

# Minimum drift times infer trajectories of ghost nets found in the Maldives.

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## Abstract

This study explores methods to estimate minimum drift times of ghost nets found in the Maldives with the aim of identifying a putative origin. We highlight that percentage cover of biofouling organisms and capitulum length of *Lepas anatifera* are two methods that provide these estimates. Eight ghost nets were collected in the Maldives and estimated drift times ranged between 7.5 to 101 days. Additionally, Lagrangian simulations identified drift trajectories of 326 historical ghost nets records. Purse seine and gill nets are found to fisheries that overlap ghost net drift trajectories between 30 and 120 days. However, ghost nets below 30 days remain inside the exclusive economic zone of the Maldivian archipelago highlighting potential illegal, unreported and unregulated fishing activity. This study highlights the urgent need for gear loss reporting by purse seine and gill net fisheries and improved data on spatial distribution in the area from large- and small-scale fisheries.

## Keywords

Ghost nets, Lagrangian, Purse seine, Gill nets, Biofouling, drift trajectories

## 1. Introduction

Abandoned, lost or discarded fishing gear (ALDFG) also known as ‘ghost gear’ has been widely recognised as one of the most important components of debris in our oceans (Watter et al. 2010; Hardesty et al. 2015; Stelfox et al. 2016; Wilcox et al. 2016; Consoli et al. 2018;

Miller et al. 2018). Historically, the majority of fishing gear was made from natural materials such as cotton, coconut or hemp. Therefore, they would have had a relatively short lifespan even when lost or abandoned. However, starting in the late 1940s and, early 50s these materials were replaced with synthetics, extending their lifetime substantially (von Brandt 1984). Now, when nets are abandoned, lost or discarded they often become locked in ocean gyres or travel great distances, crossing political borders before eventually becoming stranded or found in more nearshore habitats like coastal coral reefs (Matsuoka, 2005; Stelfox et al. 2015). Management decisions on this issue are often challenging as ‘ownership’ of the gear is often unknown and difficult to backtrack.

Large quantities of ghost gear have been reported in the Maldivian archipelago (Stelfox *et al.*, 2015), despite commercial application of pole and line for catching tuna and subsistence hand line methods dominating the fisheries in the Indian Ocean island state (Adam et al. 2015). Understanding where ALDFG are coming from would be a first step to tackling the issue and reducing the threat to marine life. To date, broad classifications of the possible fisheries responsible have been identified by statistically modelling ghost net characteristics and attempting to assign them to a specific fishery (Wilcox et al. 2013). However, aging the floating nets to provide time adrift, and analysing drifting trajectories using ocean current simulations in combination with the spatial distribution of fisheries should bring us closer to identifying their origins.

There are a number of ways of monitoring and obtaining drift times of floating debris. The assessment of fouling organisms on debris has become routine (Hellio et al. 2004; Banerjee et al. 2011; Callow et al. 2011; Kiessling et al. 2015; Fazey et al. 2016). Typically, active fishing gear is cleaned between trips, effectively minimising damage and increasing longevity and catch efficiency (Pers. Obs.). Biological growth on the surface of nets would thereby act as a ‘biological clock’ indicating how long they have been in water since they were last cleaned. Indeed, the succession of certain species or taxa and their respective growth rates have been shown to age other types of marine debris (Ye et al. 1991). In particular, diatoms and barnacles may be useful indicator groups to assess drift as they are prevalent across all oceans and are major biofouling organisms on all types of litter including nets (Saldanha et al. 2003; Magni et al. 2015). The majority of research has, to date, focused on ways of removing biofouling or preventing settlement in the first instance (Hellio et al. 2004; Banerjee et al. 2011; Callow et al. 2011). This is because biofouling can reduce efficiency on floating wave energy devices (Nall et al. 2017), block water intake pipes (Rajagopal & Jenner 2012) for example, as well as

adding weight to fixed structures (Shi et al. 2012), and increasing drag and subsequent fuel consumption in marine vessels (Schultz, 2007).

Another approach commonly utilised to predict the origin of marine litter (e.g. plastics) is the use of ocean current data (Lebreton et al. 2012; Maximenko et al. 2012; Liubartseva et al. 2016; Guerrini et al. 2019; Jalón-Rojas et al. 2019). The Maldives lies north south perpendicular to an east west current system (Shankar et al. 2002). During the northeast (NE) monsoon, surface currents approaching the islands originate from the Bay of Bengal whereas during the southwest (SW) monsoon they approach from the Arabian Sea. However, ocean circulation is complex, and currents vary not only seasonally, but in response to short term events like tropical cyclones and between years depending on pan-tropical atmospheric-ocean forcing related to phenomena like the El Niño Southern Oscillation and the Indian Ocean Dipole (Schott et al. 2009). This means broad generalisation is not always appropriate when analysing the dispersal of objects (Wood et al. 2016).

In this study, we attempted to assess the origin of ghost gear found within the Maldivian archipelago using a multipronged approach. First, we experimentally deployed nets to quantify the development and growth rates of biofouling organisms in order to estimate time adrift. Measurements included diatom population and taxonomy and percentage cover of all fouling organisms. Additionally, we deployed surface buoys to analyse growth rates of a common biofouling organism, the pelagic gooseneck barnacle (*Lepas anatifera*). Secondly, we applied these age estimate techniques to eight ghost nets found floating in the Maldives and backtracked the nets (based on these age estimates) using a Lagrangian model to find their putative origin. Additionally, a historical, larger dataset of 326 recovered ghost nets with reported times and locations of recovery in Maldivian waters but without estimates of their drift durations. For these nets, we used the Lagrangian model to backtrack their putative origin using several plausible values of drift duration (10, 30, 60, 90 and 120 days), in order to identify potential points of origin and the fisheries responsible for the deployments.

## **2. Methods and materials**

### *2.1. Experimental assessment of bioaccumulation on floating nets and buoys*

Diatom diversity and biofouling percentage cover were assessed on newly deployed, high-density polypropylene (HDPP), multifilament fishing nets (supplied by Garware Wall Ropes

Ltd). This study was conducted at the Dhuni Kholu resort, in Baa atoll, Maldives (5° 2'27.17"N, 72°53'4.01"E). A single net was divided into three separate replicate fragments (100cm X 100cm size). Two fishing buoys were attached to the sea floor, 18 m above and 20 m away from the sloping reef. The two buoys were fixed by a further rope on the surface (Supplementary material S1a). The nets were attached to the line with zip ties that were first coated with antifouling paint to minimise cross contamination. Each repeat (net) was arranged so that no direct contact could be made between replicates (Supplementary material S1b). The nets were sub-sampled (ensuring the knot and twine either side was included – Supplementary material S2) on day two, four, six, eight and ten, then every two weeks thereafter up until 112 days.

