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Drones and machine-learning for monitoring dugong feeding grounds and gillnet fishing

Damboia Cossa[1,2,*], Minda Cossa[2], Ilário Timba[3], Jeremias Nhaca[3], Adriano Macia[2], Eduardo Infantes[1,4]

[1]Department of Marine Sciences, University of Gothenburg, 45178, Kristineberg, Sweden
[2]Department of Biological Sciences, Eduardo Mondlane University, 257 Maputo, Mozambique
[3]Inhaca Marine Biology Research Station, Eduardo Mondlane University, 257 Maputo, Mozambique
[4]Department of Biological and Environmental Sciences, University of Gothenburg, 45178 Kristineberg, Sweden

ABSTRACT: Fishing provides an important food source for humans, but it also poses a threat to many marine ecosystems and species. Declines in wildlife populations due to fishing activities can remain undetected without effective monitoring methods that guide appropriate management actions. In this study, we combined the use of unmanned aerial vehicle-based imaging (drones) with machine-learning to develop a monitoring method for identifying hotspots of dugong foraging based on their feeding trails and associated seagrass beds. We surveyed dugong hotspots to evaluate the influence of gillnet fishing activities on dugong feeding grounds (Saco East and Saco West) at Inhaca Island, southern Mozambique. The results showed that drones and machine-learning can accurately identify and monitor dugong feeding trails and seagrass beds, with an F1 accuracy of 80 and 93.3%, respectively. Feeding trails were observed in all surveyed months, with the highest density occurring in August (6040 ± 4678 trails km^{-2}). There was a clear overlap of dugong foraging areas and gillnet fishing grounds, with a statistically significant positive correlation between fishing areas and the frequency of dugong feeding trails. Dugongs were found to feed mostly in Saco East, where the number of gillnet stakes was 3.7 times lower and the area covered by gillnets was 2.6 times lower than in Saco West. This study highlights the clear potential of drones and machine-learning to study and monitor animal behaviour in the wild, particularly in hotspots and remote areas. We encourage the establishment of effective management strategies to monitor and control the use of gillnets, thereby avoiding the accidental bycatch of dugongs.

KEY WORDS: Coastal management · Drones · *Dugong dugon* · Feeding grounds · Gillnet fishing · Machine learning · Monitoring · Seagrass

1. INTRODUCTION

Intensive fishing efforts and the use of destructive gear by coastal communities in developing countries can lead to declines in marine resources (Purcell & Pomeroy 2015, Selgrath et al. 2018), including the bycatch of endangered species (Reeves et al. 2013). Accidental entangling in commercial gillnets and mesh nets is considered the primary cause of mortality of endangered marine species such as dugongs (Marsh et al. 1999, 2002, Ponnampalam et al. 2022) and sea turtles (McClellan & Read 2009), although the scale of this problem remains unquantified. Effective tools to address the decline of threatened species associated with fishing pressures are not well established. Monitoring is considered essential for developing appropriate conservation and management strategies for vulnerable species (Robinson et al. 2018).

In recent years, the combined use of images from unmanned aerial vehicles (hereafter referred to as

*Corresponding author: dambcossa@gmail.com

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drones) with machine-learning (ML) methods has proved viable in long-term wildlife monitoring and conservation programs (Dujon & Schofield 2019, Corcoran et al. 2021, Dujon et al. 2021). The assumption is that once an ML model has been successfully trained, subsequent automation and processing of newly collected data becomes relatively inexpensive and suitable for long-term monitoring programs (Dujon & Schofield 2019). Moreover, drones provide accurate and large data sets in a short period compared to traditional survey methods. Therefore, they can be applied to a range of marine science surveys, such as marine species behaviour (e.g. Infantes et al. 2020), ecosystem habitat mapping (e.g. Duffy et al. 2018), and automated methods of animal surveys (e.g. Yamato et al. 2021, Infantes et al. 2022).

Dugongs are listed as Vulnerable by the International Union for Conservation of Nature (IUCN) due to habitat degradation and human disturbance (Marsh & Sobtzick 2019). They usually forage on seagrass meadows, and their foraging behaviour is influenced by factors such as seagrass biomass and nutritional requirements (Preen 1995a, Sheppard et al. 2007, Tol et al. 2016) as well as seasonal changes and physical characteristics such as tidal and diel cycles (Sheppard et al. 2010, Budiarsa et al. 2021) and the risk of stranding and human disturbance (Budiarsa et al. 2021). While dugongs likely feed on several seagrass species, such as *Halodule* spp. and *Halophila* spp., they tend to prefer high-energetic foods (Sheppard et al. 2010). Therefore, conservation strategies for dugongs must protect both the animals and their food source (Tol et al. 2016), while minimizing accidental entanglement during fishing activities (Marsh et al. 2002). Understanding how local factors, such as fishing impacts, affect dugong foraging activity can help design effective management interventions for the species.

In Eastern Africa, the dugong subpopulation has recently been reclassified as Critically Endangered by the IUCN (Trotzuk et al. 2022a). This reclassification is based on a recent assessment of dugong abundance and population viability in Bazaruto Archipelago National Park (BANP), Mozambique, which identified Bazaruto as the only known viable subpopulation along the East African coast (Trotzuk et al. 2022b). This emphasizes the need for appropriate management and conservation efforts. Dugongs at Inhaca Island, located in Maputo National Park, have been reported as having a small population and are rarely sighted. In the mid-1970s, herd sizes of 8–10 individuals were observed (Findlay et al. 2011), and aerial surveys in 2006 and 2009 reported 1–4 individuals observed, respectively (Fernando et al. 2014). Direct entanglement of dugongs in gillnets has been listed as a potential cause for their decline in Mozambique and on Inhaca Island (Guissamulo & Cockcroft 1997, Fernando et al. 2014). Although the number of incidental catches by fishermen is unofficially reported, these catches could pose a significant threat to the remaining population.

Direct observations of dugong feeding activity are difficult because they avoid human activities, and their feeding method of pulling the plants out of the sand generates clouds of sediments (Preen 1995a). Therefore, indirect methods have been adopted to assess feeding activity in surveys, including the use of fecal sampling (Preen 1995a), stomach analysis (Marsh et al. 1982), GPS telemetry tags (Sheppard et al. 2006), and acoustic methods (Tsutsumi et al. 2006). One indirect and non-invasive method used in many tropical intertidal regions is the observation of dugong feeding trails (Tol et al. 2016), which are furrows formed in seagrass during grazing. However, there is currently a lack of indirect methods using drones to monitor dugong feeding trails.

In this study, we used a cost-effective technique to identify dugong feeding hotspots based on their feeding trails while also addressing the potential risk of small-scale gillnet fishing activities on their seagrass foraging habitats at Inhaca Island, southern Mozambique. Specifically, we aimed to (1) evaluate if the use of drones and ML could be applied for monitoring dugong feeding grounds and (2) assess if fishing activities using gillnets overlap with dugong feeding patterns.

