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Revision of the Northern Prawn Trawl Fishery fishing power data series and model

Final Report

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Version	Updates	Approver
Version 1	Draft Final Report	AFMA
Version 2	Final Report	AFMA

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Acronyms

AFMA	Australian Fisheries Management Authority
CPUE	Catch Per Unit Effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GAM	Generalized Additive Model
GLM	Generalized Linear Model
NPF	Northern Prawn Fishery
NPFI	Northern Prawn Fishery Industry
NPRAG	Northern Prawn Fisheries Resource Assessment Group
PTPM	Prawn Trawl Performance Model
RAG	Resource Assessment Group
SATIG	Swept Area Tiger Prawn Index

Executive Summary

Estimating fishing power is a way to assess changes in the relative efficiency of fishing activities over time. It accounts for improvements in fishing technology and techniques over time and uses this information to standardize the effort data collected. The current method for estimating fishing power, called the "*2009 integrated model*", involves modelling daily catch per boat-day, predicting the catch rate of a hypothetical standard vessel, and calculating the ratio between the fitted and standardized catch rates. Given that these methods were developed more than a decade ago, we conducted analyses to determine the primary factors driving the trend in fishing power and reviewed the methodology considering recent developments and emerging techniques that may be applicable. The most important factor in determining fishing power is the "swept area index" (SATIG), which is derived from a separate Prawn Trawl Performance Model (PTPM). Combined, the SATIG index and other offset variables account for approximately 70% of the increase in fishing power, while the remaining 30% can be attributed to changes in other explanatory variables estimated within the GLM procedure. To determine the influential variables driving the SATIG trend, we explored the PTPM input data that are collected from annual gear surveys. The results indicate that rated engine power, net number (double vs. quad) and net ply diameter have the most influence on the SATIG index. There is a substantial increase in swept area estimates when deploying quad net configurations when compared to double net (coefficient = 1 : 1.56) and since 2008 the fleet has undergone a transformation to uptake the more efficient quad gear configuration. Quad net configuration, combined with increased engine power and thinner net ply across the fleet, explains most of the observed increase in the swept area index since 2008. The aggregated navigation variable (*accg_nav*), hull group and fishing area (subregion) were the most influential fitted variables, particularly toward the latter period of the time-series (i.e., 2000 onwards). The NPF fishing power methodology has been applied for many years such that a review of the methods and key drivers is timely, and this project focussed also on developing recommendations regarding possible revisions to the methodology. Possible revisions that were identified but require further investigation include species-specific fishing power estimates, integrating finer scale spatial information, using more flexible modelling approaches (e.g., GAMs), and incorporating the SATIG information directly into an estimation model.

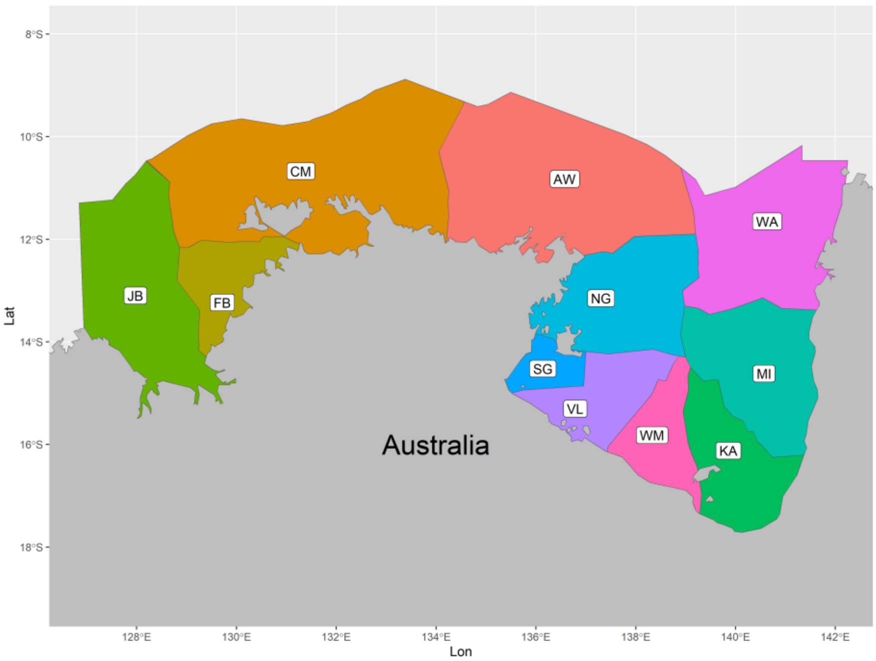
Acknowledgements

This project benefitted from consultation with, and extensive feedback from, members of the Northern Prawn Fisheries Resource Assessment Group (NPRAG). Australian Fisheries Management Authority (AFMA) and the Northern Prawn Fishery Industry (NPFI, Ltd.) are acknowledged for providing the data required for this project, and financial support was provided by AFMA and the CSIRO Oceans & Atmosphere. Dave Stirling contributed to the review of the PTPM input data. André Punt, Éva Plagányi and Sean Pascoe provided constructive feedback on an earlier draft. The work presented in this report builds on previous research conducted by Judy Upston.

1 Background

The Northern Prawn Fishery (NPF) is a trawl fishery that has been operating since the late 1960s, extending from Cape Londonderry in Western Australia to Cape York in Queensland (Gillett 2008). The fishery targets several species of prawns, including banana, tiger, endeavour, and king, and is one of Australia's most valuable federally managed commercial fisheries, having regularly returned a profit historically (Rose and Kompas, 2004). However, the fishery has experienced significant changes in fleet composition due to overcapitalization and overexploitation in the past. In response to these issues, several industry and government-funded buy-back schemes were implemented. A decade ago, more than 120 vessels operated in the fishery, and over 300 vessels were present in the 1970s and 1980s (Punt et al., 2011). Today, there are approximately 52 vessels and 19 operators in the fishery. The NPF is also managed through a series of effort controls, which include limitations on the season length, number of vessels, and most recently, the total trawl net headrope length.

Figure 1. The NPF fishery region and its sub-regions. JB: Joseph Bonaparte Gulf; FB: Foggy Bay; CM: Coburg-Melville; AW: Arnhem-Wessels; NG: North Groote; SG: South Groote; VL: Vanderlins; WM: West Mornington; KA: Karumba; MI: Mitchell; WA: Weipa.



The NPF fishing season usually runs from April to November, with a mid-season closure between June and August, although this may vary. The majority of fishing activity is focused on the western area of the Gulf of Carpentaria, specifically the Vanderlins (VL), North Groote (NG), and West Mornington (WM) stock sub-regions (**Figure 1**).

2 Needs

The Northern Prawn Fishery (NPF) is a mixed penaeids trawl fishery managed using input controls. Since inception, the fishery has undergone large changes in fleet composition and technology. Effort standardization remains a major source of uncertainty within the stock assessment and management decision-making process (Bishop et al., 2008). Estimating fishing power is an extension to the regular CPUE standardization process that accounts for changes in catchability in the stock assessment models. The method used in the NPF was developed in the early 2000s (Dichmont *et al.*, 2003) and has been revised since (Bishop *et al.*, 2008; Dichmont *et al.*, 2010). Since 1970, estimates of annual fishing power have increased six-fold. To better understand the drivers of the consistent increase in NPF fishing power, a review of the data and methodology was undertaken.

3 Objectives

The objectives as specified in the original Northern Prawn Fishery Fishing Power Analysis Project proposal are:

1. Review the historical fleet and gear data since 2010 and update the historical fleet tables with newly acquired information of vessels gear and technology obtained from the current gear survey or other source.
2. Complete Qualitative assessment of the information supplied in the gear surveys since 2010 in particular the accuracy and adequacy of the information for fishing power purposes.
3. Check data quality for trawl hours reported in the logbooks since 2010 and review the method for imputing missing trawl hours.
4. Summarise new gear and technologies that are reported in the gear surveys since 2010 or as part of survey follow-up (a component of objective (2)) and in this context, consider what future work is required on the fishing power model, or associated input datasets.

This report focusses on objective 4 of the Northern Prawn Fishery Fishing Power Analysis Project. Specifically, the report reviews the impact of gear and technologies since 2010 and to identifies areas that require future work on the fishing power model or associated input datasets. The report also considers additional objectives that emerged from interactions with AFMA and the NPFI during the November 2022 Research Meeting and the February 2023 Tiger Prawn Stock Assessment Strategic Workshop.

4 Fishing Power Model

4.1 Model structure

The current method, called the "*2009 integrated model*", involves the following steps: (1) Modelling daily catch per boat-day (i.e., CPUE) using a series of covariates; (2) Predicting the catch rate of a hypothetical standard vessel; and (3) Calculating the ratio between the nominal CPUE and standardised CPUE as fishing power. Steps (1) and (2) together is a CPUE standardisation process, a common practice in many fisheries. Deriving fishing power in Step (3) is the extension that is somewhat unique in the NPF.

The model for catch rate for vessel *i*, stock region *j*, year *k*, and month *t* has the form:

$$\log\left(C_{ijkt}\right) = \alpha_0 + \gamma \log\left(f_{ijkt}\right) + \sum_q \alpha_q X_{qjkt} + \sum_p \beta_p \log\left(V_{pik}\right) + \sum_h g(i,k,h)\delta_h + \varepsilon \qquad (1)$$

C_{ijkt} is the daily catch weight of tiger prawns plus half the endeavour prawns;

f_{ijkt} is fishing effort in hours trawled per day;

X_{qjkt} represent abundance and availability variables, including year, month and area;

V_{pik} is continuous vessel, gear, and skipper characteristics variables;

$g(i, k, h)$ is a function of categorical vessel, gear, and skipper characteristics;

e is an error term assumed independent and homoscedastic;

For the subscripts, *i* for vessel, *j* for stock region, *k* for year, and *t* for month.

The fitted model (1) is then used to predict catch by a hypothetical standard vessel. The fishing power R_k for the fleet in year *k* is the arithmetic mean of per vessel fishing powers, weighted for the effort of each vessel that year. The 2009 model uses:

$$R_{ki/sj} = \frac{\sum_{ik} f_{ik}(\exp\,(C_{ik} - C_{sk}))}{\sum f_{ik}} \qquad (2)$$

where C_{ik} is the log-scaled nominal catch for vessel *i* in year *k*, $C_{s,k}$ is the log-scaled standardized catch for the hypothetical vessel fishing in year *k*, and f_{ik} is the contribution of effort of vessel *i* to the total annual effort in year *k*. Assuming annual effort f_{ik} is the same for all vessels, this equation can be simplified as:

$R_k = C_{ik}/C_{sk}$,

where C_{ik} is the nominal catch that standard vessel *s* is produced by fixing all vessel and gear characteristics, as well as spatial coverage, to common values, then the method is the conventional approach and fishing power R_k is consistent with its application into stock assessment. That is, fishing power is the ratio of nominal catch to standardised catch, which is the same as "indirect fishing power" (see Equation 6 below).

However, the current method differs in that the model is fitted to logbook data and covariates, at the prediction step the reconstructed data fixes all *Year* values to reference year 1984 but all other covariates, including stock regions, technology variables, and vessel characteristics, remain unchanged (i.e., variables other than *Year* remain the same as the input data for the model fitting). This treatment means that the prediction dataset and the input are identical except variables *Year* (and the dependent variable C_{ijkt} is replaced by NA). As such, the definition of standard catch is the daily catch of actual vessels fishing at the fixed (standard) abundance of 1984, but the location and time variables are those in the actual (current) fishing activities observed in the given year. In addition to the different meaning of "standardized catch", annual variation in spatial distributions for both prawns and fishing effort are not accounted for. We were unable to find a clear explanation for this prediction dataset treatment. However, we found that this prediction method produced the same results as conventional CPUE standardisation where all years are included in the prediction dataset while other variables were fixed. Therefore, this method was likely used because changes in the spatial distribution of the fishery over time cannot be fully captured when using a coarse spatial resolution, such as sub-stock areas, as the spatial variable.

From R_k, the annual fishing power relative to a predefined year, either 1970 or 1993, as well as the fishing power increment each year relative to the previous year can be calculated as

$$FP_k = \frac{R_k}{R_{1970}} \quad (3)$$

$$\gamma_k = \frac{R_k}{R_{1993}} \quad (4)$$

$$q_{k,inc} = \frac{R_k}{R_{k-1}} \quad (5)$$

In Dichmont et al. (2010), an alternative definition of fishing power referred to as “indirect fishing power” was also defined. This is the ratio of annual nominal $CPUE_k$ to the annual standardised abundance U_k:

$$R_k = \frac{CPUE_k}{U_k} \quad (6)$$

This definition is in line with conventional application but is not used in the current fishing power calculation. Nevertheless, we carried out a preliminary analysis to compare the two somewhat different approaches and found they produced very similar results.

4.2 Model inputs

The fishing power model requires two input datasets: one for model estimation and the other for model prediction. There are three categories of inputs for the fishing power model: (1) dependent variable, (2) explanatory variables and (3) offsets. The information contained in each category is described below.

4.3 Dependent variable

The dependent variable, C_{ijkt} is the combined daily catch weight of the two tiger prawn species plus half of the two endeavour prawn species for each vessel *i* fishing in area *j*, during year *k* and month *t*. Records with zero catch of all four species are excluded. Unlike conventional species-specific CPUE standardisation, this model provides a species aggregated index.

4.4 Explanatory variables

A total of 17 independent variables are used to model catch rate (**Table 1**). These include:

Year **–** Year is included as a factor in the model; however, the estimation dataset does not include the last two years of the timeseries (e.g., in the 2022 estimation dataset, the final year of data is 2019). This is to account for the lag observed for industry to report technological and/or gear changes and the time taken to collate new information from gear surveys. The prediction dataset includes all years.

Areas - the *2009 Integrated Model* uses Stock Sub-region. There are 11 Stock Sub-regions: AW, CM, FB, JB, KA, ML, NG, SG, VL, WA, WM (**Figure 1**). However, data from four stock sub-regions are excluded (AW, FB, JB, and ML), leaving seven sub-regions in the model (CM, KA, NG, SG, VL, WA, WM). The excluded sub-regions have low tiger prawn catches, ranging from 0.1% to 8.0% (averaged 2.3%) of the annual tiger prawn catches from 1970 to 2021. Catches of endeavour prawns in the four excluded sub-regions vary between 0.02% to 31.8% (average 3.4%) of the total endeavour prawn catches during the 52 years. The exclusion is expected to have a negligible bias due to low tiger prawn abundance in these regions.