Samples were placed immediately in 2.5% glutaraldehyde and stored in a fridge until further sample preparation and analysis. Samples were then dehydrated via a series of 60, 75, 85, 95 and 100% absolute ethanol for 15 minutes each, with final dehydration consisting of air drying for 1 hr. Specimens were then mounted on an aluminium stub with Achesons Silver Dag (dried overnight) and coated with gold (standard 15nm) using an Emi Tech K550X Sputter Coating Unit. Specimens were then examined using a Stereoscan 240 scanning electron microscope, and digital images collected by Orion 6.60.6 software. Scanning electron micrographs (at a magnification of 1500 X) were taken along a 0.1 mm<sup>2</sup> transect in the middle of the twine and 0.1 mm<sup>2</sup> transect along the centre of the knot. We assessed each micrograph for diatoms, which were identified to the lowest taxonomic or morphological level. Diatoms that fell outside the transect frame or not attached to the net itself (i.e. likely associated with the surrounding water column) were excluded from the analyses. Moreover, diatoms that could not be identified due to partial loss of structure were also excluded. We then calculated commonly used diversity indices such as species richness (*S*), total abundance, Shannon-Wiener diversity index (*H*, Shannon & Weaver 1949), Simpson index (*D*, Simpson 1949) and the Pielou evenness index (*J*, Pielou 1966). These indices allowed us to explore species rarity, abundance and distribution for each time interval to identify patterns over time. We also opportunistically recorded additional organisms of note, in order to capture any successional changes of other biota communities over time. However, these were excluded from diversity analyses due to the difficulty in distinguishing between background noise (which may include filamentous algae, mucilage, encrusting communities and/or the high abundance of bacteria that would skew diversity indices for example). That said, we did combine diatom and other opportunistically recorded organism counts to perform a Z score hierarchical clustering using Euclidean distance

measure where each row (organism or species) was scaled before analyses using heatmap.2 function in gplot (Warnes et al. 2014). This allowed for a visual representation of community succession.

Alongside diversity indices, percentage cover of all biota growing on the surface of the net was calculated. To do this, three scanning electron micrographs along each transect (as mentioned above) were imaged to give a 0.03 mm<sup>2</sup> surface area per micrograph (six micrographs per sample, knot and twine). Images were then inputted into the digital imaging software, ImageJ (Schneider et al. 2012). The threshold of each micrograph was manually adjusted until attached biota were highlighted in red to estimate percentage cover. In rare cases, salt crystals were present on the surface however, these were excluded from all analyses and I assumed no growth under the crystal. Due to contrast and brightness variations in some images not all of the biota was captured by the threshold adjustments and in some instances, threshold only captured a small proportion of the visible surface growth. In such cases, the paintbrush tool was used to manually highlight the cover.

The growth rate of gooseneck barnacles (*Lepas anatifera*) was measured in a separate experiment at the Bodu Hithi resort, North Male atoll, Maldives (4°25'41.18"N, 73°23'7.70"E). Three surface buoys, on a fixed line 20 m away from the sloping reef, 18 m above the sea floor were deployed. When biofouling had occurred, 30 gooseneck barnacles (10 for each of the three replicates/buoys) were identified and their growth rates estimated (capitulum length (mm) measured from the apex to base (Supplementary material S3) with a ruler. In addition, when possible digital images were also taken in order to obtain more accurate sizes using image J digital software (Schneider et al. 2012). Measurements were taken once every seven days for a total of 105 days. All analyses were conducted in the statistical programming language R vs 3.4.2 (R Core Team, 2018).

## 2.2. Ghost net data

Drifting ghost nets were collected opportunistically by biologists on board a turtle expedition conducted by the Olive Ridley Project on two separate occasions; November 2017 and February 2019. In 2017 independent nets ( $n = 5$ ) were immediately stored in 2.5% glutaraldehyde, while due to limitations in the field in 2019 samples could not be fixed on site and only nets found with barnacles were recorded ( $n = 3$ ). We applied the analyses detailed above to estimate drift times of these nets.

Stranded ghost nets have been recorded by the Olive Ridley Project in 326 incidents occurring in Maldivian waters between 2013 and 2018 ( $n = 149$  from the NE monsoon and  $n = 177$  from the SW monsoon) with reported times and locations of recovery but not their age. All nets reported in this analysis were of twisted construction and made from HDPP.

### 2.3. Lagrangian modelling

To explore where ghost nets found in the Maldives may have come from, we used the final net location to backtrack possible origins. This was done using the offline Lagrangian particle dispersal model Ichthyop (Lett *et al.*, 2008; <http://www.ichthyop.org/>), with diffusion activated following Peliz *et al.* (2017), and advection using the 2D hydrodynamic data from Ocean Surface Current Analysis Real-time (OSCAR, Lagerloef *et al.*, 1999; <http://www.oscar.noaa.gov>). OSCAR is a global current product derived from remote-sensing data and provided on a  $1/3^\circ$  grid with a 5-day resolution. It was evaluated in the tropical Indian Ocean by Sikhakolli *et al.* (2013).

We initially released 1,000 ‘particles’ at the same time and location as each of the 326 ghost nets found (326,000 particles in total). For the eight aged nets we released 10,000 particles (80,000 particles in total), we used the drift times estimated from the methods described before as the duration of the simulated backwards drift. For the 326 unaged nets, without any prior knowledge of their drift times a putative origin of all nets was estimated after running the models backwards in time for 10, 30, 60, 90 and 120 days. Plots were generated to illustrate the number of ‘particles’ per  $1/4^\circ$  squares for both 326 ghost nets and eight ghost net samples.

