Mobile marine predators: an understudied source of nutrients to coral reefs in an unfished atoll

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ESM 1

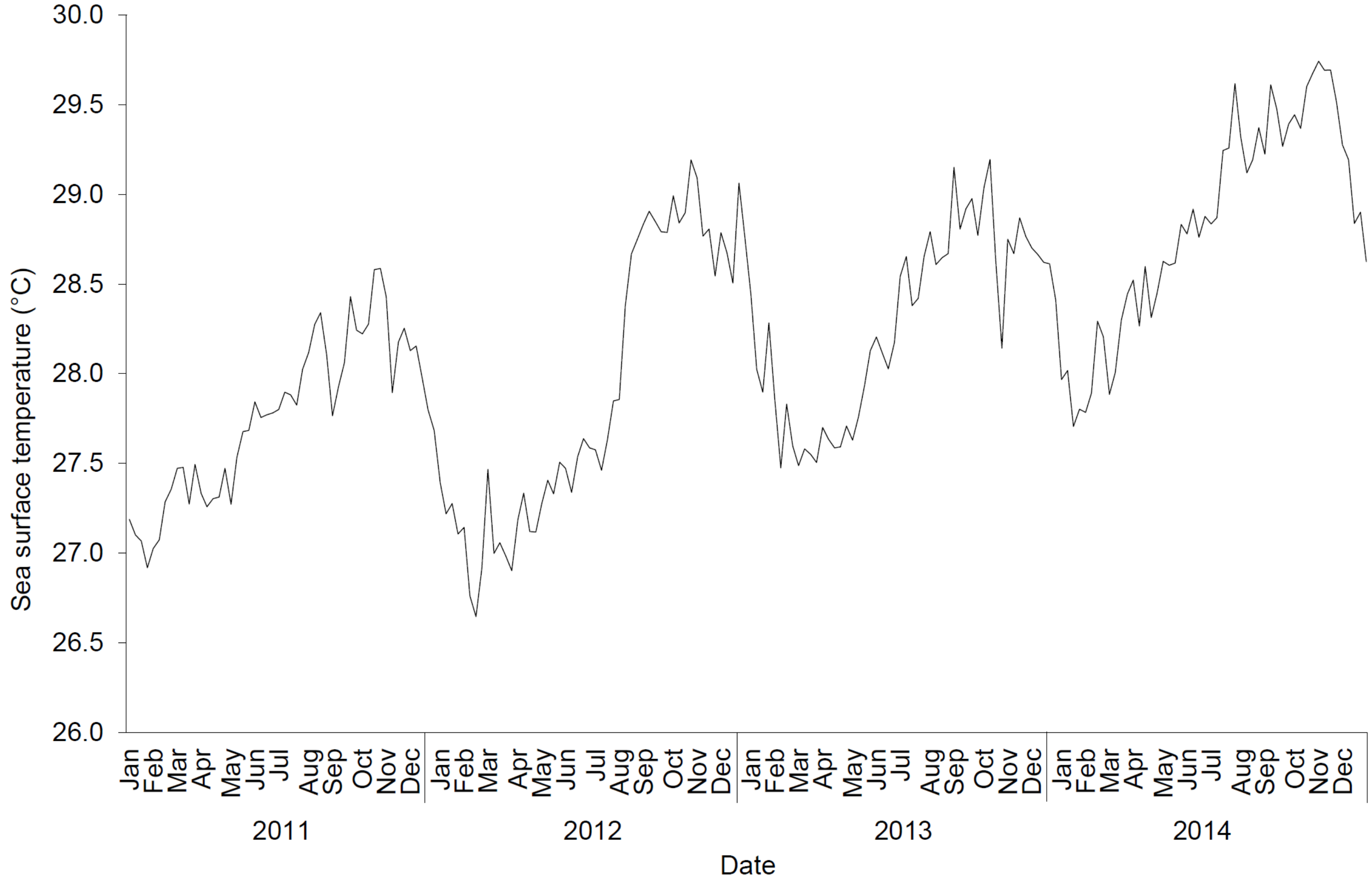

Fig. S1 Sea surface temperature at Palmyra Atoll over the course of the study period, acquired from the Coral Reef Ecosystem Division of the National Oceanic and Atmospheric Administration.

ESM 2

Further information on the method

Study site

Palmyra Atoll is approximately 12.5 km long and has an area of 27.6 km^2 [1]. Within Palmyra Atoll there are two primary lagoons connected by a small shallow channel. The western lagoon is linked to the outer reefs by a large, dredged channel, whereas shallow sand-flats connect the eastern lagoon to the outer reefs [2]. Situated off of the western and eastern shores of the atoll are large shallow reef terraces [3]. Palmyra Atoll's fore-reefs feature steep slopes and high coral cover [2]. During Palmyra Atoll's US military occupation from 1940 to 1945, major structural changes took place within the lagoons [2]. However, these modifications have been steadily broken down due to the atoll's relatively undisturbed status ever since [4].

