from each fishing trip. Scientists measure the length of these fish and estimate their age by removing and examining their otoliths (ear bones).

In 2009 and 2010, the T_4 fishery harvests were monitored through an on-board observer program to collect various data on the species composition of the catch, including interactions with other commercial and recreational important species such as tailor, snapper and pelagic bait fishes (Rowsell and Davies 2011).

The information collected from the monitoring of stout whiting is combined annually to carry out assessments of the stout whiting stocks. These assessments contribute to the management decisions of the T_4 sector, including adjustments to the TACC quota. Over recent years the methodology for assessment has needed to adjust for: out-of-date information on by-catch mortality; changes in the spatial and temporal patterns of T_4 fishing and variance in the fishery data; difficulties with ageing fish from otoliths due to indistinct annual banding; and changes in the T_4 management processes for formal setting of the TACC from a part fishing-year (April to December) to a full year over all months. For more information on the history of the fishery and TACC setting, please read Brown and Butcher (1995), O'Neill and Officer (2007), Thwaites and Andersen (2008) and O'Neill and Leigh (2014).

The stout whiting stock indicators and recommendation for reduced TACC produced herein resulted from analyses designed in an attempt to adjust for the ongoing changes in the fishery and variance of the data. Nevertheless, precaution should be used when interpreting all estimates given the fishery-dependent limitations of the data.

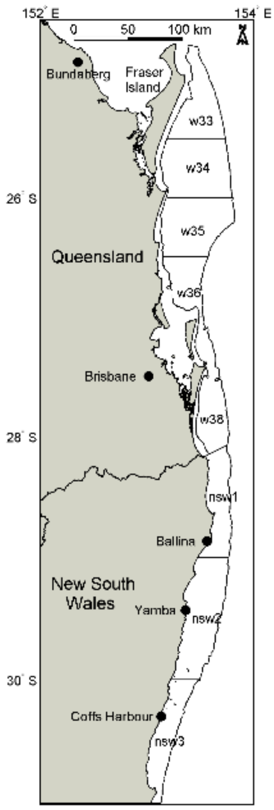


Figure 1. Map of the east Australia stout whiting fishery zoned by analysis regions. The Queensland fishing zones (w33…w38) cover offshore water depths between 20 and 50 fathoms. New South Wales fishing zones (NSW1…NSW3) cover offshore waters up to 50 fathoms. Stout whiting from New South Wales and Queensland waters are considered a single biological stock of fish based on evidence from genetic analyses (Ovenden and Butcher 1999).

Methods

Data

The data presented herein were extracted in June 2015.

For Queensland, the harvest data from each vessel were collated on a daily basis including the number of hours fished and number of catch operations (non-aggregated data retrieval 2321). Trawl shots where no stout whiting were caught, although were targeted, were included.

Commercial catch and effort data reported from New South Wales (NSW) were collated for the period 1997-2015. The data represented harvests per vessel from two databases: 1) monthly records, and 2) daily records. Major improvements in NSW logbook reporting occurred in 2009, resulting in more reliable daily records on stout whiting harvest.

Note that a separate catch rate standardisation analysis was performed for Queensland and NSW data due to the different logbook recording systems. The harvest and catch rate analyses grouped data into fishing years, for the months July to June, to better align the fish biology where stout whiting spawn primality over the spring and summer months (Appendix VI); and also to maximise data utility in the assessment process schedule.

Samples from the Queensland stout whiting (T_4) harvest were recorded to monitor patterns in the annual fish length, age and otolith weight structures. Two 5 kg boxes were collected from each vessel's fishing trip. All fish from each box were measured for length frequency. Sub-samples were taken to extract fish otoliths for aging and weighing. Estimates of each fish's age were derived from counts of otolith rings. Final age data were adjusted to age–groups (cohorts) based on fish capture dates. The fish age-length-otolith data were analysed by a calendar year following monitoring schedules and age adjustment protocols (O'Sullivan and Jebreen 2007). Alignment of the fish monitoring data to group fishing years is difficult at this time given the long processing time to age fish and provide data for TACC setting.

More detail on the data are described in the report appendices.

Catch rates

Fishery catch rates from Queensland and NSW were standardised using an area weighted approach (Campbell 2004; Carruthers, Ahrens *et al.* 2011; Walters 2003).

Catch rates of stout whiting were analysed for all fishing years, vessels and areas. The analyses followed fiscal years, labelled as 'fishing year', for the months from July to June. For example, the months starting from July 2014 through to June 2015 were labelled as the 2015 fishing year, with July = 1st fishing month and June = 12th fishing month.

For Queensland, the analysis used a hierarchical generalised linear model (HGLM) to standardised average daily catch rates of stout whiting for each fishing year and zone. Further, to correct for spatial bias, fishing zones that were not fished were imputed following the methods of Carruthers, Ahrens *et al.* (2011). The HGLM model terms considered patterns in fish catch rates between fishing years, zones, vessels, hours fished, water depths, seasons, lunar cycles, sonar use and fishing experience.

For NSW, the analysis used a generalised linear model (GLM) and considered the model terms for different fishing years, zones, the seasonal cycle in catch rates (based on the day of the year), vessels, hours fished, lunar cycle and a target factor for whiting or prawn fishing.

More detail on the catch rate analyses are described in the report appendices.

Catch curves

Catch curve analysis is the process to assess the survival of fish age *a* to age *a*+1 using changes in catch-at-age data (Hilborn and Walters 1992). The catch curve mixture model herein does this using contemporary statistics without the steady state assumptions of constant recruitment and survival. The objective of the analysis was to estimate annual survival fractions from fish age, otolith weight and length samples. Fish survival (*S*) refers to the ratio of abundance between older and younger age groups; the antonym is fish mortality which is equal to $\log(-S)$.

Stout whiting survival fractions were estimated by joining Gaussian finite mixture model, Von Bertalanffy growth and catch curve methodology. Model estimates were solved iteratively using the expectation-maximisation algorithm, by estimating differences in fish abundances by age. Two different model versions were used: Model 2 and Model 3. Model version 1, which incorporated standardised catch rates, was unsuitable due to the year-to-year variation in the stout whiting data, and the results are not reported.

Model version 2 estimated patterns of age-abundance from samples of stout whiting fish-length frequency and age-length-otolith data from 1991–2014. The analysis structure assumed the fish length data were sampled randomly each year. Survival fractions were estimated for each cohort. The fractions compared the ratio of fully recruited cohort abundances to the next younger cohort in the same years they were fished. By comparing the same years, the survival estimates can be obtained, but may be affected by strong or weak recruitment of new fish. The model estimates of survival identified inconsistency in some years between sampled fish-length frequency and age-length-otolith data. However, the data and estimates in the last few years were appropriate for the Model 2 methodology.

Model version 3 was used to analyse only the 1993–2013 matching age-length data. The model was not formulated to use fish length frequency or otolith weight data and no aging data were available in the years of 1991, 1992 and 2014. The Model 3 analysis was conditioned on the assumption that fish ages within each length category represented a random sample, and no longer assumed that the lengths themselves were sampled randomly. This assumption aimed to overcome the variance in fish length samples associated with the fishery dependency of the data (fish length data tended to vary inconsistently between fishing years, areas and vessels). So only the paired age-length fish data were analysed. Similar to Model 2, calculation of annual fish survival followed cohort abundances.

Quota

The calculations for setting the stout whiting total allowable commercial catch (TACC measured in tonnes for Queensland waters) followed the process of assessing indicators ($\bar{I}$) against reference points (I_{target}). Herein, the indicators from the stout whiting age-length data measured changes in fish survival, and from the catch rate data they measured changes in fish abundance.

The reference points gauged the status of the indicators, where if the indicator was less than the reference point the TACC would be reduced, and if the indicator was greater than the reference point the TACC would be increased. The TACC results considered the following reference points (I_{target}):

- for catch curve Model 2, an average survival faction of 0.4055 calculated from the years 1991–1993, 1996, 2012 and 2013, which were greater than the survival fraction for twice natural mortality (S_{2M} = 0.3073)
- for catch curve Model 3c, an average survival fraction of 0.3569 calculated from the years 2009–2012
- for both catch curve models, an average survival fraction of 0.4127 based on 1 ½ times the natural mortality
- for catch rates, an average standardised catch rate of 1.0 from the fishing years 2010–2015; this was equivalent to the long term average.

The selected reference points were chosen to target years of profitable fish catch rates (Little, Wayte *et al.* 2011) and stable years of fish survival greater than the fraction for twice the assumed natural mortality (noted above with natural mortality M = 0.59, estimated in O'Neill and Leigh 2014). The reference points aimed for stock viability associated with exploitable biomasses greater than the biomass required for maximum sustainable yield. The natural mortality reference points were defined in the previous assessment (O'Neill and Leigh 2014).

The annual variability of the indicators had implications for setting TACC. In the harvest control rule, direct use of annual estimates of survival fractions or catch rates in the TACC adjustment factor (linear θ_{k+1}, for x = 1 in Figure 2) may cause the quota to vary considerably from year to year. Therefore, limits on quota change (like for spanner crab, O'Neill, Campbell *et al.* 2010) were calculated to mitigate year-to-year variance in results and compare outcomes.

For this, the cube-root (x = 3, Figure 2) and square-root (x = 2, Figure 2) transformations were compared. Of the three transformations considered to adjust TACC, the cube-root was the strongest to mitigate variance and limit the magnitude of quota change; the transformation was also used to normalise the distribution of T_4 catch rate data.

The first harvest control rule was defined as:

$$\mathrm{TACC}_{\mathrm{T4},k+1} = \min\left(\mathrm{TACC}_{\mathrm{T4},k}\theta_{k+1}, \mathrm{TACC}_{\mathrm{T4,max}} = 1363\mathrm{t}\right); \theta_{k+1} = \left(\frac{\bar{I}}{I_{\mathrm{target}}}\right)^{1/x}$$ (Procedure equation 1),

where T_4 indicates the Queensland fishing sector, *k* was the fishing year for current TACC, *k*+1 was the fishing year for the next TACC setting, and *θ* was the TACC adjustment factor for the transformation *x* (Figure 2). For the indicator $\bar{I}$ in *θ*, average fish survival fractions or catch rates or both combined over the last two years were used and compared. The harvest control rule limited the TACC quota to a maximum sustainable yield of 1363 t (O'Neill and Leigh 2014).

Alternate TACC tonnages were also calculated using a second harvest control rule based on the annual average harvest taken since 2007, where

$$\mathrm{TACC}_{\mathrm{T4},k+1} = \min\left(C_{\mathrm{T4,CUR}}\theta_{k+1}, \mathrm{TACC}_{\mathrm{T4,max}} = 1363\mathrm{t}\right); \theta_{k+1} = \left(\frac{\bar{I}}{I_{\mathrm{target}}}\right)^{1/x}$$ (Procedure equation 2), and

$C_{\mathrm{T4,CUR}}$ = 850 t. $C_{\mathrm{T4,CUR}}$ was averaged over the last nine years of T_4 harvests to account for stout whiting's full lifespan (0+…8+) of age groups.

Both of the TACC equations (1) and (2) were similar to the simulation tested Tier 3 harvest rules for Southern and Eastern Scalefish and Shark (Wayte 2009) and Tropical Red Snappers of Northern

Australia (O'Neill, Leigh *et al.* 2011). The second equation form is used in a number of Australian Government managed fisheries (Australian Government 2009 (AMENDED FEBRUARY 2014)).

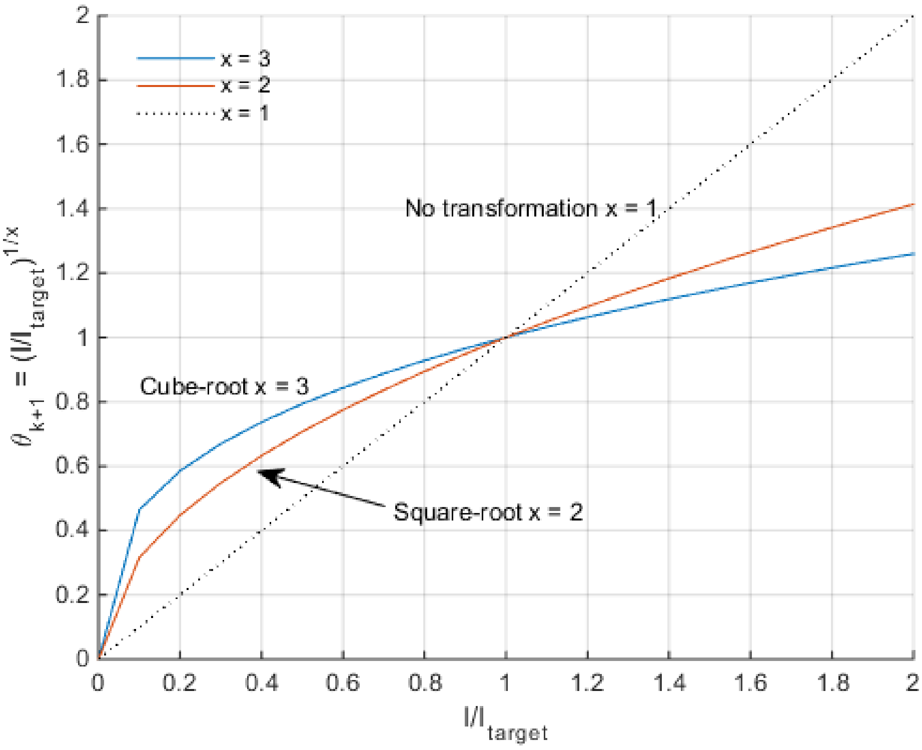


Figure 2. Comparison of transformations on the indicator ratios for 1) linear = no transformation, 2) square-root and 3) cube-root. The indicator ratios can represent either fish survival or catch rates. The y-axis for θ illustrates the different scales for the TACC multipliers. For no transformation x =1, the TACC multiplier follows the 1:1 diagonal to adjust quota proportionally to the indicator ratio.

Results

Harvests

Two T_4 vessels fished for stout whiting in the 2015 fishing year, harvesting 663 tonnes (t) (Figure 3a). Annual T_4 landings averaged about 713 t for the fishing years 2013–2015, with a maximum harvest in the last 10 years of 1140 t. T_4 harvests illustrated by calendar years are summarised in Figure 3b.

From 2011–2015, most of the T_4 harvest was taken from the ‘w38’ fishing zone (offshore waters from around the Stradbroke islands and Gold Coast; Figure 4). Prior to the year 2000, the bulk of the harvest was taken from Sunshine Coast to Double Island Point waters (zone ‘w35’). This pattern then shifted north to Fraser Island waters (zones ‘w33’ and ‘w34’) 2001–2010 and then to southern waters (zone ‘w38’) 2011–2015. Fishing for stout whiting was closed in zone w38 between 2001 and 2009.

In NSW, about 40 licences were estimated to harvest 250 t and 160 t of stout whiting in 2013 and 2014 respectively. The bulk of the NSW harvest taken was caught in offshore waters Arrawarra–Ballina (fishing zone ‘NSW2’). Vessels in NSW are part of a multispecies trawl fishery and can target other species such as eastern king prawns.

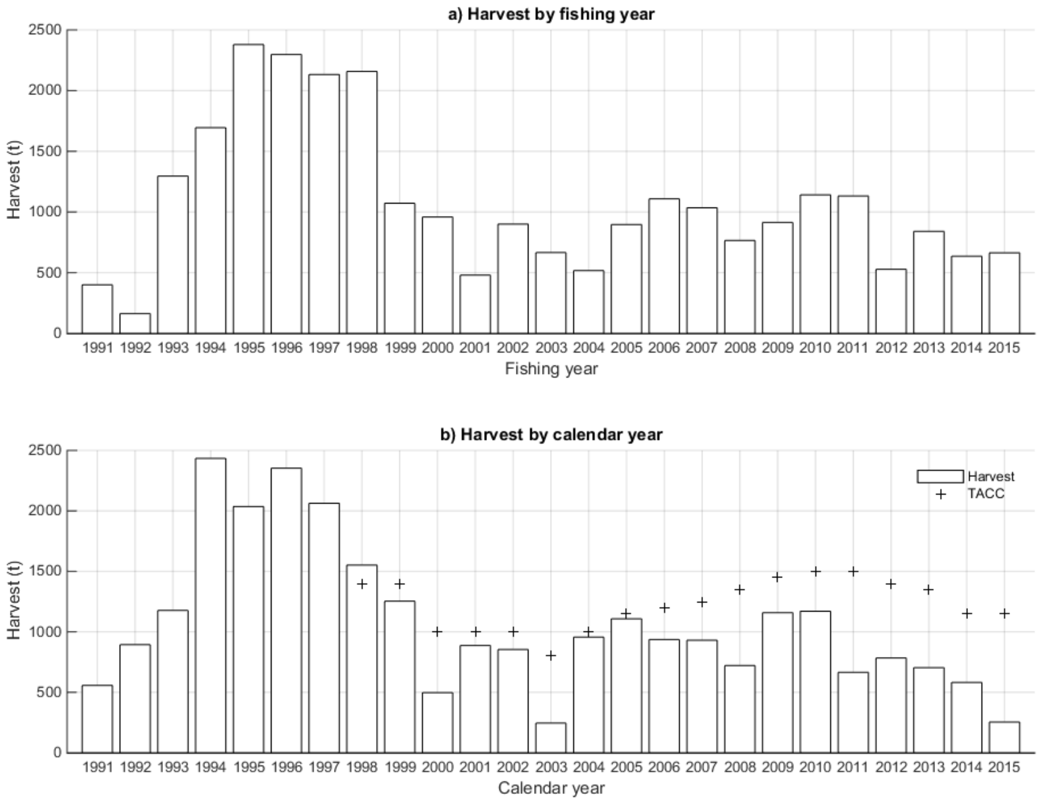


Figure 3. Tally of reported stout whiting harvests (tonnes) taken by T_4 licensed vessels in Queensland waters for a) fishing years aggregating months July–June, and b) calendar years. The tonnages were summarised from the logbook records up to June 2015. The historical TACC settings are shown on subplot b.

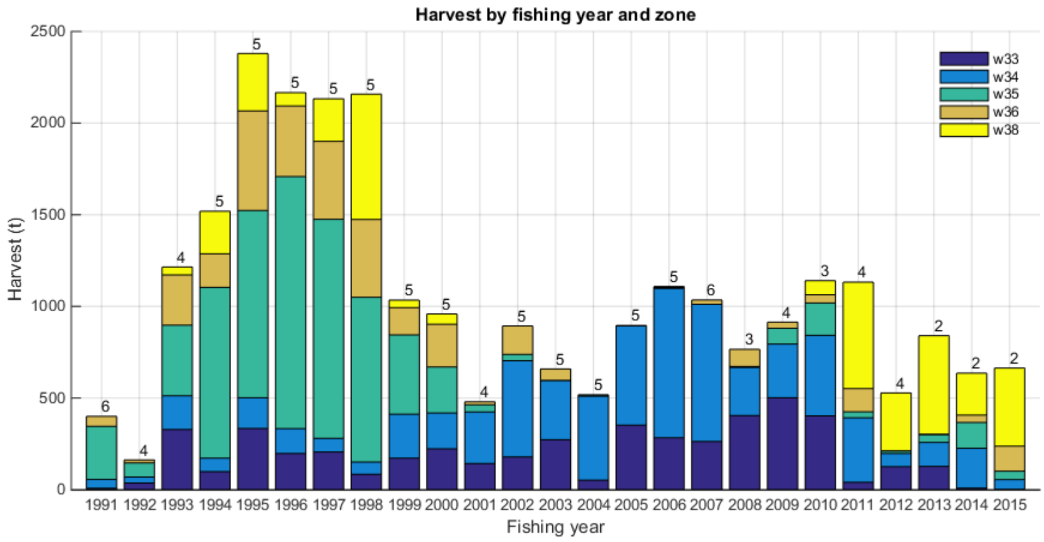


Figure 4. Tally of reported stout whiting harvests (tonnes) taken from each Queensland fishing zone. The number of fishing vessels in each fishing year is listed.

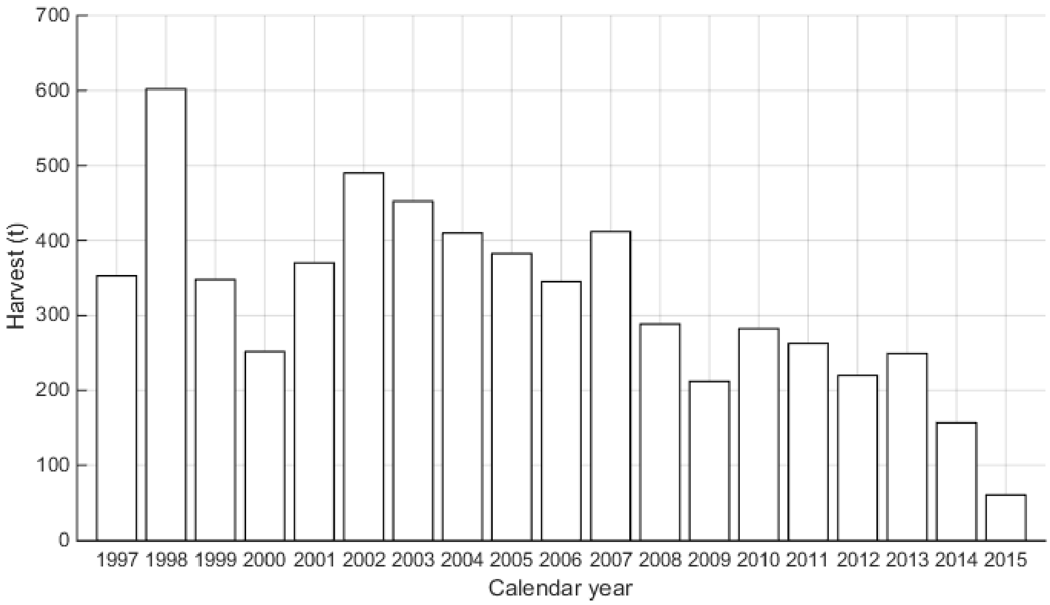


Figure 5. Estimated stout whiting harvests (tonnes) reported from NSW waters. The 2015 tally was year-to-date up to June 2015.

Catch rates

The analysis of Queensland (T_4) and NSW (T_{NSW}) stout whiting harvests are detailed in Appendices I and II. The following results were found:

- The T_4 sector's fishing power has increased significantly in recent years, with proportionally more fishing effort being conducted using the higher catching Danish seine fishing gear. In 2015, the sector's fishing power was 2.75 times that in 1991.
- Standardisation of T_4 stout whiting catch rates for changes in fishing power show the 2015 index was below the long term mean.
- Contrary to the T_4 sector, the T_{NSW} sector's overall standardised catch rate was above the 2010–2015 average. A decline was noted fishing zone 1002 (NSW2).
- Spatially standardising the sectors catch rates across states shows a stable trend from 2012–2015, with the 2014 and 2015 fishing year indices 85% of the mean catch rate (Figure 6). In 2010 the catch rate was 36% above the mean catch rate.

