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Interactions between artisanal and industrial tuna fisheries: Insights from a decade of tagging experiments

Bruno Leroy [a,*], Thomas Peatman [a], Thomas Usu [b], Sylvain Caillot [a], Brad Moore [a], Ashley Williams [a], Simon Nicol [a,c]

[a] Fisheries Aquaculture and Marine Ecosystems Division, Secretariat of the Pacific Community, BP D5, 98848 Noumea, New Caledonia
[b] National Fisheries Authority, 11th Floor, Deloitte Tower, Douglas St, PO Box 2016, Port Moresby, Papua New Guinea
[c] Institute for Applied Ecology, University of Canberra, Bruce 2617, ACT, Australia

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ABSTRACT

The suite of species taken by artisanal fishers targeting tuna often includes species caught in the larger industrial tuna fisheries, leading to concerns that industrial fisheries may reduce local fish availability and consequently impact upon artisanal catch rates. This study provides supporting evidence that industrial purse-seine fisheries may impact upon artisanal and subsistence fishers. A tagged population of skipjack and yellowfin tuna of known size was monitored through time and the probability of recapture was used as a measure of interaction with the industrial purse-seine fisheries. The probability of recapture was positively associated with areas where relative purse-seine fishing effort was higher. The results indicate that skipjack and yellowfin tuna may have longer residency times in nearshore habitats than in open ocean habitats. Lower recapture probabilities in areas currently closed to purse-seine fishing provided empirical evidence that area closures for industrial fisheries may assist with the management of artisanal fisheries. Finally the results suggest that the proximity to industrial purse-seine fishing may also be an important component for decision makers when planning and evaluating the performance of artisanal fisheries in the western Pacific region.

1. Introduction

The western and central regions of the Pacific Ocean are dominated by two categories of fisheries [1]. The industrial fisheries targeting tuna are the largest globally by volume, with annual catches exceeding 2.5 Million t [2]. Most of this product is exported to global markets, with Pacific Island economies deriving benefits through licensing and on-shore processing [1]. The artisanal and subsistence fisheries supply local markets and their catches are more modest in comparison [3]. These fisheries typically have greater social and economic impact at the local community level than their industrial counterparts because they provide the bulk of the fish used for food security [4]. Additionally, 50% of coastal households receive their first or second income from activities relating to fishing [5].

Technology has improved the fishing power of both industrial and artisanal fisheries in recent decades, increasing concerns about the long term sustainability of stocks targeted by both sectors [1]. The suite of species taken by artisanal fishers targeting tuna often includes species caught in the larger industrial tuna fisheries such as skipjack (*Katsuwonas pelamis*), yellowfin (*Thunnus albacares*) and bigeye (*Thunnus obesus*) tuna [1]. With tuna stocks depleted to levels below 50% of virgin biomass [6], legitimate concerns that industrial fisheries may reduce local fish availability and consequently impact upon artisanal catch rates have been raised [1]. This concern is further exacerbated by the proposal that tuna needs to provide 25% of all fish required for food security by 2035 for many coastal communities because production of fish from the readily-accessible coastal habitats will become insufficient to support increasing human populations, and stressors such as climate change will degrade coral reef habitats in the Pacific region [7].

Interactions between artisanal and industrial tuna fisheries have been documented [8] but are difficult to quantify, mostly due to the lack of catch data in the artisanal fishery sectors [9]. Tagging experiments provide a method to resolve this issue by creating a tagged population of known size that can be monitored through time with the recapture of the tagged individuals [10]. The potential for interactions between artisanal and industrial fishing sectors was explored by examining recapture probabilities of skipjack and yellowfin tunas tagged in Papua New Guinea and the Solomon Islands. The management regimes of the two countries differ, allowing for analyses to contrast their effects. In Papua New

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[*] Corresponding author.

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Guinea, purse-seine fishing is not allowed within 12 nm of land and the use of anchored FADs is not permitted within the Morgado Square [11]. In the Solomon Islands, the domestic purse-seine and pole-and-line fleets are allowed to fish inside the 12 nm zone. The foreign purse-seine fleets that have access agreements in the Solomon Islands Exclusive Economic Zone (EEZ) are required to fish more than 30 nm from the coastline [12].

2. Methods

2.1. Tagging

The Pacific Tuna Tagging Project has tagged and released 398,366 tunas (skipjack, yellowfin and bigeye), including 58,172 releases inside the 12 nm of Papua New Guinea (PG) and Solomon Islands (SB) and 208,479 releases throughout both EEZs outside the 12 nm zone, between 2006 and 2013 (Fig. 1 and Table 1). All tagging was undertaken on chartered pole-and-line fishing vessels from the SB National Fisheries Development Ltd. The vessels used were Soltai 6 (chartered from 2006 to 2008), Soltai 105 (2008–2012) and Soltai 101 (2013). Pole-and-line fishing vessels are ideal tagging platforms because tunas can be quickly and safely captured, tagged and released in less than 15 s on average [10]. Most tuna species have little tolerance to oxygen deprivation and a captured fish immediately builds up lactic acid in its blood leading to irreversible damage if it is out of the water for too long [10]. Hard contact with vessel surfaces and hooking damage can also compromise survival [13]. Fish condition was recorded on release and fish with obvious signs of bleeding or with flesh or fin damage were not tagged. Tag recovery agents [10] were commissioned in all major tuna unloading facilities to collect tags and report the capture of all tagged tunas by commercial fishing vessels.

