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Across borders: External factors and prior behaviour influence North Pacific albatross associations with fishing vessels

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Abstract

1. Understanding encounters between marine predators and fisheries across national borders and outside national jurisdictions offers new perspectives on unwanted interactions to inform ocean management and predator conservation. Although seabird–fisheries overlap has been documented at many scales, remote identification of vessel encounters has lagged because vessel movement data often are lacking.

2. Here, we reveal albatrosses–fisheries associations throughout the North Pacific Ocean. We identified commercial fishing operations using Global Fishing Watch data and algorithms to detect fishing vessels. We compiled GPS tracks of adult black-footed *Phoebastria nigripes* and Laysan *Phoebastria immutabilis* albatrosses, and juvenile short-tailed albatrosses *Phoebastria albatrus*. We quantified albatrosses-vessel encounters based on the assumed distance that birds perceive a vessel (≤30 km), and associations when birds approached vessels (≤3 km). For each event we quantified bird behaviour, environmental conditions and vessel characteristics and then applied Boosted Regression Tree models to identify drivers and the duration of these associations.

3. In regions of greater fishing effort short-tailed and Laysan albatrosses associated with fishing vessels more frequently. However, fishing method (e.g. longline, trawl) and flag nation did not influence association prevalence nor the duration short-tailed albatrosses attended fishing vessels. Laysan albatrosses were more likely to approach longer vessels. Black-footed albatrosses were the most likely to

approach vessels (61.9%), but limited vessel encounters (n = 21) prevented evaluation of meaningful explanatory models for this species of high bycatch concern.

4. Temporal variables (time of day and month) and bird behavioural state helped explain when short-tailed albatrosses were in close proximity to a vessel, but environmental conditions were more important for explaining interaction duration. Laysan albatrosses were more likely to associate with vessels while searching and during the last 60% (by time) of their trips.

5. Our results provide specific species–fisheries insight regarding contributing factors of high-risk associations that could lead to bycatch of albatrosses within national waters and on the high seas.

6. *Policy implications*. Given the availability of Global Fishing Watch data, our analysis can be applied to other marine predators—if tracking data are available—to identify spatio-temporal patterns, vessel specific attributes and predator behaviours associated with fishing vessel associations, thus enabling predictive modelling and targeted mitigation measures.

1 | INTRODUCTION

Human activities that augment foraging opportunities for animals are a common historical attribute of many ecosystems (Oro et al., 2013), and industrial development has increased the dependency of some species on human subsidies (McCauley et al., 2015). Human-derived resources can provide direct benefits, but also expose individuals to increased risk (Ripple et al., 2014). Animal–human interactions can be driven by factors unrelated to the frequency of human activity, such as an animal's preferred habitat (Clevenger et al., 2003). Yet, with fisheries bycatch, much of our understanding is derived from observations on fishing vessels (Lewison et al., 2004). Biologging data provide an alternative perspective. Combining movement data from predators and fishing vessels offers the opportunity to assess situational drivers (e.g. environmental conditions, predator behaviour, vessel attributes) of when predators approach fishing vessels that are needed to inform dynamic ocean management (Maxwell et al., 2015).

When and where fishing vessels operate is traditionally considered confidential information and access to these data differs by national jurisdiction. For instance, often fisheries data are required to be aggregated at large temporal–spatial scales for dissemination. On the high seas, fishing is much less regulated, monitored and enforced. Global Fishing Watch (GFW) has overcome many of these data limitations allowing for an unprecedented global understanding of fleet movements (Kroodsma et al., 2018). GFW uses automatic identification system (AIS) data to identify and track fishing vessels. Gear-specific fishing activities are identified based on vessel speed, direction, distribution and fishing time (de Souza et al., 2016). The

GFW dataset does not encompass all fishing effort because most small vessels lack, and some operators periodically disable, AIS (Ford et al., 2018). Although AIS transmits frequently (every 2–30 s), the temporal coverage in AIS databases is much less due to variation in data reception (e.g. satellite coverage). Temporal resolution is comparable to vessel monitoring systems (VMS) used within most national exclusive economic zones (EEZs), but AIS is also used on the high seas.

Fisheries offer seabirds foraging opportunities with risk. More than 50% of seabird species forage on fisheries-derived resources (Oro et al., 2013), and fisheries discards support large numbers of seabirds (Sherley, 2019). Most albatrosses populations have been severely impacted by mortalities from fisheries bycatch largely due to longline and trawl fisheries (Barbraud et al., 2012; Croxall, 2008). Individual seabirds may encounter vessels with different gear types, within multiple EEZs and on the high seas (Clay et al., 2019; Felis et al., 2019); each situation presenting different degrees of risk and reward. Although albatrosses are attracted to vessels (Hyrenbach, 2001; Wahl & Heinemann, 1979), overlap between albatrosses and fisheries distributions does not equate to interactions for all individuals (Torres et al., 2013). Individual seabirds can adapt specialized foraging strategies to exploit fisheries resources (Votier et al., 2010). Therefore, understanding why individuals interact with fishing vessels is important for quantifying the relationship between seabirds and fisheries. This individual-based approach, extended across national boundaries, may reveal intrinsic bird characteristics and behaviours associated with vessel associations not apparent in single fishery or single EEZ studies (Sztukowski et al., 2017).