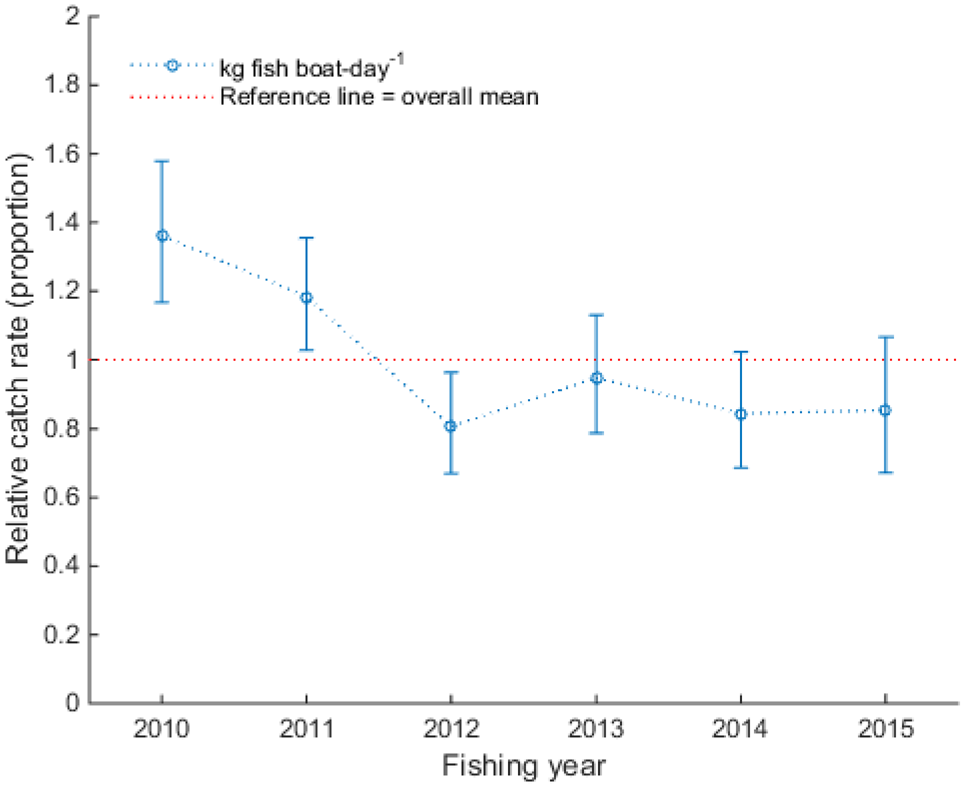


Figure 6. Final standardised catch rates of stout whiting from NSW and Queensland waters combined. Error bars indicate 95% confidence intervals on predictions. The annual time series was scaled relative to its mean catch rate (1 = mean catch rate).

Catch curves

The results from two different catch curve models are presented: Model 2 and Model 3. Model 2 estimated the patterns of fish age-abundance from the fish-length frequency and age-length-otolith data for 1991–2014. The analysis structure assumed the data were sampled randomly. Model 3 was used to analyse only the 1993–2013 sub-sampled age-length data. The Model 3 analysis was conditioned on the assumption that fish ages within each length category were sampled randomly and no longer assumed that the lengths themselves were sampled randomly. This assumption aimed to overcome the variance observed in fish length samples. In both models the calculation of annual fish survival followed cohort abundances. The analyses focused on Queensland T_4 data, as no fish length or age data were available from NSW waters or the eastern king prawn fleet.

The following results were from Model 2:

- Significant variance was observed in the sampled fish length frequencies between years, areas and fishing operations (Appendix IV). The statistical F-test for differences between years was $F = 716.21$ and $p < 0.001$. The resulting variance components for fishing zones was 0.065 (s.e. = 0.046) and fishing operations was 0.125 (s.e. = 0.059). The residual (unexplained) variance was 1.6 cm, where shifts in the length frequencies of this magnitude can significantly affect the representativeness and accuracy of predicted fish age-structures.
- The sampling in 2014 was mostly from the Danish seine fishing gear and indicated an increase in the observed fish lengths and otolith weights (Figure 7). No fish were aged in 2014 and sample sizes were lower compared to previous years.
- Predicted age-compositions from the 2014 fish length and otolith weight data suggest a higher frequency of older 2–3 year old fish; extending from the high frequency of one year old fish in 2013 (Appendix IV, Figure 33). The 2014 predicted frequencies of 0+ and 1+ year old fish was less compared to previous years.
- Estimates of fish survival show a decline from 1991–2002 (Figure 8). The survival fractions were relatively consistent 2003–2008 and 2010–2011, but increased positively in 2012 and 2013.
- Of note were the two very-strong cohort-survivals estimated in 2001 and 2009. These estimates deviated markedly from the over trend. The higher 2001 survival estimate resulted from a sudden change to older fish aged in 2002 compared to 2001 and 2003 (Figure 7d). This was inconsistent with smaller fish suggested by the length frequency samples in 2002 (Figure 7a). In 2009, the very high survival estimate resulted from larger and older fish present in 2010 samples (Figure 7). The 2001 and 2009 survival fractions suggest strong survival events (low mortality and/or high recruitment event) or highlight inconsistent data. The low survivals in years 2000 and 2002 suggest diminished recruitment after previous years of high harvest (Figure 3).

The following results were from Model 3:

- The estimated trend in stout whiting survival fractions followed the patterns in cohort strengths (Figure 9). Survival fractions were lowest between 1993 and 2003. The low survival estimates in these years, particularly 2002, suggest weak recruitment. Higher rates of survival were estimated after 2002, with strong recruitment identified in 2004. Estimated survival stabilised at higher fractions between 2009 and 2012 compared to the low estimates before 2003.
- The relative pattern of estimated survivals was not sensitive to the assumed growth curve and variance parameters (Figure 2). The annual patterns were in parallel ($\rho = 0.98$), but the scale of

the estimates reduced marginally for smaller maximum fish size (l_∞) and variance (*V*). Overall, the catch curve mixture model fitted the age frequencies well (Appendix IV, Figure 34).

- The fish growth parameters in Figure 9 a) were estimated separately outside the catch curve model using the age-length data directly [Figure 7 b) and d)]. Settings Figure 9 c) were estimated from catch curve Model 2 above, which included all length frequency and otolith age data (Figure 7). Settings Figure 9 b) were a combination of a) and c).

A number of inferences were of note from the catch curve analyses of stout whiting. First were the low estimates of fish survival around 1997–2002. It appeared the high T_4 harvests of 1300–2400 t taken 1994–1999 [Figure 3 b)] may have pushed survival rates down (together with other sectors catches), with the low 2000 and 2002 year estimates driven more by low recruitment given the corresponding lower harvests of 200–800 t [Figure 3 b)]. The higher fish survivals estimated for the years after 2003 indicated stronger recruitment. This correlated from the reduced T_4 harvests, reduced T_1 prawn fishing and the adoption of by-catch reduction devices by T_1 prawn trawl sector since the year 2000 (Braccini, O'Neill *et al.* 2012). The estimated survival fractions for the years 2007–2012 had stabilised for those years of harvest (Figure 9). The catch curve analysis identified significant changes in fish age-abundance. Representative and consistent sampling of age data is important for the methodologies in order to critically evaluate the validity of age-abundance data.

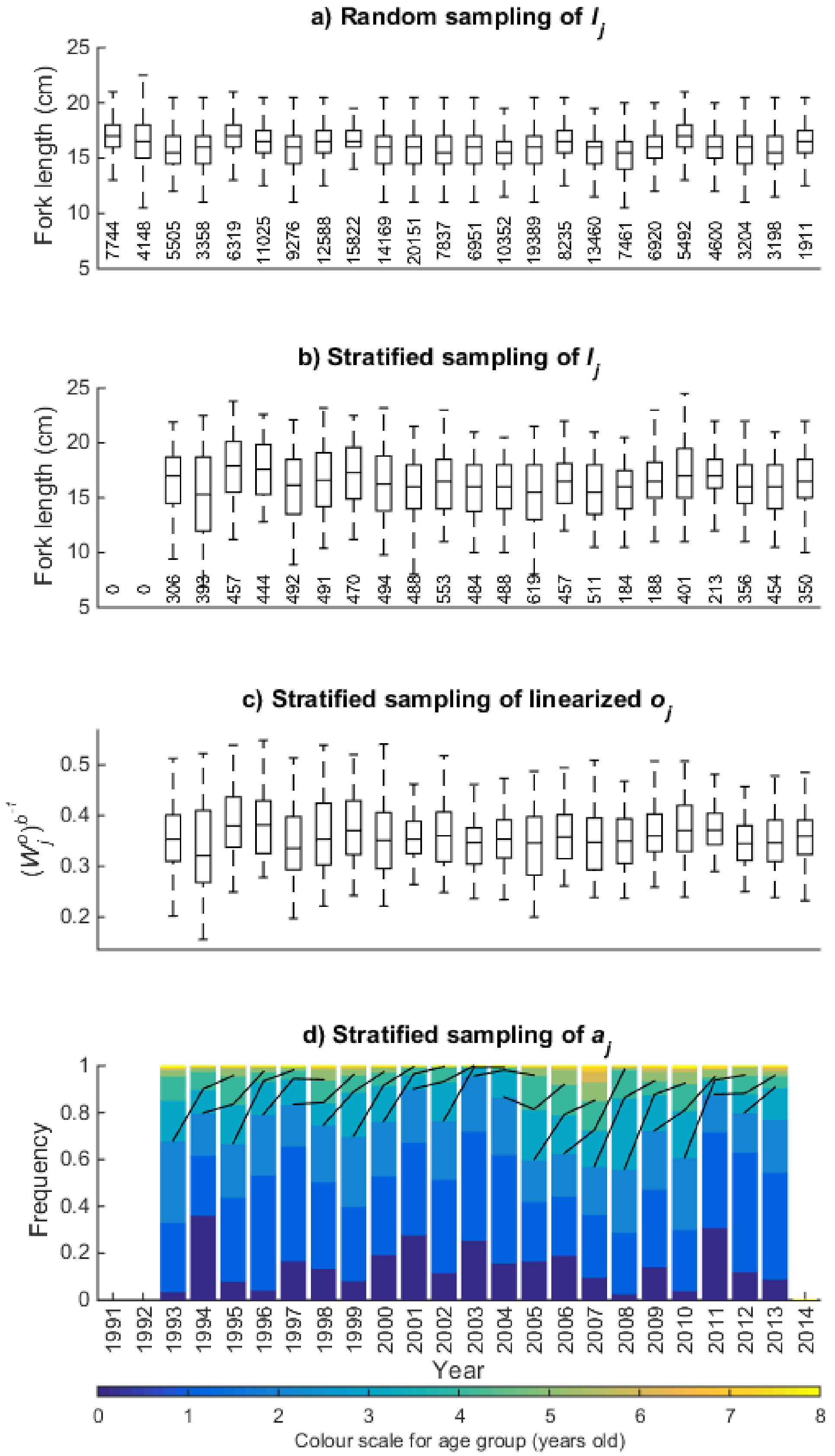


Figure 7. Summary of the stout whiting samples recorded from the T_4 fishery for a) fish length frequencies, and b–d) sub-samples of individual measures of matching fish length, otolith

weight transformed and age group. Subplots a) and b) show the annual numbers of fish measured.

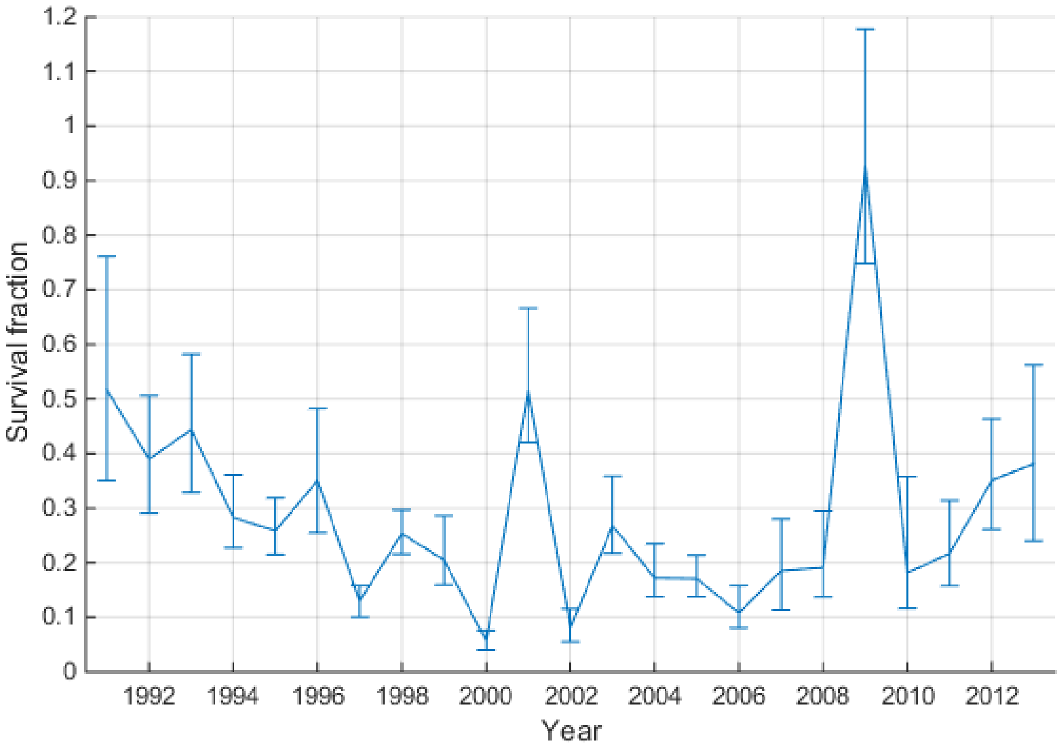


Figure 8. Estimated survival fractions of stout whiting as calculated from the catch curve Model 2. Error bars show the 95% confidence intervals.

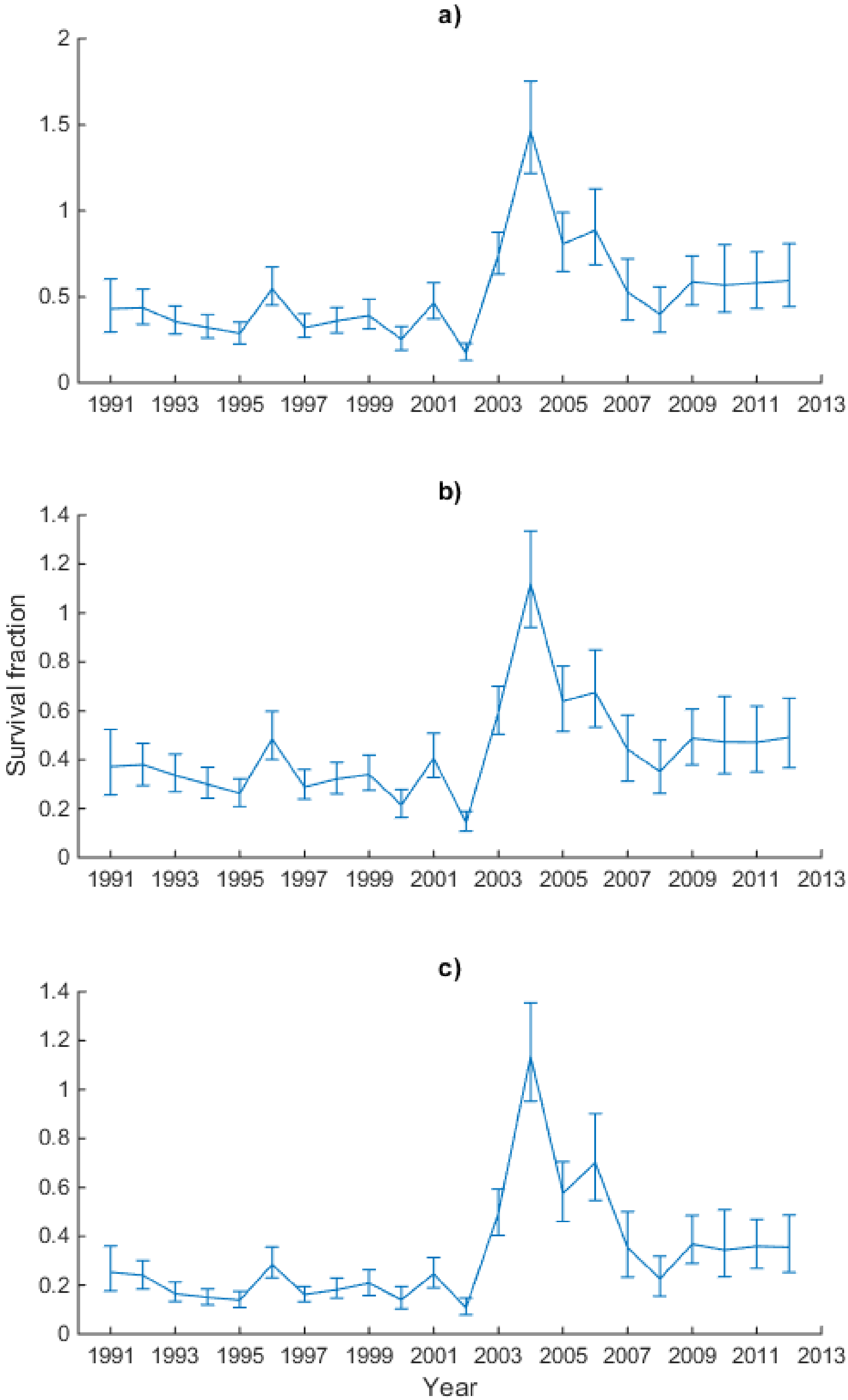


Figure 9. Estimates of stout whiting survival fractions as calculated from catch curve Model 3 comparing the growth curve parameters a) $l_\infty = 22.622, \kappa = 0.293, t_0 = -2.342, V = 3.429$ ***; b)*** $l_\infty = 20.579, \kappa = 0.321, t_0 = -2.668, V = 3.429$ ***; and c)*** $l_\infty = 20.587, \kappa = 0.323, t_0 = -2.662, V = 1.639$ ***. Growth curve parameters c) were estimated from catch curve Model 2. 95% confidence intervals are shown on all estimates.***

Quota

The calculations of the 2016 T_4 stout whiting TACC covered a range of settings outlined in Table 1. The different TACC options were produced to account for the variance in the data. The 2015 TACC of 1150 t quota was calculated based on the 1½ times the natural mortality (1.5M) reference point using Model 2 and the linear procedure for $TACC_{T4,k}$.

The procedure using $TACC_{T4,k}$ focused on adjusting quota from the previous TACC setting in year k = 2015. For this procedure, the recommended TACC for 2016 was between 1000 and 1100 t depending on the indicator, TACC multiplier and reference point used (Table 2, Table 3 and Table 4).

The procedure using $C_{T4,CUR}$ focused more directly on optimising average harvest to match the target reference points. For this procedure the recommended TACC for 2016 was about 750 to 850 t depending on the indicator, TACC multiplier and reference point used (Table 5, Table 6 and Table 7).

For comparison, the stock population modelling completed in 2014 estimated the T_4 long term maximum average harvest (maximum sustainable yield, MSY) at 1363 t (O'Neill and Leigh 2014). This value is treated as a maximum due to data uncertainty and literature recommending quotas be set below MSY (Garcia and Staples 2000). The stock population modelling also estimated an alternate TACC for obtaining more profitable yields by aiming to maintain higher exploitable biomass (B_t/B_0 = 0.6) and higher catch rates. This alternate TACC for higher profitable yield was 842 t (O'Neill and Leigh 2014).

Uncertainty in all these TACC estimates should be considered as they were sensitive to the data inputs and assumptions.

Table 1. Definition of the six TACC tables. The same reference points were applied in all tables. See quota methods and equations for detail.

Table No.	**Equation No.**	**Procedure**	**Multiplier $\boldsymbol{\theta}_{k+1}$**	**Reference points $\boldsymbol{I}_{target}$**
Table 2	1	$TACC_{T4,k}$	Cube-root	$\left\{ \begin{array}{l} \bar{S}_{Model2} = 0.4055 \\ \bar{S}_{Model3} = 0.3569 \\ S_{1.5M} = 0.4127 \\ CatchRate = 1 \end{array} \right.$
Table 3	1	$TACC_{T4,k}$	Square-root	
Table 4	1	$TACC_{T4,k}$	Linear	
Table 5	2	$C_{T4,CUR}$	Cube-root	
Table 6	2	$C_{T4,CUR}$	Square-root	
Table 7	2	$C_{T4,CUR}$	Linear	

Table 2. Equation 1 TACC$_{2016}$ using the cube-root transformation.

Year	Model 2	Model 2	Model 3c	Model 3c	Catch rate	Overall
I_{k-1}	0.3508	0.3508	0.3595	0.3595	0.8447	
I_k	0.3815	0.3815	0.3557	0.3557	0.8542	
$\bar{I}$	0.3662	0.3662	0.3576	0.3576	0.8494	
I_{target}	0.4055	0.4127	0.3569	0.4127	1.0000	
θ_{k+1}	0.9665	0.9609	1.0007	0.9534	0.9471	0.9657
$TACC_{T4,k+1}$ (t)	1112	1105	1151	1096	1089	1111

Table 3. Equation 1 TACC$_{2016}$ using the square-root transformation.

Year	Model 2	Model 2	Model 3c	Model 3c	Catch rate	Overall
I_{k-1}	0.3508	0.3508	0.3595	0.3595	0.8447	
I_k	0.3815	0.3815	0.3557	0.3557	0.8542	
$\bar{I}$	0.3662	0.3662	0.3576	0.3576	0.8494	
I_{target}	0.4055	0.4127	0.3569	0.4127	1.0000	
θ_{k+1}	0.9502	0.9419	1.0010	0.9309	0.9217	0.9491
$TACC_{T4,k+1}$ (t)	1093	1083	1151	1070	1060	1092

Table 4. Equation 1 TACC$_{2016}$ using no transformation (linear).

Year	Model 2	Model 2	Model 3c	Model 3c	Catch rate	Overall
I_{k-1}	0.3508	0.3508	0.3595	0.3595	0.8447	
I_k	0.3815	0.3815	0.3557	0.3557	0.8542	
$\bar{I}$	0.3662	0.3662	0.3576	0.3576	0.8494	
I_{target}	0.4055	0.4127	0.3569	0.4127	1.0000	
θ_{k+1}	0.9029	0.8872	1.0021	0.8665	0.8494	0.9016
$TACC_{T4,k+1}$ (t)	1038	1020	1152	996	977	1037

Table 5. Equation 2 TACC$_{2016}$ using the cube-root transformation.

