SCIENTIFIC COMMITTEE
NINETEENTH REGULAR SESSION

Koror, Palau
16 – 24 August 2023

Examining Indicators of Effort Creep in the WCPO Purse Seine Fishery

WCPFC-SC19-2023/MI-IP-07

P. Hamer[1], T. Teears, and the PNAO[2]

[1]Oceanic Fisheries Programme (OFP), Pacific Community (SPC), Noumea, New Caledonia
[2] Parties to Nauru Agreement Office (PNAO)

Executive Summary

The industrial tuna purse seine fishery in the Western and Central Pacific Ocean (WCPO) has evolved in many ways since its rapid development began in the 1980s-1990s. Over last 10-15 years, this evolution has been associated with changes to how the fishery is managed, particularly the implementation of effort management regimes, most notably the Parties to the Nauru Agreement (PNA) Vessel Days Scheme (VDS), but also the uptake of technologies, such as FAD buoys equipped with satellite tracking and acoustic sensors to estimate levels of associated biomass. The application of effort management, through vessel day limits, within the tropical tuna purse seine fishery may produce incentives for fleets to increase efficiency and effectiveness. This may occur by increasing nominal fishing effort, which refers to conducting more purse seine sets within their purchased day limits and/or the effectiveness of nominal effort, which refers to the effectiveness of purse seine sets in catching volumes of fish. Such increases in nominal effort rates and harvesting effectiveness are often collectively referred to as 'effort creep'.

While increased efficiency and effectiveness is generally a good thing for industry, as it can increase profitably and economic rents, there are potentially negative implications of effort creep for stocks managed by effort controls. Perhaps most important of these, is that effort creep can erode the effectiveness of effort limits that are designed to constrain fishing mortality. It is therefore important to monitor potential effort creep in effort managed fisheries, because if it is occurring it may be necessary to compensate for its effects on fishing mortality by reducing the total allowable effort.

Paragraph 2.4(ii) of the Vessel Day Scheme (VDS) text notes that the annual meeting of the Parties will "receive a briefing from the Administrator on catch and effort levels and any observed or potential increase in average effective fishing effort for each fishing day since the introduction of the Management Scheme (effort creep)". This paper describes a suite of effort creep indicators for the purse seine fishery operating in the WCPO, and highlights important trends that may be relevant to fishery managers, with respect to the sustainable management of tropical tuna stocks.

In 2016, Pilling et al. (2016) reviewed candidate indicators of effort creep in the WCPO purse seine fishery at the request of the PNA. In this paper, we update and summarize information available to SPC as of February 2023, on catch and effort levels and any observed or potential increase in average nominal fishing effort per day and capture effectiveness per set since the introduction of the VDS management framework. The objectives of this paper are to provide managers with information on trends in potential 'proxy' indicators of effort creep in the tropical tuna purse seine fishery (Table 1) that can be considered in the context of achieving the objectives of the VDS. These data are complete from 2007/2008 through 2021, with partial data presented for 2022 for specific indicators.

In the 2022 version of this paper we recognised an issue with logbook reported fishing days. Specifically, the raised logbook estimates of fishing days have become increasingly biased towards lower estimates of fishing days since around 2010. This bias appeared related to increased misreporting of vessel activity codes, particularly the misreporting of searching activities as

transit activities. Unlike transit activity, search activities are considered fishing effort and should contribute to fishing days, as they do under the VDS. Fortunately, Vessel Monitoring Systems (VMS) were implemented across the purse fishery in 2008. Applying a relatively simple criteria to VMS position and vessel travel speed information, we were able to generate a data set of annual fishing days (incorporating searching and active fishing) that appears more representative, and produced estimates for PNA waters that are closely aligned with the fishing days reported in the available PNA VDS data. We continued with the use of VMS derived fishing days in this paper.

With the application of the VMS fishing days the number of sets per fishing day (inclusive of searching and setting) is consistently just below 1.0 for PNA waters and shows no longer-term trend since 2008. The lack of trend is also observed for non PNA waters, but the data are more variable. The lack of trend in daily setting rates was confirmed with observer data. Observer data indicates that the percentage of active fishing days (days when sets are made) where more than one set is made has been stable at around 20-25% since 2010 for PNA waters and 5-15% for non PNA waters. Together these results suggest that for the aggregated data there is no clear increasing trend in the number of sets per day since the VDS was implemented. This suggests that nominal effort creep within the VDS limits has not occurred to any notable extent since the VDS was implemented. It is worth noting, however, that trends in nominal effort rates may occur at higher resolutions such as for specific flags or EEZs. Higher resolution analyses could be considered in future work subject to data confidentiality.

Trends in effectiveness of purse seine sets were explored primarily by comparing catch rates per set by associated and unassociated (free school) set type. We initially looked at trends since 2007 to represent the period of VDS implementation. Over this period, while there was high interannual variation, likely related to variability in skipjack availability, there were no long-term trends for either set type. The patterns of variation were also similar between PNA and non PNA waters. This suggests that the effectiveness of purse seine sets has on average not increased noticeably since the implementation of the VDS, even with the addition of newer FAD buoy technology such as acoustic sensors. There was a drop in catch rates per set for PNA waters in 2021 compared to 2020, but this was within the range of variability observed over the last decade. However, we note that the VDS was implemented at a point in the development of the fishery when the use of drifting FADs with tracking buoys had already become the dominant form of associated sets. Exploration of longer term trends in catch rates per set from 1990, did show a clear trend of increasing catch rates per set from 1990 to around 2007 for associated sets, but no increasing trend over the same period for unassociated sets, in both PNA and non PNA waters.

The increased catch rates for associated sets from 1990 to 2007 corresponds with the increasing proportions of associated sets being comprised of sets on drifting FADs. Drifting FAD sets typically have higher catch rates than other associated set types (i.e., logs, whales, anchored FADs) (Vidal et al., 2020). We therefore propose that much of the earlier increase in fishing effectiveness for the associated component of the purse seine fishery was related to the uptake of drifting FADs that mostly occurred prior to the VDS and was likely facilitated by increased availability of satellite tracking buoys. It seems that the newer technologies, specifically acoustic sensors, that are now standard on FAD bouys have had less impact on per set catch rates than might have been predicted.

While the aggregated catch rate indicators presented in this paper do not provide clear indications of effort creep over the period since VDS implementation, stock declines could offset technology/effort creep impacts on catch rates per set resulting in the observed stability of catch rate indicators. The most recent stock assessment indicates a decline in spawning biomass since the around 2010 (Castillo Jordan et al., 2022). To evaluate this in lieu of the availability of catchability parameter estimates from the catch-conditioned stock assessment models, a catchability proxy was developed for the 2021 paper (Vidal et al., 2021), and is updated based on the recent 2022 skipjack stock assessment. The catchability proxy, calculated as the aggregated average skipjack catch per fishing day in each year relative to total biomass estimated from the stock assessment, provides an indicator of the relative effectiveness of a fishing day. Over the time series available (2008-2021), using the VMS fishing days, purse seine daily fishing effectiveness within PNA and non PNA waters, while variable from year to year, does show an increasing trend of about 2 percent per year. This may indicate that while nominal effort and catch rates per set are stable some efficiency creep may be occurring in the equatorial purse seine fleet that has allowed the skipjack catches per vessel day to remain stable in the face of the estimated declines in biomass since 2010.

Effort creep is difficult to quantify with certainty because it is a multi-faceted and complex phenomenon, often lacking the full complement of data to precisely assess. Overall, the nominal effort rate and per set catch rate indicators have shown no clear trends over the period since the VDS implementation, both within and outside PNA waters. We note the positive trend in the catchability proxy that increased with the 2022 skipjack assessment. We recommend it continue to be included in this analysis, perhaps with additional consideration of uncertainty in the biomass estimates. Continued use of the VMS fishing days is recommended and we encourage more work to further improve the accuracy of VMS fishing day estimation. However, the longest time series of effort data is from the logsheet records. Effort should be made to improve the accuracy of logbook reporting of vessel activities and correcting the historic logbook data for biases due to misreporting of vessel activities. There was limited progress on this in 2022.

We invite the SC19 to note:

- over the period of the VDS implemention there is a lack of trends in the purse seine fishery metrics (sets/day, catch/set, catch/day) used as indicators for effort creep,
- however, an increasing trend in catch/set occurred for associated sets prior to the VDS implementation, and this was consistent with the transition to associated sets becoming dominated by drifting FADs,
- the positive trend in the skipjack catchability proxy, which may indicate recent declines in biomass are being offset to a certain degree by improved capture effectiveness,
- the importance of continuing to monitor and develop quantitative metrics of effort creep for management use and development of management procedures,
- the need to improve the accuracy of logbook reporting of vessel activities and correcting the historic logbook data for biases due to misreporting,
- the recommendation to continue to refine the methods for estimating purse seine fishing activities from VMS data.