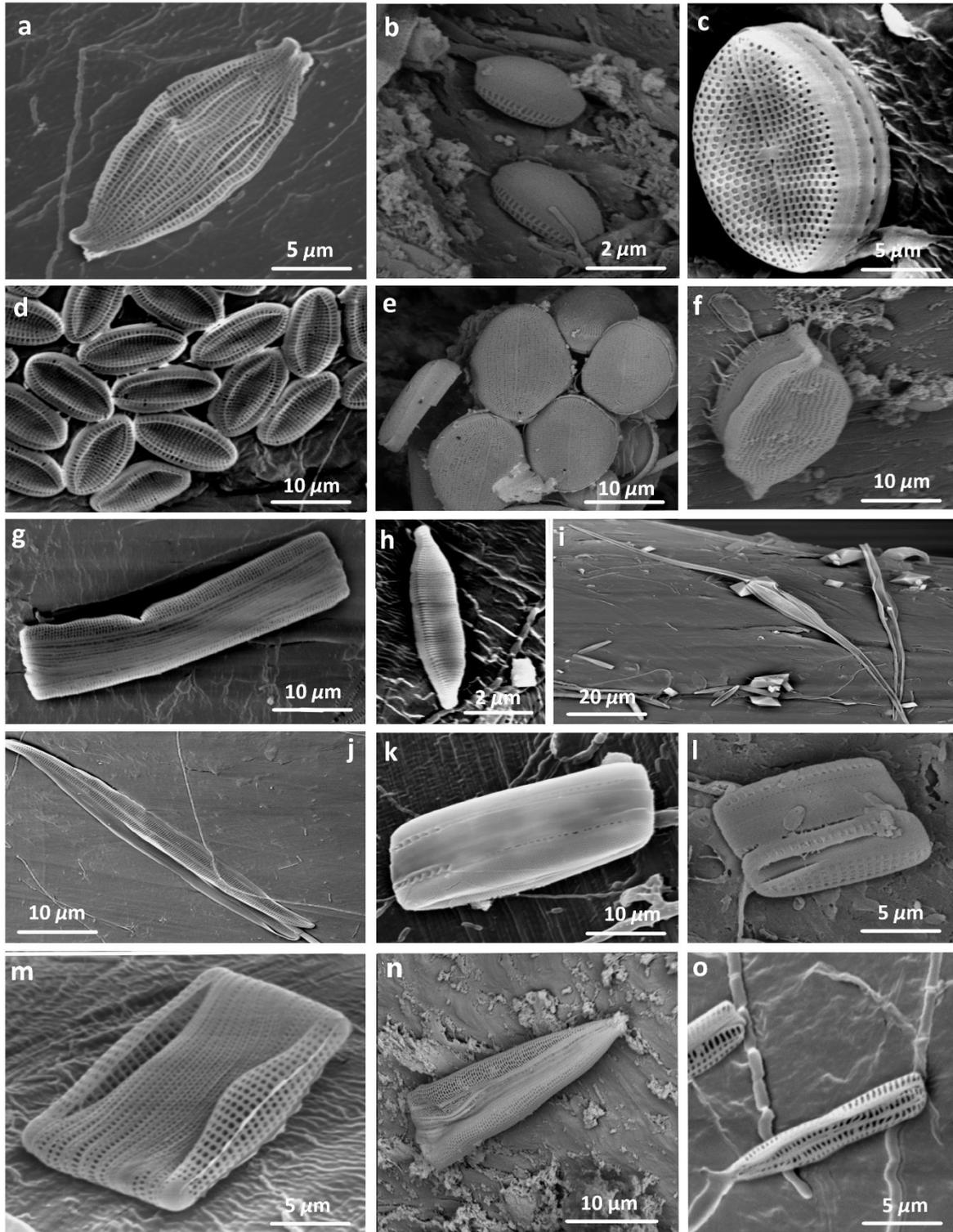
### 2.4. Fishery interaction

Data was utilised on the spatial distribution of operating fisheries reported to the Indian Ocean Tuna Commission (IOTC) at a  $1^\circ \times 1^\circ$  grid cell resolution to overlay fishing grounds onto our simulations of net origin. To do this, the grid codes from the Coordinating Working Party (CWP) of the Food and Agriculture Organisation (FAO) were converted into latitude and longitude coordinates by finding the centroid of each statistical grid. These were then layered onto the ‘particle’ distribution plots in QGIS to highlight fishery presence.

## 3. Results

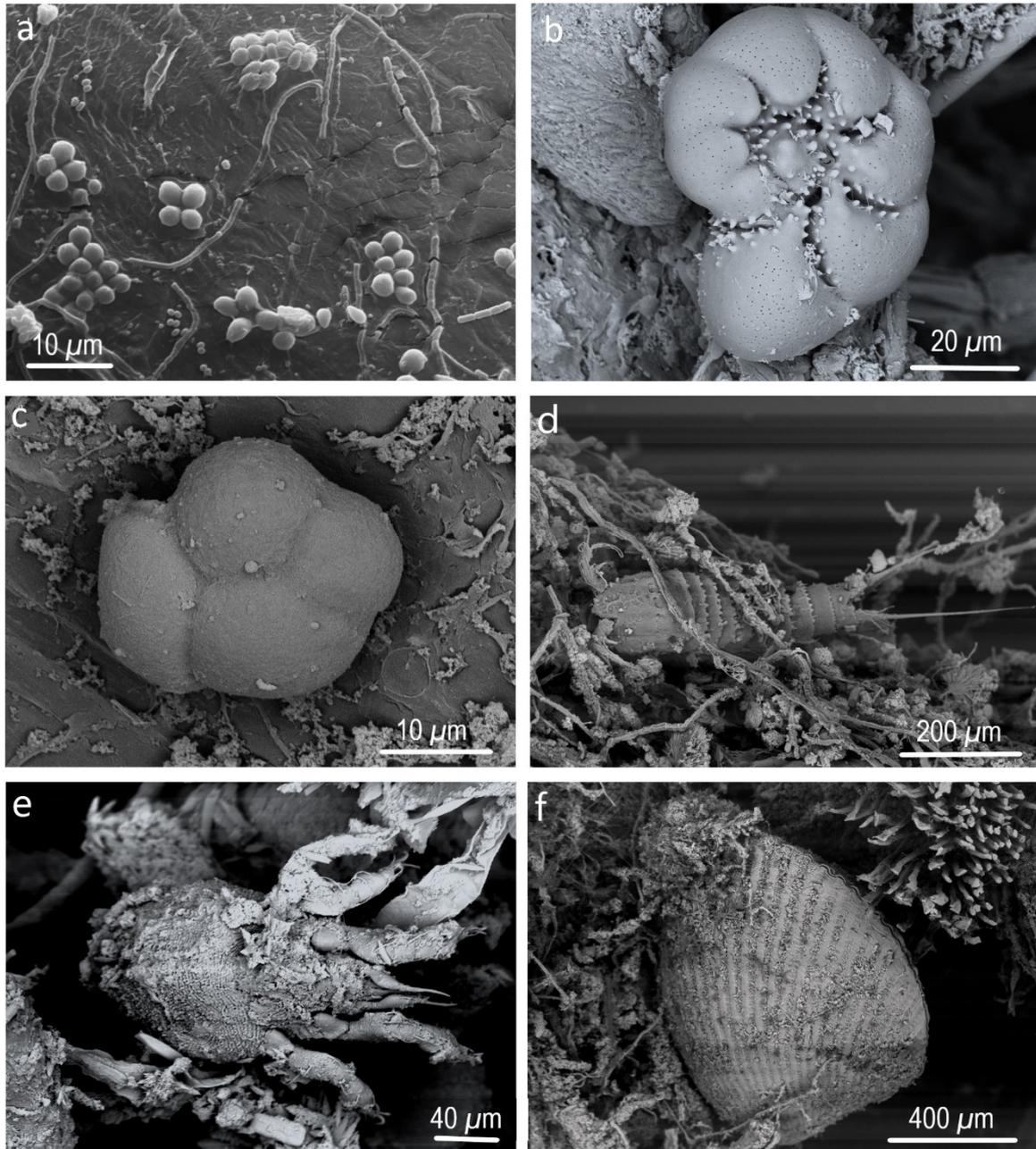
### 3.1. Experimental assessment of bioaccumulation on floating nets and buoys

Fifteen species of diatoms could be identified attached to the experimentally deployed nets at Baa Atoll, in the Maldives. These included two asymmetrical biraphid species from the genus *Amphora* (Fig. 3.1a,b), six monoraphid species (*Anorthoneis eurystoma*, two *Cocconeis* sp., *Achnanthes pseudobliqua*, *Achnanthes* sp., and *Fragilariopsis rhombica*; Fig. 1c-h). *Nitzschia longissima* (Fig. 3.1i) was also found, along with three symmetrical biraphid species (*Gyrosigma tenuissimum*, *Parlibellus delognei*, and *Delphineis* sp; Fig. 1j-l), a *Hyalosira* sp; (Fig. 1m), a *Licmophora* sp.; (Fig. 1n) and *Gomphonemopsis exigua* (Fig. 1o). Many diatoms were lying flat on the nets (i.e. valve or girdle face in contact with the net, both adnate and motile diatoms). However, some were observed to be erect and attached by peduncle or stalks. The genus *Amphora* was by far the most frequently encountered species recorded (65.6%), followed by the two *Cocconeis* spp. (8.9%), the *Licmophora* sp. (6.9%), the *Hyalosira* sp. (4.1%) and *Anorthoneis eurystoma* (2.9%). The remaining observed species accounted for less than 1% of total abundance. It should be noted that these may be an underestimation of the true abundance of species as some diatoms were positioned on the net showing only their girdle so could not be identified from this orientation (11.5%).



**Figure 1.** Diatoms found attached to the surface of fishing nets, a: *Amphora* sp. A; b: *Amphora* sp. B; c: *Anorthoneis eurystoma*; d: *Cocconeis* sp. A; e: *Cocconeis* sp. B; f: *Achnanthes pseudobliqua*; g: *Achnanthes* sp.; h: *Fragilariopsis rhombica*; i: *Nitzschia longissimi*; j: *Gyrosigma tenuissimum*; k: *Parlibellus delognei*; l: *Delphineis* sp.; m: *Hyalosira* sp.; n: *Licmophora* sp.; o: *Gomphonemopsis exigua*.

