Aquatic Conservation: Marine and Freshwater Ecosystems

WILEY

ARTICLE OPEN ACCESS

Aerial Video Surveys and Spatial Prioritization Reveal Conservation Opportunities for Endangered Dugongs in New Caledonia

Laura Mannocci[1] | Solène Derville[2,3] | Raphael Seguin[1] | David Mouillot[1,4]

[1]MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, Montpellier, France | [2]Marine Mammal Institute, Department of Fisheries, Wildlife, and Conservation Sciences, Oregon State University, Newport, Oregon, USA | [3]UMR ENTROPIE (UR-IRD-IFREMER-CNRS-UNC), Nouméa, New Caledonia | [4]Institut Universitaire de France, Paris, France

Correspondence: Laura Mannocci (laura.mannocci@ird.fr)

Received: 7 March 2024 | **Revised:** 8 July 2024 | **Accepted:** 29 July 2024

Funding: This project received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 845178 ('MEGAFAUNA'). The aerial surveys were funded by Monaco Explorations.

Keywords: aerial imagery | Coral Lagoon | dugong | habitat modelling | marine protected areas | sirenians

ABSTRACT

1. The dugong population of New Caledonia was recently assessed as endangered by the IUCN due to its low genetic diversity, its limited number of mature individuals and the continuing threats from poaching, collisions, incidental capture and seagrass degradation. No-take marine protected areas (MPAs) implemented in critical dugong habitats may efficiently safeguard the remaining population by directly or indirectly reducing these threats.
2. The goal of the present study was to develop scenarios of MPAs targeting dugongs in New Caledonia, focusing on the central west coast where they are known to aggregate during austral winter.
3. We combined 7 h of video surveys from a light airplane and habitat modelling to derive regional predictions of dugong density. We then used these predictions to (1) assess the proportion of dugong population abundance protected by existing no-take MPAs and (2) develop spatial prioritization scenarios based on explicit dugong abundance targets.
4. We found that existing no-take MPAs only protect 11% of the estimated dugong population in the study region, leaving most dugong hotspots unprotected. For the same protected area coverage, prioritization based on abundance would allow protecting nearly five times more dugong individuals.
5. Given the endangered status of the population, a 70% abundance prioritization scenario is warranted, requiring the expansion of existing MPAs toward reef passes and shallow nearshore areas where dugong abundance is the highest. Our study offers an opportunity for dynamic spatial management through the implementation of a seasonal closure strictly restricting human activities in areas where dugongs aggregate in winter.

1 | Introduction

Marine megafauna includes iconic marine mammals, sea turtles, sharks and rays that are increasingly threatened worldwide (Ripple et al. 2019; Pacoureau et al. 2021; Chen et al. 2022). Today, over 30% of marine megafauna species evaluated by the International Union for Conservation of Nature (IUCN) are at risk of extinction based on their rates of decline, low population sizes, reduced geographic distributions and high habitat fragmentation (IUCN 2022). These species face disproportionate risk in tropical coastal waters where human population growth, industrial intensification and rapid development have led to overfishing and habitat degradation (Dulvy et al. 2021; Li et al. 2023; Sherman et al. 2023). To mitigate these threats, halt species decline and promote their recovery, marine protected areas (MPAs) constitute important spatial conservation tools, as long as they are well-designed, restrictive and properly enforced (Grorud-Colvert et al. 2021). While MPAs provide little conservation benefits for highly mobile megafauna (Gilmour et al. 2022; Hampton et al. 2023), even small no-take MPAs can effectively protect species with more restricted spatial occupancy such as certain sharks and sea turtles (Dwyer et al. 2020; Hays et al. 2021; Roberts et al. 2021; Heldsinger et al. 2023).

The dugong (*Dugong dugon*), globally listed as vulnerable on the IUCN Red List of Threatened Species and locally facing high risks of extinction, is present in the coastal waters of 38 countries spanning the Indo-Pacific (Marsh and Sobtzick 2019). As megaherbivores, dugongs primarily base their spatial occupancy patterns on the seagrass meadows they feed on (Sheppard et al. 2010; Tol, Coles, and Congdon 2016; Cleguer, Garrigue, and Marsh 2020). As such, no-take MPAs implemented in critical dugong habitats could contribute to their conservation by directly or indirectly reducing the risks of incidental capture in fishing gear, poaching and collision that are major threats for this species (Marsh and Sobtzick 2019).

The location of the New Caledonian dugong population at the eastern limit of the species' Indo-Pacific distribution range makes it particularly vulnerable to extinction. A recent study revealed the very low genetic diversity of this population and its strong differentiation from all genetically documented populations, confirming its low recovery potential (Garrigue et al. 2022). This information combined with the low number of mature individuals (estimated under 900) and the continuing threats from poaching, collisions with boats, incidental capture and seagrass degradation prompted the reassessment of the New Caledonian population from vulnerable to endangered in the IUCN Red List (Hamel et al. 2022). Another study by Cleguer et al. (2015) revealed a spatial mismatch between existing MPAs and areas with the highest dugong density off the central west coast of New Caledonia. This mismatch was likely driven by the omission of information on dugong distribution in the planning of MPAs, as well as the lack of quantitative conservation targets (Cleguer et al. 2015). Expanding MPAs to better safeguard remaining dugongs is now vital to protect the species from abatable threats and ensure its persistence in New Caledonia.

With the international commitment to protect at least 30% of the oceans by 2030 (CBD 2022), coined as the "30 × 30 target", systematic conservation planning is increasingly used to guide the expansion of the current MPA network (Pike et al. 2024). Systematic conservation planning relies on optimization algorithms to select areas that meet desired targets of species protection while minimizing the costs of conservation (McIntosh et al. 2017). Species protection targets are typically set as percent area coverages of species distributions (Jones et al. 2020; Jefferson et al. 2021), with the 30% target often used as a baseline reflecting the international area-based conservation target (Harris and Holness 2023). However, when it comes to protecting locally endangered populations, spatial conservation plans based on area coverages can miss important aggregation zones. Such aggregations are known to occur for dugongs in New Caledonia, with high reported abundances near passes of the barrier reef in the central west coast during austral winter (Garrigue, Patenaude, and Marsh 2008; Cleguer et al. 2017). To effectively protect these aggregations, it is critical to incorporate information on abundance in spatial conservation plans. Indeed, prioritization based on abundance has been shown to lead to more efficient conservation by targeting fewer sites with higher numbers of individuals compared to area-based prioritization, thus maximizing population-level benefits (Johnston et al. 2020). Conservation planning should also be tailored to the local context, setting higher targets for threatened populations in their core distribution zones (Harris and Holness 2023) while integrating socio-cultural considerations (Sandbrook et al. 2023).

In this study, our objective was to derive conservation planning scenarios for the protection of endangered New Caledonian dugongs in their core distribution zone during austral winter. We opted for video surveys using a GoPro fitted to an ultralight plane due to its ability to provide high-resolution data while minimizing observer bias (Mannocci et al. 2021). We first modelled dugong density distribution obtained from video surveys as a function of environmental predictors to infer regional abundance patterns. We then used these predictions to (1) assess the proportion of dugong population abundance protected by existing no-take MPAs and (2) develop MPA scenarios based on explicit dugong abundance targets. Our study reveals conservation opportunities for New Caledonian dugongs, calling for a prompt rezoning of the MPA network to protect this endangered population facing a high risk of extinction.

