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Global prevalence of setting longlines at dawn highlights bycatch risk for threatened albatross

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ABSTRACT

Longline fishing kills over 160,000 seabirds annually, with bycatch in these fisheries contributing significantly to the widespread, global decline in albatross populations. One of the most effective ways to reduce this bycatch is for pelagic longliners to set their hooks entirely at night, when albatross are least active, and setting at night is recommended in some areas of the ocean by Regional Fisheries Management Organizations. To develop a global dataset of where and when longliners actually set their hooks, we apply machine learning to four years of GPS data of the global longline fleet (~5000 vessels). Our data reveal the vast footprint of longline fishing: over 40 % of the ocean is, at least one time during a year, within 30 km of a set, the distance within which an albatross can detect a vessel. On a given day, about 1.5 % of the ocean is within this distance of a set. Almost all of these sets were during daylight hours, with only 3 % of sets occurring entirely at night. In regions with threatened albatross species, night setting is more common (4–9 %), but it is much lower than suggested by on-board observer programs, highlighting the limitations of current monitoring. Furthermore, in albatross habitat, vessels more often set their lines during dawn hours when these birds are most active and bycatch risk is highest.

1. Introduction

Globally, seabirds are the most threatened of all bird groups, with 31 % of seabird species listed as Critically Endangered, Endangered, or Vulnerable by the International Union for Conservation of Nature (IUCN) (Allinson, 2018). Bycatch in fisheries is one of the primary threats facing seabirds (Dias et al., 2019). It is estimated that at least 160,000 seabirds, and potentially in excess of 320,000, are killed each year in longline fisheries (Anderson et al., 2011). A large proportion of these birds are albatrosses, and albatross and petrel species make up the majority of seabird bycatch in the northern Pacific and the southern Indian, Pacific, and Atlantic Oceans (Anderson et al., 2011). Consequently, bycatch in longline fisheries is the largest global driver of declines in albatross populations (Clay et al., 2019; Pardo et al., 2017; Phillips et al., 2016), and 15 of 22 albatross species are threatened with extinction (IUCN, 2021).

One of the primary fishing gears putting albatross at risk, drifting pelagic longliners, is the most spatially widespread fishing gear in the ocean (Kroodsma et al., 2018). These vessels operate by setting lines with thousands of baited hooks that can be over 100 km long, with each set taking around 5 to 6 h to deploy. After setting, the vessels let the lines float, known as “soaking”, usually for several hours, before retrieving them. The vessels generally repeat this process of setting, soaking, and hauling about once a day (Brothers, 1991; Tuck et al., 2003; Watson and Kerstetter, 2006). They also often stay at sea for weeks or months at a time, offloading their catch and getting resupplied by transshipment and support vessels (Miller et al., 2018), and this protracted time at sea makes it challenging to monitor the activity of these vessels.

To reduce the risk facing albatross, the five tuna Regional Fisheries Management Organizations (tRFMOs) mandate various conservation management measures that affect how vessels set their lines. During setting, when longline hooks are entering the water, the risk of seabird bycatch is high because birds are attracted to the bait on the sinking hooks, and they can become hooked and drown (Brothers, 1991; Løkkeborg, 2011). To reduce this risk, in the southern oceans (south of 25° or 30°S depending on the region), vessels are required to adopt two out of the three following management measures (WCPFC CMM 2018-03, n.d.; ICCAT Recommendation 07-07, 2007; IOTC Resolution 12/06, n.d.; ICCAT Recommendation 11-09, 2011): i) bird-scaring (tori)

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lines, which have colorful streamers to deter birds as the baited hooks are deployed (Løkkeborg, 2003), ii) weighted branch lines that increase the sink speed of baited hooks (Jiménez et al., 2019; Melvin et al., 2014); and iii) night-setting, which involves deploying a longline entirely between nautical dusk and nautical dawn. In the northern Pacific, depending on the exact region, vessels are required to select two mitigation measures from a wider list that also includes night setting (see methods for full list of regulations and regions). Of these methods, night setting has proven extremely effective in reducing seabird bycatch, especially for albatrosses, which are mostly inactive at night (Catry et al., 2004; Jiménez et al., 2020; Melvin et al., 2019; Phalan et al., 2007).

Although conservation management measures have been in place at tRFMOs since as early as 2007, there has been no comprehensive way to determine fleetwide compliance. The only verification comes through programs where fishery observers on vessels record compliance, and in the majority of RFMOs only about one in twenty longline vessels is required to have an onboard observer each year (Pierre, 2018; Williams et al., 2016). Onboard observers report relatively high rates of night setting (Table 1), but the vessels with observers may not be representative of the entire fleet. Verification across the wider fleet is needed to help protect albatross populations, and a better understanding of the setting practices of the global fleet can also inform these conservation methods.

Verification of compliance with conservation measures may now be possible because of new GPS tracking data. In contrast to observers, a significant portion, if not the majority of high seas vessels use the Automatic Identification System (AIS) (Sala et al., 2018), a device designed for safety at sea. This device broadcasts vessels' GPS coordinates every two to thirty seconds, and recent advances in satellites and machine learning have allowed the monitoring of fishing activity globally (Kroodsma et al., 2018). In this study, we draw on this global dataset and apply machine learning to the GPS positions of the global pelagic longline fleet. We identify the exact times that each longliner sets its lines, thus providing an independent method to verify night setting. This method presents an opportunity for fishing nations to better monitor setting of their fleets, and potentially aid researchers and tRFMOs to reduce seabird bycatch.

