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Shooting fish in a barrel? Assessing fisher-driven changes in catchability within tropical tuna purse seine fleets

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Abstract

With constant innovation to find more efficient ways to find, catch and process fish, catchability in wild fisheries can increase. Catchability is a combination of resource abundance, fishing effort and fishing efficiency: any increase in fleet efficiency can lead to undesirable effects not only on stocks, but also on the ability to assess them. When using effort controls as part of management, it is necessary to adjust for the increase in catchability due to the increases in efficiency over time to avoid stock depletion. Accounting for changes in catchability can be problematic for pelagic stocks, due to the changes in fishing behaviour and the continual change in fishing efficiency. This study investigates the success in finding patches of fish for fleets operating within the western and central Pacific purse seine fishery between 1993 and 2012. Three indices, widely used in ecological research, were used to study how spatial variation in fisher behaviour for sets on fish aggregating devices (FADs) and free-school sets was related to catchability. For free-school set types, the diversity index was negatively correlated with *Katsuwonus pelamis* catchability. When this index was low, catch rates were at their highest and there was a reduction in the area fished. In contrast, for FAD sets, catches increase when the patchiness index was low, implying a degree of random behaviour, potentially due to advances in FAD technology. An improved understanding of the spatial allocation of effort can improve catchability estimates widely used for fisheries stock assessments and in indices of global biodiversity.

KEYWORDS
catchability, CPUE, FADs, fishing efficiency, skipper skill, tuna

1 | INTRODUCTION

The western and central Pacific Ocean (WCPO) purse seine fishery is the largest oceanic tuna fishery, representing 56% of the world's tuna catch for 2015 (Williams & Terawasi, 2016), and over 80% of the tuna in the western Pacific (Harley, Williams, Nicol, & Hampton, 2012). The purse seine fishery mainly targets skipjack tuna (*Katsuwonus pelamis*, Scombridae) and yellowfin tuna (*Thunnus albacares*, Scombridae) between 20°N and 20°S and from 140°E to 150°W, while bigeye tuna (*T. obesus*, Scombridae) are also captured as by-catch by purse seiners fishing on fish aggregating devices (FADs) (Fonteneau, Chassot, & Bodin, 2013). The fleet consists of about 300 vessels from Pacific island nations and Distant Water Fishing Nations (DWFN), including Japan, Republic of Korea, Chinese Taipei, China, the United States, Philippines and Spain. WCPO tuna fisheries are managed at a number of levels: The Western and Central Pacific Fisheries Commission (WCPFC) acts as the Regional Fisheries Management Organisation (RFMO); countries with mutual interests, such as the Parties to the Nauru Agreement (PNA) (Figure 1), implement collective management arrangements subregionally across their members' jurisdictions; and coastal states implement management regimes within their individual Economic Exclusive Zones (EEZs) (Bell *et al.*, 2015). A key subregional

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management arrangement was initiated in 2007, when the PNA developed a Vessel Day Scheme (VDS) for purse seiners that limits the total number of fishing days (the Total Allowable Effort; TAE) within their EEZs, as a means to control effort and thus catch (Shanks, 2010).

When fishers are faced with effort limits, there is an incentive to adapt to their situation by substituting other inputs that will alter the relationship between catch and effort (days under the VDS scheme). The efficiency or harvesting power of fishing vessels, and hence catchability (*q*), tends to increase over time through improvements in fishing technology (e.g. vessel design, electronics, gear (see Table 1 for a review of technological changes detected in purse seine gear and vessels)) and the skill of the skipper/crew (Squires and Kirkley 1999; Tidd, Reid, Pilling, & Harley, 2016), which ultimately makes catching fish easier (Gulland, 1956).

Fishing effort is also an important parameter in stock assessment models, as it is linked to fishing mortality (*F*) via *q* with constant nominal effort (*En*), and generally implies the extent to which the stock is susceptible to fishing (the proportion of fish captured by one unit of *En*). This increase in *q* over time is generally known as "effort creep" and can be quantified in relation to *F* with constant *En* and intensified effort (*Ee*) (i.e. the variability in fishing power through changes in catch efficiency, such as skipper skill or technological differences), which is known as effective fishing effort. Consequently, increases in fishing mortality can occur even if effort is managed with a fixed number of fishing days. Effort creep, or effective effort, is usually approximated by a metric of capacity, such as gross tonnage or engine power, combined with a measure of fishing activity (time spent on a trip). It therefore represents an aggregated measure of fisher behaviour in locating the greatest densities of marketable fish (Rijnsdorp, Daan, & Dekker, 2006).

Several studies have estimated the factors that contribute to changes in catch at the level of the individual vessel or fishery (e.g. Hannesson 1983; Bjorndal and Conrad 1987), examining the relationship between fishery inputs (e.g. fishing effort, number of boats) and outputs (e.g. catch), and how that relationship has changed over time in relation to stock population biomass (*N*). The relationship is most often assumed to be linear and takes the form $F = qEn$. Catchability also links *N* to catch per unit effort (CPUE) as CPUE = qN (Gulland, 1983; Ricker, 1975). Nevertheless, in certain situations, CPUE may not be proportional to abundance, as fishers learn about, and are better able to locate, concentrations of fish. Thus, catchability can change from one time period to another (Dobby, Allan, Harding, Laurenson, & McLay, 2008; Harley, Myers, & Dunn, 2001). The success of a skipper in finding concentrations or patches influences catchability, resulting in increases in catch, potentially even with a decreasing stock size (Hilborn & Walters, 1992). Some studies on pelagic fisheries (e.g. Csirke 1988; Bjorndal 1989) suggest that there is a degree of independence between CPUE and stock abundance, and that therefore CPUE is not a good predictor of abundance. This form of disproportionality, when CPUE is stable even when stock size is decreasing, is usually the result of spatial and temporal patterns of fish distributions and of fisher behaviour (Walters, 2003). This is a situation known as "hyperstability," which can lead to overestimates of stock biomass and underestimates of fishing mortality (Crecco & Overholtz, 1990). Therefore, an improved understanding of *q* can lead to more accurate estimates of abundance.