Year	Model 2	Model 2	Model 3c	Model 3c	Catch rate	Overall
I_{k-1}	0.3508	0.3508	0.3595	0.3595	0.8447	
I_k	0.3815	0.3815	0.3557	0.3557	0.8542	
$\bar{I}$	0.3662	0.3662	0.3576	0.3576	0.8494	
I_{target}	0.4055	0.4127	0.3569	0.4127	1.0000	
θ_{k+1}	0.9665	0.9609	1.0007	0.9534	0.9471	0.9657
$TACC_{T4,k+1}$ (t)	822	817	851	810	805	821

Table 6. Equation 2 TACC$_{2016}$ using the square-root transformation.

Year	Model 2	Model 2	Model 3c	Model 3c	Catch rate	Overall
I_{k-1}	0.3508	0.3508	0.3595	0.3595	0.8447	
I_k	0.3815	0.3815	0.3557	0.3557	0.8542	
$\bar{I}$	0.3662	0.3662	0.3576	0.3576	0.8494	
I_{target}	0.4055	0.4127	0.3569	0.4127	1.0000	
θ_{k+1}	0.9502	0.9419	1.0010	0.9309	0.9217	0.9491
$TACC_{T4,k+1}$ (t)	808	801	851	791	783	807

Table 7. Equation 2 TACC$_{2016}$ using no transformation (linear).

Year	Model 2	Model 2	Model 3c	Model 3c	Catch rate	Overall
I_{k-1}	0.3508	0.3508	0.3595	0.3595	0.8447	
I_k	0.3815	0.3815	0.3557	0.3557	0.8542	
$\bar{I}$	0.3662	0.3662	0.3576	0.3576	0.8494	
I_{target}	0.4055	0.4127	0.3569	0.4127	1.0000	
θ_{k+1}	0.9029	0.8872	1.0021	0.8665	0.8494	0.9016
$TACC_{T4,k+1}$ (t)	767	754	852	737	722	766

Discussion

Stout whiting (*Sillago robusta*) are fished commercially in the waters of NSW and Queensland using Danish seine and otter-trawl methods. There are three fishing sectors (sources of fishing mortality) and each has different practises, fishing powers and data recording instructions. The Queensland stout whiting sector (T_4) is the primary target fishery with annual harvest monitored and limited under quota TACC. The Queensland eastern king prawn (*Melicertus plebejus*) shallow water sector (T_1) catches significant quantities of stout whiting as by-catch, discarded and not reported (O'Neill and Leigh 2014). The NSW fishing sector (T_{NSW}) catches both stout whiting and eastern king prawns, with stout whiting harvests only identified and reported suitably in recent years. Historical records of T_1 and T_{NSW} stout whiting harvest were not complete and fish age data had not been monitored. Consequently, the indices of stout whiting abundance and survival are reliant on the temporal and spatial data patterns sourced from the T_4 fishery. The amount of unreported T_1 stout whiting by-catch and T_{NSW} harvest has implications for setting T_4 harvest allocations and confounding signals in the fishery indicators.

In this assessment, catch curve analyses were developed to estimate an index of stout whiting survival. Herein fish survival refers to the ratio of abundance between older and younger age groups. The methods were applied with application to T_4 fish age-length data where the variability in sampling was dependent on fish retained by a small fleet of vessels (2–5 per year) and their individual spatial-temporal patterns of fishing. Over recent years inconsistent changes in the time series 1993–2013 between sampled fish length frequencies and age-length data had been identified. The patterns of age structure shifted to older fish from the year 2005, which was not evident in the length of fish harvested. The lengths of fish harvested were generally similar between years. The narrow range of fish lengths sampled each year suggested high sample correlation and small effective sample sizes that may mask signals of changing fish survival. The new method of catch curve analysis was modified to overcome issues associated with the sample collection of fishery dependent age-abundance data. However, model outputs are still reliant on consistency of fish aging.

A number of inferences were of note from the catch curve Model 3 analysis of stout whiting. First were the low estimates of fish survival 1993–2003. It appeared the 1993–2003 survival rates were down as a result of the high levels of each sectors' catch taken in the years 1994–1999. The estimates for the years 2003–2006 indicated stronger survival of fish as they recruited and aged. This timing correlated from the reduced T_4 harvests and the adoption of by-catch reduction devices by T_1 prawn trawl sector. The estimated survival fractions for the years 2007–2012 had stabilised above those from early years. The analysis identified significant changes in fish age-abundance, but was also sensitive to highlight inconsistencies in data. Therefore, representative and consistent fishery dependent sampling of age data is important for the methodology.

The annual variability of results between years (k) had implications for setting TACC for the T_4 sector. Direct use of annual estimates of survival may cause the TACC to vary notably from year to year; an undesired behaviour for industry and export markets. Therefore, it is suggested that a mean survival rate be calculated over the two most recent years to reduce variance. The use of a cube-root or square-root transformation can also be used to limit the variance of quota change. The use of transformations should be viewed in line with using procedure equation 2. This view is aimed on targeting more profitable levels of catch rates by setting TACC based on average levels of harvest and consideration of data/analysis uncertainty; and is aligned to the approach used for Australian Government managed fisheries (Australian Government 2009 (AMENDED FEBRUARY 2014)).

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Appendix I: Standardised catch rates of stout whiting from Queensland waters

This report section outlines the Queensland data and methodology used to standardise catch rates of stout whiting. The need to standardise catch rates is to reduce bias or variation in the data by accounting for factors affecting fish abundance and fishing efficiency. The aim is to result in a time series of catch rates that is more representative of trends in the exploited population.

Methods

For the Queensland T_4 sector 1991–2015, catches from each vessel were analysed on a daily basis including the number of hours fished and number of catches (number of deployments of fishing gear) in the day. Target fishing effort where no stout whiting were caught (zero catches) was included. The T_4 catch data were stratified by the five Queensland fishing zones w33…w38 (Figure 1). Data for vessel and skipper identification, fishing depth and date and associated fishing gears were considered in the statistical modelling. The catch and effort data for analysis were supplied by Fisheries Queensland on 19 June 2015 (data retrieval number = DR2377). New columns for coding calendar year, calendar month, fiscal year and fiscal month were created. Fiscal year, labelled as 'fishing year', included the months from July to June. For example, the months starting from July 2014 through to June 2015 were labelled as the 2015 fishing year, with July = 1st fishing month and June = 12th fishing month. Missing data on the number of hours fished (n=235 out of N=11128; 2%) were imputed using an over-dispersed Poisson GLM with model terms for the number of deployments of fishing gear, the vessel, the fishing year and size of the catch (log scale).

The analyses were completed using the statistical software GenStat (VSN International 2013) and standard errors were calculated for all estimates. Analysis of residuals supported their structures and transformation of catch response. The importance of individual model terms was assessed formally using Wald (Chi-squared χ^2) statistics by dropping individual terms from the full model.

The T_4 data were spatially unbalanced and incomplete, with only 2–5 vessels fishing per year in various months and zones between 1991 and 2015. As the T_4 fleet is small, the data potentially contained sources of error variation that may influence standardisation of catch rates. To allow for unequal variances (dispersion) between vessels and the random occurrence of zero catch, a Hierarchical Generalized Linear Model (HGLM) was used assuming normally distributed errors (Lee and Nelder 2001; Lee, Nelder *et al.* 2006; VSN International 2013). The model response data consisted of the cube root transformation of the daily catch (kg$^{1/3}$ boat-day^{-1}) and the expected bias corrected mean followed the Normal distribution third moment $\mu^3 + 3\mu\sigma^2$, with variance $\sigma^2 = \phi V(\mu)$. The HGLM included fixed ($\mu = \mathbf{X_1\beta_1}$) and dispersion ($\phi = \exp(\mathbf{X_2\beta_2})$) model terms, where $\mathbf{X_1}$ and $\mathbf{X}_2$ were the relevant data. The fixed explanatory model terms ($\boldsymbol{\beta_1}$) included the model intercept, interactions between fishing year × zone , vessel × effort (hours$^{1/3}$), zone × water-depth (fathoms$^{1/3}$) and the main effects of seasonality, presence/absence of sonar and computer mapping and vessel experience. Seasonality (*s*) was modelled by four trigonometric covariates, which together modelled an average monthly pattern of catch (Marriott, O'Neill *et al.* 2013): $s_1 = \cos\left(2\pi d_y / T_y\right)$, $s_2 = \sin\left(2\pi d_y / T_y\right)$, $s_3 = \cos\left(4\pi d_y / T_y\right)$, $s_4 = \sin\left(4\pi d_y / T_y\right)$, where d_y was the cumulative day of the year and T_y was the total number of days in the year (365 or 366). As some vessel ownerships had changed over time, a covariate for fishing experience was calculated to follow an exponential learning curve. This covariate was linear on the natural logarithm scale: $\log\left(v_y/1+v_y\right)$, where v_y was the cumulative number of at-sea fishing days divided by 365.25. The increase in experience was assumed sharpest in the initial fishing years, then levelling out to a limit. The dispersion model terms ($\boldsymbol{\beta}_2$) included the main effects for vessels and the incidence of zero catch. Summary of the analysis and model terms are in Table 8.

The prediction of annual standardised catch rates across the fishery involved three steps: 1) predict mean catch rates from the models year × zone terms; 2) impute missing year × zone predictions (

Table 9); 3) spatially average predictions across zones in each year using calculated area weights. These steps were applied for both Queensland and NSW and followed the spatial standardisation methods of Campbell (2004), Carruthers, Ahrens *et al.* (2011) and Walters (2003).

Mean year × zone standardised catch rates were calculated using GenStat 'HGPREDICT' procedures (VSN International 2013) for the T_4 model and using the 'effects' package in R (R Development Core Team 2012) for T_{NSW}. The procedures formed standardised predictions by fixing model terms such as the season, effort, depth, experience and sonar model terms to their average values.

Mean catch rates were imputed for year × zone strata with less than 20 boat-days of fishing (Figure 10); this was not required for the NSW 'fishonline' data. The final predictions were averaged across zones in each year using the area weights (0.151565316, 0.212920015, 0.201076614, 0.095237781, 0.142030746, 0.197169528) for each zone w33…w38 and NSW combined. Standard errors for the year × zone predictions were propagated to produce 95% confidence intervals on the standardised whole-of-fishery annual catch rates. This included calculating standard errors for missing year × zone means (VSN International 2013).

Table 8. Summary of the statistical analysis of Queensland T_4 stout whiting catches.

Analysis and components	**Statistics**
HGLM Queensland waters	
Number of data	11 128
Response variable	$kg^{1/3}$ boat-day^{-1}
Residual variance	4.115
Fixed model terms	(χ^2 statistics, d.f., *p*-value)
Fishing year × Zone	465.4, 84, <0.001
$f_1(day)$	128.3, 1, <0.001
$f_2(day)$	21.5, 1, <0.001
$f_3(day)$	60.0, 1, <0.001
$f_4(day)$	20.6, 1, <0.001
Vessel × $Hours^{1/3}$	6 462.3, 17, <0.001
Luminance	2.1, 1, 0.15
Luminance advance7 days	12.0, 1, <0.001
Zone × $Depth^{1/3}$	55.4, 5, <0.001
$f(\text{experience})$	20.7, 1, <0.001
Sonar	8.3, 1, 0.004
Dispersion model	1226.0, 17, <0.001
Vessel term	425.0, 16, <0.001
Zero catch term	791.1, 1, <0.001

Table 9. List of imputed T_4 catch rates. The following fishing year × zone means were imputed similar to the methods of Walters (2003) and Carruthers, Ahrens et al. (2011)

w33.1991&1992 = mean(w33.1993 to w33.1995)
w33.2004 = mean(w33.2003 and w33.2005),
w33.2011 = mean(w33.2010 and w33.2012),
w33.2014&2015 = mean(w33.2011 to w33.2013),
w34.1992 = mean(w33.1991 and w33.1993),
w35.2003 to w35.2008 = mean(w35.2002 and w35.2009),
w35.2012&2013 = mean(w35.2011 and w35.2014),
w36.1992 = mean(w36.1991 and w36.1993),
w36.2004 to w36.2006 = mean(w36.2003 and w36.2007),
w36.2012&2013 = mean(w36.2011 and w35.2014),
w38.1991&1992 = mean(w38.1993 to w38.1995), and
w38.2001 to w38.2009 = mean(w38.2000 to w38.2010)

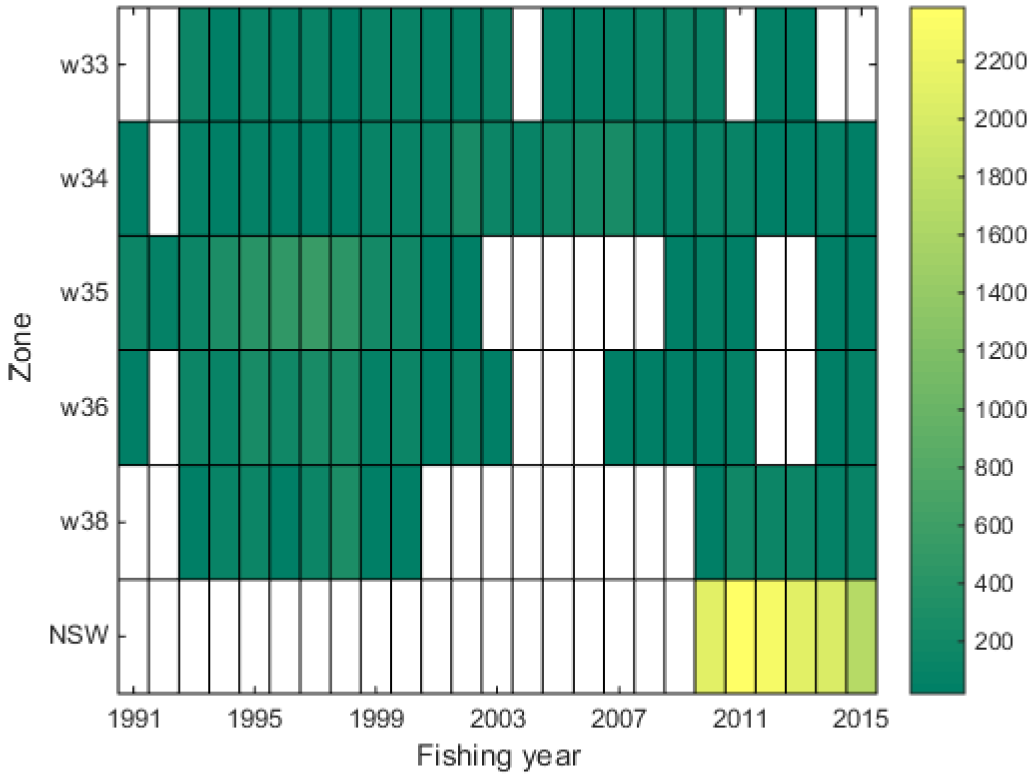


Figure 10. Colour plot showing the number of boat-days statistically analysed by fishing year and zone. For Queensland waters (zones w33…w38), the white grids identified strata with less than 20 boat-days of fishing. The white grids for NSW indicate that no data were analysed in the fishing years 1991–2009.

Results

For the T_4 sector HGLM analysis of stout whiting harvests, significant fishing power terms were detected for each vessel operation, at-sea fishing experience, sonar use and hours fishing (Table 8). Fishing using sonar technology increased average catch rates by 8.4% (s.e. = 2.2%) and it's use was fully adopted by the T_4 fleet in the 1998 fishing year. Fishing experience increased average catch rates by about 10–15% after one cumulative at-sea year (≈ 3 fishing years in time; parameter estimate = 0.37, s.e. = 0.085). Figure 11 a) highlighted the change in the T_4 fleet structure 1991–2015, with only vessels 16 and 17 licensed to fish in 2014 and 2015. Translation of the annual change in T_4 fleet structure to represent fishing power [Figure 11 b)], including the model terms for different vessels, hours fished, fishing experience and sonar use, illustrated a 275% increase from 1991–2015. The later 2012–2015 strong increase in fishing power was driven by higher use of Danish seine fishing gear.

In regard to fleet change, another important aspect was the annual shifts in the spatial patterns of fishing (Figure 12). Over the historical time series, there was a:

- shift away from fishing zone w35 from 2001
- increase in fishing the northern zones w33 and w34 from 2001–2010 and declined thereafter
- increase in fishing the southern zones w36 and w38 from 2011–2015.

Adjustment of the time series of stout whiting catch rates for the HGLM model terms (Table 8) highlighted some recent declines. The 2015 T_4 catch rate index was significantly below the long term mean, with recent declines estimated in the northern fishing zones of w33 and w34 and a strong decline in the 2012 fishing year (Figure 13). Fishing zones w35, w36 and w38 exhibit increasing catch rates from 2012–2015. Residual plots from the HGLM analysis, used to standardise catch rates, concur reasonably with the assumption for normality (Figure 14 and Figure 15).

The overall nominal catch rates of stout whiting uncorrected for fishing power and spatial bias showed no time-series decline compared to the HGLM predictions (Figure 16). However, comparison to a simpler Poisson GLM, using only the main additive terms from Table 8 assuming over-dispersion, indicated similar declines as to the HGLM (Figure 16). Statistically the comparison of nominal catch rates between fishing years was not valid.

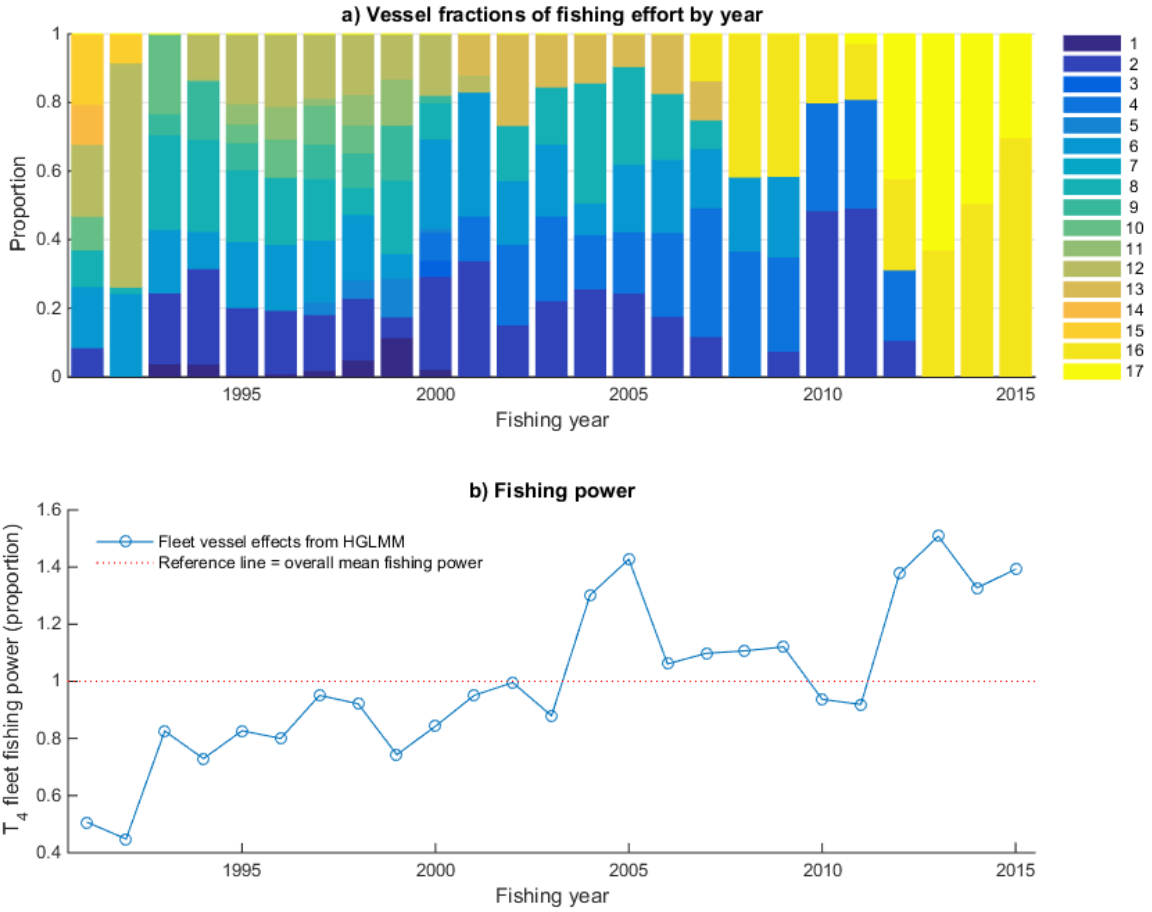


Figure 11. Summary of changes in the composition of the T_4 fleet by fishing year for a) the observed proportion of total annual fishing effort (boat days) by each historical vessel; and b) estimated annual increases in fishing power scaled against the overall fleet average. In figure

subplot a), vessel 16 used Danish-seine fishing gear whereas all other vessels used otter-trawl gear.

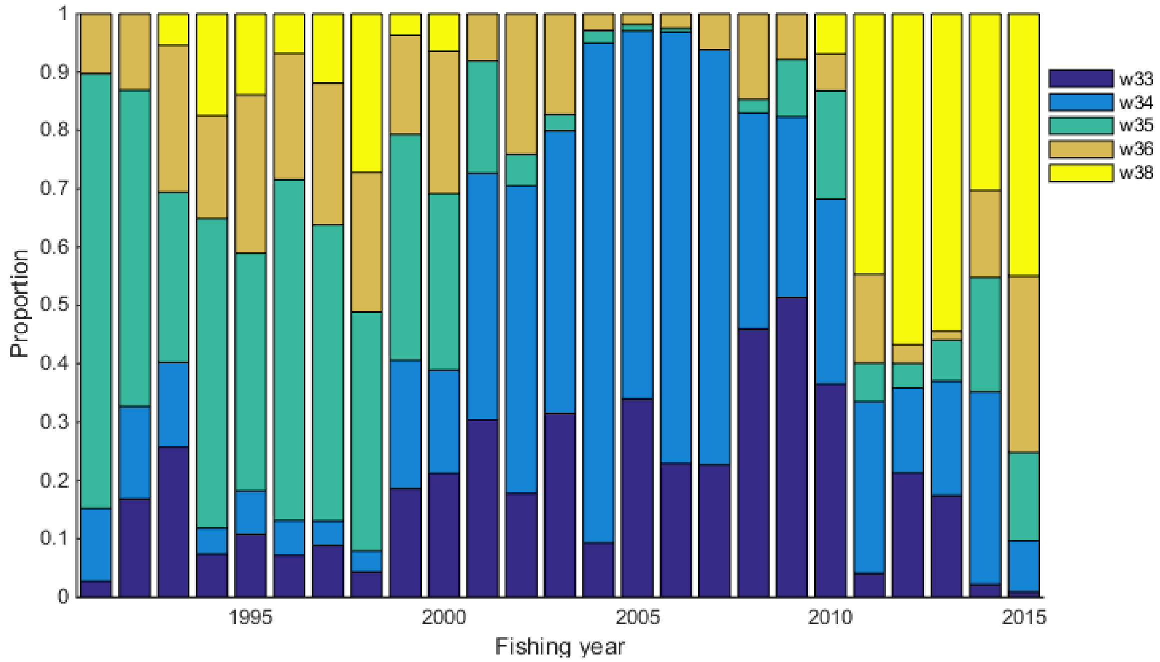


Figure 12. The proportion of total annual fishing effort (boat days) by spatial zone categories in each fishing year.