2. Materials and methods

2.1. Labeling AIS data

We drew on Global Fishing Watch's database of AIS positions of fishing vessels, and using the methods in (Kroodsma et al., 2018; Park et al., 2023), identified 4923 pelagic longline vessels and their GPS positions across four years, from 2017 to 2020. We then selected 65 vessels, some of which had observer data collected by BirdLife International's Albatross Task Force observers, and, in consultation with fisheries observers, used expert judgment and logbooks to label each GPS position as "setting," "hauling," and "other" (example labels in Fig. S1). Labeled track lengths averaged about two weeks of fishing activity, and the total time of labeled tracks was more than four years. To provide a representative sample, the vessels were from 16 different countries and operated in all oceans. After training an initial model, predicted sets were plotted on a global map, and, using expert judgment, potential areas with false positives identified. Tracks from these areas with their predicted labels were then checked, relabelled and added to the training data to help improve the accuracy of the model.

The visual inspection and labeling of vessels showed that although setting techniques vary, the pattern of setting, hauling, and engaging in other activity is extremely distinctive and relatively easy for analysts to differentiate. Setting of lines takes place generally slightly slower than steaming speed (7–8 knots). Hauling of lines occurs at a slower and more variable speed, and follows a similar path to the line setting. Either the fishing vessel stops for a few hours near the end of the set, and then hauls in the reverse direction, or the vessel travels back to the start of the set, and hauls in the same direction. Generally, the locations of the start and end of sets can be identified by matching to the start and end locations of the hauls. (Fig. S1).

AIS devices broadcast a GPS position every 2 s to 3 min depending on the device and status of the vessel. However, because of intermittent satellite coverage and reduced reception in areas of high vessel traffic (Taconet et al., 2019), the AIS messages in the database acquired by Global Fishing Watch from the companies Orbcomm and Spire have sporadic gaps between positions of minutes to, in some cases, hours. On average in our dataset, vessels had about 9 positions/h.

Table 1

Observer data included in public RFMO reports significantly overstate the proportion of longline hooks that are set at night, as determined from our AIS data.

Flag state, year and RFMO region	Percentage of fishing effort with observers	Observer data: percent of effort using night setting[*]	AIS data: sets entirely at night	AIS data: sets majority at night	Number of sets
Australia 2017 CCSBT Area 4	10.6 %	42 %	20 %	38 %	<100
Australia 2017 CCSBT Area 7	13.9 %	65 %			
Japan 2017 CCSBT Area 4	5.7 %	44 %[**]	1.1 %	8 %	≈270
Japan 2017 CCSBT Area 7	11.3 %	40 %[**]	0.7 %	9 %	≈1400
Japan 2017 CCSBT Area 8	4.3 %	13 %[**]	0.1 %	0.3 %	≈1100
Fishing Entity of Taiwan 2017 CCSBT Area 8	11.8 %	95 %	1.4 %	3 %	≈1000
New Zealand 2017 CCSBT Area 5	17.8 %	93 %	40 %	56 %	≈280
New Zealand 2017 CCSBT Area 6	22.7 %	99 %	63 %	87 %	≈30
New Zealand 2018 CCSBT Area 5	17.1 %	98 %	39 %	62 %	≈320
New Zealand 2018 CCSBT Area 6	17.2 %	100 %	59 %	63 %	<50
Korea 2017 CCSBT Area 9	18.2 %	0.5 %	1.5 %	21 %	≈850
Fishing Entity of Taiwan 2019 WCPFC S. of 30°S	6.0 %	63 %	11 %	41 %	≈2200
Fishing Entity of Taiwan 2020 WCPFC S. of 30°S	5.0 %	57 %	15 %	47 %	≈2500
Japan 2019 WCPFC S. of 30S	17.9 %	33 %[**]	1 %	6 %	≈1500
Japan 2020 WCPFC S. of 30°S	5.5 %	53 %	7 %	62 %	≈1000
New Zealand 2019 WCPFC S. of 30°S	8.4 %	97 %	39 %	59 %	≈250
New Zealand 2020 WCPFC S. of 30°S	9.9 %	92 %	58 %	76 %	≈250

[*] (Annual Report of New Zealand: Report to the Ecologically Related Species Working Group., 2019; National Report of Taiwan: Ecologically Related Species in the Taiwanese Southern Bluefin Tuna Fishery 2016–2017, 2019; Ochi et al., 2019; Patterson et al., 2019; Satoh et al., 2021; Uosaki et al., n.d.)

[**] Japanese vessels report using a combination of bird-scaring lines and night-setting up until one hour before dawn, before switching to a combination of bird-scaring lines and weighted lines mid-set. Thus, observers may report sets partially at night as being compliant with night setting.

2.2. *Training a neural net to predict sets*

Once we had tracks labeled as setting, hauling, and other, we trained a transformer based (Vaswani et al., 2017) model (Fig. S2), a type of neural network, to segment vessel tracks into regions of *setting*, *hauling*, and *other*. To train this network, we linearly interpolated vessel tracks between points so that there was one position every 5 min, and the model made a prediction for every 5 min period about whether the vessel was engaged in setting, hauling, or other. For each 5 min period, the model was provided with the x and y location, time, course, and speed. The details of the neural network, with a diagram of its architecture (Fig. S2) and justification, are provided in the supplementary materials. To turn predictions at each position into coherent sets with a start and end time, we applied a combination of Gaussian smoothing and morphological closing, as described in the supplemental materials. The result is a dataset of longline sets with a start time, end time, and location for each set.

