Western and Central Pacific Fisheries Commission

SCIENTIFIC COMMITTEE
TWENTY-FIRST REGULAR SESSION

Nuku'alofa, Tonga
13 – 21 August 2025

Examining Indicators of Effort Creep in the WCPO Purse Seine Fishery

WCPFC-SC21-2025/MI-IP-02
12th July 2025

Paul Hamer[1], Thomas Teears[1], and the PNAO[2]

[1] Oceanic Fisheries Programme of the Pacific Community
[2] Parties to the Nauru Agreement Office

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, 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. Other advances in technology such as sonar and bird radar, and refinements to purse seine gear and vessel upgrades have also likely enhanced the efficiency of the fishing operations. The application of effort management, through vessel day limits, within the tropical tuna purse seine fishery is expected to 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 considered 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 could erode the effectiveness of effort limits that are designed to constrain fishing mortality to meet stock status and or economic management objectives. 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 2025, 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 2023, with partial data presented for 2024 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 what might be previously considered as searching activities as transit activities. Unlike transit activity, search activities are considered fishing effort and should contribute to logbook fishing days, as they would under the VDS reporting. 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 more 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 a very slight declining trend since 2008, contrary to what might be predicted (i.e. increasing trend) under daily effort constraints. Sets per day is generally lower and more variable in non PNA waters, with no long-term trend. The lack of trend in daily setting rates was confirmed with observer data that only consider days when sets were actually made. Observer data indicates that the percentage of active fishing days (days when sets are made) where more than one set is made has varied around 20-25% since 2010 for PNA waters and 5-25% for non PNA waters. Overall the results do not indicate an increasing trend in the number of sets per day since the VDS was implemented and therefore that nominal effort creep within the VDS limits has not occurred since the VDS was implemented.

Trends in the effectiveness of purse seine sets were explored primarily by comparing catch rates per set by associated and unassociated (free school) set type and for combined sets types. For combined set types catch rates per set for PNA waters in 2023 where similar to 2021 and 2022, and within the range of variability observed over the last decade. Catch rates per day in PNA waters in 2023 were slightly lower than 2022, but within the range observed since 2008.

For the different set types 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. Catch rates per set were relatively low across 2021-2023 compared to 2019-2020 but with the range of variability since 2007. Associated sets have continually produced higher catch rates than unassociated sets, noting the indicator in this paper includes all unassociated effort (i.e. includes skunk sets). The stable trend in catch rates per set may indicate that the effectiveness of purse seine sets has on average not increased since the implementation of the VDS, even with the addition of newer FAD buoy technology such as acoustic sensors. 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 or 'effort creep' 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.

From the late 2000s, the gains in catch per set in the FAD fishery have stabilised. Factors that may have contributed to this include:

- Limitations on the accuracy/reliability of newer FAD technology, specifically the acoustic sensors that are now standard on FAD buoys. This technology has perhaps had less ongoing impact on per set catch rates than might have been predicted.
- The combined impacts of management and policy changes introduced by the PNA and the WCPFC from 2007, including more restrictive EEZ access requirements and fees that limit the ability for vessels to follow FADs moving through different EEZz, highs seas day limits, and increases in the Pacific Island flagged fleet fishing predominantly in the home EEZs.

Unlike tropical tuna purse seine fisheries in other oceans where the harvests have become dominated by FAD caught fish, the purse seine catch in the WCPO has remained at a roughly 50% split between free school and FAD fishing. This is despite the higher effectiveness/success rates of fishing on FADs (i.e. less skunk sets). This suggests that there are external disincentives, either management/policy or economic/market to switching to a majority FAD dependent fishery.

While the aggregated catch rate indicators presented in this paper do not provide strong indications of effort creep over the period since VDS implementation, technology related effort creep could be offsetting the impacts of declining stock levels 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 around 2010 (Castillo Jordan et al., 2022). 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 for the most recent 2022 assessment and using the VMS fishing day (2008-2021), 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 2025 update of the effort creep analysis continues to indicate that 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. The next skipjack assessment is in 2025. 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. Work is ongoing to improve the accuracy of logbook reporting of vessel activities and correct the historical logbook data.

We invite SC21 to note:

- over the period of the VDS implemention there is a lack of positive trends in the purse seine fishery metrics (sets/day, catch/set, catch/day) that would be indicative of effort creep,
- however, an increasing trend in catch/set occurred for associated sets prior to the VDS implementation, and this is consistent with effort creep occurring as the associated sets became dominated by drifting FADs,
- the potential implications of management and policy changes on effort creep in the FAD fishery,
- the positive trend in the skipjack catchability proxy, which may indicate recent declines in biomass are being offset by some improvements in capture effectiveness, this proxy should be updated with the new assessment,
- the importance of continuing to monitor and develop quantitative metrics of effort creep for management use and development of management procedures,
- the ongoing need to improve the accuracy of logbook reporting of vessel activities and correcting the historical logbook data for any biases due to misreporting,
- the recommendation to continue to refine the methods for estimating purse seine fishing activities from VMS data,
- include indicators for number of FAD deployments and FADs monitored per vessel in future reports.

Table 1: Summary of recent (average 2020-21 vs 2022-2023) and longer-term (2007-2023) trends in different indicators within and outside PNA EEZs.

Indicator	**2020/2021 vs 2022/2023**		**Per annum linear regression trend, 2007(or 2008)-2023**[3]	
	PNA	Non-PNA	PNA	Non-PNA
Sets/year	+1%	+1%	+1%	+1%
Sets/day	+6%	+12%	0%	0%
Total tuna CPUE (mt/day)	+4%	+8%	0%	0%
Total tuna CPUE (mt/set)	-2%	-3%	0%	0%
Total tuna CPUE (mt/set) - ASS sets	-5%	+2%	0%	0%
Total tuna CPUE (mt/set) - UNA sets	-3%	-4%	0%	+1%
Total tuna catch	-1%	-5%	+1%	+1%
Total skipjack catch	+2%	-11%	+1%	+1%
Vessel length (m)	+5%		0%	
Vessel gross registered tonnage (GRT)	+11%		+1%	
Vessel horsepower (HP)	+1%		+1%	
Well capacity (mt)	+6%		+1%	

[2]Percent change relative to 2007 or 2008 level, estimated through linear regression of the data across the period 2007/2008-2023. 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 be due to factors related to technology uptake ('technology creep'), 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 the 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 sets 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, including travelling from one FAD to another, even if the net is not 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 outside of archipelagic waters is managed by flag specific limits on catch or effort as specified in the Tropical Tuna Conservation and Management Measure CMM 2023-01 (https://cmm.wcpfc.int/measure/cmm-2023-01). 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 as a requirement of the implementation of the VDS. The paper is also provided to the WCPFC's annual meeting of the Scientific Committee.