2. MATERIALS AND METHODS

Field surveys were conducted in the southern bay of Inhaca Island, also known as Saco of Inhaca, located in southern Mozambique (Fig. 1). The island has an extension of 42 km^2 and a population of ~6000 inhabitants who are highly dependent on coastal ecosystems such as seagrass meadows, mangroves, and coral reefs for their food and income. Fishing is the primary source of income, but some communities around the island have seen an increase in tourism, trade, and migration. Men primarily work in fishing and cattle rearing, while women work in subsistence agriculture and harvesting invertebrates in seagrass meadows around the island (Nordlund & Gullström 2013).

Seagrass meadows at Inhaca Island cover ~50 % of the intertidal areas around the island, with 9 identified species: *Zostera capensis*, *Halophila ovalis*, *Cymo-*

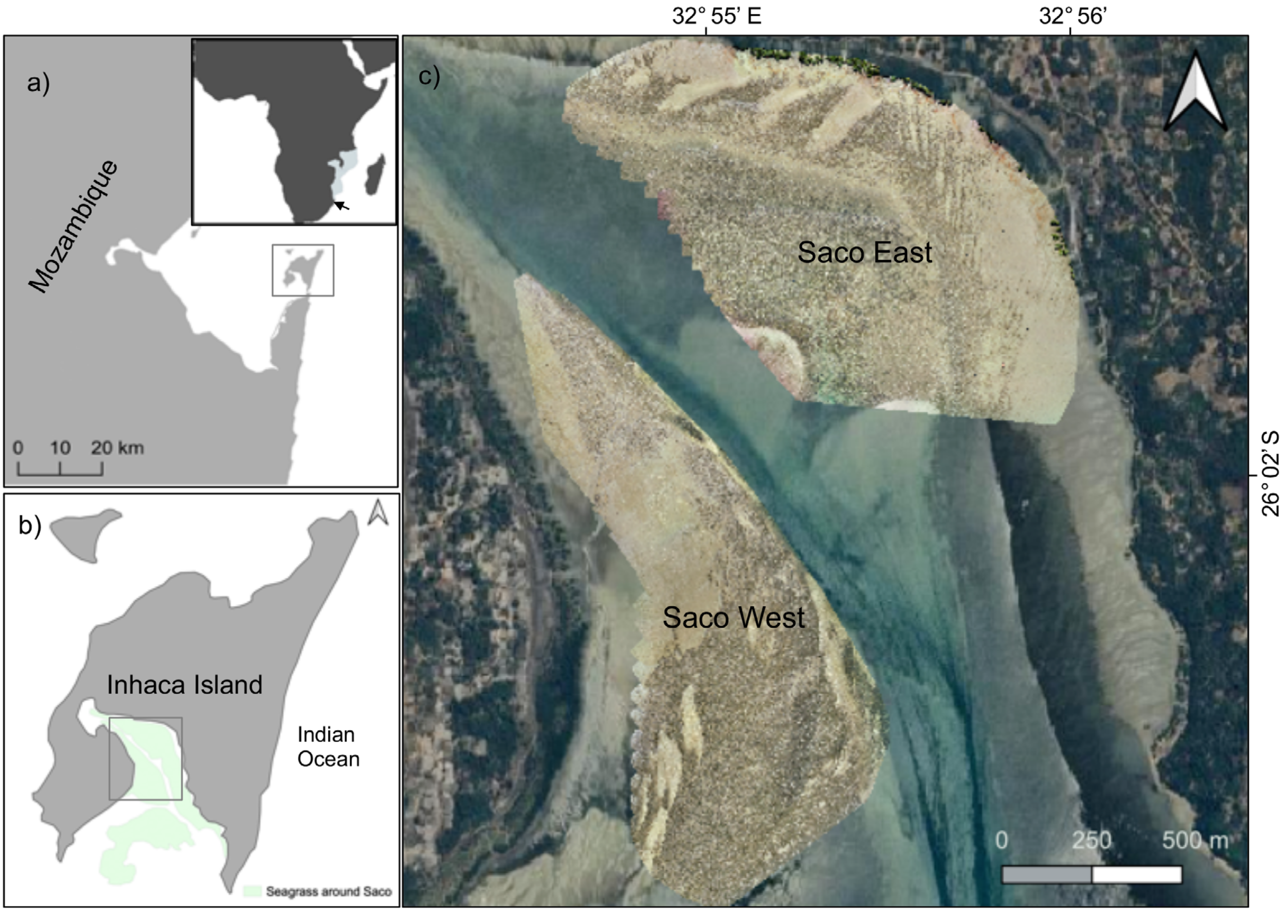

Fig. 1. Location of (a) Inhaca Island in Southern Mozambique. (b) Seagrass cover (green shading) around Southern Bay (Saco area marked by square). (c) Drone mosaics of the 2 survey areas (Saco West and Saco East)

docea rotundata, *Oceana serrulata* (formerly *C. serrulata*), *Halodule uninervis*, *Syringodium isoetifolium*, *Thalassia hemprichii*, *Thalassodendron ciliatum*, and *T. leptocaule* (Bandeira et al. 2014). Dugong feeding trails are mainly found around Saco of Inhaca, coinciding with *H. uninervis* and *H. ovalis* meadows that dominate the intertidal zone. The field surveys aimed to apply a new method that uses aerial drones and ground data to identify dugong feeding trails and fishing activities (Fig. 2).

2.1. Dugong trail identification and monitoring using drones

Surveys were conducted monthly between June and December 2020, excluding November due to weather conditions. Two locations, Saco West and Saco East in the south of Inhaca Island, were surveyed each time (Fig. 1c). All surveys were conducted during low spring tides over a period of ~2.5 h to cover the entire intertidal seagrass extent in each location. The surveys did not aim to observe dugongs during their feeding activity due to the low tide, but rather to record their feeding areas. However, in the middle of 2019, 3 dugongs were recorded on video near the study area (D. Cossa pers. comm.).