2.3. *Determining night and day setting*

We used the *suncalc* R package (Thieurmel and Elmarhraoui, 2019) to determine whether each 5 min segment was at night, between nautical dawn (when the center of the sun rises below 12° below the horizon) and sunrise (dawn), between sunrise and sunset (day), or between sunset and nautical dusk (when the center of the sun drops below 12° below the horizon). We then categorized sets whether they were mostly at night or day, and whether they overlapped with dawn or dusk.

2.4. *Assessing model accuracy*

To assess the accuracy of the model, we created a test set by labeling one day of activity from 100 different vessels. For each region of interest, 20 pseudo random day and vessel combinations were selected. These sections of track were manually labeled to create the ground truth. Each predicted set within the selected days was checked for overlap with the ground truth sets. If there was overlap between a predicted set and a ground truth set, this was recorded as a true positive (TP). Predicted sets for which there were no overlapping ground truth sets were recorded as false positives (FP). Ground truth sets for which there were no overlapping predicted sets were recorded as false negatives (FN). Recall, computed as TP / (TP + FN) was 90 % and precision, computed as TP / (TP + FP), was 98 %. The precision and recall for each region were mostly consistent with these results. This result suggests that our model is conservative; we may actually be missing some sets from vessels, but the sets that are identified are likely done so correctly.

We also validated our dataset by comparing the number of sets to the estimated number of hooks set by longlines in the Regional Fisheries Management Organizations. Data on hooks by RFMO was downloaded from each RFMO's website, except for ICCAT, which was obtained from direct correspondence. To determine if our dataset on longline sets was representative of all longline activity, we compared our longline set data from AIS with hooks reported to the tRFMOs. Fishing effort using longlines is typically reported by Flag States to tRFMOs as the aggregate number of hooks deployed in an area. Dividing the number of reported hooks reported between 2017 and 2019 by the number of detected longline sets yielded a ratio of ≈3300 hooks per set. This ratio is higher than the actual number of hooks per set, on average, largely because we detect longlines set by vessels that transmit AIS, and an unknown number of vessels are not broadcasting AIS. Nonetheless, although the number of hooks per set varies by vessel and set, it typically ranges between 1000 and 4000 hooks per set (Bigelow et al., 2006; Dunn et al., 2008; Nieblas et al., 2019). Given our ratio is in this range, it suggests that our model has likely captured a large proportion, if not the majority, of longline activity within our regions of interest.

The average duration of a set in our data (6.5 ± 1.5 h) corresponds well to published literature on set times (Gandini and Frere, 2012; Melvin et al., 2013; Tuck et al., 2003), and it shows no significant bias in predicting the start and end times. Our set model, though, does have uncertainty over the exact start and end time of sets, which is sometimes a result of intermittent satellite AIS coverage. We found that >75 % of our modeled sets started and ended within 2 h of the actual start and end. The errors in start time and end time are symmetrical, such that it is unlikely that in the aggregate we are systematically predicting sets too early or too late. Nonetheless, although we do not think our model is biased to over or undercount set time, and the mean set time in the model (6 h) is consistent with literature (Brothers, 1991), we reran our results by cutting off an hour at the start and end of the set, thus including only the times of the sets where we are most confident that the vessel is setting.

To further test the robustness of our model, we obtained VMS data from the government of Brazil for drifting longlines, and associated logbook data for 25 vessels, with set start and end times included. This data was obtained through Global Fishing Watch's partnership with the Brazilian government. We applied our model to this VMS data, which provides the same fields as AIS (GPS position, timestamp, speed, course), but with one position every 20 min. We could not measure precision and accuracy because the logbook data did not record every set. As a result, sets labeled that are identified in our model but which are missing in the logbook data are often mostly true sets and not false positives. We could, though, measure recall, and out of 855 sets in logbook data, 169 were not identified by the model, giving a recall of 80 %, suggesting that sets may be undercounted by the model. The start and end times of the remaining 686 sets, though, were accurately estimated, especially in the aggregate. The mean start time of the model was, on average, 2 min earlier than reported set time, and 8 min earlier than the reported end time. The standard deviation of the difference of start time and end time was 1.8 and 1.7 h, respectively. Thus, while individual sets may have predicted set and end times that are inaccurate, in the aggregate the model appears to be very accurate at estimating start and end times of sets.

2.5. *Selecting areas of interest*

Once we had developed and validated a model, we analyzed the start and end times of sets within albatross habitat and within a few regions of the world with specific regulations on night setting. The ranges of key albatross species were drawn from Birdlife International's database of species distributions (BirdLife Data Zone, 2022). We selected four regions based on regulations for Regional Fisheries Management Organizations. These regions included:

- S. Pacific (south of 30°S in the WCPFC convention area) and N. Pacific (areas north of 23°N). These areas were selected because the Western and Central Pacific Fisheries Commission (WCPFC) requires one measure from a choice of branch line weighting or bird-scaring line between 25°S and 30°S, and a choice of two of three measures including, bird-scaring line, weighted lines, and night setting or an additional stand-alone option of using hook shielding devices south of 30°S. In the North Pacific, WCPFC requires the use of two mitigation measures from a wider list including night setting.
- S. Atlantic (south of 25°S). The International Commission for the Conservation of Atlantic Tuna (ICCAT) requires vessels to adopt two of the following three measures south of 30°S in the Atlantic Ocean: night setting, bird-scaring lines, or weighted lines.
- S. Indian (south of 25°S). The Indian Ocean Tuna Commission (IOTC), similar to ICCAT in the Atlantic, requires vessels to adopt two of the following three measures south of 30°S in the Indian Ocean: night setting, bird-scaring lines, or weighted lines.