Table 1: Summary of recent (average 2018-19 vs 2020-2021) and longer-term (2007-2021) trends in different indicators within and outside PNA EEZs.

Indicator	**2018/2019 vs 2020/2021**		**Per annum linear regression trend, 2007(or 2008)-2021**[3]	
	PNA	Non-PNA	PNA	Non-PNA
Sets/year	-6%	-39%	+1%	+1%
Sets/day	-12%	-38%	-1%	0%
Total tuna CPUE (mt/day)	-13%	-26%	0%	0%
Total tuna CPUE (mt/set)	-2%	+19%	0%	0%
Total tuna CPUE (mt/set) - ASS sets	-1%	0%	+1%	0%
Total tuna CPUE (mt/set) - UNA sets	-4%	+9%	0%	+1%
Total tuna catch	-7%	-27%	+1%	+1%
Total skipjack catch	-15%	-28%	+1%	+1%
Vessel length (m)	+2%		0%	
Vessel gross registered tonnage (GRT)	+3%		0%	
Vessel horsepower (HP)	+1%		0%	
Well capacity (mt)	-3%		+1%	

[2]Percent change relative to 2007 or 2008 level, estimated through linear regression of the data across the period 2007/2008-2021. Values rounded to the nearest whole percentage. Starting year is 2008 for metrics that involve 'days' due to these being based on VMS estimates of fishing days only available since 2008.

Introduction

Fisheries management controls that are based on limiting effort require ongoing monitoring to track how effectively the unit of effort continues to constrain the fishing mortality. The effectiveness of a unit of effort in catching fish can change over time due to the adoption of new technologies, gear modifications, fisher skill, enhanced communication/networking among skippers and/or access to other information such as oceanographic data that helps locate fish. Changes in the effectiveness of fishing effort can potentially alter the expected relationship between effort and fishing mortality compared to that when the effort limits were initially established, and this may undermine the achievement of management objectives.

Gradual or abrupt change in fishing effectiveness, within an effort-based management framework, is generally referred to as "effort creep" (Pilling et al., 2016). While effort creep can be positive for a fishing industry when it reduces the cost and environmental impacts of harvesting fish, management systems that rely on effort controls may need to consider adjusting effort limits over time to account for effort creep. Finally, industry adaption to effort based management can also lead to sub-optimal investment in operational aspects, such as technology, whereby the effectiveness of harvesting fish may increase but the cost required to harvest them increases disproportionately.

Effort creep can be difficult to quantify because it is composed of both direct and indirect components (Eigaard et al., 2014; Palomares and Pauly, 2019; Scherrer and Galbraith, 2020). The direct components relate to nominal fishing effort (e.g. vessel fishing days, number of net hauls, sets or hook deployments etc.), while the indirect components may relate to factors related to technology uptake ('technology creep'), slight gear modifications, increased information and networking, increased knowledge and skills of individual fishers. These aspects may not influence the amount of nominal fish effort, but they can influence the effectiveness of each unit of effort, i.e., the effectiveness of a purse seine net set to catch a certain volume of fish. While the direct components of effort are relatively easy to measure and track, the influence of indirect components on fishing effectiveness are challenging to quantify.

Most of the industrial tuna purse seine fishing in the Western and Central Pacific Ocean (WCPO) is managed under the Parties to the Nauru Agreement (PNA) Vessel Day Scheme (VDS). This scheme allocates an overall number of vessel fishing days per year that are then allocated by an agreed formula to the PNA member countries (plus Tokelau). Member countries then sell the days (at or above a base minimum price) for their EEZs to fishing vessels/companies that may be flagged to other countries or territories (including Distant Water Fishing Nations), that are members or participating non-members (CCMs) of the Western and Central Pacific Fisheries Commission (WCPFC). The effort management unit is 'the vessel day', which refers to any day that is related to harvesting fish, and thus includes days in which nets are deployed and days when searching is conducted but a net is not necessarily deployed. Under the VDS system, most days when a vessel is within a member EEZ will initially be counted and charged as vessel days, but the days can be reduced through a process of claiming for non-fishing days according to specific criteria. Purse seine fishing outside of PNA member EEZs and archipelagic waters is managed by flag specific limits on catch or effort as specified in the Tropical Tuna Conservation and Management Measure CMM 2021-01 (https://www.wcpfc.int/doc/cmm-2021-01/conservation-and-management-measure-bigeye-yellowfin-and-skipjack-tuna-western-and). Further effort in archipelagic waters of some countries that are members of the PNA may not be managed under the VDS (i.e. Papua New Guinea and Solomon Islands).

In 2016 The Pacific Community (SPC) was requested by the WCPFC to explore and provide a list of potential indicators of effort creep in the WCPO purse seine fishery (Pilling et al., 2016). This initial study provided the basis for an annual update of effort creep indicators in collaboration between the SPC Oceanic Fisheries Programme (OFP) and the Parties to the Nauru Agreement Office (PNAO). This annual update has been provided since 2016 to the PNA annual meeting, and also as a paper to the WCPFC's annual meeting of the Scientific Committee. The annual effort creep paper may also provide new analysis related to research on detection and quantification of effort creep, as appendices to the main paper.

This paper provides an update on the effort creep indicators in the WCPO purse seine fishery, using the latest information available to SPC as of February 2023. This includes complete data through 2021 and partial data for 2022 for some indicators. When this report was first compiled in 2016, three groups of proxy indicators for effort creep were established:

1. trends in tuna catch levels, catch rates, and alternative fishing effort values;
2. estimates of trends in vessel and technological characteristics; and
3. trends in estimated 'catchability' from Western and Central Pacific Fisheries Commission (WCPFC) stock assessment models,

Here, we provide an update for the first two types of indicators, and note that updates on estimated catchability trends from stock assessment models are no longer available due to changes in the tropical tuna assessment modelling approaches. Details of these changes and the historic trends in catchability estimates can be found in the 2021 version of this paper (Vidal et al., 2021). An alternative catchability metric is now included in this paper Figure A5. Refinements of data inputs can influence results from previous years and **we recommend that the 2023 paper supersede previous versions** for this reason.

A key modification for the previous (2022) effort creep paper was the change to the use of the Vessel Monitoring System (VMS) data for estimating 'fishing days'. This change was necessary due to the raised logbook estimates of fishing days becoming increasingly biased towards lower estimates of fishing days since around 2010. This bias appeared related to increased misreporting of vessel activity codes, particularly the misreporting of searching activities as transit activities. Unlike transit activity, search activities are considered fishing effort and should contribute to fishing days, as they do under the VDS. The VMS fishing day estimates appear more consistent with the VDS days and are not subject to the bias towards lower recent values observed for the logbook fishing days. VMS fishing days are hence applied in this analysis. Comparisons of vessel fishing days estimated from VMS data with those from logbooks and recorded under the VDS are included in Figure A1.

SPC does not currently monitor vessel days in respect of the VDS management framework, nor does it receive information regarding claim adjustments based on fishing/non-fishing activities. Despite the intent of representing effort and catch in a way that reflects the influence of the VDS there will be some discrepancies between the indicators presented here relative to the VDS records of vessel days. The VMS data, perhaps not surprisingly, estimates higher fishing days than the VDS but the variation and trend are consistent, with exception of the earlier years of the VDS as this system was being implemented. Improvements to the calculation of fishing days from VMS data can be made using observer data for ground truthing to develop more sophisticated algorithms. This work is recommended, along with dedicated work to adjust the logbook database to account for the misreporting of activity codes.

In this analysis we have excluded archipelagic waters. The approach for data filtering is described in more detail below. We believe removing data for archipelagic waters of PNA member countries (i.e., Papua New Guinea, Solomon Islands and Kiribati) is important as purse seine effort in these areas is not subject to the VDS. A key focus of this paper is on indicators of effort creep in relation to the implementation of the VDS, therefore excluding data on catch and effort that is not limited under the VDS controls for PNA member waters seems necessary.