2 | Methods

2.1 | Study Region

The study region is located on the central west coast of New Caledonia's mainland (Figure 1a), which was previously identified as the core distribution area of dugongs in New Caledonia (Garrigue, Patenaude, and Marsh 2008; Cleguer et al. 2015). The central west coast is characterized by relatively shallow (< 20 m) and narrow lagoons (2–10 km wide) protected by a barrier reef, interrupted in several locations by deeper passes (< 30 m). This region includes four no-take MPAs (IUCN category IV), namely, Roche Percée/Baie des Tortues, Ile Verte and Ouano and Poé created in 1993, 1995, 2004 and 2006, respectively. These MPAs were originally designed to 'maintain, conserve and rehabilitate threatened endemic and emblematic species and to restore or reconstruct altered habitats'; however, neither of them mentions the dugong as one of the targeted species for protection (Cleguer et al. 2015). The study region is also included in the 'lagoons of New Caledonia' UNESCO World Heritage zone established in 2008 with dugong presence as one of the explicit reasons (UNESCO 2011) and in the West Coast Provincial Park created in 2009 (neither area falls under an IUCN protected area category due to unrestricted human activities). Finally, the entire lagoon and shelf waters of New Caledonia were recently identified as an Important Marine Mammal Area (IMMA) for the dugong and two species of cetaceans (IUCN-Marine Mammal Protected

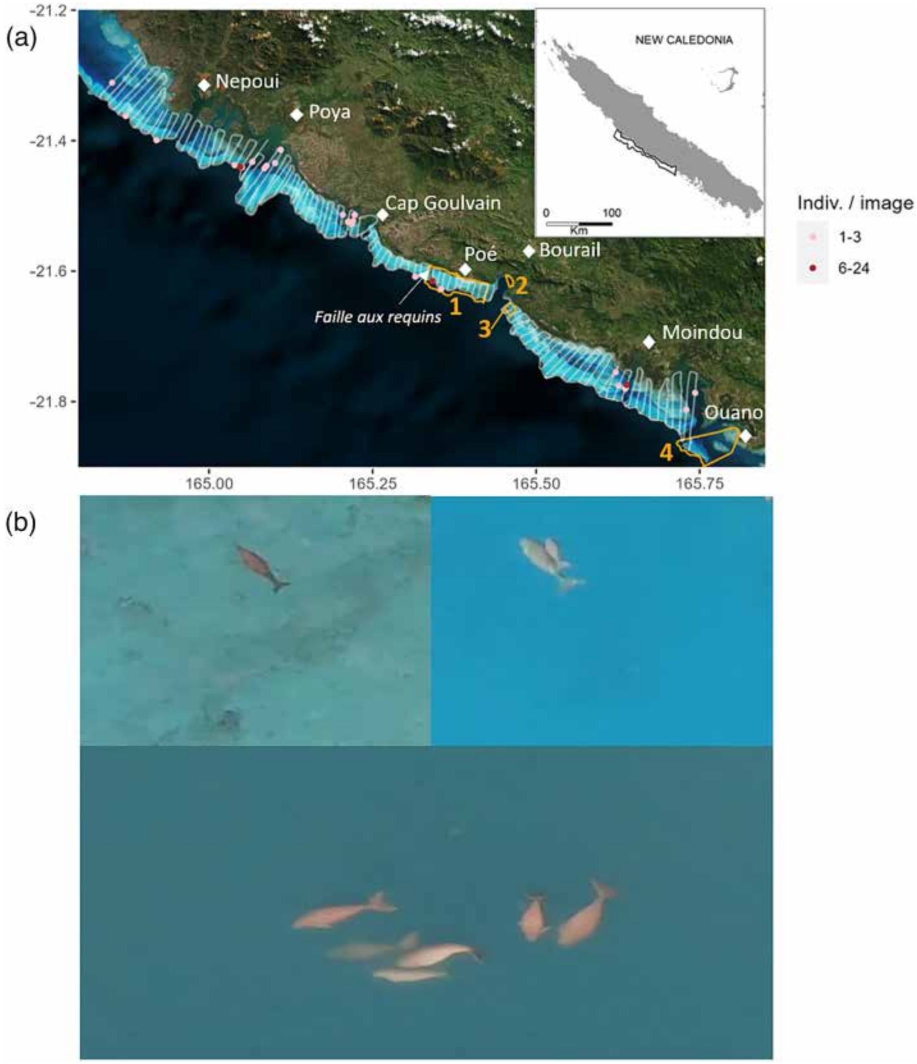

FIGURE 1 | (a) Map of the area covered by aerial video surveys showing the number of dugong (*Dugong dugon*) individuals per image (after removal of duplicates) along the transects (in white) and existing no-take marine protected areas (in orange; 1: Poé; 2: Roche Percée/Baie des Tortues; 3: Ile Verte; 4: Ouano). The pass of Poé is locally referred as *faille aux requins*. Source of background satellite imagery: OpenStreetMap. (b) Examples of images with dugongs (single individual observed in the lagoon, mother-calf pair and herd observed near the reef pass). Detailed maps of dugong observations are provided in Figure S3.

Areas Task Force 2021). However, IMMAs are discrete zones that have the potential to be identified and managed for conservation rather than legal entities.

2.2 | Aerial Video Surveys

Sirenians, including the dugong and the three species of manatees, have been traditionally surveyed from manned airplanes with onboard observers (Miller et al. 1998; Garrigue, Patenaude, and Marsh 2008; Hagihara et al. 2018) and more recently from unmanned aerial vehicles to acquire high-resolution images (Cleguer et al. 2021; Edwards et al. 2021; Hodgson, Kelly, and Peel 2023). In this study, we opted for a hybrid approach, namely, a survey from a manned airplane equipped with a video camera (Mannocci et al. 2021), which allowed the collection of high-quality image data for abundance estimation while ensuring large flight endurance (up to 4 h) to cover a large area (Mannocci et al. 2021). Specifically, video surveys were conducted from an amphibious ultralight motor plane (ULM; AirMax SeaMax) fitted with a GoPro Hero Black 7 camera. The GoPro camera was mounted under the right wing of the ULM, pointing downward and configured to record videos at a rate of 24 frames per second in linear field of view mode (eliminating the fish-eye effect typically captured by GoPro's wide-angle lens) at a resolution of 2.7 K (2704 × 1520 pixels) with integrated image stabilization. The camera was manually triggered before each flight. Telemetry data, including GPS coordinates and altitude, were recorded by the GoPro along each flight (at a rate of 8–12 positions per second). The plane followed 145 predefined transects oriented perpendicular to the coast and spaced ~1 km apart (Figure 1a). Transects were flown at a target altitude of 47 m and a speed of 110 km·h^{-1}. At this altitude, each image covered a surface of 89 m width (the 'strip width') × 50 m length, corresponding to a ground sampling distance of 3 cm per pixel.

Transects were flown in morning hours to ensure minimum wind (speed <7 knots) and sun glint conditions whenever possible. A polarizing filter was fitted to the GoPro to further reduce sun glint. Due to the large size of the region, the moderate plane autonomy and rising winds around midday, the area could not be surveyed in a single day. In total, an area of 62 km^2 was surveyed across four different days during the austral winter (4 June 2021 and 5 June 2021 for the area east of Bourail and 29 July 2021 and 4 August 2021 for the area west of Bourail), corresponding to a total video duration of 7 h and 4 min.

2.3 | Video Annotation

All videos were watched entirely by a team of trained observers who recorded the times at which they spotted dugongs along with other megafauna species. All videos were then imported into a custom online application for annotation. Frames were extracted from the videos at a rate of three per second to allow the same individual to be visible in consecutive images (with a 20% forward overlap), helping to confirm species identification. Only frames that were previously found to contain dugongs (based on recorded observation times from the corresponding videos) were annotated. The annotation procedure consisted of manually drawing rectangle bounding boxes around the individuals and associating the 'dugong' label to these boxes. Only individuals for which at least three-quarters of the body was visible were annotated. All annotations were checked by an independent expert observer. For each video, the custom application returned the GPS coordinates of all images extracted from this video along with their annotations (i.e., pixel coordinates of the bounding box and labels). Postprocessing of these annotations was performed to (1) flag and remove duplicates of individuals (i.e., when the same individual was detected in consecutive images; in that case, only the first sighting of the individual was counted) and (2) determine whether each individual was as an adult or a calf (defined as an individual at least half smaller than the adult it was closely associated with).

2.4 | Survey Data Aggregation

A spatial grid of 500 m resolution cells was chosen to provide a relatively fine grain of our study area while avoiding an excess of zeros in dugong counts. The grid was projected in the equal-area Lambert New Caledonia system (final area of the cells: 0.25 km^2) over the study region. This grid was used for aggregating survey effort by summing the area surveyed (square kilometre) per cell after removing off-effort portions of transects (corresponding to transits from/to the airport). This grid was also used for summing the numbers of dugongs per cell after applying corrections for availability bias, as described hereafter. The numbers of dugongs were divided by availability correction factors obtained from depth use data corresponding to different time periods and depth ranges in New Caledonia, as well as four levels of an Environmental Condition Index (ECI) (Hagihara et al. 2018). We stress that these correction factors were originally designed for observer-based surveys and their applicability to imagery surveys has not been assessed so far. Images were classified into the different ECIs based on visual examination. In the absence of information on precise depth of our dugong sightings, availability correction factors were averaged for the three depth ranges documented in Hagihara et al. (2018). The 8:00–16:00 time period that corresponded to the timing of our aerial survey was selected. The resulting availability correction factors were 1 (i.e., no correction) for ECI 1 (clear water and clearly visible bottom), 0.63 for ECI 2 (variable clarity and bottom visible but not clearly), 0.83 for ECI 3 (clear water but bottom not visible) and 0.47 for ECI 4 (turbid water and nonvisible bottom) (Hagihara et al. 2018). Contrary to previous studies (e.g., Hodgson, Kelly, and Peel 2023), we did not attempt to apply corrections for perception bias, as we did not compile the differences in annotations between observers.