Also, the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) requires Members to follow the requirements of overlapping RFMOs (Commission for the Conservation of Southern Bluefin Tuna

(CCSBT), n.d.).

3. Results

For the period between January 2017 and December 2020, we classified 1,451,159 sets globally from 4923 vessels. On any given day (one day shown in Fig. 1a), there were around 1000 (997 ± 125) sets in the global ocean by vessels broadcasting AIS. Albatross with radio tags have redirected towards fishing vessels up to 30 km away, suggesting that they can detect fishing vessels at this distance, which is also the limit of their visual range (Collet et al., 2015, 2017). Considering this range, we measured the area of the ocean within 30 km of a setting longline during the night, dawn, day, and dusk. We find that on an average day, about 5.3 million km^2, or about 1.5 % of the ocean, is within 30 km of a set, and this number varied between 3.1 and 6.5 million km^2 for different days in our four year time period. Over the course of a year, about 146 million km^2, or over 40 % of the ocean, is within this distance of a set, and 38 %, or 137 million km^2 is within this distance to a vessel setting during the day. The global map of longline fishing also shows that the activity is constrained by political boundaries, with many exclusive economic zones, with different regulations, not allowing some of the major fleets to operate (the mostly empty circles, representing exclusive economic zones around islands, in all ocean basins, as well as the coastal waters of many continents, Fig. 2).

Globally, the most common time to start a set is in the hour before sunrise (Fig. 3c), with almost half of the sets overlapping with the time between nautical dawn (when the geometric center of the sun is 12° below the horizon) and sunrise (Fig. 1b shows sets that start before dawn and finish during the day). Sets that were mostly during the day were far more common than sets that were mostly at night (Fig. 3b), with sets entirely at night accounting for only 3.1 % of sets globally. Performing our sensitivity analysis where we start each set an hour later and end it an hour earlier – thus accounting for potential errors in start and end times in our model – the fraction of sets entirely at night increases to only 5.3 %.

Setting entirely during the night is more common in the regions with seabird conservation management measures (blue boxes in Figs. 1 and 2), but it still accounts for just 5.5 % of the total sets. In these regions with night setting recommendations, the most common time to start setting is a few hours earlier than the global average, with sets most