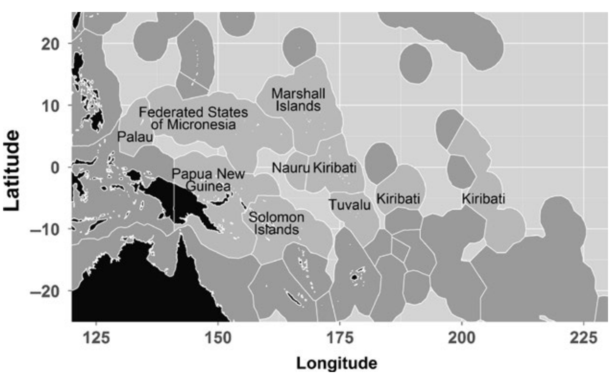

FIGURE 1 The western and central Pacific Ocean (PNA member countries indicated in light grey shading)

The performance of the skipper (or the "skipper effect") has often been considered to be a mythical concept (Palsson & Durrenberger, 1982) and is often debated in the literature (see Mahévas, Sandon, & Biseau, 2004; Robins, Wang, & Die, 1998). The latter reported and quantified that the "skipper effect" and consequential changes in fishing power had largely been reduced due to the technological advancements and the extent of fisher experience with a plotter system. Nevertheless, several studies have shown that, to a varying degree, the skills/experience/age of the skipper/crew are important factors that contribute significantly to the overall fishing power of the vessel. For example, Ruttan and Tyedmers (2007) studied the US menhaden purse seine fisheries (similar vessels with similar equipment owned by the same company) and found that catch per unit of fuel differed between fishers, which implied the influence of some level of skipper skill. Gaertner, Pagavino, and Marcano (1999) modelled catchability of Venezuelan purse seiners from fine scale observer data and found that skipper identity was a significant factor with respect to setting on a particular school of fish and the type of technical equipment used in finding and pursuing the school. The skipper effect can also be related to risk attitudes, in terms of following the fleet or fishing alone, and can be quantified in relation to both fishing effort (i.e. a risk adverse fisher may prefer to spend less time searching for fish and more time fishing) and the fishing activity they are undertaking (e.g. FAD fishing is less risky than free-school fishing due to the greater proportion of positive sets) (Wolff, Squires, & Guillotreau, 2013).

This study investigates the behaviour of four purse seine fleets (Japan, Korea, Chinese Taipei and the United States) with a long history of fishing within PNA EEZs, using a set of ecological indices to describe the spatial tactics and strategies of fishers. Accounting for changes in catchability can be troublesome, especially for pelagic stocks, due to factors such as the changes in targeting via different fishing practices, changes in fishing behaviour (tactical and strategic) and the continual change in fishing efficiency due to the skill of the skipper/crew in applying the new technologies. Tactics can be described as short-term

TABLE 1 Western and central Pacific Ocean (WCPO) sources, and sources from elsewhere of purse seine technological change

Technological factor	Year	Reference	WCPO/elsewhere
Use of FADs	Mid-1980s – early 1990s	Miyake, Guillotreau, Sun, and Ishimura (2010)	Elsewhere
		Leroy *et al.* (2013)	WCPO
		Anonymous (2012)	Elsewhere
Use of support vessels	Early 90s	Arrizabalaga *et al.* (2001)	Elsewhere
		Bayliff and Majkowski (2007)	WCPO
Gear technology			
Adoption of snap rings and roller snap rings for increased pursing speed, reduced wear –and reduced net hauling time (for those vessels not already equipped)	1988–1995	Itano (2000)	WCPO
Adoption of the Spanish style brailing systems or modified Spanish style systems which greatly reduced loading times	1988–1997	Itano (2000)	WCPO
Installation of side net rollers on the working deck to speed drying of the net and work in conjunction with the Spanish style brailing system.	1988–1999	Itano (2000)	WCPO
Improvements to refrigeration systems to handle increased brailing speed	1988–2001	Itano (2000)	WCPO
Increased use of remote sensing technologies	1988–2002	Itano (2000)	WCPO
Fad technology (radio buoy)			
Constant transmit	Pre-1980	Morón, Areso, and Pallarés (2001)	WCPO
Sel-call radio buoy	1986	Morón *et al.* (2001)	WCPO
High frequency sel-call radio buoys	1995	Morón *et al.* (2001)	WCPO
Bent-antennae sel-call radio buoys	1995	Morón *et al.* (2001)	WCPO
GPS sel-call radio buoys	1996	Morón *et al.* (2001)	WCPO
"Serpe" type GPS tracking buoy	1998/1999	Morón *et al.* (2001)	WCPO
Satellite transmitting GPS/remote sonar transmitting buoy	1998/1999	Morón *et al.* (2001)	WCPO
Second-generation frequency echo sounder buoy	Mid 2000s	Scott and Lopez (2014)	Elsewhere
Third-generation multifrequency echo sounder buoy	2012	Scott and Lopez (2014)	Elsewhere
Bird radar			
65 Kw	1997	Gaertner and Pallarés (2002)	Elsewhere
Automatic Radar Plotting Aid (ARPA)	1993	Gaertner and Pallarés (2002)	Elsewhere
60 Kw	1990	Delgado de Molina *et al.* (1999)	Elsewhere
30 Kw	1989	Gaertner and Pallarés (2002)	Elsewhere
10 Kw	1985–1988	Gaertner and Pallarés (2002)	Elsewhere
Sounders			
Side sounders	2008	Torres-Irineo, Gaertner, Chassot, and Dreyfus-León (2014)	Elsewhere
Split beam echo sounder	2001	Gaertner and Pallarés (2002)	Elsewhere
Sonar			
Low frequency	2003/2004	Torres-Irineo *et al.* (2014)	Elsewhere
Tracking sonar	1996–1999	Gaertner and Pallarés (2002)	Elsewhere
Current metre (Doppler)	1990/1999	Gaertner and Pallarés (2002)	Elsewhere
Helicopter	1981	Park, Moon, and Hwang (1998)	WCPO
Satellite maps			
First maps	2000	Gaertner and Pallarés (2002)	Elsewhere
Complete maps	2003	Gaertner and Pallarés (2002)	Elsewhere

decisions, such as where and when to go fishing, what gear(s) to deploy, and where to land the fish (all of which can be affected by factors such as fuel costs, weather, crew availability and market price). Conversely, strategies are long-term decisions, involving factors such as fuel price changes, costs for replacing gear, modifications to vessels, stock status and market prices. A better understanding of the fleet dynamics in terms of effort allocation – and hence the distribution of fishing vessels – may benefit the region in terms of explaining variation in catchability, and it may improve the precision of CPUE indices, both for inputs into the region's stock assessments and as useful indices of global biodiversity. For example, the "Living Planet Index" (LPI), which monitors the change in population abundance in vertebrae species, provides a useful guideline to assist policy-makers' decision-making (González-Maya *et al.*, 2012), ecosystem functioning and ecological processing (Loh *et al.*, 2005).