To identify dugong trails, aerial images were obtained using a low-cost commercial drone ($1500 US) with a digital RGB camera (DJI, Phantom 4-Pro). Aerial images were taken in nadir (looking straight downward), using Pix4Dcapture software, following regular transects in pre-programmed flights at an altitude of 80 m, resulting in an image resolution of 2 cm pixel^{-1} (Table 1). During transects, images had a 70% forward overlap and 60% lateral overlap. All images were geolocated by the internal GPS of the drone. Collected images were imported into Pix4Dmapper desktop software to generate high-resolution aerial maps with corrected perspective (orthomosaics). For each orthomosaic, we selected 10 ground control points (GCPs), using fixed structures distributed over

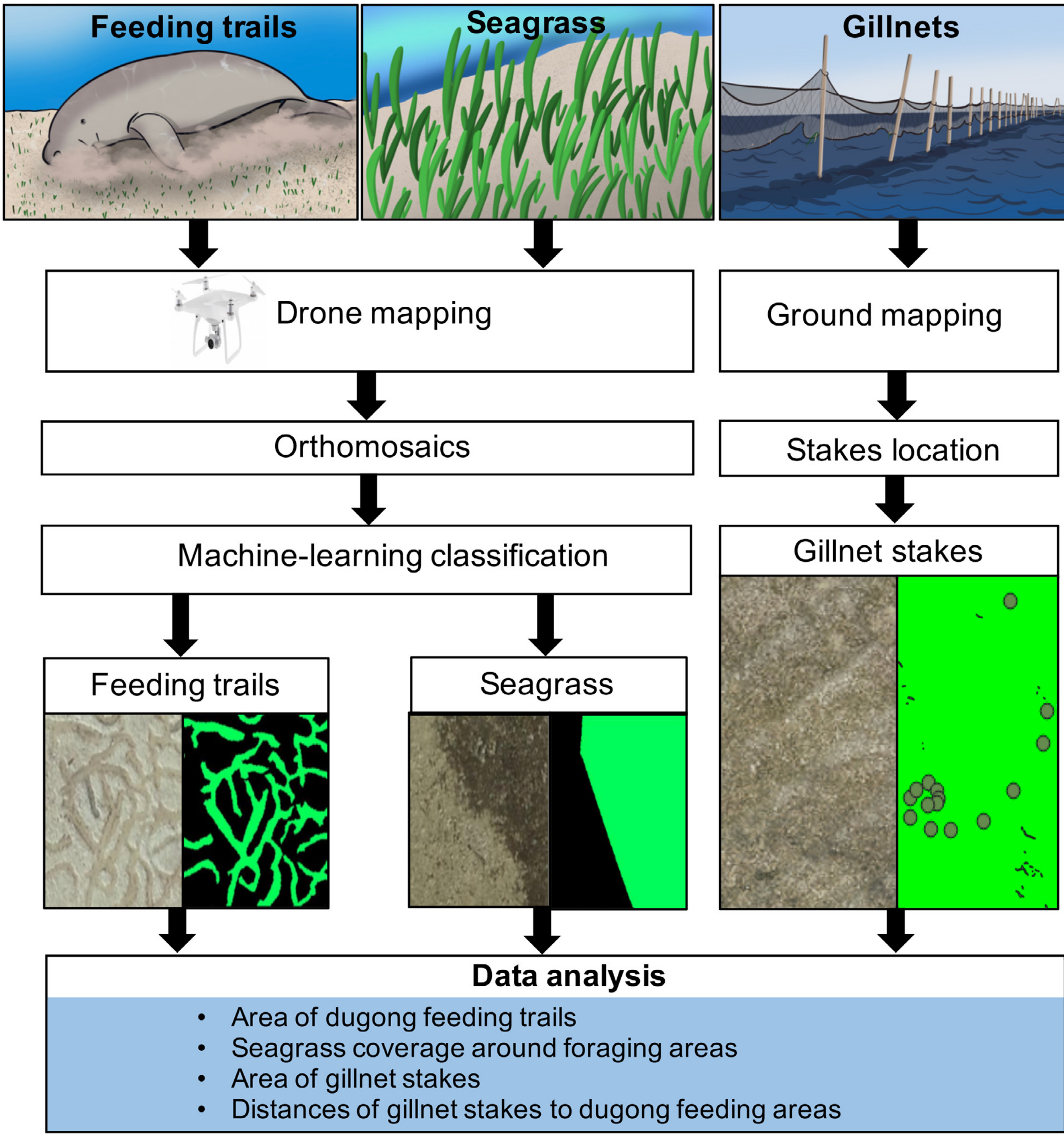

Fig. 2. Steps used for automated and manual analysis in dugong foraging areas, seagrass coverage, and gillnet mapping

the aerial observation area. The coordinates of each GCP were recorded using a GPS (Garmin GPSMap 64s) with a positioning error of ~3 m.

To validate the accuracy of the drone image capture and ML model used for classifying dugong feeding trails and associated seagrass, ground-truthing was conducted simultaneously with the drone image capture by 4 observers at both sites. During the ground-truthing process, a random subsampling of feeding trails was performed inside the dugong feeding grounds. The position and condition (old vs. new) of the feeding trails as well as the seagrass species present were recorded along with GPS coordinates. These recordings were conducted simultaneously with drone flights and at a sampling distance of around 30–50 m. Evidence of excavating feeding trails as a common feeding method was found in both locations, as the area is characterized by soft sedi-

Table 1. Drone flight information during the sampling period in 2020

Date	Site	Area covered (km^2)	No. of images	Flight time (min)
04-Jun	Saco West	0.89	705	80
05-Jun	Saco East	1.06	780	74
09-Jul	Saco West	0.89	685	52
10-Jul	Saco East	0.83	626	83
08-Aug	Saco West	0.82	636	70
09-Aug	Saco East	1	747	89
10-Sep	Saco West	0.71	554	73
09-Sep	Saco East	1	761	58
19-Oct	Saco West	0.91	660	74
20-Oct	Saco East	0.99	721	83
13-Dec	Saco West	0.92	714	72
12-Dec	Saco East	0.96	773	76

ments in which visible feeding trails can be observed. This feeding method was also reported by Fernando et al. (2014) (Fig. S1 in the Supplement at www.int-res.com/articles/suppl/m716p123_supp.pdf). The condition of the feeding trails was registered following D'Souza et al. (2015), whereby feeding trails were classified as 'new' in cases where depressions caused by grazing action were evident, with sediment and rhizomes visible. Feeding trails were classified as 'old' when depressions were less distinct, covered with plants, and rhizomes were no longer visible. The feeding trails were classified as either straight or in meandering lines, ranging from 0.4 m to several meters in length and 19.1–24.6 cm in width (n = 30). The aging of feeding trails was not tested during the survey. The feeding trail patterns were different in each month, assuming that each surveyed month represented independent observations (Fig. S1).

Before conducting automated classification, a visual census of dugong feeding trails was performed on all orthomosaics to identify the locations of dugong foraging areas within the surveyed areas, which would aid in further analysis (Fig. S2).

2.2. Automated analysis to detect dugong feeding trails and seagrass coverage

Dugong feeding trails and seagrass coverage were classified using an ML geo-spatial imagery platform, Picterra (https://picterra.ch). To develop the classifiers, detectors were trained to identify feeding trails and seagrass meadows by analyzing images using deep-learning algorithms. The detectors were created using an architecture for image segmentation based on U-net convolutional networks (Ronneberger et al. 2015).