2.2. Data analysis

Tag release and recovery data were extracted from the Pacific Tuna Tagging Project (PTTP) database [14]. Data for recovered PTTP tags were cross-validated against release data and available information from fishing and carrier vessels to confirm the accuracy of the data provided to tag recovery officers [10]. Tag recoveries that could not be validated were excluded from the analysis to reduce bias resulting from errors in reported recovery data. The number of tag releases for a given species and release event e, r_e, were adjusted to preserve observed recovery-release ratios after exclusion of unvalidated recoveries, using an approach similar to [15]. The adjusted number of releases, $\hat{r}_e$, were calculated as $\hat{r}_e = \text{round}(CF_e r_e)$, where round is the nearest integer function, CF_e is a release event specific correction factor given by

$$CF_e = \begin{cases} \dfrac{rec^V_{e,t}}{rec^T_{e,t}} & \text{for } rec^T_{e,t} > 1 \text{ and } rec^V_{e,t} > 1 \\ \text{median}\left(\dfrac{rec^V_t}{rec^T_t}\right) & \text{for } rec^T_{e,t} > 1 \text{ and } rec^V_{e,t} = 0 \\ 1 \text{ for } rec^T_{e,t} = 0 \text{ and } rec^V_{e,t} = 0 \end{cases} \tag{1}$$

and $rec^V_{e,t}$ and $rec^T_{e,t}$ are the validated and total recaptures for tagging cruise t and tagging event e. A total of 173,652 tag releases were included in the analysis after adjusting for unvalidated recaptures, with 30,765 recoveries.

Beta-binomial regression models were used to standardise species-specific release-event recapture probabilities due to the presence of extra-binomial variation. PG and SB releases were analysed separately, with species-specific models for yellowfin and skipjack. There were insufficient recoveries for analyses of bigeye. The models were implemented in R [16] using the GAMLSS package [17]. The variance of the beta-binomial distribution in GAMLSS is parameterised

$$\text{Var}(Y) = n\mu(1-\mu)\left(1 + \frac{\sigma}{1+\sigma}(n-1)\right) \tag{2}$$

where n is the number of trials, μ is the mean probability of success and σ is a dispersion parameter controlling variation in μ [18].

A range of explanatory variables were *a priori* considered to potentially influence release-event recapture probability: the region of release; the minimum distance from the point of release to shore; release year; release month; the time at liberty of the tagged fish; and, the average length of tagged fish for each release event. The PG EEZ was split into five different release regions: the Bismarck Sea; the Morgado Square; releases to the north of the

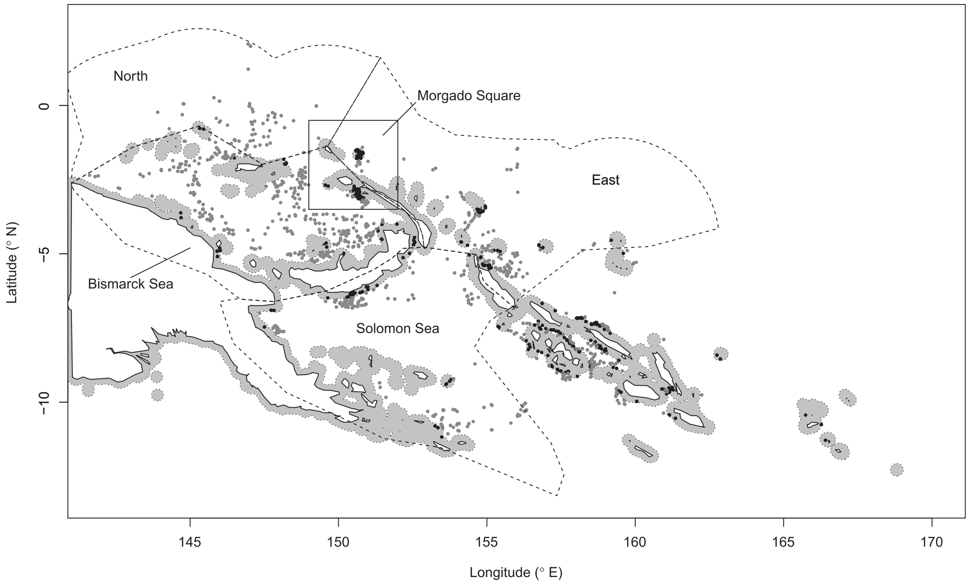

Fig. 1. The positions of tag releases in PG and SB. In black are tag releases inside the 12 nm zone and in grey tag releases outside the 12 nm zone. The 12 nm zone is displayed in grey. The back square delineates the boundaries of the Morgado Square release region in the PG EEZ. The dotted lines delineate the boundaries of the other four release regions.

Table 1
Total conventional tag releases, recaptures, observed tag recovery rates, average days at liberty (Avg.Dal.) and size at release per species (Rel.len) inside the 12 nm vs. outside for PG and SB. Average days at liberty were calculated using validated tag recoveries only.

Tags	PNG < 12 nm		PNG > 12 nm		SB < 12 nm		SB > 12 nm	
	Nb	%	Nb	%	Nb	%	Nb	%
Total releases	31,748		178,393		26,424		30,086	
Total recoveries	3857	12.1	33,339	18.7	4874	18.4	4779	15.9
BET	7	10.0	1052	24.2	33	13.1	47	15.2
SKJ	2620	11.7	23,127	18.9	2641	18.7	2722	14.2
YFT	1230	13.3	9160	17.6	2200	18.3	2010	18.9
	Avg.Dal.	**Rel.len**	**Avg.Dal.**	**Rel.len**	**Avg.Dal.**	**Rel.len**	**Avg.Dal.**	**Rel len**
BET	497.0	44.4	99.1	45.1	116.9	34.5	122.4	36.5
SKJ	149.1	45.5	81.9	42.7	68.2	41.5	99.5	40.9
YFT	228.9	49.7	124.7	42.5	117.2	37.5	131.3	39.3
Cross species average	174.6		95.0		90.6		114.0	

Bismarck Sea; releases east of the Morgado Square; and, releases in the Solomon Sea (Fig. 1). These regions were chosen on the basis of oceanographic characteristics, e.g. maintaining the semi-enclosed Bismarck Sea as a distinct region, and differing management of purse-seine fisheries in the case of the Morgado Square. The SB EEZ was treated as a single region due to limited spatial distribution of releases. Each region was also split between areas inside and outside the 12 nm zone, to allow direct comparison between inshore releases and offshore releases within a given region. Recoveries were grouped in days at liberty bins of: up to 30 days; 31 days to 60 days; 61 days to 180 days; and, 181 days to 365 days. Recoveries after 365 days at liberty were treated as unrecovered to minimise distortion in recovered proportions between release years due to delays in tag reporting. Interactions between days at liberty (DAL) and distance to shore and release region effects were also included in the analysis, reflecting the *a priori* belief that the effect of release position on recapture probability should weaken with increased DAL. Continuous explanatory variables were mean centred and scaled by standard deviations.