Network analyses

The raw acoustic detection data ranged from January 2011 to September 2015 and contained detections from 65 acoustic receivers. The data were cleaned by removing data for duplicate tags (for those sharks that had been tagged twice), and ensuring receivers had not been given more than one name in the dataset (due to the logistics of replacing receivers after a year in the field). In addition, for each individual, detections on the day of tagging and the following day were removed; this was to reduce any effects of the tagging procedure on their movements. Finally, to concentrate on the detections relating to movements, a detection was removed if the preceding and following detection for an individual were recorded by the same receiver.

After initial data exploration, to avoid receiver detection ranges overlapping, distances between receivers were obtained (by utilising the pointDistance function in the package raster), and 9 receivers were removed. A further 9 receivers were also removed because they detected less than 0.1% of the movement detections; this was generally due to these receivers having been deployed half way through the study period. This led to 47 receivers being included within the analyses. We also decided that the detections from 2015 would not be included in the analyses; this was mainly due to the data from previous years suggesting a peak in detections in the months that were missing from the 2015 dataset (Fig. S2).

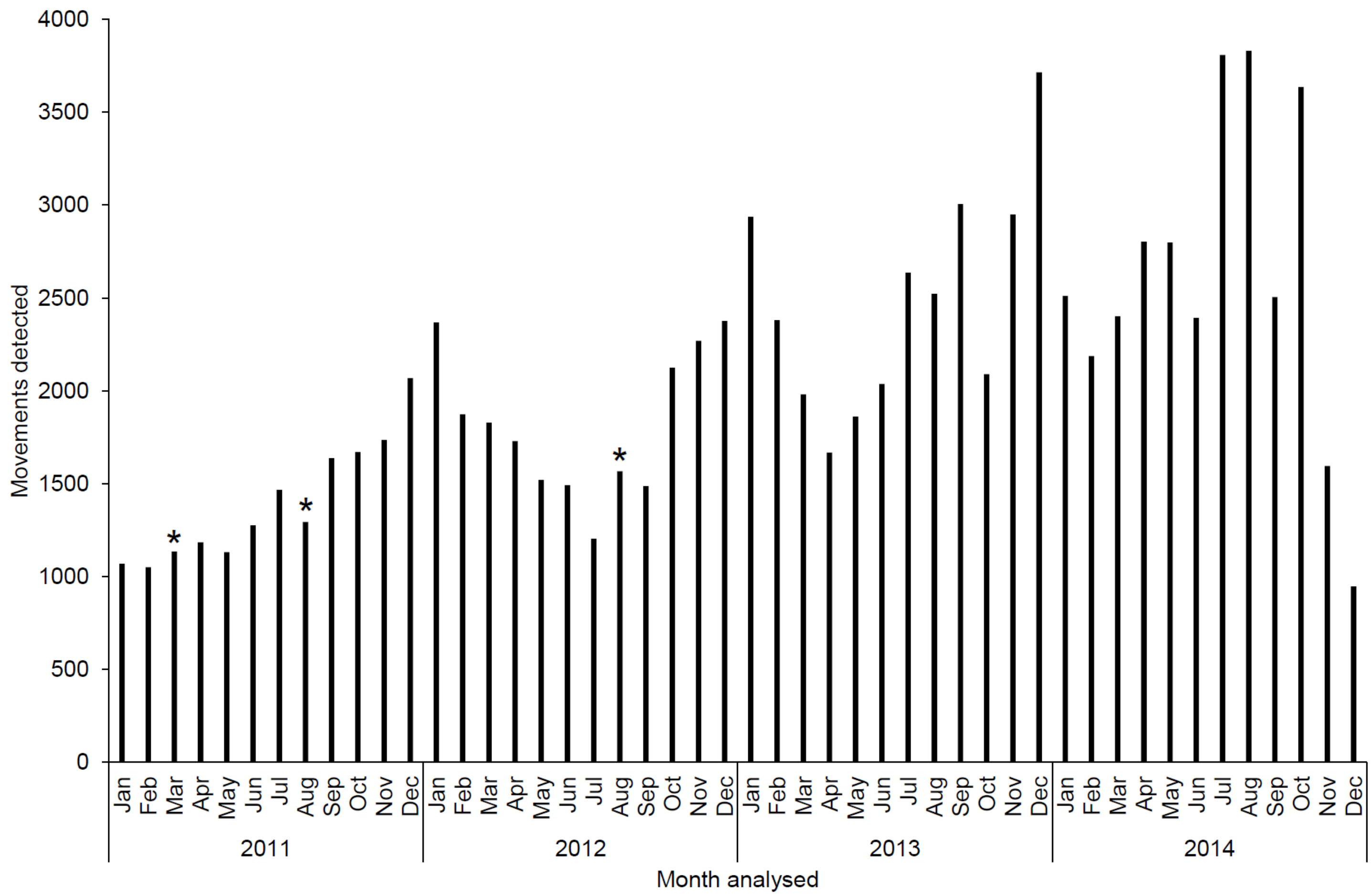

Fig. S2 The number of grey reef shark movements detected each month by the array of acoustic receivers within Palmyra Atoll; a movement occurs when an individual is detected at an acoustic receiver that is different to the receiver it was detected at previously; the asterisks (*) denote months during the study period in which more sharks were tagged with acoustic transmitters.

In this study, we used network theory to analyse the acoustic telemetry data, viewing the movements of the tagged grey reef sharks as a network based on the detections at acoustic receivers around Palmyra Atoll (Fig. S3). We created adjacency matrices for all or subsets (depending on the analysis) of the movement detection data (utilising the package asnipe). In these matrices, the *i, j*th element was a weighted value (between 0 and 1), in an n x n adjacency matrix, which indicated the frequency of direct movements that occurred between receiver v_i and receiver v_j. From these matrices, undirected movement networks were produced using the package igraph, in which nodes represented the acoustic receivers and edges denoted the direct movement of individuals between two receivers (Fig. S3). In most of the analyses, males and females were considered separately; this is due to previous studies suggesting sexual segregation in other populations of grey reef sharks, for example at Imperieuse Reef in Rowley Shoals [5].

