National Environmental Science Programme

Distribution and habitat suitability of Threatened and Migratory marine species in northern Australia

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Project A12 - Australia's Northern Seascape: assessing status of Threatened and Migratory marine species

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Important Disclaimer

Cover photo: Great Knot (*Calidris tenuirostris*), a Critically Endangered shorebird which was one of 16 key species for this project (photo: Peter Kyne).

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EXECUTIVE SUMMARY

The North Marine Bioregion is home to a diversity of threatened and data-poor marine species. In the absence of critical data on species' distributions, population connectivity, and essential habitat, decision-making to progress the current 'Developing the North' agenda has the potential to negatively impact Matters of National Environmental Significance. Following the report of the NESP Marine Biodiversity Hub Project Project A12 – Australia's Northern Seascape (Phase 1), which highlighted where gaps in knowledge are limiting the ability to understand the potential impacts of future development, Phase 2 of Project A12 – Australia's Northern Seascape includes a component on modelling and mapping Threatened and Migratory marine species distributions. This was undertaken for 16 priority Threatened and Migratory marine species (Table 1) listed by the *Environment Protection and Biodiversity Conservation* Act *1999* (EPBC Act) through a collaborative process with data custodians to compile and analyse existing spatial data. The focus area was the North Marine Region, which consists of the waters offshore from the Northern Territory to the EEZ edge, and east to the coast of Queensland including the northern tip of Cape York and waters of the Gulf of Carpentaria and where possible, we expanded the analysis beyond this region. The objective of the project was to improve the current data-poor species distribution maps held by the Department of Agriculture, Water and the Environment (DAWE) to assist with policy decisions related to these species.

To predict suitable habitat where species are likely to occur, we used a spatial distribution modelling approach (Maxent and GAMM) based on presence data from the compiled spatial datasets (121 in total) for these species and associated, remotely sensed environmental variables. The output is a series of more detailed and data driven distribution maps than are currently available at this scale that will enhance decision-makers' ability to assess potential impacts of development proposals in Northern Australia under the EPBC Act. Maps of the modelled species distribution (not the raw data) were made publicly available through the NESP Marine Biodiversity Hub's (MBH) website and the Australian Ocean Data Network (AODN). Where data sharing agreements have allowed (the majority of cases), we have provided a copy of the raw data used in the models to the DAWE for inclusion in the Species Profile and Threats (SPRAT) database that stores information on species and ecological communities listed under the EPBC Act for use in their future management of Threatened and Migratory marine species.

1. INTRODUCTION

Northern Australia is the current focus of substantial economic development. It is also an area that sustains rich marine biodiversity, encompassing critical habitats (breeding areas, foraging grounds and migration corridors) for many *Environment Protection and Biodiversity Conversation Act* (EPBC Act) listed Threatened and Migratory marine species, including Dugong (*Dugong dugon*), cetaceans, marine turtles, birds, and elasmobranchs (sharks and rays). Key to assessing EPBC Act referrals for these species in relation to proposed development is an understanding of the distribution and the most important areas of these species over a range of spatial and temporal scales.

One of the main spatial products currently available to assess referrals is the Species of National Environmental Significance (SNES) and the Species Profile and Threats (SPRAT; database providing information about species and ecological communities listed under the EPBC Act) databases and associated distribution maps (Department of Agriculture Water and the Environment 2018). However, the SNES distribution maps are typically data poor across species ranges, with maps of distribution largely built on presence only data from unstructured surveys and the use of qualitative approaches (e.g., spatial buffering around observations and extrapolation based on habitat known or thought to be preferred). For example, observed locations of the species are classified on the map as “known to occur”; areas with suitable or preferred habitat (inferred from geomorphic features and habitat types underlying observed locations) occurring in close proximity to these locations are classified as “likely to occur”; and the broad environmental envelope or geographic region that encompasses all areas that could provide habitat for the species are classified as “may occur”.

In Phase 1 of Project A12 – Australia’s Northern Seascape, we determined that there were more robust datasets in existence (e.g., in the published and grey literature and held by the Australian research community), but that these were largely not publicly available, and subsequently not used to develop the spatial products currently used by the Australia Government. Phase 2 of the project continued to build on collaboration with data custodians to develop data sharing agreements for use of these datasets to construct spatial models to refine and update species distributions.

The geographical scope of Phase 1 of Project A12 – Australia’s Northern Seascape was the North Marine Region (Figure 1); from Torres Strait, Queensland, through to the Gulf of Carpentaria and the Top End to the Northern Territory (NT)/Western Australian (WA) border, encompassing coastal and estuarine habitats to the edge of the Australian Economic Exclusion Zone (EEZ). However, as many of the species are highly mobile and have distributions extending beyond this region, we expanded the geographical scope to include other regions, including the North-west Marine Region; stretching from the NT/WA border to Kalbarri in WA and other marine regions where sufficient data were available and forthcoming. There are eight Australian Marine Parks (AMP) in the North Marine Region and13 AMPs in the North-west Marine Region, covering 157,480 and 335,341 square kilometres, respectively (Figure 1).

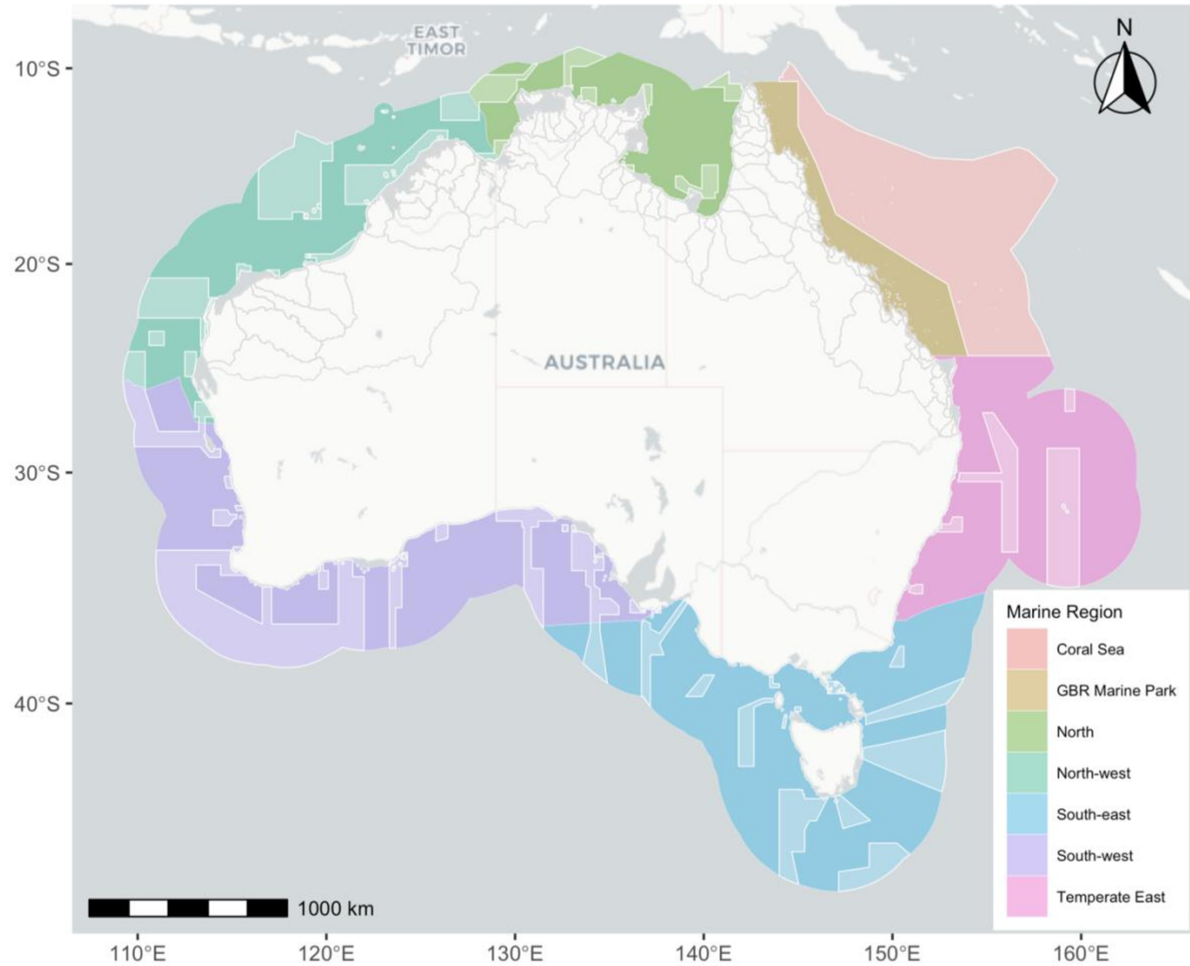

Figure 1 | Map of National Marine Regions (filled polygons) and Australian Marine Parks (AMP; shaded white polygons) within the Australian Exclusive Economic Zone. Northern river basins included in elasmobranch models outlined in grey.

1.1 Objectives

The ultimate aim of this component of Project A12 – Australia's Northern Seascape (Phase 2) was to refine and update distribution maps and occurrence data currently available to DAWE. The specific objectives were to:

1. Compile a comprehensive occurrence dataset for 16 selected Threatened and Migratory species from published and unpublished sources, including occurrences from structured surveys, opportunistic sightings, and from animal telemetry.
2. Use the datasets to build spatial models to quantify habitat suitability for species within marine, estuarine, coastal terrestrial, and freshwater systems where applicable for each species.
3. Use the model outputs to map suitable habitats for these species across Northern Australia, including the North and North-West Marine Regions and more broadly where data were available.

2. METHODS

This project built on a Phase 1 gap analysis (see Kyne et al. 2018), which aimed to identify gaps in knowledge and spatial data available to DAWE to manage Threatened and Migratory species in the North Marine Region. Phase 1 of the project consulted with research end-users and project partners to shortlist priority species from ~80 listed Threatened and Migratory species in order to ensure the project was manageable within the resources allocated. Sixteen species were selected through this process (two river sharks, three sawfishes, two marine turtles, six shorebirds, Dugong, and two inshore dolphins; Table 1) based on their EPBC status predominantly and the potential for unpublished datasets to fill important spatial data gaps in species distributions, while retaining a diversity of taxa to guide future management needs.

Following the initial identification of the existence of spatial datasets for these species in Phase 1, here we continued to search for and compile publicly available datasets and negotiate data sharing agreements for occurrence records for each species from published and unpublished sources to produce an updated dataset (see Appendix 1 for summary of data sources) from which subsequent spatial modelling (Appendix 2) was conducted. Briefly, sources from which raw occurrence datasets were compiled included public data repositories, and structured surveys conducted by Government agencies and industry, research, and conservation institutions, and independent researchers. In addition to observational sighting datasets, animal telemetry data from satellite and acoustic tagged individuals were also obtained where available. This was the case for the marine turtles and some of the elasmobranch species.

Quality control and pre-processing of the occurrence records included:

I. Duplicate occurrences across different datasets were removed based on spatial coordinates and dates.

II. In datasets where a date was associated with each occurrence record, occurrences prior to 1990 were removed to ensure occurrence data represented distributions within the last 30 years. Records without a date associated were retained to ensure contemporary records were used in models. In some species where data was extremely deficient (i.e., sawfishes, river sharks) all data were used (despite associated date), to retain as much information as possible to develop a comprehensive spatial distribution.

III. Erroneous occurrence points on land were removed (i.e., marine turtles, elasmobranchs, marine mammals), as were occurrences outside the Australian EEZ. For shorebirds, occurrence points on land were retained.

IV. For some occurrence datasets (e.g., river sharks, sawfishes, shorebirds, turtle beach surveys), occurrence points were outside the extent of regions where environmental data was available (i.e., Australian stream environmental datasets, marine environmental layers). This was primarily due to restrictions in spatial coverage of environmental data within nearshore, estuarine, and riverine areas where spatial accuracy of data derived from remote sensing products (i.e., sea surface temperature, stream environmental variables) are limited. In these cases, where occurrence points were within 5 km of environmental layers, they were adjusted to the closest point along the environmental layer. This was done to retain as many occurrence points as possible and be represented in habitat suitability predictions.

V. Multiple occurrence records of individuals of each species captured in the same location or coordinate (e.g., same set location in fishing surveys) were consolidated into a single coordinate. This process removed sampling and density dependent biases in subsequent habitat suitability models.

Table 1 | List of priority species identified from Phase 1, their *Environment Protection and Biodiversity Conservation Act 1999* (EPBC) listings and total numbers of filtered occurrence points obtained after quality-control and pre-processing (detailed above) for use in species distribution modelling.

Species	Common Name	EPBC Status++	Number of filtered occurrences
Elasmobranchs			
Glyphis garricki	Northern River Shark	Endangered (2001)	269
Glyphis glyphis	Speartooth Shark	Critically Endangered (2001)	275
Pristis clavata	Dwarf Sawfish	Vulnerable (2009)	714
Pristis pristis	Largetooth Sawfish	Vulnerable (2000)	497
Pristis zijsron	Green Sawfish	Vulnerable (2008)	225
Marine turtles			
Eretmochelys imbricata *	Hawksbill Turtle	Vulnerable (2000)	423
Lepidochelys olivacea *	Olive Ridley Turtle	Endangered (2000)	462
Shorebirds			
Calidris canutus	Red Knot	Endangered (2016)	4,561
Calidris ferruginea	Curlew Sandpiper	Critically Endangered (2015)	9,200
Calidris tenuirostris	Great Knot	Critically Endangered (2016)	6,008
Charadrius leschenaultii	Greater Sand-Plover	Vulnerable (2016)	4,552
Charadrius mongolus	Lesser Sand-Plover	Endangered (2016)	4,899
Numenius madagascariensis	Eastern Curlew	Critically Endangered (2015)	14,915
Marine mammals			
Dugong dugon **	Dugong	Listed Marine	4,628
Orcaella heinsohni	Australian Snubfin Dolphin	Listed Marine	2,062
Sousa sahulensis	Australian Humpback Dolphin	Listed Marine	3,263

Note: ++ Date of status listing was obtained from the SPRAT database (http://www.environment.gov.au/cgi-bin/sprat/public/sprat.pl).
* Data and outputs for marine turtles were restricted to within the North Marine Region.
** Data and outputs for *Dugong dugon* were restricted to within the North and North-west Marine Regions.

2.1 Species occurrence data

2.1.1 Elasmobranchs

River sharks

Occurrence data compiled for the two species of river shark, the Northern River Shark (*Glyphis garricki*) and the Speartooth Shark (*Glyphis glyphis*) (Figure 2), were sourced primarily through previous field surveys and acoustic tracking conducted by National Environmental Research Program (NERP) and National Environmental Science Program (NESP) projects (collaborative projects NERP MBH 2.4 and NESP MBH Project A1 with partners Charles Darwin University (CDU), CSIRO, Northern Territory (NT) Fisheries, Malak Ranger Group, Kakadu National Park (NP)) (Feutry et al. 2017; Feutry et al. 2020), and from other published and unpublished sources (Atlas of Living Australia; ALA, Global Biodiversity Information Facility; GBIF) (Dwyer et al. 2020; Lyon et al. 2017; Morgan et al. 2011; Morgan et al. 2004; Thorburn 2006; Thorburn and Morgan 2004) within northern river systems (see Appendix 1 for full list). Detection data from sharks monitored using acoustic telemetry within the rivers of Van Diemen Gulf (NT) and the Wenlock river system (QLD) were also included in models. Acoustic detection data were standardised to include only unique positions for all tagged individuals of each species to remove spatio-temporal biases associated with individual based tracking data within the full spatial model (see section 2.3.1 for further details).