2 | MATERIALS AND METHODS

2.1 | Data

The Pacific Community's (SPC) Catch and Effort query System (CES) database (which contains detailed commercial logsheet data by fishing event) was used to develop a time series of commercial purse seine skipjack and yellowfin fishing activity data for vessels flagged to the United States (US), Korea (KR), Japan (JP) and Chinese Taipei (TW) operating in the PNA EEZs between 1993 and 2012. Between 109 (2005) and 153 (1993) vessels were present for varying periods of time during this period across those fleets (an aggregation of fishing vessels engaged in a particular type of fishing), with 138 vessels operating in 2012.

The data were extracted at the level of a set. Data were then aggregated over all sets for a vessel in each 1° cell for each trip. However, sets within a trip can consist of associated (A – drifting FAD, log, debris or dead animal; anchored FAD; live whale; and live whale shark) and unassociated (U – free swimming school) sets, and these were kept separated in the aggregation. The data collected for each vessel and trip included days fished, per 1° cell, year and set type A or U. Fleet activity was determined by the fisher's tactic (decisions) at the level of the trip or fishing sequence within a trip at a scale of 1° cell, which is defined on the basis of the set type. The set types were considered as two separate fisheries to evaluate the strategies and tactics of the flags (see equations 1–6, below).

2.2 | Indices of strategies and tactics

Fishing tactics can be described as short-term decisions at the scale of a trip (on average between 14 and 24 days) – that is area to fish, choice of set type – while fisher strategies are the sequence of fishing trip tactics aggregated to the scale of one year. This is consistent with the approach by Marchal *et al.* (2006) and detailed in equations 1–6; variable notations for these equations are presented in Table 2.

The three different indices of vessel behaviour examined in this study are described below.

Abrahams and Healey (1990) and Marchal *et al.* (2006) obtained indices to describe vessel distributions, and hence fish distributions, in space. The first is the Shannon Wiener diversity index. This index is derived from information theory (knowledge transfer) and measures the amount of order/disorder within a system; it is widely used in ecological research to study species diversity (Hill, 1973). An index of zero indicates that only one area (1° cell) was visited on a specific fishing trip ($\text{ft\_sw}_{v,t}$) or annually ($\text{ye\_sw}_{v,y}$). An increase in the index describes how equally fishing effort is distributed across areas:

$$\text{ft\_sw}_{v,t} = -\sum_{a=1}^{A} \left(\frac{E_{v,t,a}}{E_{v,t,A}}\right) \log \left(\frac{E_{v,t,a}}{E_{v,t,A}}\right) \quad (1)$$

$$\text{ye\_sw}_{v,y} = -\sum_{a=1}^{A} \left(\frac{E_{v,y,a}}{E_{v,y,A}}\right) \log \left(\frac{E_{v,y,a}}{E_{v,y,A}}\right) \quad (2)$$

where $\text{ft\_sw}_{v,t}$ is the Shannon Wiener index for trips by vessel *v* and for trip *t*, and $\text{ye\_sw}_{v,y}$ is the same index calculated over a longer timescale by vessel *v* and in year *y*. The remaining parameters are described in Table 2. The Shannon Wiener index applied to fishing vessels is termed the "strategic diversity index," as it represents the diversity in the strategies taken by vessels in terms of areas selected for fishing.

The second index – the index of spatial extent of fishing tactics and strategies – examines the spatial extent of fishing – in particular, the average distance between fishing areas within either a fishing trip (equation 3) or annually (equation 4). Salthaug and Aanes (2003) used a similar indices to describe the spatial extent of fishing vessels, and the methods used by Marchal *et al.* (2006) are investigated. Weighted, effort-based average distances (between fishing area *a* [1° cell] and fishing area *a′* [and the next 1° cell]) are calculated to investigate the degree to which the fleet distributes its fishing operations. Low values generally indicate low spatial extent.

$$\text{ft\_dist}_{v,t} = \frac{\sum_{a=1}^{A} \sum_{a\prime=a+1}^{A} (E_{v,t,a}.E_{v,t,a\prime}.d_{v,t,a,a\prime})}{\sum_{a=1}^{A} \sum_{a\prime=a+1}^{A} (E_{v,t,a}.E_{v,t,a\prime})} \quad (3)$$

TABLE 2 Notation used in equations 1–6

Symbol	Description
E	Nominal fishing effort (days)
v	Fishing vessel
t	Trip
y	Year
a	Area (1° cell)
A	Number of fishing areas
μ & S^2	Mean and variance
d	Euclidian distance
ft_	Denotes fishing tactics
ye_	Denotes fishing strategies

$$\text{ye\_dist}_{v,y} = \frac{\sum_{a=1}^{A} \sum_{a\prime=a+1}^{A} (E_{v,y,a}.E_{v,y,a\prime}.d_{v,y,a,a\prime})}{\sum_{a=1}^{A} \sum_{a\prime=a+1}^{A} (E_{v,y,a}.E_{v,y,a\prime})} \tag{4}$$

The third index type – indices of spatial patchiness – examines the degree to which fishing effort is spatially concentrated. Several authors have used indices of spatial patchiness to describe the distribution of plants and animals (e.g. Clark & Evans, 1954; García *et al*., 2011). The indices of spatial patchiness indicate the degree of dispersion of fishing effort. A simple model used by Marchal *et al.* (2006) was used to describe the degree of dispersion of a fleet (equations 5 and 6). A value greater than 1 indicates an increasingly patchy distribution; values lower than 1 reflect increasingly uniform distribution to the point where a value of 0 indicates a uniform distribution, while a value of 1 is a random distribution.

$$\text{ft\_patch}_{v,t} = \frac{S^2_{v,t}}{\mu_{v,t}} \tag{5}$$

$$\text{ye\_patch}_{v,y} = \frac{S^2_{v,y}}{\mu_{v,y}} \tag{6}$$

2.3 | Relating catchability to vessel behaviour

To capture temporal changes in vessel performance arising from factors other than vessel behaviour, the catchability and stock biomass estimates from the MULTIFAN-CL stock assessment models were used (see Fournier, Hampton, & Sibert, 1998 for general details about these models). Estimates of stock biomass and catchability for the years 1993–2012 were obtained from SPC's 2014 stock assessments of skipjack and yellowfin tuna in the WCPO (Davies, Harley, Hampton, & McKechnie, 2014; Rice, Harley, Davies, & Hampton, 2014). A more recent stock assessment of skipjack tuna was conducted (August 2016; McKechnie, Hampton, Pilling, & Davies, 2016); however, results were not available at the time of the analyses conducted for this study.