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 2024. This includes complete data through 2023 and partial data for 2024 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. Catchability trends from stock assessment models will be estimated in the new (2025) stock assessment. These were not included in the last several versions of this paper due to a change in the assessment model methodology, however, recent model development will allow the catchability coefficiants to be calculated. Details of historic trends in stock assessment catchability estimates can be found in the 2021 version of this paper (Vidal et al., 2021). An alternative catchability metric is included in this paper Figure A5. Refinements of data inputs can influence results from previous years and **we recommend that the 2025 paper supersede previous versions** for this reason.

A key modification implemented since the 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 (effort), as they do under the VDS. The VMS fishing day estimates are 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 planned, along with dedicated work to adjust the logbook database to account for the misreporting of activity codes. Progress has been limited in 2024 due to staff resources and turnover impacts on the SPC data management team.

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 2007-2023 (with partial data for 2024 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 the 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 2022-23 compared to 2020-21 calendar years. Long-term trends were examined over the time period since the implementation of the Vessel Day Scheme (VDS; 2008-2023[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 since 2007 has varied between about 24,800 in 2007 to around 44,200 sets in 2014. There was a major increase in total sets 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). This increase may have been partly influenced by the closure of high seas pockets at around that time, with fishing days moved into PNA EEZs. In 2023 the raised total number of sets for PNA waters was 31,726 and for non-PNA waters was 6,119, compared to 36,660 and 2,650 respectively in 2022.

For PNA waters the number of associated sets since 2007 has fluctuated between around 9,200 (in

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

2010) and 15,630 (in 2015) sets per year but with no sustained trend or step changes. In 2023 the number of raised associated sets in PNA waters was estimated at 11,917 compared to 14,630 in 2022. In contrast for PNA waters a step change increase in the number of unassociated sets from approximately 9,160 to 15,635 occurred from 2009 to 2010, and the number of unassociated sets has since varied between around 19,800 (in 2023) and 30,100 (in 2013) sets per year, with no sustained trend (Figure 1). The raised number of unassociated sets in PNA waters in 2022 was higher than 2023 at 22,029 sets. The main increase in overall sets per year between 2009 to 2010 was 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 a substantial proportion of the unassociated sets.

For non PNA waters, since 2007 the total number of raised unassociated plus associated sets per year has varied between about 1,300 (in 2010) to 8,300 (in 2015). 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 660 sets in 2010 compared to around 2,600 sets in 2023). In 2023 there were 2,641 associated sets compared to 1,912 in 2022. Unassociated sets have fluctuated but remained relatively stationary over the time series, with peaks of around 6,350 and 5,550 sets in 2015 and 2019, respectively. In 2022 there were only 736 unassociated sets in non PNA waters compared with 3,477 in 2023 (Figure 1).

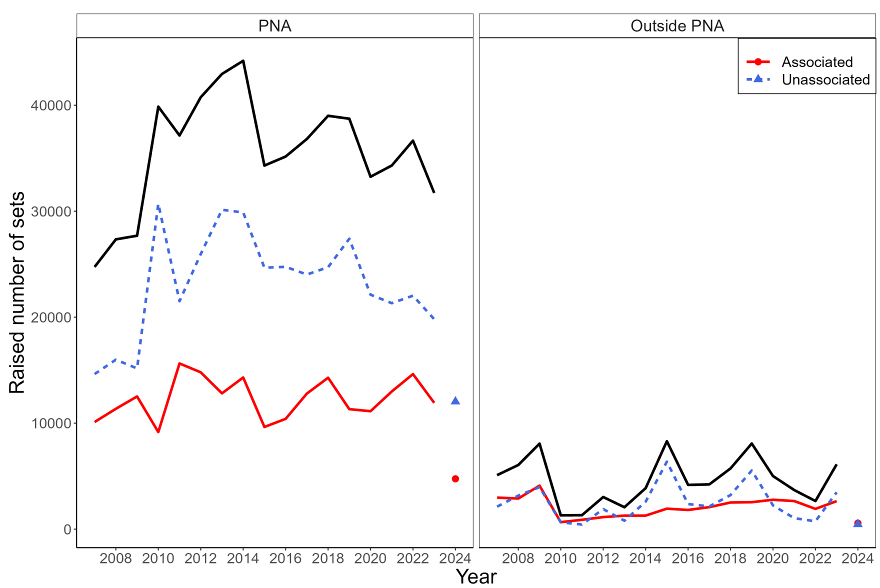

Figure 1: Time series of total raised purse seine sets per year, for associated and unassociated set types, inside (left) and outside (right) PNA EEZs from 2007-2023. Total raised sets is represented with the solid black line for each region. Note: estimated number of sets made in 2024, by set type, 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 (sets/year and sets/day) from 2020-21 to 2022-23, small increases were observed in PNA and non PNA waters (Table 1). Over the longer term (2007/2008 to 2023) there are 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. Importantly, this stability is consistent for sets/day determined from applying VMS fishing days and from observer data for days when at least open set was made (Figure 2).