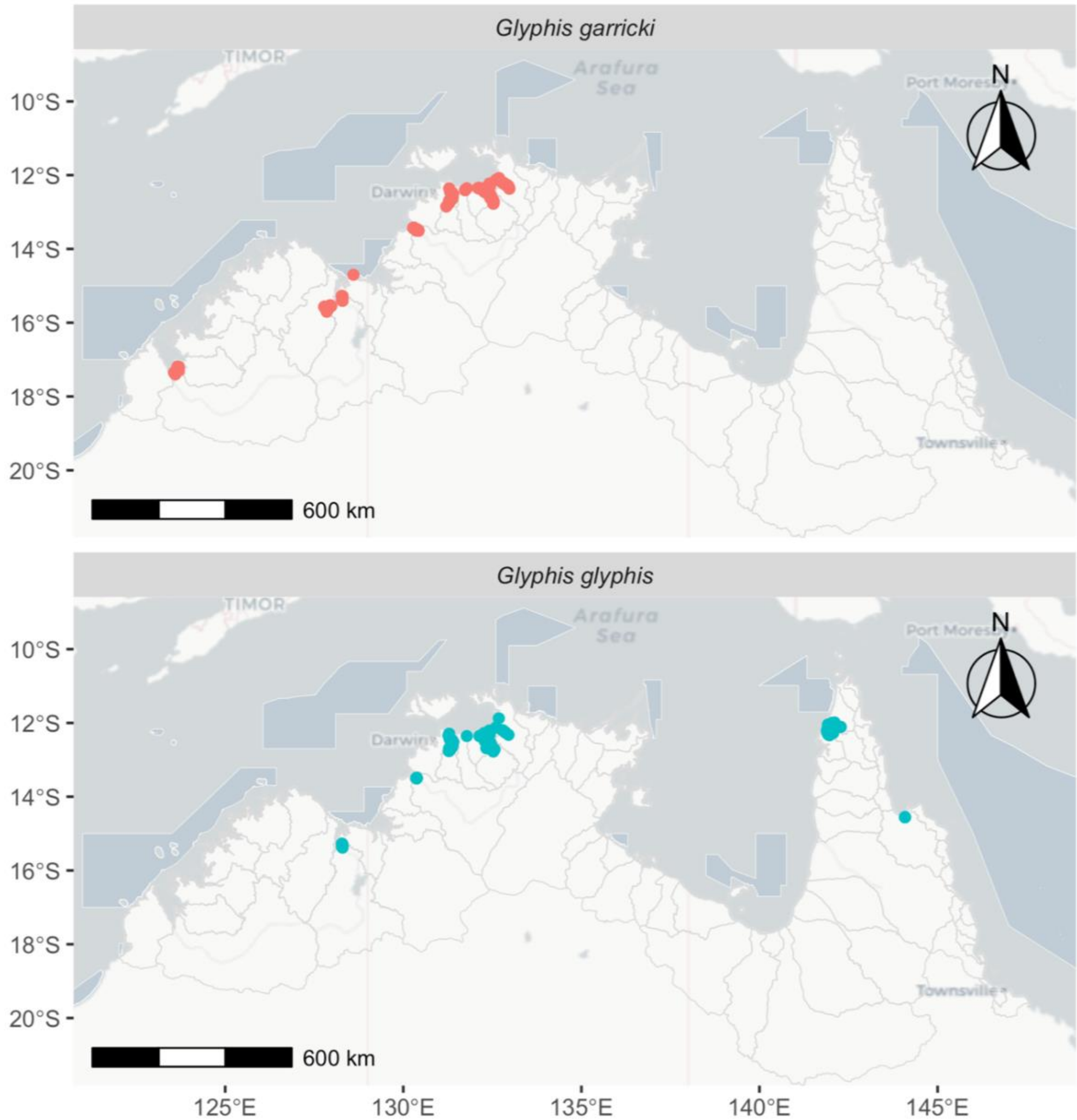

Figure 2 | Occurrence data compiled for the two river sharks; (top) Northern River Shark (*Glyphis garricki*) and (bottom) Speartooth Shark (*Glyphis glyphis*) used to model species distributions within northern Australian river systems. Northern river catchments included within the model space are outlined in grey. Blue polygons represent Australian Marine Parks.

Sawfishes

Occurrence data compiled for the three species of sawfish, the Dwarf Sawfish (*Pristis clavata*), Largetooth Sawfish (*Pristis pristis*), and Green Sawfish (*Pristis zijsron*) (Figure 3), were also sourced primarily through historic datasets (ALA, GBIF) and previous field surveys and acoustic tracking conducted by past NERP and NESP projects (collaborative projects NERP MBH 2.4 and NESP MBH Project A1 with partners CDU, CSIRO, NT Fisheries, Malak Ranger Group, Kakadu NP), fisheries bycatch data from Australian Fisheries Management Authority (AFMA), Western Australia (WA), and NT Fisheries agencies, and from other published and unpublished sources (Morgan et al. 2004; Stevens et al. 2008; B. Wueringer unpublished data ; R. Dwyer unpublished data) within river systems in northern WA, NT, and Queensland (see Appendix 1 for full list). Similar to the river shark dataset, detection data from acoustic telemetry within the rivers of Van Diemen Gulf (NT) were standardised to include only unique positions for all tagged individuals of each species to remove sampling biases associated with the tracking data within the full spatial model.

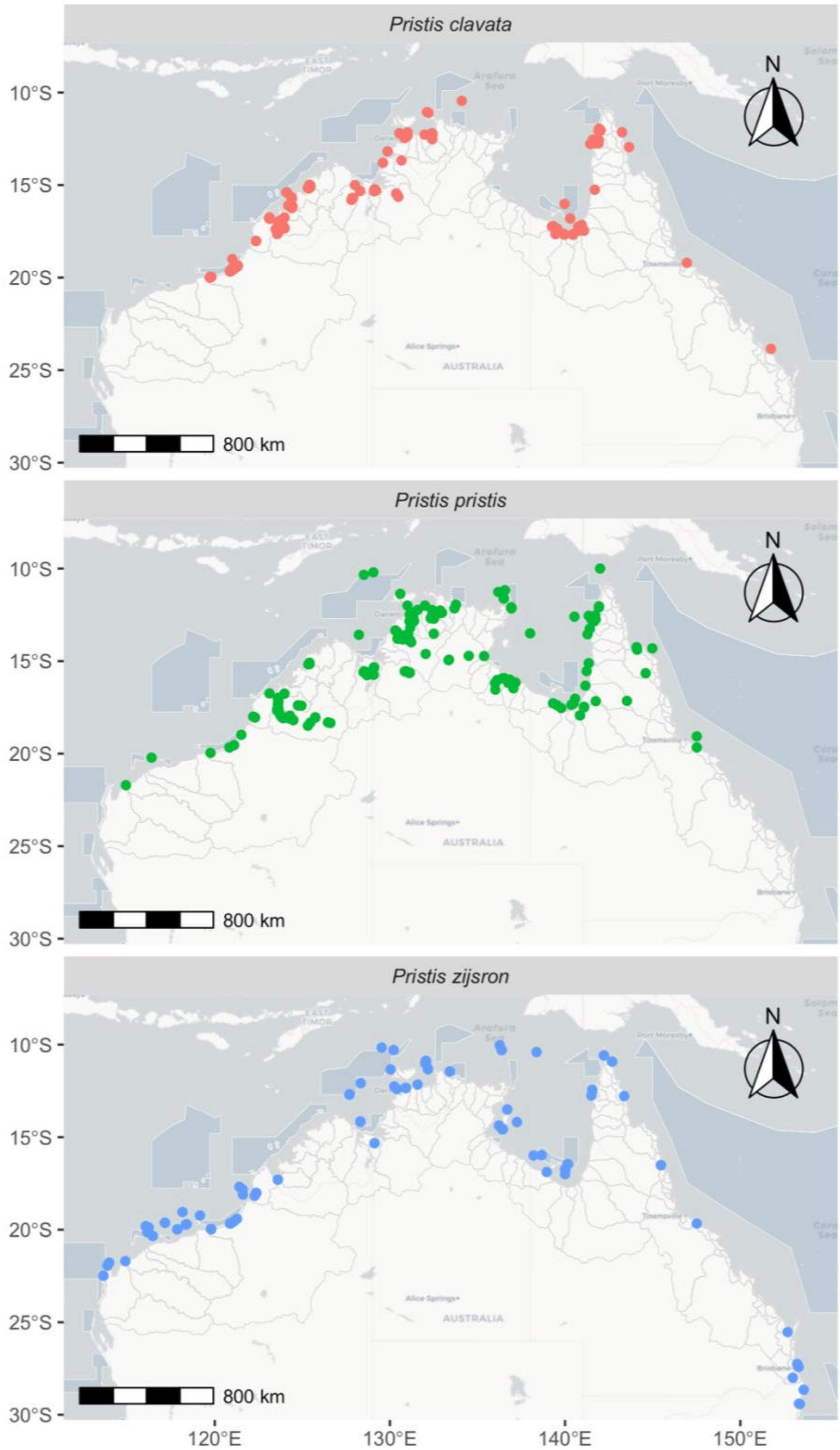

Figure 3 | Occurrence data compiled for the three species of sawfish; (top) Dwarf Sawfish (*Pristis clavata*), (middle) Largetooth Sawfish (*Pristis pristis*), and (bottom) Green Sawfish (*Pristis zijsron*) within Northern Australia used to model species distributions within northern river catchments and the marine space within the Australian EEZ. Northern river catchments included within the model space are outlined in grey. Blue polygons represent Australian Marine Parks highlighted.

2.1.2 Marine Turtles

Two data types were compiled for the two species of marine turtle, the Hawksbill Turtle (*Eretmochelys imbricata*) and the Olive Ridley Turtle (*Lepidochelys olivacea*) (Figure 4). These were i) observations from monitoring data from aerial-, beach- and boat-based surveys (from NT Government and industry monitoring programs), including opportunistic sightings on public data repositories (e.g., ALA, GBIF, NRMaps, NT WildWatch), and ii) satellite tracking data from 14 Hawksbill and 27 Olive Ridley nesting turtles collected by Government organisations (Queensland Department of Environment and Science; DES, Northern Territory Department of Environment, Parks and Water Security; DEPWS), industry (INPEX), and researchers (Hoenner et al. 2015; McMahon et al. 2007; Whiting et al. 2007; M. Guinea unpublished data) (see Appendix 1 for full list).

Data for these species were restricted to within the North Marine Region as we were not able to obtain data outside this region. Although Hawksbill Turtle data were available from the Pilbara region of WA, the distribution was not continuous between the North-west and North Marine Regions. Occurrence data from beach surveys that were outside the extent of the marine environmental datasets were adjusted so that they were retained in the model. This was done by taking the beach survey points within 5 km of environmental layers and adjusting them to the closest point along each of the environmental layers using the `points2nearestcell()` function in the `*rSDM*` R package (Rodriguez-Sanchez 2020). The two data types (observation data and satellite tracking data) were modelled separately (see section 2.3), with an overall model produced to represent coastal and pelagic habitat suitability for these species.

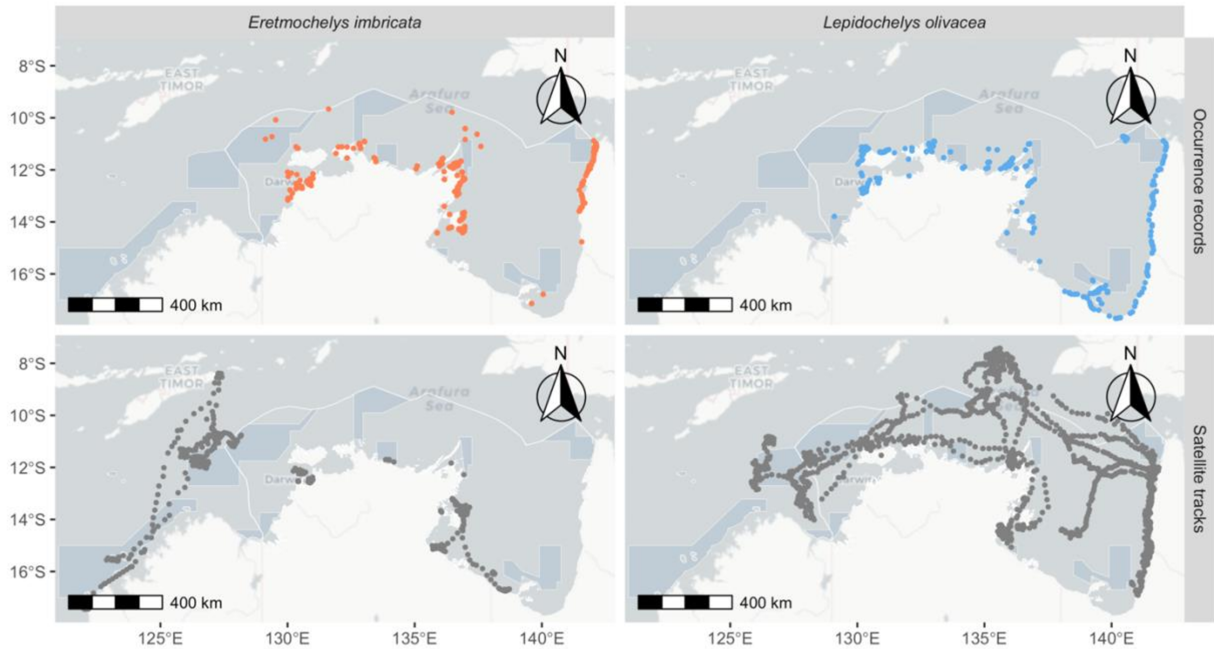

Figure 4 | Occurrence data compiled for the two species of marine turtles; (left) Hawksbill Turtle (*Eretmochelys imbricata*) and (right) Olive Ridley Turtle (*Lepidochelys olivacea*) used to model species distributions within the North Marine Region. Top panels show survey data and bottom panels show satellite tracking data (*Eretmochelys imbricata:* n = 14; *Lepidochelys olivacea:* n = 27). Blue polygons represent Australian Marine Parks.

2.1.3 Shorebirds

Occurrence data compiled for the six species of shorebird, 3 smaller sandpipers: the Red Knot (*Calidris canutus*), Curlew Sandpiper (*Calidris ferruginea*), and Great Knot (*Calidris tenuirostris*) (Figure 5); 2 plovers: the Greater Sand-Plover (*Charadrius leschenaultii*) and the Lesser Sand-Plover (*Charadrius mongolus*) (Figure 6); and the Eastern Curlew (*Numenius madagascariensis*) (Figure 7), were primarily sourced from monitoring surveys conducted by BirdLife Australia (Australian Shorebird Monitoring), and public sighting repositories (ALA, GBIF, Birdata, eBird; see Appendix 1 for full list). Spatial models for these species were restricted to the terrestrial environment within the Australian continent as occurrence data from the marine environment were not available.

Sandpipers (Calidris spp.)

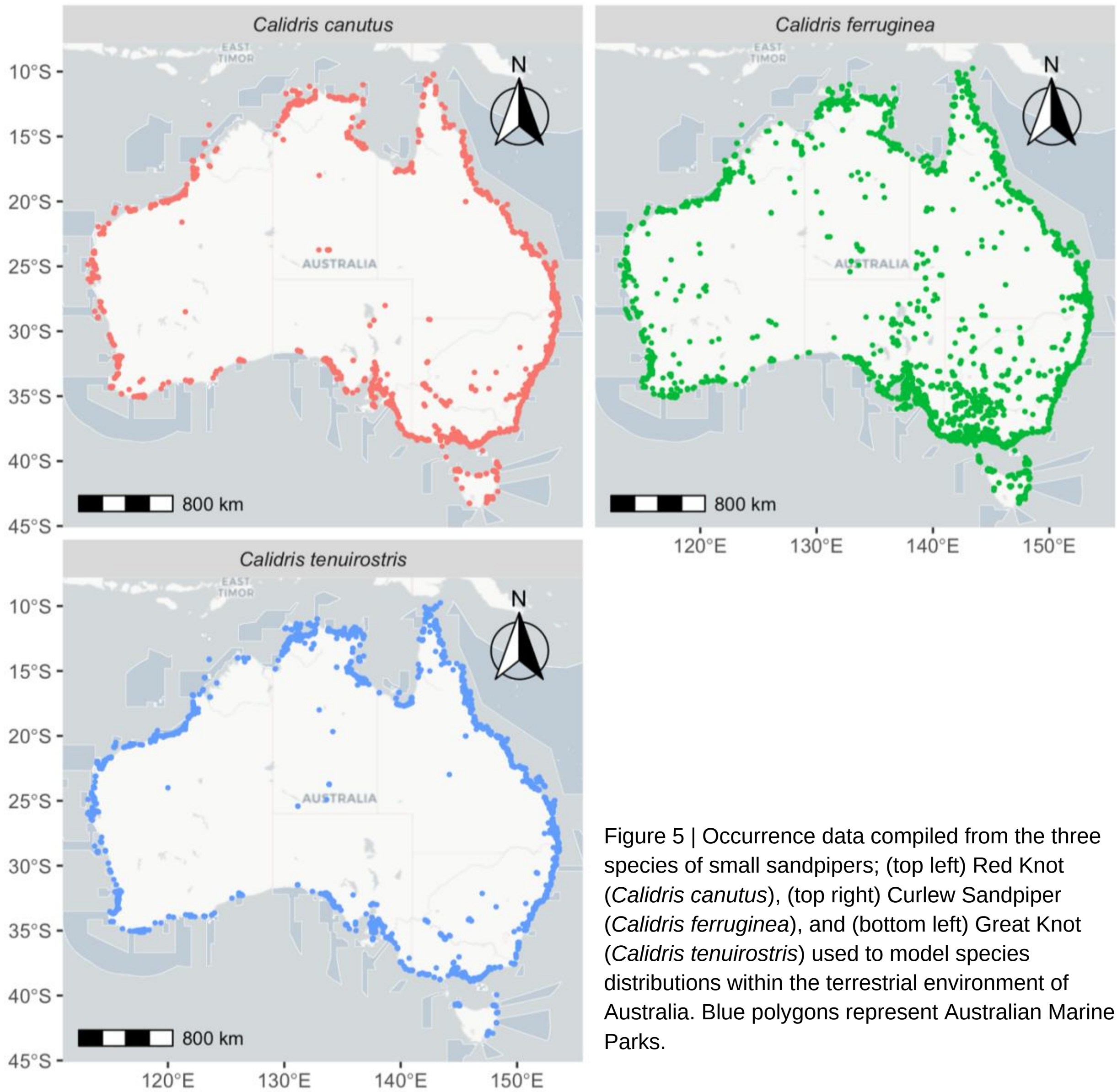

Figure 5 | Occurrence data compiled from the three species of small sandpipers; (top left) Red Knot (*Calidris canutus*), (top right) Curlew Sandpiper (*Calidris ferruginea*), and (bottom left) Great Knot (*Calidris tenuirostris*) used to model species distributions within the terrestrial environment of Australia. Blue polygons represent Australian Marine Parks.