China, Indonesia, Philippines, and Vietnam EEZs were also removed from the data set prior to analysis along with the Australian EEZ. As with past reports, the data set is also filtered to include only fishing activity between 20°N-20°S, so some of these exclusions would not have any impact on the results. Catch and effort attributed to vessels flagged to Indonesia, Philippines (domestic fleet), and Vietnam are also excluded. The decision to exclude certain flagged vessels was made because they are fleets with smaller vessels and lower catch rates, and are not considered representative of the overall industrial purse seine activity in the region of interest.

Examination of trends in effort, catch rates, and catch

Aggregate (1°x1°) raised logsheet data in combination with data on vessel activities from the Vessel Monitoring Scheme (VMS) database, were summarized by approximate EEZ/high seas, and archipelagic areas for the Western and Central Pacific Fisheries Commission (WCPFC) Convention Area within the latitudinal range 20°N-20°S. Note that for the VMS fishing days calculations, all activity outside of 10°N-10°S is not considered to be fishing. These data were used to evaluate changes in effort creep indicators from the period 2007-2021 (with partial data for 2022 included for some rate indicators). Analyses that use the VMS fishing days start in 2008 when the VMS was implemented. In this paper we also include a longer term comparison, using logbook data, of catch rates per set and proportions of associated sets according to different association categories (whale/whale shark, anchored FAD, drifting log, drifting raft/FAD). We include this longer term comparison to explore trends prior to the VDS implementation, as much of the uptake of drifting FADs with tracking buoys occurred prior to VDS being implemented.

Trends in aggregated annual catch, catch rates, effort levels, and vessel characteristics provide simple, but informative indicators of effort creep. The indicator values were estimated separately for fishing effort within and outside of the PNA waters (where for the purposes of this paper, PNA waters refers to EEZs of PNA Parties + Tokelau, and excludes the archipelagic waters of Papua New Guinea, Solomon Is and Kiribati). Recent changes in indicators are summarized by taking ratios between average effort, catch per unit effort (CPUE), and catch in 2020-21 compared to 2018-19 calendar years. Long-term trends were examined over the time period since the implementation of the Vessel Day Scheme (VDS; 2008-2021[3]) by fitting linear regressions and are expressed as percentage changes per year relative to 2008 or 2007 as specified. Statistical significance of trends or short-term changes is not assessed as the intent is to use these indicators as general indicators to highlight levels of effort creep that might be of concern rather than identify statistically significant changes.

Purse seine effort inside and outside PNA EEZs

As noted, fishing days in the WCPO tropical tuna purse seine fishery are mostly limited through the PNA VDS, EEZ-nominated effort and skipjack catch levels, and high seas effort limits (days) by flag. In this document, associated sets are defined as those that target schooling aggregations of fish associated with floating objects, whereas unassociated sets target free-schooling fish aggregations. Floating objects, in this context, include manufactured anchored and drifting FADs (e.g., buoys or rafts), as well as natural floating objects, such as logs, whales, and whale sharks, around which fish may aggregate. It should be noted that drifting FAD sets dominate the associated sets since the implementation of the VDS (Figure 7). Drifting FAD sets are typically made during the early morning hours when tuna are aggregated near the surface, prior to their movement into deeper waters for daytime foraging. For this reason, purse seine vessels typically only make one drifting FAD set per day, whereas unassociated or 'free-school' sets can be made throughout the day, but rarely after dark.

While total number of sets per year is not necessarily a reliable metric of nominal effort creep, as it depends on the total number of allocated and used fishing days per year, it is included here to provide context with respect to total fishing effort over time, within the region. The total number of raised unassociated plus associated sets per year for PNA waters have varied between about 33,200 and 44,300 sets over the last 10 years, after a major increase from around 27,800 sets in 2009 to 39,900 sets in 2010, around the time of VDS implementation (Figure 1). The increase in total sets corresponds with an increase in the number of fishing days from 2009 to 2010 (Figure A1). For PNA waters the number of associated sets since 2007 has fluctuated between around 9,200 and 15,700 sets per year but with no sustained trend or step changes. In contrast a step change increase in the number of unassociated sets from approximately 15,200 to 30,800 occurred from 2009 to 2010, and the number of unassociated sets has since varied between around 21,500 and 30,800 sets per year, with no sustained trend (Figure 1). The main increase in overall sets per year between 2009 to 2010 was clearly driven by the increased number of unassociated sets. It should be noted that the unassociated sets in this analysis include 'skunk' or failed sets that can make up

[3]The VDS was implemented in 2008, but 2007 was included as a baseline for indicators not requiring VMS based vessel day estimates.

a substantial proportion of the recent unassociated sets.

For non PNA waters, the total number of raised unassociated plus associated sets per year has varied between about 1,350 to 8,300 sets since 2007. The number of associated sets dropped from 2009 to 2010 and has displayed low interannual variation but with a steady increasing trend since 2010 (i.e., approximately 700 sets in 2010 compared to around 2,850 sets in 2020 and 2021). Unassociated sets have fluctuated but remained relatively stationary over the time series, with peaks of around 6,400 and 5,650 sets in 2015 and 2019, respectively (Figure 1).

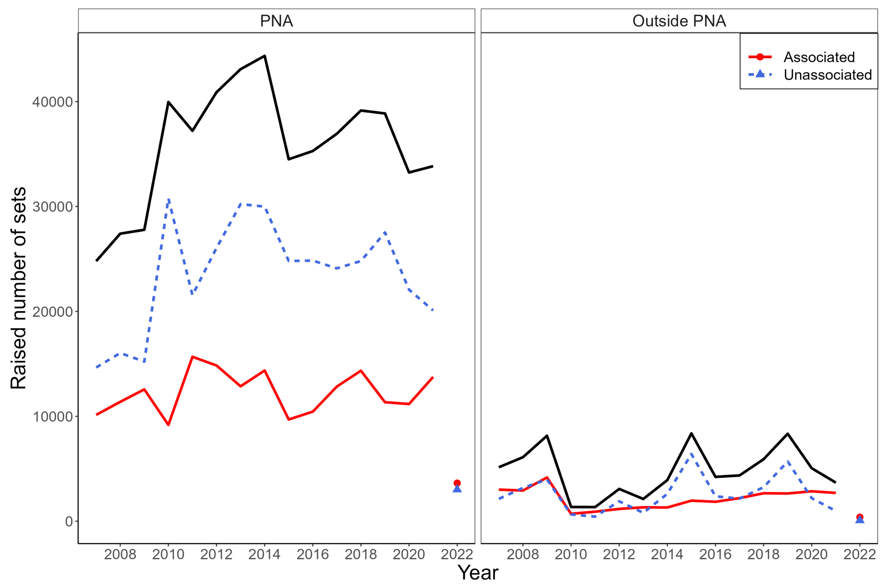

Figure 1: Time series of total raised purse seine sets per year, for associated and unassociated set types, inside (left) and outside (right) PNA EEZs from 2007-2021. Total raised sets is represented with the solid black line for each region. Note: estimated number of sets made in 2022, by set type, is included as points on each figure, but data are incomplete.

The annual data presented in this paper are sensitive to short-term variability, whereby relatively large changes can be observed from year to year compared to the longer term trends. The long-term trends can represent underlying gradual increases or decreases, with compounding effects that can be notable overtime. When comparing effort rates from 2018-19 to 2020-21, declines were observed in PNA and non PNA waters, with greater declines in non PNA waters (Table 1). Over the longer term (2007/2008 to 2021) there were no clear trends in effort rates. For sets/day, which is a more relevant indicator of nominal effort creep under the VDS, there is essentially no long-term trend in the data, this is consistent for sets/day determined from applying VMS fishing days, and sets/day from observer data (Figure 2).