Identifying and predicting situations with high bycatch risk can inform management approaches to refine broad area closures and supplement vessel-based mitigation. While attending fishing vessels does not equate to bycatch directly, it does place birds at higher risk. In the Hawai'i-based deep-set longline fishery, vessel attendance by black-footed albatrosses *Phoebastria nigripes* positively correlates with bycatch (Wren et al., 2019). There are a number of vessel-based mitigation options implemented for reducing albatrosses by-catch including streamer lines, night setting and dyed bait (Gilman et al., 2007; Melvin et al., 2019). Development of recommendations that reduce vessel attendance could increase compliance by reducing the burden on fishers. For example, loggerhead turtle *Caretta caretta* bycatch was lessened by providing fishers real-time location of the temperature front that mediates turtle distributions (Howell et al., 2008). This dynamic approach could be especially useful during environmental events like El Niño that increase albatrosses use of fisheries-associated prey (Conners et al., 2018). A contextual environmental understanding of seabird vessel attendance, therefore, is a key component for developing these targeted predictive models.

Our first goal is to assess the utility of the GFW dataset combined with biologging data. We use tracking data from the three North Pacific albatrosses that traverse multiple national EEZs and spend extensive time in international waters to identify instances when a bird likely detects a fishing vessel (encounter) and when a bird is in close proximity to a vessel (association). Our second goal is to test for contributing factors that influence these albatrosses-vessel associations. We predict that birds will approach vessels where prey resources are scarce. Hence, chlorophyll *a* (chl*a*), sea surface temperature (SST), bathymetry, oceanic biogeographic regions and month are included as indicator variables for prey availability (Kappes et al., 2010; Pinaud et al., 2005). We expect longer vessel association during low winds when taking-off is more energetically demanding (Weimerskirch et al., 2000). We predict naive juvenile short-tailed albatrosses to approach fishing vessels for foraging opportunities (Suryan et al., 2007), transiting birds to bypass and foraging birds to approach vessels. Given that risks and rewards for albatrosses differ among fisheries we anticipate that vessel characteristics will influence vessel attendance (Anderson et al., 2011; Croxall, 2008). Finally, fishing vessels cluster in space and time and thus we expect albatrosses to interact more frequently in high use fishing areas. Herein, we attempt to disentangle these factors hypothesized to influence albatrosses-vessel associations and make recommendations for applying these results in a management framework.

2 | MATERIALS AND METHODS

2.1 | Study species

In the North Pacific there are three albatrosses species that all interact with fisheries (Guy et al., 2013; Nevins et al., 2018; Suryan et al., 2006; Thiebot et al., 2018; Wren et al., 2019; Žydelis et al., 2011). Fisheries impacts on albatrosses in the northwest

Pacific, a global fisheries hot spot and on the high seas are generally unknown (Kroodsma et al., 2018; Lewison & Crowder, 2003), adding uncertainty to species management plans (Arata et al., 2009). Short-tailed albatrosses (STAL, *Phoebastria albatrus*) are recovering from human exploitation (Hasegawa & DeGange, 1982), and although the population is still <1% historical numbers, population growth is close to the predicted maximum (Zador et al., 2008). Bycatch of STAL is observed infrequently and most are juvenile birds (USFWS, 2014). However, a ~2.5% increase in annual fisheries mortality would substantially slow population growth (Finkelstein et al., 2010). Despite the implementation of streamer lines by large vessels in Alaska in 2002, bycatch of black-footed albatrosses (BFAL) has increased in the sablefish fishery (Melvin et al., 2019). Similarly, despite mitigation efforts, bycatch by the Hawaiian deep-set tuna longline fleet is also increasing (Gilman et al., 2016; Wren et al., 2019). Much uncertainty exists in how bycatch mortalities are impacting BFAL populations (Bakker et al., 2017). Although Laysan albatrosses (LAAL, *Phoebastria immutabilis*) are of the lowest bycatch concern, partially due to their large population size, LAAL are bycaught by both Alaskan and Hawaiian fleets (Krieger et al., 2019), and encounter fisheries on the high seas (Žydelis et al., 2011).

2.2 | Albatrosses movements

We compiled albatrosses GPS tracking data from breeding BFAL(n_{birds} = 57) and LAAL(n_{birds} = 75), and juvenile/sub-adult STAL(n_{birds} = 18) from 2012 through 2016 (Table S1). This dataset represents 9,992 albatrosses-days at-sea. BFAL and LAAL GPS tags recorded locations every 30 s to 20 min. STAL GPS tags recorded locations every 2 hr for 12 hr on and 12 hr off or every 4 hr. Following recommendations for large-bodied flying seabirds, tracking devices weighed <3% of the birds' body mass (Phillips et al., 2003). Analyses were run with R 3.6.0 (R Core Team, 2019).