The stock assessment models estimate catchability for each fishery defined in the models. These fisheries are defined as homogenous groups of fishing activity (usually based on gear-type) within a defined assessment region, which have similar selectivities and catchabilities. The purse seine fisheries in the equatorial regions of the skipjack and yellowfin stock assessments are separated into unassociated and associated fisheries, and their catchabilities are allowed to vary in a structural time-series manner. For each species, the annual catchability values to be correlated with the fishing behaviour indices were calculated as the mean over the catchabilities of the relevant fishery (associated or unassociated), over the regions encompassing the PNA waters (stock assessment regions 2 and 3, and regions 3 and 4, for SKJ and YFT, respectively; Rice *et al*., 2014; Davies, Harley *et al*., 2014), over the four quarters (the assessment model timescale) within each year (Figures 1 and 2). The q and stock biomass estimates for each species were then correlated with each of the calculated indices (equations 1–6, which were averaged over all vessels and nationalities at the scale of the year). The estimates were assessed using Pearson's correlation to determine the significance of the relationship.

3 | RESULTS

Estimates of mean catchability and total stock biomass are presented in Figure 2a,b, respectively. These show that for both species, there has been an increase in catchability for both set types, with the most significant increases in associated sets on skipjack occurring since the mid-1990s. A sudden increase is evident for yellowfin just prior to 2000. In contrast, there have been declines in stock exploitable biomass estimates for both species, but most notably for the yellowfin stock. Linear regression was used to correlate the annual means of the three indices describing the spatial behaviour of the fleet by set type with the trends in mean annual species catchability and the species annual stock biomass estimates (Figure 2). The relationships were compared via their statistical significance (see Table 3), using scatter plots. To highlight the changes in catchability over the 20-year period, the data were divided equally into two 10-year time periods (Figures 3 and 4), and Figure 5 reflects the mean indices over time, which is a summary of the indices presented in Figures 3 and 4.

Several spatial indices of fisher behaviour were correlated with estimates of catchability for both tuna species but, as expected, the nature and strength of these relationships differed between associated and unassociated sets and the timescales of the fishing behaviour (trip-level versus annually averaged).

3.1 | Associated sets

The strategic diversity index for the fleet (ye_sw) and the degree of dispersion (ye_patch) were both negatively correlated with skipjack q ($p < .05$, $r = -.52$, $n = 20$) and ($p < .001$, $r = -.70$, $n = 20$), respectively. Increased skipjack catchability in more recent years (depicted by grey circles, 2003–2012; Figure 3) was correlated with lower ye_sw values, implying fishers were concentrating their effort in specific areas, compared with earlier years where the higher ye_sw values indicated that vessels distributed their effort more evenly through the region, and catchability was lower. However, catchability in recent years increased as the fleet distributed its effort more heterogeneously (i.e. ye_patch dispersion index close to 1), while in the past (1993–2002, depicted by black circles), the distributions appear to be more "patchy" (indices >1, up to a maximum value of 1.5).

In contrast, ye_patch was positively correlated with yellowfin stock biomass estimate. When yellowfin stock biomass estimate was higher, the strategic patchiness index increased linearly, indicating a patchier distribution of effort, and this relationship was highly significant ($p < .001$, $r = .75$, $n = 20$). Similarly, at the level of the trip, the relationship between q for both species and the patchiness index (ft_patch) was also highly significant (skipjack: $p < .01$, $r = -.66$, $n = 20$; yellowfin; $p < .01$, $r = -.63$, $n = 20$) and negatively correlated. When observing the tactical indices of spatial extent for the fleets (ft_dist), there was no significant difference, although the linear relationship suggests increases

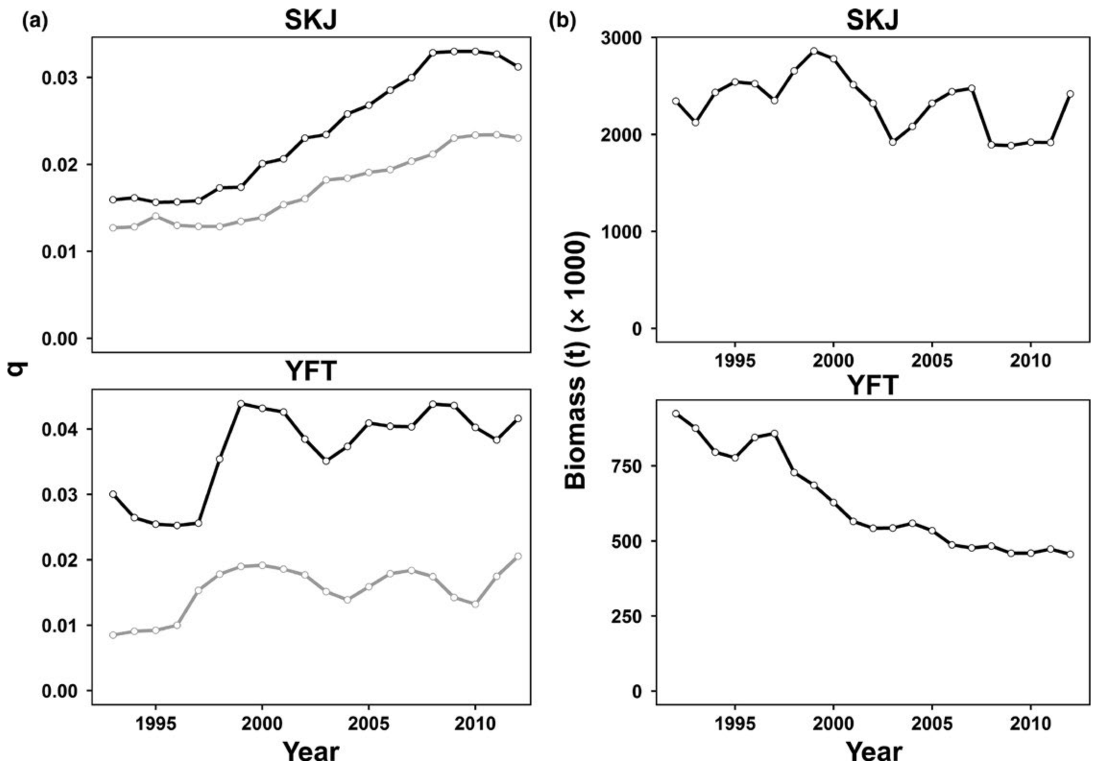

FIGURE 2 Mean annual catchability (a), and aggregated exploitable stock biomass estimates in metric tonnes (unassociated and associated set types) (b), aggregated over all fleets, and over each region encompassing the PNA EEZs, by year and set type (grey line = U and black line = A), for skipjack (SKJ) and yellowfin (YFT) tuna, as estimated by stock assessment models

TABLE 3 Coefficients of Pearson's correlation between indices of strategies and tactics (equations 1–6) and skipjack/yellowfin stock biomass estimates (skjBiom/yftBiom), and *q* (skjq/yftq), for associated set types (a) and unassociated (b)