2.5 | Environmental Variables

Environmental variables were derived over the 500 m resolution grid of the study region from various datasets (Table S1 and Figure S1 in Supporting Information). Distance to shallow seagrass and percentage coverage of shallow seagrass were obtained from a nationwide effort to characterize seagrass meadows in New Caledonia (Andréfouet et al. 2021). Distance to passes of the barrier reef was derived from a typology of reef passages in New Caledonia (Breckwoldt et al. 2022). Distance to reef, distance to land, percentage coverage of reef flat and percentage coverage of deep lagoon (considering a threshold of c. 10 m for the classification of deep lagoon) were derived from the Millennium Coral Reef Mapping Project (Andréfouët et al. 2009). Median depth and median slope were derived from a digital terrain model of New Caledonia at 100 m resolution (Roger 2020). All variables but distance to reef passes, coverage of deep lagoon and coverage of reef flat were previously used in a modelling study of dugong habitat utilization from satellite tagging data in New Caledonia (Derville, Cleguer, and Garrigue 2022).

2.6 | Habitat Modelling

Generalized additive models (GAMs) were used to predict dugong density as a function of the above environmental covariates in the study region. GAMs are the preferred technique for modelling species relative densities from line or strip transect surveys owing to their ability to cope with nonlinear and non-monotonic relationships (Miller et al. 2013). GAMs were fitted as follows:

$$E\left(\widehat{N}_j\right) = A_j \exp\left[\beta_0 + \sum_k f_k\left(z_{jk}\right)\right].$$

where N_j is the number of dugongs in cell j (response variable), A_j is the surveyed area in cell j (model offset), f_k are the smooth functions of environmental covariates z_k and β_0 is the model intercept.

Pearson correlation coefficients were first calculated between all pairs of covariates to explore their collinearity. Distance to land and slope were discarded because they had strong correlations with distance to seagrass and depth, respectively (coefficients 0.87 and 0.91). Saturated GAMs (i.e., including all remaining covariates) were fitted using the mgcv package (Version 1.8.41) (Wood 2023) in R. Restricted maximum likelihood, which is known to penalize overfitting and lead to more pronounced optima, was used as the criterion for estimating smooth parameters (Wood 2011). Tweedie and negative binomial distributions were considered to model dugong abundance, which was characterized by a heavy tailed distribution and a high proportion of zeros. The best fitting distribution was selected based on Akaike's information criterion score followed by an examination of diagnostics plots (including quantile-quantile plots of deviance residuals, autocorrelogram of residuals and plots of response vs. fitted values). A backward stepwise procedure was applied for variable selection, considering a *p* value of 0.05 as the threshold for removal of nonsignificant covariates.

The ability of the model to discriminate between cells of dugong presence and absence was assessed based on true skill statistic (TSS, ranging from −1 to 1) (Allouche, Tsoar, and Kadmon 2006). To convert dugong abundance data to presence–absence data, we relied on the sensitivity–specificity sum maximization approach for the selection of a presence threshold (Liu et al. 2005). The predictive accuracy of the model was further assessed geographically by computing the ratios of observed-to-predicted abundances across three geographic strata (corresponding to the northern, central and southern parts of the study region) (Becker et al. 2020).

The model was then used to predict the relative density of dugongs (number of individuals per 0.25 km^2 cell) while holding the offset (i.e., surveyed area) constant. Predictions were geographically interpolated throughout the study region while being constrained to the multidimensional environmental space of the surveyed data using the dsmextra package (Version 1.1.5) (Bouchet et al. 2020). A coefficient of variation (CV) map was produced alongside the prediction map to document the uncertainty within the model. Abundance predictions (number of individuals) were used to assess the proportion of the estimated dugong population protected by existing no-take MPAs.

2.7 | Spatial Prioritization

The prioritizr package (Version 7.2.2) (Hanson 2021) with the Gurobi optimizer in R was used to derive spatial prioritization scenarios protecting various targets of dugong abundance in the study region. We also derived prioritization scenarios protecting various area-based targets of the study region, representing 'control' scenarios in the absence of dugong abundance data to inform prioritization. Abundance prioritization scenarios are aimed at identifying a set of sites that contained a given proportion of the *population* whereas control scenarios simply identified a set of sites that contained a given proportion of the *study region's area*. In prioritizr, optimization problems are expressed using integer linear programming (ILP) so that they can be solved using exact algorithm solvers. ILP has been shown to outcompete conventional spatial prioritization algorithms in terms of cost-effectiveness (Hanson et al. 2019). Prioritizations were generated using the 500 m resolution cells (the same equal-surface cells used in habitat modelling) as planning units. We identified the minimum set of cells to protect in order to reach percentage targets of dugong abundance or of region area, an optimization problem referred as to the 'minimum-set objective' (Ball, Possingham, and Watts 2009; Hanson et al. 2019). We explored targets from 10% to 90% (with a 10% increment) for both abundance and area, selecting three values based on heuristic principles (Harris and Holness 2023): a 'baseline target' of 30%, a 'core use target' of 50% accounting for the fact that the region is a core use zone for dugongs (Cleguer et al. 2015; Derville, Cleguer, and Garrigue 2022) and an 'endangered status target' of 70% adjusting for the endangered status of the population (Hamel et al. 2022). The cost was set to a constant value of 1 in all planning units, since the goal here was to identify priority areas for dugong conservation independently of socioeconomic considerations. Abundance and control prioritization scenarios were compared by calculating their respective proportions of protected individuals and surface area in the study region.

3 | Results

The aerial survey led to the collection of 74,375 images covering a total area of 62 km^2 through the 753 km^2 surveyed block (corresponding to a sample rate of about 8%) in the central west coast of New Caledonia (Figure S2). Of these images, 35 contained at least one dugong, representing a mean number of dugongs per image of 2.7 ± 3.9 standard error. After the removal of duplicates, a total of 119 unique dugong sightings (100 adults and 19 calves) were counted across these 35 images. The highest numbers of dugongs (up to 24 individuals per image) were observed just outside the passes of Poya and Poé (on the outer slope of the barrier reef), as well as inside the pass of Moindou (Figure 1 and Figure S3). Fewer individuals (one to three per image) were observed inside the lagoon and on the barrier reef.

Dugong numbers counted on images were then corrected for availability bias and summed per grid cell, resulting in 25 cells with nonzero abundance out of the 1,733 surveyed cells. The negative binomial distribution was selected based on its best fit to the dugong count data. The selected covariates were distance to reef passes, depth and coverage of shallow seagrass, accounting for 39.1% of the deviance in the GAM. Dugong abundances increased close to reef passes, but also in areas with shallow depths and high coverage of seagrass (Figure 2a). Abundances were predicted to be the highest near barrier reef passes with a decreasing gradient toward the shore (Figure 2b). The associated CV map revealed higher uncertainty on the outer reef slope where depth values were the highest (Figure S4). The model had a good discriminatory ability (TSS = 0.49), with a slightly better ability to model absences than presences, indicated by a specificity of 0.88 and a sensitivity of 0.61. Finally, the model had a spatially unbiased predictive accuracy, as revealed by ratios of observed-to-predicted abundances of 0.68, 0.84 and 0.71 for northern, central and southern strata, respectively.