2.3 | Fishing vessel encounters and associations

As a simple definition of spatial scale we applied a threshold of 30 km to define vessel encounters and 3 km to define vessel associations; this also allows for comparison between studies (Collet et al., 2015). The encounter threshold is roughly at the limit of visual detection due to the curvature of the earth (Haney et al., 1992). Encounters with the same boat were considered distinct if they occurred more than a day apart. To limit the quantity of AIS data analysed, we identified vessels within 80 km of interpolated albatrosses locations (10 min for BFAL and LAAL, 1 hr for STAL) and obtained the Maritime Mobile Service Identity (MMSI) of fishing vessels engaged in fishing activities from the GFW daily gridded dataset (0.1°, Kroodsma et al., 2018, Orben & Torres, 2021). We then acquired associated AIS tracks (GPS interval 1.76 ± 1.54 hr).

We matched vessel and albatrosses tracks at 10-min resolution, using 'prox', which is robust to changes in sampling intervals

(Long et al., 2014). Then we evaluated each encounter and association. We first removed 52 STAL and 3 LAAL encounters with <5 vessel locations to ensure encounters were not spurious, short-term events. We sub-set and re-interpolated the high resolution GPS data, to assess the use of lower resolution STAL data and identified low location error of interpolated data when limited to <2 hr from an observed GPS location (Appendix S1). This <2 hr cut-off removed 713 STAL encounters. Although initial identification of encounters were restricted to vessels engaged in fishing activities, actual encounters assessed were not necessarily during fishing activity.

2.4 | Model covariates

We extracted conditions from either the encounter or the association location. Predictor variables fell into five groups: vessel or bird characteristics, environmental parameters, temporal periods and spatial domains (Table 1, Appendix S2). We identified the Longhurst bioregion to distinguish large-scale habitats (Longhurst, 2010). SST and chl*a* were extracted using 8-day composites from Aqua MODIS (4 km, https://oceancolor.gsfc.nasa.gov/data/aqua/); this spatiotemporal scale reflects mesoscale processes. Wind speed was calculated from *u* and *v* vector components extracted from 6-hr layers (0.25°, https://www.ncdc.noaa.gov/data-access/marineocean-data/blended-global/blended-sea-winds). Bathymetry was extracted from ETOPO1 (0.01°, Amante & Eakins, 2009). Daily fishing density was quantified as the number of MMSI within a 60-km radius, fishing effort as the sum of the fishing hours within 60 km, and for each vessel we extracted flag nation, fishing gear type and vessel length (0.1°, Kroodsma et al., 2018). Each encounter was classed as within a EEZ or the high seas (Flanders Marine Institute, 2018), and fisheries management units including EEZs and regional fisheries management organizations (RFMOs) in the North Pacific (FAO, 2019).

Three behavioural states were classified by calculating the difference between residence time and residence distance (residuals), both normalized by dividing by the highest value, within a radii around each point (Residence in Space and Time [RST]; Torres et al., 2017). This approach is robust to differences in sampling interval; radii were selected dynamically for each track as half of the distance at which the prevalence of transit locations approaches zero. When the residual is zero, locations are classified as transit behaviour. For higher resolution movement data, positive residuals indicate search and negative residuals indicate rest. For lower-resolution STAL data, positive residuals indicate large-scale search, and negative residuals indicate small-scale search. We classified the behavioural state within a 15-day window for STAL and 5 days for LAAL and BFAL. RST radii were 13.5 ± 5.93 km (STAL), 3.26 ± 0.56 km (LAAL) and 4.17 ± 0.97 km (BFAL). Behavioural state was summarized for the 24 hr before the bird-vessel encounter for STAL and the previous 2 hr for LAAL and BFAL. For breeding birds, we delineated foraging trips using a radius of 5 km from the colony and calculated the per cent time into each trip.

2.5 | Explanatory models

We addressed two questions through multivariate models: (a) what factors influence an encounter at 30 km transitioning to an association at 3 km? (b) What factors influence association duration? Question 1 could only be addressed for STAL and LAAL due to limited encounters by BFAL, and Question 2 was only applied to STAL due to limited associations by LAAL. Species specific models were generated using Boosted Regression Trees (BRTs), a machine learning method that combines decision tree methods (models that partition predictor data by recursive binary splits) with a boosting algorithm to iteratively optimize model performance

TABLE 1 Initial predictor variables included in multivariate Boosted Regression Tree (BRT) models to assess the approach of albatrosses to fishing vessels (LAAL and STAL) and albatrosses-vessel association duration (STAL). Factors are italicized and levels are included in parenthesis

Bird (LAAL)	Bird (STAL)	Temporal	Vessel	Environment	Spatial
Bird ID	*Bird ID*	*Month*	*Flag nation (Canada, China, Korea, Russia, USA, other)*	Wind speed (m/s)	*high seas or EEZ*
Dominant behaviour state (transit, forage, rest) in previous 2 hr	Behaviour state % in previous 24 hr (transit, large-scale search, small-scale search)	*Time (day, night, dusk)*	*Gear type (Longline, Trawler, Other, Unknown)*	Depth (log(m))	*Longhurst bio-region*[a]
% into foraging trip	Age		Fishing effort (60 km; hr/km^2)	Sea Surface Temperature (°C)	*Fisheries Management Unit (Hawaii, Alaska, Russia, Canada, Japan, FAO high seas regions)*
Colony (Tern, Midway, Oahu, Kauai)			Fishing density (60 km; boats/km^2)	Chlorophyll a concentration (mg/m^3)	
			Vessel length (m)		

[a]See Appendix S2 for map and regions.

by combining a large number of decision trees (Elith et al., 2008). BRT models are capable of modelling nonlinear relationships to examine complex relationships among multiple predictor variables and a given response variable. BRTs can handle co-linearity and interactions between variables, and can simultaneously assess both continuous and categorical data as predictors in the model, making them well-suited for ecological studies (Elith et al., 2008; Leathwick et al., 2006).