Plovers (Charadrius spp.)

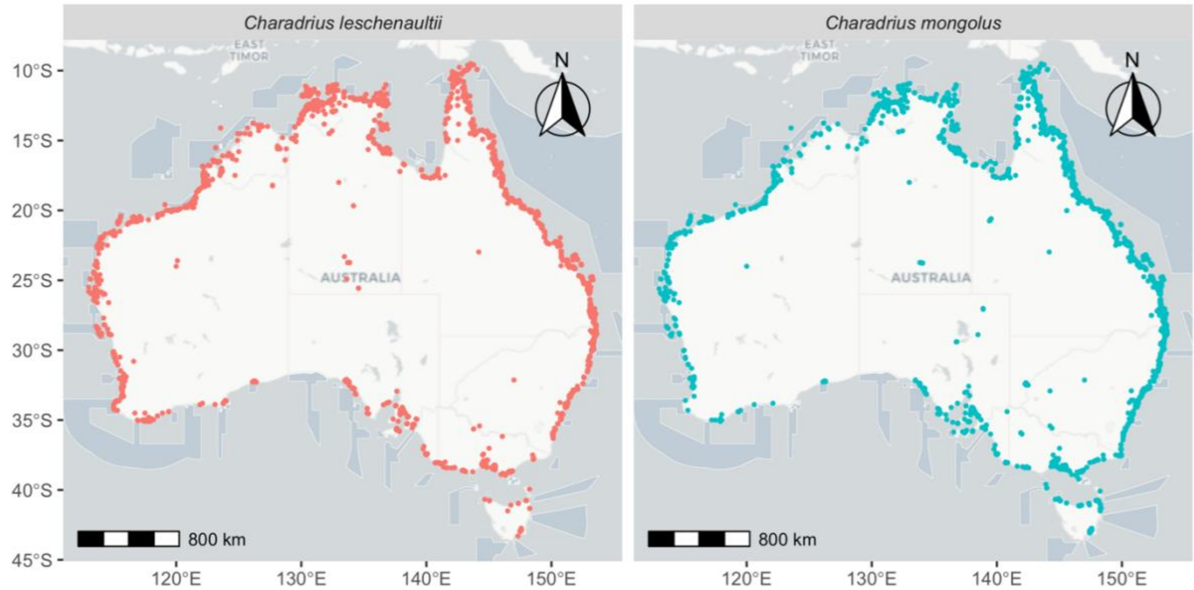

Figure 6 | Occurrence data compiled for the two species of plovers; (left) Greater Sand-Plover (*Charadrius leschenaultii*), and (right) Lesser Sand-Plover (*Charadrius mongolus*) used to model species distributions within the terrestrial environment of Australia. Blue polygons represent Australian Marine Parks.

Eastern Curlew (Numenius madagascariensis)

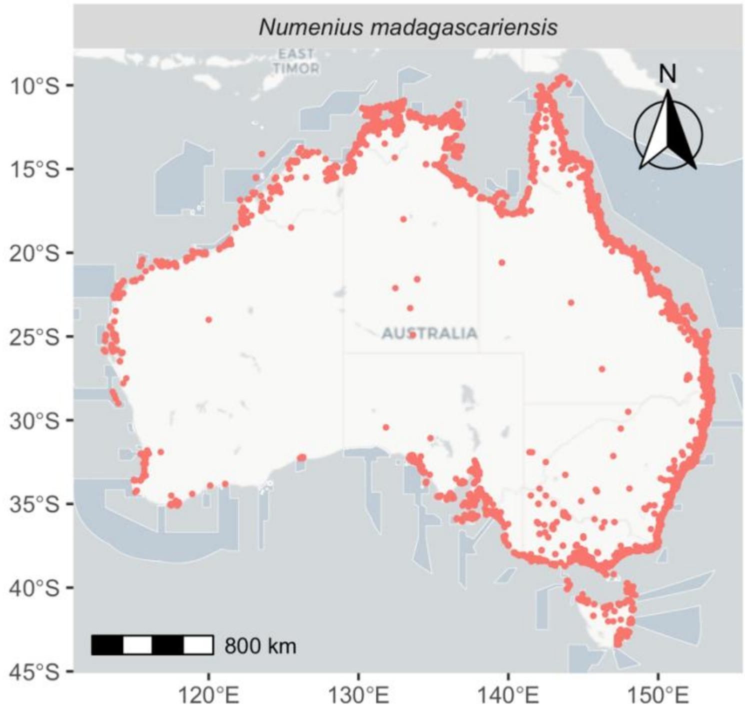

Figure 7 | Occurrence data compiled for the Eastern Curlew (*Numenius madagascariensis*) used to model distribution within the terrestrial environment in Australia. Blue polygons represent Australian Marine Parks.

2.1.4 Marine Mammals

Dugong

Occurrence data for Dugongs (*Dugong dugon*) was sourced from public data repositories (ALA, GBIF, WildWatch, NRMaps) and from structured aerial surveys (see Appendix 3) conducted by Government agencies (DEPWS, Western Australian Department of Biodiversity, Conservation and Attractions; DBCA), and boat-based surveys by industry (INPEX) and researcher organisations (WAMSI 1.2.5: Bayliss et al. 2017; Groom et al. 2015; Groom et al. 2017; Marsh et al. 2008; Marsh et al. 1995) (Figure 8, see Appendix 1 for full list). Spatial model output for this species was restricted to within the North and North-west Marine Regions due to restrictions in availability of sufficient standardised data from the east coast of Queensland. Offshore occurrence points adjacent to Ashmore Reef were filtered as coverage of covariate environmental variables in that region were sparce. Separate models were constructed for each of the two Marine Regions to account for differences in environmental variables driving their distribution and produce more regionally relevant model subsets. Regional models were then combined into a single output encompassing both the North and North-west Marine Region. Additionally, at the request of data contributors, separate seasonal models were also constructed, based on the month of occurrence of records (dry season: May – October; wet season: November – April) and are presented in Appendix 10.

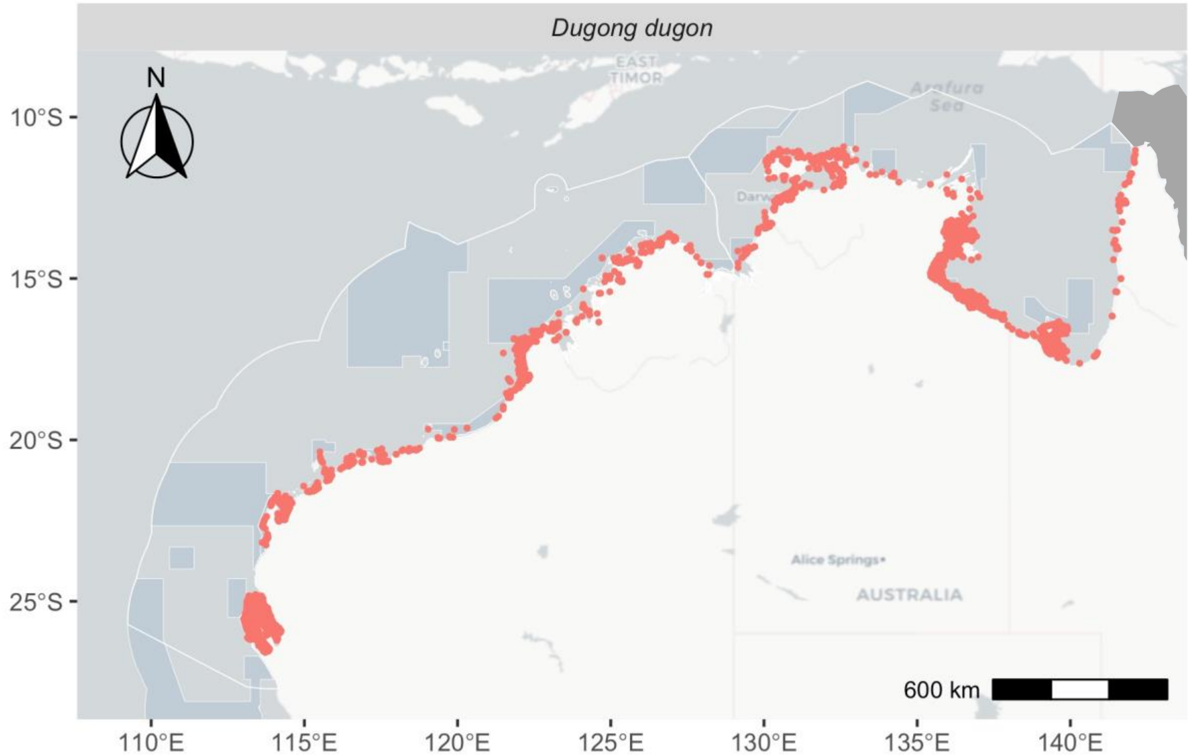

Figure 8 | Occurrence data compiled for Dugong (*Dugong dugon*) used to model distribution within the North and North-west Marine Regions of Australia (outlined in white). Data within the Torres Strait and Queensland (grey polygon) was not available for modelling. Aerial transects used to collect this data presented in Appendix 4. Blue polygons represent Australian Marine Parks.

Inshore dolphins

Occurrence data compiled for the two species of inshore dolphins, the Australian Snubfin Dolphin (*Orcaella heinsohni*) and the Australian Humpback Dolphin (*Sousa sahulensis*) (Figure 9), were sourced from sightings in public repositories (ALA, GBIF, WildWatch, NRMaps) and from structured aerial and boat surveys (see Appendix 3) conducted by Government agencies (DEPWS, DBCA), industry (Rio Tinto: GHD 2015) and research organisations (Center for Whale Research; Dolphin Research Australia Inc.; Allen et al. 2012; Bayliss et al. 2017; Brooks et al. 2017; Brown et al. 2012; Brown et al. 2017; Costin and Sandes 2009, 2011; Hodgson 2007; Hunt et al. 2020; Tulloch et al. 2020; Tulloch et al. 2018) within WA, NT, and Queensland (see Appendix 1 for full list of sources). Although occurrence data for these species occurred in rivers, the spatial model extent for these species were restricted to within the coastal marine environment across Northern Australia as less than 0.1% of the compiled occurrence data occurred in rivers and it was insufficient to model with.

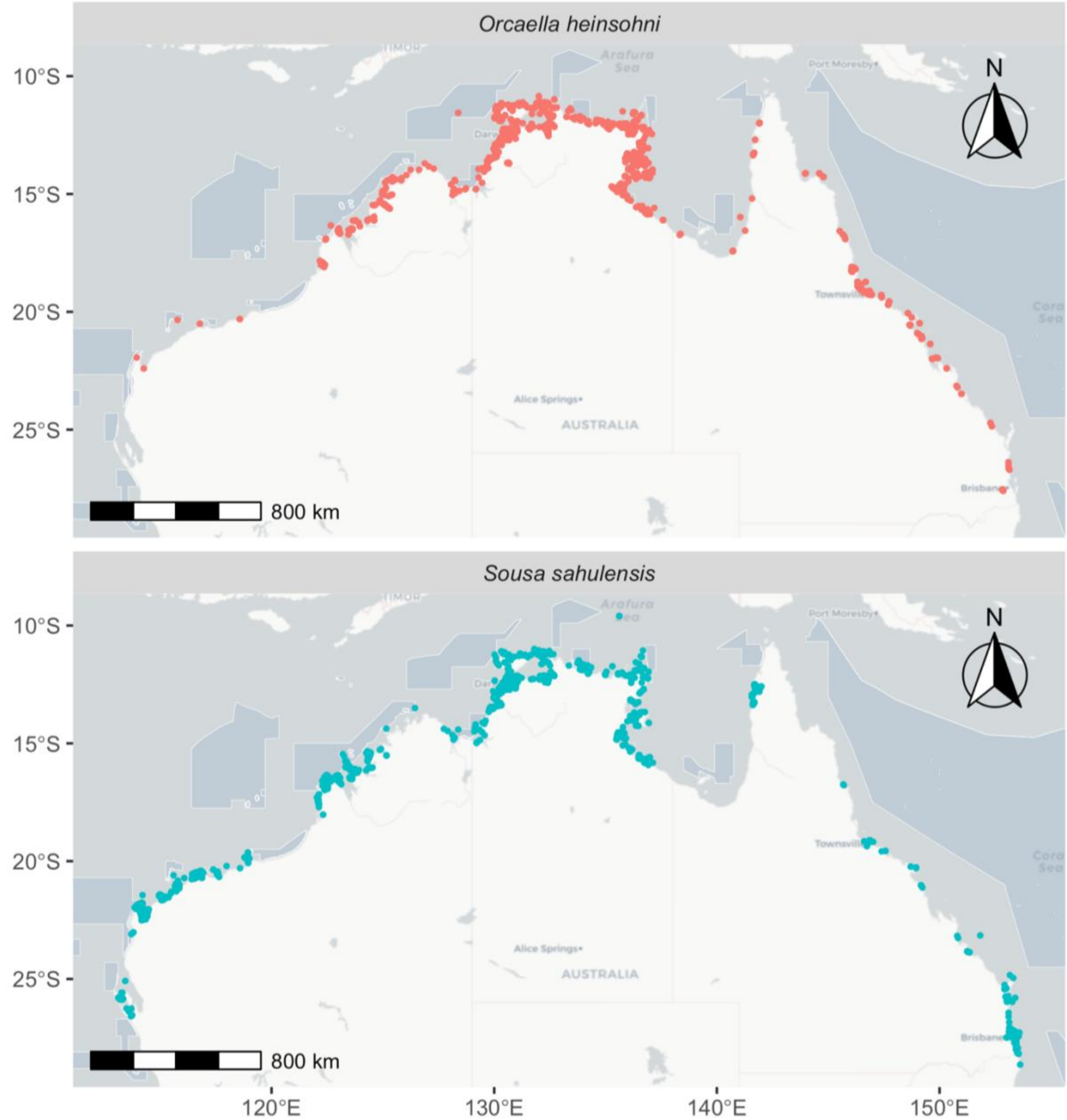

Figure 9 | Occurrence data compiled for the two species of inshore dolphins; (top) Australian Snubfin Dolphin (*Orcaella heinsohni*), and (bottom) Australian Humpback Dolphin (*Sousa sahulensis*) used to model species distributions within the marine environment within Northern Australia. Blue polygons represent Australian Marine Parks highlighted.