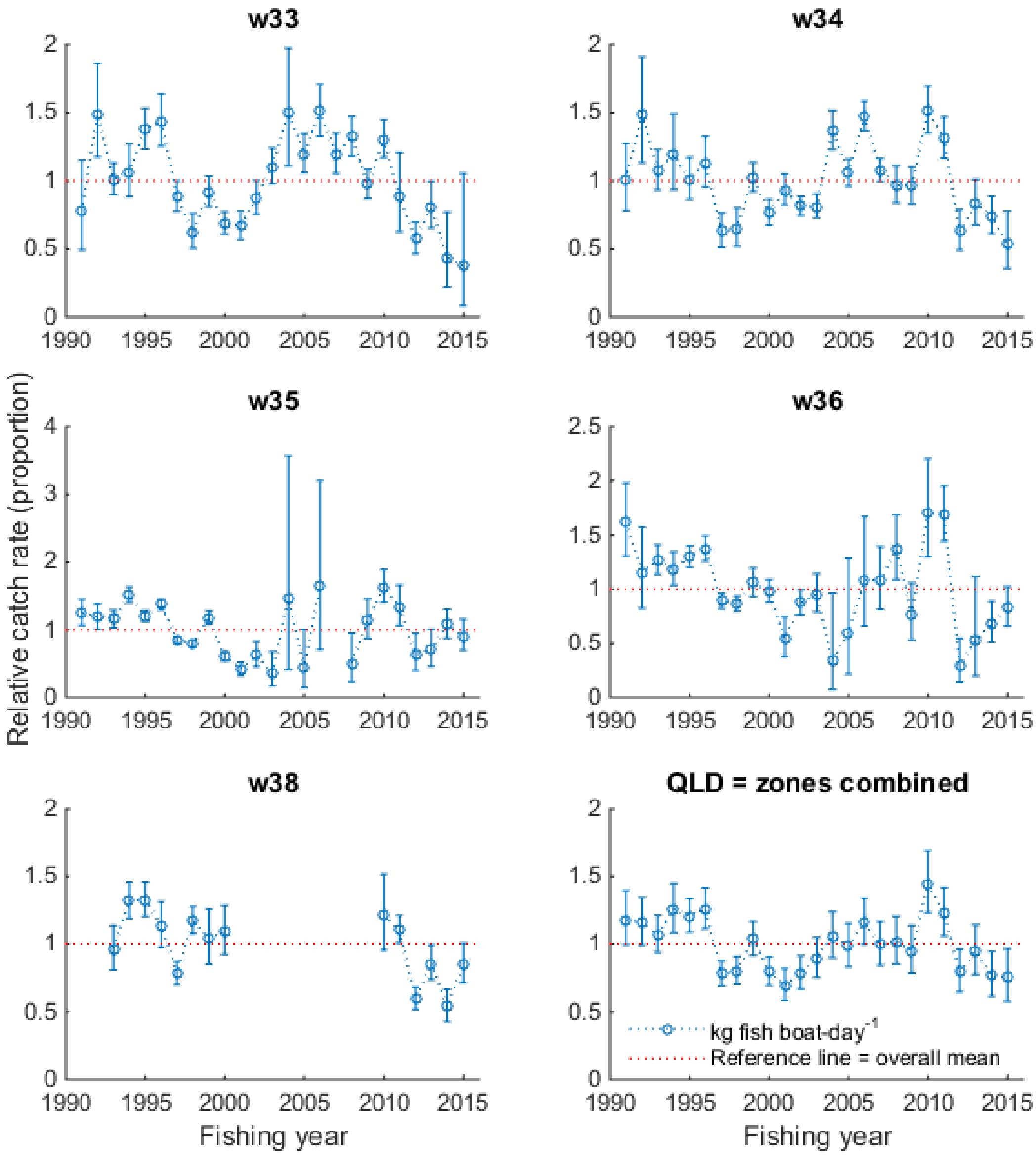


Figure 13. Model (HGLM) standardised average harvests taken per boat day from fishing zones w33 to w38 and for Queensland overall (zones combined). Error bars indicate 95% confidence intervals on predictions. Each annual time series was scaled relative to its mean catch rate (1 = mean catch rate).

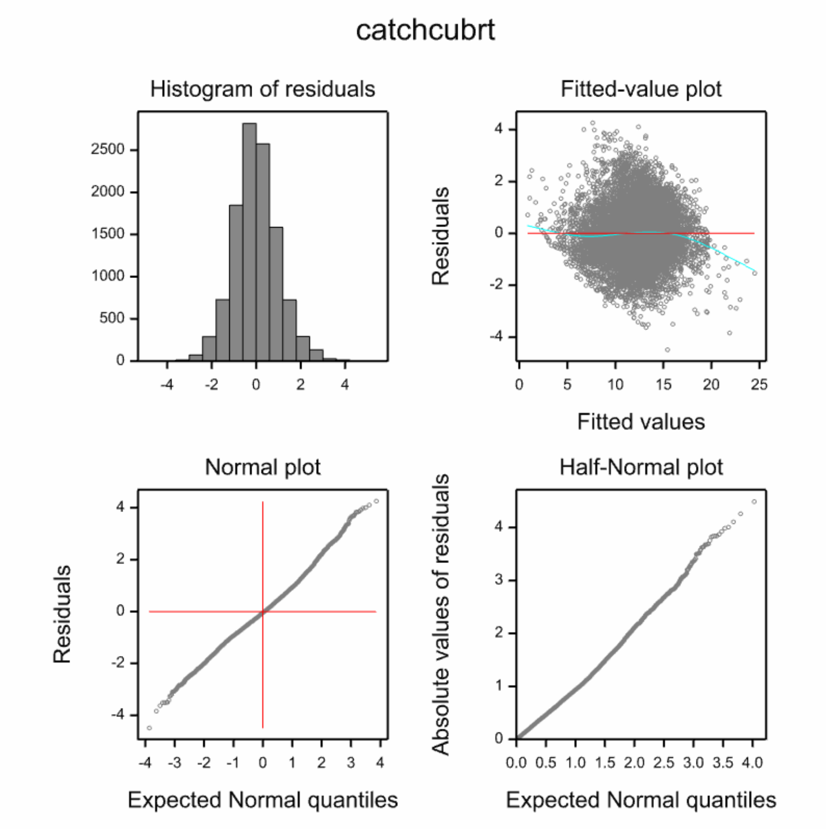


Figure 14. Residual checking plots for the hierarchical generalized linear model (HGLM) analysis.

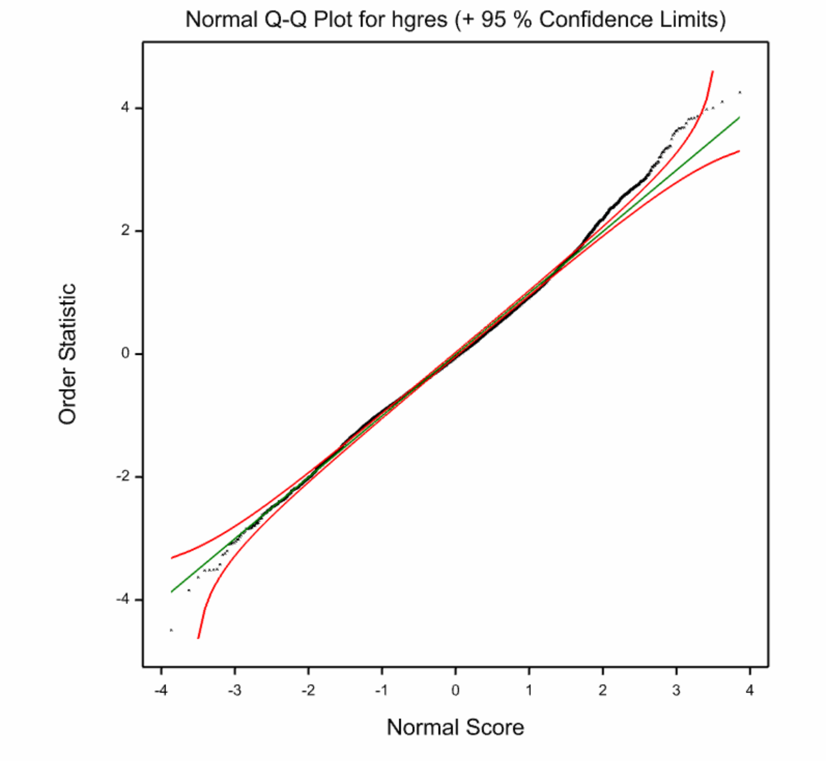


Figure 15. Q-Q plot comparing residuals against the theoretical envelope for normality.

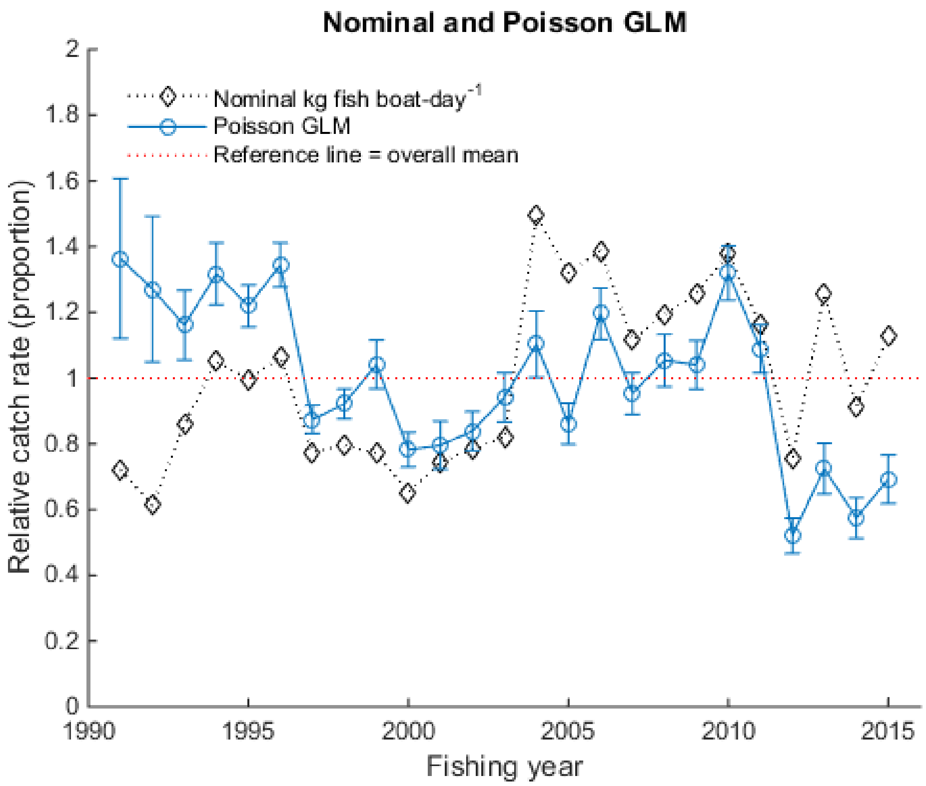


Figure 16. Comparison of the observed (nominal – unstandardised) average harvests taken per boat day and alternate Poisson GLM standardised predictions for Queensland overall. The annual time series was scaled relative to the overall nominal mean (1 = mean catch rate).

Appendix II: Standardised catch rates of stout whiting from New South Wales waters

This report section outlines the New South Wales data and methodology used to standardise catch rates of stout whiting. The need to standardise catch rates is to reduce bias or variation in the data by accounting for factors affecting fish abundance and fishing efficiency. The aim is to result in a time series of catch rates that is more representative of trends in the exploited population.

Data

The trawl whiting data were supplied by the New South Wales Department of Primary Industries on 11 June 2015. The data were formatted in the Excel file 'Stout whiting2.xlsx'. The Excel file contained four data sheets (Table 10). 'NULL' text characters were removed from all numerical fields and replace as blanks. 'NULL' boat codes (LFBNoEncr) were replaced with zeros to represent an unknown vessel.

The Excel data sheets were imported into the MS Access database 'nsw_trawl_whiting_june_2015'. New data tables were appended for lunar phase and seasonal cycles (described in Appendix I). Description of all data tables are contained in their table properties. The New South Wales (NSW) fishery zone labels 1001, 1002 and 1003 correspond to the map areas NSW1, NSW2 and NSW3 respectively (Figure 1).

Statistical analysis to standardise stout whiting catch rates was conducted on the 'StoutWhitingFishOnline' data (Table 10). Major improvements in NSW logbook reporting occurred in 2009, with the 'StoutWhitingFishOnline' data now representing the most reliable daily records of trawl whiting harvests (kg) and fishing effort (hours) by boat. The analysis data merged the 'StoutWhitingFishOnline' data with the lunar phase and seasonal cycle data through MS Access queries 'glm1' and 'glm2', with the following adjustments applied:

- Daily species harvests as reported per boat were tallied into categories for bugs, squid and cuttlefish, crabs, flatheads and flounders, goat fish, prawns, sharks and rays, shell fish, trawl whiting – eastern school, trawl whiting – stout, trawl whiting – combined (eastern + stout) and other minor species combined. Effort data where the 'trawl whiting – combined' harvest was zero were removed from the analysis as these records may not be consistent due to unknown discarding practices.
- Stout whiting harvests were allocated based on the 'trawl whiting – combined' harvest multiplied by the stout species ratios of 0.68, 0.59 and 0.2 for the fishing zones 1001, 1002 and 1003. The stout whiting ratios were calculated from the observer-program estimated total catches for both retained and discarded trawl whiting (Table 3, Kennelly, Liggins *et al.* 1998). The stout whiting ratio was assumed zero for fishing zone 1004 and further south based on Kennelly, Liggins *et al.* (1998). The original Stout Whiting species ComCatch business rules of 1, 0.5, 0 and 0 for the fishing zones 1001, 1002, 1003 and 1004 was not used; the origin of these values was unclear and not comparable to Kennelly, Liggins *et al.* (1998).
- For daily fishing effort quantities hours ≥ 180, values were divided by 60 (raw data n=101). Quantities > 23 and < 180 or 'NULL' or zero were imputed assuming a normal distribution with $\mu = 10.46$ and error $\sigma = 1.33$ (raw data n = 4927). The distribution was quantified using a finite mixture model on the data. For analysis, 4% of the final hours data were corrected.

- Only known boat codes (LFBNoEncr <> 0) were analysed; the number of raw data for unknown boats = 39697 (17% raw data).
- New columns for coding calendar year, calendar month, fiscal year and fiscal month were created. Fiscal year, labelled as 'fishing year', included the months from July to June. For example, the months starting from July 2014 through to June 2015 were labelled as the 2015 fishing year, with July = 1st fishing month and June = 12th fishing month.
- From FRDC 2008/019 page 121 in Courtney, O'Neill *et al.* (2014), target whiting fishing was defined where prawn harvests were < 60th percentile of the prawn harvest distribution. Exploratory analyses of the multispecies harvests recorded in the 'StoutWhitingFishOnline' data showed no clear discrimination to identify target fishing species (like in Courtney, O'Neill *et al.* 2014). Different percentile rules were examined using finite mixture modelling with little result.

The final daily data per boat for statistical analysis was stored in the Excel file 'glm_fishonline_tw.xlsx' (n = 12621).

Table 10. Description of the New South Wales fishing data supplied in Excel file "Stout whiting2.xlsx'. N indicates the number of raw data provided 11 June 2015.

Data sheet name	Description
1. 'StoutWComCatch' **N = 377422**	All species catch and effort derived from daily logbook returns. Represents monthly harvest returns July 1997 to June 2009. Eastern School Whiting and Stout Whiting species allocated based on original ComCatch business rules. Data from "Fisheries" Ocean Fish Trawl and Ocean Prawn Trawl
2. 'StoutWComCatch84_97' **N = 528494**	All species catch only from ComCatch database. Monthly harvest returns July 1984 to June 1997. Eastern School Whiting and Stout Whiting species allocated based on original ComCatch business rules. All fishing methods. Note "Fisheries" were not defined on harvest logbook returns prior to July 1997. Also, harvests could only be associated with method if fishers only used a single effort type in the fishing month.
3. 'StoutWFishOnlineComCatchSpecies' **N = 256411**	All species catch and effort from Fish Online database. Daily returns from July 2009 to May 2015 Eastern School Whiting and Stout Whiting species reallocated to original ComCatch business rules. Data from "Fisheries" Ocean Fish Trawl and Ocean Prawn Trawl.
4. 'StoutWhitingFishOnline' **N = 235497**	All species catch and effort from Fish Online database. Daily returns from July 2009 to May 2015. Eastern School Whiting and Stout Whiting species as reported by fishers. Data from "Fisheries" Ocean Fish Trawl and Ocean Prawn Trawl

Results and Discussion

The New South Wales (NSW) allocated stout whiting catch rates were highly skewed (Figure 17). Preliminary analysis of the data suggested a natural logarithm of the data was required to normalise error structures (box-cox λ was low = 0.12). Three different generalised linear models (GLM) were then compared to explore this result further. Application of glm1 (Table 11) assumed a normal distribution for log transformed data, but did not conform to model assumptions (Figure 18). The over-dispersed Poisson glm2 model resulted in marginally better residuals (Figure 19) and higher adjusted R^2 (Table 11). The gamma glm3 model further improved the shape of residuals, but exhibited some unwanted bias (Figure 20) and had lower adjusted R^2 (Table 11). No one model's pattern of residuals was flawless.

Based on the different GLM results, the over-dispersed Poisson glm2 model was selected to standardise catch rates. Leigh and Baxter (In press) highlight a number of advantages of using an over-dispersed Poission GLM in that:

- The model will allow for "over-dispersion", in which the harvest events are no longer independent but occur in clumps (e.g. schools of fish). The dispersion parameter takes a value roughly equal to the average size of a clump (i.e. average weight of fish in a school).
- The major advantage of the over-dispersed Poisson model for catch rates is that it automatically weights the data correctly.

Table 12 lists the glm2 model terms used to standardise catch rates; variables for lunar cycle were non-significant and excluded ($p > 0.05$). Significant differences in mean catches were identified between fishing years, areas and seasons (c12 and cs12). Significant fishing power differences were detected between boat licenses (lic), and hours of fishing between target (slope = 0.0617; s.e. = 0.0061; Figure 21) and non-target harvests (slope = 0.0246; s.e. = 0.0063; Figure 21). The pattern of standardised catch rates from fishing zone 1002 was different to zones 1001 and 1003 (Figure 22). Overall the NSW combined standardised catch rate index was above the mean and 75th percentile for the 2010–2015 estimates (Figure 22).

Future considerations for the monitoring and analysis of stout whiting data in NSW include:

1. Improve the temporal and spatial species identification of eastern school and stout whiting using at-sea sampling methodology. For example, observers or fishers to sample boxes of fish according to a random-stratified design.
2. Improve the identification of target fishing for stout whiting, eastern school whiting and eastern king prawns.
3. Establish fish length or age based sampling to complement Queensland monitoring to establish 'whole-of-stock' management processes.
4. For both the NSW and Queensland prawn sectors, clarify the level of eastern school and stout whiting take (harvest + discards). Discarding practices by boat need to be recorded annually.
5. Establish target and limit catch rate reference points. 'StoutWhitingFishOnline' data now representing the most reliable records of trawl whiting harvests. Even so, the time series of data are short from 2010–2015. Analysis of early data sets are required to establish appropriate reference points in line with economic considerations and avoid any possible issue associated

with a long-term time-based shift in levels of catch rates. Concepts for defining catch rate reference points have been published by Little, Wayte *et al.* (2011), Little, Wayte *et al.* (2008), O'Neill, Campbell *et al.* (2010) and O'Neill, Leigh *et al.* (2014).

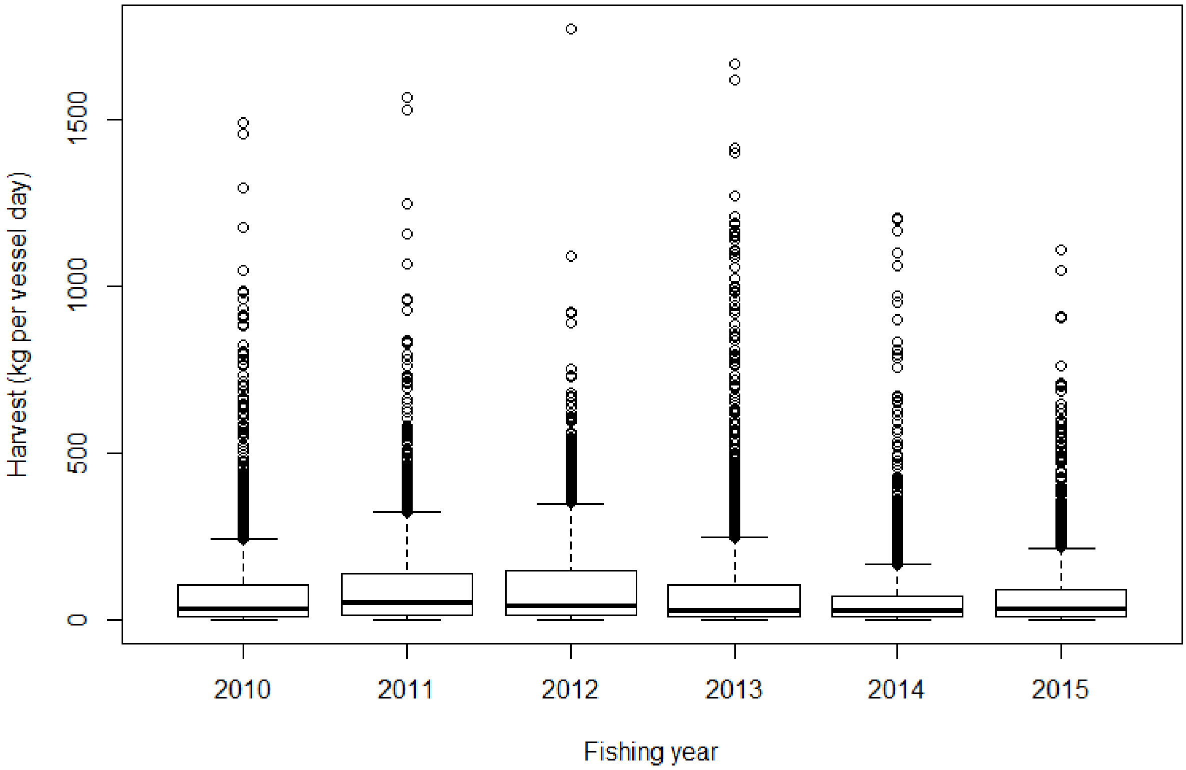


Figure 17. Boxplot of stout whiting harvests per boat day.