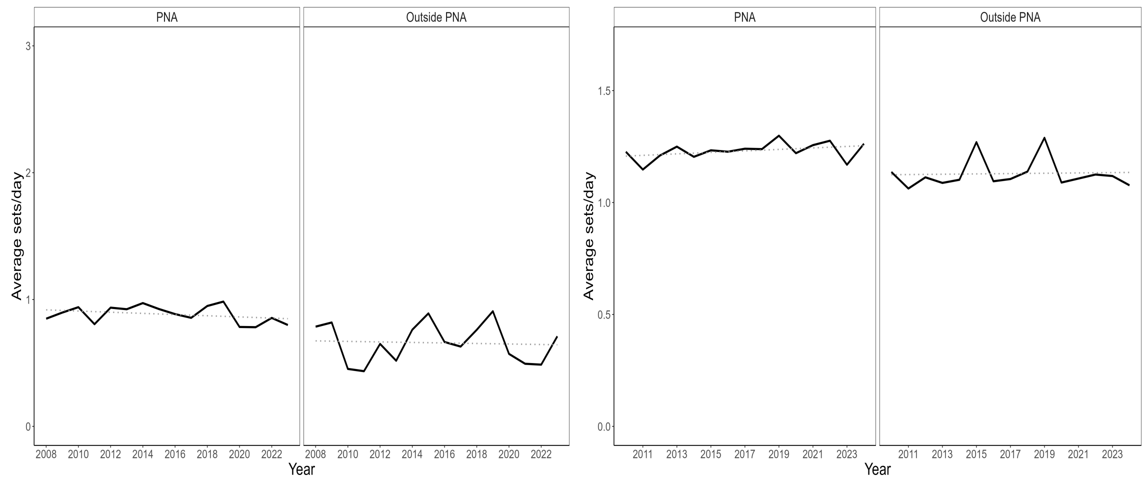

Figure 2: Time series of setting rate (sets per fishing day) for waters inside and outside PNA EEZs. The linear trend (dotted line) through the data points is plotted, but is not statistically significant for any plot. Left plot represent the time series of sets/day using VMS fishing days and raised sets from logbooks (2008-2023). 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 (2010-2023).

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 is no increasing trend in the proportion of days with more than one set. 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. The increase 2015 and 2019 may relate to El Nino conditions in those two years that tend to see more free school sets in high seas towards the central Pacific (Figure 3).

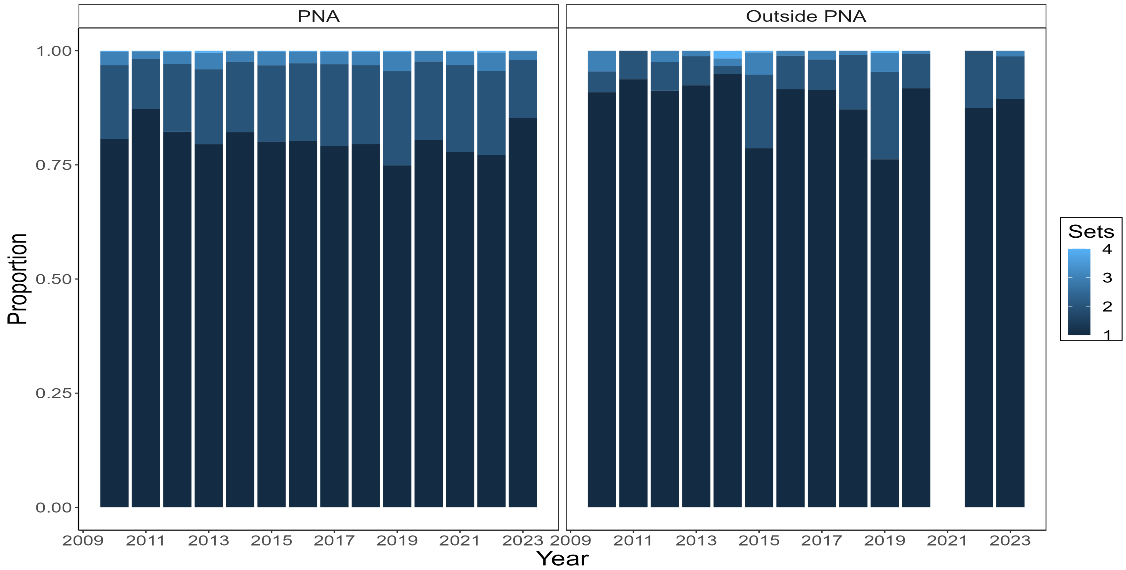

Figure 3: The proportion of observed fishing days (i.e. days when sets were conducted) characterized by number of sets per day (1-4) from 2010-2023 (data unavailable for outside PNA in 2021 - low observer coverage).

The motivation for making multiple sets per day may vary. Previous analysis has shown that the distributions of catches per set are similar irrespective whether it's the first or later sets in a 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 9), which drives these trends. The stable catch composition data in Figure 9 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 tuna CPUE between 2020-21 and 2022-23 showed a decrease of 2% for mt/set and an increase of 4% for mt/day for PNA waters, with a decrease of 3% for mt/set and increase of 8% for mt/day for non PNA waters (Table 1). There are no long-term trends in catch per set and catch per day for both PNA and non PNA waters (Table 1, Figure 4).

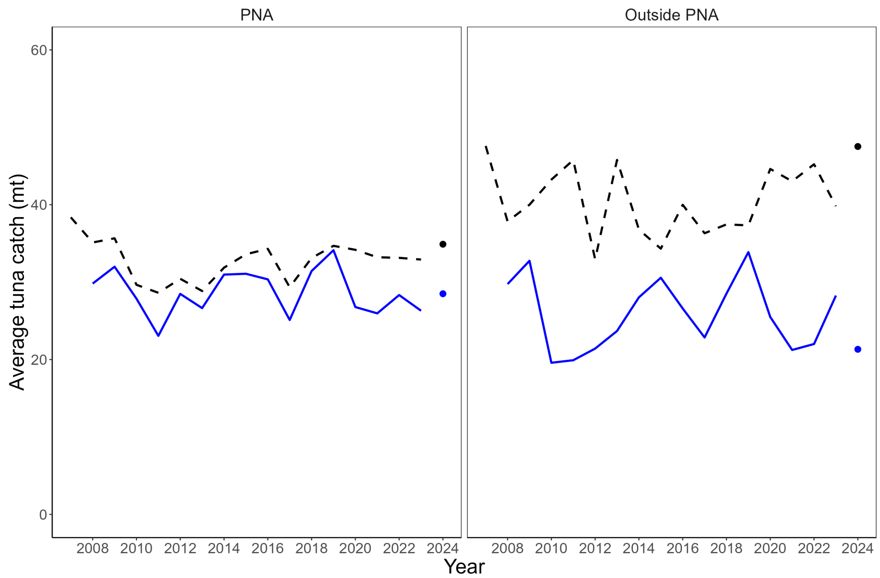

Figure 4: Time series of nominal raised purse seine total tuna CPUE in terms of mt/day (blue; solid lines) and mt/set (black; dashed lines) inside and outside PNA EEZs, from 2007-2023. Note: 2024 is included as points on each figure but data are incomplete.