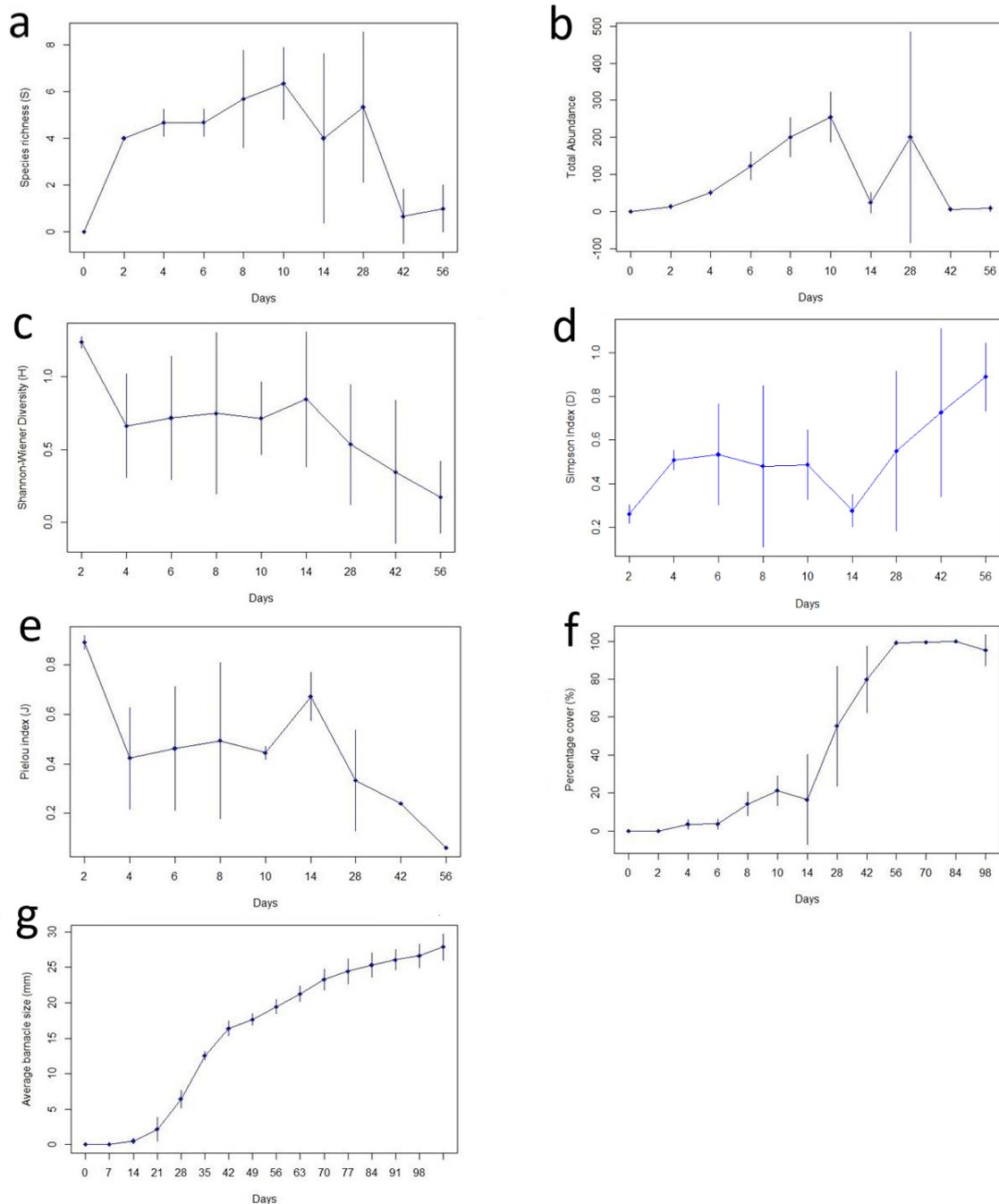
Unsurprisingly a large number of bacteria (Cocci shaped) appear on nets in the Maldives within 4 days and rapidly begin to colonise the surface; by number of individuals they are the most abundant fouling organisms (Fig. 2a). We also observed something encrusting at the same time, but this was not discernible under the scanning electron microscope. Other organisms including amoeboid protists (Foraminifera) such as an *Elphidium* sp., (Fig. 2b) and a *Foraminifera* sp. (Fig. 2c) started to colonise after 42 days and would be actively feeding on the diatoms. There were also several unidentified invertebrates, which were observed after this time point. These included an isopod (Fig. 2d), an unknown invertebrate (Fig. 2e) and a bivalve (Fig. 2f).



**Figure 2.** Rounded cells, Foraminifera and unknown crustaceans and invertebrates. a: bacteria (Cocci); b: *Elphidium* sp.; c: *Foraminifera* sp.; d: unidentified *isopod* sp.; e: unknown invertebrate; f: unknown bivalve.

After 56 days, each net was densely covered in unidentifiable fouling organisms or attached detritus, effectively obstructing the view of any diatoms if indeed present. Therefore, we truncated diversity analyses for the first 56 days only, and it is suggested that this method for aging nets would only be suitable for the first couple of months at best. Overall, species richness

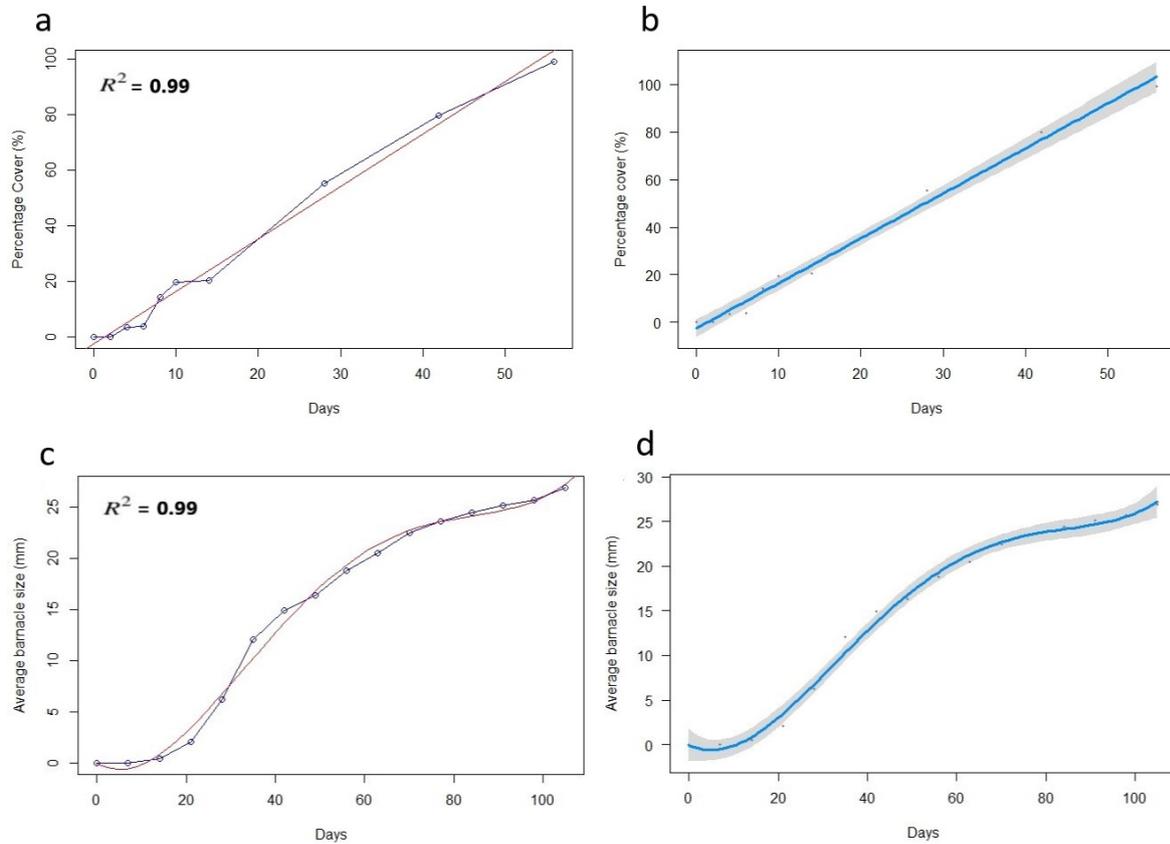
and abundance steadily increased for the first 10 days, reflecting the fast colonisation of a newly introduced ecological niche (Fig. 3a,b, Supplementary material S4). With early dominance by *Amphora* spp. (Fig. 1a, Supplementary material S4). Interestingly, after day 14, diatom diversity decreased (Fig. 3c,d), but certain species such as *Amphora* sp. (B) and *Licmophora* sp. occurred at this time and were dominant (Supplementary material S4, Fig. 1b,n). The observed decline in diatom diversity is also reflected in a decrease in evenness (Fig. 3e). Although not included in the diversity analyses, the heatmap (Supplementary material S4) also highlights that after 14 days, round shaped (*Cocci*) bacteria (Fig. 2a) peak in abundance and then become difficult to record as percentage cover of biofouling communities increases. Similarly, *Foraminifera* sp. (Fig. 2b,c). and various unidentified invertebrates (Fig. 2d-f) first start appearing around 42 days and then dominate as percentage cover of biofouling communities increases, again making it difficult to record the presence and indeed attachment of diatoms to the nets.