The training data set for the dugong feeding trails and seagrass coverage detectors was generated by manually annotating images based on information from ground-based observations from each surveyed month. Annotations were made by drawing polygons inside the orthomosaics and selecting the desired feeding trails or seagrass areas while avoiding undesirable features. Only visible trails were annotated. Detectors were trained using orthomosaics from all months to cover all light conditions encountered during the flights and avoid confusion with background features. A total of 188 and 65 annotations were used for the dugong feeding trails and seagrass coverage detectors, respectively. However, it was not possible to train the detector to distinguish old and new dugong feeding trails since old marks were not clearly visible at the sampling distance of 80 m used by the drones.

To evaluate the accuracy of both detectors, dugong feeding trails, and seagrass coverage, F1 scores were calculated. The F1 score is a measure of the accuracy of a binary classification model taking the false positive (FP) and false negative (FN) rates into account (Eq. 1) (Csurka et al. 2013), calculated as:

$$F1 = \frac{2 \times \text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \quad (1)$$

where precision represents the positive predictive value and is defined as TP/(TP + FP), while recall is defined as TP/(TP + FN), with TP denoting the true positive rate.

The spatial distribution, total area, and perimeter of dugong feeding trails as well as the area of seagrass were computed for each month using ML, and the results were exported to QGIS v.3.4 (QGIS Development Team 2022). The orthomosaics for October were excluded from the analysis due to poor mosaic quality caused by high levels of sun glint reflection. The percentage of seagrass foraged by dugongs was determined by dividing the total area of dugong feeding trails and seagrass coverage generated through orthomosaic segmentation in both areas (Saco West and Saco East) for each survey.

2.3. Fishing interactions around dugong foraging areas

Gillnet fishing is a common practice in the study area, where fishermen utilize permanently fixed fishing structures (stakes) to deploy temporary nets.

These stakes are made of wood and are arranged in different configurations and lengths among fishing sites. During each drone survey, the GPS position of gillnet structures was recorded using a Garmin GPSMap64s in both Saco West and Saco East. The number of stakes found within the surveyed areas was counted. Since the arrangement of the stakes was not in a straight line but varied between structures, the perimeter and area were measured by drawing polygons close to the stakes, with a ~50 cm buffer around each net (see Table 4, Fig. 4b, Fig. S3).

To determine the overlap between fishing areas and dugong feeding areas, the data were imported into QGIS, and shapefiles with the gillnet stakes and gillnet stake areas around dugong feeding locations were generated. Manual annotations were made by overlaying polygons on the areas of dugong feeding trails using QGIS geoprocessing tools. The nearest distance of the gillnet fishing structures (stakes) to the dugong feeding areas was calculated per month at both sites using the 'geopandas' Python library (Jordahl et al. 2021).

2.4. Statistical analyses

All statistical analyses were conducted using R v.4.2.0. Normality of the data was tested using a Shapiro-Wilk test (α = 0.05), and homoscedasticity was assessed with Levene's test. Data for dugong feeding trails were transformed using square root transformations to ensure normality and homogeneity of variances. Dugong feeding trails, expressed as density (number of feeding trails km^{-2}) were compared among the surveyed months and study locations using a parametric 2-way ANOVA. Post hoc comparisons using Tukey's HSD test (at a significance level of α = 0.05) were conducted when significant differences were found.

To evaluate the influence of fishing activities (distance of gillnet stakes from dugong feeding areas and total area of gillnet stakes) on the density of dugong feeding trails, a generalized linear model (McCullagh & Nelder 1989) with a negative binomial distribution and logarithmic link function was performed. The explanatory variables included site, time, distance from gillnet stakes, and area of gillnet stakes, while the response variable was dugong feeding trail density.

A Poisson distribution with a log-link function was tested since the number of feeding trails represents density data (Table S2). The negative binomial distribution was then chosen to adjust for the over-dispersion of the data (Mangiafico 2016). Before the analysis, explanatory variables were checked for collinearity using Spearman rank correlation. As a result, the number of gillnet stakes was not included in the final model. The assumptions of the model were evaluated by comparing the residuals vs. predicted values, and no deviations from expectations were observed. The final model was selected based on the likelihood ratio and the lower Akaike information criterion (AIC) value. Finally, the explanatory power (deviance explained) of the model was calculated.

3. RESULTS

3.1. Automated analysis of dugong feeding trails

A total of 385 and 538 field observations were recorded as feeding trails on the seagrass meadows in Saco West and Saco East of Inhaca Island, respectively, during all sampling periods (Table S1). Drone surveys allowed for coverage of an area of approx. 1 km^2 in 76 ± 6.7 min of drone flights with a resolution of 2 cm pixel^{-1}. The classification of feeding trails and seagrass beds showed an F1 accuracy score of 80% for dugong feeding trails and 93.3% for seagrass (Table 2).

The highest density of feeding trails was observed in Saco East in August (mean ± SD: 6040 ± 4678 trails km^{-2}), while in Saco West the density was less than half, at 2160 ± 1904 trails km^{-2} (Fig. 3a). The mean number of feeding trails changed significantly between the surveyed months (ANOVA, F_4 = 3.15, p = 0.026) and locations (ANOVA, F_1 = 4.87, p = 0.034). Four seagrass species were found as dominant in dugong foraging areas (Fig. 4), with 85.8% of dugong feeding trails observed within *Halodule uninervis*; <10% of feeding trails were also observed in mixed seagrass meadows dominated by *Thalassia hemprichii* in both Saco West

Table 2. Accuracy of detectors developed for automatic detection using machine learning for dugong feeding trails and seagrass. The probability of detecting a feature is determined by precision and recall, which are used to calculate the F1 score (see Eq. 1)

Detectors	No. of annotations	Precision (%)	Recall (%)	F1 Score (%)
Dugong feeding trails	188	72	91	80
Seagrass	65	87.5	100	93.3