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 (2020-21 to 2022-23) suggest that catch rates (mt/set) for associated and unassociated sets inside PNA waters have decreased by 5 and 3% respectively, and outside PNA waters there was an 2% increase for associated sets and a 4% decrease for unassociated sets (Table 1, Figure 5). Catch rates for associated sets are on average higher than for unassociated sets (which includes skunk sets as they are considered as effort), 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 increasing trends (2007-2023) 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 2007-2023. Note: 2024 is included as points on each figure but data are incomplete.

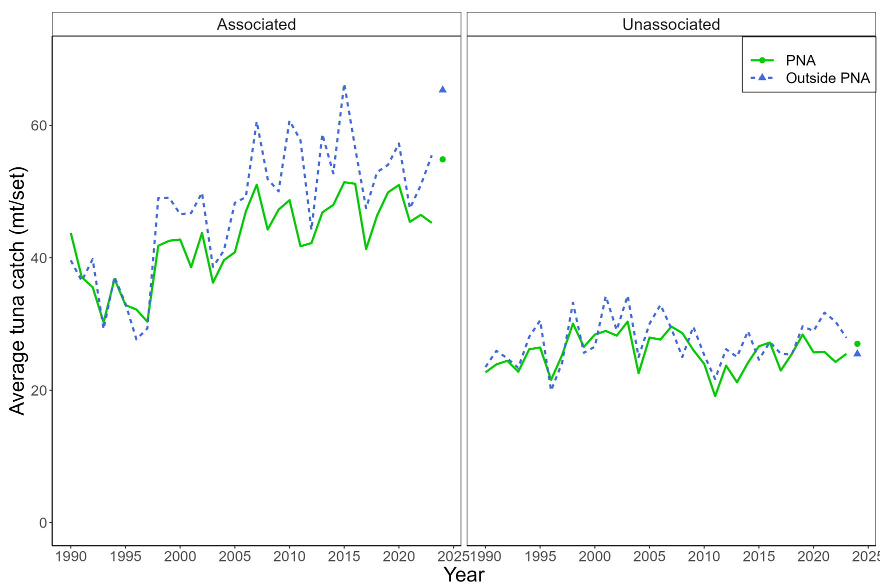

Figure 6: Time series of nominal purse seine total tuna CPUE (mt/set) for associated sets (left) and unassociated sets (right) inside and outside PNA waters from 1990 to 2023. Note: 2024 is included as points on each figure but data are incomplete.

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 FAD buoys. 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 potentially improving profit. However, there are some limitations to FAD use, in particular once a FAD is deployed the vessel has no control over its drift. Therefore many of the FADs that a vessel could be monitoring, including those with potentially higher biomass, may not be accessible due to having drifted out of acceptable steaming range or into EEZs or other areas where a vessel does not have access rights or VDS days. Vessels can only fish accessible FADs irrespective of the potential associated biomass. The cost of FADs also has to be factored in and would place some limit on deployments.

Within these limitations there has been an increase in dependence of associated sets on the deployment of manufactured FADs versus natural floating objects(Escalle et al., 2021). This can be clearly seen in Figure 7 where prior to 2000 drifting logs dominated the associated sets, whereas from the late 2000s manufactured drifting FADs have taken over as the dominant associated set type. This coincides with the uptake of FAD buoys with satellite tracking and enhanced more recently by acoustic sensors.

Overall, however, the WCPO purse seine fishery still conducts the majority of sets on free swimming schools not associated with floating objects, including drifting FADs. This can be seen in Figure 8 showing that around 70% of sets are still made on unassociated schools. However, roughly 50% of the catch now comes from manufactured drifting FADs due to the greater effectiveness of sets on drifting FADs. This is largely due to a high proportion of failed sets on free schools. Given the lower success rates of free school fishing, it is perhaps surprising that the WCPFC purse seine fishery has not mostly switched to FAD sets as has occurred in other oceans. This has not occurred for all key fleets accept the USA, which suggests there are various external factors (discussed above) that discourage against predominant FAD use for the majority of purse seine vessels.

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 affordable satellite tracking buoys. These gains in effectiveness have stabilised since the late 2000s when the VDS, FAD closure periods and high seas effort limits were implemented, despite the uptake of additional FAD buoy technologies, specifically acoustic biomass sensors.

Factors that may have contributed to limiting the gains in effectiveness of fishing on FADs include:

- The effectiveness of FAD technology: it may be that the acoustic technology is not sufficiently accurate or reliable 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/fishing masters. The benefit of acoustic technology on FAD buoys in the WCPO may in fact be more related to economic efficiency, i.e. reduced travel costs, rather than increasing catch rates per set, and this is providing the incentive for investment in this technology. Further analysis to explore this hypothesis could be considered using VMS data. In addition, as noted above vessels can only target FADs that are accessible and within a certain range, so they can not necessarily cherry pick FADs with the highest biomass signal

- The impacts of management and policy changes: from 2007, the package of policy changes introduced by the PNA and the WCPFC brought a level and speed of change to the WCPO purse seine fishery that is beyond anything seen in other major tuna fisheries. Key elements potentially affecting fleet effectiveness and CPUE in the FAD fishery include the VDS limits and pricing, controls on the use of FADs, high seas effort limits and closure, the replacement of wider roaming distant water fleets with domestic fleets focused more on fishing in domestic waters, and free school fishing market incentives. Some evidence of these effects is indicated by a comparison of the patterns of FAD use by ocean region. In the other tropical ocean regions, the share of catches from FADs has continued to increase steadily since the late-2000s, including to around 80% in the Atlantic and Indian Oceans; while the share of catches from FADs in the WCPO has remained relatively stable at around 50% (Figure 8) (Pons et al. (2023)). Further work on comparative trends in CPUE across tropical ocean regions in relation to FAD use could be useful.