**Figure 3.** Mapping variations over time against species richness (a), total abundance (b), Shannon-Wiener diversity (c), Simpson index (d), Pielou index (e), percentage cover of biofouling communities (f) and average capitulum size (mm) of *Lepas anatifera* (g). Error bars equate to standard deviations.

Broadly, the diversity indices illustrate a stochastic relationship between the replicates associated with this study. In contrast, percentage cover of biofouling communities and average capitulum size of the pelagic gooseneck barnacle, *L. anatifera* (Fig. 3f,g), shows less variation between replicates. Up to 60 days (when percentage cover reaches near 100%), a positive linear

relationship occurred ( $R^2 = 0.99$ ) (Fig. 4a). Fitted linear regression models show that the expected (predicted) values match closely with actual values with small confidence intervals (Fig. 4b).



**Figure 4.** (a) linear relationship between number of days and percentage cover of biofouling communities. 100% cover is reached at 56 days; therefore, here we only show the trend from day 0 to this time point. (b) shows the expected value (blue line) and the confidence interval for the expected value represented as the grey band. Partial residuals are shown as dark grey dots. (c) Polynomial 4<sup>th</sup> order trend line relationship between number of days and capitulum length (mm) of *Lepas anatifera*. (d) shows the expected value (blue line) and the confidence interval for the expected value represented as the grey band. Partial residuals are shown as dark grey dots.

*L. anatifera* started to appear on the buoys between seven and 14 days after deployment. The largest individual barnacle measured 35 mm in capitulum length (maximum average 27.9 mm) and the end of the experiment (105 days). Although the rate of growth appeared to slow down as barnacle shell size approached the average size (27.9 mm) it is unlikely the maximum size for this species as sizes in excess of 50 mm have been reported (Magni et al. 2015).

Nevertheless, a clear sigmoidal curve was observed for the first 105 days when an average of all barnacle sizes was taken for each time interval. A polynomial 4<sup>th</sup> order trend line (Fig. 4c) was the best fit for average *L. anatifera* capitulum size ( $R^2 = 0.99$ ). The expected values match closely with actual values and partial residuals show little variance (Fig. 4d).

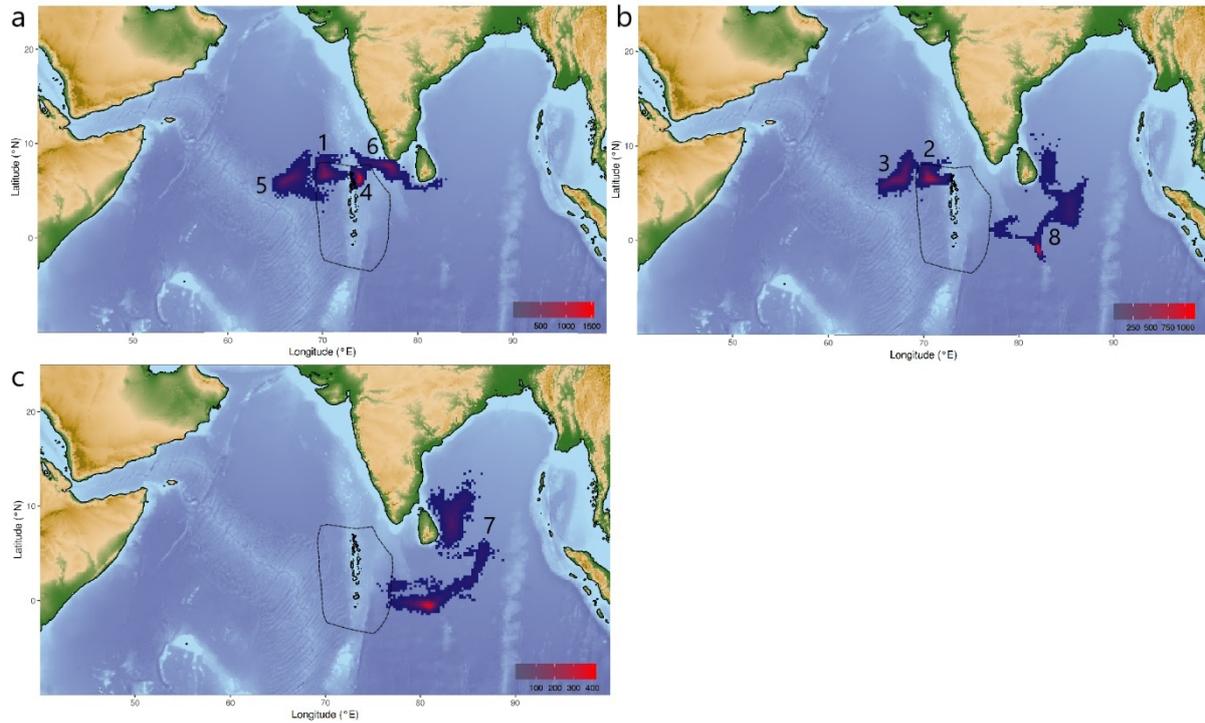
### 3.2. Ghost net age estimates and their putative origin

We analysed percentage cover of biofouling organisms and capitulum length of gooseneck barnacles to estimate minimum drift times of eight ghost nets found in the Maldives (Table 1). We applied these two methods as they illustrate clear trends and had little variance between replicates in the controlled experiments. We were able to confirm the species of barnacle growing on each net through genetic analyses and all were *Lepas anatifera*. Although we did not explore diatom diversity, we did observe large clusters of *Amphora sp.* (identified as the same in Fig. 1b) present on net three, giving an independent indication that this net had been drifting for at least 28 days as inferred by our heatmap (Supplementary material S4) and diversity analyses. However, we observed no invertebrate present on any of our ghost nets which contradicts the heatmap (Supplementary material S4) which would suggest that ghost net five should have invertebrates present which it did not. This further highlight the variation in organism's succession and the unreliability of using diversity indices or key taxa as markers to estimate age alone.

**Table 1.** Drift time estimates of eight ghost nets found in the Maldives during the south west monsoon (SW) and north east monsoon (NE). Estimation were found by either measuring the capitulum length of the barnacle *Lepas anatifera* or by analysing the percentage cover of biofouling communities in image J. NA represents no data taken due to limitations in the field.