Variable	skjq	yftq	skjBiom	yftBiom
(a)				
skjBiom	−0.61**	−0.09		
yftBiom	−0.92***	−0.82***	0.42	
ft_sw	−0.01	0.1	−0.03	−0.07
ft_patch	−0.66**	−0.63**	0.28	0.56*
ft_dist	0.24	0.41	0.08	−0.31
ye_sw	−0.52*	−0.35	0.06	0.42
ye_patch	−0.70***	−0.82***	0.24	0.75***
ye_dist	0.11	−0.05	−0.03	−0.18
(b)				
skjBiom	−0.65**	0.22		
yftBiom	−0.89***	−0.61**	0.42	
ft_sw	−0.67**	−0.13	0.51*	0.52*
ft_patch	0.16	0.08	0.06	−0.01
ft_dist	0.41	0.21	−0.36	−0.46*
ye_sw	−0.65**	0.04	0.61**	0.53*
ye_patch	−0.05	−0.45*	−0.01	0.29
ye_dist	0.15	0.38	−0.06	−0.16

Statistical significance at ***.001, **.01, *.05.

in spatial extent of the effort at the level of the trip (for the most recent years), but no relationship was found at the level of the year.

When examining all observations for associated sets, a significant negative correlation was detected between skipjack catchability and skipjack stock biomass estimate, that is, as the stock declines *q* increases. A similar relationship was observed for yellowfin.

3.2 | Unassociated sets

The fleet strategies show a significant negative correlation between the strategic diversity index (ye_sw) and skipjack catchability ($p < .01$, $r = -.65$, $n = 20$), which implies that catchability is higher when the fleet is spatially restricted. This pattern is more evident in recent years, and this relationship showed a similar correlation at the trip level ($p < .01$, $r = -.67$, $n = 20$).

The relationship between spatial extent (ft_dist) and yellowfin stock biomass estimate at the trip level was significantly negatively correlated ($p < .05$, $r = -.46$, $n = 20$). When yellowfin stock biomass estimate decreased, the spatial extent of effort increased. In contrast, at the trip level, the diversity indices (ft_sw) of the fleet were positively correlated with yellowfin stock biomass estimate; that is, when stock biomass estimate was low, the fleet reduced the number of spatial cells fished, and vice versa.

Significant relationships were found when examining the patchiness of the spatial distribution of fishing effort on unassociated sets, for the fleets and yellowfin catchability. When yellowfin

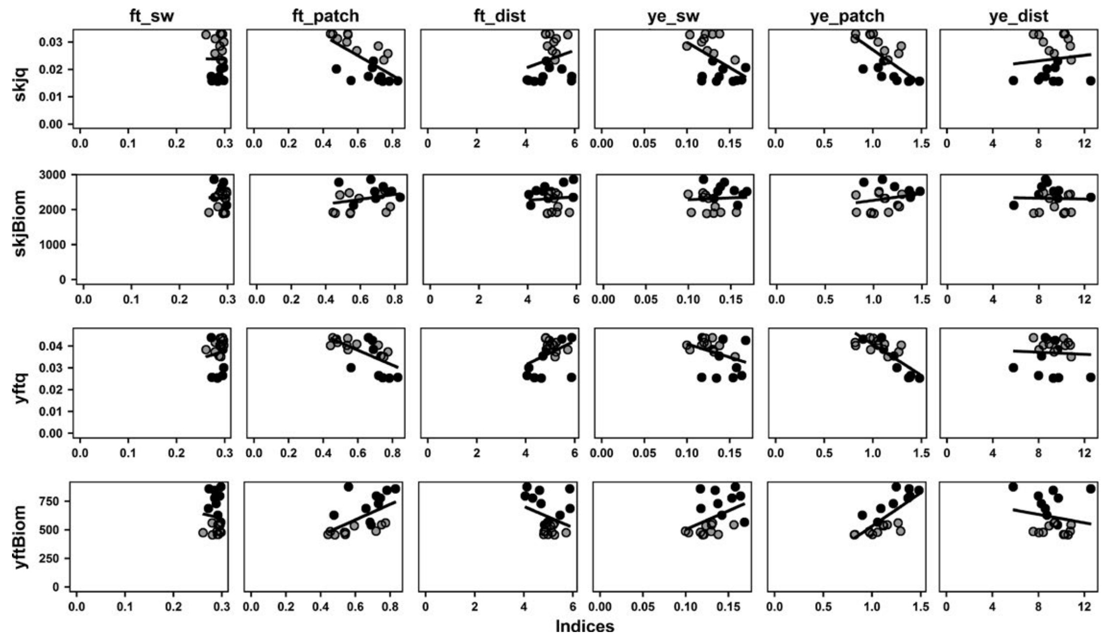

FIGURE 3 Associated catchability and estimated stock biomass versus indices (black dots indicate years 1993–2002; grey dots indicate years 2003–2012, reflecting midway between 20 year periods) (skjq = skipjack catchability; yftq = yellowfin catchability; skjBiom = skipjack estimated stock biomass; yftBiom = yellowfin estimated stock biomass; ft_sw/ye_sw = Shannon Wiener diversity index for tactics/strategies; ft_patch/ye_patch = patchiness index for tactics/strategies; ft_dist/ye_dist = weighted effort-based distance indices for tactics/strategies)