Figure 7: Time series of proportions of associated sets attributed to different association categories, 1990-2024, noting 2024 data is incomplete.

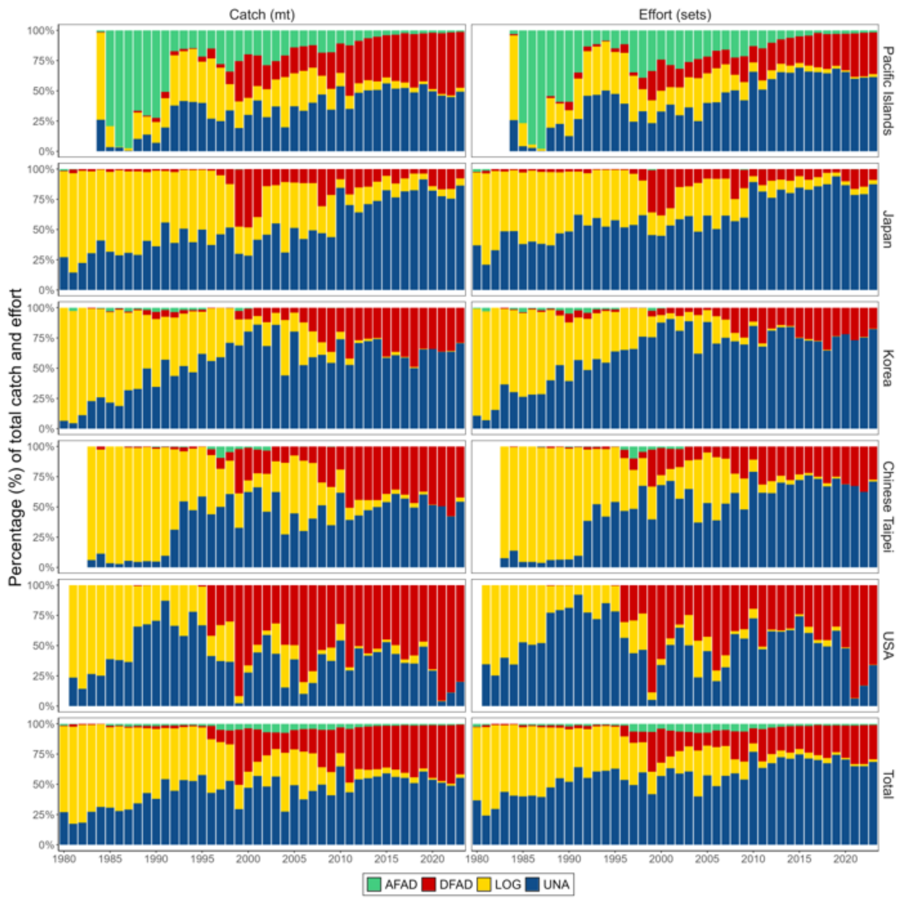

Figure 8: Time series showing the percentage of total sets (right) and total catch (left), by school type for the major purse seine fleets operating in the WCPFC–CA. (Figure 8 from WCPFC-SC20-2024/GN-WP-01 rev1).

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. This contrasts to the total raised associated sets for both PNA and non-PNA waters estimated in 2023 at around 17,730. Many FAD buoys are apparently deployed but never have sets made on them, consistent with the fact that vessel can only set on FADs that are accessible.

Analysis of the 50 vessels in the dFAD tracking database deploying the highest number of buoys in the WCPO per year showed a median number of active buoys per day ranging from 45 in 2016 to 75 in 2019 compared to 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 and these factors could both influence changes in fishing strategies and catch rates. Integration of FAD numbers information is a continued priority for future work to increase understanding of the indirect and difficult to measure drivers of effort creep.

Improved FAD reporting requirements now being implemented under the PNA fourth implementing arrangement will be important in enhancing the data available to better monitor and understand the dynamics of FAD use in the WCPO. Availability of FAD data is now increasing through the PNA FAD logbook reporting, and SPC is developing a database for housing FAD data, and methods to quantify numbers of FAD buoys deployed and monitored per vessel within this database. We recommend future versions of this paper include data on FAD deployments per vessel and FADs monitored per vessel, as the number of FADs available to a vessel on average in any particular day is potentially an important component of fishing effort that is currently not captured in this effort creep analysis.

Aggregate purse seine catches inside and outside PNA waters

Within PNA waters, annual total tuna catch in 2022-23 decreased by 1% while annual skipjack catch increased by 2% from 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 9). Outside PNA waters, annual tuna catch decreased by 5% while skipjack catch decreased by 11%, from 2020-21 to 2022-23 (Table 1). There is a positive 1% longer term (2007-2023) trend for skipjack and total tuna catch for non PNA waters (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 9). 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.