2.2 Environmental, biophysical and habitat variables

A wide array of climatic, habitat, and geomorphological variables were compiled to model species distributions within the marine, riverine, and terrestrial environments within Australia (Table 2, Table 3, Table 4). Ecological knowledge of each species was used to make an *a priori* selection of variables for each species relating to climate, geophysical and habitat conditions. Some key ecological variables were unavailable at the scale of the models (e.g., river salinity across north Australian catchments), therefore surrogate variables were used in their place (i.e., seasonal rainfall, stream order) to incorporate the influence of these variables in habitat suitability models. A multicollinearity test using a pairwise Pearson's correlation analysis was then conducted to remove highly collinear variables from each model. A pairwise absolute cut off coefficient value of 0.6 was used to select final variables in the final model. Environmental data was standardised to the smallest spatial resolution available for within the marine (0.0083˚ resolution), terrestrial (0.0083˚ resolution), and riverine predictor variables (0.0025˚ resolution).

Table 2 | Environmental, biophysical, and habitat parameters considered as covariates to model species distributions within the marine environment. Blue shaded cells in table indicate *a priori* variables considered for each species model, cells with cross hatching were retained after multicollinearity test.

Environmental Variable	Variable name	Species							
		DS	*LS*	*GS*	*HT*	*OR*	*DU*	*AS*	*AH*
Oceanographic variables [1]									
Mean annual sea surface temperature (˚C)	sst_mean	☒	☒	☒	☒	☒	■	■	■
Variance in annual sea surface temperature (˚C)	sst_sd	☒	☒	☒	☒	☒	☒	☒	☒
Mean SST during coldest month (˚C)	sst_coldest_mnth	■	■	■	■	■	■	■	■
Mean SST during warmest month (˚C)	sst_warmest_mnth	■	■	■	☒	☒	☒	■	■
Mean annual salinity (psu)	salinity_mean	☒	☒	☒	■	■	■	■	■
Variance in annual salinity (psu)	salinity_sd	☒	☒	☒	☒	☒	☒	☒	☒
Mean salinity during wettest month (psu)	salinity_fresh_month	■	■	■	■	■	■	■	■
Mean salinity during driest month (psu)	salinity_salt_month	■	■	■	☒	■	☒	☒	☒
Mean annual Chlorophyll a (mg.m^{-2}.day^{-1})	chlorophyll_mean	☒	☒	☒	☒	☒	☒	☒	☒
Variance in annual Chlorophyll a (mg.m^{-2}.day^{-1})	chlorophyll_sd	■	■	■	☒	☒	■	■	■
Mean annual turbidity (K490; 1.m^{-1})	turbidity_mean	■	■	■	■	■			
Variation in annual turbidity (K490; 1.m^{-1})	turbidity_sd	■	■	■	☒	■			
Seabed geomorphology [2]									
Proportion of gravel substrate (%)	gravel	■	■	■					
Proportion of mud substrate (%)	mud	■	■	■					
Proportion of sand substrate (%)	sand	■	■	■					
Seabed topography [2]									
Bathymetry (m)	bathymetry	☒	☒	☒	☒	☒	☒	☒	☒
Habitat variables [3]									
Proximity to the coast (km)	dist_to_land	☒	☒	☒	■	☒	■	■	■
Proximity to reef systems (km)	dist_to_reef				■	■			
Proximity to seagrass habitats (km)	dist_to_seagrass	■	■	■	■	■	☒	☒	☒
Proximity to mangrove habitats (km)	dist_to_mangrove	■	■	■	■	■			
Geographic position									
Longitude	longitude	☒	☒	☒	■	■	☒	☒	☒
Latitude	latitude	☒	☒	☒	☒	☒	☒	☒	☒

Note: Data were sourced at 30 arc-second resolutions (0.0083˚) from:
[1] Australian Ocean Data Network (AODN; http://portal.aodn.org.au/)
[2] Geosciences Australia (GA; https://www.ga.gov.au/data-pubs)
[3] Calculated using habitat distribution spatial layers from Seamap Australia (https://seamapaustralia.org).
DS: Dwarf Sawfish, *LS*: Largetooth Sawfish, *GS*: Green Sawfish, *HT*: Hawksbill Turtle, *OR*: Olive Ridley Turtle, *DU*: Dugong, *AS*: Australian Snubfin Dolphin, *AH*: Australian Humpback Dolphin

Table 3 | Environmental, biophysical, and habitat parameters considered as covariates to model species distributions for elasmobranch species within the riverine environment. Blue shaded cells in table indicate *a priori* variables considered for each species model, cells with cross hatching were retained after multicollinearity test.

Environmental Variable	Variable name	Species				
		NRS	*SS*	*DS*	*LS*	*GS*
Climate variables [1]						
Mean annual water temperature (˚C)	mean_temp	■	■	■	■	■
Maximum water temp during warmest month (˚C)	maxtemp_warmmonth	■	■	■	■	■
Minimum water temp during coldest month (˚C)	mintemp_coldmonth	■	■	■	■	■
Mean annual rainfall (mm)	mean_rainfall	■	■	■	■	■
Mean rainfall during dry season (mm)	rainfall_dry_season	☒	☒	☒	☒	☒
Mean rainfall during wet season (mm)	rainfall_wet_season	■	■	■	■	■
Mean solar radiation (mJ)	mean_radiation			■	■	■
Riverbed geomorphology [1]						
Percentage of sand within stream segment (%)	percent_sand	■	■	■	■	■
Percentage of clay within stream segment (%)	percent_clay	☒	☒	■	■	■
Riverbed topography [1]						
Mean stream segment elevation (m)	mean_stream_elevation	☒	☒	☒	☒	☒
Mean downstream slope (degree)	mean_stream_slope	☒	☒	☒	☒	☒
Mean slope of valley (degree)	valley_slope	☒	☒	☒	☒	☒
Habitat variables [1]						
Proximity to stream outlet (km)	dist_to_outlet	■	■	☒	☒	☒
Proximity to stream source (km)	dist_to_source			■	■	■
Geographic position [2]						
Catchment name	catchment	☒	☒	☒	☒	☒
Strahler stream order	stream_order	☒	☒	☒	☒	☒
Longitude	longitude	☒	☒	☒	☒	☒
Latitude	latitude	☒	☒	☒	☒	☒

Note: Data were sourced at 9 arc-second resolution (0.0025˚) from:
[1] Stein et. al (2014; http://www.bom.gov.au/water/geofabric/about.shtml)
[2] Geosciences Australia (GA; https://www.ga.gov.au/data-pubs) or calculated using GIS.
NRS: Northern River Shark, *SS*: Speartooth Shark, *DS*: Dwarf Sawfish, *LS*: Largetooth Sawfish, *GS*: Green Sawfish

Table 4 | Environmental, biophysical, and habitat parameters considered as covariates to model shorebird species distributions within the terrestrial environment. Blue shaded cells in table indicate *a priori* variables considered for each species model, cells with cross hatching were retained after multicollinearity test.

Environmental Variable	Variable name	Species					
		RK	*CS*	*GK*	*GSP*	*LSP*	*EC*
Climate variables [1]							
Mean annual temperature (˚C)	mean_annual_temp	■	■	■	■	■	■
Diurnal temperature range (˚C)	diurnal_temperature_range	☒	☒	■	■	☒	☒
Temperature seasonality (˚C)	temperature_seasonality	■	■	■	■	☒	■
Mean annual precipitation (mm)	mean_precipitation	■	■	■	☒	☒	■
Precipitation seasonality (mm)	precipitation_seasonality	☒	☒	■	■	■	☒
Mean windspeed (km.h^{-1})	mean_windspeed	■	■	☒	☒	☒	■
Windspeed range (km.h^{-1})	windspeed_range	■	■	■	☒	☒	☒
Mean solar radiation (mJ)	mean_solar_radiation	■	■	☒	☒	☒	■
Mean water vapour pressure (Pa)	mean_vapour_pressure	■	■	■	■	■	■
Topography [2]							
Elevation (m)	elevation	☒	☒	☒	☒	☒	☒
Habitat variables [2]							
Proximity to coast (km)	dist_to_coast	☒	☒	☒	☒	☒	☒
Proximity to tidal flats (km)	dist_to_tidalflats	■	■	■	■	■	☒
Dynamic Land Cover	dynamic_land_cover	☒	☒	☒	☒	☒	☒
Fraction of Photosynthetically Active Radiation	f_par	■	■	☒	☒	☒	■
Enhanced Vegetation Index	enhanced_vegetation_index	☒	☒	☒	☒	☒	☒

Note: Data were sourced at 30 arc-second resolutions (0.0083˚) from:
[1] Xu and Hutchinson (2011; http://fennerschool.anu.edu.au/research/software-datasets/anuclim)
[2] Geosciences Australia (GA; https://www.ga.gov.au/data-pubs) or calculated using GIS.
RK: Red Knot, *CS*: Curlew Sandpiper, *GK*: Great Knot, *GSP*: Greater Sand-Plover, *LSP*: Lesser Sand-Plover, *EC*: Eastern Curlew

2.3 Modelling frameworks

The spatial modelling approach used to model habitat suitability for the 16 key species followed one of two main frameworks. The framework was selected based on the available occurrence data to model habitat suitability for each species. Both frameworks utilised a correlative presence-pseudoabsence modelling approach and were chosen for their ability to account for occurrence data collected opportunistically (i.e., museum collections, opportunistic and non-structured surveys) or serial autocorrelation from individual-based telemetry data.

2.3.1 Maximum entropy models

A correlative modelling approach, using maximum entropy models (MaxEnt [version 3.4.1]; Phillips et al. 2006) was used for species and groups where occurrence data was sourced through surveys (e.g., aerial monitoring) or opportunistic records (e.g., museum records). Correlative modelling is often subject to biases from '*ad hoc*' sampling, and/or variable detectability of target species during surveys (Yackulic et al. 2013). Sampling bias in geographic space was addressed in two ways. First, occurrence records were regularised through consolidation of multiple records within each grid cell of the raster resolution used for model prediction (30 arc second). Second, a `bias grid` (as per Clements et al. 2012) was constructed, which was a Gaussian probability distribution function based on all known records of each taxa from the region. Spatial sampling effort for marine mammals, where available (e.g., aerial survey transects; Appendix 3) was included in bias grid estimation. This bias grid was used for selecting pseudo-absence points from within the model space.

The background used to generate pseudo-absences for models was defined to be either within the Australian continent (i.e., for shorebird models), within river catchments (i.e., for river sharks and sawfishes), or within the Australian Marine Regions from where occurrence data was available (i.e., for marine turtle and mammals). 10,000 pseudo-absence points were randomly selected at the same spatial density as the bias grid for each species model. Model predictions were restricted to the same region as the training domain (background) to avoid the dangers of extrapolating correlative models (Elith and Leathwick 2009), either outside the univariate range of covariates (Type 1 novelty; Mesgaran et al. 2014) or into novel covariate combinations (correlations) still within the univariate range of covariates (Type 2 novelty). All data pre-processing and spatial modelling was conducted in the R statistical environment (R Core Team 2021).

Model tuning was first undertaken to test a range of model setting combinations specific to MaxEnt models and determine the ideal hyperparameters for each species model. These include the regularization multiplier (*rm*); a parameter that adds constraints to the model to avoid model overfitting, and feature class selection (*fc*); parameters that determine the shape of environmental correlations in the model. Model tuning was undertaken using the '*SDMtune*' R package (Vignali et al. 2020) which undertakes a bootstrapped maximum likelihood process to estimate ideal hyperparameters. A series of MaxEnt models across a range of *rm* (between 0.5 and 4 in 0.5 steps) was tested across all combinations of *fc* (i.e., linear, quadratic, hinge, produce and threshold features). Occurrence and pseudo-absence datasets for each model were first divided into five sets. A five-fold cross validation process was used, where a model was trained using all but one set and was tested against the retained set. This was iterated five times each using each unique divided set as a testing dataset each time. In total, 48 setting combinations were tested for each cross validation run resulting in 48 x 5 models for each species. Optimal model settings were selected using an Akaike Information Criterion adjusted for small sample size (AICc; Burnham and Anderson 2002). An average model output across the iteration with the optimal model settings was used to produce the final model predictions. The standard deviation within the predictions across the iterations was also calculated to provide a spatial measure of variance in model prediction and identify spatial patterns in prediction variability (Figure 10; final model outputs for each species including mean prediction, prediction variance can be found in Appendix 2).

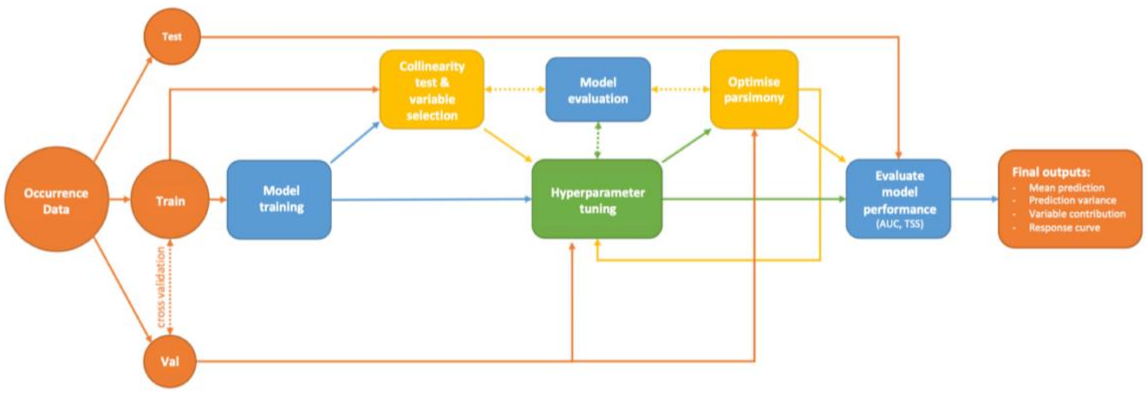

Figure 10 | Maximum entropy modelling workflow from occurrence dataset, model training, variable selection, hyperparameter tuning, and model optimisation. Workflow used followed that proposed by Vignali et al. (2020). Colours indicate different steps: preparation of data and results (orange), model training and evaluation (blue), variable selection (yellow), and hyperparameter tuning (green). Dashed lines represent iterative processes.

2.3.2 Generalised additive mixed models

A generalised additive mixed modelling (GAMM) framework was used when satellite telemetry data was available; this was the case for the marine turtles only. A mixed modelling framework accounts for the inherent sample size bias due to repeated measures from the same tagged individuals, by including tagged individual as a random effect within the model.

A state-space model was first fitted the individual turtle satellite tracking data with a correlated random walk model using the `*foieGras*` package (Jonsen et al. 2020). This was done to regularise the data (in this case to a common timestep of 24 hours) and to account for the position error associated with each satellite location estimate.

The GAMM modelling framework then followed methods described by Reynolds et al. (2017). Pseudo-absence points for each individual track were simulated within the study region. Simulated tracks began at the same point as each of the actual turtle satellite tracks on which they were based but proceeded randomly throughout the available marine environment constrained by the actual satellite track duration, and distribution of step lengths and turning angles of actual tracks. Simulated tracks represented movement of the tagged turtle but without any preference for any particular environmental conditions. Ten simulated tracks were generated for each individual satellite tracked turtle. Habitat and environmental conditions at the locations along the actual turtle satellite tracks represented habitats used by the individual (presence points), while those along the simulated turtle tracks represented habitat and environmental conditions that could potentially have been used by the individual but was not (pseudo-absence points; Figure 11).

The same predictor variables used in MaxEnt models (Table 2) were considered as initial predictor variables. Similar to MaxEnt models, a multicollinearity test was used to remove highly collinear variables prior to being used to model habitat suitability with tracking data. Relationships between the variables and presence of animals were modelled using binomial GAMM with a logistic link function using the `*mcgv*` package (Wood et al. 2016) with turtle ID used as a random factor. Optimal smoothing terms for each predictor variable were estimated using a Penalised-Quasi Likelihood process across 50 iterations (Venables and Ripley 2002). AICc associated with each smoothing term was used to identify optimal model configuration. Population-level coefficients from optimal models were used to predict habitat suitability across the model space (North Marine Region). Standard deviation in coefficients from models were used to predict variability in habitat suitability predictions.