A stepwise Akaike information criterion (AIC) [19] based procedure was used to select terms to model mean recapture probability, μ, and the dispersion parameter , σ, using the GAMLSS function stepGAICAll.A(). Step 1: forward selection to select terms to model μ, with σ fitted as a constant. Step 2: test for varying overdispersion in μ using forward selection for σ terms, given the model for μ from step 1. Step 3: backward selection to select terms to model μ, given the model for σ from Step 2 and using the model for μ from step 1 as a starting point.

The full models for μ and σ were

$$\begin{aligned}\log\left(\frac{\mu}{1-\mu}\right)=&\beta_0+\beta_1\text{region}+\beta_2\text{year}+\beta_3\text{month}+\beta_4\text{DAL}+\beta_5\\&\text{length}+\beta_6\text{length}^2\\&+\beta_7\text{distance}+\beta_8\text{distance}^2+\beta_9\text{DAL distance}+\beta_{10}\\&\text{DALdistance}^2+\beta_{11}\text{DAL region}\end{aligned}\tag{3}$$

$$\log(\sigma)=\alpha_0+\alpha_1\text{DAL}\tag{4}$$

Figures of mean recapture probability against a specific explanatory variable, or interaction, were generated by setting other explanatory variables to a reference level. The reference levels were: release region–offshore Bismarck Sea for PG releases, offshore for Solomon Islands releases; release year—2007; release month—March; days at liberty—≤ 30 days; and, release length and distance to shore—the mean of the observations for the model concerned.

Distance to shore and average release length were centred and standardised. The specification of release regions resulted in multicollinearity between distance to shore and release region, as inshore release events by definition had distances to shore of less than 12 nm and vice versa. Multicollinearity did not appear to adversely impact model fits, as parameter coefficients and standard errors were insensitive to the removal of distance to shore terms.

Effort data for purse-seine fishing in the western and central Pacific were extracted from the Catch and Effort Query System managed by the Secretariat of the Pacific Community (SPC). Purse-seine fishing effort was calculated as the total number of days fished for the period 2005–2013 per 1 degree cell, based on raised and aggregated effort for all fleets based on vessel logbook data.

3. Results

The final models for PG releases of skipjack and yellowfin included all terms from the full parameterisation of mean recapture probability. The variation in mean recapture probability was heavily influenced by days at liberty with a ΔAIC of 452 and 434 for skipjack and yellowfin respectively (Table 2).

Recapture probabilities of PG skipjack varied by release region and days at liberty (Fig. 2). Recapture probabilities of inshore releases were lower than for offshore releases in the Bismarck Sea, for fish at liberty for a maximum of 30 days (means of 0.015 and 0.085) and for fish at liberty for 31–60 days (means of 0.016 and 0.033). There was no evidence of differences in inshore and offshore recapture probabilities for Bismarck Sea releases at liberty for greater than 60 days. There was no evidence of differences in inshore and offshore recapture probabilities of skipjack released in the Morgado Square or the Solomons Sea region, irrespective of time at liberty, and for releases in the Eastern region at liberty for more than 30 days. However, there was some suggestion of lower recapture probabilities for inshore Eastern releases at liberty for less than 30 days relative to offshore releases (means of 0.0074 and 0.018). The effect of distance to shore on recapture probabilities of PG skipjack varied by days at liberty (Fig. 3). Recapture probabilities were insensitive to distance to shore for skipjack at liberty up to 30 days, with mean recapture probabilities ranging from 0.082 at 50 nm to 0.099 at 100 nm. Recapture probabilities increased with distance to shore for skipjack at liberty for more than 30 days. Recapture probabilities increased by 87% from 10 nm to 100 nm (means of 0.035 and 0.066) for skipjack at liberty for 31–60 days, 42% for skipjack at liberty for 61–180 days (means of 0.054 and 0.077) and 37% for skipjack at liberty for 181–365 days (means of 0.015 and 0.021).

Recapture probabilities of PG yellowfin varied by release region and days at liberty (Fig. 2). Recapture probabilities of inshore

Table 2
Akaike Information Criterion (AIC) values for the final models, and increases in AIC from the final model when removing individual terms from the parameterisations of mean recapture probability and dispersion. Terms were only removed if model marginality could be maintained.

	PG SKJ	PG YFT	SB SKJ	SB YFT
Final model	10,681	7255	2809	2964
Mean recapture probability terms				
Release region				
Release year	274	68		
Release month	32	11	30	17
Days at liberty			97	64
Release length	251	60	32	45
Release length^2	126	58	5	11
Distance to shore				
Distance to shore^2				
Days at liberty: distance to shore	−2	14		
Days at liberty: distance to shore^2	3	4		
Days at liberty: release region	198	194		
Dispersion terms				
Days at liberty	452	434	111	67

yellowfin were lower than for offshore releases in the Bismarck Sea, for fish at liberty for a maximum of 30 days (means of 0.014 and 0.13) and for fish at liberty for 31–60 days (means of 0.014 and 0.041). There was no evidence of differences in inshore and offshore recapture probabilities for Bismarck Sea yellowfin at liberty for greater than 60 days. There was no evidence of differences between inshore and offshore recapture probabilities of yellowfin released in the Morgado Square, the Solomons Sea or the Eastern region, irrespective of time at liberty. The effect of distance to shore on recapture probabilities of PG yellowfin varied by days at liberty (Fig. 4). Recapture probabilities of yellowfin decreased with increasing distances to shore for fish at liberty up to 30 days, with mean recapture probabilities decreasing from 0.21 at 10 nm to 0.12 at 100 nm. Recapture probabilities increased with distance to shore for yellowfin at liberty for 31–180 days. Recapture probabilities increased by over 200% from 10 nm to 100 nm (means of 0.037 and 0.12) for yellowfin at liberty for 31–60 days, and doubled for yellowfin at liberty for 61–180 days (means of 0.056 and 0.11). Recapture probabilities of yellowfin at liberty for 180–365 days were insensitive to distance to shore, increasing from 0.03 at 10 nm to 0.036 at 100 nm.