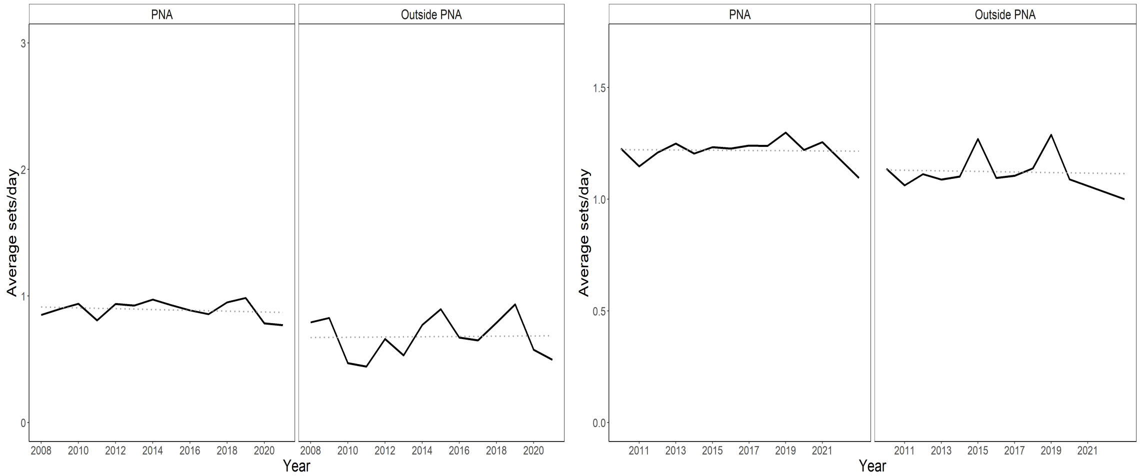

Figure 2: Time series of setting rate (sets per fishing day) for waters inside and outside PNA EEZs. The linear trend (dotted line) through the data points is plotted, but is not statistically significant for any plot. Left plot represent the time series of sets/day using VMS fishing days and raised sets from logbooks (2008-2021). Right plot represent the sets/day from observer observations which just includes days when sets are observed and therefore is higher as it does not include search days (2010-2021).

Disaggregated sets per day: observer data

An important aspect to understanding effort creep is how individual vessel behaviours and characteristics change over time. Here we have summarized operational (set-level; unraised data) effort data collected by fishery observers which would include most activity since 2007 (after which 100% observer coverage was implemented), to track the proportion of fishing days with two or more sets. Consistent with the data on sets/day presented above, there are no obvious trends in the relative portions of days with 1,2,3 or 4 sets conducted. For PNA waters, roughly 20-25% of days when sets are made involve more than one set in the day, whereas for non PNA water this is generally lower from 5-15%, with the exception of 2015 and 2019 when this increased to around 25% of days (Figure 3).

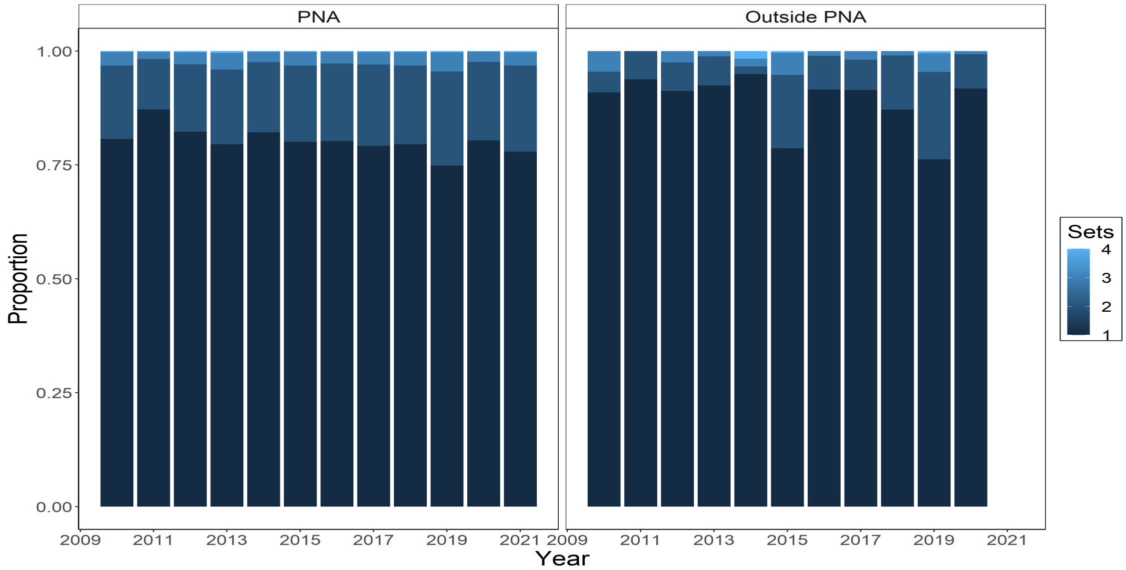

Figure 3: The proportion or observed fishing days (i.e. days when sets were conducted) characterized by number of sets per day (1-4) from 2010-2021 (need to check why no data for outside PNA in 2021).

The motivation for making multiple sets per day may vary. Previous analysis has shown that the distributions of catches per set are similar irrespective of how many sets per day suggesting that the motivation for doing more sets in a day is likely to increase harvest rather than to make up for notably lower per set catches earlier in the day (Vidal et al., 2021).

Purse seine CPUE inside and outside PNA EEZs

Trends in nominal catch per unit effort (CPUE) were measured as total tuna metric tonnes caught per set (mt/set) and per VMS fishing day (mt/day) (Figure 4). The majority of the catch (approximately 70-90%) was comprised of skipjack (Figure 8), which drives these trends. The stable catch composition data in Figure 8 also suggests that increased numbers of free school sets is not clearly due to increased targeting of yellowfin.

Catch rates per set within PNA waters have generally been lower than non PNA waters (Figure 4), but average catch rates per day are of similar magnitude within and outside PNA waters. It should be noted that similar daily catch rates occur in PNA waters despite far greater effort and catch in PNA waters than non PNA waters. CPUE inside and outside PNA waters has shown similar dynamics since 2007, although the catch rates outside PNA waters have been more variable. Comparison of average CPUE between 2018-19 and 2020-2021 showed decreases of 2% for mt/set and 13% for mt/day for PNA waters, an increase of 19% for mt/set and decrease of 26% for mt/day for non PNA waters (Table 1). There were no notable long-term trends in catch per set and catch per day for both regions, linear trends ranged from 0 to +1%, per annum (Table 1, Figure 4).

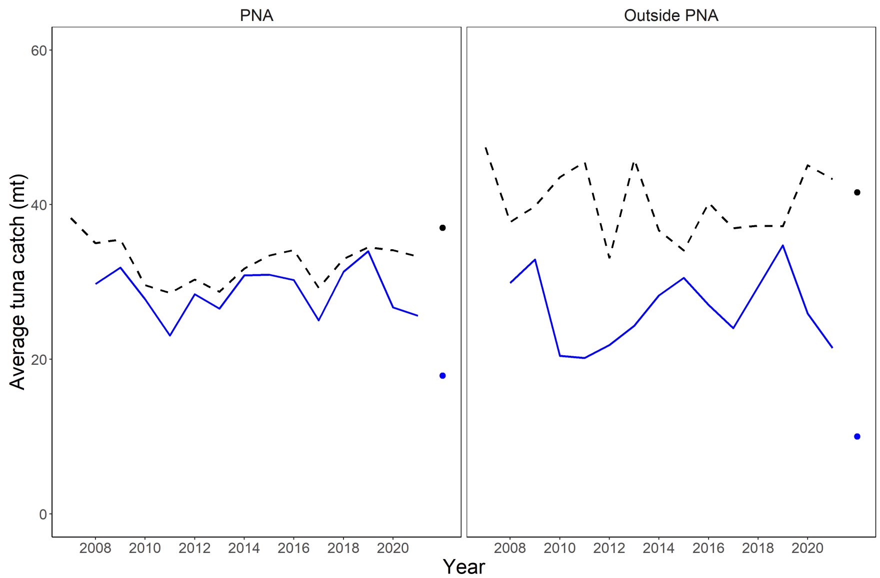

Figure 4: Time series of nominal raised purse seine total tuna CPUE in terms of mt/day (blue; solid lines) and mt/set (black; dashed lines) inside and outside PNA EEZs, from 2007-2021. Note: 2022 is included as points on each figure but data are incomplete.

The two main purse seine fishing modes, associated and unassociated sets, are quite different in nature, and it is of interest to evaluate catch rates separately for each mode when considering effort creep. The recent trends (2018-19 to 2020-21) suggest that catch rates (mt/set) for associated and unassociated sets inside PNA waters have decreased by 1 and 4% respectively, and outside PNA waters there was no change for associated sets and a 9% increase for unassociated sets (Table 1, Figure 5). Catch rates for associated sets are on average higher than for unassociated sets, and areas outside PNA waters have generally produced higher associated catch rates per set, but the time series from both regions show similar dynamics, also noting that catches outside PNA waters are much lower overall compared to PNA waters.

There are no longer-term trends (2007-2021) in catch rates per set that would be clearly indicative of increased efficiency of purse seine sets over the period of the VDS implementation (Table 1, Figure 5). However, longer term trends in catch rates per set for associated sets are clearly present in historical data from the early 1990's until around 2007 just prior to VDS being implemented (Figure 6). In contrast catch rates per set for unassociated sets do not show the same increasing trend. These long term patterns are similar for PNA and non PNA waters (Figure 6).