Net ID	Monsoon found	Capitulum length (mm)	Percentage biofouling cover (%)	Estimated drift time (Days)
1	SW	NA	51	28 ( $\pm 2$ )
2	SW	NA	43	24 ( $\pm 1.5$ )
3	SW	NA	72	40 ( $\pm 2.5$ )
4	SW	NA	16.6	7.5 ( $\pm 1.5$ )
5	SW	NA	89	48 ( $\pm 3$ )
6	NE	5	NA	24 ( $\pm 2$ )
7	NE	26	NA	101 ( $\pm 10$ )
8	NE	18	NA	54 ( $\pm 2$ )

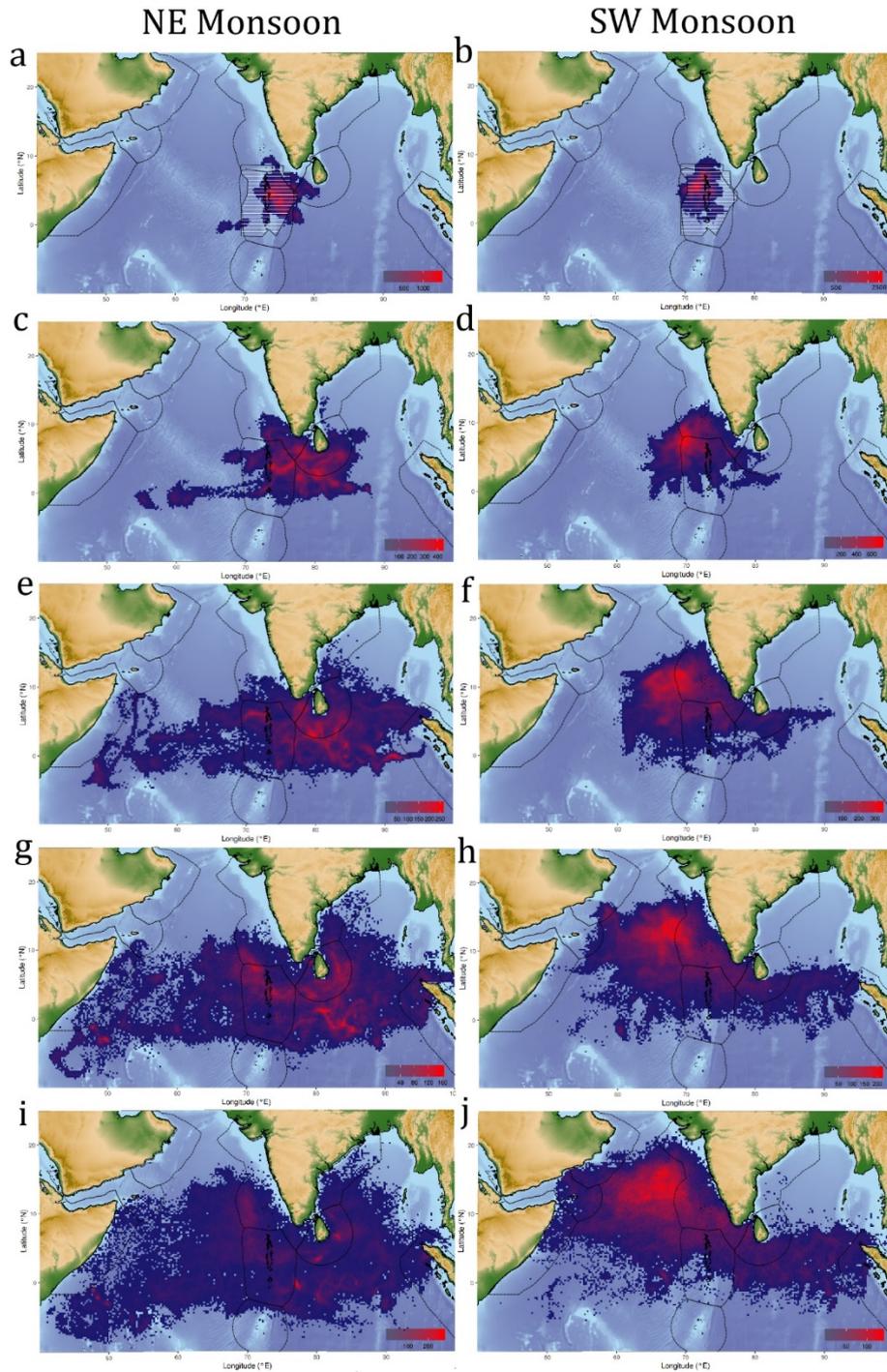
Particles were released at each of the eight ghost nets locations and backtracked according to age estimates above (Table 1, Supplementary material S5). Simulations for nets one, four (Fig. 5a) and two (Fig. 5b) suggest that they did not come from outside the EEZ of the Maldives. Providing evidence that times below 30 days typically do not travel far outside the EEZ of the Maldives. Ghost nets analysed in this study with the longest drift times (nets seven and eight, Table 1, Supplementary material S5) showed a comparatively wide dispersal of particles (Fig 5b,c) with some drifting close to shorelines of Sri Lanka.



**Figure 5.** Number of particles per  $1/4^\circ$  squares backtracked from each of the eight-net location and grouped to avoid overlapping (a) nets 5, 1, 4, and 6; (b) nets 3, 2, and 8; (c) net 7. Drift duration was set at the estimated drift times calculated for each net. Red areas indicate higher particle density. Maldivian exclusive economic zone (EEZ) is shown as black dotted line.

### 3.3. Putative origin for ghost nets without drift time estimates

At first look, simulations revealed a level of uncertainty with regards to a putative origin for the 326 ghost nets without drift time estimates. This is particularly true for long drift durations such as 120 days in this study. When modelling with the smallest drift time (10 days here), the simulated particles did not travel far outside the Exclusive Economic Zone (EEZ) of the Maldives as indicated by high densities found well within the EEZ (Fig. 6a-b). The only fisheries operating in this area that are reporting to the IOTC are the Maldivian bait net fisheries (Fig. 6a-b). At 30 days of drift or more (Fig. 6c-j) the most likely origins fall outside of this zone and are therefore likely to be coming from other fisheries and EEZs from other countries. The results of the models obviously vary strongly depending on the season, indicating likely hot spots of net origin.