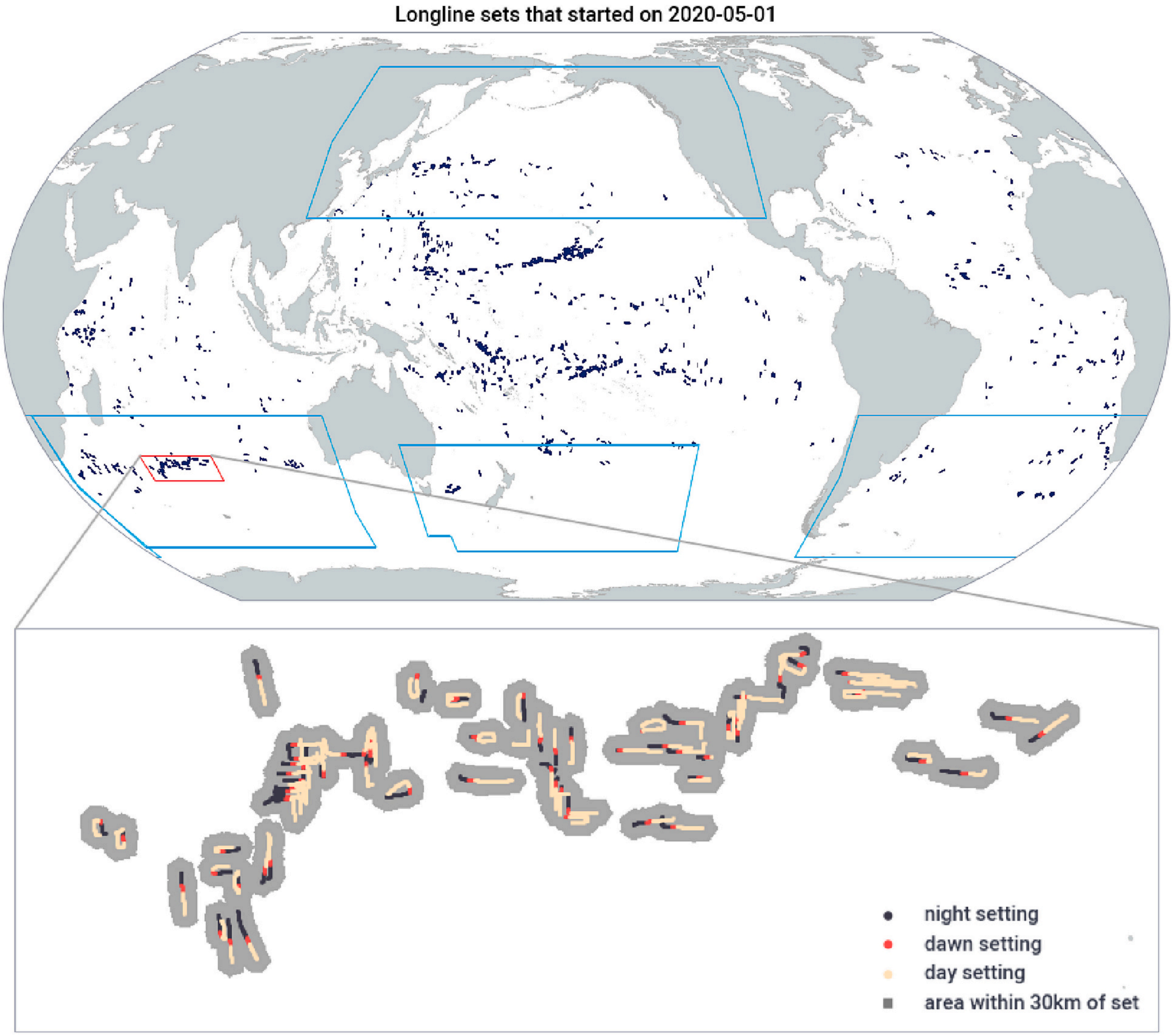

Fig. 1. (a) One day of longline sets in the global ocean. Bounding boxes represent regions with tRFMO regulations: South Indian Ocean, North Pacific, South Pacific, and South Atlantic. Shown are all longline sets (1166 sets) that started on 1 May 2020. (b) A zoomed in region (red box on a) shows 75 sets and the time of day of the different parts of the set (night, dawn, day — for these sets there was no overlap with dusk). In this region, virtually all sets started before dawn and continued into the day. The area within 30 km of the set, the distance an albatross can detect a vessel, is shown in gray. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

commonly starting 3 to 4 h before sunrise (Fig. 3f, i, l, o). Because most sets are longer than 3 h, however, and because nautical dawn usually starts >40 min before sunrise, most of these sets overlap with the dawn hour.

The number of longline sets, globally, is extremely constant over the study period, with about 1000 sets/day. In the northern and southern oceans, there is a strong seasonal variation (Fig. 3d, g, j, m), which is especially strong in the southern oceans, where fishing is concentrated in the austral autumn/fall and winter. In the South Pacific, in 2020 there was a marked increase in night setting and number of sets that were entirely at night. Otherwise, the fraction of day and night setting is relatively unchanged between years.

These patterns of setting longlines are a threat to endangered and threatened albatrosses. In a given year, the fraction of an albatross' range within 30 km of a longline set varied from 7 % of the range for the Southern royal albatross (*Diomedea epomophora*), whose range is farther south than most longline activity, to 65 % for Amsterdam albatross (*Diomedea amsterdamensis*), whose range is in areas of intensive longlining in the southern Indian Ocean. In every species' range, there were a few tens of thousands of sets per year between 2017 and 2020. For all but one of 14 species that have a range of greater than 5 million km^2 and that are listed as Vulnerable, Endangered, or Critically Endangered by the IUCN, the majority of sets overlapped with dawn, and in none of the ranges was the fraction of night sets >7 % (Fig. 4).

Comparing our findings with onboard observer data on night setting is limited to available data reported to WCPFC and CCSBT. The CCSBT requires Members to report levels of night setting in their longline fleets, and data are available for 2017 and 2018 for some fleets. Also, in 2019 and 2020, in areas where mitigation measures are required, member States to the WCPFC began reporting the fraction of their fishing effort that uses night setting (previously they were required to report night setting rates for all ocean areas, meaning that it was not possible to check compliance with mitigation measures). Although all Members are supposed to submit data, our review of the public documents published by the WCPFC revealed that, according to onboard observers, only three Members, the Fishing Entity of Taiwan, Japan, and New Zealand complied. Also, because onboard observers observe only a fraction of the fishing effort (usually <10 %), these reported numbers may not be representative of the entire fleet.

Nonetheless, the reported amount of night setting is far higher than revealed by our AIS analysis, with the possible exception of Japan in 2020 (the 2020 observer data, however, are less reliable than for previous years because fewer observers were available due to the COVID-19 pandemic). The Fishing Entity of Taiwan, for example, reported that 57–95 % of its observed fishing effort from 2017 to 2020 was conducted using night setting, i.e., 57–95 % of hooks were set at night. Our algorithm, however, suggests that only 1.4–15 % of sets were done entirely at night, and only about 3–47 % of sets overlapped more with night than daytime (Table 1). For Japan in 2019 and 2020 (the years that data are reported for South of 30°S), night setting was reported on 33 % and 53 % of hooks respectively, while our algorithm shows only 1 % and 7 % of sets were entirely at night. However, this discrepancy could be explained by the fact that Japanese vessels report using a combination of bird-scaring lines and night-setting up until 1 h before dawn, before switching to a combination of bird-scaring lines and weighted lines mid-set. Our algorithm does show that some Member States do have higher