Based on these predictions, existing no-take MPAs (representing 58 km^2 or 7% of the region area) would only protect 11.2% of the estimated dugong population (orange triangle; Figure 3), hence

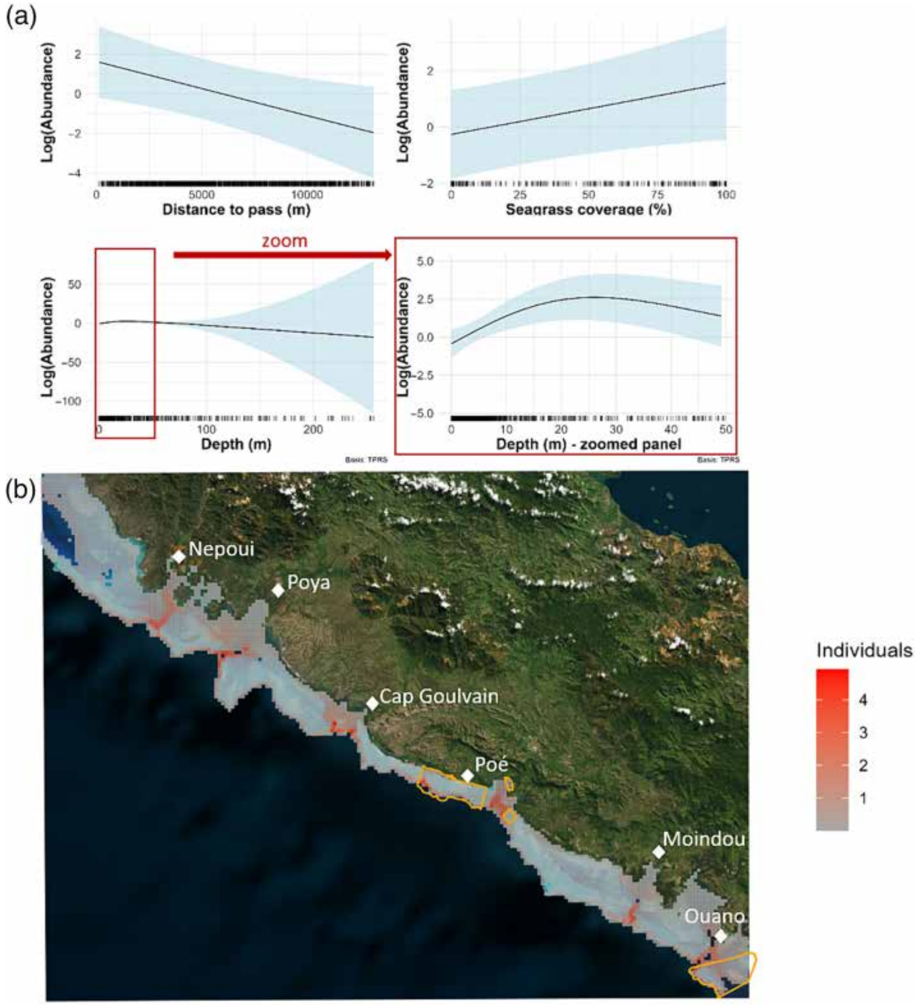

FIGURE 2 | (a) Statistical relationships between dugong abundance (log-transformed) and environmental covariates estimated from the generalized additive model. Solid lines represent the marginal effects of covariates on dugong abundances and dashed lines represent the 95% approximate confidence intervals. Rug plots represent the distribution of the data. The *y*-axis indicates estimated smooth functions of each covariate with respect to log-transformed abundance. (b) Predicted abundance (individuals/500 m resolution cell) of dugongs. Existing no-take marine protected areas are overlaid in orange. Source of background satellite imagery: OpenStreetMap. The associated coefficient of variation map is displayed in Figure S4.

leaving most high abundance sites unprotected (Figure 2b). For a similar MPA coverage, prioritization informed by abundance would allow securing nearly 50% of the estimated population, so representing nearly a five-time increase (orange arrow; Figure 3).

Abundance prioritization scenarios selected cells near reef passes and shallow nearshore areas where dugong abundance was the highest (Figure 4a–c and Figure S5) in contrast to randomly selected cells in control scenarios that ignored abundance (Figure 4d–e and Figure S6). When informed by abundance, prioritization scenarios required between 47 and 2 times less area to reach protection targets of 10% and 90%, respectively (Figure 3). For the 'baseline' target (30%), the abundance scenario required a protection coverage of 20 km^2, representing just 3.5% of the region area. Increasing from the baseline to the 'core use' target (50%) resulted in a three-fold increase in protection coverage (from 20 to 63 km^2), representing 8.7% of the region area. For the 'endangered status' target (70%), protection coverage increased to 150 km^2 (19.3% of the region's area), representing a 2.4 times increase in MPA coverage compared to the 'core use' target.

4 | Discussion

In this study, we combined aerial video surveys, habitat modelling and spatial prioritization informed by abundance to derive spatially explicit zoning scenarios for the protection of endangered dugongs in New Caledonia. Our study expands on the work of Cleguer et al. (2015) who identified a spatial mismatch between dugong hotspots and existing restrictive MPAs (including no-take MPAs) in New Caledonia. We highlight underprotected dugong hotspots on the central west coast of New Caledonia in winter, going further by examining different MPA scenarios to improve their protection. While the existing network of no-take MPAs only protects 11.2% of the estimated dugong population, for the same spatial coverage, prioritization based on abundance would provide protection for nearly five times more individuals

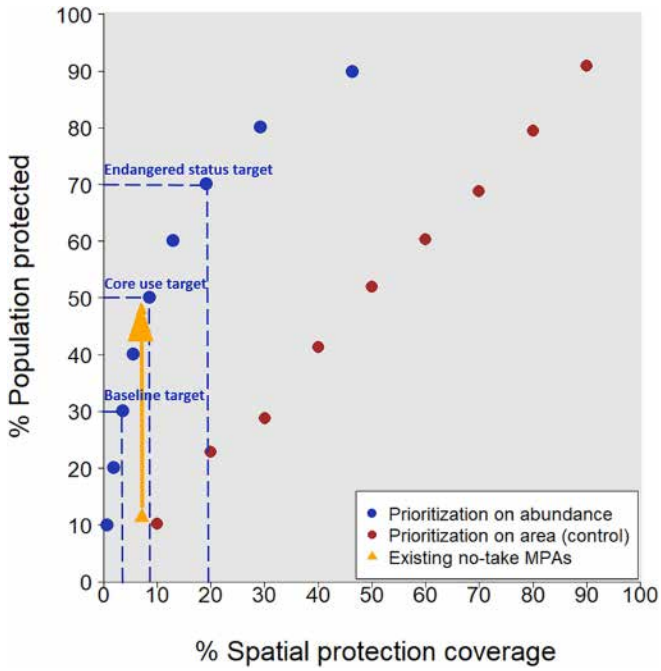

FIGURE 3 | Proportions of dugong population protected by existing no-take marine protected areas (MPAs) (orange triangle) and the different prioritization scenarios (blue and red dots). Blue dashed lines show the 30%, 50% and 70% abundance targets and corresponding percentages of spatial protection coverage. Existing no-take MPAs encompass 11.2% of the dugong's abundance for a protected surface corresponding to 7% of the region's area. The orange arrows point out the percentage of population that could be protected with the same protected surface if prioritization was informed by abundance.

(Figure 3). Given the endangered status of the population, a 70% abundance protection scenario is warranted, requiring the expansion of existing MPAs toward reef passes and neighbouring nearshore areas, especially Nepoui, Poya, Cap Goulvain, Poé, Mouindou and Ouano.