The release length effects on skipjack and yellowfin recapture probabilities were consistent for PG releases. Recapture probabilities increased to a maximum at release lengths of approximately 50 cm, before declining (Fig. 5).

The final models for SB releases of skipjack and yellowfin included terms for release month, days at liberty, release length and release length^2 in the parameterisation of mean recapture probability. The remaining terms were excluded during the forward selection phase. Variation in mean recapture probability was

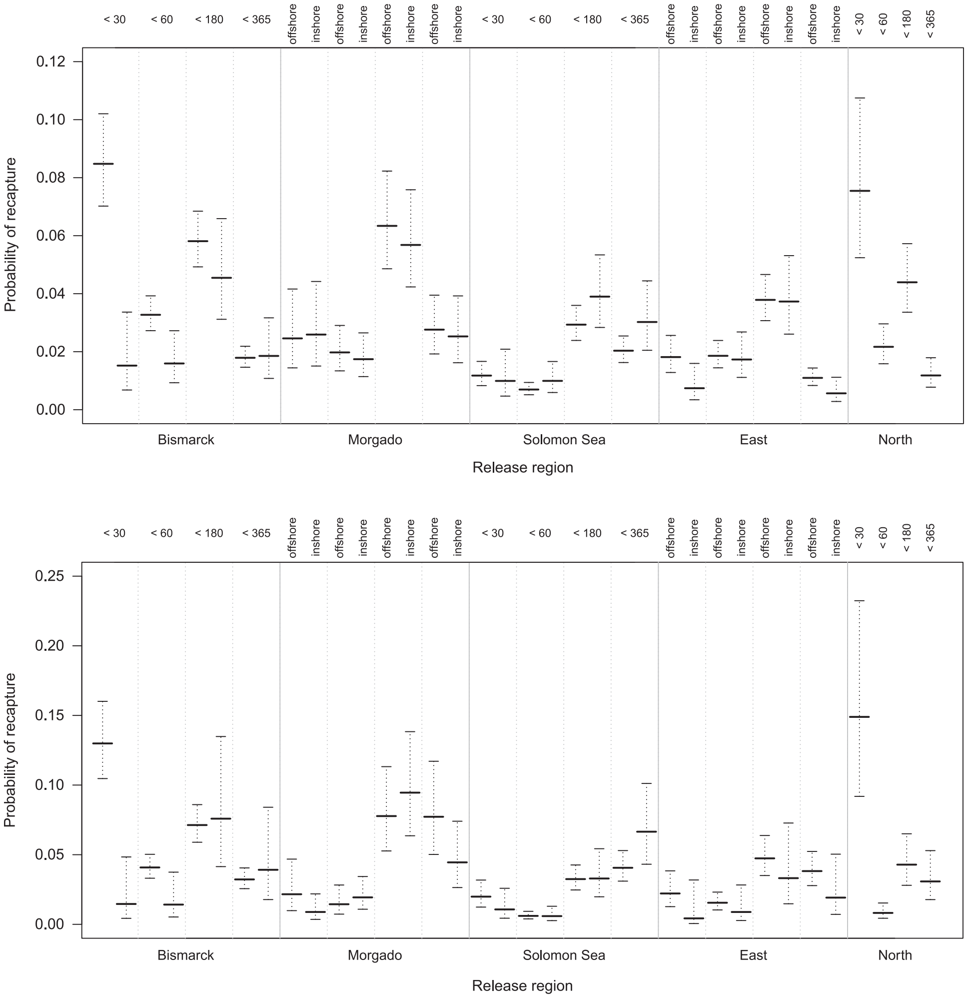

Fig. 2. Probability of recapture against release region and days at liberty for skipjack (top) and yellowfin (bottom) released in Papua New Guinea. Probabilities are ordered by release region, days at liberty bin and then offshore/inshore. There were no inshore releases in the Northern region.