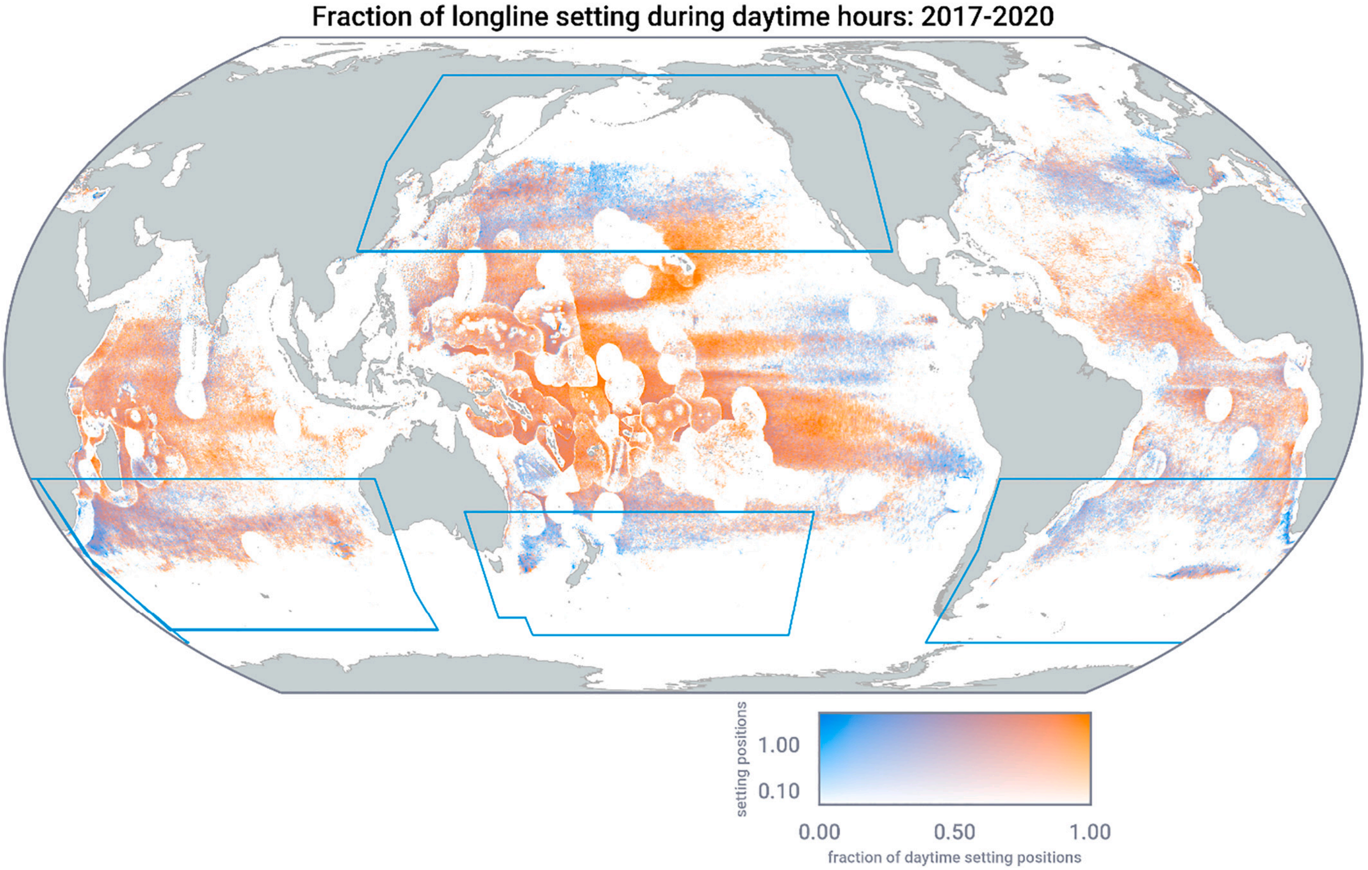

Fig. 2. Day setting dominates almost everywhere in the ocean. Blue areas indicate that most setting happens at night, and orange indicates that most setting happens during the day. Bounding boxes represent regions with tRFMO regulations in the South Indian Ocean, North Pacific, South Pacific, and South Atlantic. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

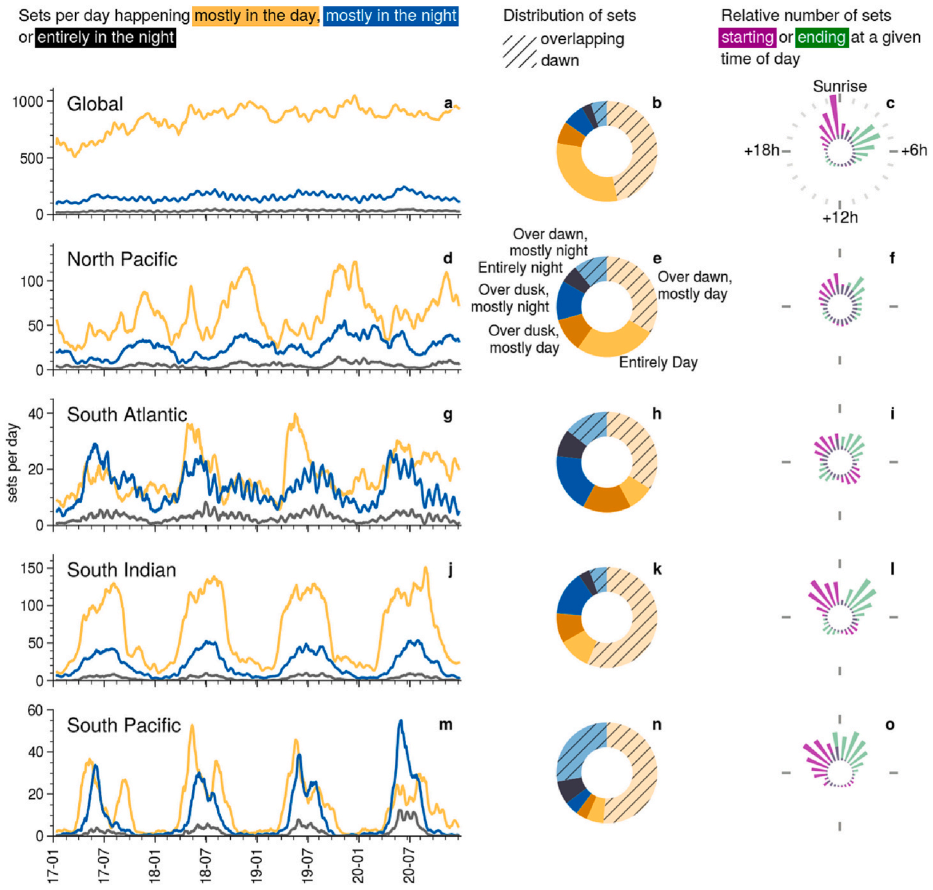

Fig. 3. Day setting and setting during dawn are common both globally and in each region. The number of sets by region that are mostly during the day, mostly at night, and entirely at night show seasonal patterns in each region (a, d, g, j, m). Globally (b), and in all regions except the North Pacific (e, h, k, n), the majority of the sets overlap with nautical dawn (hatched marks), with the most common sets being those that overlap with the dawn but are mostly during daytime hours. The most common times to start in every region (red bars in c, f, i, l, o) are the hours before sunrise, with most sets ending a few hours after sunrise (green bars). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

rates of complete night setting, such as New Zealand, who set 39–63 % of sets entirely at night in 2017–2018; their observer data, however, showed much higher night setting rates for the same period, 93–100 %.