Boosted Regression Trees estimate the relative influence of each predictor variable on the response variable based on the number of times the variable was selected for tree splitting and weighted by model improvement as a result of each split (Friedman & Meulman, 2003). BRT models were fit using 'gbm' (Greenwell et al., 2019) and 'dismo' (Hijmans et al., 2017). The bag fraction (proportion of data selected at random for each decision tree) was set to 0.75 for STAL and 0.9 for LAAL due to a smaller dataset. The tree complexity (number of allowed interactions between predictor variables) was tested from 1 to 4, with final choice dependent on model performance and favouring lower tree complexity values for similar performance metrics. Learning rate (contribution of each tree to the model) initialized at 0.01 and was allowed to increase until the optimal number of trees was reached (Elith et al., 2008).

Models evaluating the drivers of an encounter becoming an association used a binomial response variable (outcomes). Binomial BRT model performance was evaluated and compared to select the 'best' model using two model performance metrics: (a) the Area Under the receiver operator Curve (AUC) score based on the training data, and (b) the cross-validation AUC (cv.AUC) score derived from the withheld data. AUC measures the true negative rate against the true positive rate at various discrimination thresholds and values range from 0 to 1, with higher values indicating better model performance. Association duration was natural-log transformed for normality. These Gaussian BRT models were evaluated based on correlation scores between predictions and observed values of withheld data (training correlation). No correlations were identified between continuous variables, but vessel length and flag nation were correlated (ANOVA: $F_9 = 263$, $p < 0.001$), with smaller vessels from Canada and the United States; therefore, flag nation was not included in the final models. Depth and fisheries management unit were confounded for LAAL; therefore, depth was not included in the LAAL final model.

3 | RESULTS

We identified 1,812 encounters between albatrosses and fishing vessels (Figure 1), with 520 unique vessels. For BFAL and LAAL, encounters were from just a few individuals, 14% ($n = 8$) and 21% ($n = 16$) respectively, while all but two STAL (89%) encountered fishing vessels. BFAL and STAL predominantly encountered trawlers, while LAAL encountered longliners (Table 2). BFAL and STAL encountered most vessels within EEZs, while most vessels LAAL encountered were on the high seas (Table 2). Encounters became associations most frequently for BFAL, then LAAL, and STAL (Table 2). Association duration did not differ among species ($F_{2,28} = 1.13$, $p = 0.337$, log[duration], individual random effect, 'lme', Pinheiro et al., 2019; Table 2). STAL each encountered 108 ± 98 boats and had 31 ± 25 associations. We found three STAL association hotspots: (a) the continental shelf to the east of the Kuril Islands, (b) north of Unimak Pass in the Bering Sea and (c) Navarin Canyon in the Northern Bering Sea (Figure S1).

3.1 | Drivers of vessel associations among LAAL and STAL

Model assessment of influential factors predicting LAAL vessel associations had strong model performance despite small sample size ($n = 53$, Table 3) and included six predictor variables (Figure 2; per cent contribution given in parentheses): fishing effort (32.0%), per cent into foraging trip (21.1%), fisheries management region (15.4%), dominant behaviour state during previous 2 hr (14.3%), fishing density (9%) and vessel length (8.2%; Figure 2). The likelihood of vessel association was low when fishing effort was low, during the initial portion of a foraging trip (<40% into trip), highest in Alaskan waters, high if a bird had been predominantly foraging during the previous 2 hr, high when vessel density was low, and low with smaller vessels. Behaviour variables contributed 35.3% to the model and fisheries characteristics contributed the remaining 64.7%.

The final BRT model predicting STAL-vessel associations had strong model performance (Table 3) and indicated that vessel (41.2%), temporal (25.4%), bird (21.9%) and environmental (11.5%) factors all contributed (Figure 3a). The likelihood of an association was greater when fishing effort was high, but vessel density was low, during the day, at shallow depths (75–1,500 m) and during April and December. Associations were more likely, if during the previous 24 hr, the bird spent >40% and >30% time making small- and large-scale searching movements and conversely decreased with increasing transit behaviour.