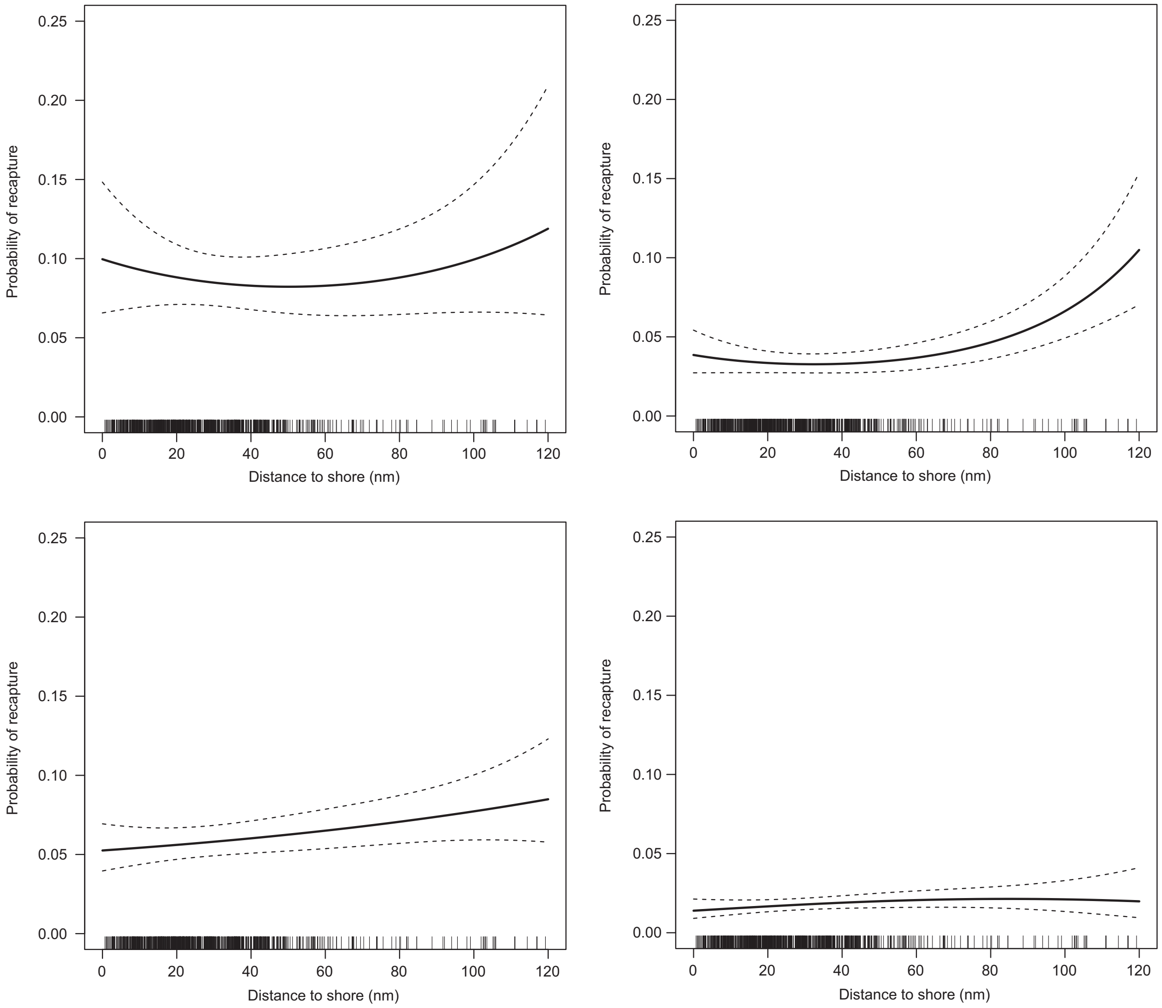

Fig. 3. Probability of recapture against distance to shore for skipjack released in Papua New Guinea and at liberty ≤ 30 days (top left), 31–60 days (top right), 61–180 days (bottom left) and 181–365 days (bottom right).

heavily influenced by days at liberty with a ΔAIC of 111 and 67 for skipjack and yellowfin respectively (Table 2). The release length effects on skipjack and yellowfin recapture probabilities were consistent for the SB releases. Recapture probabilities increased to a maximum at release lengths of approximately 53 cm, before declining (Fig. 5).

The effect of days at liberty on the variance of mean recapture probability was consistent for the four models, with significantly higher variances for recaptures within 30 days of release (Fig. 6). The effects of release year and month are not informative with respect to effects of release location on recapture probabilities and are not reported.

Purse-seine fishing effort was plotted as a contour of total days fished, with the 40 nm distance marked to aid interpretation of the recapture probabilities (Fig. 7). Fishing effort in PG was highest in the Bismarck Sea, and to a lesser extent the eastern region. Fishing effort in SB was highest in the main group archipelago (MGA). In general, relative purse-seine effort was higher in areas further than 40 nm from shore than areas closer to shore, corresponding to areas where the probabilities of recapture of skipjack, and yellowfin after more than 30 days, were highest.

4. Discussion

This study provides supporting evidence that industrial purse-seine fisheries may impact upon artisanal and subsistence fishers by reducing local fish availability. The importance of purse-seine effort, however, was dependent upon where it was located. Using probability of recapture of tagged tuna as a measure of interaction with the industrial purse-seine fisheries, it was observed that these probabilities were positively associated with geographic areas where the relative purse-seine fishing effort was higher. Area closures could be inferred as a method for mitigating this effect. In areas with high fishing effort, and a 12 nm exclusion of purse-seine fishing, the recapture probabilities were lower for releases inside the exclusion zone than outside. Area closures are often proposed in pelagic fisheries management as a means of minimising fishing impacts [20,21] but rarely is empirical evidence available to support such proposals. The results presented here provide empirical evidence that area closures for industrial fisheries may assist with the management of artisanal fisheries in this region.

There was insufficient data to estimate the threshold at which purse-seine effort impacts upon recapture probabilities of skipjack and yellowfin in this study. In part, this was due to the relatively sharp boundary between the occurrence of low and high purse-seine fishing effort, approximately 40–60 nm from shore (Fig. 7). Observations of a distance to shore effect corresponded to this distribution of industrial fishing effort. Recapture probabilities were higher from 40 nm and beyond and lower within 40 nm for skipjack. The observations for yellowfin were more complex. The pattern of recapture probabilities was highest closer to shore for