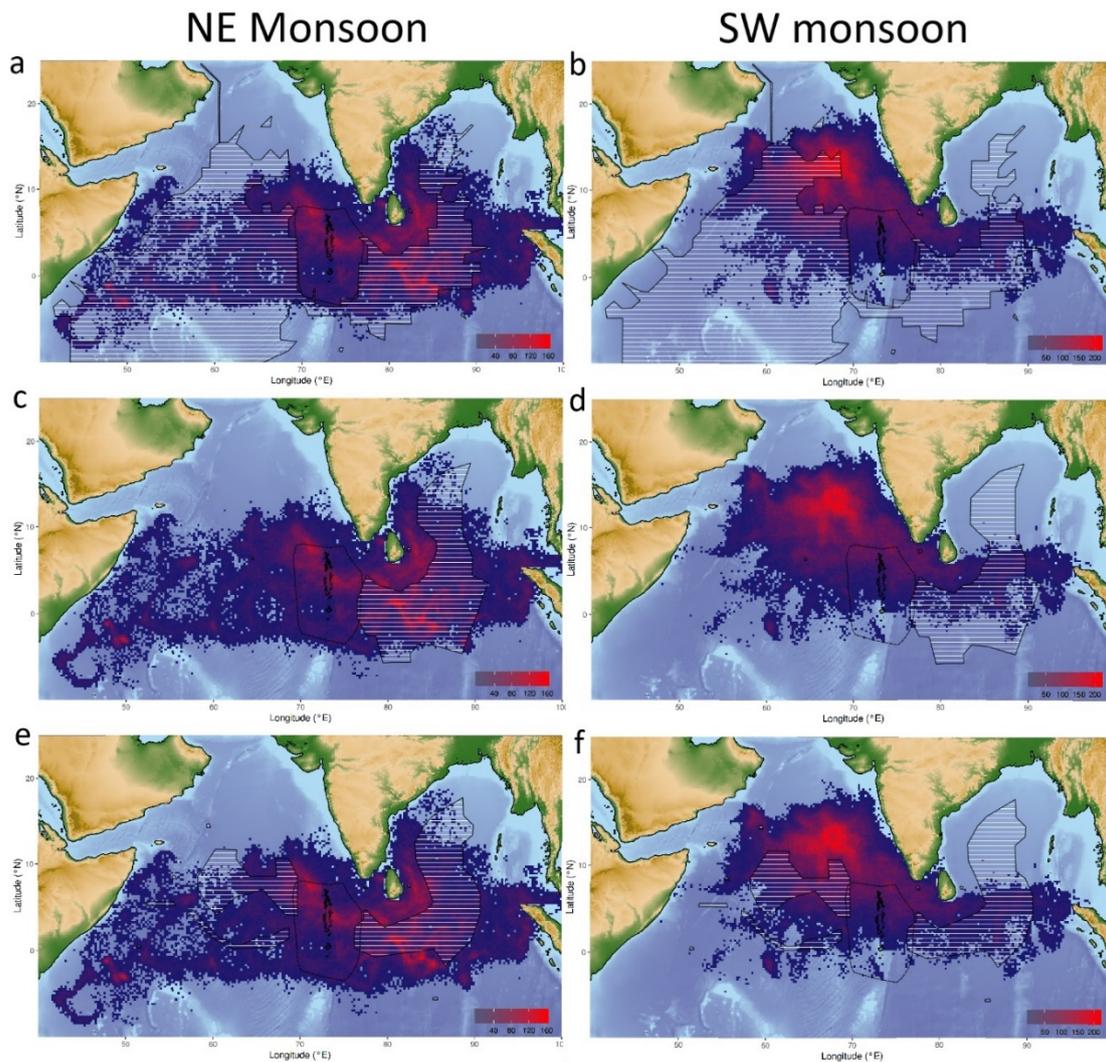
**Figure 6.** Number of particles per  $1/4^\circ$  squares backtracked from the location and time of the 326 ghost nets collected during the NE monsoon (left) and SW monsoon (right). As there was no drift time estimates for these nets drift periods of 10 (a-b), 30 (c-d), 60 (e-f), 90 (g-h) and 120 days (i-j) were used. Red areas indicate higher particle density. Exclusive economic zones (EEZ) are shown as black dotted line for each surrounding country. Maldivian bait fishery area of operation highlighted as white horizontal lines (a-b).

For the first 90 days during the NE monsoon, the model indicated that particles typically drift westerly. Numerous clusters accumulated well within the EEZ of the southern tip of India, Sri Lanka and the Maldives, very close to shore (Fig. 6a,c,e,g). After 90 days (Fig. 6i) it became increasingly difficult to determine a putative origin as particles were more dispersed. However, clusters continued to accumulate north of the Maldives within the EEZ of Western India and to the east in Sri Lanka and eastern India. Interestingly, particles spread as far as Somalia, Yemen and Indonesia (Fig. 6g,i) but in lower densities. Comparatively, during the SW monsoon, particle clusters were much more defined, and a putative origin was more prominent in the open ocean of the Arabian Sea (Fig. 6b,f,h,j). Further, particles aggregated in higher densities when compared to the NE monsoon within the EEZ of Yemen, Oman, Western India and Western Sri Lanka (Fig. 6j).

#### *3.4. Possible fisheries responsible for ghost nets in the Maldives*

For drift times longer than 10 days our simulations suggest that purse seine fisheries (Korea, Mauritius, Philippines, Spain, France and Seychelles) and gill nets from Sri Lanka are ‘high risk’ fisheries that overlap dense particle clusters, particularly at 90 days of drift across both seasons (Fig. 7a-d). In comparison, ring nets from Sri Lanka appear to be only a seasonal threat (Fig. 7e-f). However, the ‘level’ of threat from each country appears to vary depending on drift times. For example, nets that have been drifting for 60 days or less during the NE monsoon show a clear overlap in high density areas (red areas) where Sri Lankan purse seine fisheries operate. However, after this time, the dense clusters overlapped more with purse seine fisheries from flags of the EU (Spain and France), particularly after 90 days adrift (Fig. 7a-b, Supplementary material S6). As drift time increases beyond 90 days to 120 days and possibly beyond, particles become more dispersed, making it much more difficult to assign high risk fisheries in the area. Comparatively the SW monsoon simulations provide a clearer putative origin for all drift times analysed in this study. Here the dense clusters of particles push north into the Arabian Sea as drift time increases. For the first 30 days the only major concern is from gill nets operated by Sri Lanka. At 60 days purse seiners from Spain and the Seychelles begin to overlap with these areas of high density and by 120 days purse seine fisheries from Mauritius, Korea, and Seychelles join the ranks of Spain and France (Supplementary material S7).

It should be noted that Japanese purse seine fisheries are also shown to be fishing in areas where high particle density occurs during the NE monsoon. However, a large number of Japanese coordinates appeared on land when we mapped them. This is obviously an error on the reporting and therefore based on this level of uncertainty we had to exclude Japanese purse seine fisheries from our analyses.



**Figure 7.** Number of particles per  $1/4^\circ$  squares backtracked from the collected ghost net locations after 90 days of drift during the NE monsoon (left) and SW monsoon (right). Red areas indicate higher particle density. Maldivian exclusive economic zone (EEZ) is shown as black dotted line. Spatial distribution of purse seine fisheries (shown in white shaded area) operating from Sri Lanka, Philippine, Korea, Spain, France, Mauritius and the Seychelles (a-b), Ring net fisheries from Sri Lanka (c-d) and Gill net fisheries from Sri Lanka (e-f).

## 4. Discussion

The aging of abandoned, lost or discarded fishing gear (ALDFG), more specifically ‘ghost nets’, is possible, at least to some degree. Percentage cover of biofouling communities and the capitulum size of the goosenecked barnacle, *Lepas anatifera* appeared as the most reliable methods in order to determine minimum drift times due to the low variability between replicates and clear trends in overall measurement. Succession of diatom communities and arrival of rare and macrofouling organisms may also provide additional information that compliments such estimations. The Lagrangian particle dispersal simulation shows the possibility of wide spatial origin of particles (i.e., nets here), arriving in the Maldivian waters yet defines likely hotspots where a putative origin of a given net came from. Overlapping spatial distribution of fisheries onto these simulations allows the identification of fisheries that are most likely to contribute to the ghost nets found in the Maldives archipelago.

### 4.1 Biofouling communities and ghost gear ageing

Fishing nets provide a novel and niche habitat for a wide diversity of fouling organisms (Reisser et al. 2014, Fazey et al. 2016, Kooi et al. 2017). Here, we illustrate that a relatively high diversity of diatoms arrives in the first few days, followed by a number of other unidentified organisms including bacteria and invertebrates, collectively known as the ‘plastisphere’ (Zettler et al. 2013). It is reasonable to assume that this plastisphere may be the initial driver that attracts larger predators such as sea turtles to ghost nets in search of food. Interestingly, we found that bacteria quickly colonise the plastic surface and eventually flourish to become the most abundant organisms. It has previously been shown that these bacteria impact the surface floating plastic, forming pits and groves as a result of biodegradation (Arthum et al. 2009, Reisser et al. 2014). This may mean that the bacteria are directly influencing the breakdown of ghost nets.