Fig. S3 An example movement network: the movements of a female grey reef shark during June 2014 viewed as a network based on the female's detections at acoustic receivers around Palmyra Atoll; only receivers that detected the female's movements during this month are plotted. The asterisk (*) is located next to the node (acoustic receiver) with the highest betweenness centrality, which means it has the highest number of shortest paths (the route with the smallest number of edges between a pair of nodes) passing through it (this node's betweenness centrality = 29). The width of the edges represents the frequency at which the female made that movement relative to other movements detected in that month. The edge density of this network is 0.0139, because 15 edges are present in the network, out of the 1,081 edges that could be present if all the 47 receivers included within analyses were linked to each other by movements. The Palmyra Atoll habitat map displays areas within the atoll with different benthic habitat classifications, according to [6].

Connectivity within the network

To assess the connectivity of the reef ecosystem generated by grey reef shark movements, for each sex, the network's edge density for every month and for every year over the study period was extracted (using igraph). Analyses of variance were run for males and females to determine whether the monthly movement network edge densities differed between sexes, seasons or over the years.

Estimating nitrogen transfer through the atoll

To estimate the quantity of nitrogen (*N*) egested over the study for each individual the following equation from Nelson et al. [7] was used:

$$N = BW \times BI \times \mathrm{E} \times \mathrm{A} \times \mathrm{N} \times R$$

where *BW* is the estimated body weight of the shark (kg), *BI* is the percent of body weight ingested (2% [8]), E is the percent of matter consumed daily available for egestion (24% [9]), *A* is the percent of consumed matter that is absorbed (76% [9]), *N* is the percent of nitrogen found in grey reef shark tissue at Palmyra Atoll (0.148 ± 0.065 % N mean ± SE [10]), and *R* is the number of days the individual was detected within the array.

To calculate the dynamic residency score (I_D) of each acoustic receiver for each sex, firstly the residency index (I_R) of each receiver was calculated:

$$I_R = \frac{\text{Number of days the receiver detected a male/female shark}}{\text{Total number of days during the study period}} \times 100$$

This index was then incorporated into the following equation to work out each receiver's dynamic residency score:

$$I_D = I_R \times \frac{S_i}{100}$$

where S_i is the node strength of each receiver.

All statistical analyses were completed in R (R Core Team 2016, [11]) and mapping in QGIS 2.14.0 (QGIS Development Team 2016, [12]).

ESM 3

Table S1 The network metrics extracted to assess connectivity within the grey reef shark movement network each year; mean values displayed in the table are presented with one standard deviation.

	Edge density (%)					
	Per year			Mean per month (SD)		
Year	All	Female	Male	All	Female	Male
2011	47.4	42.7	25.2	9.83 (3.57)	12.65 (2.86)	7.02 (1.05)
2012	45.9	40.5	28.5	10.72 (3.84)	13.94 (1.62)	7.50 (2.35)
2013	48.3	40.2	32.5	11.44 (3.07)	13.93 (1.86)	8.94 (1.65)
2014	49.1	38.9	36.2	10.84 (3.03)	11.96 (3.57)	9.72 (1.93)

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