Calendar day - In addition to a linear term *cday*, calendar day is further included in the model as a series of splines:

c2 = cday * cday

c3 =cday^3

c4 = (cday > 196) * (cday - 196)^3

c5 = (cday > 249) * (cday - 249)^3

c6 = (cday > 287) * (cday - 287)^3

Depth – depth is included as a linear term, but depths that are equal to or deeper than 70 m are excluded prior to analysis.

Hull group – Five categories of hull, based on hull material and size. Includes an "unknown" category for missing or unknown information.

Corrected trawl hours - missing values are imputed from available trawl hours.

Local tiger effort – this is an index of localised effort for the fishing week, calculated by summing the effort in the 6-nautical-mile square grid and eight neighbouring grids, for the week centred on the current day.

Technology - Vessels in the NPF have adopted various technologies over the years and the transition to the fleet adopting an advancement is generally quick (**Figure 10**). The following technological advancements are included as factors:

I. *Hull groups (five groups, including an “unknown” group)*
II. *Try gear*
III. *Colour echosounder onboard*
IV. *PC with satellite connection onboard*
V. *Navigation - SatNav, GPS, D_GPS onboard*

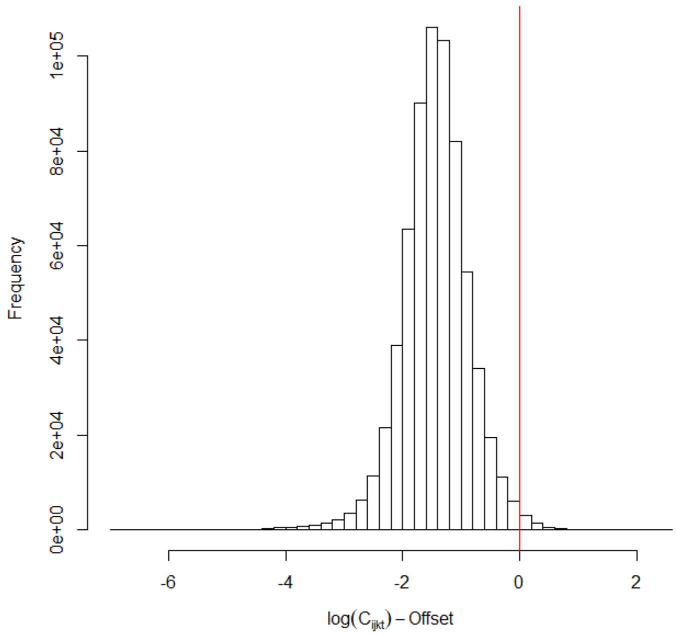
Table 1. Reported explanatory variables from Dichmont et al. (2010).

Variable Name	Variable explanation	Input form
YEAR	Fishing year	Category
STOCK_SUB_REGION	Stock sub-region	Category
CDAY	Calendar day	Numeric
DEPTH	Depth	Numeric
HULLG	Hull groups	Category
SATIG	Swept area rate	Offset
Log_HOURS	Corrected trawl hours	Offset
O_BRDN	Presence of TED and BRD	Offset
RADAR	Presence of Radar	Offset
NAV_ACCG	SatNav, GPS, D_GPS	Category
B&W_Echo	Black and white echosounder	Offset
TRYGEAR	Try gear used	Category
PLOTTER	Plotter used	Category
PC_SAT	PC with Satellite connection	Category
AUTOPILOT	Autopilot	Offset
LTEG	Local tiger effort group	Category
ECHOCOL	Colour echosounder	Category

4.4.1 Offsets

Although technically a form of dependent variable, the treatment of offsets in this model is such that offsets are subtracted from log(C_{ijkt}) before the model fitting as opposed to being included in the modelling procedure. For example, prior to fitting the *2009 integrated model*, the following treatment is performed: LC08J = LC - OS08J where LC is log-catch [i.e., log(C_{ijkt})] and OS08J is the offset for the *2009 integrated model* (see below). Offsets tend to be large, resulting in most values of the dependent variable (log(C_{ijkt})) being negative (Error! Reference source not found.). Once the fitted values are obtained, the offset values (Offset OS08J) are added to the predicted log-scale catch. Such a treatment seems to yield the same result as simply modelling LC as dependent variable and including offset directly in the model.

Figure 2. Value of dependent variable LC08J, indicating that most daily catches are smaller than offset.



Several variables are used as offsets which, as previously described, are subtracted directly from the model estimate of log(C_{ijkt}). In the current model, the offsets are combined to form a single offset index, OS08J, which is calculated as:

OS08J = O_BRDN + LOG(SATIG) + 0.95*LOG(HOURS) + OFFSET2J;

where *O_BRDN* refers to whether the vessel had TEDs/BRDs, *SATIG* (Tiger swept area index) is an index derived from the Prawn Trawl Performance Model (PTPM), an engineering model that tracks the annual swept area ability of the fleet and is derived from data collected in annual gear surveys (Sterling, 2005), *HOURS* is the corrected trawl hours where unrealistic and missing values are imputed from available data, and OFFSET2J is calculated as:

OFFSET2J = OFFAUTO2J + OFFECHO2J + OFFRADAR2J;

where *OFFAUTO2J* refers to the presence of an autopilot, OFFECHO2J refers to presence of black/white echosounder, and OFFRADAR2J refers to the presence of radar.

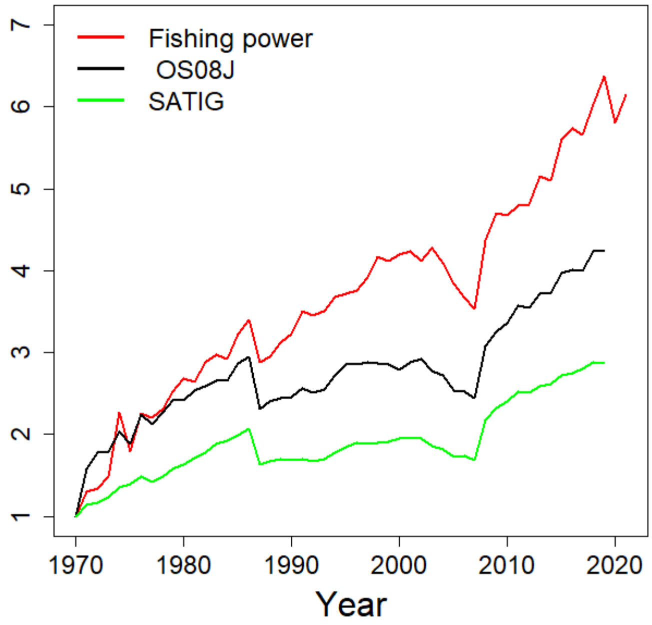
OS08J is the combined offset index currently used for *2009 integrated model*. A different offset, OS08R, was used in the "Mid-High Model" that was applied in the past (Dichmont et al. 2010) and is not presented here.

Once the model parameters have been estimated, a reconstructed dataset is used for model prediction. The prediction dataset has the same variables and structure as the estimation dataset except: (1) dependent variable LC08J (or LC08R) is blank; (2) *year* is set to 1984. After model fitting and prediction, the standardized catch is obtained by the exponential of the model predicted log-scale catch plus offset OS08J and bias correction 0.5mse.

5 Relative influence of explanatory variables and offsets

Since 1970, estimates of annual fishing power have increased six-fold (**Figure 3**). The increase in fishing power is largely driven by the swept area index (SATIG) derived from the engineering PTPM. The SATIG accounts for approximately 50% of the observed increase. When SATIG is summed with the other offsets (i.e., OS08J), the OS08J offset accounts for approximately 70% of the increase in fishing power. The remaining 30% of the increase can be attributed to the estimated explanatory variables within the GLM procedure.

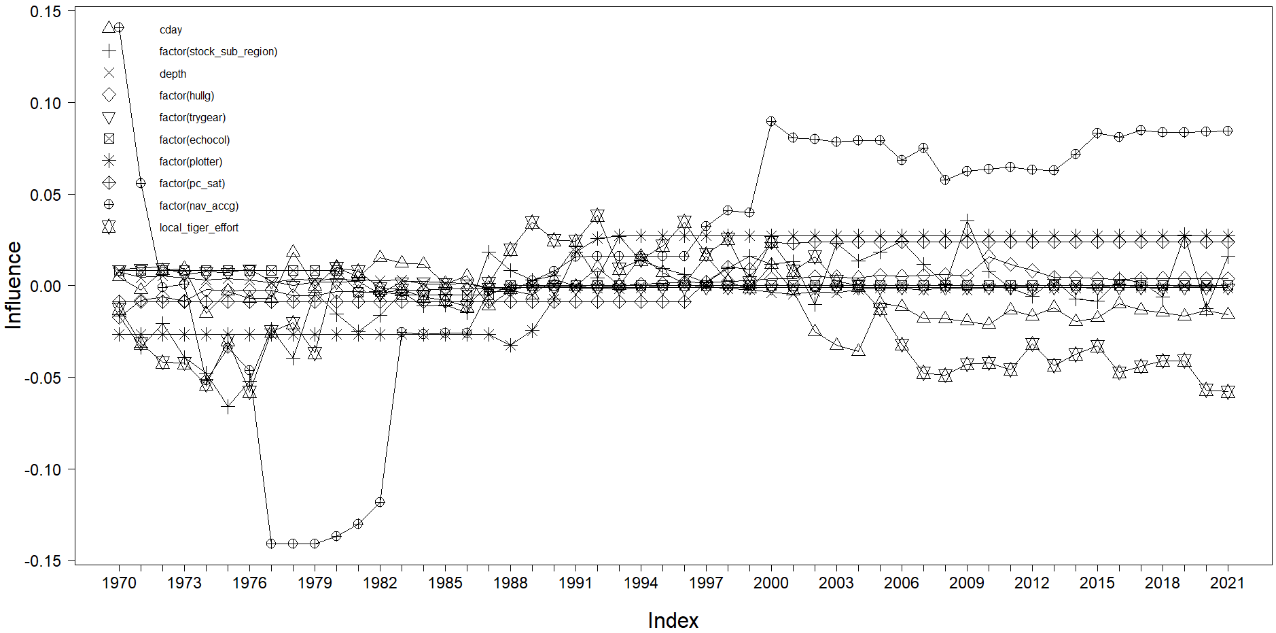
Figure 3. Time-series of the NPF Fishing Power index (red) for the period 1970 - 2021. This index can be further disaggregated into the combined offsets index, OS08J (black line) and the swept area index, SATIG (green line).



4.5 5.1 Explanatory variables

There are 10 independent variables (excluding offsets) used to model catch rate in the *2009 integrated model*. When applying GLMs for CPUE standardization, or in this case fishing power estimation, the objective is to remove the confounding effects of unimportant variables. Therefore, it is common practice to include all explanatory variables and scrutinise the influence of each variable on the model output. To do this effectively, Bentley et al., (2011) developed influence plots and the metrics that are applied here. **Figure 4** compares the normalised influence of each of the explanatory variables across the period of the fishery (1970-2021). Positive values indicate a positive relationship with the dependent variable, in this case log-catch minus offsets, with higher magnitudes exerting more influence. Likewise, for negative values, while values near zero are least influential. The aggregated navigation variable (*accg_nav*) has the highest positive influence, while both *plotter* and *pc_sat* variables are consistently positive. In contrast, the day of year (*cday*) and effort (*local_tiger_effort*) were the only variables with a consistently negative influence after the year 2000 (**Figure 4**).

Figure 4. Combined plot depicting normalised influence of explanatory variables on the NPF Fishing Power index for the period 1970 - 2021.



Variable-specific influence analyses are shown in coefficient–distribution–influence (CDI) plots (**Figures 5a-5j**). In all plots, (1) the top panel of the plot provides normalized coefficients and their standard errors – this is the relative magnitude of the estimated coefficient (2) the bottom left panel, bubbles indicate the annual distribution of records across each level of the variable - this is the proportion of records from each variable in each year, and (3) the bottom right panel shows the annual values of influence for the given variable – essentially, this shows the relative influence of the specific parameter on fishing power estimates across the timeseries. Notably, the aggregated navigation variable (*accg_nav*) seems to have the highest positive influence, especially from 2000 onwards (**Figure 5a**). Unsurprisingly, the most accurate category of *accg_nav* (*1-15m* accuracy) has the highest normalised coefficient – most vessels fall in this category from 2012 onwards. Hull group also has a positive influence with more vessels falling into the *steel>86<=26* category toward the latter period of the time-series (**Figure 5b**). Subregion had a positive influence over time, with more effort within the Vanderlins area in the latter years; Vanderlins has the highest coefficient (**Figure 5c**). The variable *plotter* shifts from a negative to positive influence from 1987-1993 and remains constant with a coefficient of 1.03 thereafter (**Figure 5d).** Similarly, *pc_sat* shifts from a negative to positive influence from 1996-2000 and remains constant with a normalised coefficient of 1.025 thereafter (**Figure 5e**).