4.1 | Pros and Cons of Aerial Video Surveys

Contrary to previous dugong aerial surveys in New Caledonia that involved human observers (Garrigue, Patenaude, and Marsh 2008; Cleguer et al. 2017), the present survey relied on video footage recorded from an off-the-shelf camera fitted to a light aircraft. There is evidence that aerial video surveys provide more accurate and precise abundance estimates of marine megafauna than observer-based surveys (Ferguson et al. 2018; Garcia-Garin et al. 2020; Kelaher et al. 2020). For dugongs specifically, Hodgson, Kelly, and Peel (2023) recently compared sightings obtained from simultaneous imagery surveys from a fixed-wing drone and observer-based surveys from a manned aircraft. While group sighting rates were similar between the two platforms, group sizes detected in drone images were significantly larger (Hodgson, Kelly, and Peel 2023). Their study shows that imagery surveys may provide higher quality data than observer surveys, although the potential transferability of these findings from unmanned to manned aircraft imagery remains to be investigated. In fact, observer biases due to missed individuals or misidentified species may have led to discrepancies between dugong abundance estimates obtained from observer-based surveys conducted in New Caledonia in 2003 and the following years (Cleguer et al. 2017). In addition to limiting these biases, video surveys from manned aircraft reduce carbon emissions, as they can be conducted from smaller and lighter airplanes with just a pilot onboard. However, these surveys generate large amounts of data that require automated treatments. A deep learning algorithm is available for the automated count of dugongs in New Caledonia (Mannocci et al. 2021), but its current recall of 0.80 means that 20% of individuals remain undetected. To avoid underestimating abundance, we thus opted for the manual review of images by human observers. Improved algorithms allowing the full automated and accurate processing of images should decrease image processing costs in the future, thereby substantially improving the cost-effectiveness of video surveys. Finally, a perspective of this study is to compare individual counts obtained from observer- and video-based techniques onboard the same manned aircraft, as previously done for other megafauna (Garcia-Garin et al. 2020). A higher accuracy of dugong abundance estimates derived from video-based surveys would support the application of this technique across a broader geographical scale, with potential direct benefits to dugongs and other sirenians in other parts of the world.

4.2 | Comparison With Previous Dugong Studies in New Caledonia

Our results are consistent with previous findings on dugong distribution and densities on the central west coast of New Caledonia. A New Caledonia-wide map of dugong densities (binned into low, medium, high and very high categories) was previously derived from observer-based aerial surveys analysed with a kriging technique not incorporating environmental predictors (all

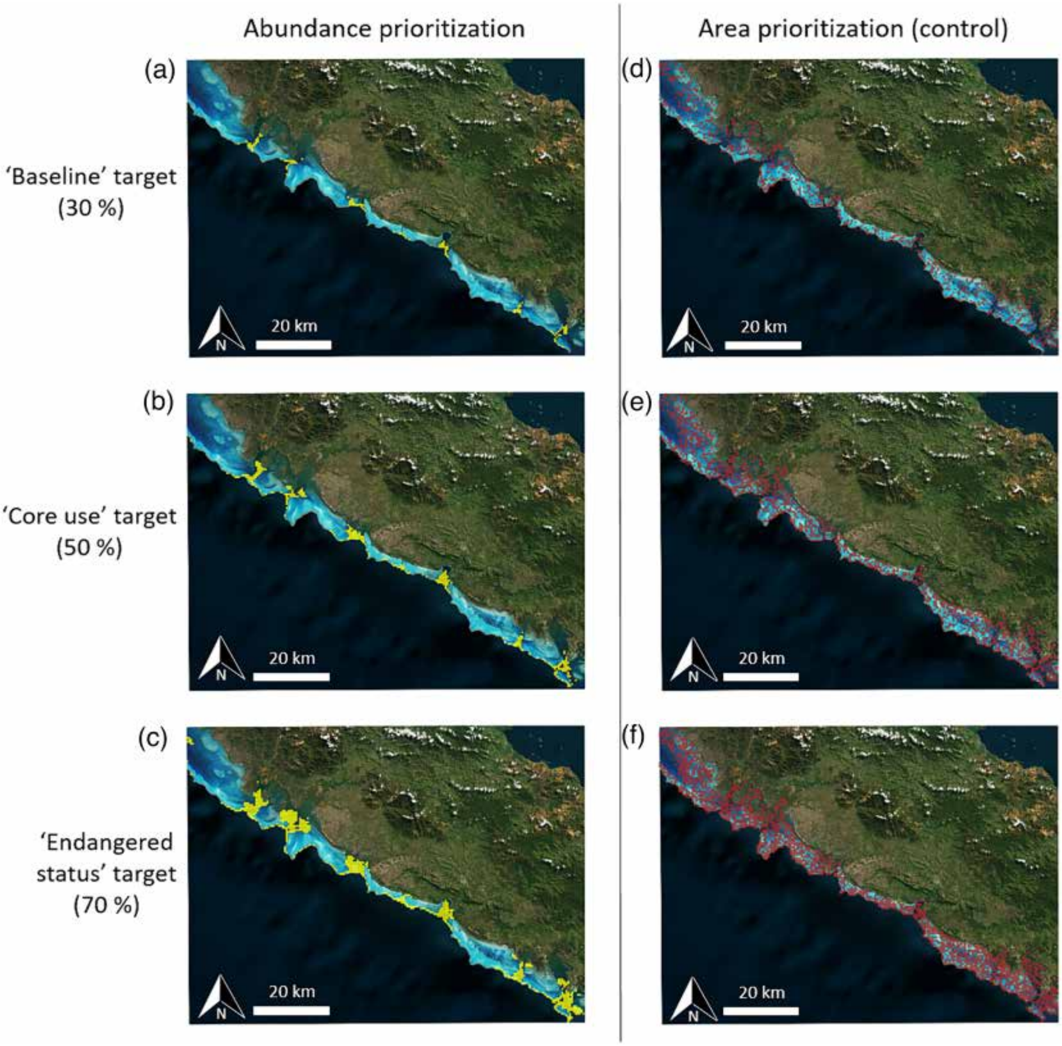

FIGURE 4 | Prioritization scenarios targeting the protection of 30%, 50% and 70% of dugong abundance in yellow (a–c) and of region area in red (d–f). Source of background satellite imagery: OpenStreetMap. Prioritization scenarios for all targets are shown in Figures S5 and S6 for abundance and area, respectively.

seasons and years combined: 2003, 2008, 2011, 2012) (Cleguer et al. 2015). Although the map's resolution (1.6 km) was coarser than that of our study (500 m), it similarly showed high dugong densities in the Cap Goulvain, Nepoui and Mouindou areas. Our results also align with observed high densities over the fore reef shelf off Cap Goulvain during a year-round fine scale study of dugong habitat in 2012–2013 (Cleguer et al. 2024). Moreover, our study confirmed the potential for dugongs to aggregate in large groups outside of the Poé's pass locally referred as *faille aux requins* (one observation on 29 July 2021, $n = 28$ individuals), an area where herds were only anecdotally reported before (Derville pers. comm.). The comparison of our results with those of previous surveys suggests that dugongs have displayed relatively consistent winter habitat across two decades in this part of the New Caledonian west coast. Yet, considering the decline of the New Caledonian dugong population (Hamel et al. 2022) and the rapid climate change directly and indirectly affecting dugongs (Marsh et al. 2017), monitoring their potential shifts in geographic or habitat distribution will be a priority in the future.

Highest dugong abundances recorded from our aerial survey were found on the fore reef shelf in proximity to passes of the barrier reef (large herds) as well as in areas of high seagrass coverage and shallow depth (small groups of < 3 individuals). The preference of dugongs for shallow waters (< 20 m) was previously identified by Derville, Cleguer, and Garrigue (2022) who modelled individual's spatial intensity of use from satellite tracking data. Dugongs also displayed a preference for waters inside the lagoon (< 5 km from the coast), but their intensity of use varied across three ecoregions, with seagrass coverage and distances to the barrier reef and intermediate reef patches identified as significant predictors in the central west coast ecoregion (Derville, Cleguer, and Garrigue 2022), the one targeted by the present study. Dial patterns in habitat use were also identified, suggesting that dugongs come closer to shore at night (potentially to feed in higher density seagrass meadows) and that excursions to the fore reef shelf generally occur at dawn (Derville, Cleguer, and Garrigue 2022). This dial pattern influences dugong habitat use in combination with tides (Derville, Cleguer, and Garrigue 2022; Cleguer et al. 2024), as also observed in Australia (Sheppard et al. 2010). Since the spatially explicit zoning derived from our study is based on daytime aerial transects conducted at variable tidal phases (two flights during ebb and two flights during flow), it cannot account for nighttime distribution of dugongs or tide effects on their habitat use. Nevertheless, our aerial video surveys have added to the current knowledge of important dugong habitats derived from satellite telemetry (Cleguer, Garrigue, and Marsh 2020; Derville, Cleguer, and Garrigue 2022) by emphasizing the importance of the fore reef shelf for this species. To better account for the dynamics of dugong distribution in relation to dial patterns and tides, future studies should incorporate both abundance and dial habitat use information into zoning scenarios.