3.2 | Determinates of STAL-vessel association duration

The BRT model addressing the factors influencing STAL-vessel association durations performed moderately well (Table 3). In the final model, environmental variables contributed the most (49.9%), followed by fishing effort (22.0%), month (16.9%), behaviour (5.9%) and bird age (5.2%, Figure 3b). Association durations were more likely to be longer where fishing effort was high, during low winds (<10 m/s), over deeper water (>250 m), during March and June–August, where SST was >8°C, chl*a* concentrations were low (<0.3 mg/m^3), and birds spent about 50% time in localized searching movements. Younger birds (<1.3 years) were more likely to have longer associations.
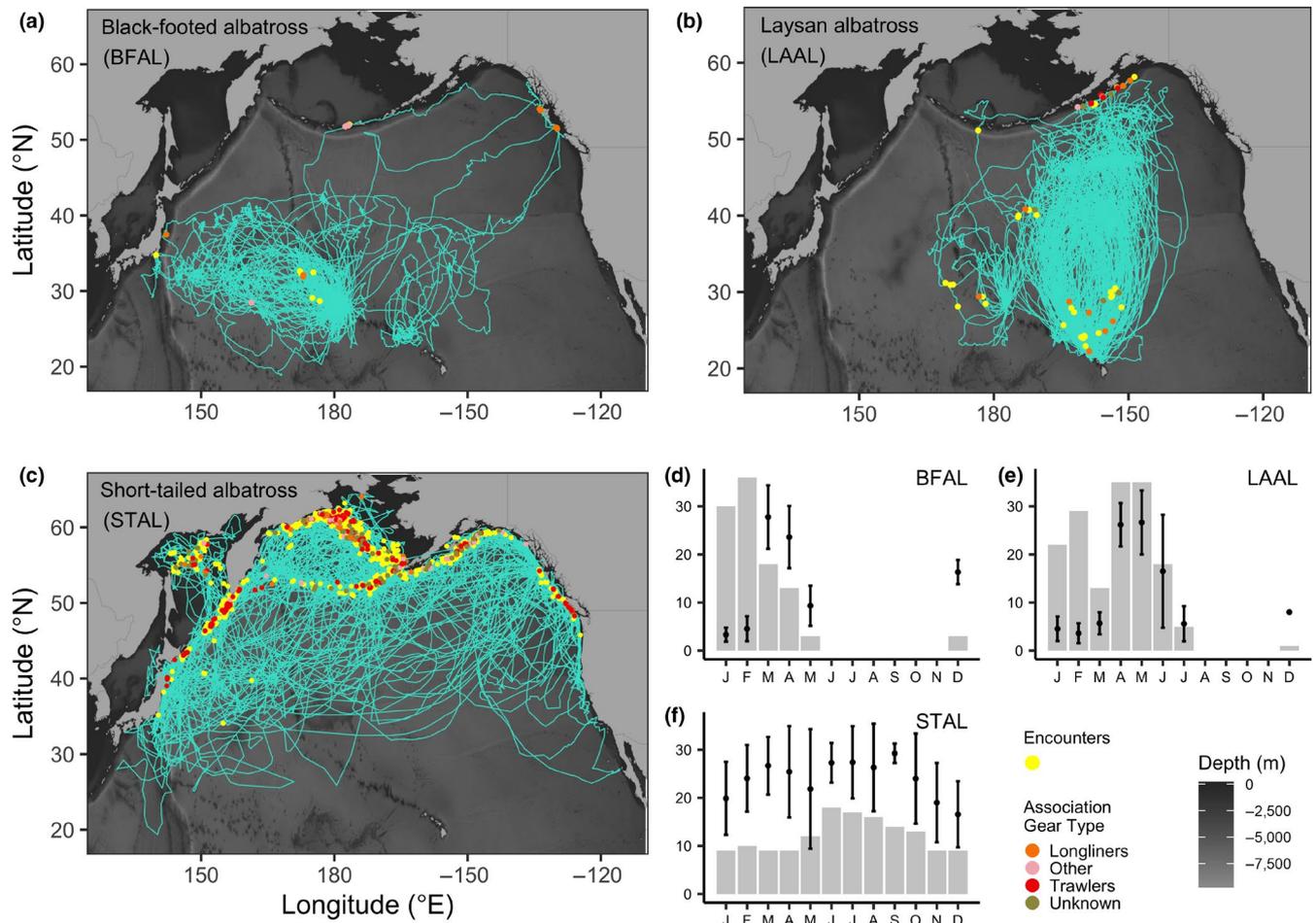
FIGURE 1 GPS tracks of albatrosses analysed relative to global fishing watch (GFW) data on fishing vessel distribution, and the locations of identified encounters (≤30 km; yellow dots) and associations coloured by gear type (≤3 km) for (a) black-footed albatrosses (BFAL), (b) Laysan albatrosses (LAAL) and (c) short-tailed albatrosses (STAL). Panels d–f show the number of birds tracked each month (grey bars) and the number of days tracked (mean and *SD*, black)

TABLE 2 Characteristics of identified encounters and associations between albatrosses and fishing vessels in the North Pacific. Percentages are followed by binomial confidence intervals transformed to percentages

Species	Encounters (≤30 km)	Associations (≤3 km)	Associations (%)	Association Duration (hr)	Encounters within EEZs (%)	Predominate gear type encountered (%)[a]
BFAL	21	13	61.9 (40.8, 79.2)	1.78 ± 1.99	57.1 (36.5, 75.5)	Trawlers (85.7)
LAAL	56	20	35.7 (24.4, 48.8)	3.01 ± 5.38	46.4 (34.0, 59.3)	Longliners (64.9)
STAL	1,735	496	28.6 (26.5, 30.7)	3.21 ± 5.50	99.4 (98.8, 99.6)	Trawlers (76.2)

[a]Percentages were calculated from totals after vessels of unknown gear type were subtracted ($n_{BFAL} = 7$, $n_{LAAL} = 19$, $n_{STAL} = 435$).