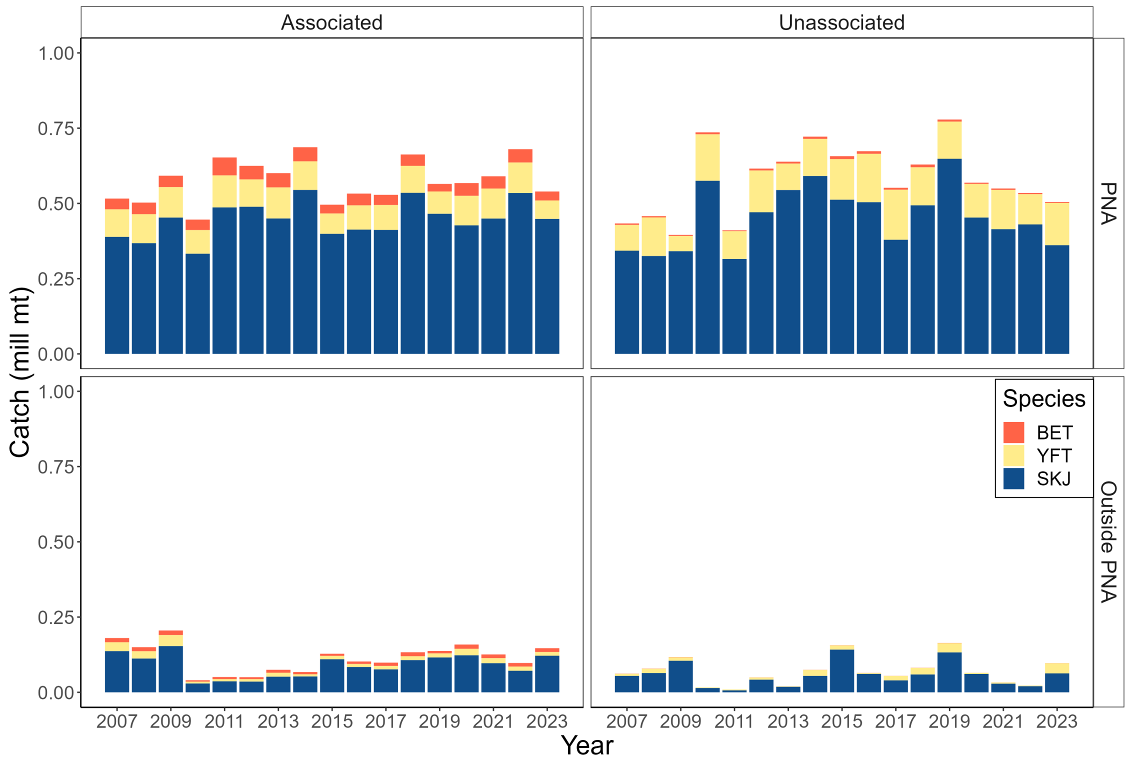

Figure 9: Time series of purse seine catches inside (top) and outside (bottom) PNA EEZs, for associated (left) and unassociated (right) sets from 2007-2023.

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 2024, and the data coverage is affected by COVID-19, most notably in 2021 and 2022.

Vessel metrics (LOA, GRT, HP, Well size) show recent changes between +1 to +11% from 2020-21 to 2022-23. Longer-term trends from 2007 range from no change to a 1% increase, per annum (Table 1; Figure 10). 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 (e.g. more powerfull sonars, bird radars etc.), communication systems, FAD-mounted echo-sounders, land-based analysts, access to high resolution oceanographic/sea surface temperature data etc.. Furthermore, a key factor in constraining growth in purse seine vessel size is the increased cost of vessel days for larger vessels under the VDS charging scheme. 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 was suggested as 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 require not only more data on technology use by individual vessels in the WCPO purse seine fishery but a more sophisticated analytical/modeling approach to quantify how integrated technology use influences catch rates and may contribute to effort creep and how the economics of the VDS daily fees and limits constrains investment in technological advancements (Eigaard et al., 2014; Eigaard, 2009).

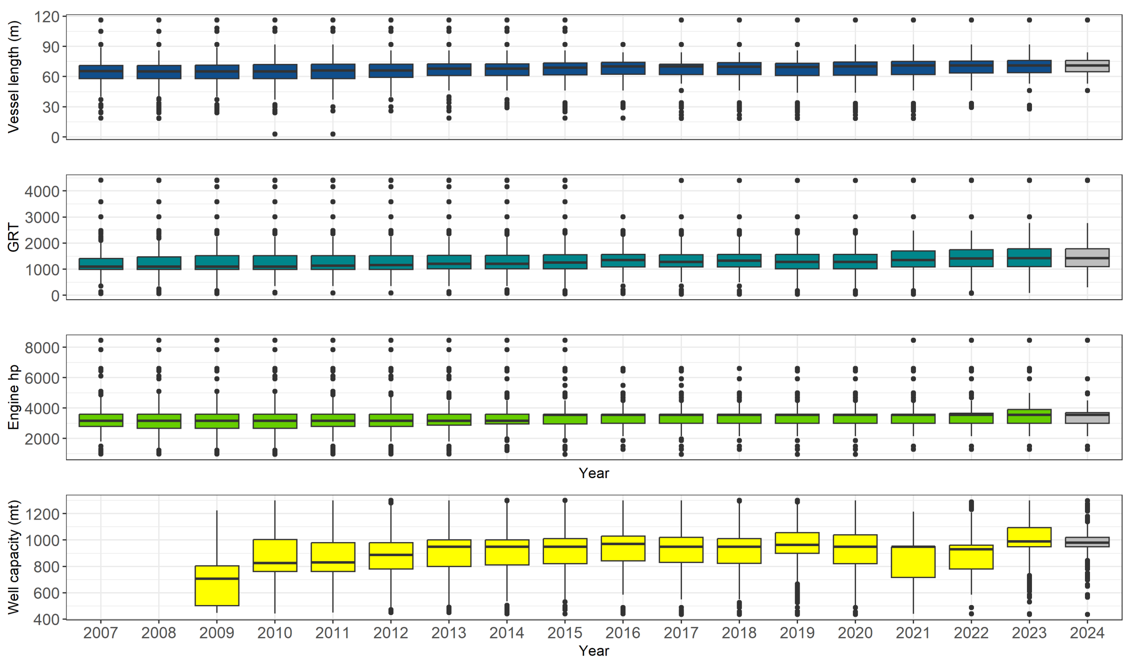

Figure 10: Boxplots illustrating the distribution of vessel size characteristics of purse seine vessels registered annually on the FFA Vessel Register in terms of length overall (m; top); gross registered tonnage (GRT); engine horsepower; and well capacity (mt; bottom). The well capacity data were obtained 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 clear 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 set by the WCPFC. 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 purchased 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 and FAD fishing closure periods, 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. Finally, it is clear that increases in effectiveness of associated sets did occur prior to the VDS implementation. This appeared related to the transition to dominant use of drifting FADs facilitated by the availability of affordable satellite tracking buoys. This likely represents the most important period of effort creep in the history of the purse seine fishery.