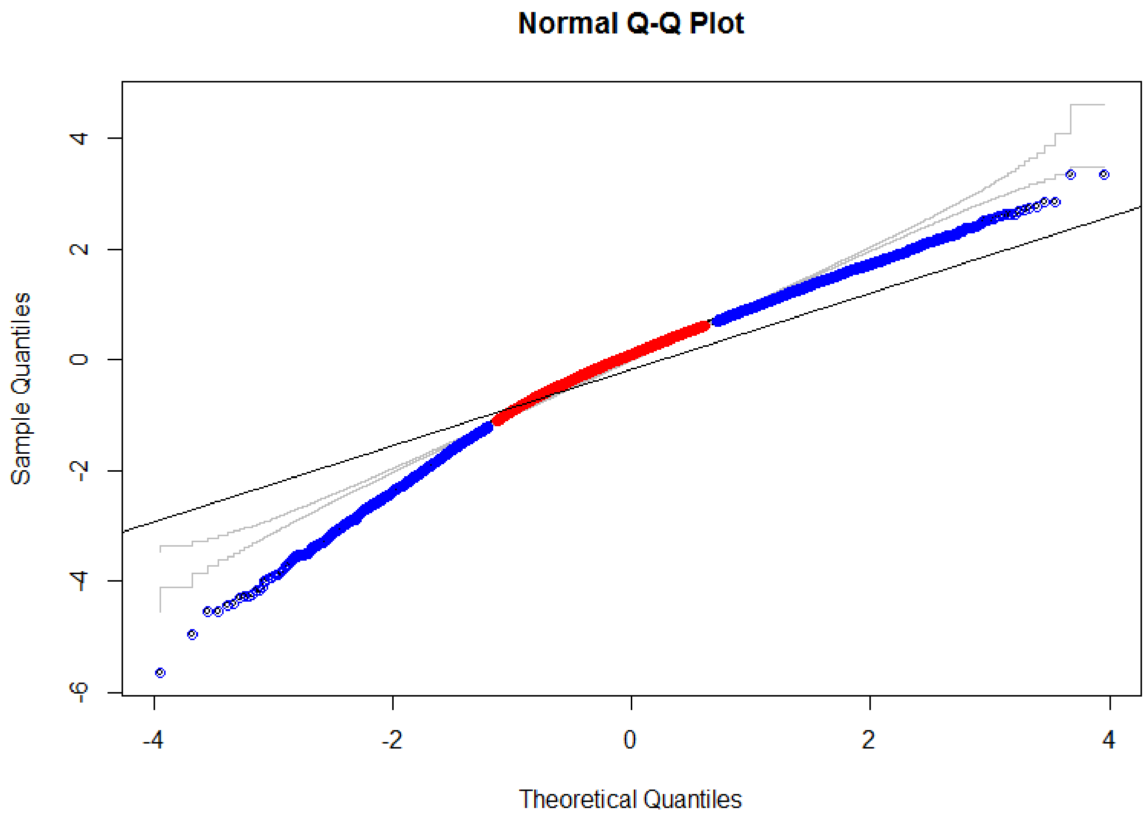


Figure 18. Q-Q plot of glm1 model residuals (circles) compared against the predicted envelope for Normality. Many of the larger standardised residuals (blue circles) were not normally distributed.

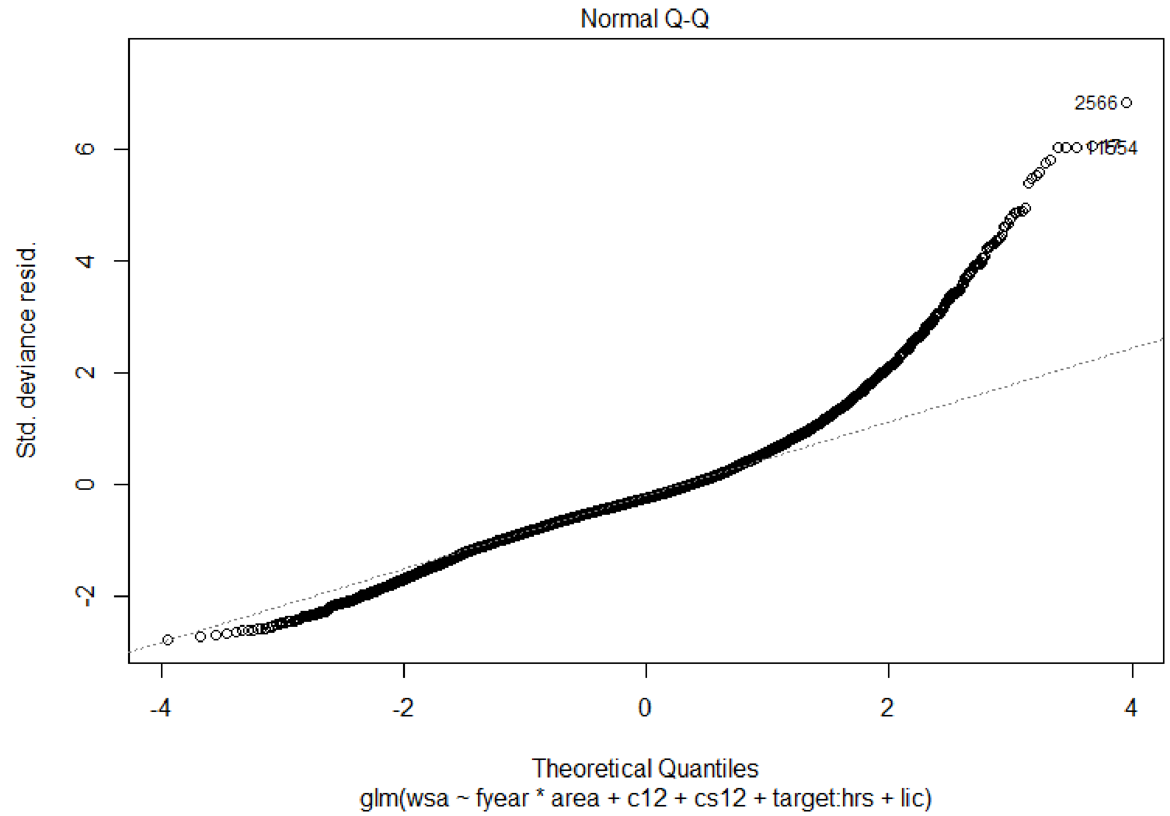


Figure 19. Q-Q plot of the over-dispersed Poisson glm2 model residuals.

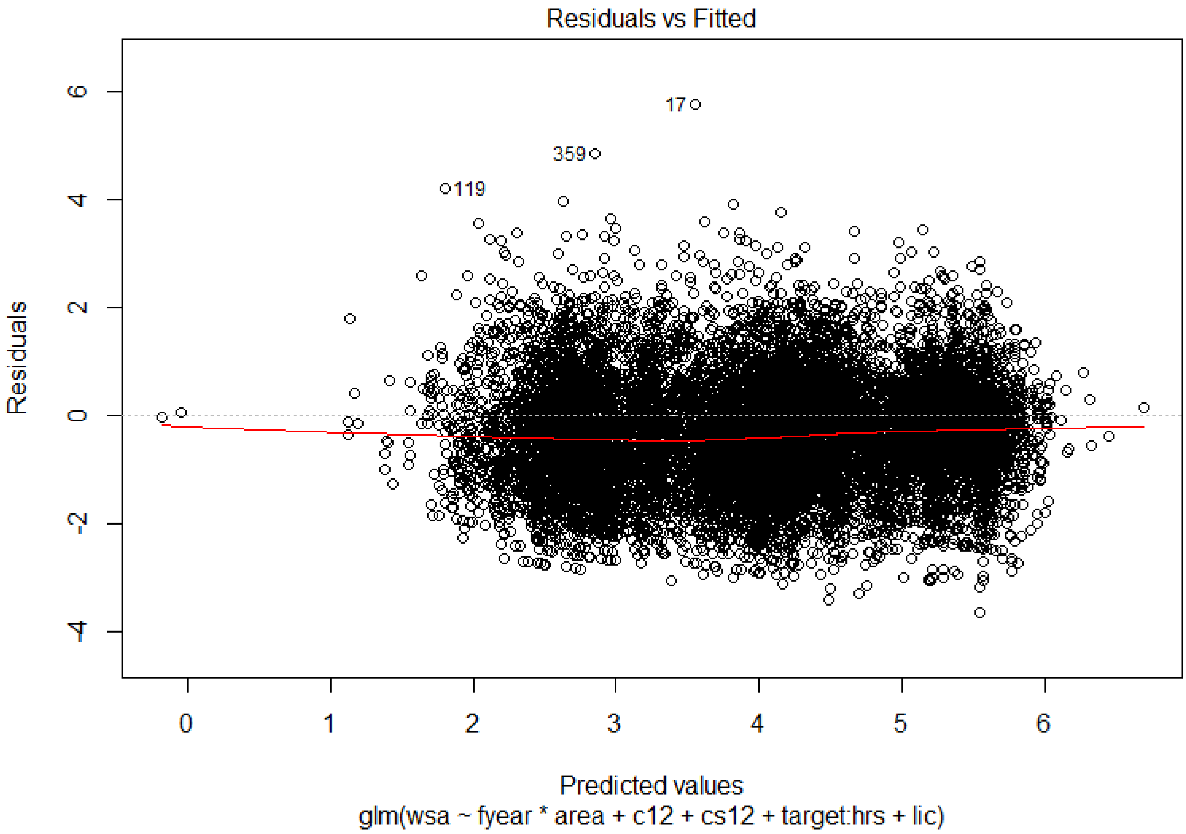


Figure 20. Scatter plot of the fitted values against residuals from the Gamma glm3 model. The red line indicates some bias (mean < 0).

Table 11. Three generalized linear models (GLM) were compared. glm2 was used to predict standardised catch rates. Adjusted R^2 are shown.

glm1 <- glm(wsalog ~ fyear * area * target + c12 + cs12 + target:hrs + lic, data=d, family=gaussian(link="identity")); adj R^2 = 0.461
glm2 <- glm(wsa ~ fyear * area + c12 + cs12 + target+target:hrs + lic, data=d, family=quasipoisson(link="log"))")); adj R^2 = 0.513
glm3 <- glm(wsa ~ fyear * area + c12 + cs12 + target+ target:hrs + lic, data=d, family=quasi(link="log",variance="mu^2")); ")); adj R^2 = 0.454