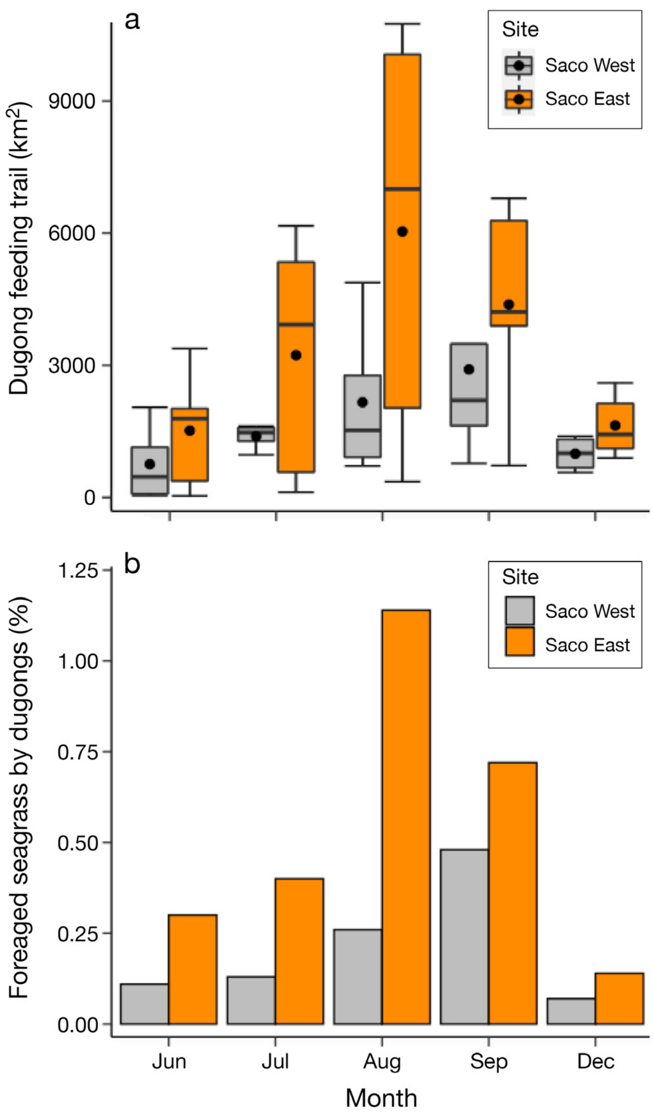

Fig. 3. (a) Dugong feeding trail density at Saco West and Saco East during surveyed months, determined through drone surveys and machine learning. The lower (Q1) and upper (Q3) quartile, median, and mean observations are representative of all months. (b) Percentage of seagrass foraged by dugongs at Saco West and Saco East during surveyed months, determined through drone surveys and machine-learning

and Saco East (Table 3). However, the highest percentage of seagrass foraged by dugongs was found to be less than 1.5% of the total seagrass available in both sites in August (Fig. 3b). The dugong feeding trails were non-randomly distributed in both studied sites during all sampling periods, suggesting that dugongs regularly use the same meadows and show a spatially structured feeding pattern (Fig. 4, Fig. S3).

3.2. Fishing and dugong foraging areas overlap

During all surveyed months, gillnet stakes were present in both Saco West and Saco East of Inhaca Island. The number of stakes did not vary throughout the sampling period, and fishermen reported that they replace old stakes with new ones in the same position for gillnet deployment. The number of stakes in Saco East was 3.7 times lower (n = 52) than in Saco West (n = 195), and the area covered by gillnet stakes was also 2.6 times lower (18 527 m^2) in Saco East compared to Saco West (48 461 m^2; Fig. 4, Table 4). This represents 2.9 times lower gillnet stakes in Saco East per surveyed area (0.97 ± 0.08 km^2) compared to Saco West (0.86 ± 0.08 km^2). Generalized linear models (GLMs) indicated that 70.5% of the deviance in the frequency of dugong trails could be explained by site, time, distance of the gillnet structures from the dugong feeding area, and gillnet structure area. The frequency of dugong feeding trails decreased with an increase in the distance from gillnet structures ($p = 0.006$; Fig. 5a, Table 5). A positive correlation between dugong feeding trails and the area of gillnet stakes was found ($p < 0.0001$), particularly in Saco West (Fig. 5b, Table 5). Differences in the frequency of dugong feeding trails between sites ($p < 0.0001$) and survey months were found to be statistically significant ($p = 0.003$).

4. DISCUSSION

This study demonstrates that the use of drones and ML can be employed to detect dugong feeding grounds at a meadow scale by indirectly surveying indicators of feeding activity. Since obtaining accurate estimates of individual dugong population sizes is challenging due to the species' elusive nature, indirectly monitoring their presence through cost-efficient drone observations could contribute to their conservation and management by tracking their activities. In both study sites, there was a clear overlap between dugong foraging areas and fishing grounds, increasing the risk of dugong entanglement when the gillnets are deployed on the stakes. Therefore, establishing effective management initiatives to control gillnet fishing activity in the area is crucial to sustain the small dugong population without disrupting their feeding habitat. This presents an opportunity to support conservation and management strategies for dugong populations in intertidal seagrass meadows.