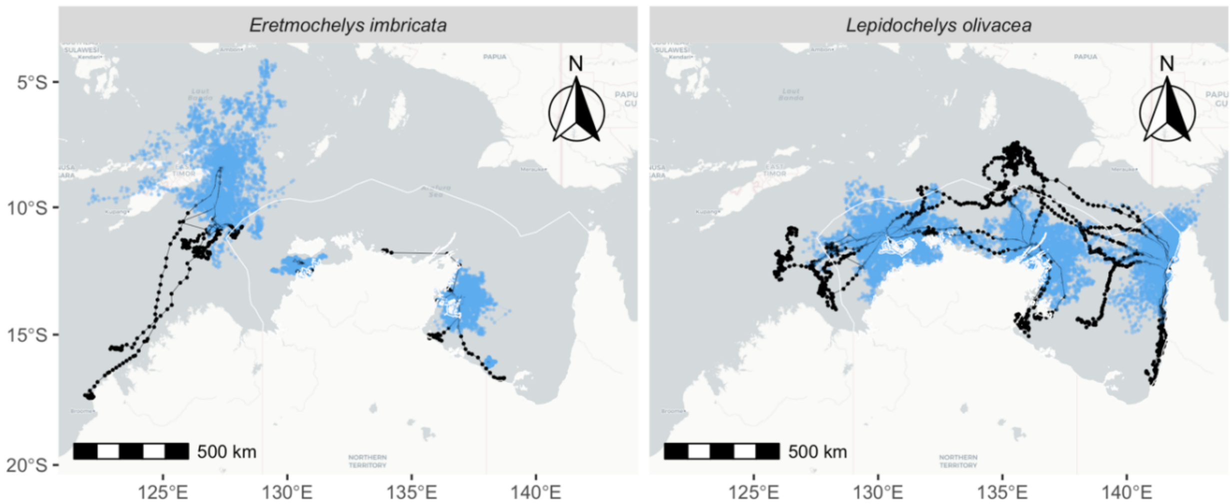

Figure 11 | Turtle satellite tracks (black paths) and simulated background tracks (blue paths) for; (left) 14 tracked Hawksbill Turtles (*Eretmochelys imbricata*), and (right) 27 Olive Ridley Turtles (*Lepidochelys olivacea*) within and in close proximity to the North Marine Region (white boundary). Positions of actual turtle satellite tracks represented presence points, while positions of simulated tracks represented pseudo-absence points for subsequent GAMMs to predict habitat suitability.

2.3.3 Model evaluation

Model outputs were evaluated by testing optimal model predictions alongside occurrence and pseudo-absence data used to train the optimised model. The area under the receiver operating curve (henceforth AUC; Fourcade et al. 2017), and a true skill statistic (TSS) were used to assess the ability of the model to discriminate between presence and pseudo-absence points. An AUC score ranges between 0 and 1, where a score of 0 represents a complete mismatch between the model prediction and actual occurrence data, while a score of 1 represents a perfect alignment between the prediction and occurrence data. The true skill statistic (TSS) accounts for both model omission (false positive) and commission (false negative) errors, and ranges from -1 to +1, where +1 indicates perfect agreement and values of zero or less indicate a performance no better than random (Fourcade et al. 2017). Variable contributions were used to identify key environmental covariates that influence species-specific habitat suitability. Variable contribution estimates are calculated by tracking the change in performance of each model across multiple iterations to quantify the contribution of each predictor variable to model coefficients. Response curves were produced to identify how each environmental variable retained within optimal models influenced habitat suitability.

2.3.4 Model prediction, interpretation and identification of suitable habitats

Model predictions provided a spatial representation of habitat suitability based on the known occurrences and correlative relationships with predictor variables used in each species-specific model. The models predict habitat suitability ranging from 0 (unsuitable) to 1 (suitable habitat) and indicate increasing probability of occurrence. Measures of habitat suitability do not provide an estimate of regional density but are a density-independent measure of how suitable a location may be for each species modelled. Although, there may be a correlation between habitat suitability and population density (i.e., more suitable habitats house greater densities of a species), there are a range of demographic and ecological factors that define that correlation (see Oliver et al. 2012), and were not included in the present models. Other methods (e.g., distance sampling, density modelling) are required to ascertain population density estimates, which was outside the scope of this project. In addition, these models have many assumptions and input parameters which for the majority of species (and datasets) was unavailable.

To quantify ‘suitable’ and ‘unsuitable’ habitats from habitat suitability predictions, thresholds are often applied to model outputs to simplify continuous outputs into binary maps, which often aids in validation and interpretation (Peterson et al. 2011). We identified the threshold level by estimating the level of model prediction that maximises both the True Positive Rate (Sensitivity) and the True Negative Rate (Specificity) (Pearson et al. 2007) (Figure 12). This threshold is considered a conservative estimate of a species’ tolerance to each environmental variable and can provide an ecological basis to habitat suitability and thus probability of occurrence (Peterson et al. 2011). Here, we present the thresholded suitable habitat maps in the results section, and the maps of habitat suitability scaled between 0 and 1 are provided in Appendix 4.

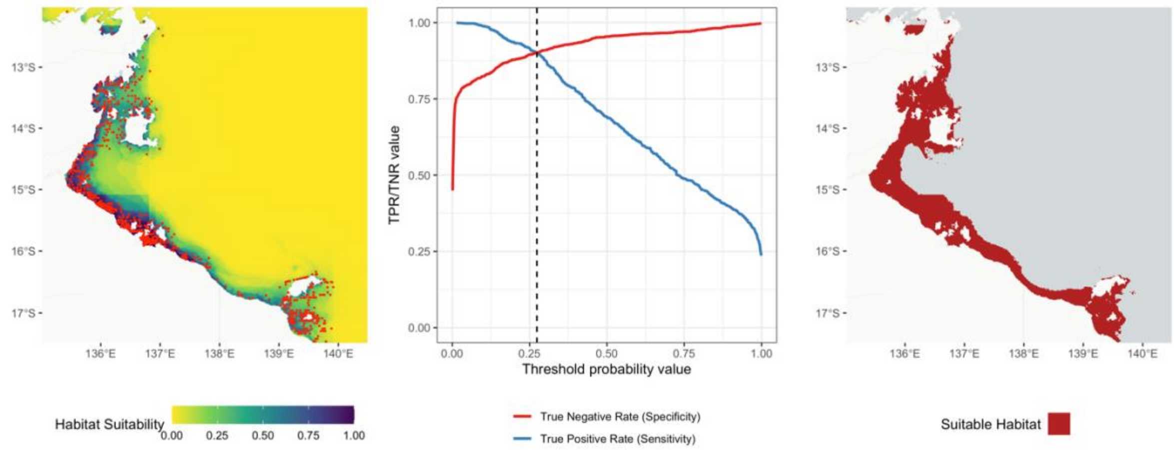

Figure 12 | Using an example from the western Gulf of Carpentaria from the Dugong modelling, we show the continuous model output (left panel with occurrence points in red) used to calculate Sensitivity and Specificity of model. The threshold value that maximises both sensitivity and specificity (middle panel) can then be estimated and used to convert the continuous output into a binary output, identifying suitable habitat (right panel).

3. RESULTS AND DISCUSSION

AUC and TSS scores across all species models were high (> 0.7), indicating all model predictions matched well with the occurrence records for species on which they were trained (Table 5, Figure 13). Regions of suitable habitats aligned with the currently defined SNES distributions (Department of Agriculture Water and the Environment 2018).

3.1.1 Elasmobranchs

Distributions of river sharks were modelled only within river environments, whereas sawfishes were modelled within the marine and river environments. In the case of sawfishes, separate models were built for the marine and riverine components due to differences in drivers that influence occurrence probability and habitat suitability in each of the environments (see Table 2 and Table 3 for details on covariates available for each environment). Overall, model outputs for river systems were at a finer resolution (0.025˚; ~250 m) than marine systems (0.083˚; ~1 km) as river systems modelled included outermost tributaries with widths of less than 100 m (Strahler stream order ranged from 1 – 8; Stein et al. 2014).

Table 5 | Summary of optimal model hyperparameters (feature classes; *fc*, regularisation multiplier; *rm*) and model evaluation scores for marine (M), riverine (R) and terrestrial (T) environments (env) including the area under the receiver operating curve (AUC) and true skill statistic (TSS) are provided. Threshold values indicate probability value of model predictions that maximises the true positive rate (sensitivity) and the true negative rate (specificity)

.

Species	Common Name	env	*fc*	*rm*	AUC	TSS	Threshold
Elasmobranchs							
Glyphis garricki	Northern River Shark	R	lqh	1.0	0.996	0.941	0.432
Glyphis	Speartooth Shark	R	lqh	4.0	0.995	0.941	0.349
Pristis clavata	Dwarf Sawfish	R	lqpht	3.5	0.990	0.925	0.101
		M	lqph	3.5	0.990	0.912	0.482
Pristis	Largetooth Sawfish	R	lqh	2.5	0.982	0.872	0.257
		M	lqpht	3.0	0.980	0.867	0.764
Pristis zijsron	Green Sawfish	R	lqh	3.0	0.993	0.947	0.211
		M	lqh	1.0	0.966	0.836	0.610
Marine turtles							
Eretmochelys imbricata *	Hawksbill Turtle	M	lqpht	1.0	0.965	0.812	0.173
Lepidochelys olivacea *	Olive Ridley Turtle	M	lqpht	3.5	0.971	0.847	0.241
Shorebirds							
Calidris canutus	Red Knot	T	lqph	1.0	0.930	0.711	0.438
Calidris ferruginea	Curlew Sandpiper	T	lqpht	1.5	0.875	0.797	0.739
Calidris tenuirostris	Great Knot	T	lqpht	0.5	0.936	0.736	0.394
Charadrius leschenaultii	Greater Sand-Plover	T	lqpht	1.0	0.925	0.709	0.305
Charadrius mongolus	Lesser Sand-Plover	T	lqpht	2.5	0.922	0.700	0.221
Numenius madagascariensis	Eastern Curlew	T	lqpht	0.5	0.927	0.708	0.214
Marine mammals							
Dugong dugon **	Dugong	M	lqpht	1.5	0.923	0.790	0.263
Orcaella heinsohni	Australian Snubfin Dolphin	M	lqh	1.0	0.979	0.881	0.267
Sousa sahulensis	Australian Humpback Dolphin	M	lqph	2.0	0.982	0.870	0.153

Note: * Data and outputs for marine turltes were restricted to within the North Marine Region. ** Data and outputs for *Dugong dugon* were restricted to within the North and North-west Marine Regions.
- Feature class (*fc*) indicates mathematical transformations of covariates that were included to optimal models to allow complex relationships. These include linear (l), quadratic (q), product (p), hinge (h) and threshold features (t) (see Elith et al. 2011).
- Regularisation multiplier (*rm*) indicates parameters that imposes penalties to models to prevent overfitting (Morales et al. 2017).
- AUC scores range between 0 and 1, where a score of 0 represents a complete mismatch between the model prediction and actual occurrence data, while a score of 1 represents a perfect alignment between the prediction and occurrence data.
- TSS scores ranges from -1 to +1, where +1 indicates perfect agreement and values of zero or less indicate a performance no better than random.

Figure 13 | Summary of the relative contribution of each variable calculated for each model for each taxonomic group used in optimal models for each of the 16 species within the riverine, marine, and terrestrial components of the model space. Variables on the y-axis are ranked in decreasing order based on average, overall variable importance across all species models within each environment. Details of the sources of variables displayed on y-axes can be found in Table 2 for marine variables, Table 3 for river variables, and Table 4 for terrestrial variables. Full list of model evaluation metrics is provided in Appendix 2.

River sharks

River sharks are euryhaline species primarily occupying macrotidal river systems and estuaries as well as coastal areas (Dwyer et al. 2020; Dwyer et al. 2019; Feutry et al. 2017; Feutry et al. 2020; Lyon et al. 2017; Pillans et al. 2010; Thorburn and Morgan 2004). These two species have a preference for brackish water and are not true freshwater species although they will occur in very low salinities. As occurrence data were primarily restricted to the riverine environment (Figure 2), so were the river shark models, specifically from coastal catchments of King Sound in Western Australia across the north, to northeast Queensland. The distribution presented here is an improvement of the SNES (Department of Agriculture Water and the Environment 2018) distribution map (see Kyne et al. 2018) and representative of the species distribution within river systems of northern Australia, however, the lack of data in coastal waters still represents a substantial gap for these species. There are few coastal and marine records for these species and records are patchy across the north given their occurrence in discrete river systems.

Model predictions for both species fit the occurrence data very well (AUC > 0.99, TSS > 0.94; Table 5). Model predictions highlighted the Adelaide, Mary, and Alligator catchments in the Northern Territory as suitable river systems for both species (Figure 14 and Figure 15; finer scale model outputs can be accessed via Appendix 2). These rivers flow into the Van Diemen Gulf, a known area of importance for river sharks (Bravington et al. 2019; Feutry et al. 2017; 2020). The suitability identified for these catchments is most certainly biased by the higher sampling effort in this region (the Van Diemen Gulf has been the main field study region under the NERP and NESP Marine Biodiversity Hub projects). Suitable habitats for the Northern River Shark were also identified within the Daly, Moyle, and Meda River (Lennard catchment) systems (Figure 14); and habitats for the Speartooth Shark included the Ducie, Mitchell, and Normanby River systems in Cape York (Figure 15). While there are records of these species in the Daly River (both Northern River Shark and Speartooth Shark; Feutry et al. 2020, Kyne et al. in prep.) and the Ducie River (Speartooth Shark), there are no records in the other systems mentioned above where suitable habitat was predicted.

Stream elevation, order (level of branching of river system), and catchment were key variables influencing habitat suitability models (Figure 13), with suitable habitats predicted in higher order streams close to the coast (sea level) within catchments within the Northern Territory (Appendix 5). The selection of these variables is likely associated with the preference for riverine and estuarine environments by juvenile and sub-adult river sharks which are the age-classes accessible to researchers while adults remain poorly documented (Feutry et al. 2017; 2020; Pillans et al. 2010).

Our results highlight the need for further data collection to improve the known distribution in more river systems along northern Australia, and particularly for adult river sharks in the marine environment.

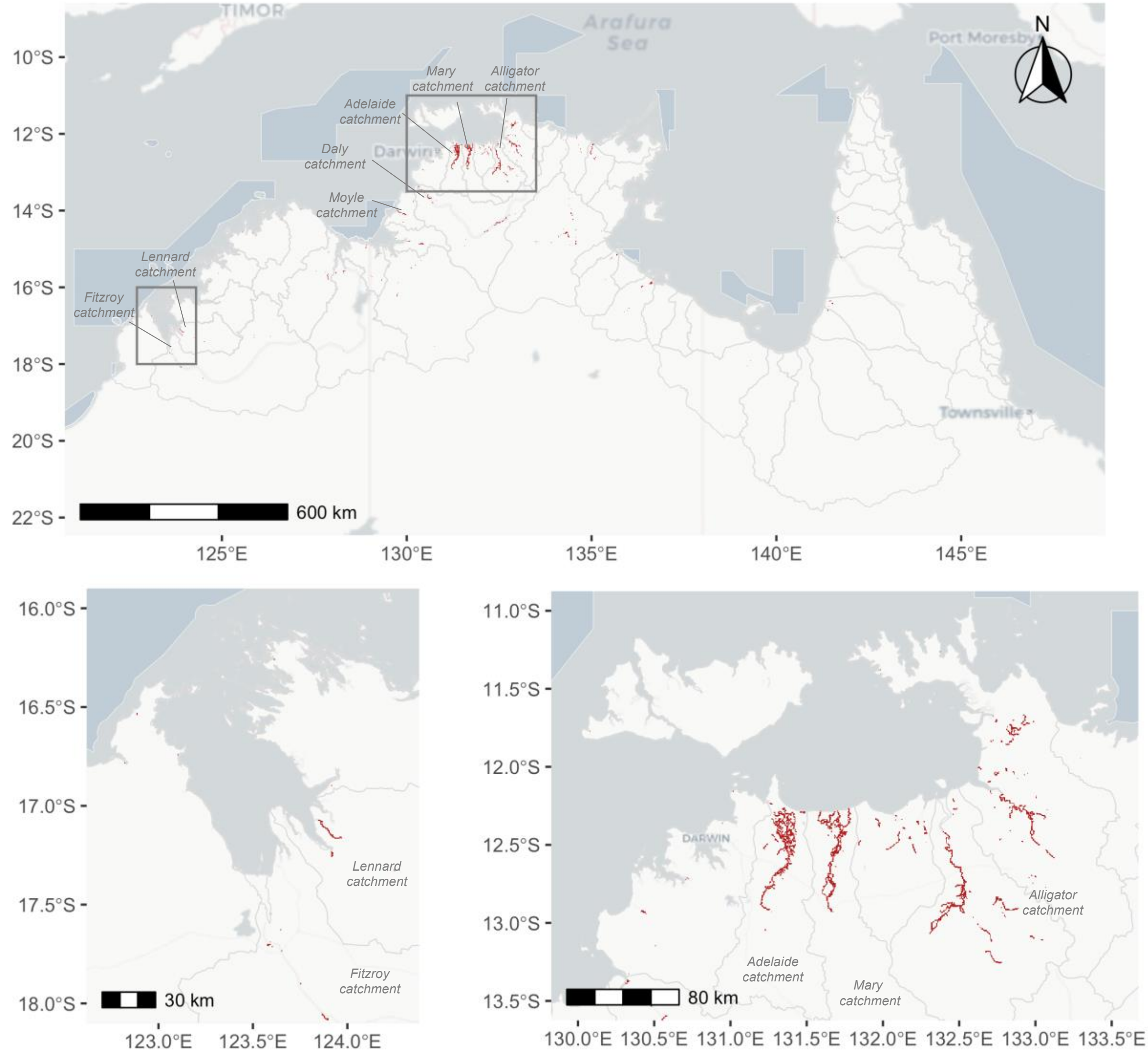

Figure 14 | Thresholded MaxEnt model predictions of habitat suitability (red) for the Northern River Shark (*Glyphis garricki*), (top) across the northern river catchments, and zoomed into the (bottom left) Fitzroy catchment, and (bottom right) the Adelaide, Mary and Alligator catchments adjacent to the Van Diemen Gulf. Models were restricted to within river systems. Scaled model prediction of habitat suitability provided in Appendix 4. Response curves for model predictions provided in Appendix 5. Blue polygons represent Australian Marine Parks.