Figure 5 a. CDI plot depicting the influence of the aggregated navigation variable (accg_nav) on the NPF Fishing Power index for the period 1970 - 2021

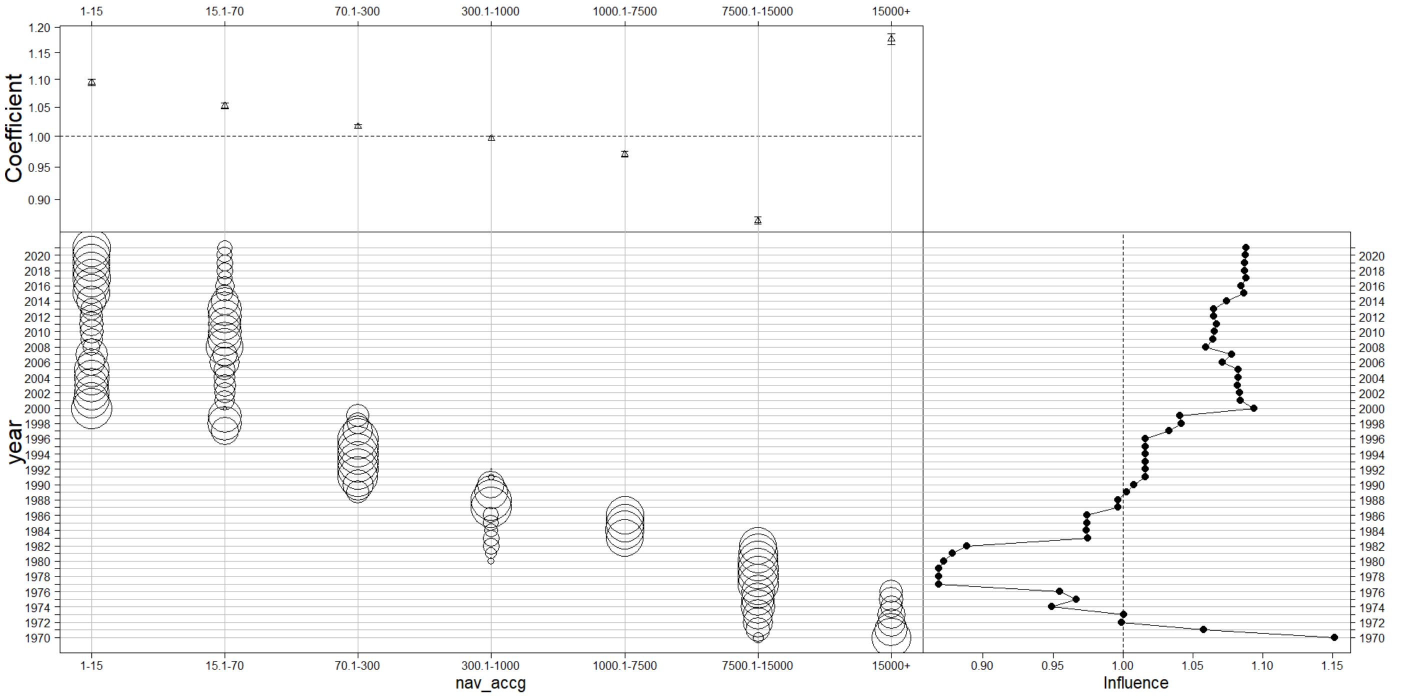


Figure 5 b. CDI plot depicting the influence of hull group (hullg) on the NPF Fishing Power index for the period 1970 - 2021

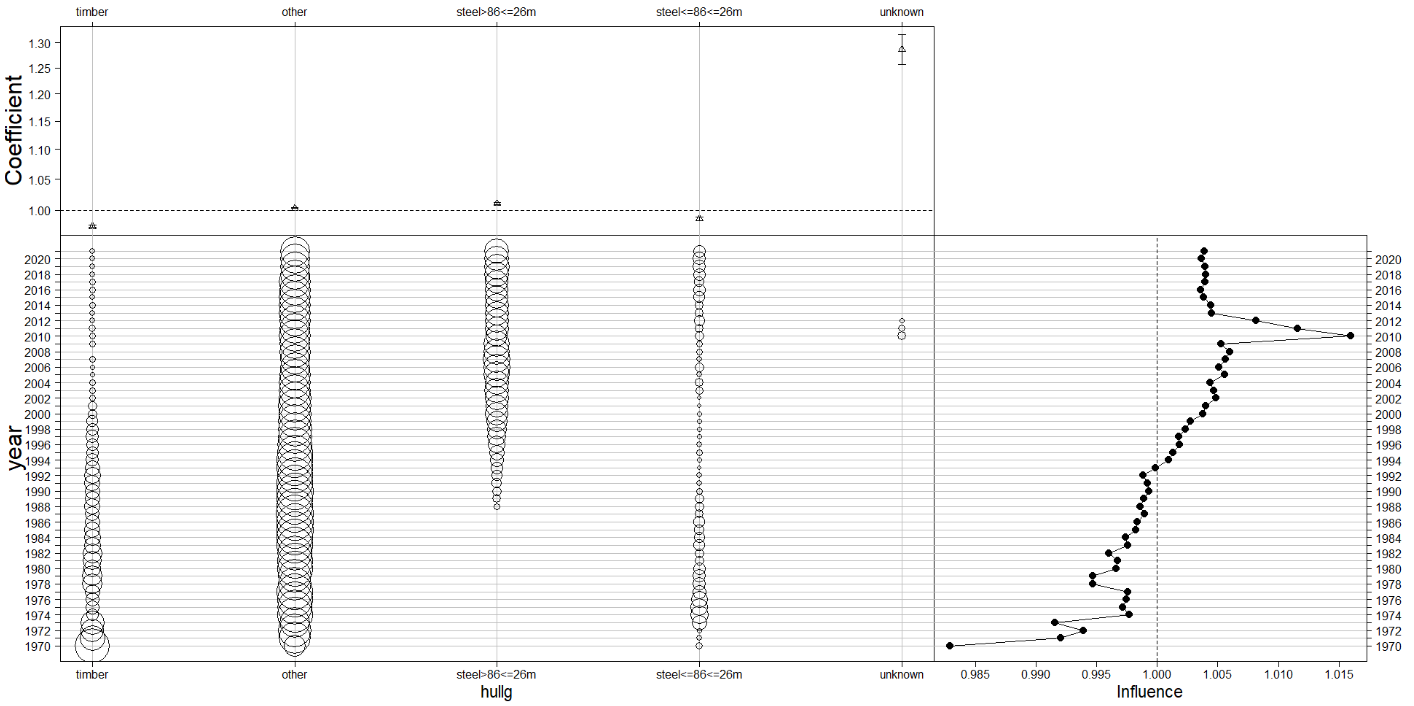


Figure 5 c. CDI plot depicting the influence of sub-region (stock_sub_region) on the NPF Fishing Power index for the period 1970 – 2021

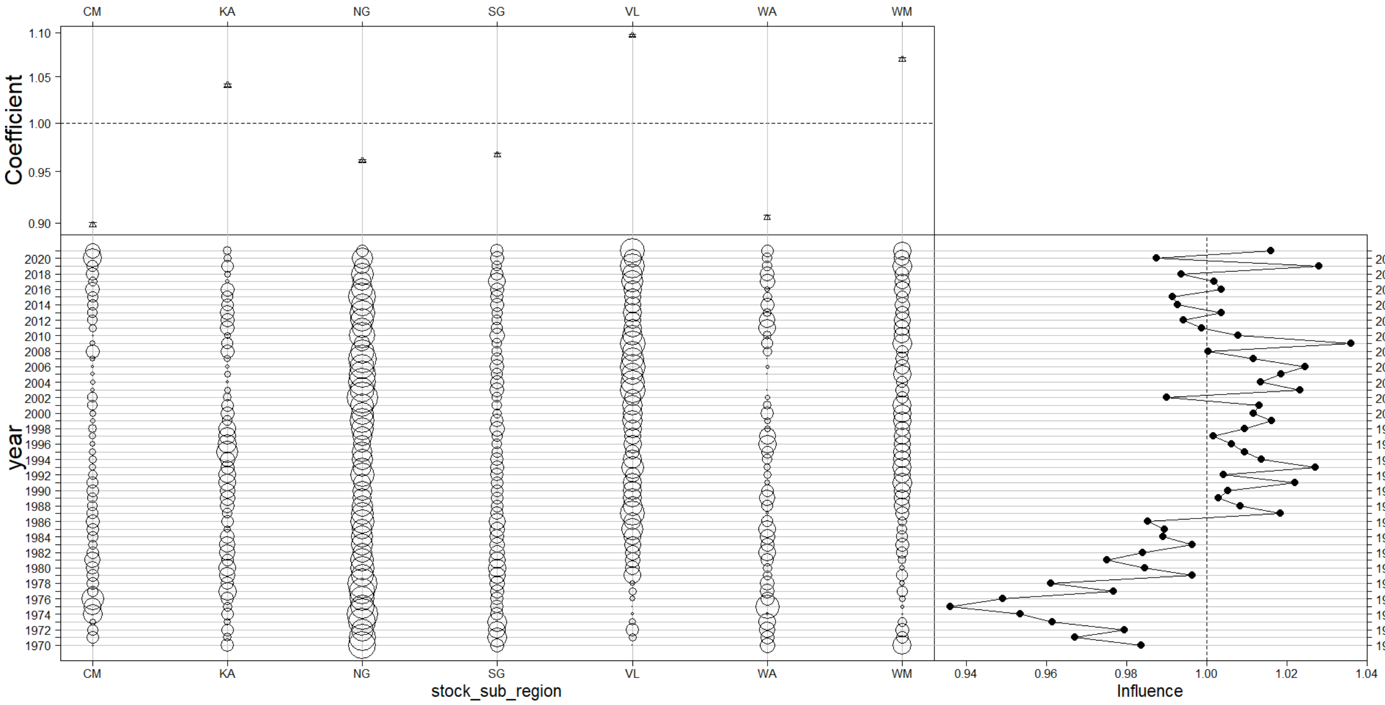


Figure 5 d. CDI plot depicting the influence of plotter used (*plotter*) on the NPF Fishing Power index for the period 1970 – 2021

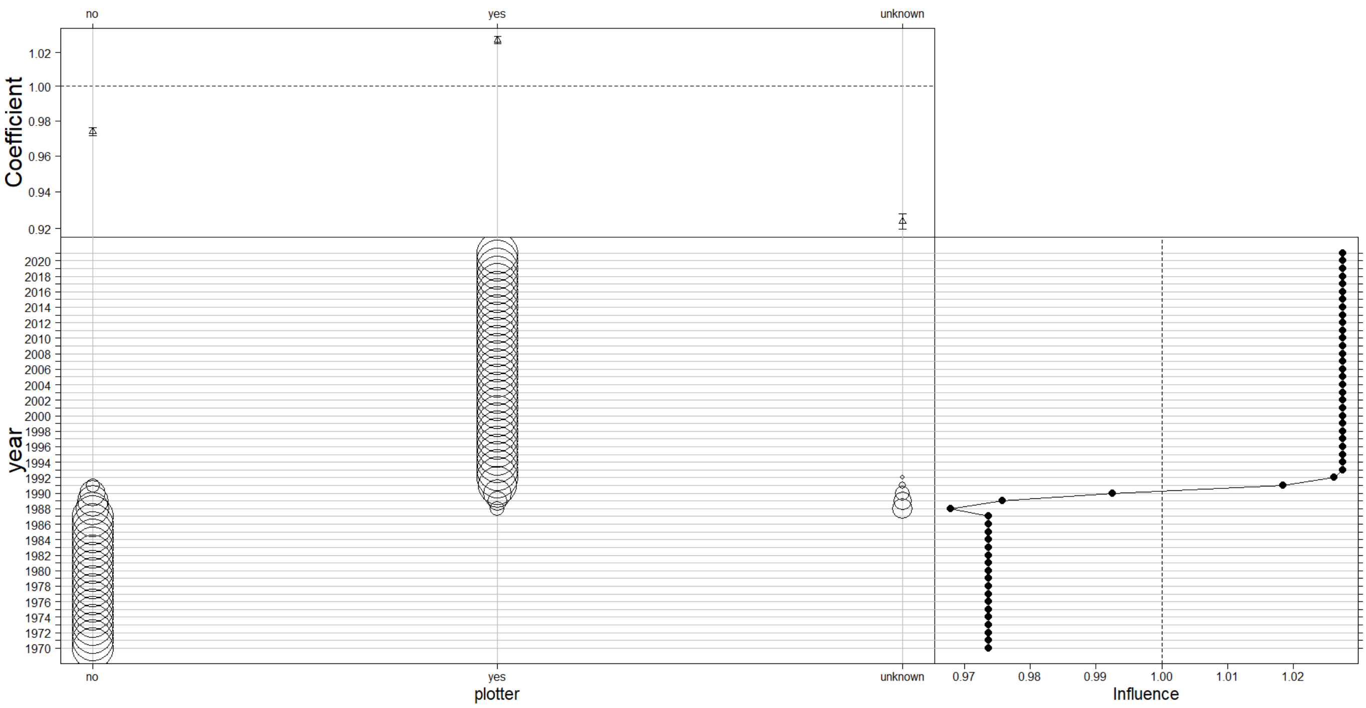


Figure 5 e. CDI plot depicting the influence of computer with satellite connection (pc_sat) on the NPF Fishing Power index for the period 1970 - 2021

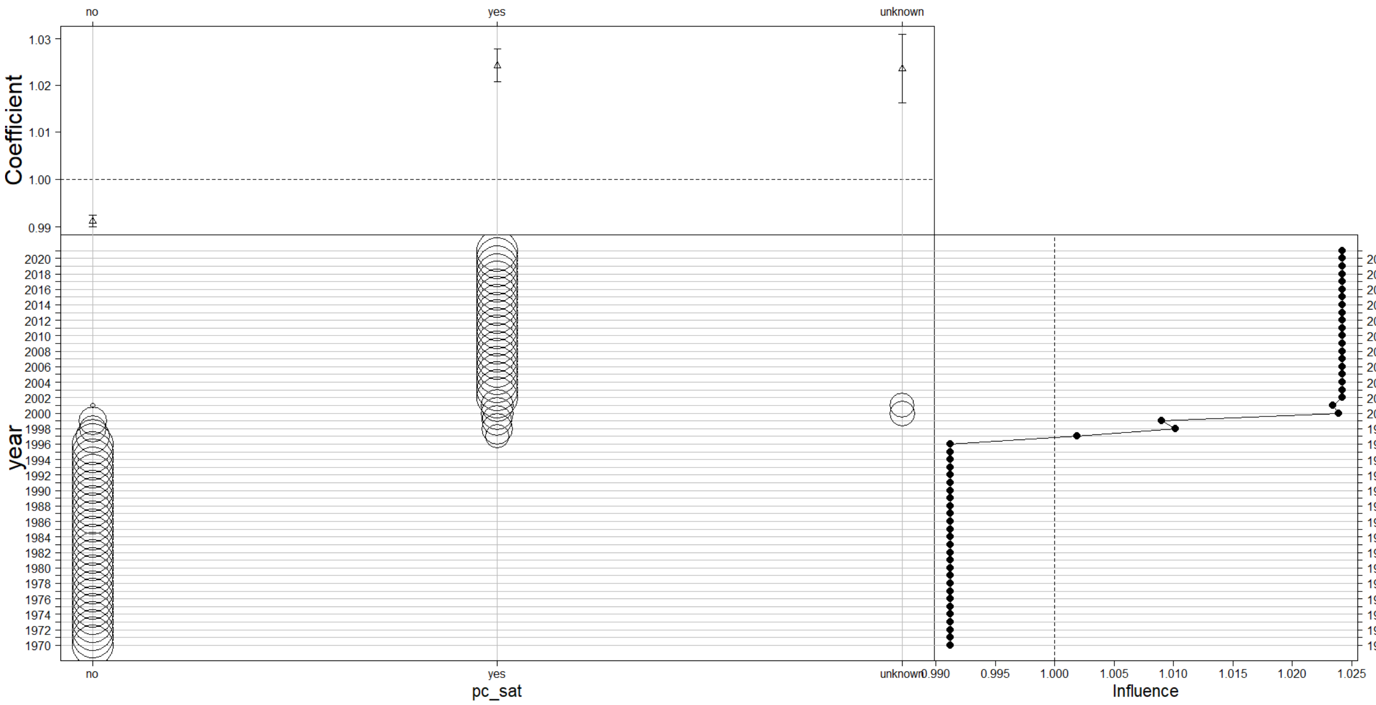


Figure 5 f. CDI plot depicting the influence of depth on the NPF Fishing Power index for the period 1970 - 2021