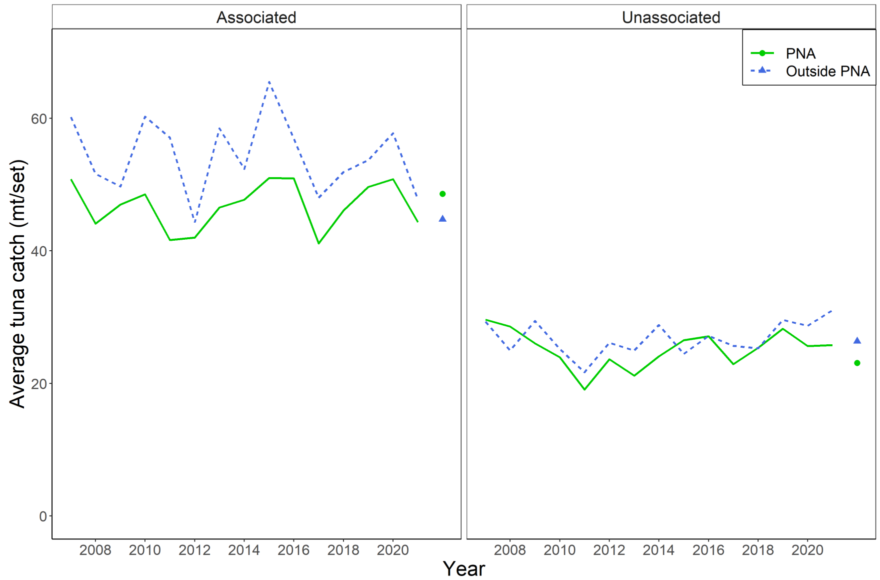

Figure 5: Time series of nominal purse seine total tuna CPUE (mt/set) for associated sets (left) and unassociated sets (right) inside and outside PNA waters from 2007-2021. Note: 2022 is included as points on each figure but data are incomplete.

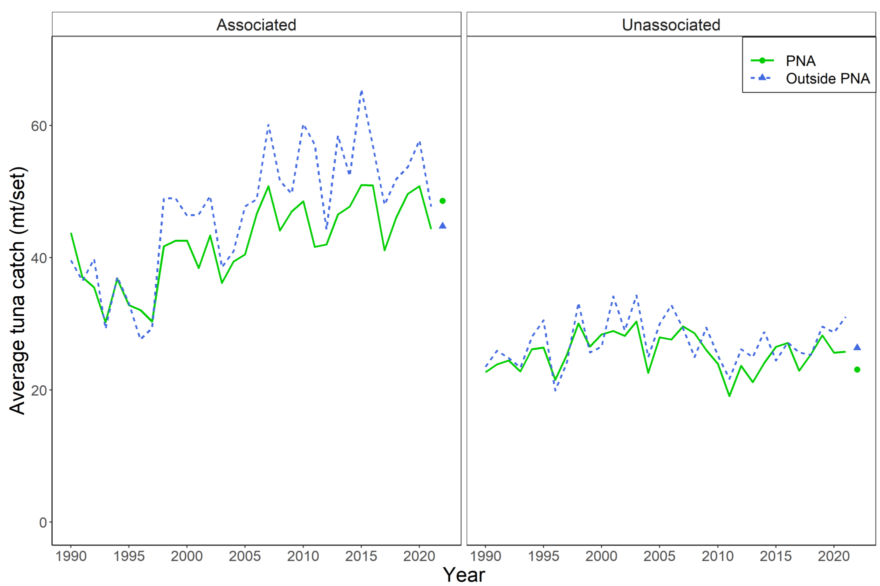

Figure 6: Time series of nominal purse seine total tuna CPUE (mt/set) for associated sets (left) and unassociated sets (right) inside and outside PNA waters from 1990 to 2021. Note: 2022 is included as points on each figure but data are incomplete.

FAD dynamics and implications

The technology associated with FAD fishing has become more sophisticated through time, specifically with the adoption of satellite tracked and sonar-equipped FADs. It is now possible for vessels to have a general sense of the presence and even size of the fish aggregations present at a FAD at a given time, based upon acoustic information provided by the FAD's sonar system. With this knowledge, fishers can, in theory, more efficiently direct their efforts towards the most productive FADs, while minimizing the risk of fishing an unproductive FAD. Further, being able to accurately locate FADs with high biomass associated can reduce the amount of steaming time, allowing more time for other fishing operations, and improve the cost efficiency of fishing operations, thus improving profit. Through time, there has been an increase in the reliance on drifting FAD-fishing for associated sets, and along with that reliance, there has been an increase in the deployment of manufactured drifting FADs (Escalle et al., 2021). This can be clearly seen in Figure 7 where prior to 2000 drifting logs and anchored FAD sets dominated the associated sets, whereas from the late 2000s drifting FADs have taken over as the dominant association type. This likely coincides with the uptake of FAD buoys with satellite tracking and more recently acoustic sensors.

The increases in catch rates per set for associated sets through the 1990s and 2000s appears linked to the transition to drifting FADs that was facilitated by the increased availability of relatively cheap satellite tracking buoys. These gains in effectiveness appear to have stabilised since the late 2000s when the VDS was implemented, despite the uptake of additional FAD buoy technologies, specifically acoustic biomass sensors. It may be that the acoustic technology is not sufficiently accurate in estimating volumes of fish under a FAD, as opposed to providing a more coarse indicator of availability, or that the technology is still not being used effectively by skippers. It may also be that the benefit of acoustic technology on FAD buoys in the WCPO is currently more related to economic efficiency, i.e. reduced travel costs, rather than increasing catch rates per set, and this is providing the incentive for the investments in this technology. Further analysis to explore this hypothesis could be considered using VMS data.

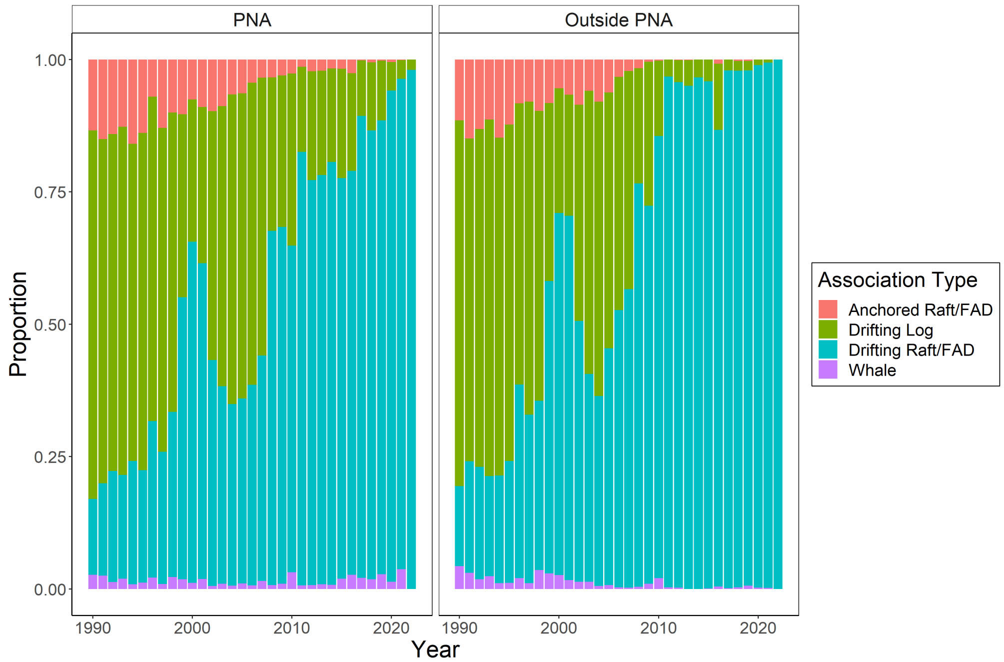

Figure 7: Time series of proportions of associated sets attributed to different association categories, 1990-2022.