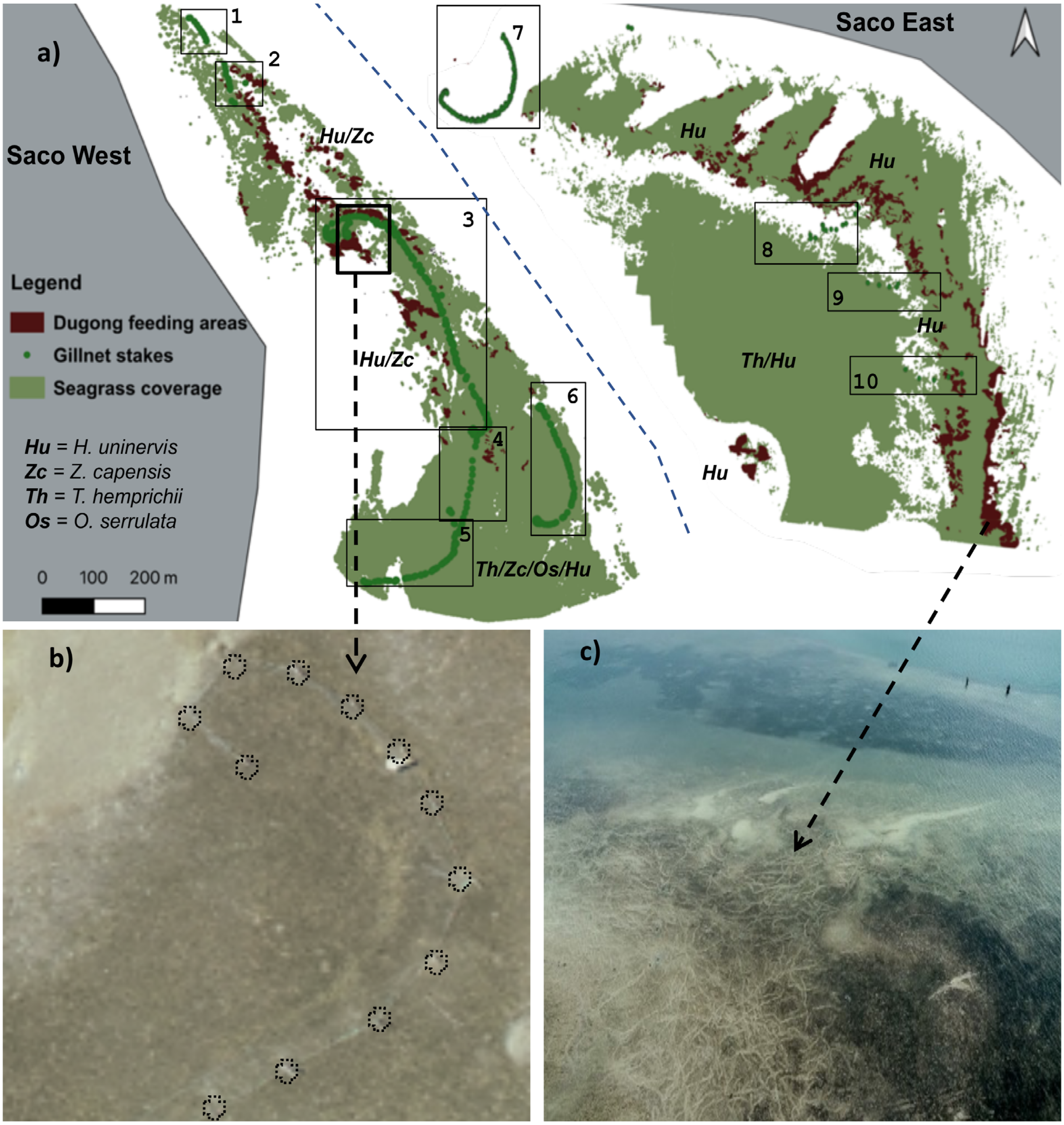

Fig. 4. (a) Location of the gillnet structures (within surveyed quadrats 1 to 10) and the dugong foraging areas (manually annotated) in seagrass meadows of West Saco and East Saco. Seagrass species in both sites were also registered as single or mixed meadows: Hu: *Halodule uninervis*; Zc: *Zostera capensis*; Th: *Thalassia hemprichii*; Os: *Oceana serrulata* (formerly *Cymodocea serrulata*). (b) Gillnet structures deployed by fishermen (stakes highlighted in black), and (c) a drone image of dugong feeding trails in the area

4.1. Automated analysis for monitoring dugong foraging hotspots

Wildlife surveys using drones have been reported to be more precise and have significantly higher counts due to the ability to collect data with higher accuracy and precision and less bias (see Hodgson et al. 2016, 2018). ML has been integrated with ecological workflows (Tuia et al. 2022), with convolution neural networks (CNNs) widely used as a deep-learning approach to monitoring wildlife (e.g. Corcoran et al. 2021, Dujon et al. 2021), allowing accurate

Table 3. Total number of dugong feeding trails observed and the seagrass species where they were located in the study areas. Asterisks indicate mixed meadows dominated by species mentioned

Seagrass composition	No. of feeding tails	%
Halodule uninervis	792	85.8
*Thalassia hemprichii**	73	7.9
*Zostera capensis**	50	5.4
Oceana serrulata (formerly *Cymodocea serrulata*)*	7	0.8
Zostera capensis + *Oceana serrulata**	1	0.1

Table 4. Gillnet stakes deployed by fishermen in Saco West and Saco East during the sampling period. The exact location of gillnet stakes (represented by numbers) is shown in Fig. 4

Location	Gill-net stakes (no.)	Gill-net perimeter (m)	Gill-net area (m^2)
Saco West [1]	10	60.7	2339
Saco West [2]	9	53.1	2736
Saco West [3]	88	727.7	21008
Saco West [4]	17	193.5	4021
Saco West [5]	25	281.2	8803
Saco West [6]	46	315.6	9555
Saco East [7]	36	337.4	10489
Saco East [8]	6	152.9	2175
Saco East [9]	5	78.5	1785
Saco East [10]	5	145.1	4079
Sum West	195	1631.8	48462
Sum East	52	731.9	18527

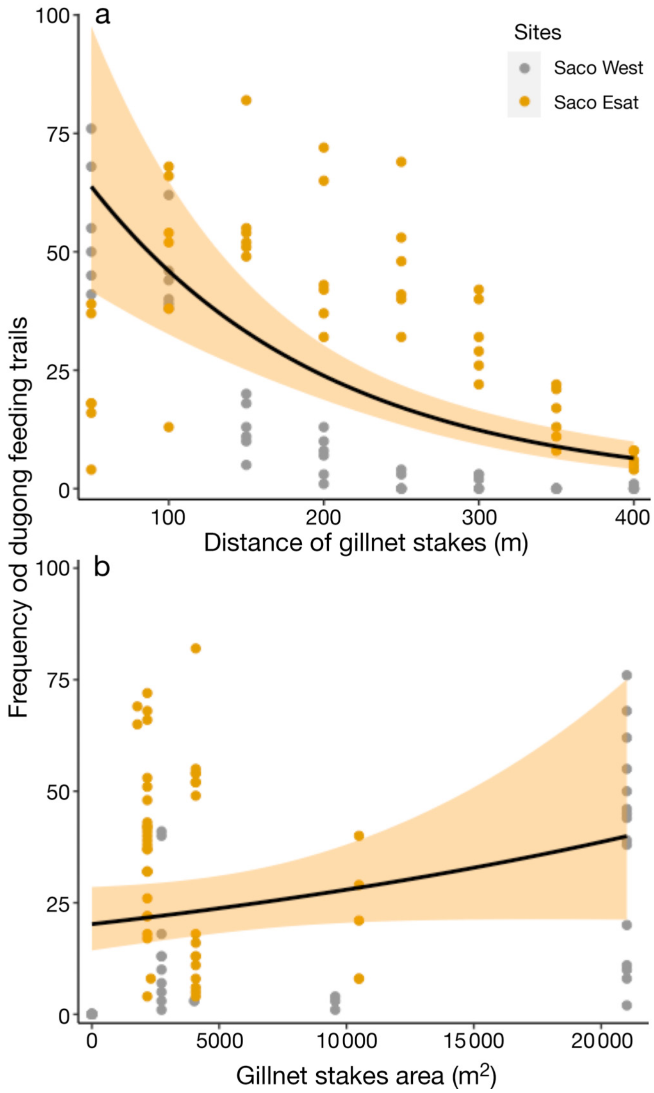

Fig. 5. Negative binomial regression model showing the interaction of (a) distance from gillnet stakes and (b) total area of gillnet stakes on the frequency of dugong feeding trails during all sampling periods. Plotted points correspond to the fitted values of the model. Panels display the fitted effect (smooth line) and 95 % confidence intervals (shaded bands)

detections of species with small training data sets compared to other ML methods. For example, automated analysis of drone imagery has emerged as a novel application for monitoring complex aggregations of wildlife such as birds (Hong et al. 2019) and harbour seals (Infantes et al. 2022). This combination of drones and automated analysis allows for time-efficient monitoring of wildlife, particularly in areas that are difficult to access.