Table 12. Analysis of variance table for glm2.

```
Analysis of Deviance Table (Type II tests) Quasi Poisson

Response: wsa
           LR Chisq Df  Pr(>Chisq)
fyear          72.8  5  2.713e-14 ***
area          492.5  2  < 2.2e-16 ***
c12            93.6  1  < 2.2e-16 ***
cs12          422.0  1  < 2.2e-16 ***
target         87.2  1  < 2.2e-16 ***
lic          5231.1 91  < 2.2e-16 ***
fyear:area    190.4 10  < 2.2e-16 ***
target:hrs    103.6  2  < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

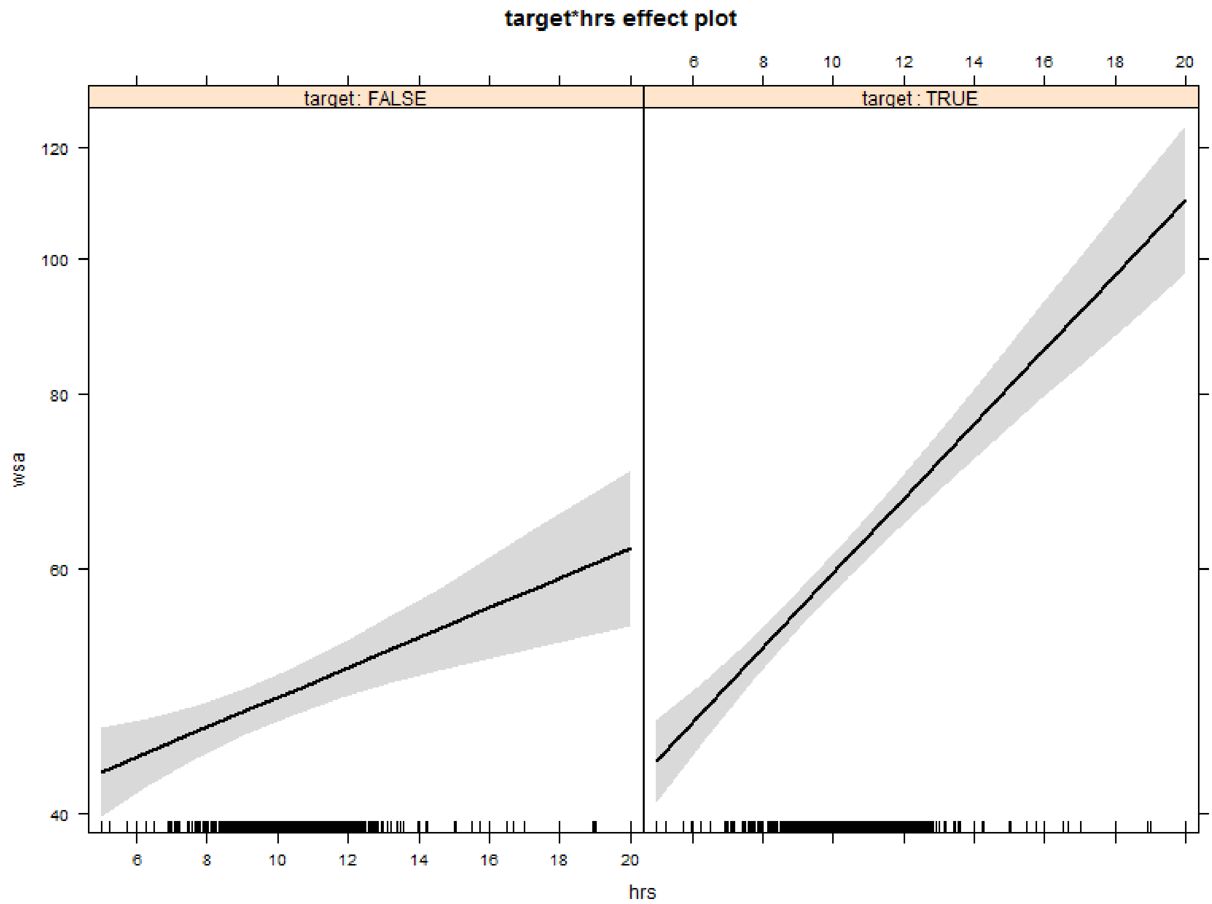


Figure 21. Predicted mean relationship for hours fished per boat day between target and non-target fishing; wsa = kgs stout whiting.

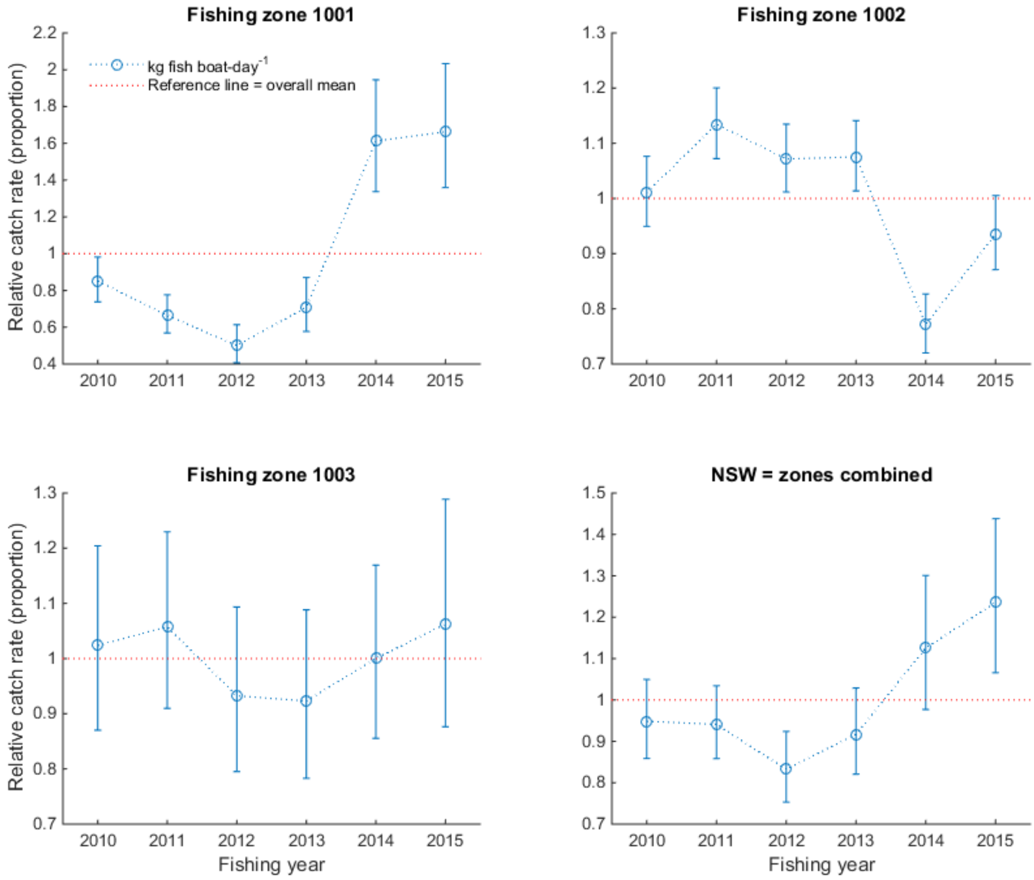


Figure 22. Model (glm2) standardised average harvests taken per boat day from fishing zones 1001, 1002, 1003 and for NSW overall (zones combined). Error bars indicate 95% confidence intervals on predictions. Each annual time series was scaled relative to its mean catch rate (1 = mean catch rate).

Appendix III: Spatial patterns of the Queensland T_4 fishing sector

Spatial latitude and longitude data as recorded by the Fisheries Queensland Vessel Monitoring System (VMS) were analysed. The data were provided on 16 June 2015 and represented hourly position data (latitude and longitude measured in decimal degrees) and speed data (knots) for each T_4 fishing operation (~ vessel). The data were analysed to verify fishing locations in order to complete and understand the spatial variances in the fish length-age data as collected by the long term monitoring program (Appendix IV).

To separate the possible mix of VMS stout whiting and prawn fishing, the VMS data were appended to the T_4 logbook harvest data by linking fishing dates and vessel codes. This linking step identified the VMS stout whiting records. The trawl speed data were then analysed in a finite mixture model using the 'gmdistribution.fit' function in Matlab (MathWorks 2015).

The results are displayed in Figure 23 and Figure 24. Fishing was identified by assessing the dominant mixture components (distributions) for vessel speed. From averaging the results for each fishing operation (Table 13), stout whiting fishing was identified using a simple speed rule of between one and two knots for otter trawling and less than one knot for Danish seining. It was unclear if faster speeds were associated with fishing events. Further authentication is required.

This simple speed rule was sufficient in order to verify fishing locations recorded between VMS and logbooks. Direct comparison of position data showed a strong correlation between VMS and logbooks (ρ = 0.96 for latitude and ρ = 0.83 for longitude, $p < 0.001$), with dispersion typically within one 30 x 30 minute logbook grid (Figure 25). Figure 26 further illustrates the comparison of the position data, showing similar pictures of the fishing grounds.

From the results, the spatial zones (analysis regions) used in the T_4 logbook data were concluded to be adequate to regionally assess the spatial variances in the LTMP fish length-age data. For finer spatial scales, use of the VMS data is recommended after further verification of the vessel speeds used to identify fishing.

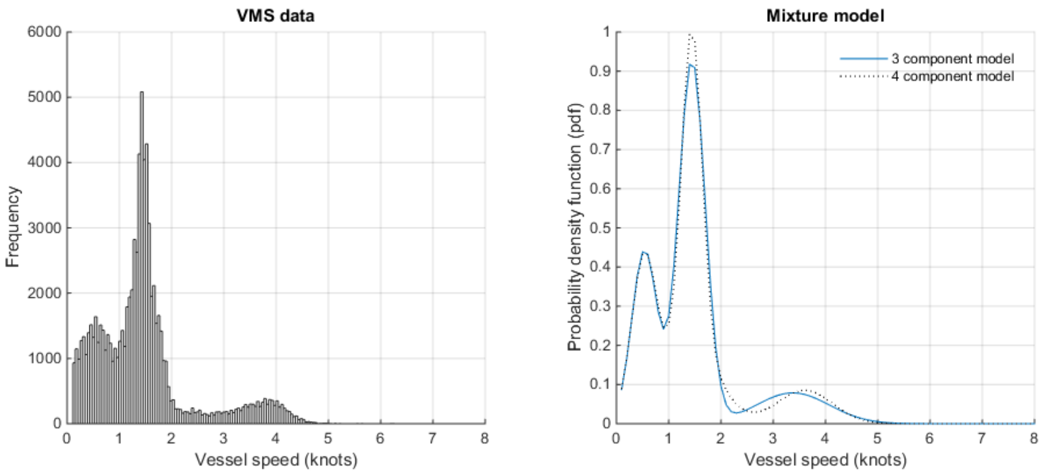


Figure 23. Histogram of VMS calculated vessel speeds and Gaussian mixtures used to identify trawling locations.

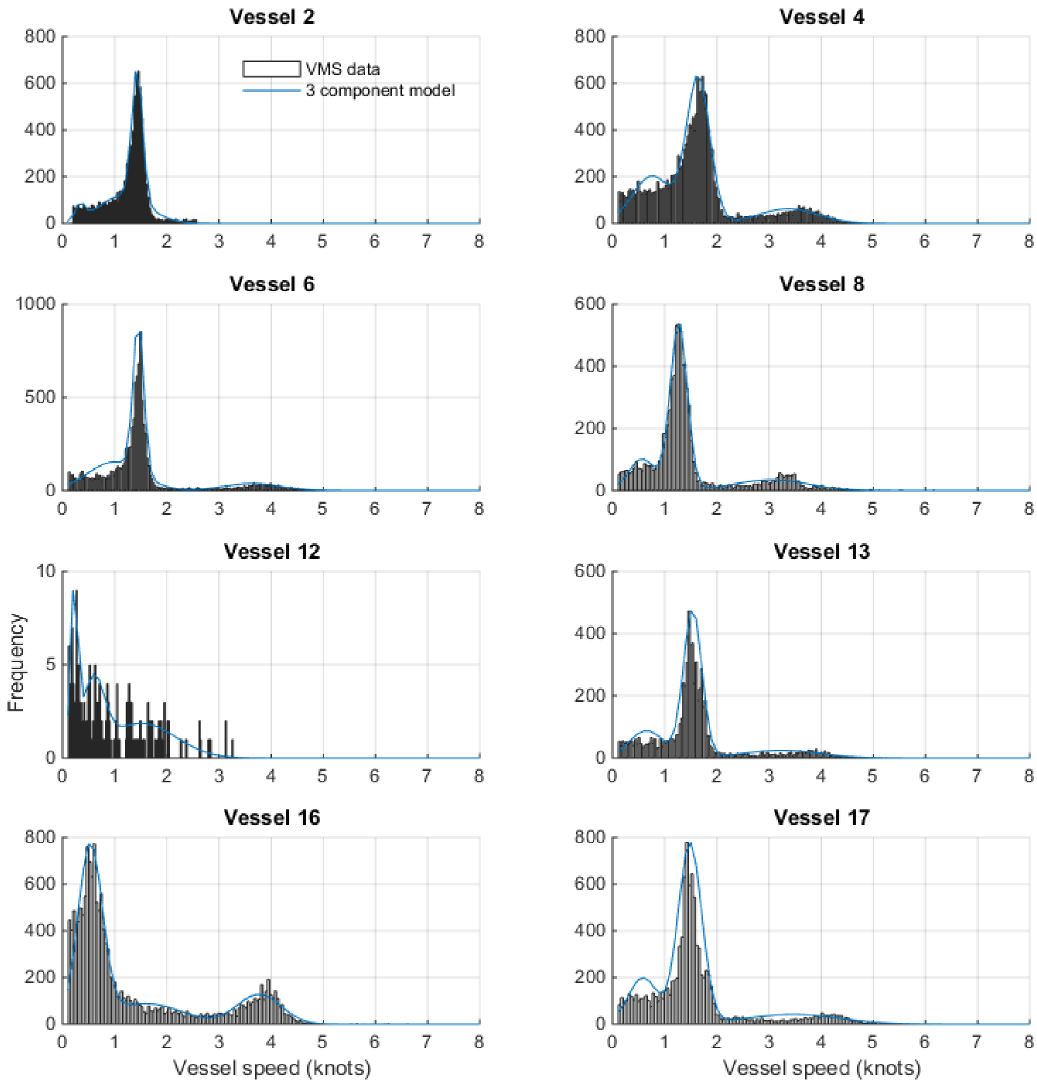
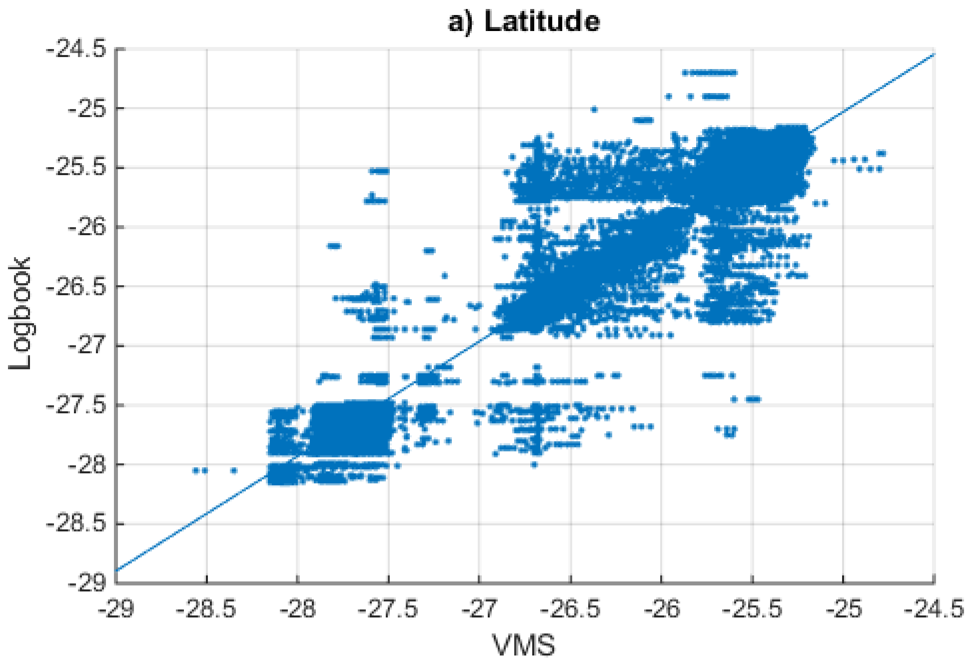


Figure 24. Histogram of VMS calculated vessel speeds by fishing operation and Gaussian mixtures used to identify trawling locations.

Table 13. Mean vessel speeds and standard deviations for the dominant components as defined by the mixture models (Figure 24).

Fishing operation	Mean fishing speed (knots)	Standard deviation
Otter-trawl		
2	1.4315	0.102064
4	1.6418	0.222326
6	1.4564	0.099318
8	1.2695	0.162126
12	1.5128	0.654339
13	1.5351	0.174980
17	1.4845	0.224323
Average	1.475943	0.234211
Danish Seine		

16	0.52966	0.235021



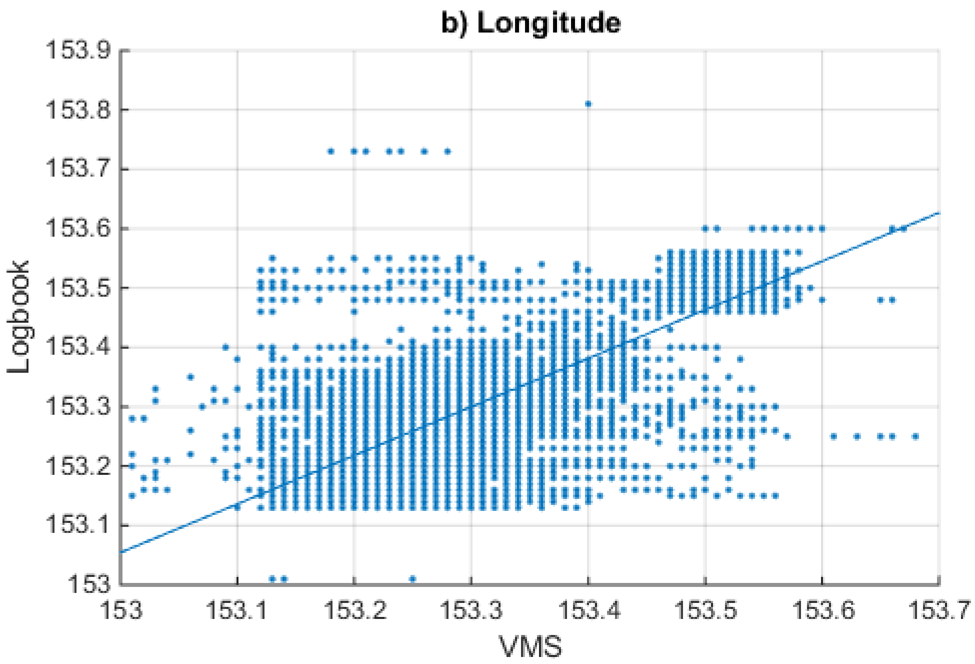


Figure 25. Comparison of VMS and Logbook harvest coordinates for a) spatial latitude and b) longitude.

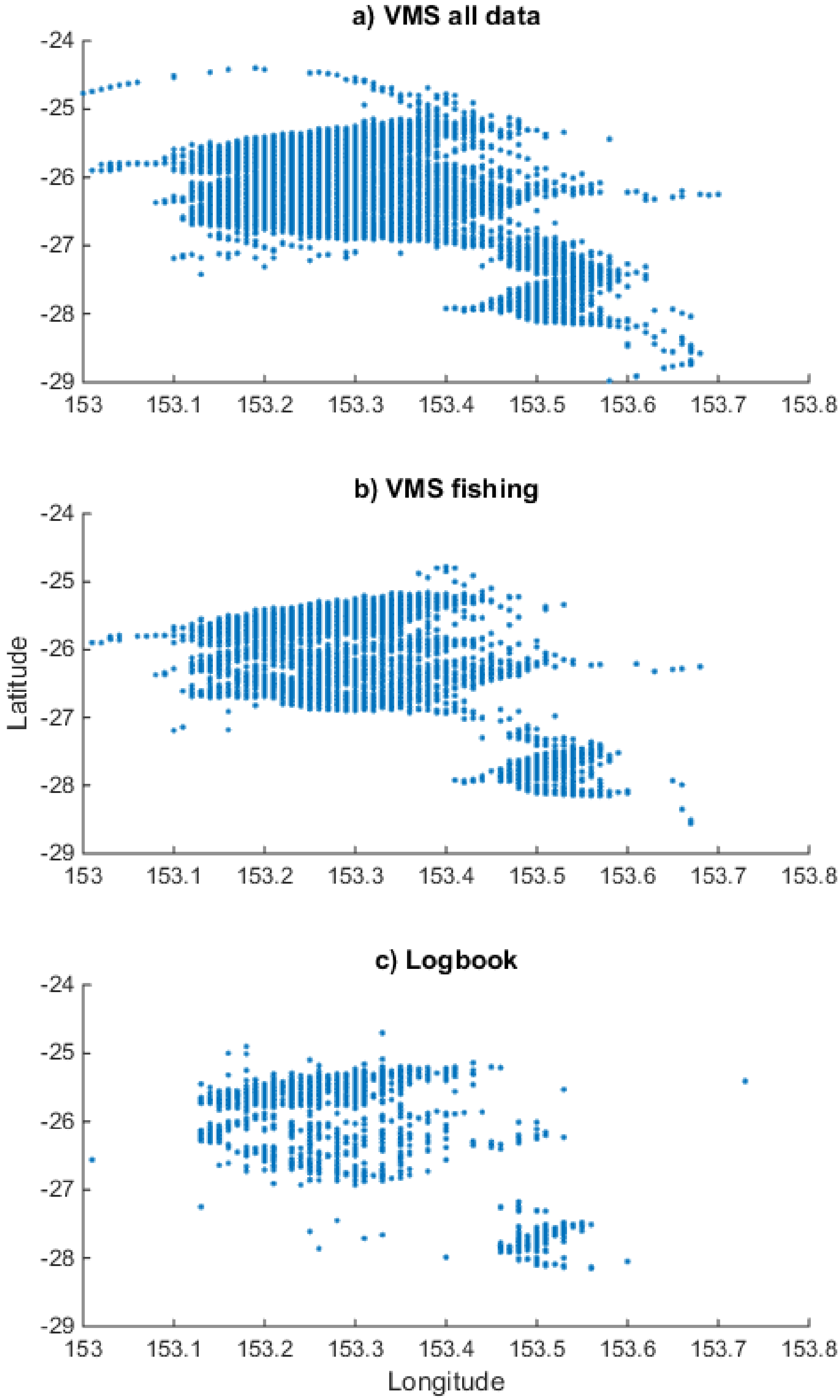


Figure 26. Scatter plot of spatial coordinates of a) all VMS data unfiltered; b) VMS data filtered based on vessel speed rules assumed for fishing; and c) logbook data.

Appendix IV: Monitoring of fish length

The fishery dependent sampling of stout whiting length-age data 1991–2015 followed a multistage process, where the primary sampling unit (PSU) was a vessel's daily harvest of stout whiting. After selection of the PSU, the fish length-age data was then sampled from the PSU in two stages: 1) sample a box of random fish from the harvest to measure fish length frequency; and 2) subsample individual fish otoliths from stage 1 to measure otolith weight and count otolith rings to allocate fish age. The PSU and stage 1 sub-sampling were considered random; whereas the stage 2 sub-sampling was length stratified with the aim to measure fish ages across a complete range of fish lengths (i.e. form an age-length key).

The hurdle of analysing and developing a fish indicator from this data is the systematic change and variance in the temporal and spatial operation of vessels. Consequently, it is difficult to consistently measure and interpret changes in the fish length-age data; especially to differentiate fish age-abundance measures relating to population processes of fish recruitment, growth and survival.

In this report, section the patterns and variance of the stout whiting length data were detailed to elucidate ideas to improve future sampling design or analysis of the data. For this, we also compared results from statistically weighting as opposed to unweighting length frequency distributions.

Data

Stout whiting length and age sampling from the T_4 sector was conducted in 1991–2014 following long term monitoring protocols (Department of Primary Industries and Fisheries 2007). Two 5 kg boxes were collected at random from each T_4 vessel's fishing trip. All fish from each box were measured as fork-lengths (5 mm length categories) for length frequency. From each box, 1 to 3 fish from every 5 mm size class were dissected to extract otoliths for aging until a subsample of about thirty fish per size class per year was achieved (length stratified sampling). Historically, the number of fish sampled each year was dependent on the amount of fishing and catch. For fish age determination, both otoliths were removed, cleaned and sectioned. All otolith reading was done without knowledge of fish size, date or location of capture. Age estimates were counts of complete opaque rings. In 2004, fish otoliths from the 1993–2000 years were re-aged independently by Australia's Central Aging Facility (unpublished report; C. P. Green and K. Krusic-Golub). This was done to standardise fish aging protocols to ensure otolith aging was consistent in time and completed by qualified staff as tested against a reference otolith collection (O'Sullivan 2007; O'Sullivan and Jebreen 2007). Final age frequencies were adjusted to age–groups (cohorts) based on fish capture dates (O'Sullivan and Jebreen 2007). Verification of a single annual cycle in ring formation, coinciding with spring months in 0+ to 3+ age groups, had been demonstrated for stout whiting otoliths with clear banding (Butcher and Hagedoorn 2003).

T_1 and T_{NSW} stout whiting age data were not sampled historically, so these fishing sectors were not able to be used in analysis.

The T_4 data were supplied by Fisheries Queensland (J. McGilvray) on 22 June 2015. The data were provided in a MS Access database and contained two newly formatted tables:

1. a 'site' table with all vessel, fishing date, fishing location, fish length, otolith weight and sample details (N=35491, for January 1991 to June 2015), and
2. an 'age' table with otolith increment counts, readability, edge type, reader and reading number (N=12451). Duplicate fish age data were identified in 1994. These data were not used.

For the ‘site’ table, the following properties were noted:

- For tallies of fish length frequency prior to 2012, the aggregated data variables for ‘SizeClass’ and ‘TotalCount’ were used. For the years 2012–2015, individual fish lengths were recorded and frequencies were tallied by grouping the fish lengths.
- Length frequency data from vessel # 7 (Deep Tempest) using experimental T_1 fishing gear on 28 January 1993 and 14 December 1992 were not used (n=325).
- Data field ‘SizeClass’ was converted from type ‘Text’ to type ‘Number’.
- Vessel ‘xxxx’ was identified as ‘fwdn’ (n=33).
- Null boat marks in 2014 were allocated based on CFISH and VMS fishing dates (n=920); 18 December, 20 December and 29 December = ‘fwdn’.
- Records for Gold Coast beach catches were removed (n=21); they were line caught stout whiting from off the sand pumping jetty.
- The 2015 calendar year data were not completed and not analysed (n=732, vessel days = 11).
- A new boat table was created to link CFISH and VMS spatial zones and position (latitude and longitude) data based on ‘fishing_operation’ codes (≈ vessel-owner-gear identifier). The table was created using the GLM daily analysis data in ‘stout_whiting_catch.mdb’.
- Recommendation - FQ stout whiting ltmp database to be updated with fishing region codes, and latitude and longitude data for all ‘site’ data; using vms and logbooks as appropriate.

Estimators of fish length

The estimators for the proportion of fish in length class l (cm fork length) in year k followed the theory from Aanes and Volstad (2015):

1. $\sum_r \sum_i n_{kril}$ for a length frequency distribution directly from raw data, and
2. $\sum_r \sum_i n_{kril} \times w_x$ for a length frequency distribution where w is the weighting parameter for strata x.

The weighting parameter could represent values based on spatial area measures for region strata r or long term average harvest from region strata r. The weighting parameter could also be defined at finer scale based on total harvest of the PSU i.

Applying a statistical weight by region w_r has the aim to estimate a more consistent design-based comparison of the data; in attempts to reduce the effects of vessels changing their spatial patterns of fishing between years. Estimators 1 and 2 using w_i will represent the spatial patterns of the observed harvests and sampling.

Irrespective of which estimator is used, the issue of correlated data and low effective sample size is a challenge for fishery dependent sampling.

Results

A summary of the T_4 stout whiting length frequency distributions (LF) are displayed between calendar years, fishing zones and fishing operations (~ vessel) from Figure 27 to Figure 32. The data were produced from the stage 1 sub-sampling, where fish lengths were measured but not aged. The following observations are noted from the LF data:

- Significant variance was observed in the sampled fish length frequencies between years, areas and fishing operations (Appendix IV). The statistical F-test for differences between years was F = 716.21 and $p < 0.001$. The resulting variance components for fishing zones was 0.065 (s.e. = 0.046) and fishing operations was 0.125 (s.e. = 0.059). The residual (unexplained) variance was 1.6 cm, where shifts in the length frequencies of this magnitude can significantly affect the representativeness and accuracy of predicted fish age-structures.