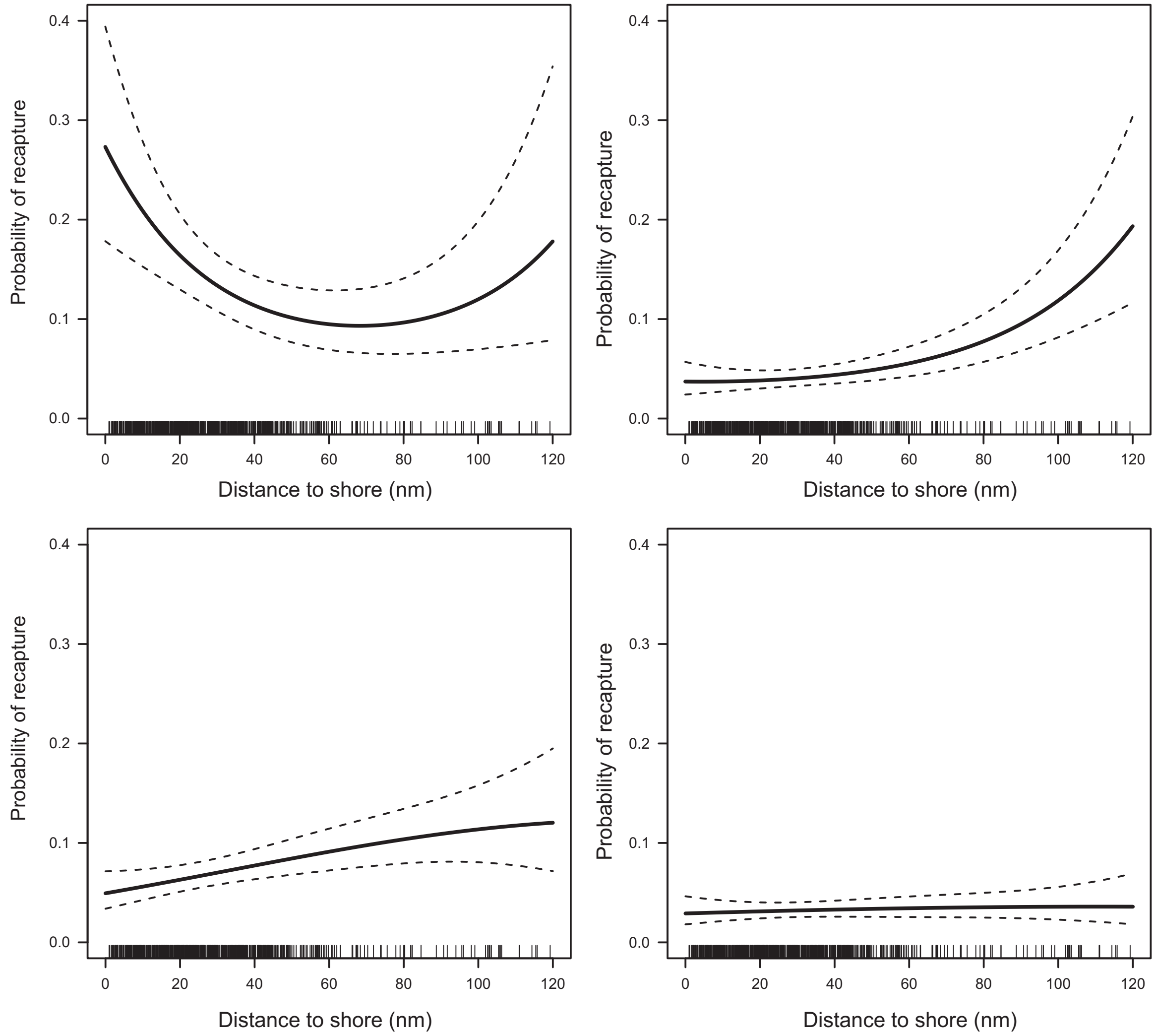

Fig. 4. Probability of recapture against distance to shore and days at liberty for yellowfin released in Papua New Guinea and at liberty ≤ 30 days (top left), 31–60 days (top right), 61–180 days (bottom left) and 181–365 days (bottom right).

the first 30 days and then followed the skipjack pattern of higher recoveries further from shore. This is likely due to the number of release events and their locations. More yellowfin tuna were tagged near shallower habitats than skipjack, which are typically closer to shore. Many of these locations were also in relatively close proximity to high purse-seine effort areas resulting in higher capture closer to shore during the first 30 days before the tagged fish dispersed more broadly.

The results indicated that this distance to shore effect could be detectable for up to 180 days. This was consistent with the conclusions that the tuna tagged in PG and SB as part of the PTTP may not be fully mixed with the broader population until 6 months after release [22]. Kleiber and Hampton [23] also reported an island attraction effect for skipjack tuna in the Solomon Islands with the propensity for skipjack to move away from the island archipelago less than half the propensity for them to move within the archipelago.

The highest areas of effort corresponding to the highest probabilities of recapture were also evident in the detection of a significant area effect. A difference in the probabilities of recapture was not detected between those tagged within or outside of the 12 nm exclusion zone where purse-seine fishing effort was lowest (Morgado Square and Solomon Sea). However, in the areas where relative purse-seine fishing was highest (Bismarck Sea in PG and the MGA in SB), a difference was detected in recapture probabilities where the 12 nm exclusion was in place (Bismarck Sea). These observations are consistent with the hypothesis that fish in the Bismarck Sea that are tagged closer to shore have a lower vulnerability to recapture for a limited time after release. This reduced vulnerability is afforded through spending a greater proportion of time inside the 12 nm exclusion zone, where large-scale commercial fishing is prohibited and artisanal and subsistence fishing effort is low in comparison to off-shore regions. Conversely, in SB, where there is no 12 nm exclusion zone and fishing effort is similar inside and outside of the 12 nm zone, the recapture proportions for tagged fish were equivalent irrespective of how close to shore fish were released. Similarly, in the Morgado Square and Solomon Seas regions of PG, the fishing effort inside and outside of the 12 nm zone was similar and no difference in recapture rates was detected. In the Bismarck Sea, where fishing effort was highest, the effect of the 12 nm exclusion zone was not detectable after 60 days suggesting that tuna occupying habitats within the exclusion may be fully mixed with neighbouring areas by 60 days.

These results have implications for regional and national policy on food security and sustaining Pacific Island livelihoods. Many species of fish in pelagic environments naturally associate under floating objects [24] and fishermen have been exploiting this behaviour for hundreds of years by fishing near floating objects that have aggregated sparsely distributed schools or individuals. In recent decades, man-made floating objects, or Fishing Aggregating