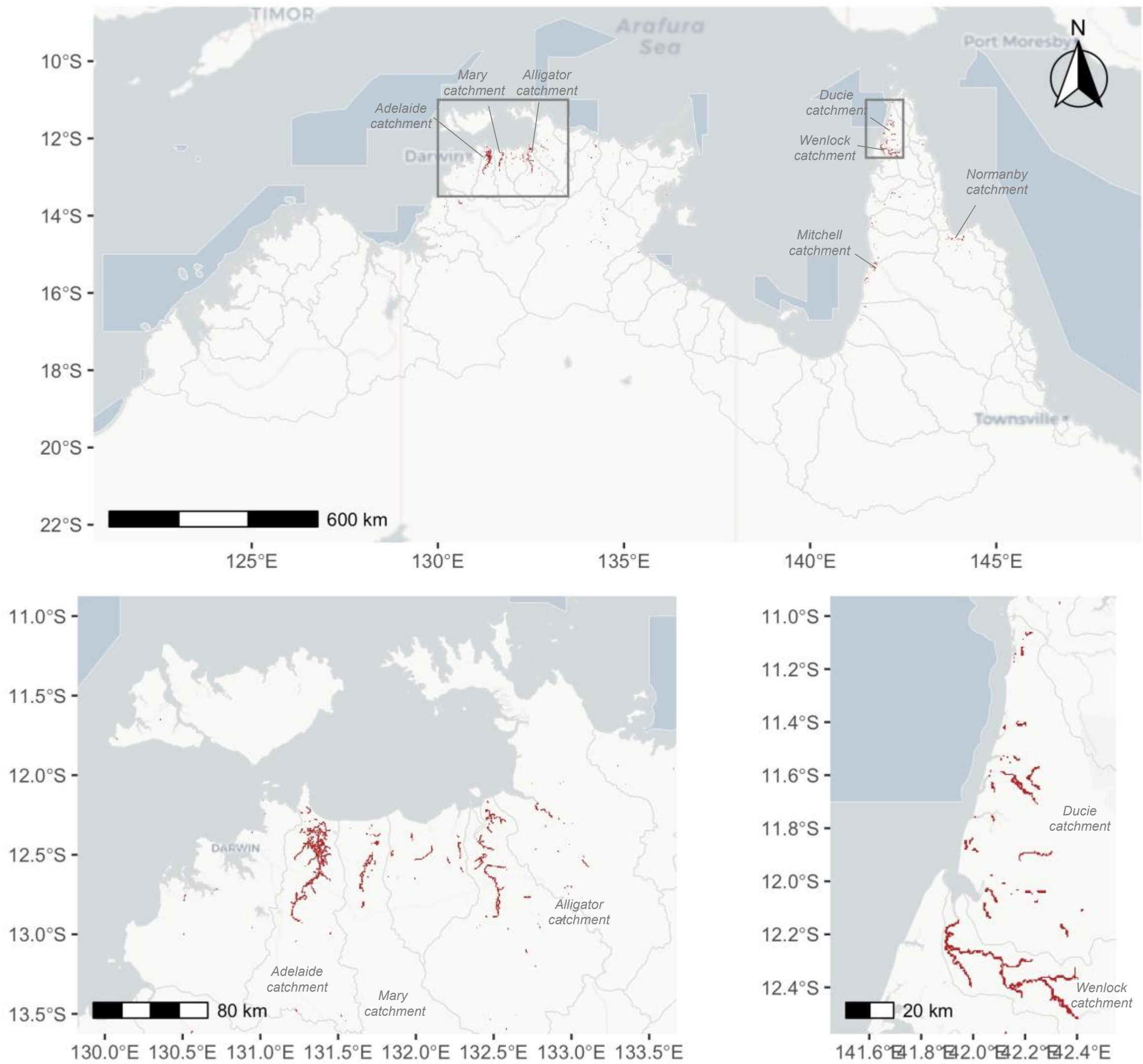

Figure 15 | Thresholded MaxEnt model predictions of habitat suitability (red) for the Speartooth Shark (*Glyphis glyphis*), (top) across the northern river catchments, and zoomed into the (bottom left) he Adelaide, Mary and Alligator catchments adjacent to the Van Diemen Gulf, and (bottom right) the Ducie and Wenlock catchments in northern Cape York. Models were restricted to within river systems. Scaled model prediction of habitat suitability provided in Appendix 4. Response curves for model predictions provided in Appendix 5. Blue polygons represent Australian Marine Parks.

Sawfishes

Sawfish models were constructed in two components: the marine and river environments (Table 5, Figure 13). The marine models included waters within the Australia EEZ, whereas river models were restricted to coastal catchments from the Gascoyne River catchment north of Exmouth, across to the Logan River catchment in the Gold Coast. The river models were restricted to these catchments as all occurrence records of sawfish fell within these catchments (Figure 3). It is worth noting that these catchments include upper freshwater reaches of rivers and brackish downstream reaches where rivers are macrotidal and therefore under the influence of tidal salinity. The marine distribution is a marked improvement of the SNES distribution map where much of the likely habitat has been resolved (see Kyne et al. 2018). The division between river and marine models roughly represents the differential habitat use between adult and juvenile sawfishes. In Australia, immature sawfish are generally restricted to shallow inshore estuarine and coastal waters, as well as freshwater rivers for Largetooth Sawfish, while mature individuals generally occupy marine waters (Lear et al. 2019; Morgan et al. 2011; Morgan et al. 2017; Peverell 2010; Thorburn 2006; Whitty et al. 2009).

Model predictions for both marine and river components across all species fit the occurrence data very well (AUC > 0.96, TSS > 0.83; Table 5). Marine model predictions highlighted the southern and south-eastern Gulf of Carpentaria, Joseph Bonaparte Gulf, and Kimberley regions as suitable coastal environments. The Green Sawfish displayed a more offshore distribution than the other two species modelled (Figure 16). River model predictions highlighted streams in close proximity to the shore had higher habitat suitability (Figure 13, Appendix 6 and), with the Largetooth Sawfish displaying the most extensive distributions furthest upstream in the Fitzroy River system (Figure 16). Note that for Green Sawfish, while habitat is modelled to southern Queensland and point data were available from NSW, this species has been declared Extinct in NSW and is also likely extinct in southern Queensland given a lack of contemporary records.

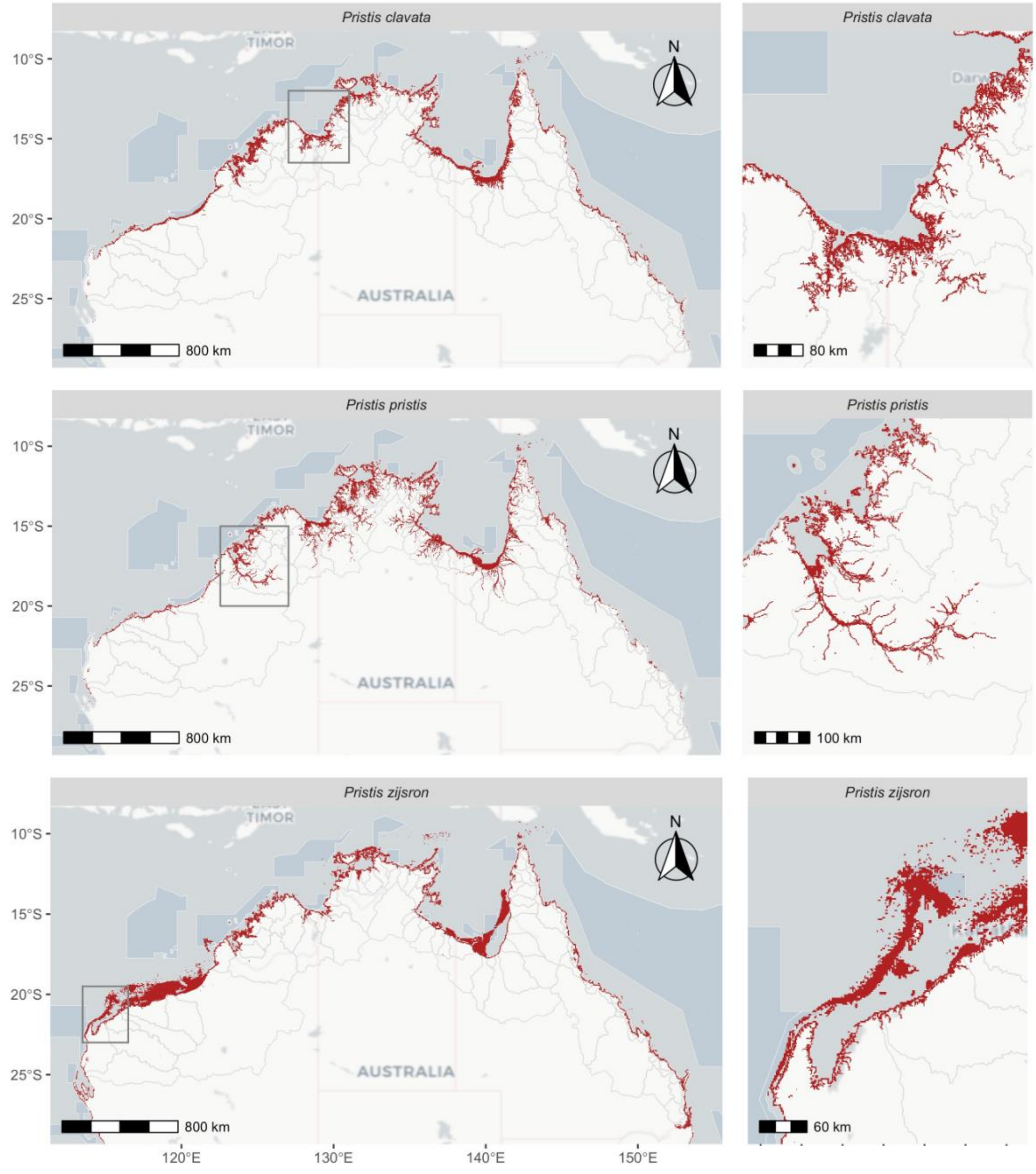

Figure 16 | Thresholded MaxEnt model predictions of habitat suitability (red) for (top row) Dwarf Sawfish (*Pristis clavata*), (middle row) Largetooth Sawfish (*Pristis pristis*), and (bottom row) Green Sawfish (*Pristis zijsron*) within river catchments and coastal marine habitats in Northern Australia. Zoomed in distributions displayed in plots in the right column. Separate models were constructed within northern river systems and marine environment and combined here. Scaled model prediction of habitat suitability provided in Appendix 4. Response curves for model predictions provided in Appendix 6. Blue polygons represent Australian Marine Parks.

3.1.2 Marine Turtles

Using beach survey (spatial coordinates of turtles and turtle tracks on beaches) and sighting data in shallow waters, the nearshore component of marine turtle habitat suitability was modelled using a maximum entropy model (MaxEnt). In addition, turtle satellite tracking data was used to model the pelagic and nearshore components of marine turtle habitat suitability using GAMM (Figure 4). An overall model was calculated by averaging the standardised predictions produced from the MaxEnt (using survey and sighting data) and GAMM models (using satellite tracking data).

Overall model predictions for both species fit the occurrence and tracking data very well (AUC > 0.96, TSS > 0.81; Table 5) and the overall area of suitable habitat was within the SNES distribution, however it did not extend to the EEZ for Hawksbill Turtles (Figure 17) as per the SNES distribution (see Kyne et al. 2018). However, much of the deeper parts of the SNES distribution were classified as “may occur”. Bathymetry and proximity to land were the most important variables that influenced habitat suitability for turtles (Figure 13, Appendix 7) with highest habitat suitability and probability of occurrence in waters up to around 40 m and primarily within 40 km from shore (Appendix 7). This matched with previously published work showing that the majority of Hawksbill Turtles used waters <9 m and with 2 of the 7 tagged turtles using areas 0 – 49 m (Hoenner et al. 2015). Olive Ridley Turtles showed quite a range of water depths used but were generally between around 40 – 60 m (Whiting et al. 2007). For Olive Ridley Turtles, diving depths on average (mean maximum) were 21 – 47 m (McMahon et al. 2007), but the maximum recorded was much deeper at 150 – 200 m (McMahon et al. 2007; Whiting et al. 2007), suggesting that deeper regions are also used.

The coastal regions all along the Northern Territory coast and including the Tiwi Islands, as well as areas along the Queensland coast of the Gulf of Carpentaria had the highest habitat suitability for both species with the western coast of the Gulf of Carpentaria also highly suitable for Hawksbill Turtles (Appendix 4f). For Hawksbill Turtles we had only limited satellite tracking data in general and none from Queensland. This limitation was somewhat alleviated by our approach of making use of the extensive beach survey data (Chatto and Baker 2008) to model nearshore habitat suitability. However, there is a lack of data from the Top End and Arafura Sea. Satellite tag deployments on nesting Hawksbills in some key sites such as at Ashmore Reef, the Tiwi Islands and in Arnhem Land and from rookeries from the northern Queensland genetic stock and potentially the Northern Kimberley area would provide data to fill these gaps. The two satellite tagged turtles from Timor-Leste provided some data for the Arafura Sea, suggesting that if other telemetry datasets from this region were available, they could provide further insights into use of this region. As the model predicted into habitat with no occurrence data (e.g., the Queensland part of the Gulf of Carpentaria), this also suggests more data is needed to validate these model predictions.

For Olive Ridley Turtles the satellite tracking data was much more extensive, including data from northwest Queensland and thus there was less reliance on the beach survey data for ensuring adequate occurrence data in the near- and off-shore parts of the distribution. However, there was no satellite tracking data from rookeries within the Gulf of Carpentaria, where there is generally a paucity of information for this species (see Kyne et al. 2018). However, it is unclear how important these rookeries are. There was a large area within the Gulf of Carpentaria with no prediction of suitability suitable habitat. Whether this is an area that is not used by Olive Ridley Turtles or a result of gaps in the dataset is unclear. However, the SNES distribution classifies a large part of this area as “may occur”. Increasing the sample size of satellite tagged individuals from the Wessel Islands and additional tag deployments at other sites such as Groote Eylandt and Western Cape York may be able to validate the prediction. Doing so would be useful given potentially large numbers caught in ghost nets (Jensen et al. 2013; Wilcox et al. 2013), and high rates of interactions with fisheries reported in the Gulf of Carpentaria (Australian Government 2017).

The main improvement on the SNES distribution maps is that there is more certainty around the habitat suitability and thus probability of occurrence outside of the nesting and inter-nesting areas, on the foraging grounds. There was little data to inform the SNES distribution beyond the breeding distribution with all the offshore area classified in the SNES distribution as “likely to occur” or “may occur” (see Kyne et al. 2018).

Apart from the spatial gaps discussed above, the other limitation with the occurrence data modelled is that it is largely from adult females. There is a lack of occurrence and movement data from males and sub-adults as is usually the case for marine turtle studies. This is largely because adult females come ashore to nest and are the sex and life stage counted in beach track counts and most easily accessed for deployments of satellite tags.