4.3 | Temporal Aspects

Since aerial surveys were only conducted during austral winter, the abundance predictions and zoning scenarios derived from this study should not be extrapolated outside this colder season. Dugong distribution is known to vary seasonally, with large herds forming off Cap Goulvain during winter months when the lagoon's temperature drops below the temperature of offshore waters (Cleguer et al. 2024). Dugongs are quite sensitive to changes in temperature, with evidence of seasonal movements and behavioural thermoregulation at the high latitude limits of their Australian range (Sheppard et al. 2006; Zeh et al. 2018). Seagrass coverage, canopy height and caloric content also vary throughout the year (Van Wynsberge et al. 2013; Aller et al. 2019; Andréfouet et al. 2021), likely influencing dugong seasonal patterns of habitat use. It is thus unlikely that our scenarios would apply to other seasons, since dugongs can disperse over large areas, as shown by tagged individuals who moved up to 75 km from their tagging location (Cleguer, Garrigue, and Marsh 2020).

The observed high abundances in specific habitats of the central west coast in winter may provide the basis for dynamic spatial management through the implementation of a seasonal closure in the proposed zoning areas. To support such a seasonal closure, multiy-ear aerial surveys are warranted to better inform statistical models and confirm the consistent importance of central west coast habitats for dugongs in winter months. Spatial prioritizations incorporating model outputs from both abundance surveys and movement studies may also help to more realistically incorporate connectivity in reserve scenarios (Williams et al. 2020).

4.4 | Implications for Dugong Conservation

None of the existing no-take MPAs within the study region were designed to protect dugongs, partly due to the absence of dugong distribution data at the time of their creation (Cleguer et al. 2015). In addition, the environment code of the New Caledonian South Province does not list the species that are targeted by each no-take MPA (Province Sud de la Nouvelle Calédonie 2009). However, the West Coast Provincial Park (WCPP) encompassing most of the study region mentions the dugong as one of the emblematic species inhabiting the park. The management plan of the WCPP (2018–2022) includes several specific objectives for dugongs, such as population monitoring, seagrass mapping, opportunistic observations reporting by tourism operators and awareness-raising (Province Sud de la Nouvelle Calédonie 2018). Despite its classification as a UNESCO World Heritage zone, the WCPP does not fall under an IUCN protected area due to its unrestricted human activities; it can be considered as a minimally protected areas *sensu* Grorud-Colvert et al. (2021). Our proposed zoning scenarios are therefore valuable for dugong conservation because they have the potential to inform the creation of highly protected MPAs in high dugong abundance areas within the WCPP. For example, our 70% abundance protection scenario proposes the creation of no-take MPAs near reef passes and neighbouring nearshore areas off Cap Goulvain, Poya, Nepoui and Mouindou to safeguard 70% of the dugong abundance. Importantly, the protection of these areas may also benefit other vulnerable species of megafauna such as sharks (Bonnin et al. 2019) and sea turtles (Barbier et al. 2023) that regularly occur in these waters.

Although we propose the designation of no-take MPAs to safeguard dugong aggregation hotspots in winter, we acknowledge that a diverse array of regulations may be more appropriate to allow the long-term protection of dugongs while composing with the conservation and sustainable use of other resources in the western lagoon of New Caledonia. These regulations may include no-entry MPAs that not only prohibit fishing but also boat traffic and recreational nautical activities that can induce collisions—one of the main anthropogenic causes of dugong mortality in New Caledonia (Garrigue et al. 2023). Mandatory reduction in boat traffic speed in areas where dugong abundance peaks in winter (e.g., near reef passes) would also help to reduce the risk of collision, as proposed for other sirenians (Rycyk et al. 2018). As poaching continues despite strict legislation rules that prohibit dugong hunting in the southern province and require special permits in the Northern Province (Hamel et al. 2022), increased police patrols would act as deterrents to stop these illegal activities. However, a restrictive system of MPAs with seasonal regulation of boat traffic and recreational activities may not be socially acceptable. A possible alternative would be to enhance the sustainable use of MPAs, with a focus on reducing poaching, boat collisions, incidental captures and regulating coastal development (including construction, mining and aquaculture). To implement a more holistic approach to MPA design, future zoning scenarios should also include relevant spatially explicit sociocultural data (Sandbrook et al. 2023), as they become available in the region. Finally, actions toward education, outreach and community engagement on dugong and seagrass conservation will be critical to allow the appropriation of future management measures while ensuring public compliance.

Acknowledgements

We are grateful to all students for their help with the annotation of aerial images. We thank Air Paradise for their continuing collaboration in data collection. We thank Morgan Mangeas, Laurent Vigliola and Claire Garrigue from UMR ENTROPIE for hosting Laura Mannocci during her stay in Nouméa and for contributing ideas and expertise for fieldwork organisation. This project received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 845178 ('MEGAFAUNA'). The aerial surveys were funded by Monaco Explorations.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data and code that support the findings of this study are openly available in dugong_mapping at https://github.com/LauraMannocci/dugong_mapping.

References

Aller, A. E., J. S. Eklöf, M. Gullström, U. Kloiber, H. W. Linderholm, and L. M. Nordlund. 2019. "Temporal Variability of a Protected Multispecific Tropical Seagrass Meadow in Response to Environmental Change." *Environmental Monitoring and Assessment* 191, no. 12: 774. https://doi.org/10.1007/s10661-019-7977-z.

Allouche, O., A. Tsoar, and R. Kadmon. 2006. "Assessing the Accuracy of Species Distribution Models: Prevalence, Kappa and the True Skill Statistic (TSS)." *Journal of Applied Ecology* 43, no. 6: 1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x.

Andréfouët, S., G. Cabioch, B. Flamand, and B. Pelletier. 2009. "A Reappraisal of the Diversity of Geomorphological and Genetic Processes of New Caledonian Coral Reefs: A Synthesis From Optical Remote Sensing, Coring and Acoustic Multibeam Observations." *Coral Reefs* 28, no. 3: 691–707. https://doi.org/10.1007/s00338-009-0503-y.

Andréfouet, S., S. Derville, J. Buttin, et al. 2021. "Nation-Wide Hierarchical and Spatially-Explicit Framework to Characterize Seagrass Meadows in New-Caledonia, and Its Potential Application to the Indo-Pacific." *Marine Pollution Bulletin* 173: 113036. https://doi.org/10.1016/j.marpolbul.2021.113036.

Ball, I., H. Possingham, and M. Watts. 2009. *Marxan and Relatives: Software for Spatial Conservation Prioritisation*. Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools, 185–195. Oxford, UK: Oxford University Press.

Barbier, M., D. Lafage, H. Bourgogne, et al. 2023. "Assessment of the Nesting Population Demography of Loggerhead Turtles (Caretta caretta) in La Roche Percée: First Long-Term Monitoring in New Caledonia." *Aquatic Conservation: Marine and Freshwater Ecosystems* 33, no. 6: 579–591. https://doi.org/10.1002/aqc.3949.

Becker, E. A., J. V. Carretta, K. A. Forney, et al. 2020. "Performance Evaluation of Cetacean Species Distribution Models Developed Using Generalized Additive Models and Boosted Regression Trees." *Ecology and Evolution* 10, no. 12: 5759–5784. https://doi.org/10.1002/ece3.6316.

Bonnin, L., W. D. Robbins, G. Boussarie, et al. 2019. "Repeated Long-Range Migrations of Adult Males in a Common Indo-Pacific Reef Shark." *Coral Reefs* 38, no. 6: 1121–1132. https://doi.org/10.1007/s00338-019-01858-w.

Bouchet, P. J., D. L. Miller, J. J. Roberts, L. Mannocci, C. M. Harris, and L. Thomas. 2020. "Dsmextra: Extrapolation Assessment Tools for Density Surface Models." *Methods in Ecology and Evolution* 11, no. 11: 1464–1469. https://doi.org/10.1111/2041-210X.13469.

Breckwoldt, A., A. Nozik, N. Moosdorf, et al. 2022. "A Typology for Reef Passages." *Frontiers in Marine Science* 9: 786125.

CBD. 2022. "Conference of the Parties to the Convention on Biological Diversity Fifteenth Meeting Part II, Montreal, Canada, Decision 15/4: The Kunming-Montreal Global Biodiversity Framework."

Chen, C., T. A. Jefferson, B. Chen, and Y. Wang. 2022. "Geographic Range Size, Water Temperature, and Extrinsic Threats Predict the Extinction Risk in Global Cetaceans." *Global Change Biology* 28, no. 22: 6541–6555. https://doi.org/10.1111/gcb.16385.