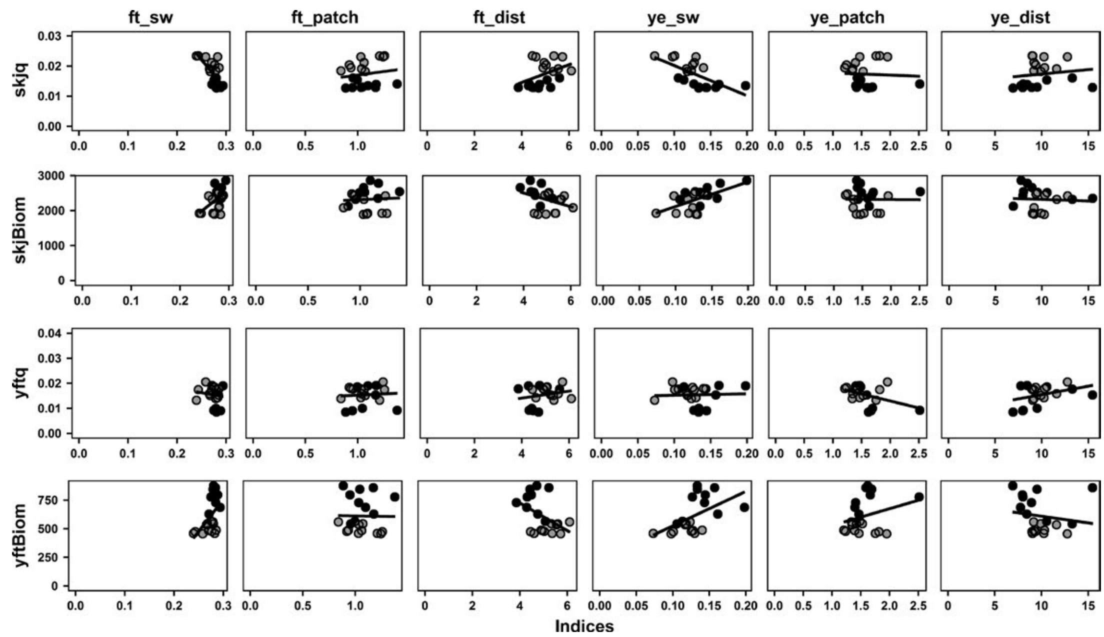

FIGURE 4 Unassociated catchability and estimated stock biomass versus indices (black dots indicate years 1993–2002, grey dots indicate years 2003–2012 reflecting midway between 20-year periods) (skjq = skipjack catchability; yftq = yellowfin catchability; skjBiom = skipjack estimated stock biomass; yftBiom = yellowfin estimated stock biomass; ft_sw/ye_sw = Shannon Wiener diversity index for tactics/strategies; ft_patch/ye_patch = patchiness index for tactics/strategies; ft_dist/ye_dist = weighted effort-based distance indices for tactics/strategies)

catchability was high, the ye_patch index decreased (i.e. fleet effort was less patchy). For instance, in the period 1993–2002, there is a patchiness index at 2.5, with a q of 0.01; in contrast, the majority of data points in more recent years were lower, at 1.5, with a q of 0.015.

In terms of the diversity of locations visited (ye_sw or ft_sw), the fleets showed significant relationships with yellowfin and skipjack stock biomass estimate. For these fleets, spatial diversity of areas fished was positively related to stock biomass estimate, in terms of how effort was both tactically (trip-level) and strategically (year-level) distributed. For

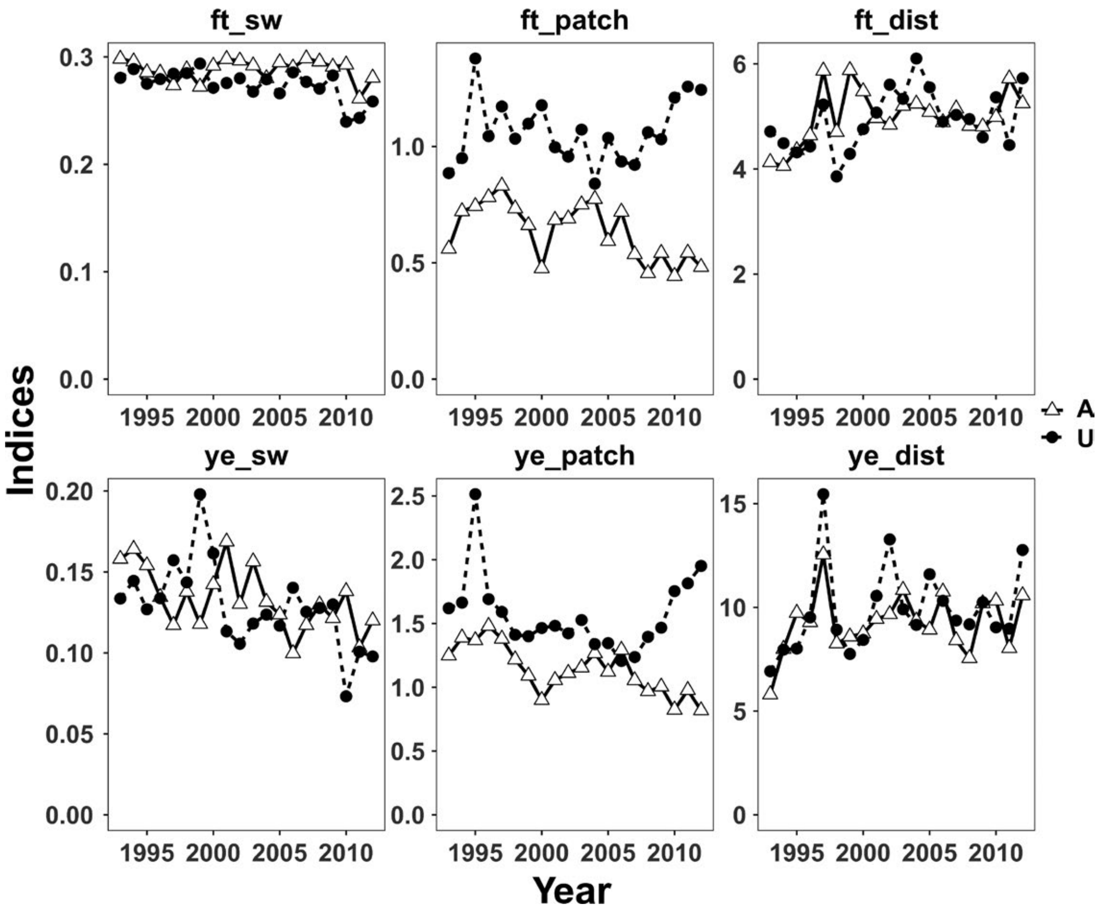

FIGURE 5 Time series of mean indices by set type (A = Associated/U = Unassociated) ft_sw/ye_sw = Shannon Wiener diversity index for tactics/strategies; ft_patch/ye_patch = patchiness index for tactics/strategies; ft_dist/ye_dist = weighted effort-based distance indices for tactics/strategies)

example, when yellowfin stock biomass estimate was lower, the fleets were more spatially limited, compared to periods where stock biomass estimate was higher and fleet effort was more extensively distributed.

3.3 | Catch summaries

Figure 6 shows the spatial distribution of mean total catch weight (1993–2012) of skipjack and yellowfin by set type for the fleets under investigation. The skipjack catch ranged from ~1000–2800 tonnes per 1° cell, and yellowfin catches per 1° cell at ~150–500 tonnes. A similar pattern was observed for unassociated fishing for both species. Annual summary statistics are presented in Figure 7, showing that annual catch for skipjack increased for both set types, while yellowfin-associated set catches declined. However, between 2006 and 2012, there was an increase in the number of unassociated sets from average of around 7500 in 2006 to 17,000 in 2012 and increases in the catches of both species. Figure 7 shows the change in the area used to achieve the catch by set type through the time series. For both set types, the area fished has expanded over time; for example, in 1993 for both set types 5 million km^2 was covered, while in 2012 for unassociated sets this value increased to 6 million km^2 and for associated sets to 7 million km^2.