TABLE 3 Model fit statistics of final Boosted Regression Trees (BRTs) used to identify factors influencing albatrosses-vessel associations and duration

Model	Model type	Model interactions (#)	Bag fraction	Learning rate	Trees (#)	AUC	cv.AUC	Training correlation
LAAL: encounter to association	Binomial	2	0.90	0.00125	1,500	0.969	0.788	—
STAL: encounter to association	Binomial	4	0.75	0.005	1,600	0.916	0.813	—
STAL: duration of association	Gaussian	4	0.75	0.000625	1,750	—	—	0.617

FIGURE 2 Boosted Regression Tree (BRT) partial dependency plots for the predictor variables contributing to LAAL-vessel associations with the model contribution percentage. Panels show the effect of each variable on the probability of an association while fixing other variables at their mean. The functional (black) and smoothed (blue-dashed) response curves are shown. Rug plots show distribution of values, in deciles. Plots were constructed with 'pdp' (Greenwell, 2017)
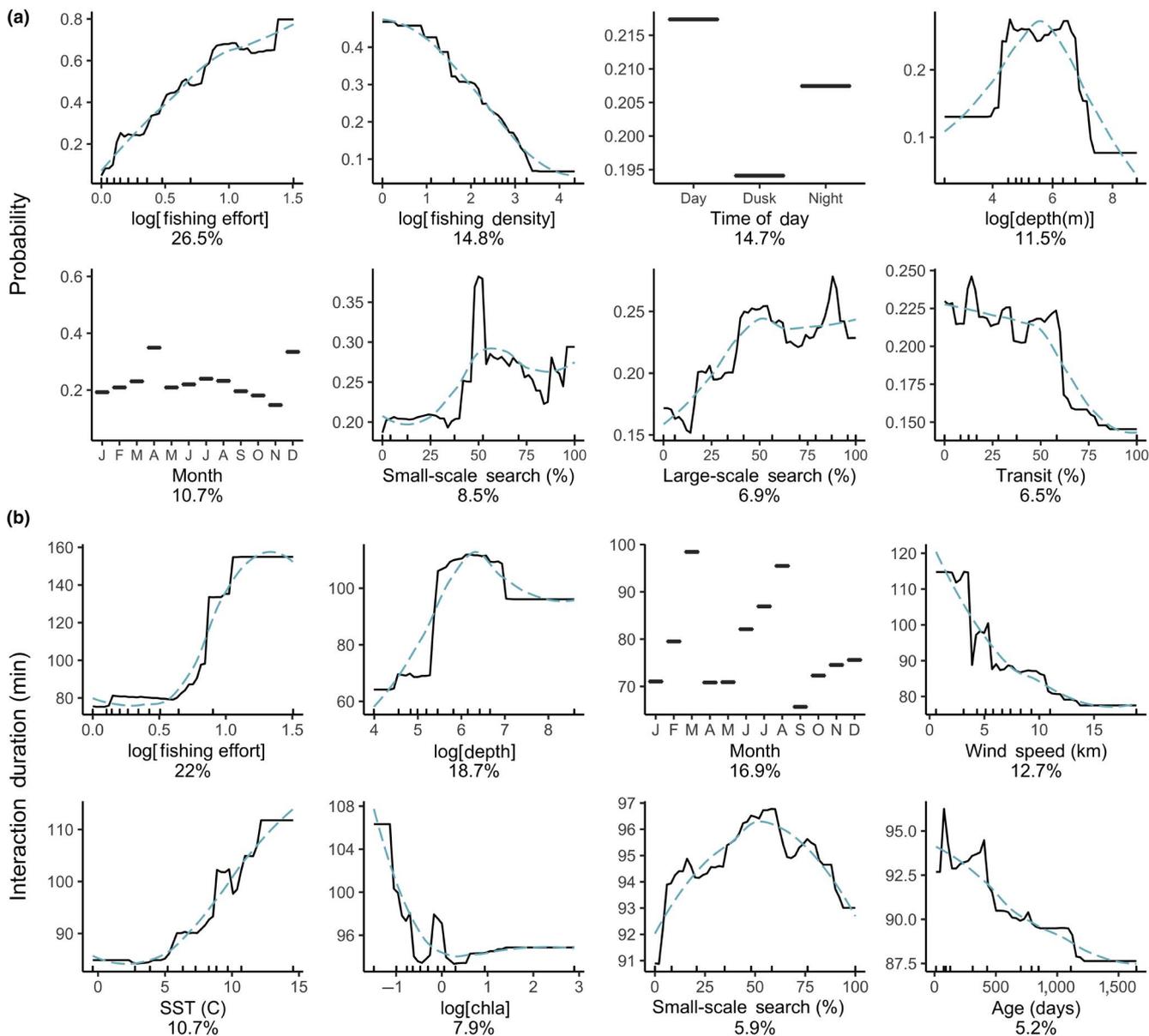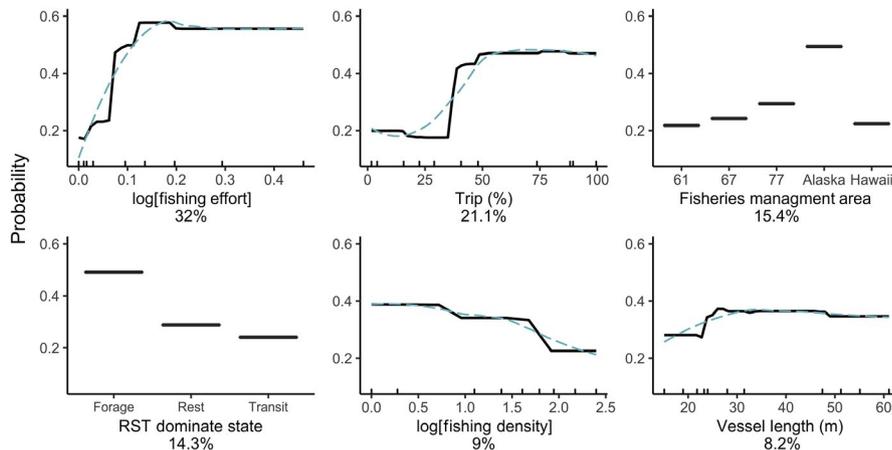
FIGURE 3 Partial dependency plots for the predictor variables contributing to the (a) occurrence of STAL-vessel associations and (b) the duration of an association. The *y*-axes are scaled to each variable to highlight the functional response