The workflow developed in this study uses drone images and ML–CNNs to classify dugong feeding trails and associated seagrass meadows, providing a potentially powerful method for assessing the feeding patterns of this threatened species in intertidal seagrass meadows. Yamato et al. (2021) used a deep-learning approach to develop methods for the classification of dugong feeding trails based on a ground sampling distance of 1 and 0.5 cm pixel^{-1}, achieving model accuracies of 89.5 and 87.7 %, respectively. Additionally, aerial photography and photogrammetry were successfully employed to sample dugong feeding activity and seagrass change at a large spatial scale in Port Curtis and Rodds Bay, Australia (Rasheed et al. 2017). In our study, flights were designed to have an image resolution of 2 cm pixel^{-1} (at 80 m altitude), enabling the monitoring of larger areas in less time (covering approx. 1 km^2 in 76 ± 6.7 min of drone flights) without compromising model accuracy (F1 accuracy of 80 and 93.3 % for dugong feeding trails and seagrass coverage extractions, respectively). However, the classification of dugong feeding trails was affected by drone image quality

Table 5. Results of generalized linear model (GLM) that best fit the variation of numbers of dugong feeding trails based on site, surveyed months, distance of gillnet stakes from dugong feeding area, and area of gillnet stakes. AIC: Akaike's information criterion

Source	Parameter estimates	SE	p(>|z|)	Deviance explained (%)
Frequency of dugong trails				70.5
(Intercept)	2.22	0.31	<0.0001	
Months:				
June (reference)				
Dec	–0.79	0.26	0.003	
Site:				
Saco West (reference)				
Saco East	2.22	0.18	<0.0001	
Distance from gillnet stakes:				
50 m (reference)				
200 > 250 m	–0.80	0.30	0.007	
250 > 300 m	–1.35	0.29	<0.0001	
300 > 350 m	–2.01	0.32	<0.0001	
350 > 400 m	–2.90	0.34	<0.0001	
Area of gillnet stakes	9.06×10^{-5}	1.33×10^{-5}	<0.0001	
Null deviance: 366.12 on 95 df				
Residual deviance: 108.17 on 81 df				
AIC: 700.82				

when mosaics showed high sun glint reflections, which lead to the exclusion of the October orthomosaics and limited the detection of old feeding trails. Additionally, drone flights were limited to low tides during spring tides, constraining the time available for surveys. Yamato et al. (2021) also reported incidences of FPs and FNs when extracting old feeding trails in intertidal seagrass, independent of image quality. Therefore, it is essential to pay close attention to weather conditions (e.g. high wind, rain, sun angle) to ensure the safety of operations and maintain image quality. Furthermore, drone image capture was enhanced through 3 approaches: (1) conducting early morning flights when the sun is lower and the thermally driven winds are minimal; (2) flying during low tide when vegetation is exposed, reducing sun glint on the water surface; and (3) orienting the camera backwards to the sun.

Our results revealed the presence of feeding trails during all surveyed periods, showing that dugongs regularly visit and forage on seagrass around Inhaca Island. So far, there is no clear evidence that the dugong population around Inhaca Island is resident in the area. However, further studies using drones could answer this question by monitoring hotspots and possibly identifying and tracking individuals using the scars in the dorsal area, as described by Infantes et al. (2020). Findlay et al. (2011) reported an observed dugong population during the 1970s at Inhaca Island (Maputo Bay) of 8–10 individuals, whereas only 1–4 individuals were observed through aerial surveys in 2006 and 2009, respectively (Fernando et al. 2014). Small and localized dugong populations have also been reported in other Western Indian Ocean countries, such as Tanzania, with ~32 dugong sightings since 2000, including 24 incidental captures in gillnets and 8 live animal observations (Muir et al. 2003), the Kenyan coast, with an estimated population size of ~20 individuals (Awadh et al. 2021), and in Mayotte lagoon, Indian Ocean, with ~5 dugongs recorded in 2005 (Kiszka et al. 2007). The lack of accurate estimation of dugong population sizes, as well as the relationship to habitat usage, makes designing management strategies for dugongs a challenge. This highlights the need for low-cost, novel methods capable of monitoring dugong abundancies and behaviour in the absence of animal sightings.

The seagrass species *Halodule uninervis* was found to be common around dugong feeding trails, while the number of trails was less frequent (<10%) in meadows dominated by *Thalassia hemprichii*, *Zostera capensis*, and *Oceana serrulata* (formerly *Cymodocea serrulata*) (Table 3). Previous studies around Inhaca Island (Fernando et al. 2014) and in other locations such as Moreton Bay and Hervey Bay, Australia (see Preen 1995a, Sheppard et al. 2007), and Sibu Archipelago, Malaysia (Heng et al. 2022), have also reported the presence of feeding trails on pioneer seagrass species such as *H. uninervis* and *Halophila ovalis*. Dugong foraging strategies are determined by their nutritional and energetic needs, and *H. uninervis* is considered to be an important nutritional seagrass species due to a low content of indigestible fibre and high nitrogen content (Marsh et al. 1999, Sheppard et al. 2007). In this study, the area of seagrass foraged by dugongs was less than 1.5% of the total seagrass present (Fig. 3b), suggesting that food availability is not a limiting factor in dugong habitat usage since the dugongs had access to unutilised seagrass biomass and seagrass species.

However, our results also indicate that dugongs regularly feed in the same area of the *H. uninervis* meadows (Fig. 4, Fig. S3). This feeding behaviour, known as 'cultivation grazing', was described by

Preen (1992, 1995b). It allows dugongs to enhance the regrowth of pioneer species and improve the quality of their diet. While we did not evaluate the seagrass quality in this study, a separate investigation on the nutritional composition of seagrass species within dugong feeding areas at Saco of Inhaca Island revealed that *H. uninervis* had the highest nutritional value in terms of whole-plant nitrogen, crude protein, and low crude fibre compared to adjacent *Zostera capensis* meadows (Chunguane 2021). This suggests that this strategic feeding pattern may be associated with higher seagrass quality. The regular use of seagrass meadows by small populations of dugongs has also been described in other studies (De Iongh et al. 2007, D'Souza et al. 2015, Heng et al. 2022), indicating that 'cultivation grazing' is not limited to large herds of dugongs as described by Preen (1995b). This highlights the importance of monitoring the condition and enhancing conservation efforts of *H. uninervis* meadows in the study site.