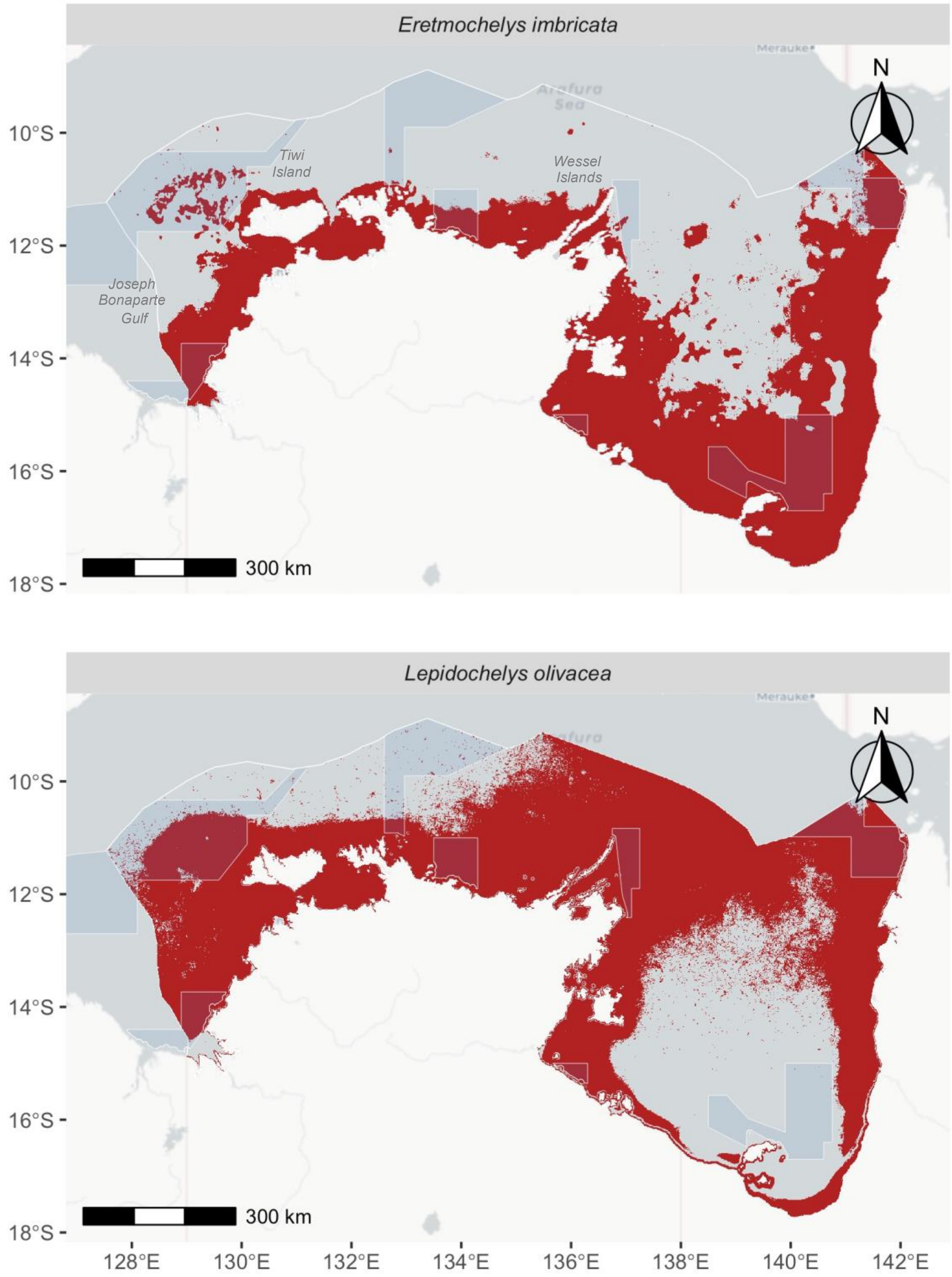

Figure 17 | Thresholded overall model predictions of habitat suitability (red) for (top) Hawksbill Turtle (*Eretmochelys imbricata*) and (bottom) Olive Ridley Turtle (*Lepidochelys olivacea*) within the North Marine Region. Overall model consisted of average outputs from MaxEnt model predictions from occurrence data, and GAMM predictions from satellite telemetry datasets. Scaled model prediction of habitat suitability provided in Appendix 4. Response curves for model predictions provided in. Appendix 7. Blue polygons represent Australian Marine Parks.

3.1.3 Shorebirds

Migratory shorebirds undertake seasonal migration between wintering grounds in Australia and breeding grounds in the Arctic Circle through a migratory pathway known as the East Asian-Australasian Flyway (Minton et al. 2005). Most migratory shorebirds species using the East Asian- Australasian Flyway that visit Australia are classified as Migratory under the EPBC and some are also classified as Threatened (including those treated here), with habitat loss identified as the major threat to populations (Barter 2002; International Wader Study Group 2003; Iwamura et al. 2013; Minton et al. 2005). Models for all species of shorebird highlighted a coastal distribution (Figure 18, Figure 19 and Figure 20; Appendix 4) reflecting the underlying occurrence data available for these species. This is a significant improvement over the SNES distribution in northern Australia which provides spatial information with only low confidence (“likely to occur” and “may occur” categories) and large areas with high uncertainty for all six species (Kyne et al. 2018).

Elevation, distance to coastline, and mean annual windspeed were variables that significantly influenced model predictions (Figure 13). Shorebird habitat suitability was highest in areas with low elevation near the coast and wind speeds of 2 – 4 knots (Appendix 8). These are likely to be the environmental variables preferred by shorebirds in Australia for roosting as most of the occurrence datasets used here were collected during high tide at roost sites (Gosbell and Clemens 2006). Shorebirds normally feed on intertidal flats during low tide and roost in areas just above the high tide mark (Rogers et al. 2006) with roost site selection being driven by local environmental and habitat characteristics such as distance to feeding sites (Rogers et al. 2006), predation risk (Piersma et al. 1993; Rosa et al. 2006) and substrate type (Granadeiro et al. 2004).

The SNES distribution of smaller sandpipers (Red Knot, Great Knot and Curlew Sandpiper) showed large sections of the coast as “likely to occur” based on limited or no previous occurrence data. The distribution of suitable habitat for all smaller sandpipers showed a marked improvement from the SNES distributions, particularly for the Great Knot with our model output showing an almost continuous distribution along northern Australia (Figure 18). However, for Red Knots, gaps remain in sections of the Gulf of Carpentaria and Kimberley region (for all sandpipers) with limited data available (Figure 5), affecting model outputs that indicated low habitat suitability (Appendix 4).

Model outputs indicated an almost continuous distribution of suitable habitat for plovers along coastal areas of northern Australia (Figure 19). This greatly improves the existing SNES distribution which was limited to small sections of the coast around Darwin southwest to Anson Bay and south-eastern Gulf of Carpentaria.

Sandpipers (Calidris spp.)

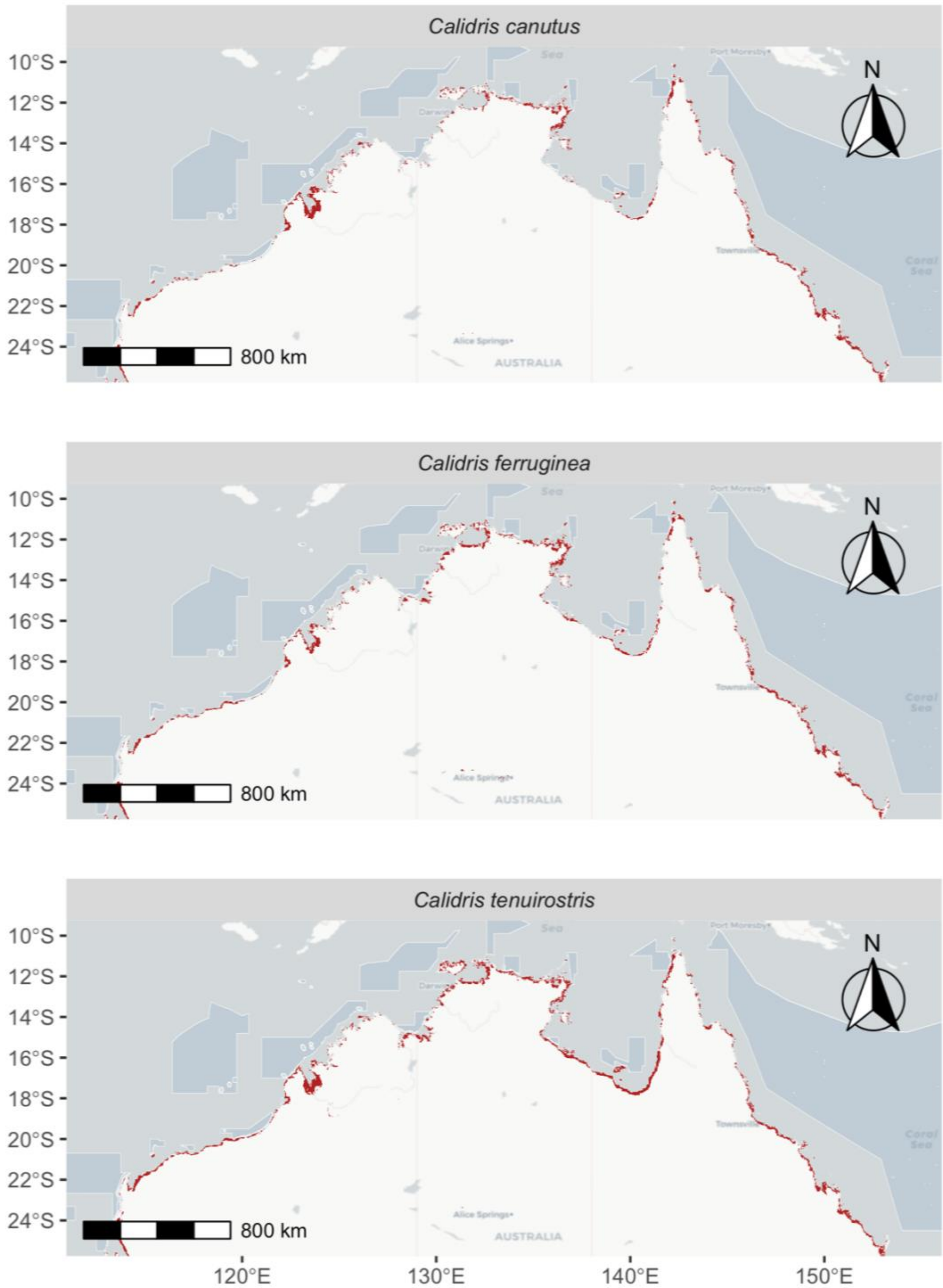

Figure 18 | Thresholded MaxEnt model predictions of habitat suitability (red) for (top) Red Knot (*Calidris canutus*), (middle) Curlew Sandpiper (*Calidris ferruginea*), and (bottom) Great Knot (*Calidris tenuirostris*) within northern Australia. Full models across the entire Australian continent provided in Appendix 2. Models were constructed within the terrestrial environment within the Australian continent Scaled model prediction of habitat suitability provided in Appendix 4. Response curves for model predictions provided in Appendix 8. Blue polygons represent Australian Marine Parks.

Plovers (Charadrius spp.)

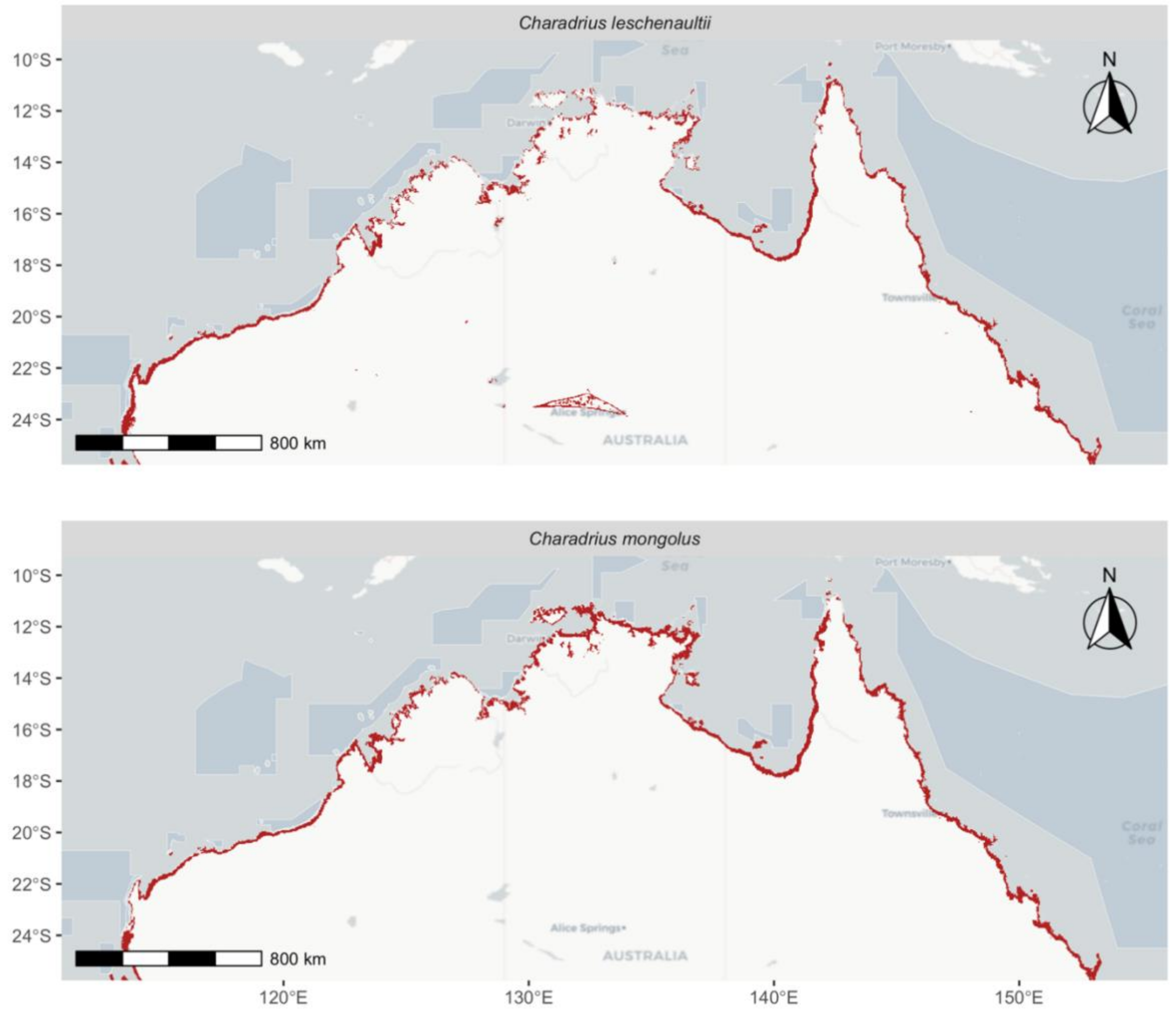

Figure 19 | Thesholded MaxEnt model predictions of habitat suitability (red) for (top) Greater Sand-Plover (*Charadrius leschenaultii*), and (bottom) Lesser Sand-Plover (*Charadrius mongolus*) within northern Australia. Full models across the entire Australian continent provided in Appendix 2. Models were constructed within the terrestrial environment within the Australian continent. Scaled model prediction of habitat suitability provided in Appendix 4. Response curves for model predictions provided in Appendix 8. Blue polygons represent Australian Marine Parks.