- The sampling in 2014 indicated an increase in the observed fish lengths (Figure 27). The nominal sample size in 2014 was lower compared to previous years. Increases in LF also occurred in the years 1995, 1998–99, 2006 and 2010. Smaller sized fish were harvested in 1993, 2002, 2004 and 2008.
- The patterns of LF by year were different between fishing operations (Figure 28). The ability to consistently interpret a time series of LF by fishing operation was difficult. This was due to the change in vessels entering and leaving the fishery. The data from fishing operations 16 and 17 represent recent years.
- Figure 29 shows clear differences in LF between years and fishing zones. It is important to note that not all zones were fished in each year. This situation complicates the overall comparison of LF between years in Figure 27, as spatial variance can influence the pattern. Some strong changes in the LF are observed, such as in zone w33 between 2000 and 2001 where the decrease in fish LF in one year indicates prevalence of only young fish.
- Figure 30 illustrates that fishing operations harvest different sized fish between years and Figure 31 illustrates the full variance in LF between years, zones and fishing operations.
- The use of weighted estimators of fish length significantly changed the patterns of LF from the observed data in a number of years (Figure 32). Input of the area weighted LFs in catch curve Model 2 resulted in similar estimates. The survival fractions were estimated at $I_{k-1} = 0.326$ for 2012 and $I_k = 0.370$ for 2013. The average was $\bar{I} = 0.348$. Application of these indicator results into the linear TACC control rules (equation 1, used in Table 4) suggested quota of 987 t and 970 t for the two reference points. Thus the sensitivity of using weight LF reduced estimated TACC by about 50 t.

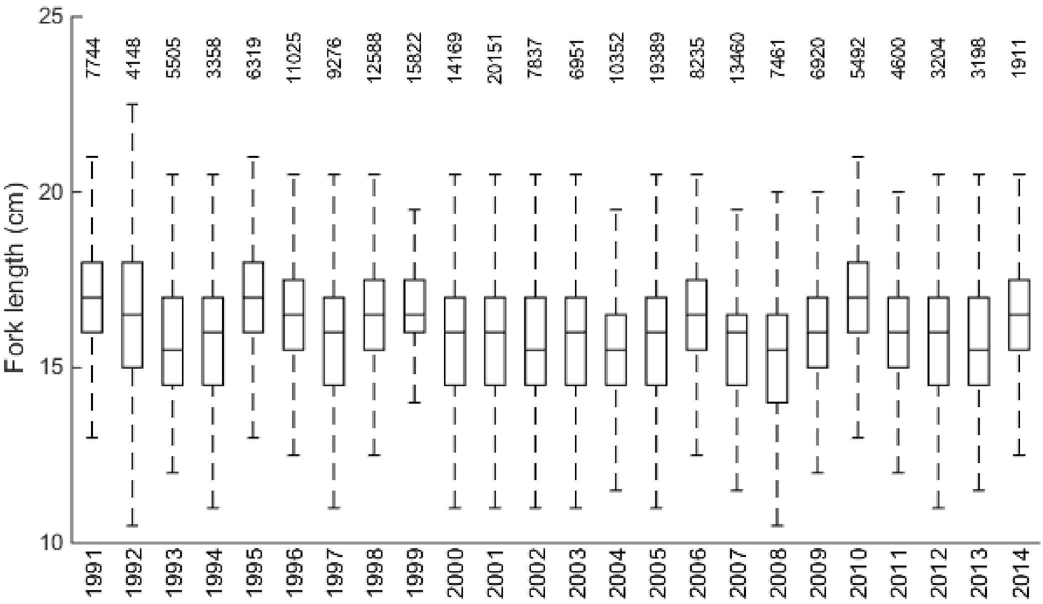


Figure 27. Box plot of the stout whiting length frequency samples recorded each calendar year. The plot shows the number of fish measured each year. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles and the whiskers extend to the most extreme data points.

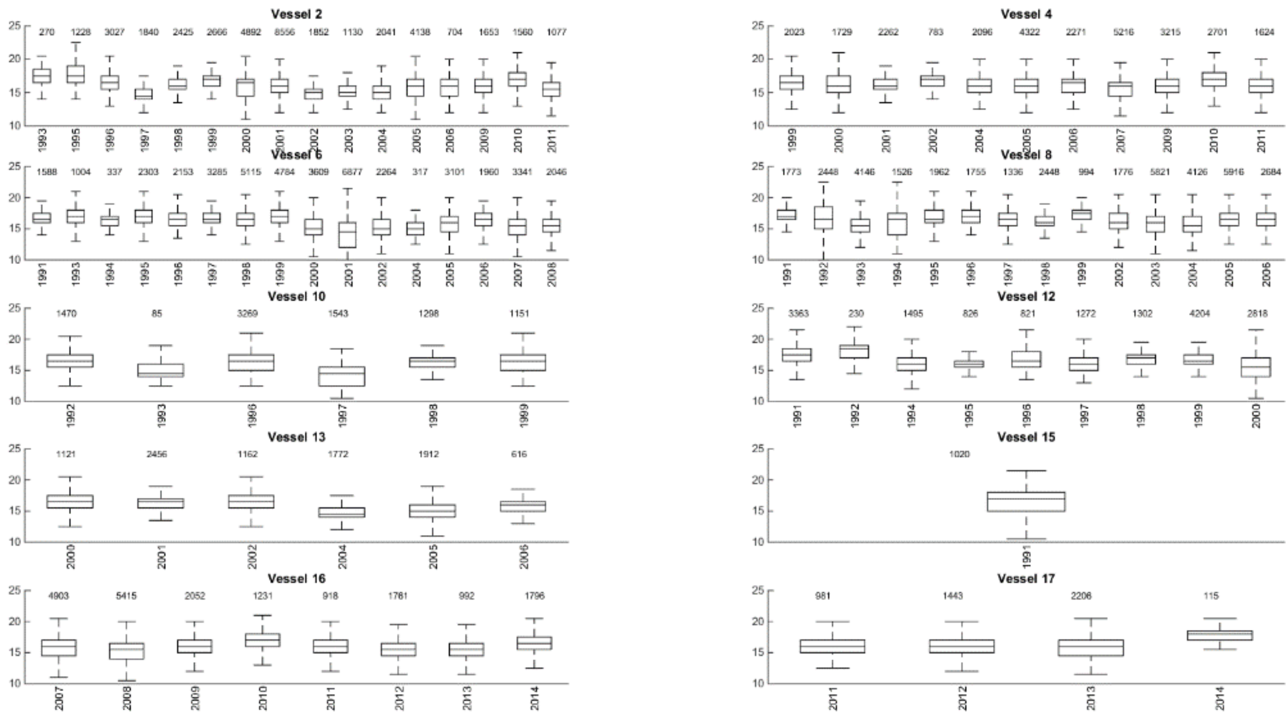


Figure 28. Box plot summaries of the stout whiting length frequency samples recorded from each fishing operation (~ vessel-owner-gear) by calendar year. The plots show the number of fish measured by each category.

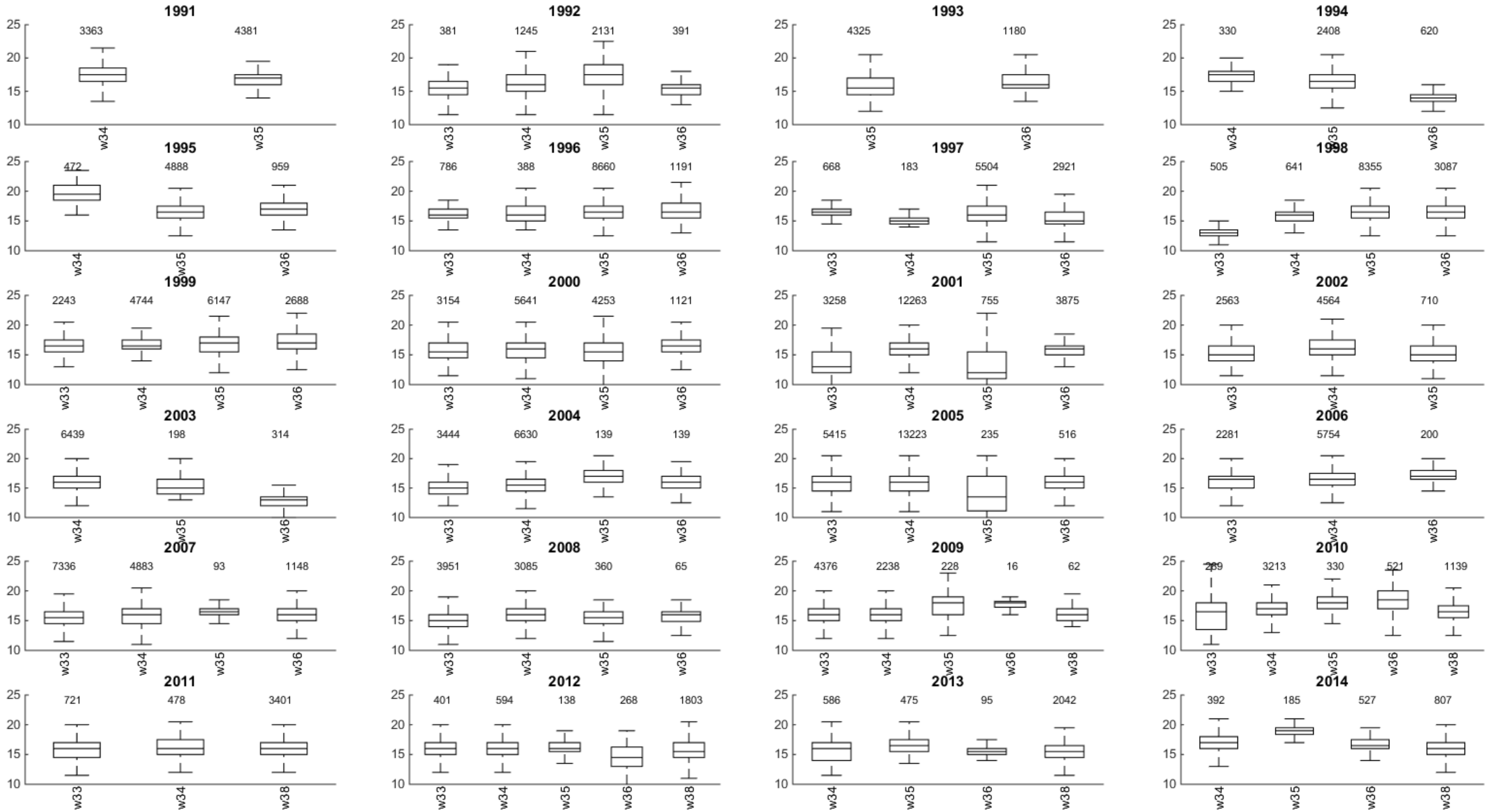


Figure 29. Box plot summaries of the stout whiting length frequency samples recorded each calendar year, by fishing zone. The plots show the number of fish measured by each category.

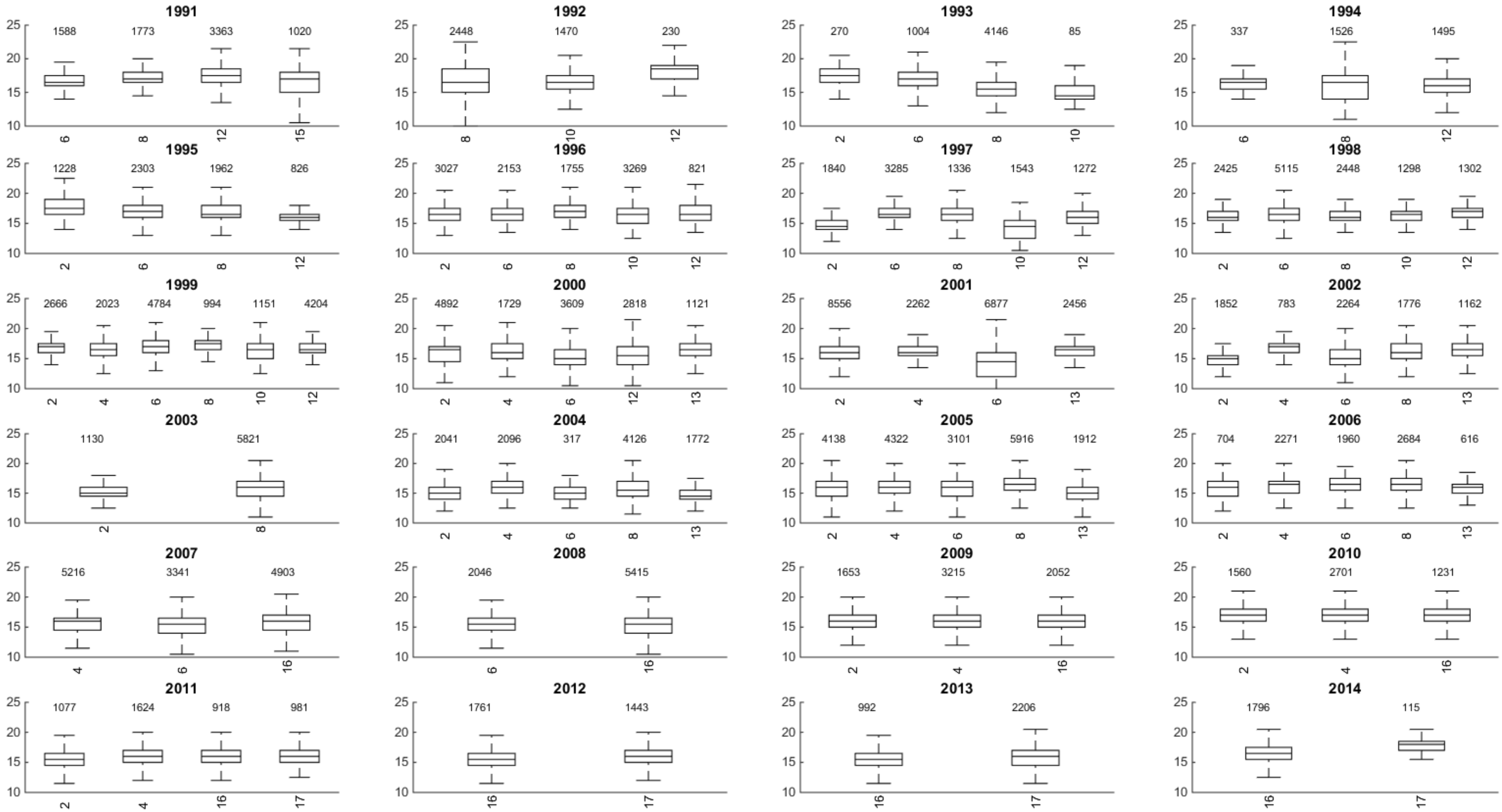


Figure 30. Box plot summaries of the stout whiting length frequency samples recorded each calendar year, by fishing operation (~ vessel-owner-gear). The plots show the number of fish measured by each category.

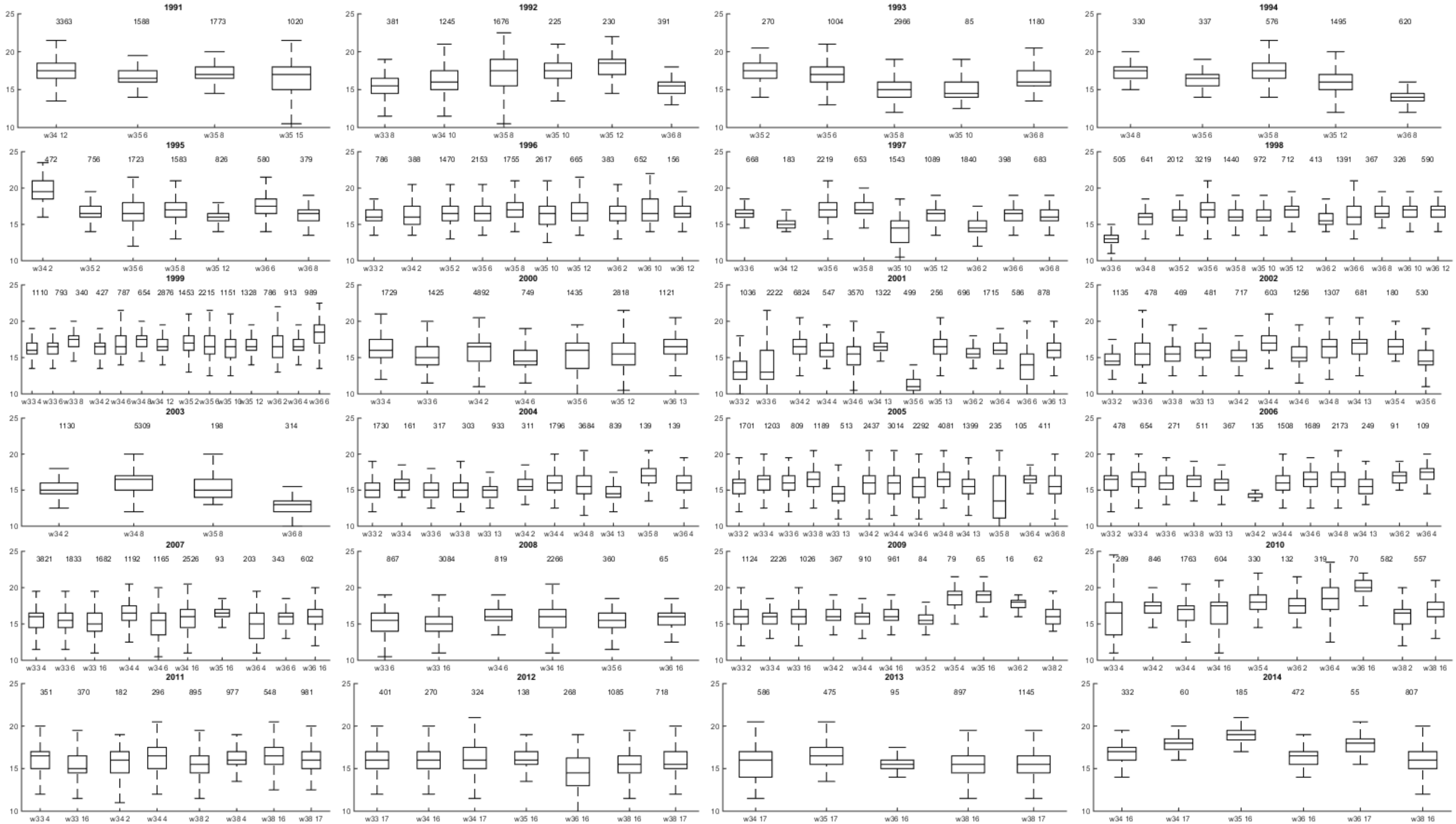


Figure 31. Box plot summaries of the stout whiting length frequency samples recorded each calendar year, by fishing zone and fishing operation (~ vessel). The plots show the number of fish measured by each category. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles and the whiskers extend to the most extreme data points.

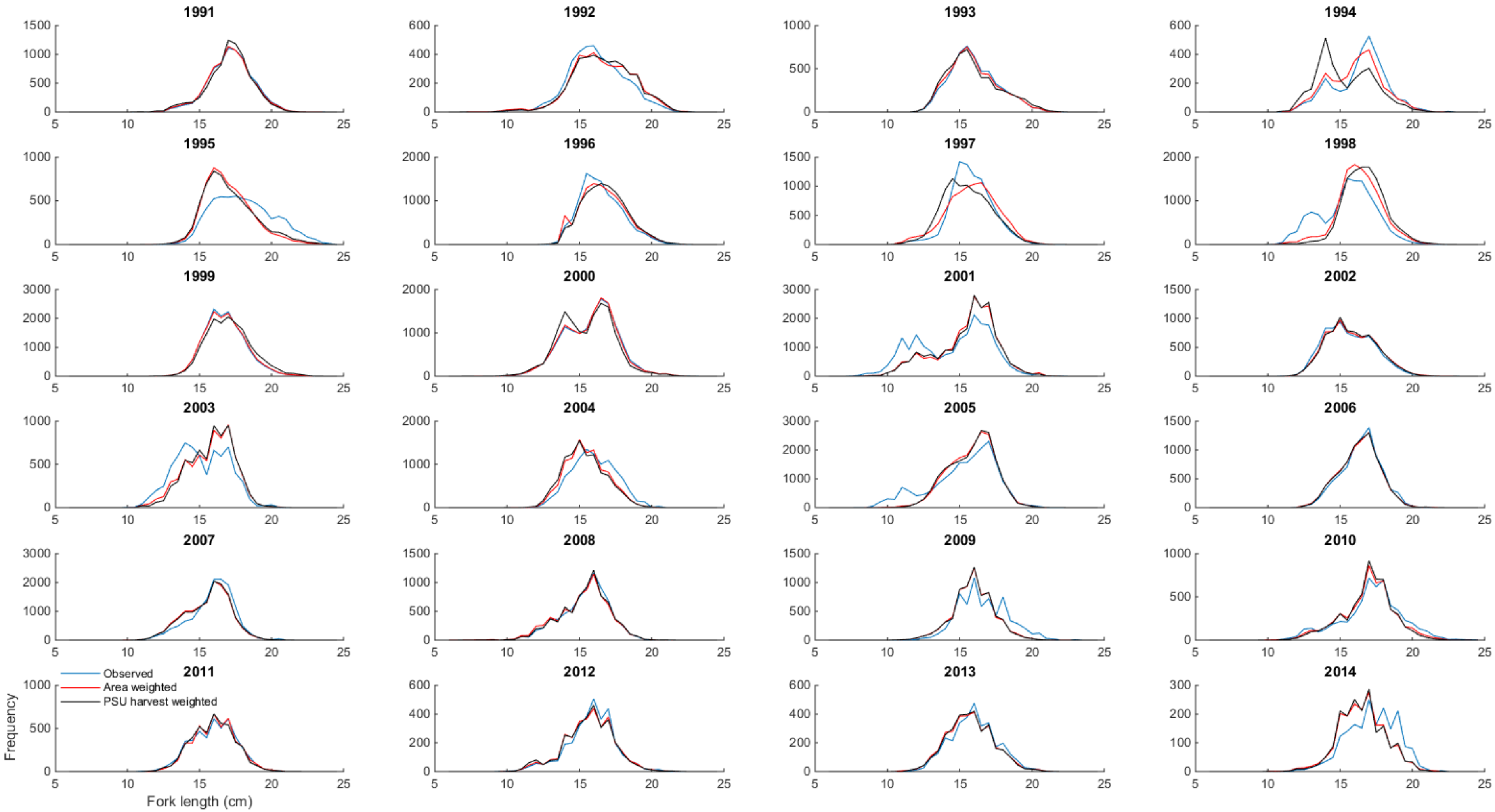


Figure 32. Length frequency plot of stout whiting by year comparing 1) the observed distribution; 2) a regional area-weighted distribution; and 3) a harvest-weighted distribution based on total harvest of the PSU (kg per vessel day).

Appendix V: Catch curve models

This report section describes developmental analyses for estimating stout whiting survival. The developmental analyses are called Model 1, Model 2 and Model 3. The model contexts are described in the following paragraphs.

Model 1 was designed first to connect the stout whiting standardised catch rate directly with the separate fish-length frequency and age-length-otolith data. In this model the standardised catch rate was used to represent stout whiting abundance and to scale the patterns of age-abundance (from the sampled fish length frequencies and age-length-otolith data). This linkage allowed for the variation in cohort strength (recruitment) and survival fractions to be estimated year by year; i.e. mitigate confounding by separating the signals for recruitment verse survival. The problem of estimated survival or mortality being confounded by cohort strengths is inherent in traditional cross sectional (year-by-year regression) catch-curve methodology, where estimated low survival in a year can imply high rates of fishing mortality, or it can imply high recruitment (more new younger fish compared to old). Only repeated annual measures of fish survival or methodology that accounts for variable cohort strengths can resolve this confounder to provide clearer inferences. Unfortunately, the advantages of Model 1 and the flexibility of model parameters were concluded to be unsuitable due to the year-to-year variation in the stout whiting data.

Model 2 was designed without catch rates, but still used the same fish-length frequencies and age-length-otolith data to scale age-abundances. As for Model 1, the analysis structure assumed the data were sampled randomly from the population in each year. Survival fractions were still estimated for each cohort. The fractions compared the ratio of fully recruited cohort abundances to the next younger cohort in the same years. By comparing the same years, the survival estimates can be obtained but may be affected by strong or weak recruitment of new fish. The model estimates of survival identified inconsistency in some years between sampled fish-length frequency and age-length-otolith data. However, the data and estimates in the last few years seemed reasonable for the methodology (Model 2).

Model version 3 was used to analyse only matching age-length data. The model was not formulated to analyse separate fish length frequency or otolith weight data. The Model 3 analysis was conditioned on the assumption that fish ages within each length category were sampled randomly and no longer assumed that the lengths themselves were sampled randomly from the fish population. This assumption aimed to overcome the variance in fish length samples associated with the fishery dependency of the data (length data tended to vary randomly between fishing years, areas and vessels). So only the paired age-length fish stratified data were analysed. Similar to Model 2, calculation of annual fish survival followed cohort abundances.

The following describes the analysis procedures for models 2 and 3.

Catch curve mixture Model 2

No T_4 2014 stout whiting were aged for this assessment, with only fish length and otolith-weight data supplied by Fisheries Queensland. This data was sufficient to run catch curve mixture Model 2 in order to estimate fish survival.

For catch curve Model 2, the data consisted of multiple years *k* of sequential mixed data $\vec{y}_{jk}$ (l_j: fork length mm, o_j: power transformed otolith weight W_j^o, and a_j: age-group) for each fish *j*. The data were mixed in two parts for univariate sampling of l_j and separate multivariate sampling of matching l_j–o_j–a_j. The number of all sampled fish in each year was denoted n_k. The Gaussian finite mixture distributions were defined by the mixing proportions π_{ik}, means $\mu_i^{l,o}$ and covariance matrix $V^{l,o}$, in order to calculate the posterior scores τ_{ijk}; where age component label $i = 1 \ldots 9$ corresponded to age groups $a = 0 \ldots 8$ years old. As the a_j data related directly to model predicted age-proportions τ_{ijk} and was not available for all fish, it was used to set $\tau_{ijk} = 1$ where a fish was aged *i* and not used directly as a third dimension in the mixture model; noting $\sum_i \tau_{ijk} = 1$.

The overall algorithm for finding maximum likelihood parameter estimates was implemented in Matlab® (MathWorks 2015) using the equations in Table 14 as follows:

1. Linearise otolith weight with length using the transformation: $o_j = \left(W_j^o\right)^{b^{-1}}$, where parameter *b* was estimated from the power function $W_j^o = al_j^b$.
2. From the data calculate initial values for the EM algorithm: $\mu_i^{l,o}, V^{l,o}, \pi_{ki}$.
3. Define the first fully recruited age component for catch curve calculation; for Model 2 the peak-plus criterion was used *r* = 3 (Smith, Then *et al.* 2012).
4. EM algorithm (Table 14):
   a. Calculate derivatives $\frac{\partial \vec{\mu}_i}{\partial \vec{\theta}}$ (Table 14).
   b. Calculate τ_{ijk} using mixture density functions and set $\tau_{ijk} = 1$ where a fish had been aged.
   c. Calculate $\hat{n}_{ki}$.
   d. Calculate $\hat{\vec{\theta}}$ and $\hat{V}^{l,o}$.
   e. Calculate $\hat{S}_k$.
   f. Calculate $\hat{\alpha}_{ki}$.
   g. Calculate $\hat{\pi}_{ki}$.
   h. Replace all initial values by their estimated updates: $\hat{\mu}_i^{l,o}, \hat{V}^{l,o}, \hat{\pi}_{ki}$.
   i. Return and loop until parameter estimates converge.

For the predicted means $\mu_i^{l,o}$ (*l* and *o* at age) to be calculated from the Von Bertalanffy growth curve $\hat{\mu}_i^{l,o} = l_\infty^{l,o}\left(1 - \exp\left(-\kappa^{l,o}\left(t_i - t_0^{l,o}\right)\right)\right)$ (Haddon 2001), each iteration in the EM algorithm followed a single step of the Gauss-Newton algorithm (θ and ϕ in Model 1 or 2). The derivatives $\frac{\partial \vec{\mu}_i}{\partial \vec{\theta}}$ were a 6×2 dimensional matrix for each age component *i*. The matrix cells (1:3,1) were for the fish length derivatives $\frac{\partial \mu_i^l}{\partial l_\infty^{\ l}}$, $\frac{\partial \mu_i^l}{\partial \kappa^l}$, and $\frac{\partial \mu_i^l}{\partial t_0^l}$ and matrix cells (4:6,2) for otolith weight derivative $\frac{\partial \mu_i^o}{\partial l_\infty^{\ o}}$, $\frac{\partial \mu_i^o}{\partial \kappa^o}$, and $\frac{\partial \mu_i^o}{\partial t_0^o}$ (Table 14, equations 1…3). The cross derivatives between *l* and *o* were assumed all zero; matrix cells (4:6,1) and (1:3,2) = 0.

For Model 2 the calculation of annual fish survival $\hat{S}_k$ followed cohort abundances ($\hat{n}_{ki}$ matrix diagonals; equation 8, Table 14). The structure of Model 2 equation 8 was based on truncation of matrix $\hat{n}_{ki}$ for fully recruited fish (Table 14). $\hat{S}_k$ compared two diagonal vectors of cohort *c* and *c*+1 abundance. $\hat{S}_k$ was the sum abundance of cohort *c* divided by the sum abundance of the next younger cohort *c*+1 in the same years for fully recruited fish. The $\hat{S}_k$ ratio therefore represented fish survival in year *k*.

Table 14. Catch curve Model 2 equations.

	Equations	Notes
(1)	$\frac{\partial \mu_i^{l,o}}{\partial l_\infty} = 1 - \exp\left(-\kappa^{l,o}\left(t_i - t_0^{l,o}\right)\right)$	Derivative for asymptotic maximum average length l_∞. t_i is the specified mid-year age of fish in component *i*.
(2)	$\frac{\partial \mu_i^{l,o}}{\partial \kappa^{l,o}} = l_\infty^{l,o}\left(a_i - t_0^{l,o}\right)\exp\left(-\kappa^{l,o}\left(t_i - t_0^{l,o}\right)\right)$	Derivative for annual growth rate labelled κ.