The number of dugong feeding trails varied among the months, suggesting that dugongs modify their foraging behaviour dynamically in response to various environmental factors, including water temperature, seagrass availability (Sheppard et al. 2006), human disturbances (Hodgson & Marsh 2007), and other seasonal cues such as mating, pupping, and lactating. Surprisingly, the highest numbers of feeding trails were observed in August, which is typically a colder month, while the lowest numbers were observed in December, the warmest month. Similar to our results, Zeh et al. (2018) found that during the warmest year, dugongs stayed outside Moreton Bay, Australia, for longer periods. They suggested that inter-annual differences in seagrass biomass might be related to this behaviour. In contrast, seasonal movements of dugongs between foraging grounds in response to low temperatures were previously reported in Australia (Marsh et al. 1999, Sheppard et al. 2006), where they regularly swim with the currents in and out of the bay during winter to move between cool-water feeding areas and warm-water resting areas. Although significant differences were found between months, sea temperatures were not recorded, and a longer-term replication of the study would be necessary to assess these patterns.

4.2. Fishing interactions around foraging areas

Our results indicate that dugong feeding areas are frequently located in close proximity to gillnet fishing activity (<400 m), which raises concerns about potential conflicts between these activities. Dugongs are particularly vulnerable to human activities due to their dependence on seagrass habitats, which are often situated in coastal areas that are used heavily by humans for fishing and other activities (Marsh et al. 1999). The use of gillnets without proper law enforcement along Mozambique's coastline is believed to be a primary cause of dugong entanglement (Cockcroft & Krohn 1994, Findlay et al. 2011). Entanglement in mesh nets and traps set by fishers constitutes a main concern in many countries (Marsh et al. 2002). For instance, Jaaman et al. (2009) estimated that around 479 dugongs were unintentionally caught in artisanal gillnets in the east of Malaysia from 1997 to 2004. Dugongs have also been reported to be caught in gillnets in East African countries. In the Bazaruto Archipelago (southern Mozambique), which has the largest dugong population on the East African coast, the number of dugongs caught incidentally is still unknown. However, it has been estimated that 4–6 individuals are caught each year out of an estimated population of 359 individuals (Findlay et al. 2011). Thus, managing gillnet fishing in areas where dugongs forage may reduce their incidental capture.

This study also indicates that dugongs primarily feed in Saco East, where the number and area covered by gillnets is lower than in Saco West. This finding suggests that dugongs may be avoiding areas with fishing gear and the risk of entanglement, as supported by Budiarsa et al. (2021)'s observations of dugongs frequently visiting locations far from anthropogenic disturbances. Thus, monitoring these areas is crucial for enhancing the efficacy of future conservation efforts.

4.3. Management implications and conclusions

Interest in developing time- and cost-efficient approaches to acquire data relating to animal behaviour has been growing and can be combined with spatial risk-assessment models and/or interviews with fishermen to develop a more holistic understanding of challenges and solutions in conservation (Grech & Marsh 2008, Briscoe et al. 2014). A particular problem is that the reporting of incidental captures of marine mammals in small artisanal fisheries is scarce. This is a significant challenge for the conservation and management of dugongs and sustainable fisheries initiatives worldwide (Marsh 2000, Marsh et al. 2011).

Dugongs are protected by national legislation in most countries. In Mozambique, the protection of coastal ecosystems and biodiversity as well as the regulation of fishing practices (e.g. fishing gears, fishing licenses, and fishing closure seasons) are detailed in national instruments such as the Environmental Act 20/97 and the Fisheries Act 22/2013. The Forest and Wildlife Regulation (Decree 12/2002) legislates protections for endangered species (such as sea turtles and dugongs) and outlines fines for illegal hunting. However, enforcement is still ineffective, making the implementation of appropriate management initiatives crucial. Considering the findings of this study, the importance of establishing initiatives to protect dugong foraging areas should be emphasized. Specifically, we recommend:

(1) Monitoring dugong feeding hotspots and gillnet use. Monitoring dugong feeding hotspots and seagrass beds using innovative technology such as drones to obtain cost-efficient data is key to supporting management initiatives. Tracking the presence of dugong feeding trails can provide valuable information about their presence in specific areas, their distribution, and their relative abundance. Simultaneously monitoring the extent of seagrass to assess changes in plant biomass available for dugongs, along with monitoring feeding trails, can be performed during aerial surveys using drones. In addition, monitoring fishing activities around dugong feeding areas might prove crucial to avoiding dugong entanglements in the future. Tracking gillnet deployments using drones or field surveys around dugong feeding hotspots might enable effective enforcement of existing legislation to reduce incidental dugong bycatch. Moreover, data obtained by monitoring gillnets and dugong feeding hotspots can be used to identify locations where these activities overlap. Here, we emphasise the use of drones coupled with automated analysis and systematic surveys (every 2, 4, or 6 months) as a method for identifying dugong foraging areas, seagrass beds, and gillnets, and for collecting meaningful data that can be later applied to design management actions.

(2) Involvement of local communities for managing gillnet use. The involvement of local communities in the preservation of dugong foraging areas is key to dugong conservation. Once dugong feeding hotspots have been identified, a significant challenge is convincing fishers to abandon harmful fishing practices without providing alternative sources of income. Acoustic pingers designed to reduce bycatch by producing aversive sounds that keep marine mammals away from nets have been shown to be ineffective deterrents in reducing dugong mortalities in fishing nets (Hodgson et al. 2007). Therefore, areas with high levels of gillnet fishing activity should be prioritised, and reducing gillnet operations (including controlling the size, length, and arrangements of nets deployed) should be considered as management measures. For example, in the Saco area, deployed gillnets form a barrier for dugongs, preventing them from moving from the deeper channels to seagrass beds. This is particularly evident in Saco West, where a total of 1630 m of gillnets are deployed. Therefore, reducing the total amount of nets and increasing the spacing between them would allow for more dugong movement, reducing the risk of bycatch.

In addition, developing culturally appropriate education and awareness programs targeting key fishing areas by conducting interviews with fishers, including questions on the extent of gill netting use, should be carried out alongside an evaluation of the value of fishing resources collected by gillnet fishers and the number of fishers involved. Based on this information, additional management options can be designed to target these fishers, including developing alternative livelihoods in exchange for the reduction of gillnet usage. The adoption of educational and awareness programs, as well as compliance with best practices to reduce threats to dugongs and their habitat, has been an important management measure in many countries. For example, Hines et al. (2005) emphasized the importance of developing educational materials and enforceable regulations along the Andaman Coast, Thailand, as an example of effective management measures for dugong conservation. This also involves the active participation of local stakeholders in surveillance programs. Educating coastal communities about compliance with fishing regulations is an important management recommendation for reducing incidental dugong bycatch in Sabah, Malaysia (Jaaman et al. 2009). Indeed, monitoring programs to control gillnet fishing should involve the participation of local communities, as in most of the dugong's range, accidental entanglements by gillnets come from locally based artisanal fisheries (Marsh et al. 2002).

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