Despite the increased use of technologies such as acoustic sensors on FAD bouys, we do 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 as effective in increasing catch rates per set or capacity for higher setting rates per day. Furthermore, the package of policy changes introduced by the PNA and the WCPFC may have reduced fleet effectiveness in the FAD fishery, limiting their ability to achieve the potential gains in effectiveness that might be expected from electronic FAD buoy technology.

The lack of recent 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 recent estimated decline in biomass from the 2022 stock assessment. This metric, along with the catchability coefficients from the stock assessment, will be updated in the 2026 report after the new skipjack assessment in 2025.

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, funding and SPC staff time. Overall, the indicators presented do not suggest that effort creep is undermining the VDS control on fishing mortality compared to when it was implemented. This is contrary to what might have been predicted. The lack of indication of effort creep should be considered in more detail in relation to management and economic constraints through a dedicated economic modeling project.

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 vessel level data on FAD deployment and monitoring. The current progress with the FAD logbook implementation and building the FADs database is an important advancement. 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, particularly as improved data becomes available under the PNA fourth implementing arrangement.

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: Tiffany Vidal, Emmanuel Schneiter, and 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.

Pons, M., Kaplan, D., Moreno, G., Escalle, L., Abascal, F., Hall, M., Restrepo, V., and Hilborn, R. (2023). Benefits, concerns, and solutions of fishing for tunas with drifting fish aggregation devices. *Fish and Fisheries*, 24(6):979–1002.

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

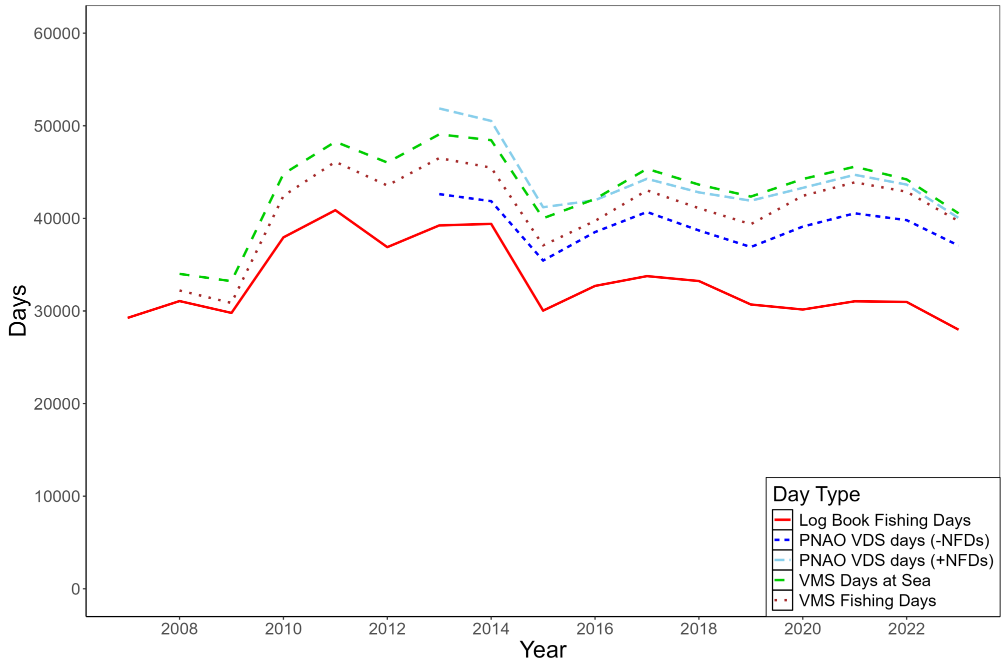

Figure A1: Comparison of time series of vessel fishing days estimated from logbook (ACE) records, the Vessel Monitoring System (VMS), and the Vessel Day Scheme (VDS) with and without non-fishing days (+-NFDs). Note that the days estimated by VMS are days when vessels are in PNA EEZs for part or all of that day. Transit days from a port to and from a fishing ground within a PNA EEZ are included in the VMS days at sea but not the VMS fishing days. VDS days were provided by PNAO. 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 for the VDS. These differences would explain why the VMS fishing days are consistently higher than the VDS fishing days where the non-fishing days are removed.

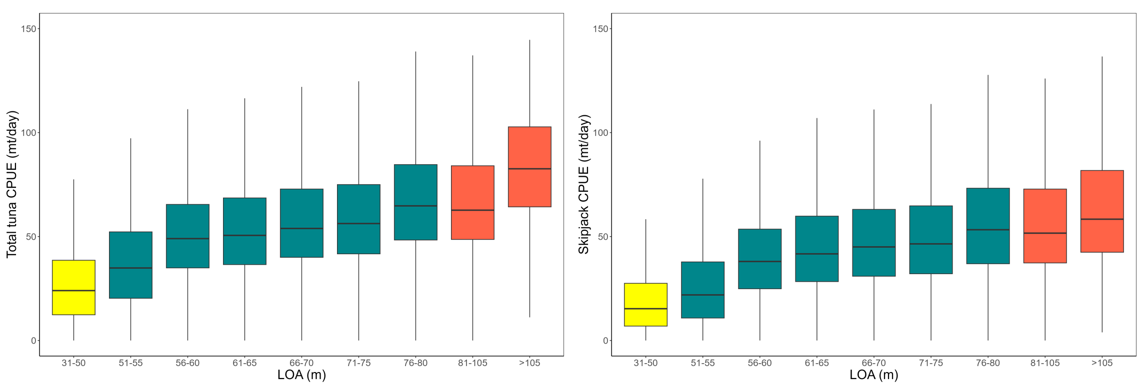

Figure A2: Boxplots illustrating the distribution of trip level total tuna (left) and skipjack (right) catch per day from vessel logsheet data, grouped by vessel size class, from 2007-2023. The colors indicate the vessel size classes associated with the VDS. Note: species compositions here have not been corrected for observer sampling.