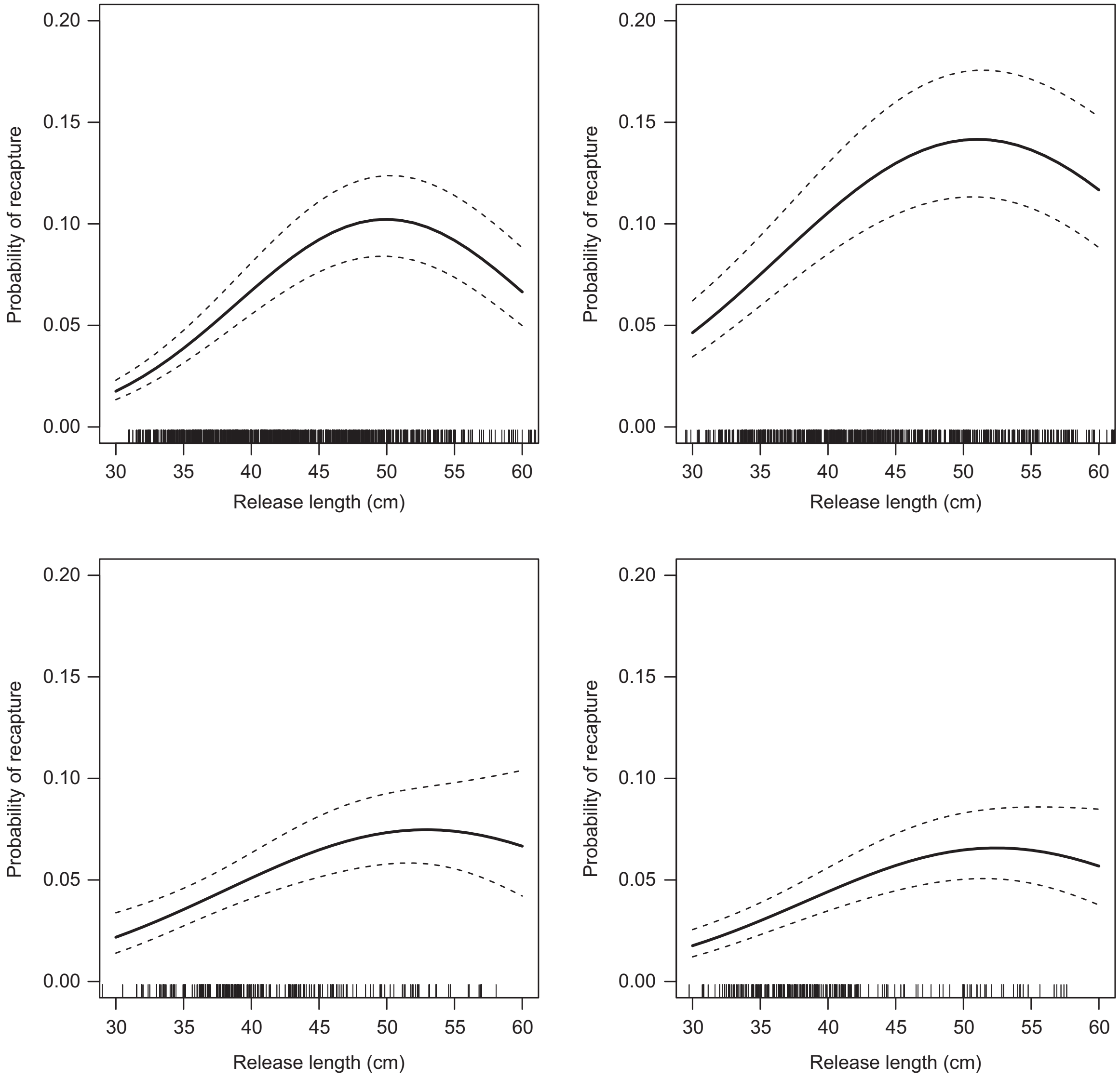

Fig. 5. Probability of recapture against mean release length for skipjack (left) and yellowfin (right) released in Papua New Guinea (top) and the Solomon Islands (bottom).

Devices (FADs), have become mainstream infrastructure used in pelagic fisheries, both in the industrial purse-seine tuna fishery sector [25] and artisanal and subsistence fisheries to improve catch rates [7,26,27,28]. Nearshore FADs have been actively promoted as a measure to increase access to fish protein, relieve exploitation on other coastal ecosystems, increase resilience to climate change by increasing access to tunas [29,30], and promote alternate income sources such as tourism-related recreational fisheries [31]. Understanding local effects are likely to be critical to planning the performance of nearshore FADs. The criteria for the placement of nearshore FADs include bathymetry (typically at 300–700 m depth), accessibility and a history of catch. The geography and bathymetry surrounding most Pacific Island Countries can be characterised as steep-to with limited continental shelf. This typically limits opportunities to deploy FADs at depths suitable to attracting neritic midwater or pelagic fishes such as scads, fusiliers, or small coastal tuna species. Nearshore FADs, however, can still be deployed in deep water if mooring sites and FAD materials are carefully chosen, and they can attract a fish assemblage that is more oceanic than neritic in composition. This oceanic assemblage includes skipjack, yellowfin and bigeye tuna that are the target of the large industrial tuna fisheries operating in the Pacific countries' EEZs [2]. The results of this study suggest that the proximity to industrial purse-seine fishing may also be an important component for decision makers if the intent is to attract these species. Pacific Island Countries that are considering deployment of FADs to enhance artisanal and subsistence fisheries by increasing oceanic tuna catch in areas that have high purse-seine effort may want to consider an exclusion zone (e.g. a 12 nm boundary) for their industrial purse-seine fisheries. In scenarios where industrial purse-seine effort is low, management measures may not be warranted.