(3)	$\frac{\partial \mu_i^{l,o}}{\partial t_0^{l,o}} = -l_\infty^{l,o}\kappa^{l,o}\exp\left(-\kappa^{l,o}\left(t_i - t_0^{l,o}\right)\right)$	Derivative for the fish age (t_0) at zero length.
(4)	$\tau_{ijk} = \pi_{ki} f_i\left(\vec{y}_{jk}\right) \Big/ \sum_i \pi_{ki} f_i\left(\vec{y}_{jk}\right)$	f is a d-dimensional multivariate normal density function, for univariate l_j or multivariate l_j - o_j.
(5)	$\hat{n}_{ki} = \sum_{j=1}^{n_k} \tau_{ijk}$	Estimated number of fish in each year *k* and age component *i*.
(6)	$\hat{\vec{\theta}} = \vec{\theta} + \left\{\sum_i \left[\sum_k \sum_{j=1}^{n_k} \tau_{ijk}\right]\left(\frac{\partial \vec{\mu}_i}{\partial \vec{\theta}}\right)^T V^{-1}\frac{\partial \vec{\mu}_i}{\partial \vec{\theta}}\right\}^{-1} \times$ $\left\{\sum_i \left[\left(\sum_k \sum_{j=1}^{n_k} \tau_{ijk}\vec{y}_{jk}\right)^T - \left(\sum_k \sum_{j=1}^{n_k} \tau_{ijk}\right)\vec{\mu}_i^T\right] V^{-1}\frac{\partial \vec{\mu}_i}{\partial \vec{\theta}}\right\}^T$	Updating equation for parameters $l_\infty^{l,o}, k^{l,o}, t_0^{l,o}$ of the *a-l* and *a-o* growth curves.
(7)	$\hat{V}^{l,o} = \left\{\sum_k \sum_{j=1}^{n_k} \sum_i \tau_{ijk}(\vec{y}_{jk} - \hat{\vec{\mu}}_i)(\vec{y}_{jk} - \hat{\vec{\mu}}_i)^T\right\} \Big/ \sum_k n_k$	The 2×2 covariance matrix for *l* and *o*.
(8)	$\hat{S}_k = \begin{cases} \sum_{m=1}^{end} n_{ki}^{c} \Big/ \sum_{m=1}^{end-1} n_{ki}^{c+1} & \text{for years} < k = 1 \\ \sum_{m=2}^{end} n_{ki}^{c} \Big/ \sum_{m=1}^{end-1} n_{ki}^{c+1} & \text{for years} \geq k = 1 \end{cases}$	Survival rates S_k of fish in year *k*. The notation represents cohort *c* diagonals of the truncated matrix n_{ki} for fully recruited ages (*i*>*r*). *m* indicates the cohort vector elements that are summed. n_{ki} contains information on S_k prior to thr 1st year of data k=1.
(9)	$\hat{\alpha}_{ki} = \prod_{m=k-i+r}^{k-1} \hat{S}_m$	Scaled abundance of age group α_{ki} relative to the abundance of the youngest fully recruited age group in year *k*. The abundances satisfy the catch curve for fish age components ≥ *r*, calculated as the cumulative product of age-based survival. *m* indicates the $\hat{S}_k$ used.
(10)	$\hat{\pi}_{k,1\ldots r-1} = \frac{\hat{n}_{ki}}{n_k}; \hat{\pi}_{k,r\ldots g} = \left(1 - \sum \hat{\pi}_{k,1\ldots r-1}\right)\alpha_{ki} \Big/ \sum_{i=r}^{g} \alpha_{ki}$	Updating equation for π_{ki} age proportions.

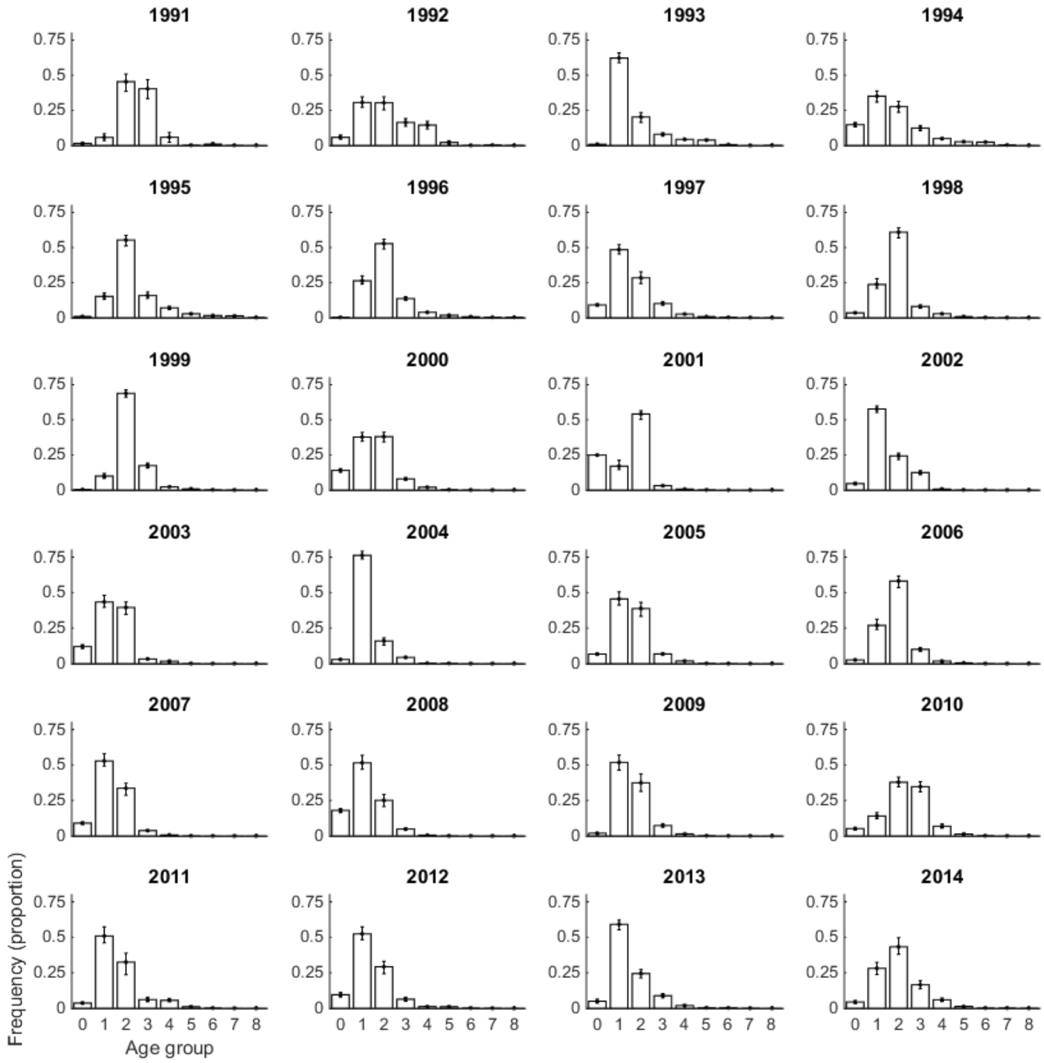


Figure 33. Predicted fish age frequencies of stout whiting by year. The predicted proportions were from catch curve Model 2, with 95% confidence intervals shown.

Catch curve mixture Model 3

For stout whiting, we had multiple years *k* of sequential mixed data $\vec{y}_{jk}$ (l_j: fork length mm and a_j: age-group) for each fish *j*. The data analysed represented multivariate samples of matching l_j–a_j. The number of sampled aged fish in each year was denoted n_k, with fish age mixing proportions π_{ki}, mean length at age μ_i, variance of mean length at age V and individual fish age scores τ_{ijk}; where age component label $i = 1 \ldots 9$ corresponded to age groups $a = 0 \ldots 8$ years old and $\sum_i \tau_{ijk} = 1$.

The algorithm for finding maximum likelihood parameter estimates of fish survival was implemented in Matlab® (MathWorks 2015) using the equations in Table 15 as follows:

1. Calculate and set values for Von Bertalanffy growth curve μ_i and V.
2. Define the first fully recruited age component *r* for catch curve calculation; the peak-plus criterion was used for stout whiting *r* = 3 (Smith, Then *et al.* 2012).
3. Tally the observed numbers of aged fish n_{ki} for each year *k* and age component *i*.
4. For non-recruited fish *i* < *r*, calculate initial values $\pi_{ki} = n_{ki} \Big/ \sum_i n_{ki}$ and $\beta_k = 1 - \sum_{i=1}^{r-1} \pi_{ki}$.
5. Calculate initial values for survival fractions S_q for fully recruited fish $i \geq r$ (equation 1). Here the subscript *q* replaces *k* to represent survival fractions that can also be calculated for years before *k*=1; from the n_{ki} diagonal cohort calculations.
6. Calculate initial values $\hat{\pi}_{ki}$ for $i \geq r$ (equation 2).
7. EM algorithm (loop calculations until estimates $\hat{\pi}_{ki}$ and $\hat{S}_q$ converge):
   a. Calculate τ_{ijk} from the mixture density function (equation 3)
   b. Calculate $\tilde{n}_{ki}$ (equation 4)
   c. Update $\hat{\pi}_{ki}$ for $i < r$ and β_k (equations 5 … 8)
   d. Calculate $\hat{S}_q$ (equation 9)
   e. Update $\hat{\pi}_{ki}$ for $i \geq r$ (equation 2).

The calculation of annual fish survival $\hat{S}_q$ followed cohort abundances (diagonals of the truncated $\hat{n}_{ki}$ matrix for $i \geq r$; equations 1 and 9, Table 15). In equation 1, initial values for $\hat{S}_q$ were obtained by comparing two diagonal vectors of cohort abundance. Initial $\hat{S}_q$ was the sum abundance of cohort *q* divided by the sum abundance of the next younger cohort *q*+1 in the same years for fully recruited fish. To obtain maximum likelihood estimates for $\hat{S}_q$, the updated calculations in equation 9 were expanded across the truncated $\hat{n}_{ki}$ matrix so that the observed and fitted numbers match when summed over every diagonal. Equation 9 matched the fitted numbers to the observed ratio of the number of fish in cohort *q* to the number in all cohorts older than *q*, where the numbers are summed over all years in which cohort *q* occurs. The final estimated survival fractions $\hat{S}_q$ applied to a cohort in the year between when it became fully recruited and when the next younger cohort became fully recruited. Therefore S_q cannot be calculated for the final year of data. For confidence intervals on $\hat{S}_q$, the observed data were resampled at random with replacement to generate 500 separate data sets. Each data set was analysed and results stored. Simple 95% confidence intervals were calculated from the distribution of results.

For this model, analysis of stout whiting, the direct estimation of Von Bertalanffy length-at-age parameters and variance, was not considered feasible. This was because the model was conditioned on the assumption that fish ages within each length category were sampled randomly and no longer assumed that the lengths were randomly sampled; the conditional model contained no information on length at age (as opposed to age at length). Therefore, survival results were compared for three growth settings:

a) $l_\infty = 22.622, \kappa = 0.293, t_0 = -2.342, V = 3.429$;

b) $l_\infty = 20.579, \kappa = 0.321, t_0 = -2.668, V = 3.429$;

c) $l_\infty = 20.579, \kappa = 0.321, t_0 = -2.668, V = 1.647$.

The growth parameters for setting a) were estimated separately outside the catch curve model using the same age-length data. Settings c) were estimated from catch curve mixture Model 2, which included all length frequency and otolith age data. Settings b) were a combination of a) and b).

Table 15. Catch curve Model 3 equations for the EM algorithm.

Equations	Notes
(1) $\hat{S}_q = \begin{cases} \sum_{m=1}^{end} n_{ki}^{q} \Big/ \sum_{m=1}^{end-1} n_{ki}^{q+1} & \text{for years} < k = 1 \\ \sum_{m=2}^{end} n_{ki}^{q} \Big/ \sum_{m=1}^{end-1} n_{ki}^{q+1} & \text{for years} \geq k = 1 \end{cases}$	Initial survival rates S_q of fish in cohort year q. The notation represents cohort q diagonals of the truncated matrix n_{ki} for fully recruited ages $i \geq r$. m indicates the cohort vector elements that are summed.
(2) $\hat{\pi}_{ki} = \beta_k \prod_{q=k-i+r}^{k-1} \hat{S}_q \Big/ \sum_{i \geq r} \prod_{q=k-i+r}^{k-1} \hat{S}_q$	Updating equation for π_{ki} age proportions, relative to the abundance of the youngest fully recruited age group in year k. The proportions satisfy the catch curve for $i \geq r$, calculated as the cumulative product of age-based survival.
(3) $\tau_{ijk} = \pi_{ki} f_i\left(\vec{y}_{jk}\right) \Big/ \sum_{i} \pi_{ki} f_i\left(\vec{y}_{jk}\right)$	f is a normal density function for l_j.
(4) $\tilde{n}_{ki} = \sum_{j=1}^{n_k} \tau_{ijk}$	Estimated number of fish in each year k and age component i.
(5) $\pi_{ki}^{(\text{int})} = \pi_{ki}^{(\text{old})} n_{ki} / \tilde{n}_{ki}$ (6) $\beta_k^{(\text{int})} = \beta_k^{(\text{old})} \sum_{i \geq r} n_{ki} \Big/ \sum_{i \geq r} \tilde{n}_{ki}$ (7) $\pi_{ki}^{(\text{new})} = \pi_{ki}^{(\text{int})} \Big/ \left(\sum_{i<r} \pi_{ki}^{(\text{int})} + \beta_k^{(\text{int})} \right)$ (8) $\beta_k^{(\text{new})} = \beta_k^{(\text{int})} \Big/ \left(\sum_{i<r} \pi_{ki}^{(\text{int})} + \beta_k^{(\text{int})} \right)$	Equations 5 … 8 are maximum likelihood updates for β_k and π_{ki} for $i < r$. The superscript (init) denotes an intermediate value that still needs to be scaled. The scaling of these two equations ensures that the sum of the new updated values of π_{ki} over i equals to 1.
(9) $\hat{S}_q^{(\text{new})} = \hat{S}_q^{(\text{old})} \dfrac{\left(\sum_{i \geq r} \tilde{n}_{ki}^{q} \right) \left(\sum_{k=q}^{M_q} \sum_{i \geq r} n_{ki}^{q^*} \right)}{\left(\sum_{i \geq r} n_{ki}^{q} \right) \left(\sum_{k=q}^{M_q} \sum_{i \geq r} \tilde{n}_{ki}^{q^*} \right)}$	The notation represents cohort q diagonals of the truncated matrix n_{ki} for fully recruited ages $i \geq r$. The double $\sum\sum$ terms sum over the n_{ki} values for fully recruited cohort diagonals q^* positioned to the right (upper side) of cohort q in the same years as cohort q. M_q indicates the final year in which there are data from each cohort q^*.

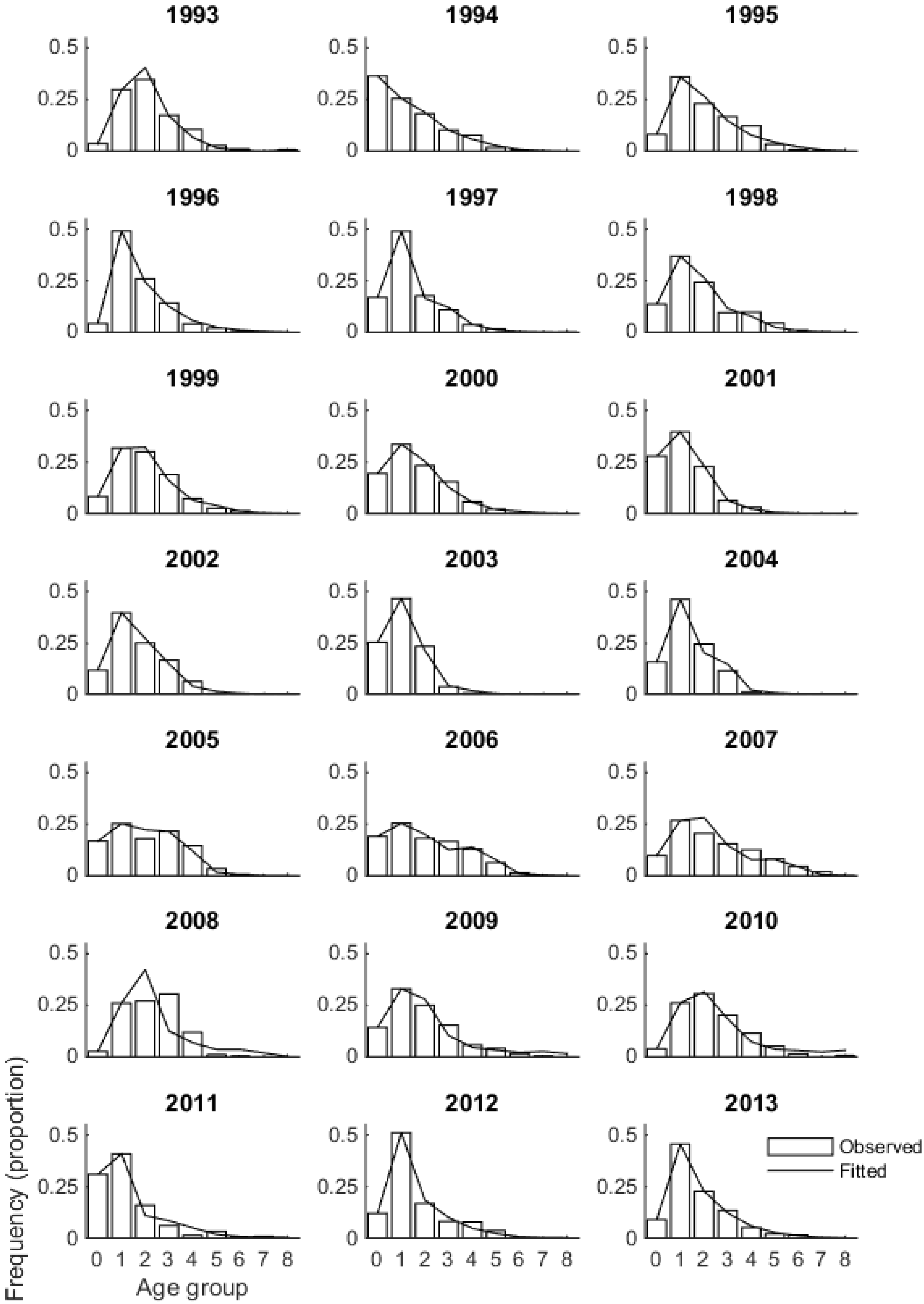


Figure 34. Comparison of the observed and fitted age frequencies by year from Model 3.

Appendix VI: Basic fish biology

Stout whiting are endemic to Australia, occurring between Shark Bay and Fremantle in Western Australia and between Bustard Head and northern New South Wales along the east coast. The stout whiting population along Australia's east coast appears to constitute a single stock unit (Ovenden and Butcher 1999). Its distribution overlaps with the northern distribution of the red spot whiting, also known as the eastern school whiting (*Sillago flindersi*).

Sexually mature fish can occur in all areas of the fishery for more than eight months of the year, with peak spawning in the spring and summer months. Stout whiting grow to a maximum size at 23 cm fork length (FL) at about eight years of age. Adult stout whiting generally form relatively dense schools on sandy substrates. The timing and patterns that schooling aggregations form can significantly affect the variance of catch rates and fish age structures.

Average gonosomatic index (GSI) for each month was estimated by fitting a generalised linear model. Gonad weight (square root transformed) was modelled against fish weight, year and month factors for male and female fish separately. GSI was estimated by the model monthly means (adjusted by the squared power). For both male and female stout whiting, there was a significant change in GSI between months. The gonad index peaked (for both sexes) during the months of August, September and October.

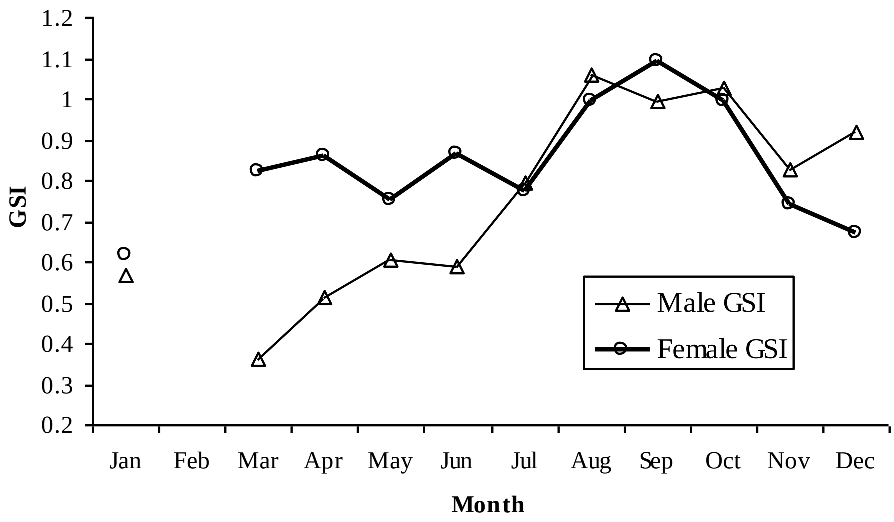


Figure 35. Stout whiting average monthly GSI for the years 1999 and 2000 combined (male fish n = 1468 and female fish n = 1344).