4 | DISCUSSION

Our integrated analysis of fishing vessel and albatrosses movements offers an improved understanding of drivers of albatrosses–fisheries associations across multiple borders and in the high seas of the North Pacific. Unexpectedly, fishing vessel characteristics, such as vessel type or gear, were not significant contributing factors influencing an albatrosses's likelihood to associate with a vessel; however, local fishing effort, density and vessel length contributed. We found that prior bird behaviour was an important factor contributing to the likelihood of an encounter becoming a vessel association. The vessel attraction rates (percentage of encounters resulting in associations) of BFAL were the highest (61.9%) and comparable to wandering albatrosses (57.8%), but lower than black-browed albatrosses (79.1%; Collet et al., 2017). On the high seas, encounters between albatrosses and fishing vessels were more common for birds breeding in Hawai'i, but for juvenile STAL, EEZs are clearly where fisheries bycatch mitigation is important. Environmental conditions influenced the amount of time STAL spent near vessels, presenting an opportunity for developing predictive models to alert fishers of high-risk areas.

4.1 | Limited response of albatrosses to fishing vessel characteristics

Given the variety of fishing vessels in the North Pacific and the different foraging opportunities they offer, we expected vessel characteristics would have contributed more significantly to our models. Perhaps, to an albatrosses, fishing vessels appear similar from a distance? Indeed, LAAL were more likely to approach longer vessels that could be more visible, but no vessels characteristics were significant for STAL. In the Mediterranean, Scopoli's shearwaters *Calonectris diomedea* prefer attending trawlers to longliners (Soriano-Redondo et al., 2016). In contrast, our models found that gear type was not a significant factor leading to an association. Considering the low vessel attraction rates, and few identified encounters of LAAL and BFAL, tracking additional age classes or during other seasons might revel individuals with distinct preferences. Similarly, only 11% of chick rearing LAAL had evidence of fisheries-associated resources in their diet and the proportion of use was low (<10%; Conners et al., 2018). This suggests that use of fisheries resources may be more opportunistic than preferred for breeding LAAL, as has been documented for black-browed albatrosses (Collet & Weimerskirch, 2020). While encounters were more common for STAL, the low frequency of attendance could be due to avoidance and/or a large zone (>3 km) of available discards around trawlers (the most frequent vessel type encountered). Additionally, both LAAL and STAL were more likely to approach vessels when regional fishing effort was high, but vessel density was low. This result could indicate that the time spent attending one vessel limits the number of vessels a bird might attend.

4.2 | Influence of environmental conditions on associations

Contrary to our prediction, we did not find strong support that proxies of prey availability, as characterized by environmental co-variates, influenced when albatrosses associated with vessels. However, STAL increased association durations at lower chl*a* values and higher SSTs—two environmental characteristics generally associated with seabird prey (e.g. Ichii et al., 2011). We found that for STAL, associations occurred slightly more frequently during the day and occurred less frequently during twilight and night. This diel pattern may help explain why albatrosses bycatch is greatly reduced at night (Melvin et al., 2019). Observed STAL bycatch is infrequent (Good et al., 2019), thus the efficacy of night setting to reduce bycatch has not been evaluated for this species, although higher daytime activity levels were observed in previously tracked individuals (Suryan et al., 2007). Breeding LAAL tend to forage both during the day and night (Conners et al., 2015), and this is consistent with our results that time of day was not a significant predictor of LAAL vessel associations.