Understanding the interactions between commercially important tuna stocks and the fisheries exploiting them is important for defining appropriately scaled management that balances sustainable exploitation and conservation objectives [32,33]. The results of this study represent a diverse response from tuna when comparing between: tuna tagged in near shore habitats versus those more distant from shore; species; and management regimes. The differences in recapture probabilities between areas of release could be caused by the relative levels of fishing effort between regions or localised bathymetry and oceanography that slow mixing rates with regions. These effects may result in increased residency of tuna schools to some areas. Generalisations upon the way that tuna behave within near-shore habitats will need to take account of local and species effects. Importantly, it can be inferred

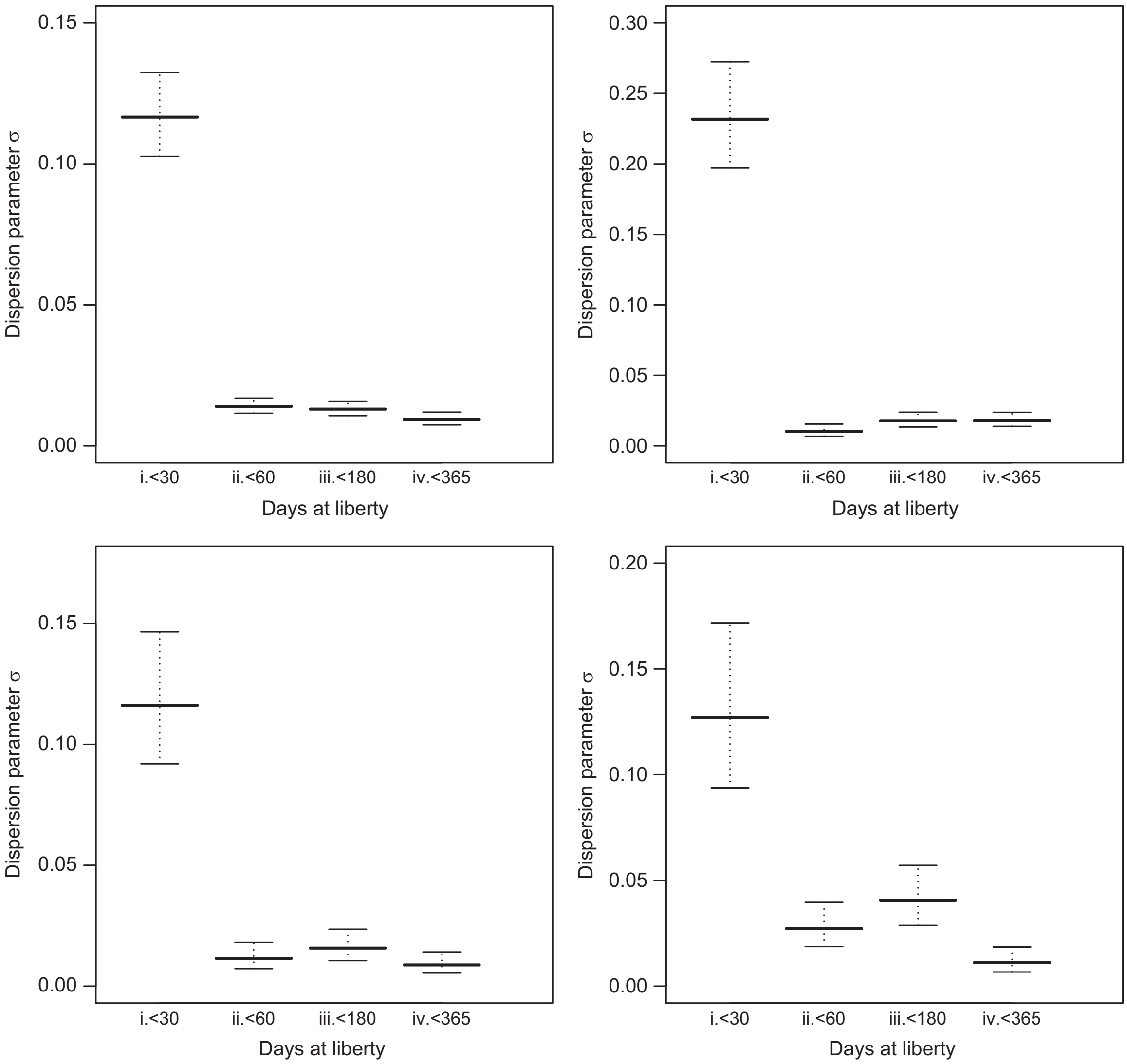

Fig. 6. Dispersion parameter σ against days at liberty for skipjack (left) and yellowfin (right) released in Papua New Guinea (top) and the Solomon Islands (bottom).

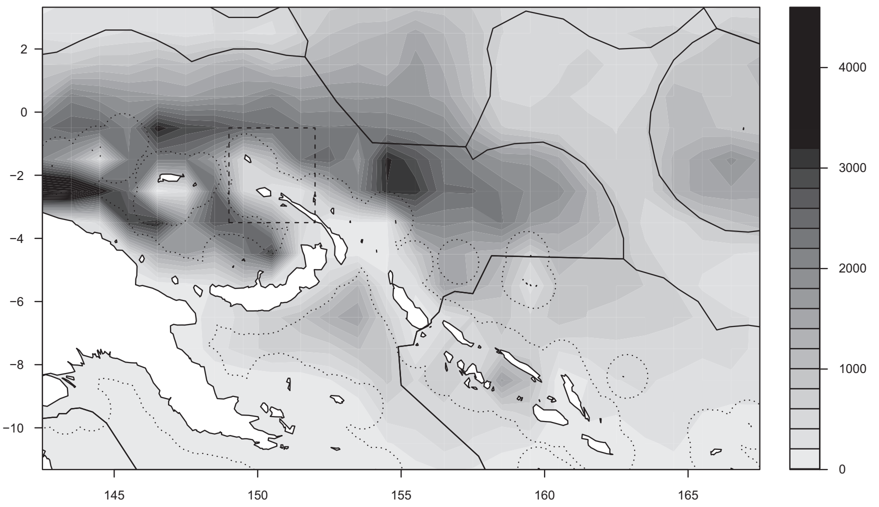

Fig. 7. Contour plot of total purse seine effort (days fished) by 1° square for the period 2005–2013. The Morgado Square (broken black line), 40 nm to shore (dotted black lines) and indicative EEZ limits (solid black lines) are shown for reference. EEZs are indicative only of agreed and potential maritime jurisdictional limits within the Pacific Islands.

from the present results that interactions are likely to be highest where purse-seine fishing effort is highest. Although this is intuitive and not surprising, it does provide fisheries managers with a simple indicator to assist with evaluating the likely performance of artisanal and subsistence fishers and the potential for nearshore FADs to enhance access to oceanic tunas.

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