4. Discussion

This study reveals, for the first time, the extremely large global footprint of longline sets and the global prevalence of daytime setting. In a given year, the area within 30 km of a longline set is comparable to the entire land area of earth, about 140 million km^2, and throughout the majority of this area longlines are set mostly during the day. Given that many seabirds, and particularly albatross, can travel tens of thousands of miles at sea in a given year (Carneiro et al., 2020; Clay et al., 2016; Croxall et al., 2005; Weimerskirch et al., 2015), and that 7–65 % of the ranges of Endangered and Threatened albatross species overlap with areas within 30 km of a daytime longline set, it seems likely that birds will frequently encounter longlines as they are being set.

This study also reveals a global preference for setting longlines over the dawn period, when many seabirds are most active. In all regions with mitigation requirements and for the ranges of all assessed albatross species, the most common time to start a set was before dawn or at sunrise and the most likely time to end was after sunrise. This preference may reflect that target species are easier to catch at this time of day (Løkkeborg and Pina, 1997; Melvin et al., 1999; Murray et al., 1993), but this timing is concerning for albatross conservation. During the day, albatross fly in search of prey, relying on their visual and olfactory senses to find food (Nevitt et al., 2008; Weimerskirch et al., 1997). At night, when prey are harder to detect visually and diel vertical migration results in a higher concentration of prey near the water's surface, the more optimal foraging strategy may be to rest on the water's surface and forage opportunistically (Phalan et al., 2007; Weimerskirch et al., 1997). At dawn, however, when “foraging-in-flight” again becomes the optimal strategy, albatross will take flight to forage on the high concentration of prey still available at the water's surface (Phalan et al., 2007; Weimerskirch et al., 1997). This foraging pattern results in a peak in albatross flight activity over dawn (Pajot et al., 2021; Phalan et al., 2007). According to our data, setting over dawn is more common in regions of albatross habitat than outside these regions. It appears that in these regions sets usually start a few hours earlier (Fig. 3f, i, l, o versus c), with most sets starting before sunrise and continuing into the dawn hour. The result is that although there is more setting at night in these regions, which should decrease bycatch risk, there is also more setting over dawn, which will likely increase it. More research is needed to know how this shift might affect overall bycatch risk.

There may be several reasons why few vessels have adopted complete night-setting as a bycatch mitigation measure. Fishers may believe it is too costly or inconvenient to change setting practices. These fleets are often operating at the edge of profitability or are even losing money (Sala et al., 2018). If night setting is perceived to reduce catch and profitability, this financial pressure may create a barrier to higher adoption by the fleets. Indeed, some fishers believe that night setting reduces target catch, and night-setting also raises concerns over crew safety (Melvin et al., 2014). Another barrier is that individual captains may not have a say in setting times, because vessels often set in groups,