Current US fishing regulations allow discretionary streamer lines use in heavy winds >56–83 km/hr (Federal Register, 50 CFR Part 660). Consistent with this, our results indicate that STAL vessel associations were longer during low winds (<5 m/s; 18 km/hr); STAL tend to favour higher wind speeds for long distance flights (~36 km/hr) and have high wing loading for their body size (Suryan et al., 2008). Relationships between wind and albatrosses bycatch vary as heavy seas increases black-browed albatrosses bycatch mortality (Weimerskirch et al., 2000), while wind speed did not relate to albatrosses bycatch in Alaskan fisheries (Dietrich et al., 2009). The apparent complex relationship with wind may be the result of a combination of factors including species and fisheries characteristics, different drivers of vessel attendance and bycatch, and/or the effectiveness of bycatch mitigation measures during low wind conditions.

4.3 | Influence of bird behaviour and age on associations

Bird behaviour contributed to each of our models, however, it was not a dominate predictor variable. Prior bird behaviour state was influential in all three models. As predicted, birds engaged in searching behaviour were more likely to encounter vessels, while transiting birds tended not to approach vessels. Adult LAAL had a higher frequency of associations on their homebound leg, typically with longliners. We suggest birds departing on a foraging trip are more direct in their travel to predictable feeding areas, whereas on the inbound leg, opportunistic scavenging of fisheries-associated food might be more appealing, especially when feeding a growing chick. Due to the stereotypical nature of their wind facilitated foraging trips it may be possible to predict the spatial distribution of these return trips and reduce these opportunities—however, the majority of these events occur on the high seas.

Younger STAL were more likely to have longer association durations, thus, placing them at increased risk of bycatch. Young seabirds need to develop effective foraging strategies and may be more likely to depend on fisheries discards than adults (Afán et al., 2019; Walker et al., 2015). As they age, juvenile STAL use less oceanic waters and are more likely to use shelf-break habitats (Orben et al., 2018), where fisheries operate, thus increasing fisheries overlap while decreasing vessel attendance duration. STAL juveniles also have different plumage and distributions from adults (Suryan et al., 2007), and continued fisheries management efforts are needed across their range to monitor and reduce associations by this vulnerable young age class.

4.4 | Implications for management and conservation

Our modelling framework highlights environmental, temporal and fisheries drivers of vessel attendance that could be leveraged to develop dynamic management (Welch et al., 2018). For STAL, association durations were strongly influenced by dynamic and static environmental variables that could be used to predict high-risk regions and timeframes. Durations were also longer when local fishing effort was higher—a condition that during high-risk periods could be regulated or avoided by fishers. Providing fishers information on high-risk regions and timeframes is appealing because STAL bycatch is rare but comes with high stakes. For instance, within the US EEZ mortality of only a few birds can trigger severe regulatory action. Most STAL-vessel encounters were with trawlers, and this reinforces the need to account for unobserved fisheries mortality via warp-cable strikes (Croxall, 2008; Zador et al., 2008). More generally, a comparison of vessel associations with spatially explicit bycatch data from fishery observer programs would help calibrate when the perceived threat from close proximity between birds and vessels is a realized threat in observed bycatch.

Admittedly, our approach is data hungry and reliant on marine predator biologging data. Thus, while we found that BFAL were more likely than either of the other two species to associate with fishing vessels—with most associations within EEZs; our small sample size of encounters prevented explanatory models. This higher frequency of association is concerning and consistent with at-sea observations of vessel following behaviour (Hyrenbach, 2001) and rising BFAL bycatch (Melvin et al., 2019; Wren et al., 2019). Furthermore, it remains unknown if BFAL have preferences for particular fisheries. If, like STAL, environmental conditions lead to longer vessel associations then it would be possible to develop a predictive framework to alert fishers, improve observer coverage and enhance bycatch mitigation efforts in higher risk regions. Augmenting this analysis with VMS data from small vessels within EEZs and detection of illegally fishing vessels (Weimerskirch et al., 2020), would help complete the picture. Due to limitations in AIS data coverage, we refrained from calculating encounter rates, but with recent increases in AIS data capture and estimates of uncertainty in vessel coverage this would be possible.

These methods are useful for assessing association of highly mobile megafauna with fishing vessels in multiple EEZs and the high seas. This is exemplified by LAAL, as our results indicate that birds approach high seas fishing vessels at similar rates to those within the Hawaiian EEZ. Furthermore, not all high seas regions are currently fished. By overlaying GFW data and marine predator movement data, it is possible to identify regions where predators have refugia from fisheries. Understanding risks on the high seas to marine megafauna is challenging, yet GFW data offer an unprecedented opportunity to instigate our understanding of human–wildlife associations in this vast region.

AUTHORS' CONTRIBUTIONS

L.G.T., R.A.O., J.A. and S.A.S. conceived the ideas and designed methodology; D.A.K., S.A.S., M.G.C., C.C., R.M.S., J.A., L.C.Y., M.H., R.A.O., T.D., K.O. and F.S. collected the data; R.A.O., L.G.T. and

D.A.K. analysed the data; R.A.O. and L.G.T. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.