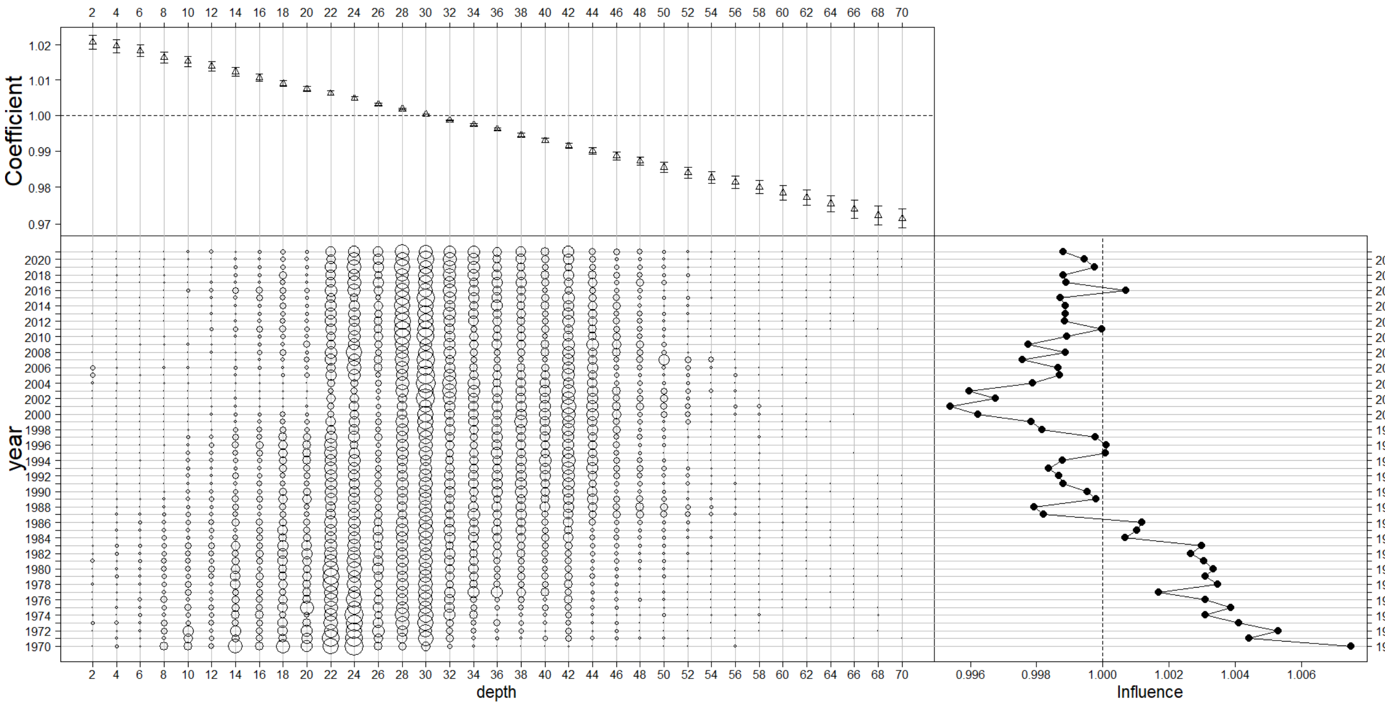


Figure 5 g. CDI plot depicting the influence of day of the year (cday) on the NPF Fishing Power index for the period 1970 – 2021

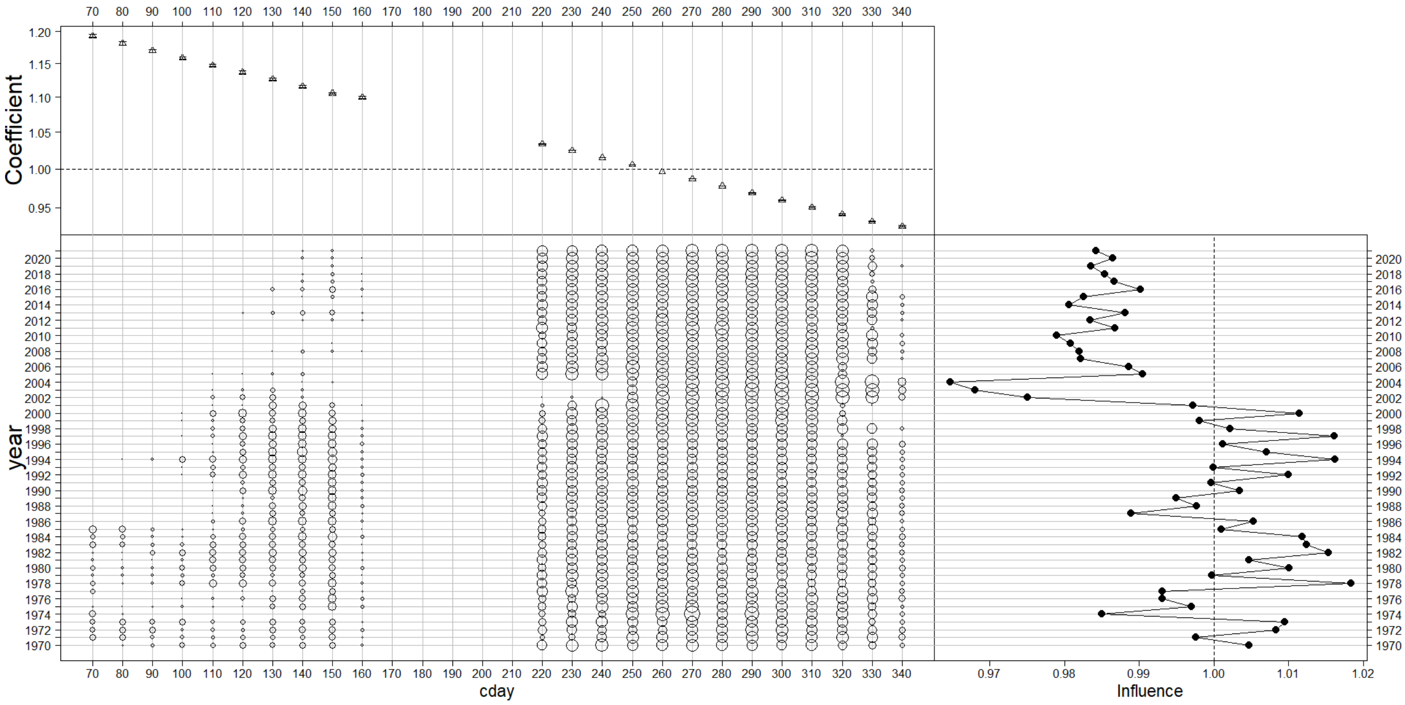


Figure 5 h. CDI plot depicting the influence of colour echosounder (echocol) on the NPF Fishing Power index for the period 1970 - 2021

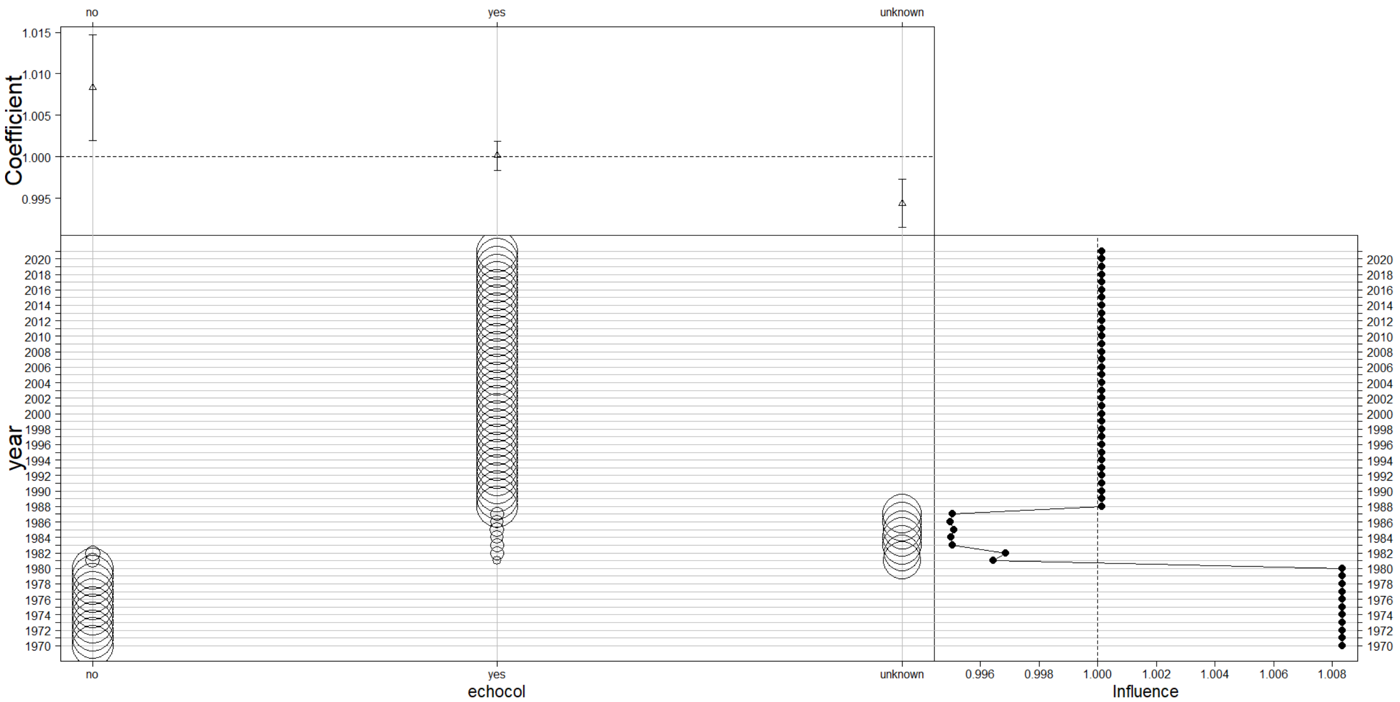


Figure 5 i. CDI plot depicting the influence of local tiger effort (local_tiger_effort) on the NPF Fishing Power index for the period 1970 - 2021

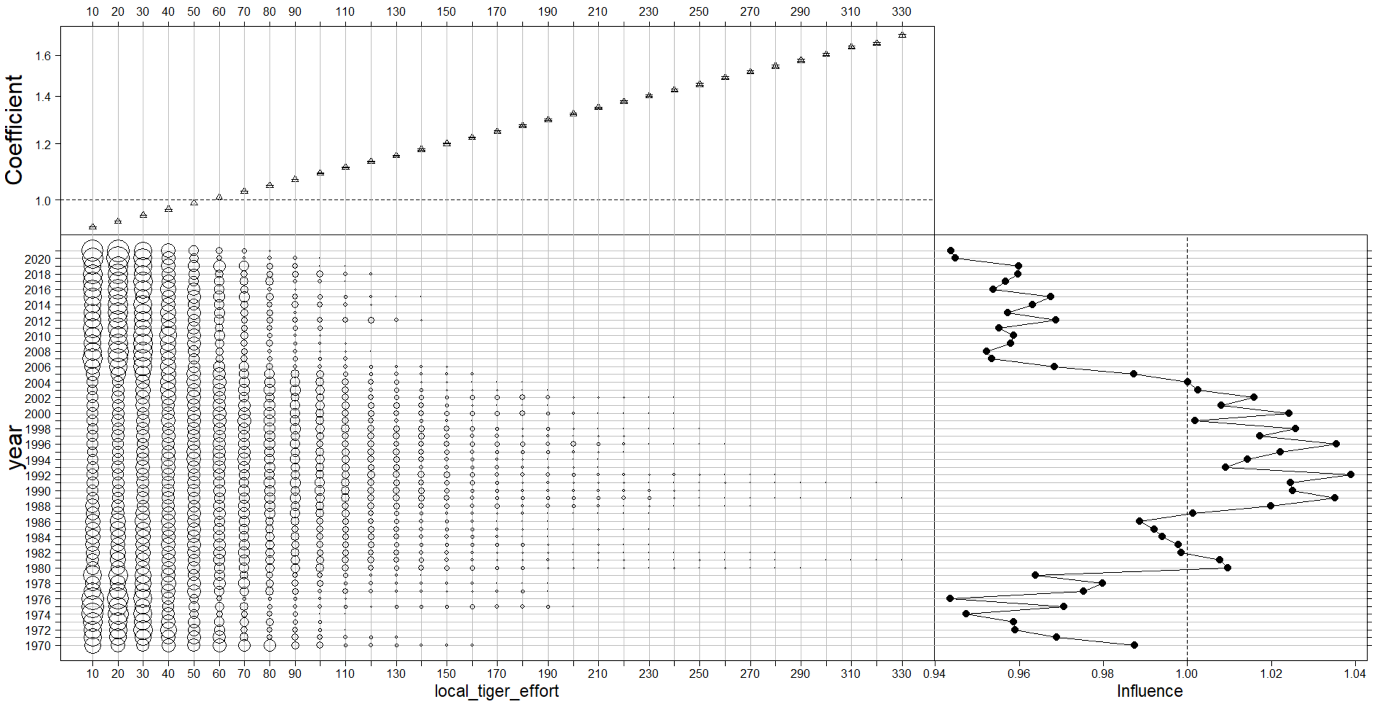
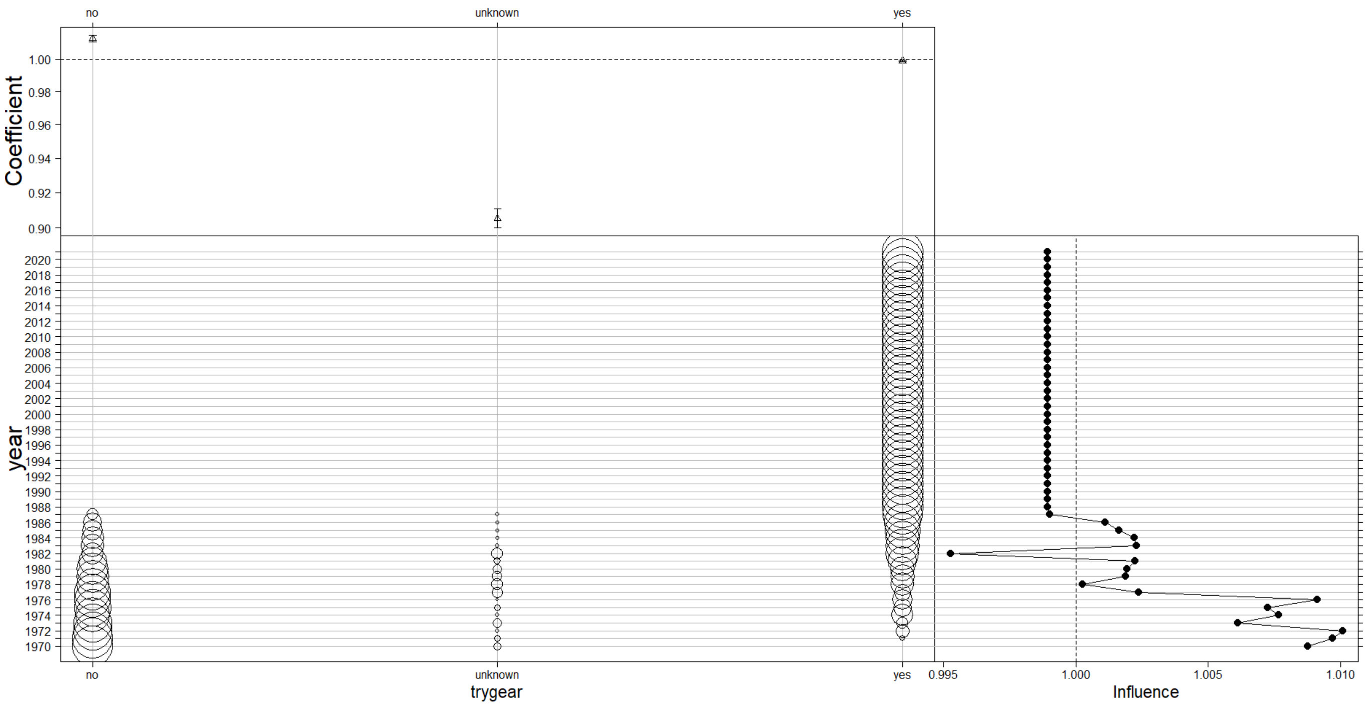