Cleguer, C., C. Garrigue, M. Fuentes, et al. 2017. "Drivers of Change in the Relative Abundance of Dugongs in New Caledonia." *Wildlife Research* 44, no. 4: 365–376.

Cleguer, C., C. Garrigue, M. M. P. B. Fuentes, M. Hamann, C. Payri, and H. Marsh. 2024. "Temporal Changes in Habitat Use by Dugongs in a Spatially Restricted Coral Reef Environment." *Pacific Conservation Biology* 30, no. 2: PC23036. https://doi.org/10.1071/PC23036.

Cleguer, C., C. Garrigue, and H. Marsh. 2020. "Dugong (Dugong dugon) movements and Habitat use in a Coral Reef Lagoonal Ecosystem." *Endangered Species Research* 43: 167–181. https://doi.org/10.3354/esr01061.

Cleguer, C., A. Grech, C. Garrigue, and H. Marsh. 2015. "Spatial Mismatch Between Marine Protected Areas and Dugongs in New Caledonia." *Biological Conservation* 184: 154–162. https://doi.org/10.1016/j.biocon.2015.01.007.

Cleguer, C., N. Kelly, J. Tyne, M. Wieser, D. Peel, and A. Hodgson. 2021. "A Novel Method for Using Small Unoccupied Aerial Vehicles to Survey Wildlife Species and Model Their Density Distribution." *Frontiers in Marine Science* 8: 640338.

Derville, S., C. Cleguer, and C. Garrigue. 2022. "Ecoregional and Temporal Dynamics of Dugong Habitat Use in a Complex Coral Reef Lagoon Ecosystem." *Scientific Reports* 12, no. 1: 552. https://doi.org/10.1038/s41598-021-04412-3.

Dulvy, N. K., N. Pacoureau, C. L. Rigby, et al. 2021. "Overfishing Drives Over One-Third of All Sharks and Rays Toward a Global Extinction Crisis." *Current Biology* 31, no. 21: 4773–4787.e8. https://doi.org/10.1016/j.cub.2021.08.062.

Dwyer, R. G., N. C. Krueck, V. Udyawer, et al. 2020. "Individual and Population Benefits of Marine Reserves for Reef Sharks." *Current Biology* 30, no. 3: 480–489.e5. https://doi.org/10.1016/j.cub.2019.12.005.

Edwards, H. H., J. A. Hostetler, B. M. Stith, and J. Martin. 2021. "Monitoring Abundance of Aggregated Animals (Florida Manatees) Using an Unmanned Aerial System (UAS)." *Scientific Reports* 11, no. 1: 12920. https://doi.org/10.1038/s41598-021-92437-z.

Ferguson, M. C., R. P. Angliss, A. Kennedy, et al. 2018. "Performance of Manned and Unmanned Aerial Surveys to Collect Visual Data and Imagery for Estimating Arctic Cetacean Density and Associated Uncertainty1." *Journal of Unmanned Vehicle Systems* 6: 128–154. https://doi.org/10.1139/juvs-2018-0002.

Garcia-Garin, O., A. Aguilar, A. Borrell, et al. 2020. "Who's Better at Spotting? A Comparison Between Aerial Photography and Observer-Based Methods to Monitor Floating Marine Litter and Marine Mega-Fauna." *Environmental Pollution* 258: 113680. https://doi.org/10.1016/j.envpol.2019.113680.

Garrigue, C., C. D. Bonneville, C. Cleguer, and M. Oremus. 2022. "Extremely Low mtDNA Diversity and High Genetic Differentiation Reveal the Precarious Genetic Status of Dugongs in New Caledonia, South Pacific." *The Journal of Heredity* 113, no. 5: 516–524. https://doi.org/10.1093/jhered/esac029.

Garrigue, C., S. Derville, C. Bonneville, et al. 2023. "Marine Mammal Strandings Recorded in New Caledonia, South West Pacific Ocean, 1877 to 2022." *Pacific Conservation Biology* 30, no. 1: 1–25. https://doi.org/10.1071/PC23016.

Garrigue, C., N. Patenaude, and H. Marsh. 2008. "Distribution and Abundance of the Dugong in New Caledonia, Southwest Pacific." *Marine Mammal Science* 24, no. 1: 81–90. https://doi.org/10.1111/j.1748-7692.2007.00173.x.

Gilmour, M. E., J. Adams, B. A. Block, et al. 2022. "Evaluation of MPA Designs That Protect Highly Mobile Megafauna Now and Under Climate Change Scenarios." *Global Ecology and Conservation* 35: e02070. https://doi.org/10.1016/j.gecco.2022.e02070.

Grorud-Colvert, K., J. Sullivan-Stack, C. Roberts, et al. 2021. "The MPA Guide: A Framework to Achieve Global Goals for the Ocean." *Science* 373: eabf0861. https://doi.org/10.1126/science.abf0861.

Hagihara, R., R. E. Jones, S. Sobtzick, C. Cleguer, C. Garrigue, and H. Marsh. 2018. "Compensating for Geographic Variation in Detection Probability With Water Depth Improves Abundance Estimates of Coastal Marine Megafauna." *PLoS ONE* 13, no. 1: e0191476. https://doi.org/10.1371/journal.pone.0191476.

Hamel, M. A., H. Marsh, C. Cleguer, C. Garrigue, and M. Oremus. 2022. "IUCN Red List of Threatened Species: *Dugong dugon* New Caledonia Subpopulation." IUCN Red List of Threatened Species.

Hampton, J., P. Lehodey, I. Senina, S. Nicol, J. Scutt Phillips, and K. Tiamere. 2023. "Limited Conservation Efficacy of Large-Scale Marine Protected Areas for Pacific Skipjack and Bigeye Tunas." *Frontiers in Marine Science* 9: 1060943.

Hanson, J. 2021. "prioritizr: Systematic Conservation Prioritization in R." Version 5.0.3.

Hanson, J. O., R. Schuster, M. Strimas-Mackey, and J. R. Bennett. 2019. "Optimality in Prioritizing Conservation Projects." *Methods in Ecology and Evolution* 10, no. 10: 1655–1663. https://doi.org/10.1111/2041-210X.13264.

Harris, L. R., and S. D. Holness. 2023. "A Practical Approach to Setting Heuristic Marine Biodiversity Targets for Systematic Conservation Planning." *Biological Conservation* 285: 110218. https://doi.org/10.1016/j.biocon.2023.110218.

Hays, G. C., J. A. Mortimer, A. Rattray, T. Shimada, and N. Esteban. 2021. "High Accuracy Tracking Reveals How Small Conservation Areas Can Protect Marine Megafauna." *Ecological Applications* 31, no. 7: e02418. https://doi.org/10.1002/eap.2418.

Heldsinger, M., C. Hepburn, T. Jowett, and W. Rayment. 2023. "Small Marine Reserves Provide Conservation Benefits for Coastal Sharks in Southern New Zealand." *Aquatic Conservation: Marine and Freshwater Ecosystems* 33, no. 2: 144–159. https://doi.org/10.1002/aqc.3911.

Hodgson, A., N. Kelly, and D. Peel. 2023. "Drone Images Afford More Detections of Marine Wildlife Than Real-Time Observers During Simultaneous Large-Scale Surveys." *PeerJ* 11: e16186. https://doi.org/10.7717/peerj.16186.

IUCN. 2022. "The IUCN Red List of Threatened Species. Version 2022-2." Accessed June 1, 2023. https://www.iucnredlist.org.

IUCN-Marine Mammal Protected Areas Task Force. 2021. "New Caledonian Lagoons and Shelf Waters IMMA Factsheet." https://www.marinemammalhabitat.org/wpcontent/uploads/imma-fact-sheets/PacificIslands/newcaledonian-main-island-lagoons-and-shelf-PacificIslands.pdf.

Jefferson, T., M. J. Costello, Q. Zhao, and C. J. Lundquist. 2021. "Conserving Threatened Marine Species and Biodiversity Requires 40% Ocean Protection." *Biological Conservation* 264: 109368. https://doi.org/10.1016/j.biocon.2021.109368.