4 | DISCUSSION

For highly migratory pelagic species, such as tunas, accounting for changes in catchability can be problematic due to changes in fishing behaviour (tactical and strategic) and the continual change in fishing efficiency due to the skill of the skipper/crew in applying the new technologies (Campbell, 2014). Accumulation of these factors makes relationships between catch rates and abundance non-proportional over time (Maunder *et al.*, 2006). The mean catchability of skipjack and yellowfin estimated from the assessment models (Figure 2) over all fleets, for both associated and unassociated sets, has been increasing since 1993, particularly for associated fishing, even though the number of sets has remained relatively stable (Figure 7). Stocks have been declining, concurrent with increased catches (Figure 7) due to improvements in catching abilities, either through technological advancements or the skill of the skipper/crew. Several authors have investigated behavioural aspects governing how fishers spatially distribute their effort (e.g. Hilborn, Orensanz, & Parma, 2005; Smith, Sanchirico, & Wilen, 2009). For future policy decisions to be successful, accurate information on the amount of effort used is imperative. To assess changes in effort, an understanding of how human

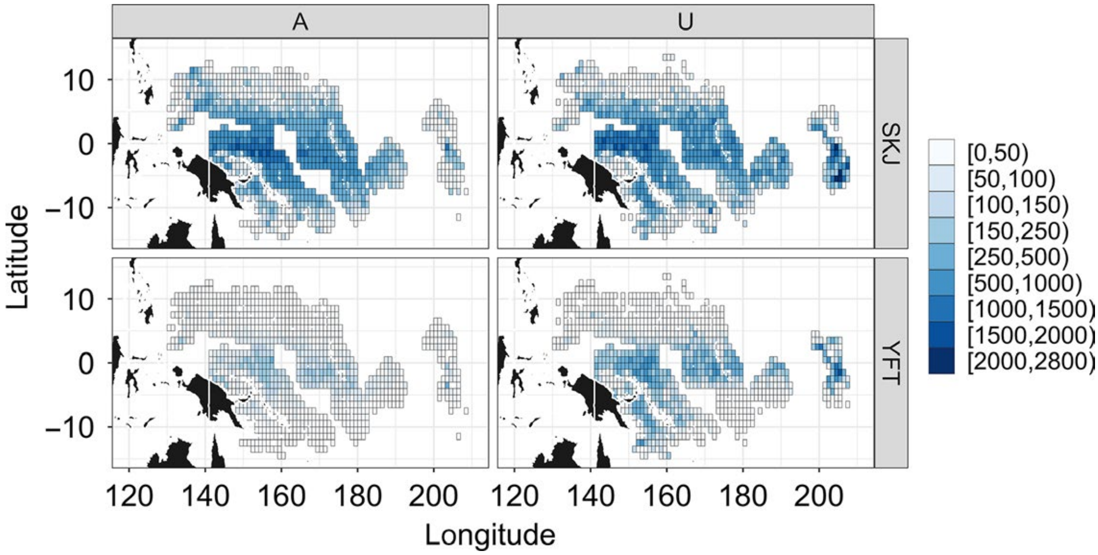

FIGURE 6 Mean catch (t) of SKJ (skipjack) and YFT (yellowfin) by 1°×1° square and set type (A = Associated/U = Unassociated) for all study fleets in PNA waters 1993–2012

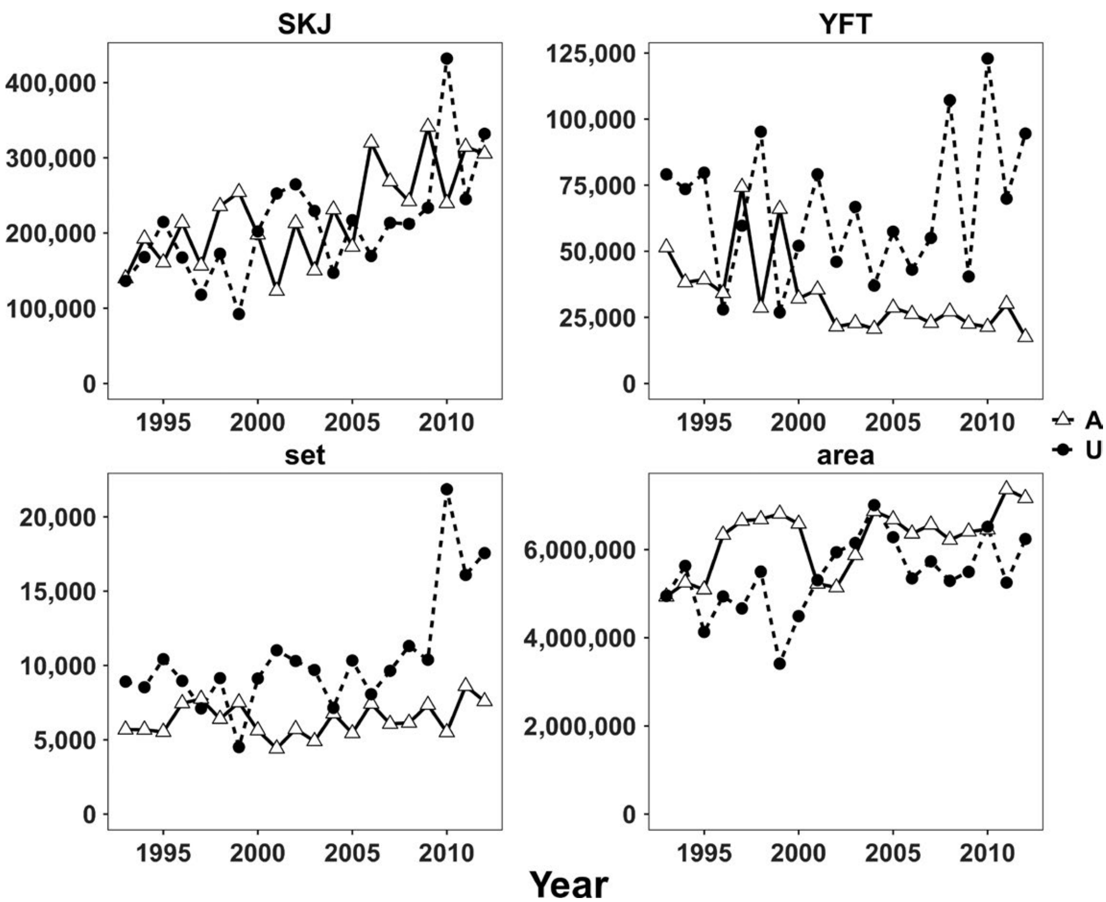

FIGURE 7 Total catch (t) of SKJ (skipjack tuna) (top left) and total catch (t) YFT (yellowfin tuna) (top right) by set type (A = Associated/U = Unassociated), and the total number of sets by set type (bottom left) and the total unique area fished (km^2) by set type (bottom right) for all study fleets in PNA waters 1993–2012

behaviour and accumulated knowledge can change fleet efficiency and thus reduce biodiversity loss is required. This is of global importance, given the Convention of Biological Diversity (CBD), which has over a 190 member countries that have committed to conserving biological diversity by developing general goals and policies to achieve a specific target (e.g. monitoring changes in abundance) (see UNEP

2002). Therefore, understanding the way humans interact to contribute to human well-being is critically important in achieving effective conservation.