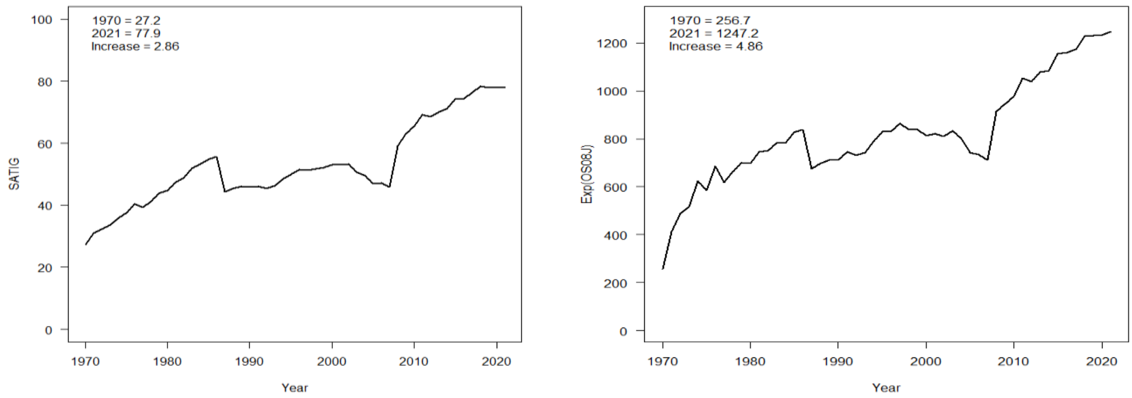
Figure 5 j. CDI plot depicting the influence of use of try gear (trygear) on the NPF Fishing Power index for the period 1970 – 2021



4.6 Offsets

The multiple offsets, including SATIG, are combined to form a single variable, OS08J, which is subtracted from the dependent variable prior to running the model, then added to the model outputs. The summed offset for OS08J increased by a factor of 4.86 for the period 1970 – 2021. The swept area index (SATIG) is the most influential variable in the fishing power analyses, explaining between 50% - 60% of the variation in the seasonal catching performance of trawlers in the NPF (Sterling, 2005). The SATIG estimate increased by a factor of 2.86 for the period 1970 – 2021. Combined, SATIG and the other offsets (i.e., OS08J) account for the majority (approx. 80%) of the increase in fishing power (**Figure 6**).

Figure 6. Comparison of (left) the swept area index (SATIG) derived from the PTPM and (right) the combined offset index OS08J.



In addition to the swept area index, the remaining variables that contribute to the summed offset variable (OS08J) are *corrected trawl hours*, *autopilot, radar, B&W echosounder, TED & BRD.* A comparison of the annual variation on these offset values is provided in **Figure 7a**, as well as their relative change over the period 1970-2022, when normalised to the starting (1970) values (**Figure 7b**). Corrected trawl hours, as described above, remain relatively constant except for the early (pre-1980) period. The highest corrected trawl hours value was observed in 2021 (2.61), and the lowest in 1970 (2.22) and the average is 2.49. These values are in log space. The combined offset of *autopilot, radar, B&W echosounder (i.e., OFFSET2J)* increases substantially from 1970-1980, but remains constant thereafter – this is particularly clear in **Figure 7b**, where the normalized index almost doubles over this period. This value was determined in consultation with industry in the development of the *2009 integrated model* and reflects the cumulative increase in fishing efficiency given the concurrent introduction of autopilot, radar, and echosounders to the NPF fleet. In contrast, the introduction of Turtle Exclusion Devices (TEDs) and Bycatch Reduction Devices (BRDs) has a constant, negative coefficient of -0.01 after the year 2000.

Figure 7 a. Comparison of annual values of the offset variables included in the *2009 integrated model.*

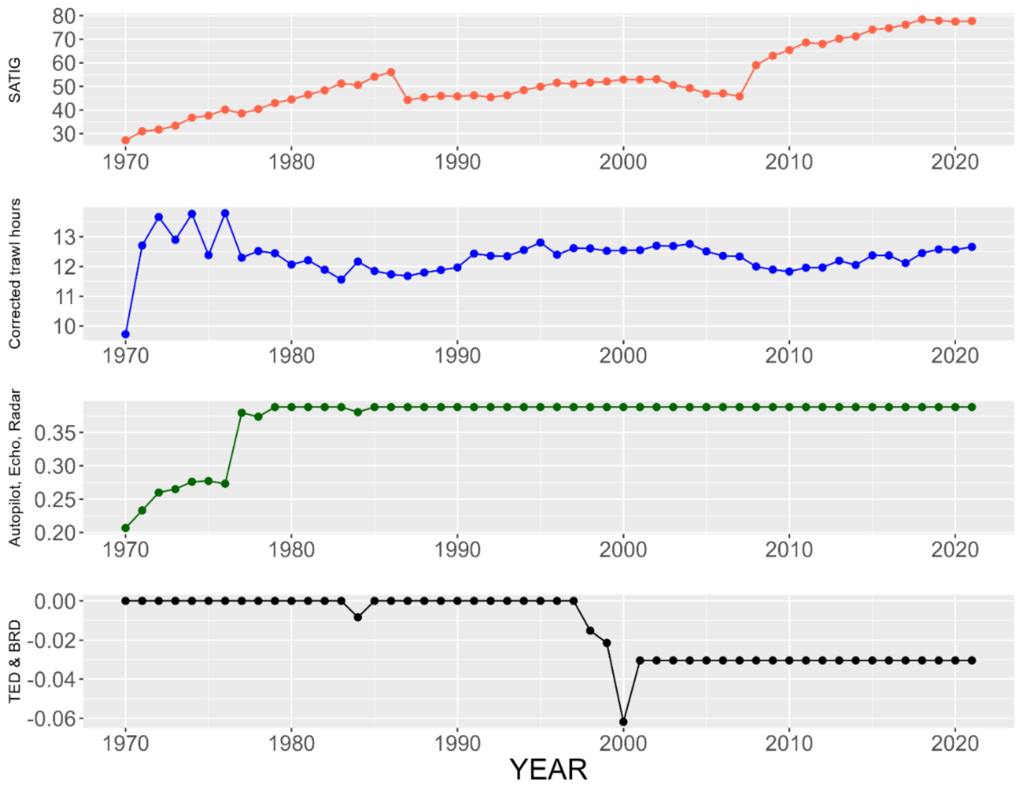
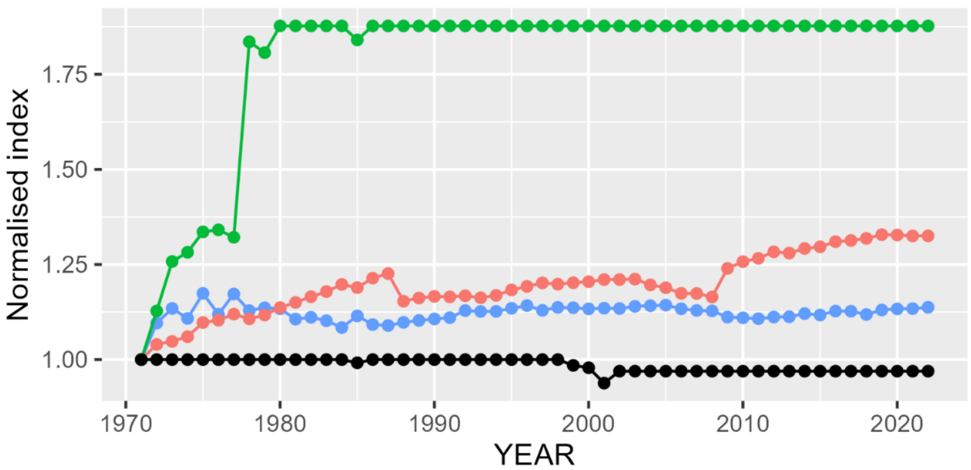


Figure 7 b. Normalised trends for the offset variables included in the *2009 integrated model.*



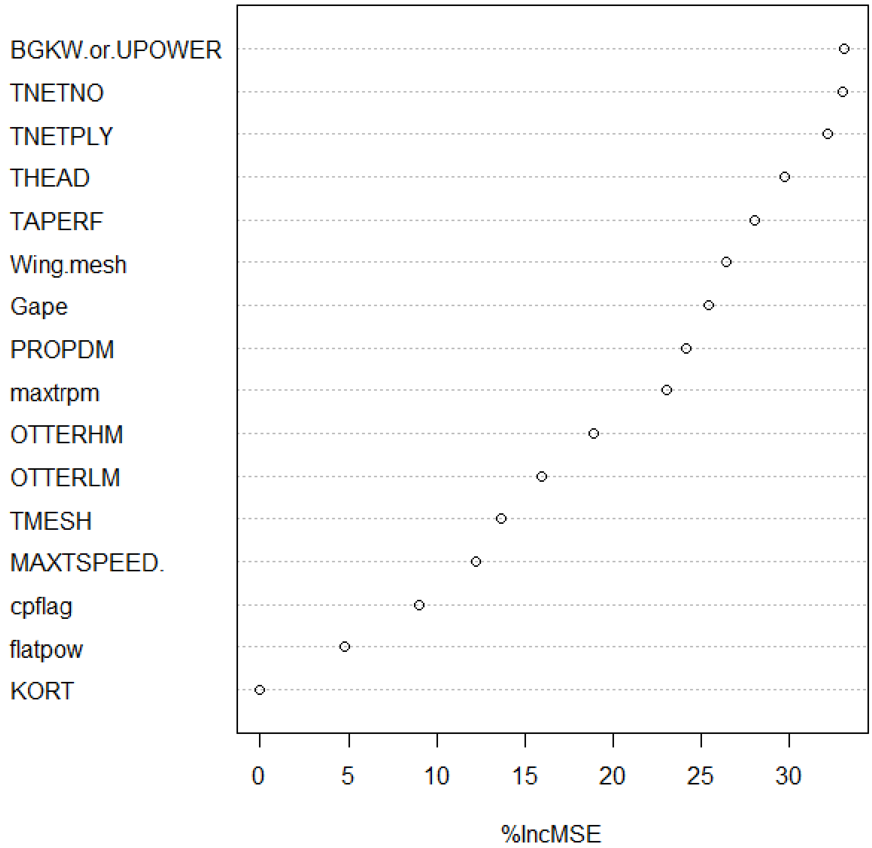
4.7 5.2 The swept area index - SATIG

To determine the influential variables driving the SATIG trend, we explored the PTPM input data derived from annual gear surveys. A Random Forest analysis was used to evaluate the relative importance of PTPM input variables. The ensemble method 'random forests' (RF; Breiman 2001) is an extension of the Classification and Regression Tree approach (CART; Breiman et al. 1984), whereby many classification trees are constructed from randomly selected subsets of the original data and grouped to form a 'forest' algorithm. One of the by-products of RF calculations is a measure of variable importance. The RF indicates that *engine power, net number* (double vs. quad) and *net ply diameter* were the three most important variables (**Figure 8**). Although the remaining variable certainly contributes to the observed SATIG trend, preliminary analyses, and expert opinion (pers. comm David Sterling) suggests that their combined contribution may be less important. As such, the results below are limited to engine power, net number (double vs. quad) and net ply diameter. Results for the remaining variables are included in **Appendix 1**.

Table 2. Explanation of variables included in the Prawn Trawl Performance Model (PTPM). Derived from Sterling (2005).