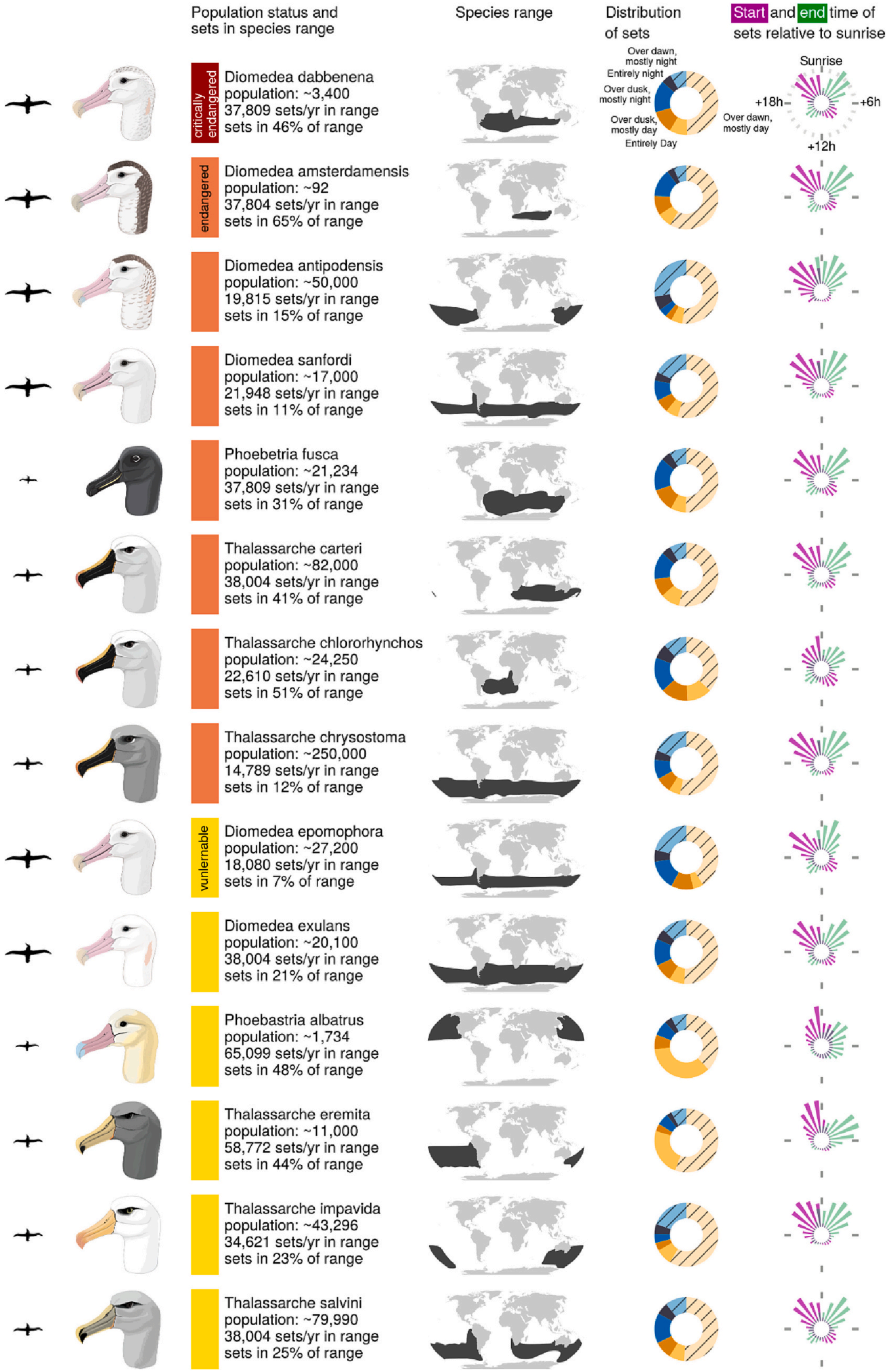

Fig. 4. The ranges (column 2) of vulnerable, endangered, or critically endangered albatross species overlap extensively with longline sets. For all except one species (*Phoebastria albatrus*), the majority of sets overlap with dawn (hatched lines, column 3). The start and end time of sets in the species' range (column 4) reveals the strong preference to start before dawn and finish in the day, overlapping dawn when albatrosses are most vulnerable. Column 1 shows relative bird size. Only species that have a range of greater than 5 million km^2 are shown.

as can be seen in Fig. 1b, where all the longlines appear to be set at the same time of day; setting in groups may reduce the chance of interference with one another. Because of these costs, fishers may instead be turning to other methods to mitigate seabird bycatch, including bird-scaring lines or line weighting.

Perhaps most importantly, this study highlights the need for more comprehensive and economic ways to monitor compliance with regulations to reduce seabird bycatch. Existing methods that rely on onboard observers are not sufficient because they likely overestimate compliance; our method, which likely covers a majority of the fleet, suggests that night setting is about one third as common as is reported by observers (Table 1). This difference could be due to misreporting, technicalities in how effort is recorded by observers, or, more likely, because vessels with observers behave differently than those without (Benoît and Allard, 2009; Burns and Kerr, 2008; Hurtubise et al., 2020). The sampling of vessels with observers may also be biased because logistical constraints limit which vessels have observers.

Unfortunately, this discrepancy between reported and actual night setting also raises the question of how well other mitigation measures are being followed, as vessels have incentives to not follow those regulations. Bird-scaring lines, for example, can become entangled with longline floats or the mainline. Line weights are perceived by some fishers to reduce target catch because the weights make the bait look ‘dead.’ And some types of weighted lines may increase the risk of injury to crew during hauling. Onboard monitoring can give compliance rates only if far more observers are used.

Observers cannot be entirely replaced by these methods, but the methods outlined here can estimate the levels of compliance of the fleets. Moreover, even more comprehensive monitoring by satellite may be possible because the methods outlined here could also be easily applied to GPS data from vessel monitoring systems (VMS), which are on more of the longline fleet than AIS. These GPS based algorithms could also complement onboard electronic monitoring, which can include cameras and other sensors to monitor vessel activity, and which can provide more detailed information about a vessel's behavior and catch (Brown et al., 2021; Gilman et al., 2020).

As many seabird populations continue to decline due to bycatch in longline fisheries, existing and newly developed mitigation measures, including night-setting, have the potential to save thousands of seabirds. The effectiveness of these technical solutions, however, depends on the design and correct deployment of mitigation measures. Without effective reporting, it is impossible to understand the uptake of these measures across the global longline fleets. As this study shows, monitoring 10 % or less of vessels is unlikely to provide effective reporting – and this problem is unlikely to improve as Members of tRFMOs have struggled to recruit and train observers, and, during the COVID19 pandemic, observer coverage has declined, to zero in some regions. Algorithms applied to GPS tracking offer an avenue to verify wider compliance. Such compliance is necessary if these fisheries are to stay productive while also protecting these declining populations of seabirds.

CRediT authorship contribution statement

All authors contributed to the study Conceptualization, Writing, Review, and Editing. Writing of initial draft by SP, DK, and CL. Study Methodology was conducted by DK, JT, TH, and NAM. Validation and Data curation by PA, DK, NAM, SP. Longline model development by TH and JT. Visualization by JT and DK. Supervision by DK. Funding acquisition by SP.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Code and most data are available at the github repository https://github.com/GlobalFishingWatch/paper-global-longline-sets. AIS data available for purchase from satellite companies Orbcomm and Spire.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110026.

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