More detailed information on FAD deployments, in particular the proportion of sonar-associated FADs, FAD technology, the influence of the FAD closure period, and related per set catch rate changes is needed. In particular, the number of deployed and actively monitored FAD rafts could be a key characteristic of vessel fishing strategy that may influence effort creep. The number of active FADs and FAD deployments per vessel in the WCPO between 2011 and 2019 were estimated in a recent analysis by Escalle et al. 2021. Using fishery data combined with FAD tracking information, it was estimated that at the scale of the WCPO there were 31,000 FAD buoy deployments in 2016 and approximately 34,500 in 2017, 39,500 in 2018 and 33,400 in 2019. If these estimates are reliable this means the number of FAD buoys deployed per year is similar to the number of FAD sets per year. The median number of active buoys monitored per vessel per day ranged from 45 to 75 depending on the year, well below the current management limit of 350. It remains unclear how close the number of FAD buoy deployments is to the number of actual FAD rafts deployed, as raft theft and buoy change over is considered a common occurrence. More work is required to better estimate the number of FAD raft deployments to account for theft and exchange of buoys, and any trends in these activities. FAD density may influence catch rates along with FAD technologies (e.g., sonar-equipped FADs) and these factors could both influence changes in fishing strategies and catch rates. Integration of FAD information is a continued priority for future work to increase understanding of the indirect and difficult to measure drivers of effort creep.

Aggregate purse seine catches inside and outside PNA waters

Within PNA waters, annual total tuna catch decreased by 7% while annual skipjack catch decreased by 15% from 2018-2019 to 2020-21. Over the longer-term there is a positive linear trend of 1% per year, relative to 2007, in total tuna and skipjack catch in PNA waters (Table 1; Figure 8). Outside PNA EEZs, average annual tuna catch decreased by 27% while skipjack catch decreased by 28%, from 2018-19 to 2020-21 (Table 1). Not surprisingly, both longer (2007-2021) and short-term (2018-19 versus 2020-21) trends for skipjack catch are similar to overall tuna catch (Table 1). The species catch composition in both associated and unassociated sets has remained dominated by skipjack (annual average of approximately 80% skipjack for both set types). The FAD sets, however, tend to catch a higher proportion of bigeye tuna than the unassociated sets, while unassociated sets have a slightly higher proportion of yellowfin tuna (Figure 8). Total catch serves as an important proxy indicator for fishery impact, but can be directly influenced by factors unrelated to effort creep such as the number of vessels participating in the fishery and stock biomass; and therefore, CPUE metrics and daily setting rates are considered a more informative indicator of effort creep.

Figure 8: Time series of purse seine catches inside (top) and outside (bottom) PNA EEZs, for associated (left) and unassociated (right) sets from 2007-2021.

Changes in vessel, gear, and technological characteristics within the purse seine fishery

Changes in the size of vessels or other specific vessel or gear characteristics, are a possible indicator of effort creep. There are three potential sources of vessel characteristic data which may cover different components of the tropical purse seine fishery: the WCPFC Record of Fishing Vessels; the FFA Vessel Register; and the PNA VDS Register. Additional information with respect to vessel and gear/technological characteristics as well as access to, and use of, different information technologies are available from observer collected data. It should be noted that the observer data are incomplete for 2022, and the data coverage is affected by COVID-19 since 2020, which may explain why there is slightly lower and less variable well capacity in the most recent years.

These metrics show recent trends in mean values between -3 to +3% and longer term trends ranging from no change to a 1% increase, per annum (Table 1; Figure 9). Although physical characteristics are important, the physical and power characteristics of the purse seine fleet in the WCPO appear very stable since the VDS implementation. Other variables are likely influencing the modern fishery now more so than the physical characteristics, these may include; new electronics, communication systems, FAD-mounted echo-sounders, land-based analysts, access to high resolution oceanographic/sea surface temperature data etc.. Greater understanding (i.e., through discussion with vessel skippers and fishing company staff) and reporting of how technological advances and information streams are being incorporated into fishing operations and decision making is important to be better understand how these aspects influence both economic efficiency and catch rates. A recent industry survey (Wichman and Vidal, 2021) suggested that FAD-mounted echosounder buoys were perceived as the most important technology for improving FAD catch rates. For unassociated sets, on the other hand, helicopter use is important, and we can assume drone use will become more important, along with use of remote oceanographic sensing tools/data. The survey responses suggested an overall increased reliance on information technology in the contemporary fishery, as opposed to the more physical technologies they relied on for efficiency gains a decade or two prior. Clearly the importance of technology use in fishing is increasing and it is the combinations of individual technologies that likely leads to the greatest gains in efficiency. We will require not only more data on technology use by individual vessels in the WCPO purse seine fishery but a more sophisticated analytical approach to quantify how integrated technology use influences catch rates and may contribute to effort creep (Eigaard et al., 2014; Eigaard, 2009).

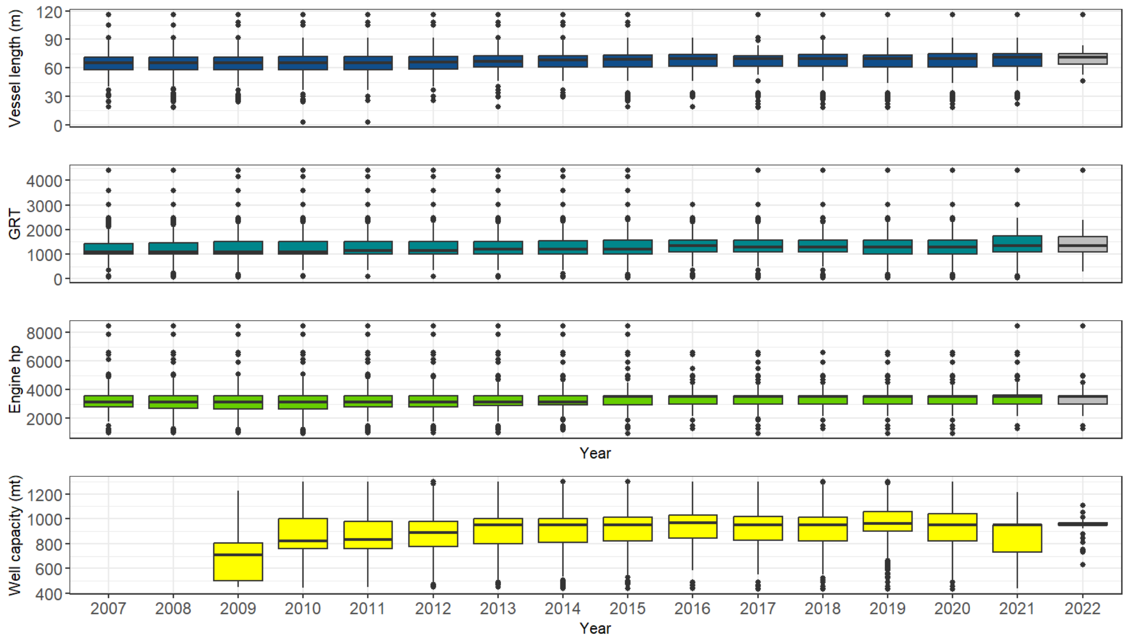

Figure 9: Boxplots illustrating the distribution of vessel size characteristics of purse seine vessels registered annually on the FFA Vessel Register in terms of length overall (m; top); gross registered tonnage (GRT); engine horsepower; and well capacity (mt; bottom). The well capacity data were obtained from observer collected data.

Summary

Understanding effort creep as it relates to effort-based management requires coupling changes in nominal effort indicators, in this case purse seine sets, with changes in the effectiveness of nominal fishing effort, in this case the effectiveness of purse seine sets in catching tuna. This paper presents simple aggregated annual estimates of indicators of nominal effort creep in terms of numbers of purse seine sets per year and per fishing day, and the effectiveness of nominal effort in terms of catch rates per set. For both types of indicators there were no long-term trends since the implementation of the VDS system, either for the PNA waters under the management of the VDS or non PNA waters where the fishery is managed under flag specific catch or fishing day limits. The lack of trend in catch rates per set was also consistent for associated and unassociated set types. While there was considerable interannual variability in the indicators, the lack of sustained increasing trends suggest that despite the implementation of an effort based management systems based on fishing days, there was not an overall increase in the amount of nominal effort realised within the fishing day effort unit. We do note however that at the introduction of the VDS there was a major increase in the total number of sets each year for PNA waters, largely driven by an increase in the number of unassociated sets. This step change may be a result of the change in the management system, but is not indicative of effort creep. In fact this change is entirely consistent with an increase in the number of fishing days from 2009 to 2010, and there is no notable increase in sets/day over the same period. We note that the aggregated nature of the data presented does not preclude that nominal and effective effort creep could be occurring for specific flags and EEZs. A more detailed analysis at flag and EEZ level is required to explore this possibility. Finally, it is clear that increases in effectiveness of associated sets did occur prior to the VDS implementation that appeared related to the transition to dominant use of drifting FADs facilitated by the availability of affordable satellite tracking buoys.