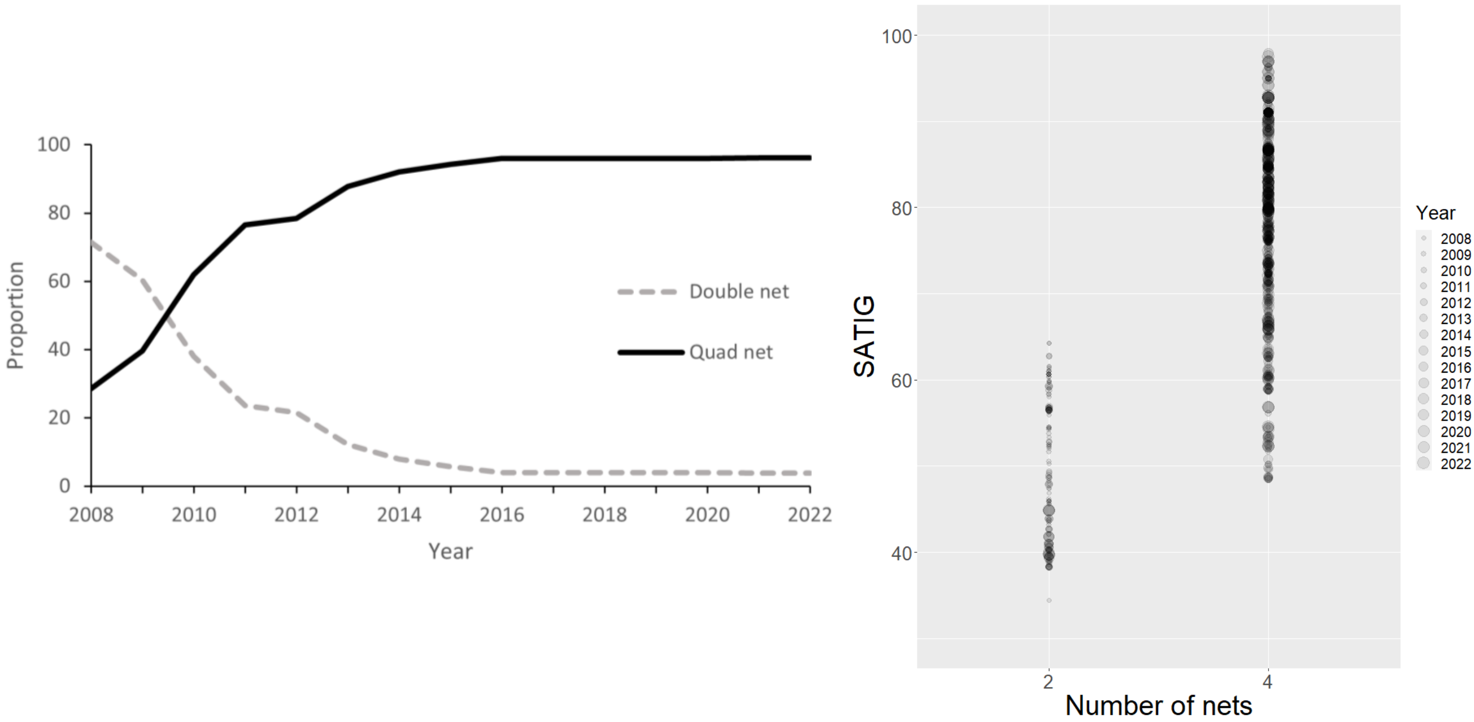
Variable	Name	Description
TNETNO	Net number	*The net configuration (double vs. quad)*
THEAD	Headline length	
TAPERF	Body taper	
TNETPLY	Netting ply diameter	*Thickness of netting ply in mm*
TMESH	Mesh size	
OTTERLM	Otter board length	*Length of otter board in metres*
OTTERHM	Otter board height	*Height of otter board in metres*
CL	Lift coefficient	*Lift coefficient based on otter board type*
MAXTSPEED	Maximum trawling speed	*Trawling speed in knots*
BGKW or UPOWER	Rated power of the engine	*The engine Maximum Continuous Rating*
PROPDM	Propeller diameter	*Propellor size in metres*
KORT	Kort nozzle thrust factor	
cpflag	Control pitch flag	
maxtrpm	Maximum trawling engine speed	*Engine speed in revolutions/minute*
ratedrpm	Rated engine speed	*Engine speed in revolutions/minute*
orpm	Operating engine speed	*Engine speed in revolutions/minute*
Wing mesh	Wing-end mesh size	
Gape	Headline gape	*Inherent spread ratio*

Figure 8 . A random forest analysis to determine the relative importance of the Prawn Trawl Performance Model (PTPM) variables on the resultant swept area index (SATIG).



Data from the PTPM annual gear surveys indicate a shift in the number of nets deployed over time, with the quad rig being preferred in recent years. In 2008, the composition of the fleet configurations was 72% double net rigs and 28% quad net rigs. In 2021, this ratio inverted and is now 4% double net rigs (only two vessels) and 96% quad nets rigs (**Figure 9a**). The relationship between the number of nets deployed and the swept area index is significantly positive i.e., the more nets the higher the average swept area. The PTPM annual gear survey data also indicates a significant positive relationship between the rated engine power and the average swept area index value (**Figure 9b**). In 2008, the range of rated engine power values was 272-495KW. While the minimum value remains constant across the period, several highly rated engines have been introduced into the fleet (maximum of 691KW in 2022), which has increased the average engine rated value across

Figure 9 a. (left) The proportion of vessels configuration *(double vs. quad)* in the NPF for the period 2008-2021 and, (right) the relationship between the *number of nets (double vs. quad)* and the swept area index (SATIG).



the fleet. This is apparent in the vertical extension of the violin plots since 2015 in **Figure 9b**. Finally, there is a negative relationship between netting ply diameter and the average swept area index, and over time vessels have generally adopted the use of thinner netting ply, moving from 36 to 26 mm ply (**Figure 9c**).

Figure 9 b. (top) The relationship between rated engine power and the swept area index (SATIG) and, (bottom) the distribution of rated engine power observations obtained from annual gear surveys performed from 2008 to 2022.

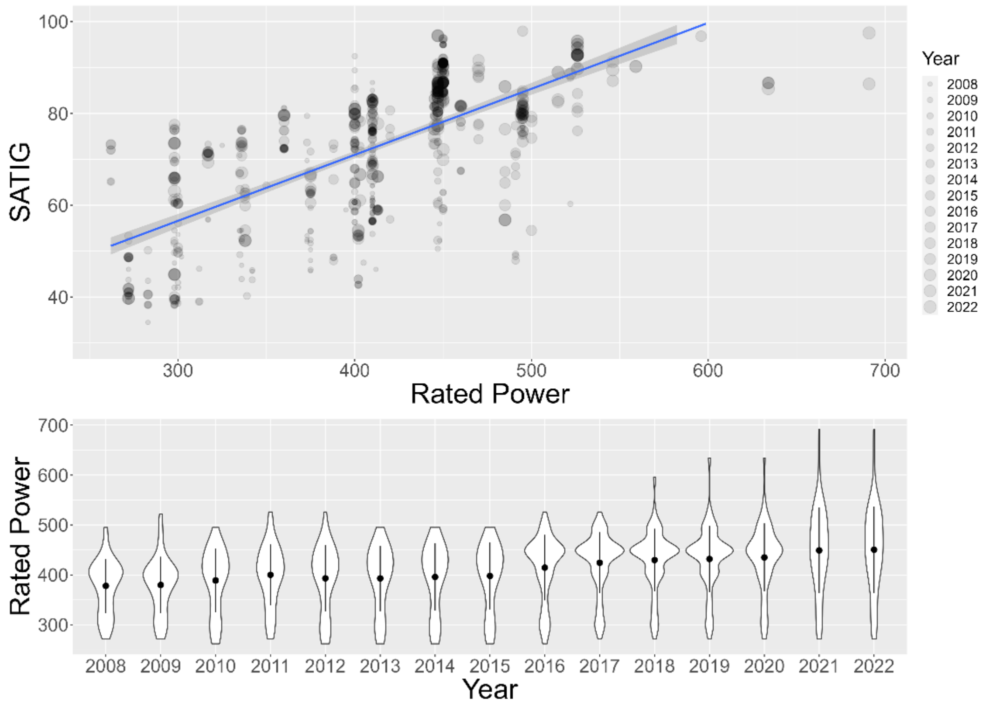
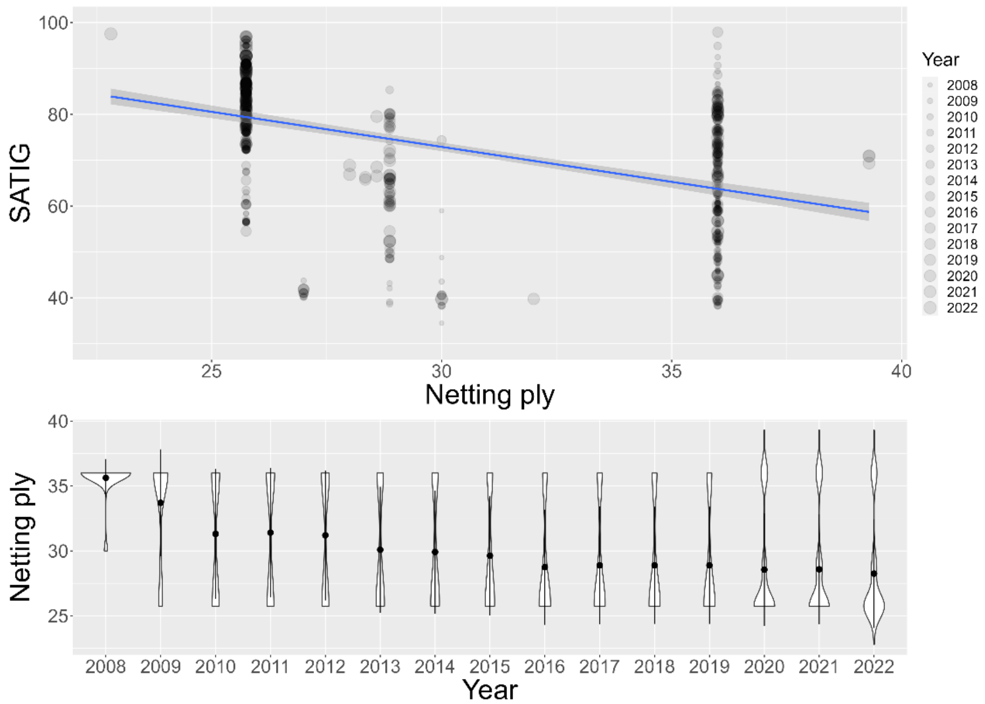


Figure 9 c. (top) The relationship between netting ply diameter and the swept area index (SATIG) and, (bottom) the distribution of netting ply diameter observations obtained from annual gear surveys performed from 2008 to 2022.



6 Fishing power & the Tiger Prawn stock assessment

It is necessary to understand how fishing power is used in stock assessment models before further review and discussing implications. Fishing power is used in both the size-structured models for tiger prawns and the biomass dynamics models for endeavour prawns.

In the size-structured stock assessment method, time series of relative fishing power is used to adjust nominal fishing effort when calculating fishing mortality rate (Punt et al. 2023):

$$F_{k,y,w,l} = A_{k,w}\,\gamma_{y,w}\,S^F_{k,l}\,(q^G_k E^G_{y,w} + q^B_k E^B_{y,w}) \tag{7}$$

where $E^G_{y,w}$ and $E^B_{y,w}$ are the levels of nominal effort during week *w* of year *y* by the fleet targeting grooved (G) and brown (B) tiger prawns, respectively, q^G_k and q^B_k are the catchability coefficients for the fishing strategies targeting G and B, respectively, $A_{k,w}$ is the relative availability of animals of species *k* during week *w*, $\gamma_{y,w}$ is the relative fishing power of the two fishing strategies during week *w* of year *y*, and $S^F_{k,l}$ is the selectivity of the fishery on animals of species *k* in size-class *l*. Here q^G_k and q^B_k are species-specific but fixed values for year 1993. This equation implies that change in fishing power is the same for both target and bycatch species. By setting $\gamma_{1993} = 1$, time series of relative fishing power can be viewed as either adjusting catchability so $q_{y,k} = \gamma_y * q_k$ is the year-specific catchability, or $sE_y = \gamma_y * E_y$ becomes standardized effort analogous to fishing power (catchability) in 1993.

In the biomass dynamics model, nominal CPUE is linked to biomass by catchability and fishing power:

$$CPUE_{k,y} = \gamma_y q_k B_{k,y} \tag{8}$$

This is equivalent to adjusting nominal $CPUE_{k,y}$ by fishing power to obtain standardized

$sCPUE_{k,y}$, i.e.,

$$\frac{CPUE_{k,y}}{\gamma_y} = sCPUE_{k,y}.$$

The applications of fishing power in stock assessments show: (1) each of the two tiger prawn species are modelled as target species as well as bycatch species; (2) fishing power is used to convert nominal catch rate (or effort) to standardised catch rate (or effort).

7 Discussion

The swept area index is the most influential of all offset variables and accounts for approximately 50% of the observed increase in the NPF fishing power. This index, which is calculated from the PTPM, increased by a factor of 1.32 since 2008. The combined offset variable, OS08J, (which includes SATIG) increased 1.38 times since 2008 and 4.86 times since 1970. The variable OS08J contributes approximately 70% to the observed increase in fishing power. The remaining 30% increase can be attributed to explanatory variables fitted in the GLM procedure (i.e., navigation accuracy, sub-region etc.).

To determine the influential variables driving the SATIG trend, we explored the PTPM input data derived from annual gear surveys. This revealed that engine power, net number (double vs. quad) and net ply thickness were the three most important variables. There is a substantial increase in swept area estimates associated with quad net configurations when compared to double net (coefficient = 1 : 1.56). Since 2008, the fleet has undergone a transformation to uptake the more efficient quad gear configuration. In 2008, the composition of the fleet configurations was 72% double net rigs and 28% quad net rigs. In 2021, this ratio inverted and is now 4% double net rigs (only two vessels) and 96% quad nets rigs. The Northern Prawn Fishery (NPF) fleet used double rigs between 1987 to around 2006; prior to 1987 most trawlers towed quad rigs. Around 2005, there was interest in the NPF to improve economic efficiency and again allow the use of quad rig. In response to this interest, a report titled "*The introduction of Quad rig in the NPF – seeking an effort neutral transition, and implications for TED/BRD performance*" was produced by Stirling et al., (2005) to estimate the increase in swept area and catch efficiency between two and quad rig configurations - the non-technical summary of this report is provided in Appendix 2. The results indicate that under constant engine power there would be a 19.2 - 26% increase in catch benefit when switching from double to quad rig configurations. Under constant trawl speed, the estimated increase in catch benefit was 10 - 16%. Our analyses of the PTPM input data indicate that neither of the assumptions of constant engine power or trawl speed have been maintained and there is all likelihood that the increase in catch benefit is higher than those presented in Stirling et al., (2005). Notably, rated engine power (*BGKW.or.UPOWER*) was determined to be the most important variable driving the SATIG trend; there is a significant positive relationship between rated engine power and SATIG. Furthermore, rated engine power has increased over time. In 2008, the average weighted power across the fleet was 378KW and a maximum value of 495KW. By 2022, the average rated engine power increased to 450KW with a maximum of 691KW. The third most important variable in the estimation of SATIG is the diameter of netting ply. There is an inverse relationship between netting ply diameter and SATIG - the thinner the ply the higher the swept area estimate. This is likely a result of reduced drag. The fleet predominantly deploys three diameters of netting ply, 26, 29 and 36 mm, but there has been a clear trend towards using the thinnest (26 mm) ply in recent years. The steady shift of the fleet from double to quad net rigs, in conjunction with a fleet wide increase in rated engine power and increased deployment of the thinnest netting ply, are the major factors responsible for the observed increase of the swept area index since 2008.