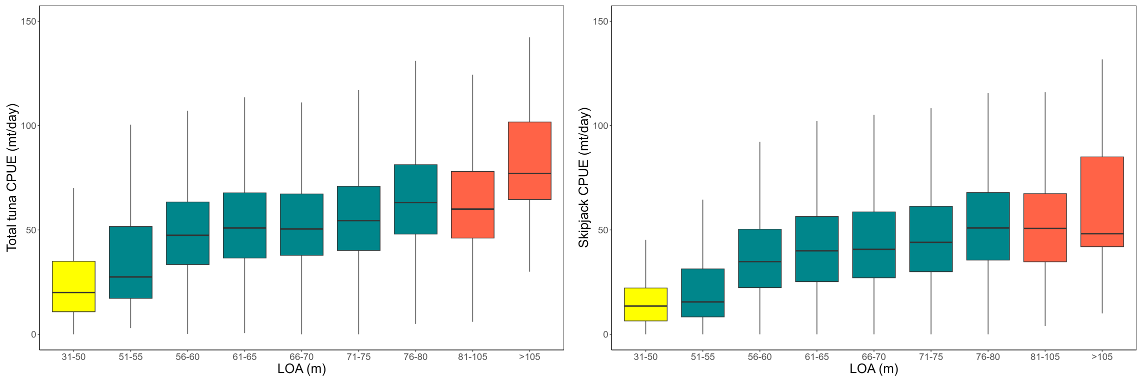

Figure A3: Boxplots illustrating the distribution of trip level combined tuna (left) and skipjack (right) catch per day from vessel logsheet data, grouped by vessel size class, from 2020-2023. The colors indicate the vessel size classes associated with the VDS. Note: species compositions here have not 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.

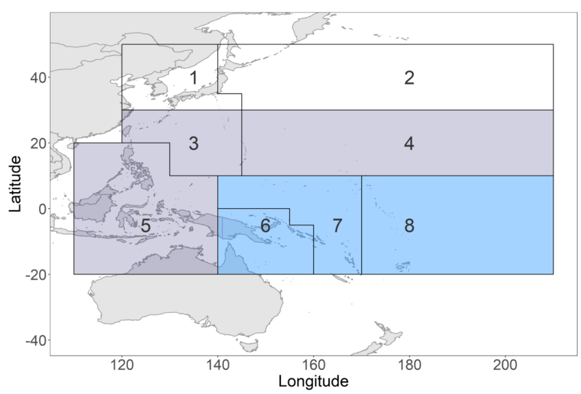

Figure A4: Skipjack assessment regions used for the catchability proxy (Regions 3-8, shaded in blue).

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). This up to date for the most recent skipjack assessment (conducted in 2022) for which the last year of data was 2021. The next skipjack assessment will be in 2025.

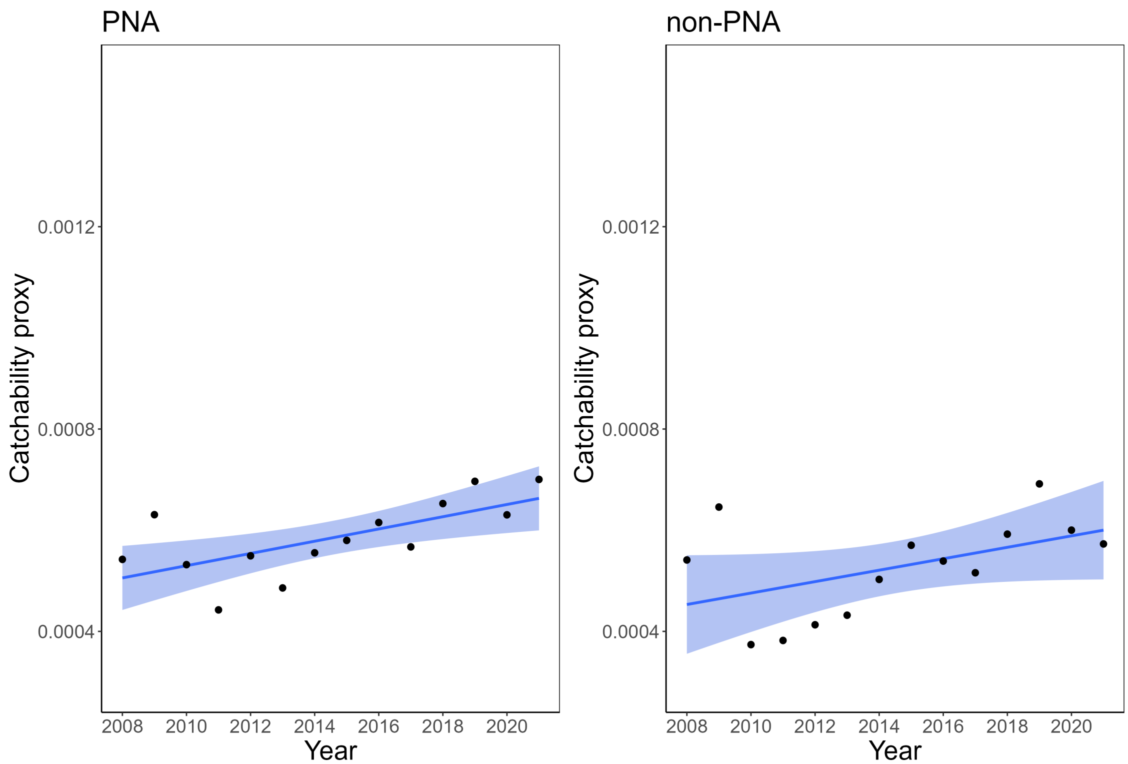

Figure A5: Catchability proxy (presented as a percentage) by management area (inside and outside PNA EEZs) from 2008-2021.

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.