Despite the increased use of technologies such as acoustic sensors on FAD bouys, we did not see any sustained increase in catch rates per set for associated sets since the VDS was implemented. This is a somewhat surprising result in light of industry perceptions that FAD technologies have been a major contributor to improving their effectiveness (Wichman and Vidal, 2021). It may be that the FAD technologies have improved the efficiency and economics of fishing operations (i.e. time and travel) to the extent that employing these technologies improves profitability but that they have not been so effective in increasing catch rates per set or capacity for higher setting rates per day.

The lack of positive trends in catch rates per set is, however, not entirely conclusive that no efficiency creep is occurring. If increased efficiency at catching fish is occurring against a backdrop of stock decline, it could result in stable catch rates per set (i.e., the effort/efficiency creep compensates for declining stock abundance/availability). Furthermore, even if efficiency creep is not occurring the highly selective nature of purse seine fishing (both associated and unassociated modes) can result in hyperstable catch rates per set even when the stock may be declining or even increasing. The strong potential for hyperstability in purse seine catch rates presents an issue when interpreting how these data indicate both stock trends and effort creep. The catchability proxy included in this analysis considers daily catch rates in relation to biomass estimates. In a scenario where harvest efficiency is stable, catch rates would be expected to decline as biomass declines. The increasing trend in the catchability proxy for purse seine skipjack suggests that increased capture efficiency may be offsetting the recent estimated decline in biomass from the 2022 stock assessment. This may be influencing the stability in the catch rate indicators.

Effort creep can have implications for the performance of the VDS in relation to meeting stock conservation objectives and economic returns to PNA members. Increased efficiency could have at least three implications: i) if vessels can catch more fish in one day they may not need to purchase as many days, ii) if fishers can catch more fish in one day without incurring significant additional cost, the value of a day could be higher, and iii) if fishers can catch more fish in one day this could undermine the ability of the VDS to constrain fishing mortality to the expected level. The aggregated data presented in this study suggest the variation in catches per day is dominated by interannual variation that is likely difficult to predict. However, it is possible that different EEZs and or flags may show different patterns and or sustained trends in catch rates per set or sets per day that could be of interest to individual PNA members for optimizing economic returns from their allocations of VDS days. These higher resolution type analyses are beyond the scope of this paper but could be considered in future work, subject to data confidentiality and SPC staff time. The indicators presented do not suggest that overall effort creep is undermining the VDS control on fishing mortality compared to when it was implemented.

In this analysis, we have examined catch and effort indicators independently from vessel characteristic indicators (e.g., vessel length, GRT, well capacity); further analyzing changes in catch rates with respect to changes in vessel characteristics or technologies employed may improve our ability to assess effort creep. Continued research into the development of suitable effort creep indicators should focus on these integrated analyses, including improved understanding of changes in operational decision making and fishing strategies influenced by advances in technology. This would require closer collaboration with industry which has proven difficult. We would encourage enhanced data collection or reporting of technology and information sources used by purse seine fishing operations. We also note the importance of enhanced data collection from the fishery, including the wide array of drifting FADs throughout the Pacific. Building a more complete and accessible database with information on the location, movement, and characteristics of FADs should enhance these analyses. In addition, Vessel Monitoring System (VMS) data will become increasingly important as we investigate changes in fisher behaviour over time.

SPC looks forward to continuing to work with the PNA on effort creep in the purse fishery.

Acknowledgements

We would like to thank the Pacific-European Union Marine Partnership (PEUMP) programme for supporting staff time that facilitated the analysis. We also thank staff in the OFP data management team for their assistance, including: Peter Williams, Emmanuel Schneiter, Bruno Deprez amd Benoit Pohl.

References

Castillo Jordan, C., Teears, T., Hampton, J., Davies, N., Scutt Phillips, J., McKechnie, S., Peatman, T., Macdonald, J., Day, J., Magnusson, A., Scott, R., Scott, F., Pilling, G., and Hamer, P. (2022). Stock assessment of skipjack tuna in the western and central Pacific Ocean: 2022. Technical Report WCPFC-SC18-SA-WP-01.

Eigaard, O. R. (2009). A bottom-up approach to technological development and its management implications in a commercial fishery. *ICES Journal of Marine Science*, 66(5):916–927.

Eigaard, O. R., Marchal, P., Gislason, H., and Rijnsdorp, A. D. (2014). Technological Development and Fisheries Management. *Reviews in Fisheries Science & Aquaculture*, 22(2):156–174.

Escalle, L., Hare, S. R., Vidal, T., Brownjohn, M., Hamer, P., and Pilling, G. (2021). Quantifying drifting Fish Aggregating Device use by the world's largest tuna fishery. *ICES Journal of Marine Science*, 78(7):2432–2447.

Palomares, M. L. D. and Pauly, D. (2019). On the creeping increase of vessels' fishing power. *E&S*, 24(3):art31.

Pilling, G., PNA Office, Norris, W., and Hamp (2016). Examining indicators of effort creep in the WCPO purse seine fishery. Technical Report WCPFC-SC12-2016/MI-WP-08, Bali, Indonesia, 3–11 August 2016.

Scherrer, K. J. N. and Galbraith, E. D. (2020). The risk of underestimating long-term fisheries creep. *E&S*, 25(1):art18.

Vidal, T., Hamer, P., Escalle, L., and Pilling, G. (2020). Assessing trends in skipjack tuna abundance from purse seine catch and effort data in the WCPO. Technical Report WCPFC-SC16-2020/SA-IP-09.

Vidal, T., Wichman, M.-O.-T.-A., Hamer, P., Pilling, G., and PNAO (2021). Effort creep within the WCPO purse seine fishery. Technical report, The Pacific Community and the Parties to the Nauru Agreement Offfice.

Wichman, M.-O.-T.-A. and Vidal, T. (2021). Incorporating industry knowledge to understand purse seine effort creep and evolution of fishing strategies in the WCPO. Technical Report WCPFC-SC17-2021/MI-IP-07.

Appendix

Figure A1: Comparison of time series of vessel fishing days estimated from logbook records, the Vessel Monitoring System (VMS), and the Vessel Day Scheme (VDS). Note that the days estimated by VMS are days when vessels are in PNA EEZs for part or all of that day. Transit days from a port to and from a fishing ground in a PNA EEZ are included in the VMS days at sea but not the VMS fishing days. VDS days were provided by PNAO and exclude approved non-fishing day claims. VMS fishing days may also include days where vessels transited between fishing ground in EEZs, and would include other days that may have been claimed as non-fishing days and were not included in the VDS fishing days. These difference would explain why the VMS fishing days are consistently higher than the VDS fishing days.

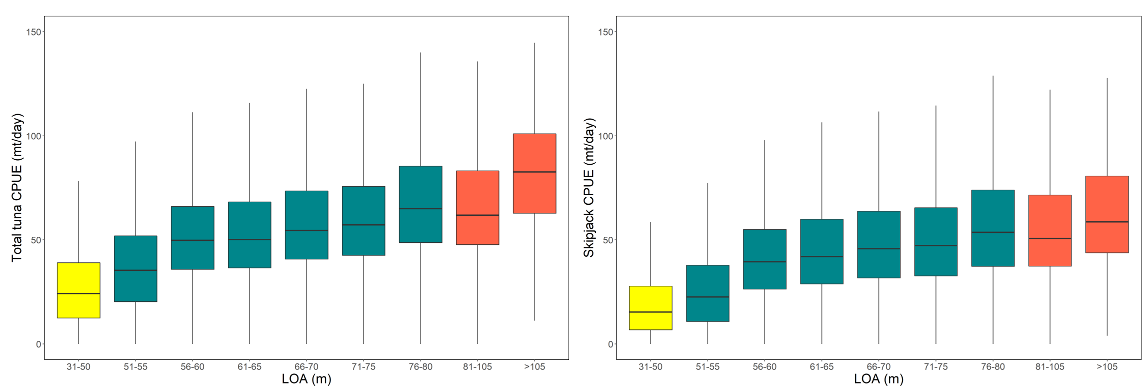

Figure A2: Boxplots illustrating the distribution of trip level total tuna (left) and skipjack (right) catch per day from vessel logsheet data, grouped by vessel size class, from 2007-2021. The colors indicate the vessel size classes associated with the VDS. Note: species compositions here have not been corrected for observer sampling.