The remaining variables that contribute to the summed offset variable (OS08J) are *corrected trawl hours*, *autopilot, radar, B&W echosounder, TED & BRD.* Corrected trawl hours, an offset originally included to deal with missing effort information in the early period (i.e., pre-1980), has remained relatively constant after 1980. The O*FFSET2J* offset increases substantially from 1970-1980 but remains constant thereafter. The plausibility of the constant coefficient placed on technological advances employed three decades ago should be reviewed. As expected, the introduction of TEDs and BRDs decreases catching efficiency slightly due to prawn escapement.

When assessing the influence of explanatory variables fitted within the model, the aggregated navigation variable (*accg_nav*) has the highest positive influence, especially for the latter period i.e., post-2000. The most accurate category of this variable (*1-15m* accuracy) has a normalised coefficient of 1.1. Hull group and fishing area (subregion) also has a positive influence with more vessels falling into the *steel>86<=26* category and more fishing effort being observed within the Vanderlins area toward the latter period of the time-series. Certain variables, such as *plotter* and the use of computers with satellite connection (*pc_sat*), have a single step increase in their coefficient as the fleet implements the new technology over a short period (1-3 years). The values of these constant offset coefficients were determined through consultation with industry when developing the *2009 integrated model.* As with O*FFSET2J*, the influence of these variables remains constant and perpetual thereafter. The plausibility of this requires review, as technologies are likely to become outdated and their contribution to improved catch efficiency is likely to depreciate with time.

8 Further Development & Possible Revisions

The fishing power estimation method used in the NPF was developed in early 2000s (Dichmont *et al.*, 2003) and has been revised since (Bishop *et al.*, 2008; Dichmont *et al.*, 2010). Our review of the methodology prompted several discussions regarding possible revisions in the procedure.

Catchability and fishing power can be affected by both gear efficiency and the spatial distribution of both prawns and fishing effort. The four species of prawns are known to have different spatial distributions; therefore, it may be more appropriate to estimate fishing power for each species separately. Effort distribution, across both season and space, also differs depending on the target species. It is, therefore, likely that fishing power and its temporal trend should differ between species (i.e., target; non-target). Furthermore, the *2009 integrated model* method does not account for spatial variation over time because the model uses sub-stock areas that remain unchanged over time. Spatial heterogeneity is one of the primary interests in CPUE standardisation. Although *Stock Region* or *Sub-stock Area* is intended to capture spatial variability, this level of resolution is often too coarse for species with patchy distributions and for gear types that have a relatively small affective area per unit effort. Efforts to utilise the finer spatial scale information that is available seems prudent. Vector-Autoregressive Spatio-Temporal (VAST) models are becoming popular for CPUE standardisation where reliable spatio-temporal data exist, to better understand population density of one or more species at multiple locations within an ecosystem and how this may change over time (Thorson 2019). The VAST package is publicly available (www.github.com/james-thorson/VAST).

Tiger prawn fishing mortality is a function of fishing power and catchability (see Equation 7). During the recent NPF Tiger Prawn Strategic Planning Workshop it was noted that the current estimate of catchability for Grooved Tiger Prawns may be outdated, while the catchability for Brown Tiger Prawns is not estimated but rather assumed to be the same as that of Grooved Tiger Prawns. In light of the review of the fishing power, it would be prudent to also review whether catchability estimates require revision.

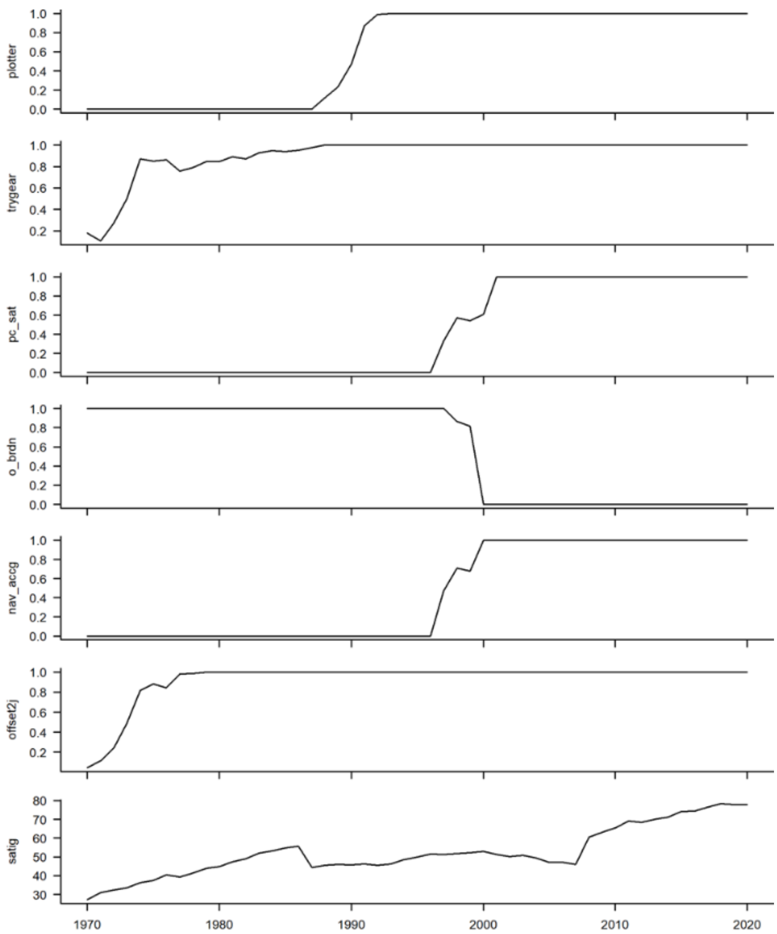
The review of the NPF fishing power clearly identified the swept area index (SATIG) as the most influential explanatory variable. Provided accurate vessel and gear information is available, an alternative estimation process whereby the SATIG variables be incorporated directly into an estimation model could be explored. Alternatively, if we believe that the estimated SATIG index is accurate and continue to use it, another method could be to include this index as a continuous variable in the model instead of an offset.

The rationale for introducing offsets into the *2009 integrated model* is twofold:

a) The possible confounding with population trends when estimating the influence of a specific technological advance - *Three types of preliminary investigation were made while developing the estimation models…….(iii) as confounding of technological variables with abundance was suspected, the effect of supplying tentative or hypothetical additional information on the impact of a given variable was investigated by fixing (or offsetting; McCullagh and Nelder, 1983) the coefficient for that parameter at some reasonable value, and observing the effect on all the other technology coefficient estimates* (taken from Bishop et al., 2008).

b) Model stability and/or convergence - *However, it was found necessary to fix the coefficients for the three most unstable variables, to stabilize the remainder of the results* (taken from Bishop et al., 2008).

Figure 10. Examples of technology adoption in the NPF over time. The y-axis scale is proportion of vessels adopting the technologies (except for the swept area index - SATIG).



As stated above, the inclusion of parameters as offsets, as opposed to parameters within the model framework, was to avoid confounding with changes in biomass but also to improve model stability (i.e., convergence). Confounding is particularly problematic when the uptake of a novel technology is quick, thus, during that period the model is unable to separate whether variation in catches is a result of a variations in catchability (fishing power) or abundance. Here, the adoption of technology within the NPF is quick and generally vessels introduce the technology within 3 years of the first adoption (**Figure 10**). Moreover, the latest technology included as an offset was fully adopted in the early 2000's. It may, therefore, be more accurate to now include these parameters as categorical variables (apart from SATIG which is a continuous variable) within the chosen modelling framework (GLM or GAM) and estimated their influence on catchability.

Modelling frameworks, and computational power, have developed markedly since the first implementation of the *2009 integrated model*. Previous issues regarding model stability and/or convergence can likely be overcome with the use of more flexible and readily available modelling frameworks, such as Generalized Additive Models (GAMs).

It must be noted that previous attempts to include these offsets directly into the estimation model have been attempted. Sensitivity runs in the original development of NPF fishing power analyses (Bishop et al., 2008) indicate substantial variation when fitting parameters in the model compared to including the same parameters as offsets - the latter always resulted in greater fishing power estimates relative to the former case, as shown in Figure 3 c-d of bishop et al., (2008).

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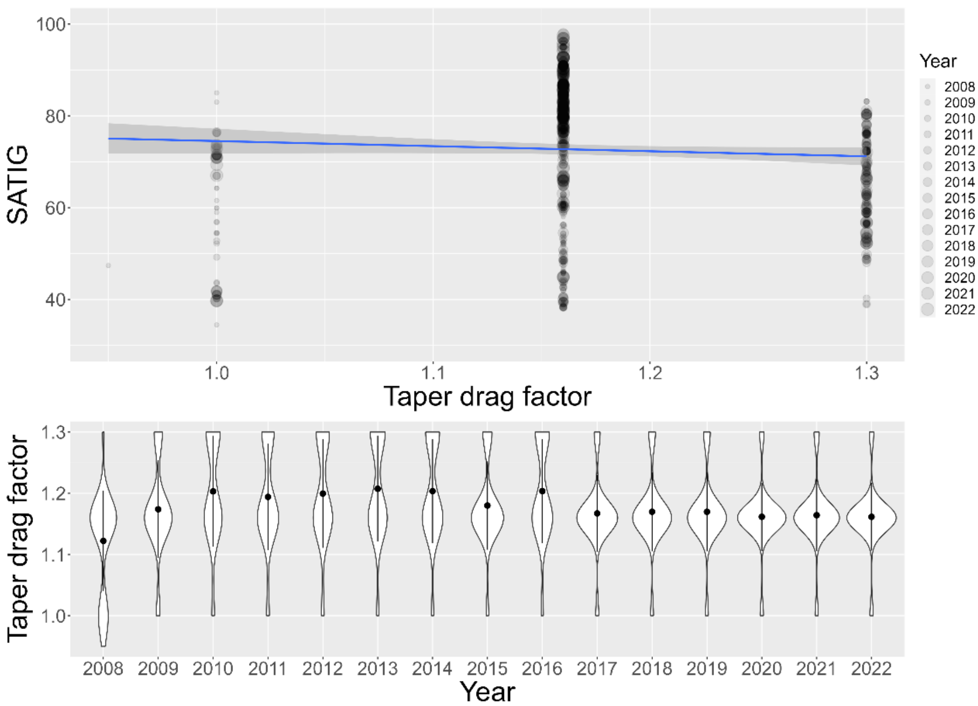
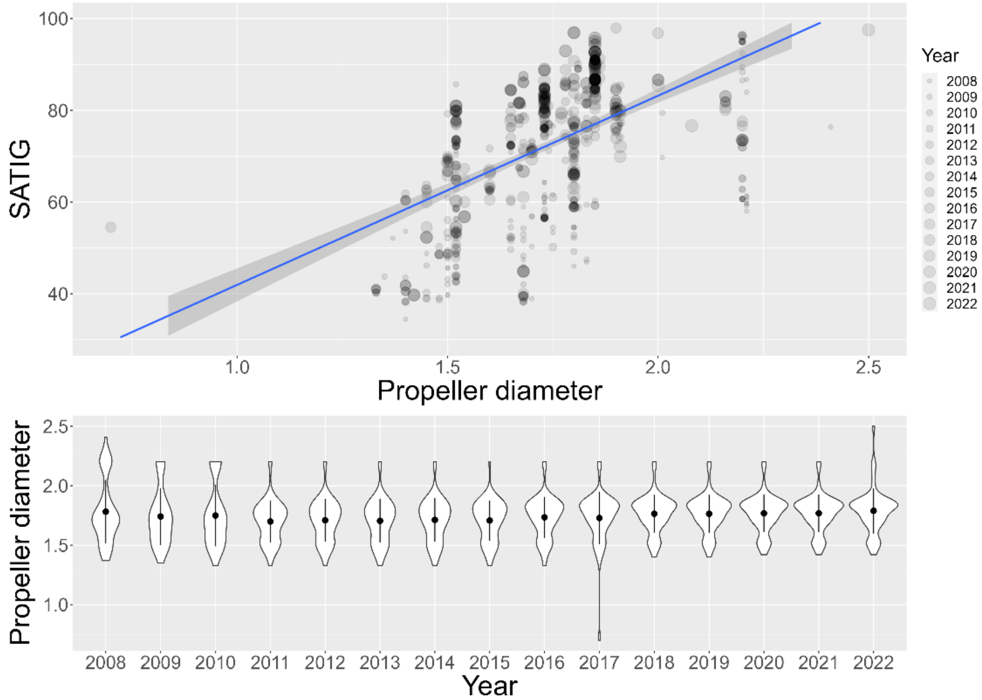
Appendices

Appendix 1. The relationship of PTPM variables and the swept area index and their observed distribution for the period 2008-2022.

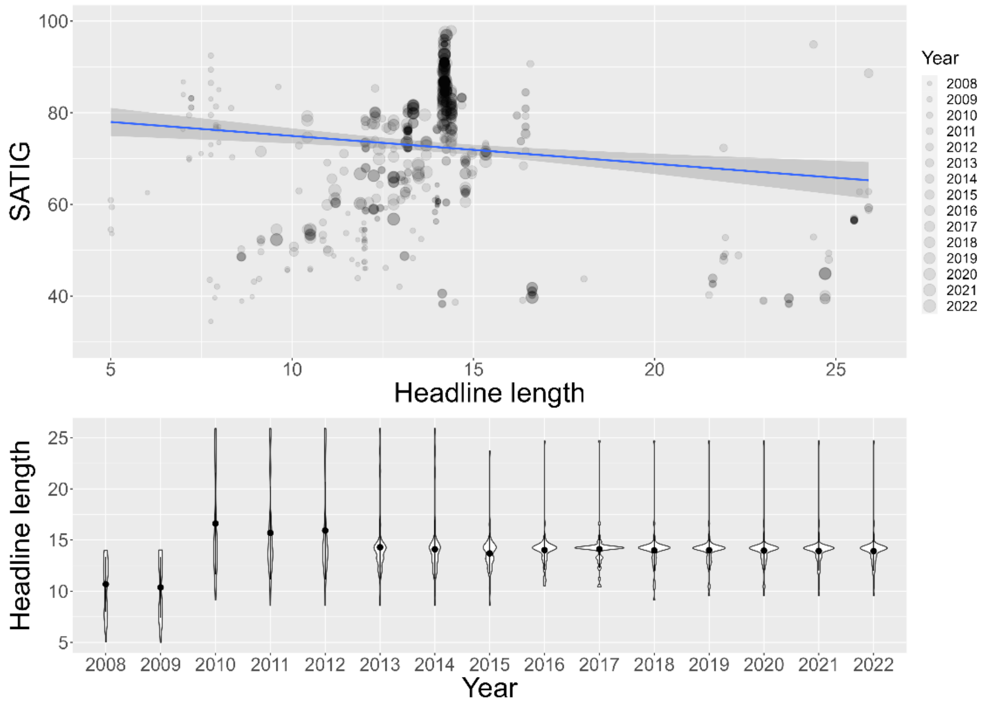
Appendix 1a. (top) The relationship between taper drags factor and the swept area index (SATIG) and, (bottom) the distribution of taper drag factor observations obtained from annual gear surveys performed from 2008 to 2022.