Percentage cover of biofouling organisms on the experimental nets show a characteristic sigmoidal curve (Fig. 3f), in a similar pattern to the biofouling which occurs on marine glass samples in Europe (Lehaitre et al. 2008). Moreover, our largest barnacle found on the ghost nets (26 mm) was of a similar size to that reported previously (25 mm, Evans, 1958). Further, they were aged similarly (101 and 107 days respectively). These latter studies were undertaken in countries other than the Maldives (and the wider Indo-Pacific) indicating that our tools for estimating drift time may well have global reach.

Aging drift times had the highest confidence up to the first 100 days in the water. Percentage

cover of biofouling communities become largely unusable after 56 days. However, capitulum size of *L. anatifera* tracked well up to 105 days and possibly expands past this time point as the barnacles in this study had not reached their known maximum growth size (De Wolf, 2008). It is however important to recognise, as stated previously, that surface roughness and topography play important factors in bioaccumulation and growth rates (Scheuerman et al. 1998). Twisted nets are typical of net types found in the Maldives (Stelfox et al. 2015). Future analyses should focus on rates of growth on monofilament and braided nets to compare similarities and differences in bioaccumulation rates and diversity. Additionally, minimum drift time analyses are based on growth rates in coastal environments on fixed objects. This was undertaken for obvious practical and ethical reasons. That said, it should be noted that free-floating ghost nets may well be subject to spatial fluctuations in environmental conditions that may impact biofouling organisms and their succession (Sudhakar et al. 2007).

#### *4.2. Lagrangian simulations*

Including diffusion in Lagrangian simulations, backwards in time, is a valuable approach to obtain probability distributions of past positions (Batchelder et al. 2006). At least in the context of either limited spatial (here  $1/3^\circ$ ) or temporal (here 5 days) resolutions of the forcing current product (here OSCAR). Despite their coarse resolution, current products based on remote sensing data, like OSCAR, have been shown to simulate surface drift trajectories satisfactorily (Hart-Davis et al. 2018, using GlobCurrent) with similar (or even higher) accuracies than higher-resolution oceanographic model outputs (Scott et al. 2012, using Surcouf). Using OSCAR, Davies et al. (2017) showed that simulated trajectories of fish aggregating devices (FADs) were generally consistent with observations. However, in the Indian Ocean OSCAR velocities were shown to be generally lower than velocities derived from oceanographic drift trajectories (Imzilen et al. 2019). That said, the zonal component of OSCAR velocities appears to be more accurate than the meridional component (Sikhakoli et al. 2013).

#### *4.3. Fishery interaction*

The youngest ghost net analysed in this study (estimated at drifting for only 7.5 days) along with nets one and two (28 and 24 days respectively), indicates that these nets originate from inside the EEZ of the Maldives. The relatively large mesh size associated with these nets is untypical of those usually used as bait nets in this area. A result which indicates the possibility of illegal, unreported, and/or unregulated fishing practices taking place within the Maldives. Comparatively, ghost net seven (Fig. 5c), found during the NE monsoon, was the longest drifter

at around 101 days. Multiple clusters were simulated overlapping a wide variety of fisheries including gill and ring nets from Sri Lanka and purse seine fisheries from Spain, France, Seychelles and Korea.

Fisheries operating in the area of study are widespread (IOTC 2018) and those labelled as 'high-risk' fisheries (with regard to likely contributors of the majority of nets) fluctuate depending on spatial distribution, season and estimated drift times. However, gill nets from Sri Lanka appear to be high risk fisheries regardless of season at all drift times longer than 30 days. Additionally, the wide dispersal of particles (nets) for the longer modelled drift times (approaching 120 days, Fig. 6), coupled with the invasion of multiple EEZs particularly close to shorelines of Sri Lanka and India (Fig. 6) suggest that an unconfirmed proportion of ghost nets entering the Maldives could be from a variety of small scale artisanal fisheries. This is further supported by observations of fragments of ghost nets drifting into the Maldives with Indian markings on floatation devices (Stelfox et al. 2015). Although purse seine nets appear to be problematic across both seasons (Fig. 7a-b), there are temporal changes that influence the risk that specific countries pose. Here, the Sri Lankan purse seine fisheries pose significant risks at all drift times during the NE monsoon, but this is reduced during the SW monsoon. Comparatively, when drift times are more than 60 days during the NE monsoon, purse seine fisheries from France and Spain are the only additional high-risk fisheries analysed in this study during this period (Supplementary material S6). Interestingly, if a net is drifting for only 30 days during the SW monsoon, it is unlikely to be originating from these fisheries. However, if the nets drift for longer periods, fisheries associated with Spain and the Seychelles increase in their likelihood of being the origin of the nets and Korea, Mauritius and France come into play past 90 days (Supplementary material S7). Evidence to support the modelling and implicating purse seine fisheries in the origin of a proportion of nets found floating in the Maldives comes from the stranding of FADs (Stelfox et al. 2015). Further, a recent study has also implicated these fisheries in the stranding of FADS in the same country specifically (Imzilen et al. in prep.). Identifying ghost nets to a specific fishery and/or location can, however, be challenging, as more often than not the gear is unmarked (Stelfox et al. 2015). In the Maldives it is thought that many of the ghost nets that drift into the EEZ originate from neighbouring countries (Stelfox et al. 2015), and our Lagrangian simulations support this hypothesis. However, spatial distribution data from major fisheries such as India, Pakistan, Oman and Yemen and those from coastal fisheries from all surrounding countries (which dominate the Indian Ocean) are sparse and, in some cases, completely absent in the IOTC database (IOTC 2018). This lack of

reporting means that although our analysis is as thorough as possible, we may still be overlooking the risk of the fisheries associated with these countries (where no spatial distribution data is available).

#### *4.4. Future recommendations*

A lack of data on gear types and spatial distributions of small and large-scale fisheries means it remains difficult to accurately identify responsible fisheries in the Indian Ocean. The IOTC working party on data collection and statistics note this to be the case especially for artisanal fisheries and in particular for gill nets (IOTC 2018b). A cross sectorial collaboration between governments, NGOs, IGOs and the private sector should take precedent, aimed at improving the collection and transparency of such data and share resources where possible. Simulations and age estimates (combined), do however highlight that purse seine fisheries and gill nets are likely key candidates for a major part of the ghost gear found drifting into the EEZ of the Maldives. To minimise damage to sensitive habitats in this country, a recovery project (similar to “FAD watch” set up in the Seychelles; Zudaire et al. 2018) could be initiated throughout the Maldives. Such a project would require the collaboration of Maldivian NGOs, the government and purse seine fisheries from the EU (Spain and France), Mauritius, the Seychelles and Korea. In the Seychelles, FAD watch allows for the recovery of FADs that come within 3-5 nautical miles of selected islands in the Seychelles. Through this project a 20% and 41% reduction in beaching events have been observed in 2016 and 2017, respectively.

It should also be noted that for the modelling, we assumed ghost nets behave like particles and we do not include net geometry and/or vertical profile or the impact of Stokes drift into account (Dobler et al. 2019). Future analyses of ghost net drifts should focus on how bioaccumulation may impact floating times and vertical profile and how ghost net geometry may influence drifting trajectories. Although diversity indices were not effective in estimating age in this study, different species of diatoms and other macrofoulers can provide additional tools to help estimate drift times. Categorising bioaccumulation composition for different regions may help identify region specific organisms that could give additional clues towards drift trajectories and ghost gear origins. Finally, we only report diatoms that could be visually identified, future analyse of fouling communities should focus on utilising molecular tools to increase the known diversity at any given time point.



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