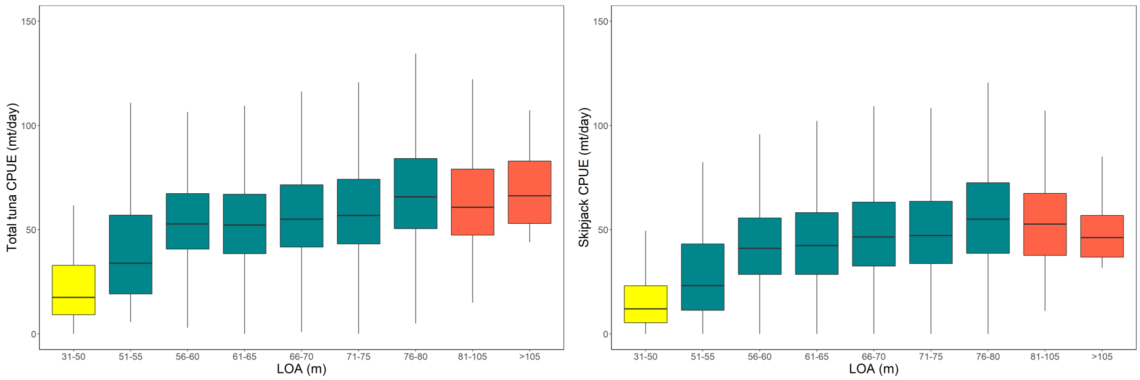

Figure A3: Boxplots illustrating the distribution of trip level combined tuna (left) and skipjack (right) catch per day from vessel logsheet data, grouped by vessel size class, from 2018-2021. The colors indicate the vessel size classes associated with the VDS. Note: species compositions here have not been corrected for observer sampling.

Updates to additional analysis

Catchability proxy

In previous reports, catch and effort metrics have been presented without direct reference to estimates of the underlying biomass. Available biomass will undoubtedly influence the abundance and distribution of tropical tunas, and therefore have an impact on catch rates. In addition, one of the main concerns with respect to using purse seine catch and effort data for assessment and monitoring is the notion of hyperstability. If effort creep exists and is unaccounted for, declines in biomass may be masked by increasing efficiency, referred to here as increased catchability. Similarly, it is difficult to think about effort creep without the context of changes in biomass. Therefore, in the 2021 effort creep paper, in lieu of catchability estimates from the assessment models,Vidal et al., 2021 presented a new catchability proxy. This proxy used the nominal annual catch per day, year, and region (inside and outside PNA waters), divided by estimated skipjack biomass in each year (summed for the tropical assessment regions 3-8; Figure A4), from the skipjack stock assessment diagnostic model to yield a catchability proxy that could be compared across time.

Purse seine catch rates are not entirely composed of skipjack, but largely a combination of both skipjack and yellowfin tuna. However, skipjack is the primary landed species and therefore used for this proxy indicator.

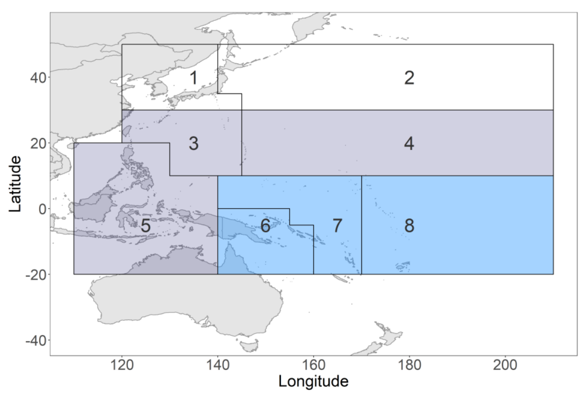

Figure A4: Skipjack assessment regions used for the catchability proxy (Regions 3-8, shaded in blue).

The catchability proxy uses annual catch (mt) C_y divided by total fishing days E_y as an approximation of average catch per day. This was then divided by biomass in each year B_y, from the most recent skipjack stock assessment diagnostic model (Castillo Jordan et al., 2022), to derive the catchability proxy q_y, or the relative proportion of the stock caught in one day of fishing. It should be noted that the same annual regional total biomass estimates were applied to both the

PNA and non-PNA waters; biomass has not been weighted by the area of the respective regions.

$$q_y = \frac{C_y/E_y}{B_y}$$

Due to the change in how fishing days have been estimated in the current paper we have recalculated the catchability proxy using the VMS estimated fishing days (Figure A5).

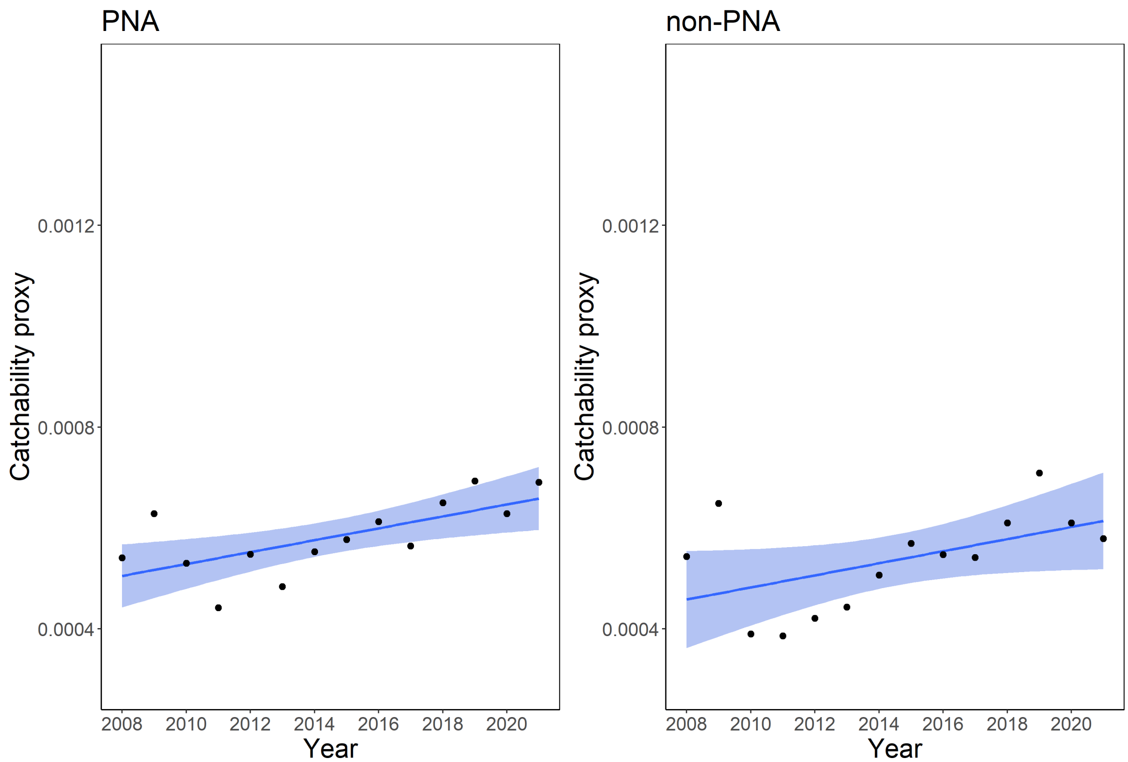

Figure A5: Catchability proxy (presented as a percentage) by management area (inside and outside PNA EEZs) from 2008-2021.

The estimated Skipjack biomass has declined over the time series considered here (i.e., since 2008) (Castillo Jordan et al., 2022). The recalculation of the catchability proxy with the biomass estimates from the 2022 diagnostic model, while interannually variable, shows an increasing trend since 2008 of 2% per annum for fleets both inside and outside PNA waters (Table A1). This is higher than the previous version of this paper that used the 2019 assessment (i.e., 1% v 2%). The positive trend may indicate that while nominal effort and catch rates per set are stable some efficiency creep may be occurring in the purse seine fleet that has allowed the skipjack catches per vessel day to remain stable in the face of estimated declines in biomass since 2010. However, we caution that the model biomass estimates used are based on the diagnostic model only. Future calculations of this index could consider the uncertainty in the biomass estimate by using the assessment uncertainty model grid.

Table A1: Summary of relative daily exploitation rate (average 2020-21 v average 2018-19) and longer-term (2008-2021) trends within and outside PNA EEZs.

Indicator	**2018/2019 vs 2020/2021**		**Per annum linear regression trend, 2008-2021**	
	PNA	Non-PNA	PNA	Non-PNA
Catchability proxy[4]	-2%	-9%	+2%	+2%

[4]Skipjack biomass estimates are from the 2022 stock assessment with the last year of data being 2021.