This study shows that spatial diversity indices for fishing strategies and tactics were strongly correlated with the catchability of skipjack and yellowfin by purse seine fleets, for both associated and unassociated sets. Strong positive relationships between catchability and stock biomass estimates were evident for both yellowfin and skipjack tunas, and these relationships are likely to be affected, in turn, by the spatial behaviour of the fish and fishers. The spatial distribution of the fleet is a representation of the target fish aggregations, and the results suggest that, for unassociated fishing, a low diversity index will result in a higher catch rate, as these fishers have strategies and tactics that improve their efficiency in finding aggregations within a fishing year or trip. These findings are important because if the stock biomass estimate is already at a low level, the index for ye_sw and ft_sw will also be low, and catchability may increase. If catch rates remain high even with a low stock biomass estimate, this would suggest that the fleet is very successful in finding the fish aggregations, and this may be an indication of hyperstability in CPUE data.

This work made an important finding for associated fishing, where in the past a greater portion of fishing effort was consumed with searching for fish schools (i.e. prior to 2002, a higher diversity index was evident for skipjack, and a lower skipjack catchability was shown, than after 2002). There is an increasing reliance on sophisticated FADs (which have locator beacons and eco sounders fitted to them), and the size of the school dictates the decisions to travel to, and set on, a FAD (minimizing risk of a negative set); accordingly, search time may be a less meaningful measure of effort than it was previously (Fonteneau *et al.*, 2013). The previously described fishing behaviour is supported by the finding for associated fishing that catchability is increasing for both species, but with random fishing activity in recent times (2003–2012), in contrast with earlier periods, where fishing activities were patchier. The early associated fishing techniques adopted by the fleets were log sets (natural flotsam) (Itano, 2007), compared to the more sophisticated FADs presently used. Logs generally originate from nutrient-rich areas (i.e. mangroves or coastal run offs) in the western Pacific, and these concentrate along boundaries formed by different equatorial currents. Initially, radio beacons and reflectors were added to the logs so that detection could be made over greater distances (Davies, Mees, & Milner-Gulland, 2014; see Table 1). Now FADs are more advanced and human-made. For example, they can be set in areas devoid of logs but that are favourable for tuna aggregations (Itano, 2007). Many FADs are also fitted with echo sounder buoys that can relay information on the size of the school below the FAD to the vessels or fishing company and therefore determine the trajectories of vessels seeking fish. This may be important in explaining apparently random behaviour of fleets – that is, rather than travelling to the known boundaries formed by the equatorial currents, fleets are directed by information relayed from FADs. This may help explain why the fleet is fishing a greater area (Figure 7). Furthermore, many of these purse seine fishers have been in the fishery for a long period of time (although we do not have information about crews, skippers or companies, historical operational details may exist with the boat), and so it is expected that experienced fishers have become less exploratory, due to their knowledge of resource distribution and habitat (Arrizabalaga *et al.*, 2015; Pet-Soede, van Densen, Hiddink, Kuyl, & Machiels, 2001). The only finding of real significance for distance travelled between fishing sites was for unassociated fishing: in recent years, on average, vessels travel further within a trip when yellowfin stock biomass estimate is lower, but the overall fleet travels less. This suggests that knowledge transfer results in the fleet moving to similar areas (where catch rates are known to be good for skipjack), and therefore, the ft_sw is lower, perhaps reflecting the tactical behaviour of the fleet in minimizing travel where information transfer allows for the fleet to move directly to likely higher-yielding areas. The results for the fleet reflect that the total area fished has, over time, remained relatively consistent and could support this theory (Figure 7). In a recent social study with purse seine fishers, Lopez *et al.* (2015) state that real-time communication with other vessels and crew members over the last two decades was a significant factor affecting fishing efficiency. They also note that information transfers via telephone and/or Internet are now cheaper and faster, which promotes information sharing and increases fishers' response to productive fishing grounds.

The approach used here illustrates the interrelationships between spatial fisher behaviour, stock biomass estimates and catchability. A recommendation for future work would be to apply this methodology to various purse seine fleets targeting tunas from other oceans, and to compare the results to those presented here. Nevertheless, quantifying these interrelationships is dependent on having accurate information on catchability, abundance, catch per unit effort, fishing costs and the value of catch. Catchability and biomass estimates used within this analysis arise from stock assessment models and are dependent upon a number of factors; for example, the input data and assumptions required within those models. In a management context, it is important to understand and document the behaviour of fishers, and how they evolve, learn and adapt to survive in their industry (Boonstra & Hentati-Sundberg, 2014; Fulton, Smith, Smith, & van Putten, 2011). For example, when abundance is high and the constraints are tight, profits in the fishery will decline; conversely, when the controls are loose, capacity increases through investment, and catch and profits increase in the short term, with risks of future declines in catch and therefore profits. This is particularly relevant, as, in recent years, a result of management action (e.g. the four-month FAD closure; Conservation and Management Measure for Bigeye and Yellowfin Tuna in the western and central Pacific Ocean, CMM 2014-01 (WCPFC 2014); and the PNA's Third Implementing Arrangement (3IA)), has been an increase in fishing activity of free schools and a corresponding increase in efficiency of the free-school fishery (Williams & Terawasi, 2014). Skippers have been forced to improve fishing on unassociated schools to remain competitive, and this is reflected in the recent rise in catchability of vessels catching yellowfin. However, there did not appear to be significant changes in the effort allocation indices for the two species, potentially because the fishers would allocate their effort according to pre- and post-FAD closure, to maximize their return to compensate for the closure. Therefore, at the level of the trip or year, the CMM would not show the initial effect of these changes. Documenting skipper experience and skill, and accounting for technological advances, is important in explaining how these changes may cause CPUE hyperstability and thereby how to correct catchability to account for the spatial behaviour of fishers if standardized CPUE indices were to be used in assessment models.

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