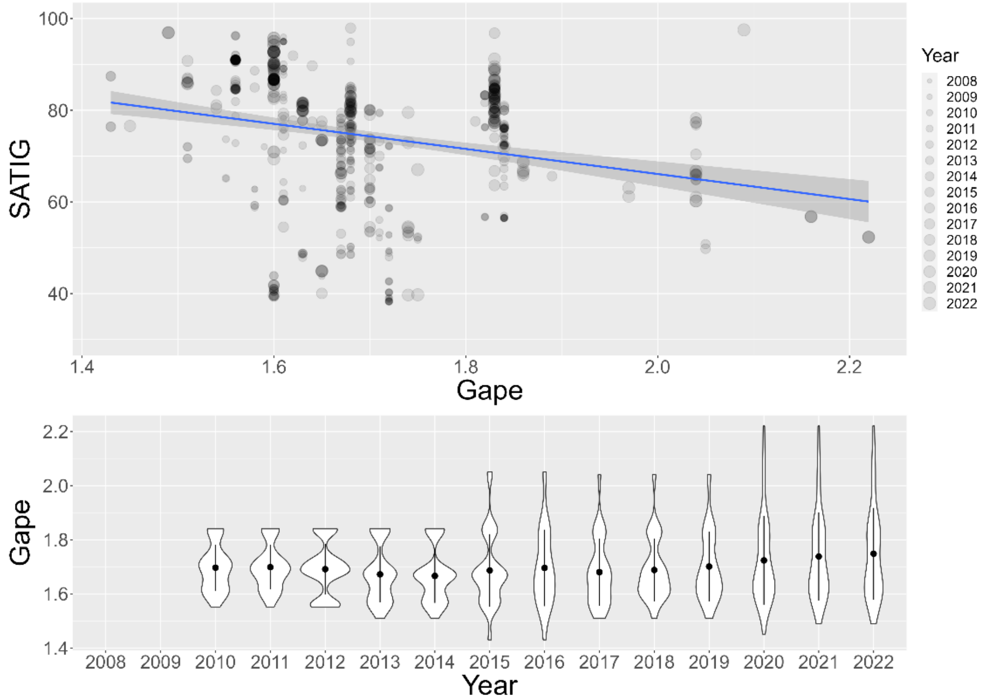
Appendix 1b. (top) The relationship between *propeller diameter* and the swept area index (SATIG) and, (bottom) the distribution of *propeller diameter* observations obtained from annual gear surveys performed from 2008 to 2022.



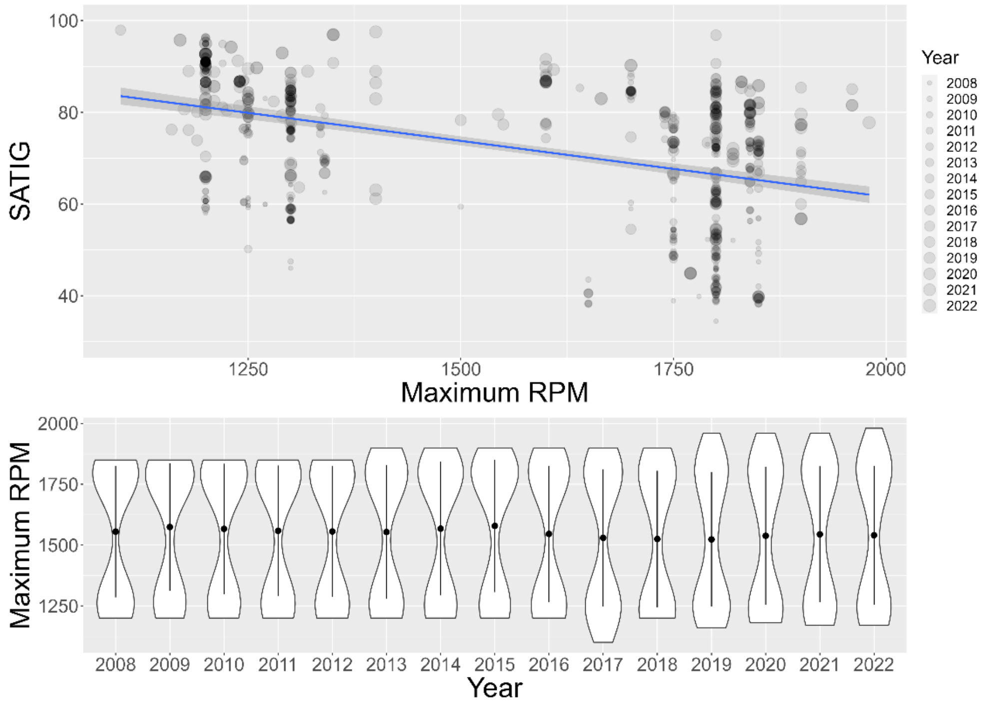
Appendix 1c. (top) The relationship between headline length and the swept area index (SATIG) and, (bottom) the distribution of headline length observations obtained from annual gear surveys performed from 2008 to 2022.



Appendix 1d. (top) The relationship between *gape* and the swept area index (SATIG) and, (bottom) the distribution of *gape* observations obtained from annual gear surveys performed from 2008 to 2022.



Appendix 1e. (top) The relationship between maximum RPM and the swept area index (SATIG) and, (bottom) the distribution of maximum RPM observations obtained from annual gear surveys performed from 2008 to 2022.



Appendix 2. Non-technical summary of "The introduction of Quad rig in the NPF – seeking an effort neutral transition, and implications for TED/BRD performance."

NON-TECHNICAL SUMMARY

Since 1987 the Northern Prawn Fishery (NPF) fleet has towed double rigs (two nets). Prior to this most trawlers towed quad rig (four nets). To improve economic efficiency in the fishery there is great interest to again allow the use of quad rig.

This work has two objectives:

- *Establish conversion factors to ensure effort neutrality between double gear and quad gear.*
- *Produce a short document listing issues connecting the question of TED/BRD specification and performance with respect to a transition from double rig to quad rig.*

Since 2000 the NPF has been managed under a gear units system. During this time there have been a number of gear unit reductions (SFR devaluations) applied to assist with stock recovery and recently to improve economic efficiency.

Derivation of effort neutral translation formulae

The derivation of effort neutral translation formulae is a two-step process. The first step was to evaluate the proportional increase in catch performance when a vessel converts from double to quad rig, and the second was to identify appropriate effort neutral translation formulae.

Assessing the performance benefit of quad rig

To assess the performance advantage of quad rig we need to predict catch and also assume characteristics for the boat and gear before and after conversion to quad rig.

For each current NPF trawler, the catch benefit of converting to quad rig was estimated using the Prawn Trawling Performance Model (PTPM) ver. 3 (Sterling, 2005). The PTPM primarily estimates of swept area of the trawl gear per second as an index of catch performance. The PTPM can also account for the effect of increased headline height on taking a greater proportion of prawns in the path of the net. The data used was for the 2004 NPF fleet and included specification details for each vessel on the propulsion system and the trawl gear, and operation details for the main engine. The PTPM also estimates trawl speed and the degree to which the nets are stretched (spread ratio).

A variety of quad rig systems were investigated for each vessel. The main series had the same headline length as the original double rig, but had different trawl board specifications according to a plausible path for adoption and subsequent refinement of quad gear. In the first instance the ***same trawl boards*** as used in double rig were assumed, being the low cost option for operators. Quad rig refinements investigated were; ensuring the ***same angle of attack*** of the trawl board as double rig, using the size of ***traditional trawl boards*** from prior to 1987 (the period when quad gear was used in the fishery), and using ***optimum trawl boards***, as determined by the PTPM.

In estimating the performance for each scenario, both the gear characteristics and operator behaviour were considered. For the latter, two assumptions define the range of possibilities; **Constant Engine Power** and **Constant Trawl Speed**.

This analysis found that the median catch benefit of quad rig, assuming constant engine power, increased with refinement from 15% to a range of 19.2% to 26% for the traditional trawl boards scenario depending on the catch performance index used e.g. Swept Area Rate or the version accounting for prawn loss over the headline. The lower value for the traditional trawl boards scenario (19.2%) reflects the correction for catch loss due to lower headline height, which reduces the predicted benefit of quad rig. The estimated median catch benefits of quad rig for the optimum trawl board scenario were similar. Assuming constant trawl speed, the catch benefit of quad rig is reduced to a range of 10% to 16%.

An evaluation of the sensitivity of the results to the configuration of double rig used on each boat, as specified for 2004, showed that the performance benefit of quad rig is lower for vessels that towed smaller double rig nets. This is consistent with what was found in studies conducted after the banning of quad rig in 1987 (Robbins and Somers, 1993). The decrease in benefit for smaller boats is about 2%, in absolute terms (e.g. decrease from 22.5% to 20.5%), as the headline length on each side of the vessel decreases by 3m. The results also indicate that the application of gear cuts in the double rig fleet, such as that occurring during 2005, further erode the catch benefit of converting to quad rig if a lack of gear trading causes trawl speed and trawl spread ratio for vessels to increase. The ultimate result of large gear reductions, where there is limited fleet restructure, is a situation where the fleet tow smaller nets that are stretched to the same degree as quad gear and at very high trawl speed. Here the catch advantage of quad gear, assuming constant engine power will be small and under the constant trawl speed assumption will be zero. This situation, where the catch per unit of headline does not change when quad rig is introduced can be called a **Constant Trawl Utilisation** condition. There is strong industry opinion that the fleet has reached this condition, particularly since the latest gear reduction of 25% in 2005.

Analysis of configuration data for the 2005 double rig fleet may be able to establish whether or not the constant gear utilisation condition for the fleet has been reached. A component of the constant gear utilisation condition is the condition of constant trawl speed. VMS measurements of trawl speed would be very helpful in analysing the situation because they are more accurate and more procurable than predictions from the PTPM (Dichmont et al., 2003).

Translation formulae

What is an appropriate translation formula to ensure effort neutrality, given an assumed catch benefit for quad rig over double? The current gear units system does not provide a management environment where a distinct formula can be determined except for particular circumstances e.g. where constant trawl utilisation applies. At an individual boat level, modifying the headline length can result in range of possible responses. The type of response at the vessel and fleet level affects the fishing capacity of the vessel and fleet to varying degrees. Reducing gear size reduces the technical efficiency of the operation (area trawled per litre of fuel used), because it pushes operators to higher spread ratio and speed; further away from optimum values. This evokes an incentive to buy SFR units. Trading of SFR units, if it occurs, tends to maintain a lower trawl speed across the fleet by allowing over-powered vessels to increase gear size rather than operate at high speed and/or reduced power.

If the efficiency of the trawl fleet has been driven down to a point where trading occurs readily, then the limits to high spread ratio and trawl speed may have been reached (assuming the industry is economically viable). Under these circumstances constant trawl utilisation might be assumed and determining an effort neutral formula for any situation is straightforward. The appropriate SFR devaluation simply needs to directly offset the catch enhancement from conversion to quad rig.

On the other hand if an increase in spread ratio and/or trawl speed is possible and no trading occurs for an individual, the PTPM can be used to calculate gear reductions (SFR devaluations) required to ensure effort neutrality for both constant engine power and constant trawl speed circumstances.

Where trading occurs the amount of gear units purchased needs to be known in order to derive the correct effort neutral SFR devaluation.

Final recommendations and conclusions

The following table provides a summary of effort neutral formulae (SFR devaluations) for the degree of catch benefit reported above for quad rig conversion and the different circumstances and assumptions that can apply.

CATCH BENEFIT PERCENTAGE FOR QUAD RIG OF SAME SIZE			
CONVERSION ASSUMPTION			
Constant Engine Power	Constant Trawl Speed	Constant Trawl Utilisation	
19.2% - 26%	10% - 16%	0%	
EFFORT NEUTRAL SFR DEVALUATION FOR DOUBLE TO QUAD CONVERSION			FISHER AND FLEET RESPONSE
0.839 - 0.794	0.909 – 0.862	1	Constant Trawl Utilisation Assumption
Unknown	unknown	1	No Constant Trawl Utilisation Assumption SFR Trading Occurs
NA	0.90 - 0.82	NA	No SFR Trading Occurs Constant Trawl Speed Assumption
0.68 - 0.49	NA	NA	No SFR Trading Occurs Constant Engine Power Assumption

A range is given for each situation due to uncertainties in estimating the effect of headline height on the catching performance of the gears.

The catch benefit of quad rig could be made more accurate with the integration of catch comparison data from field trials on trawl gear to establish the effect of speed, headline height and leadahead on the proportion caught of prawns in the path of the trawl.

The extent to which the application of gear unit reductions since 2000 have made it appropriate to assume constant trawl utilisation rather than constant engine power could be clarified if vessel speed data from the VMS system and gear configuration information for 2005 is analysed.

The uncertainty in an appropriate SFR translation formula is mainly a result of uncertainty in the degree to which the current engineering status of NPF trawl gear can be considered “constant trawl utilisation” as opposed to “constant engine power”, and uncertainty in the amount of SFR trading that will occur when an effort neutral translation formula is applied. In respect to the latter an economic understanding of the situation needs to be considered.

Impact of quad rig conversion on TEDs and BRDs

While the existing TED and BRD specifications should continue to be effective as fishers adopt quad-rig, the use of very small nets, increased spread ratio and increased towing speed has the potential to compromise the performance of these devices. The use of very small nets is perhaps the greatest risk to effective TED performance and protection of turtles and may also reduce BRD performance through limiting the size and location of the device, and the number of escape openings available for bycatch to escape. Higher towing speed will reduce the ability of small fish to swim through the escape openings of a BRD. It should be noted that AFMA is legislating minimum TED and escape opening dimensions for the fishery in 2006. This should ensure the continued escapement of turtles and large marine organisms.

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