Johnston, A., T. Auer, D. Fink, et al. 2020. "Comparing Abundance Distributions and Range Maps in Spatial Conservation Planning for Migratory Species." *Ecological Applications* 30, no. 3: e02058. https://doi.org/10.1002/eap.2058.

Jones, K. R., C. J. Klein, H. S. Grantham, et al. 2020. "Area Requirements to Safeguard Earth's Marine Species." *One Earth* 2, no. 2: 188–196. https://doi.org/10.1016/j.oneear.2020.01.010.

Kelaher, B. P., A. P. Colefax, A. Tagliafico, M. J. Bishop, A. Giles, and P. A. Butcher. 2020. "Assessing Variation in Assemblages of Large Marine Fauna Off Ocean Beaches Using Drones." *Marine and Freshwater Research* 71, no. 1: 68–77. https://doi.org/10.1071/MF18375.

Li, X., H. Wang, D. J. McCauley, et al. 2023. "A Wide Megafauna Gap Undermines China's Expanding Coastal Ecosystem Conservation." *Science Advances* 9, no. 32: eadg3800. https://doi.org/10.1126/sciadv.adg3800.

Liu, C., P. M. Berry, T. P. Dawson, and R. G. Pearson. 2005. "Selecting Thresholds of Occurrence in the Prediction of Species Distributions." *Ecography* 28, no. 3: 385–393. https://doi.org/10.1111/j.0906-7590.2005.03957.x.

Mannocci, L., S. Villon, M. Chaumont, et al. 2021. "Leveraging Social Media and Deep Learning to Detect Rare Megafauna in Video Surveys." *Conservation Biology* 1, no. 11: e13798. https://doi.org/10.1111/cobi.13798.

Marsh, H., E. M. Arraut, L. K. Diagne, H. Edwards, and M. Marmontel. 2017. "Impact of Climate Change and Loss of Habitat on Sirenians." In *Marine Mammal Welfare: Human Induced Change in the Marine Environment and Its Impacts on Marine Mammal Welfare*, edited by A. Butterworth, 333–357. Cham: Springer International Publishing.

Marsh, H., and S. Sobtzick. 2019. "Dugong dugon (Amended Version of 2015 Assessment)." The IUCN Red List of Threatened Species 2019: e.T6909A160756767. *IUCN Red List of Threatened Species*. Accessed September 3, 2020. https://www.iucnredlist.org/en.

McIntosh, E. J., R. L. Pressey, S. Lloyd, R. J. Smith, and R. Grenyer. 2017. "The Impact of Systematic Conservation Planning." *Annual Review of Environment and Resources* 42, no. 1: 677–697. https://doi.org/10.1146/annurev-environ-102016-060902.

Miller, D. L., M. L. Burt, E. A. Rexstad, and L. Thomas. 2013. "Spatial Models for Distance Sampling Data: Recent Developments and Future Directions." *Methods in Ecology and Evolution* 4, no. 11: 1001–1010. https://doi.org/10.1111/2041-210X.12105.

Miller, K. E., B. B. Ackerman, L. W. Lefebvre, and K. B. Clifton. 1998. "An Evaluation of Strip-Transect Aerial Survey Methods for Monitoring Manatee Populations in Florida." *Wildlife Society Bulletin (1973–2006)* 26, no. 3: 561–570.

Pacoureau, N., C. L. Rigby, P. M. Kyne, et al. 2021. "Half a Century of Global Decline in Oceanic Sharks and Rays." *Nature* 589, no. 7843: 567–571. https://doi.org/10.1038/s41586-020-03173-9.

Pike, E. P., J. M. C. MacCarthy, S. O. Hameed, et al. 2024. "Ocean Protection Quality Is Lagging Behind Quantity: Applying a Scientific Framework to Assess Real Marine Protected Area Progress Against the 30 by 30 Target." *Conservation Letters* 17, no. 3: e13020. https://doi.org/10.1111/conl.13020.

Province Sud de la Nouvelle Calédonie. 2009. "CODE DE L'ENVIRONNEMENT DE LA PROVINCE SUD."

Province Sud de la Nouvelle Calédonie. 2018. "PLAN DE GESTION DE LA ZONE CÔTIÈRE OUEST (2018–2022)."

Ripple, W. J., C. Wolf, T. M. Newsome, et al. 2019. "Are We Eating the World's Megafauna to Extinction?" *Conservation Letters* 12, no. 3: e12627. https://doi.org/10.1111/conl.12627.

Roberts, K. E., B. J. Smith, D. Burkholder, and K. M. Hart. 2021. "Evaluating the Use of Marine Protected Areas by Endangered Species: A Habitat Selection Approach." *Ecological Solutions and Evidence* 2, no. 1: e12035. https://doi.org/10.1002/2688-8319.12035.

Roger, J. 2020. "Données bathymétriques et topographiques de Nouvelle-Calédonie: Réalisation d'un MNT terre-mer pour l'étude de l'aléa tsunami (projet TSUCAL)."

Rycyk, A. M., C. J. Deutsch, M. E. Barlas, et al. 2018. "Manatee Behavioral Response to Boats." *Marine Mammal Science* 34, no. 4: 924–962. https://doi.org/10.1111/mms.12491.

Sandbrook, C., S. Albury-Smith, J. R. Allan, et al. 2023. "Social Considerations Are Crucial to Success in Implementing the 30×30 Global Conservation Target." *Nature Ecology & Evolution* 7, no. 6: 784–785. https://doi.org/10.1038/s41559-023-02048-2.

Sheppard, J. K., H. Marsh, R. E. Jones, and I. R. Lawler. 2010. "Dugong Habitat use in Relation to Seagrass Nutrients, Tides, and Diel Cycles."

Marine Mammal Science 26, no. 4: 855–879. https://doi.org/10.1111/j.1748-7692.2010.00374.x.

Sheppard, J. K., A. R. Preen, H. Marsh, I. R. Lawler, S. D. Whiting, and R. E. Jones. 2006. “Movement Heterogeneity of Dugongs, Dugong dugon (Müller), Over Large Spatial Scales.” *Journal of Experimental Marine Biology and Ecology* 334, no. 1: 64–83. https://doi.org/10.1016/j.jembe.2006.01.011.

Sherman, C. S., C. A. Simpfendorfer, N. Pacoureau, et al. 2023. “Half a Century of Rising Extinction Risk of Coral Reef Sharks and Rays.” *Nature Communications* 14, no. 1: 15. https://doi.org/10.1038/s41467-022-35091-x.

Tol, S. J., R. G. Coles, and B. C. Congdon. 2016. “Dugong dugon Feeding in Tropical Australian Seagrass Meadows: Implications for Conservation Planning.” *PeerJ* 4: e2194. https://doi.org/10.7717/peerj.2194.

UNESCO. 2011. “Decision 35 COM 7B.22. Lagoons of New Caledonia: Reef Diversity and Associated Ecosystems (France) (N 1115).” UNESCO World Heritage Centre.

Van Wynsberge, S., A. Gilbert, N. Guillemot, C. Payri, and S. Andréfouët. 2013. “Alert Thresholds for Monitoring Environmental Variables: A New Approach Applied to Seagrass Beds Diversity in New Caledonia.” *Marine Pollution Bulletin* 77, no. 1: 300–307. https://doi.org/10.1016/j.marpolbul.2013.09.035.

Williams, S. H., S. A. Scriven, D. F. R. P. Burslem, et al. 2020. “Incorporating Connectivity Into Conservation Planning for the Optimal Representation of Multiple Species and Ecosystem Services.” *Conservation Biology* 34, no. 4: 934–942. https://doi.org/10.1111/cobi.13450.

Wood, S. 2023. “mgcv: Mixed GAM Computation Vehicle With Automatic Smoothness Estimation.”

Wood, S. N. 2011. “Fast Stable Restricted Maximum Likelihood and Marginal Likelihood Estimation of Semiparametric Generalized Linear Models.” *Journal of the Royal Statistical Society Series B: Statistical Methodology* 73, no. 1: 3–36.

Zeh, D. R., M. R. Heupel, M. Hamann, R. Jones, C. J. Limpus, and H. Marsh. 2018. “Evidence of Behavioural Thermoregulation by Dugongs at the High Latitude Limit to Their Range in Eastern Australia.” *Journal of Experimental Marine Biology and Ecology* 508: 27–34. https://doi.org/10.1016/j.jembe.2018.08.004.

Supporting Information

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