Eastern Curlew (Numenius madagascariensis)

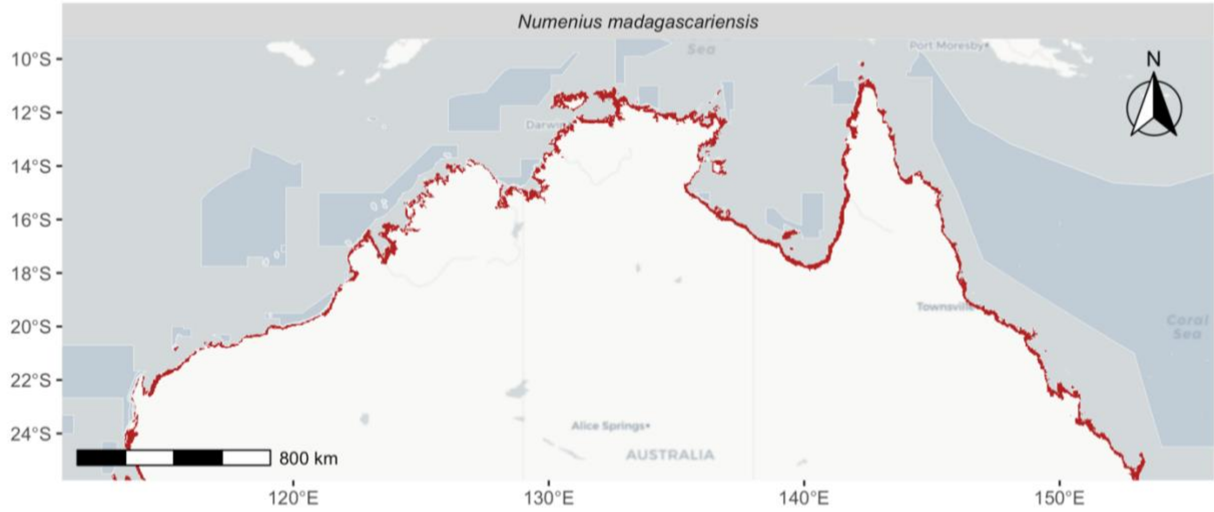

Figure 20 | Thesholded MaxEnt model predictions of habitat suitability (red) for Eastern Curlew (*Numenius madagascariensis*) within northern Australia. Full model across the entire Australian continent provided in Appendix 2. Model was constructed within the terrestrial environment within the Australian continent. Scaled model prediction of habitat suitability provided in Appendix 4. Response curves for model predictions provided in Appendix 8. Blue polygons represent Australian Marine Parks.

Suitable habitat was predicted for most of the coastline for Eastern Curlew (Figure 20). We have not been able to provide information on the marine component of the Red Knot and Eastern Curlew distributions (classified as “may occur” in the SNES distribution) as we had no occurrence data from the marine environment. However, while over-wintering in Australia, these species are most often associated with coastal and intertidal habitats (Finn et al. 2007). The marine region is only used by migratory shorebirds as part of their migratory pathway to northern breeding grounds. Even if occurrence data were available during migration, habitat suitability models would not likely be appropriate to model these data during migration for these species given they are on the wing and not using any surface habitat. However, satellite tracking data is being used by shorebird researchers to identify the migratory pathways used by some species between the Australian coast and breeding grounds which will assist with conservation efforts for shorebirds within the East Asian-Australasian Flyway.

Our model outputs provided robust national scale distribution maps for shorebirds that greatly improved the existing spatial information for these species. However, we note that data gaps exist, particularly for the smaller sandpipers, in sections of the Gulf of Carpentaria, Queensland and the Kimberley region of WA. Hence, intensified survey efforts in these areas with little occurrence data are still needed. The updated distributions can be readily incorporated into spatial planning and conservation actions for the Australian Government’s Wildlife Conservation Plan for Migratory Shorebirds.

3.1.4 Marine Mammals

Distributions of marine mammals were modelled within the marine environment (see Table 2 for details on covariates considered for model). Spatial distribution models for Dugong (*Dugong dugon*) were constructed within the North and North-west Marine Regions only as sufficient standardised data within the Queensland part of their distribution was unavailable. A small proportion of occurrences for the Australian Snubfin Dolphin (*Orcaella heinsohni*; 0.05%), and the Australian Humpback Dolphin (*Sousa sahulensis*; 0.09%) were not included in models as occurrences fell within inland river systems. Model outputs within the marine systems included coastal, estuarine and nearshore habitats and were at 0.083˚ resolution (~1 km at equator).

Dugong

The distribution model for Dugongs (*Dugong dugon*) included waters within the Australian North and North-west Marine Region from south of Shark Bay across the Kimberly and Northern Territory to the Torres Strait. The model predictions across these regions fit the occurrence data very well (AUC = 0.92, TSS = 0.79; Table 5). Proximity to seagrass habitats and proxies to coastal productivity (Chlorophyll a concentration, and water temperature) were the most significant drivers of habitat suitability (Figure 13, Appendix 9).

The predicted habitat suitability matched well with the SNES known distribution. The model also predicted habitat suitability in areas previously classified as “likely to occur” and “may occur” in the SNES distribution such as Eighty Mile Beach and Kimberley region and some areas of the Gulf of Carpentaria and the coast of Cape York (Figure 21) which had not yet been updated with data from surveys conducted in those regions by Bayliss et al. (2017), Groom et al. (2017) and Marsh et al. (2008). However, the SNES distribution includes Ashmore Reef and Cartier Island as there is a small but significant population of Dugongs occurring on Ashmore Reef (Whiting and Guinea 2005). The limited occurrence data and environmental predictor coverage from that site restricted our ability to model habitat suitability around Ashmore Reef.

Highest habitat suitability occurred within Shark Bay, Exmouth Gulf, Darwin Harbour, parts of the coast of the Tiwi Islands, the Coburg Peninsula, Groote Eylandt and the western Gulf of Carpentaria, closely followed by the eastern Gulf of Carpentaria (around the Wellesley Islands) and the Northern Kimberley (Figure 21, Appendix 4g). These areas broadly match the main areas of high density for Dugongs (Bayliss et al. 2017; Grech et al. 2011; Groom et al. 2017), however the Wellesley Islands has previously been found to have the highest relative density of Dugongs within the Gulf of Carpentaria (Grech et al. 2011; Groom et al. 2017; Marsh et al. 2008). Although our predicted habitat suitability at the Wellesley Islands was not the highest across the study region, relatively high suitability was predicted there (Figure 21, Appendix 4g). In addition, our model predicted high habitat suitability in Darwin Harbour (Appendix 4g), an area not previously recognised as having high density of Dugongs, although they do occur there (Groom et al. 2017). Although Dugong density cannot be directly inferred from our modelled Dugong habitat suitability (see section 2.3.4), a potential reason for this apparent discrepancy might be the spatial error in the spatial layer for seagrass used in the model. The main driver of Dugong distribution is presence of seagrass habitat, and high-resolution seagrass distribution maps are not available over the scale that we developed the models (northwest and northern Australia). In the absence of any other dataset, we used seagrass distribution model predictions (Jayathilake and Costello 2018). Thus, this limitation may have resulted in the apparent discrepancy in our modelled Dugong habitat suitability and previously published information on Dugong density at the Wellesley Islands and Darwin Harbour (Grech et al. 2011; Groom et al. 2017).

Similarly, the model may not have identified some smaller scale habitats used by dugongs and known by Traditional Owners in the Kimberley for the same reason and that modelling occurred at the national scale. An additional compounding factor may have been that most of the data were from the dry season, particularly for the Pilbara and Kimberley region of WA and thus misses any seasonal changes to distribution. Seasonal models constructed identified more extensive suitable habitats during the dry season (May – October; Appendix 10). The lack of occurrence data in some regions between seasons (e.g., eastern Gulf of Carpentaria during the dry season) means that seasonal models should be interpreted with caution. Comparisons of model outputs between seasons are likely more accurate in regions where sufficient seasonal occurrence data is available (e.g., Northern Territory, Exmouth Gulf and Shark Bay; Appendix 10).

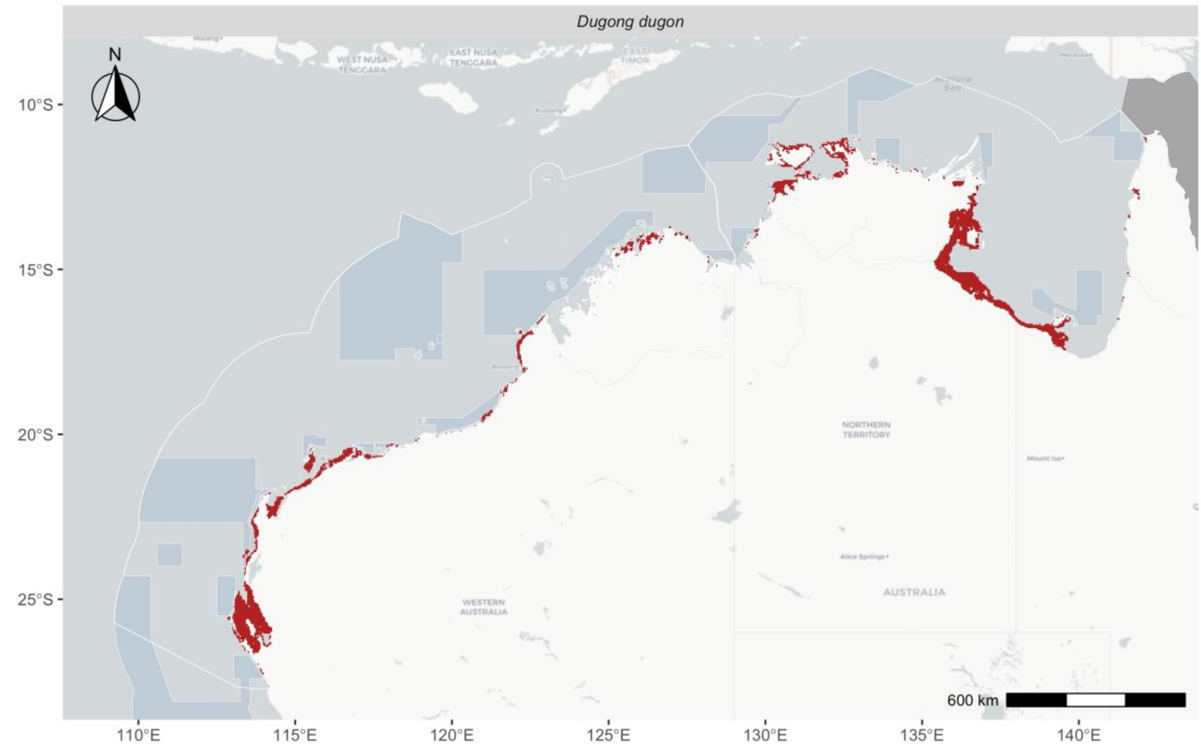

Figure 21 | Thresholded MaxEnt model predictions of habitat suitability (red) for Dugong (*Dugong dugon*) within the North and North-west Marine Region of Australia. Data within the Torres Strait and Queensland (grey polygon) was not available for modelling. Scaled model prediction of habitat suitability provided in Appendix 4. Response curves for model predictions provided in Appendix 9. Blue polygons represent Australian Marine Parks. Separate wet and dry season scaled and thresholded model predictions for Dugong are provided in Appendix 10.

Inshore dolphins

Model predictions for both species fit the occurrence data very well (AUC > 0.92, TSS > 0.87; Table 5). Model predictions of habitat suitability were within the SNES distribution for Snubfin Dolphins, but for Humpback Dolphins our prediction was expanded to include Shark Bay (Figure 22) where additional data has since been collected in recent surveys (i.e., Allen et al. 2012; Brown et al. 2012; Brown et al. 2017) which had not previously been included. Model predictions highlighted the southern Kimberley, Top End and Arnhem regions, and parts of the coastline of Cape York as the most suitable coastal habitats for both species (Appendix 4h, Figure 22). We expected coastal areas to be highlighted as suitable habitat, given that both dolphin species are commonly sighted in and around shallow inshore waters in proximity to freshwater inputs, such as intertidal channels, coastal inlets, creeks, estuaries, and river mouths (Atkins et al. 2004; Bouchet et al. 2021; Hanf et al. 2016; Palmer et al. 2014a; Palmer et al. 2014b; Parra 2006; Parra et al. 2006).

Although there has been anecdotal evidence of their presence in deeper waters for >4 years (e.g., Brown et al. 2017), these offshore deeper waters have not been identified previously in modelled distributions as areas where this species is “likely to occur” (i.e., in the SNES distribution map). Our models highlighted deep water areas adjacent to the Dampier Peninsula and Darwin as suitable habitat for both species (detailed below, Figure 22), thus, greatly improving our existing knowledge of the distribution of these inshore dolphins. Although overall model prediction fit occurrence data well, the habitat suitability in deeper habitats are likely a conservative prediction reflecting the few deep-water occurrences.

In addition to those areas highlighted above, suitable habitats for Australian Snubfin Dolphins were also identified along the Queensland coast (Figure 22). Our understanding of suitable habitat for Australian Snubfin Dolphins has been greatly improved in Northern Territory offshore waters south of Darwin through to the Joseph Bonaparte Gulf, coastal and offshore areas east of Darwin through Van Diemen Gulf to West Arnhem, and coastal and offshore waters of the Dampier Peninsula, Western Australia. Model predictions in these coastal regions were driven by improved occurrence data for the Northern Territory from aerial surveys and boat observations in this region (Brooks et al. 2017; Palmer et al. 2014a; Palmer et al. 2017), and boat-based surveys in Cygnet Bay and Roebuck Bay (Allen et al. 2012). These findings broadly agree with previous research identifying Cape Ford and Fog Bay as high density regions for snubfins (Brooks et al. 2017; Palmer et al. 2017), but some spatial discrepancies between previous density models and our findings can be seen in Arnhem Bay in the Northern Territory. This is likely due to the predominance of key variables in our models such as bathymetry and salinity, which were not included in the earlier density models.

Although there are few historical sightings of Australian Snubfin Dolphins in the deeper offshore regions identified as suitable habitat in our model, these offshore areas may be ecologically important to the species due to their proximity to identified Biologically Important Areas in Darwin Harbour (known coastal breeding and foraging area), around South Alligator River in Van Diemen Gulf (known coastal breeding and foraging area), and Roebuck Bay (known calving, breeding and high foraging area). Our model also predicts new areas of suitable habitat in the Gulf of Carpentaria along the east coast of Groote Eylandt and

Carpentaria coastal waters west of Karumba, and these findings broadly agree with high density areas previously identified (Brooks et al. 2017; Palmer et al. 2017). Other new areas of suitable habitat were identified in north-west Queensland along the Yagoonya coast and offshore waters of Mission River; and along the east coast of Queensland between Cairns and Mission Beach, and the peninsula north of Yepoon. These regions have previously been designated as low or no likelihood of occurrence (see Kyne et al. 2018) but were identified as suitable habitat in our model. Although model predictions in these regions were largely driven by newly acquired data from recent surveys (Cagnazzi 2016; GHD 2015; Tulloch et al. 2018), there are still many survey data gaps in areas such as the south-east Gulf and central Queensland.

Model predictions for Australian Humpback Dolphins also highlighted coastal regions in the southern Pilbara and southeast Queensland as suitable habitats (Figure 22). The predictions of highly suitable habitat (predictions near 1) (Appendix 4) in the Pilbara are supported by recent sightings in this region (Brown et al. 2017; Hunt et al. 2017), with research suggesting high abundances of Humpback Dolphins in these waters (Brown et al. 2012; Brown et al. 2017). Our models also provide improved knowledge of suitable habitat for Australian Humpback Dolphins in offshore areas of the Admiralty Gulf, King Sound North and Yampi Sound in north-east Kimberley (Figure 22). The SNES distributions (see Kyne et al. 2018) do not include these areas as potential occurrence for Humpback Dolphins.

The coastal extent of these two locations have been identified as Biologically Important Areas for Australian Humpback Dolphins with high abundances estimated at both Cygnet Bay and Dampier Bay in the Kimberley (Brown et al. 2017), however our model predicts suitable habitat up to 100 km further offshore than existing data and models (Parra and Cagnazzi 2016). The extension of suitable habitat in our model to Shark Bay is in agreement with previous sightings of Humpback Dolphins, reported in Hodgson (2007) and Allen et al. (2012). Further confidence in Australian Humpback Dolphin distribution has also increased based on our model outputs in the region around Darwin Harbour extending into the Beagle Gulf, which was identified as suitable habitat. Previously, the deeper waters offshore in this area had not been identified as likely habitat (see Kyne et al. 2018). Our model findings of high suitability around Melville Island and Kakadu agree with previous research identifying high densities of Humpback Dolphins in these waters (Palmer et al. 2017). There are some discrepancies between these density models and our results, particularly around English Company and Groote Eylandt, which have high densities of Humpback Dolphins (Palmer et al. 2017) but were not predicted to be highly suitable habitat by our models.

Proximity to coastline, bathymetry and seasonal variance in salinity were key variables influencing habitat suitability models (Figure 13, Appendix 8). In particular, bathymetry was a strong contributor for Australian Humpback Dolphins, and salinity for snubfin dolphins, which, as a proxy for distance to freshwater inputs, is in agreement with recent research by Bouchet et al. (2021). For both species we had a paucity of data for the eastern Gulf of Carpentaria, Eight Mile Beach and North Queensland which was partly a result of our inability to obtain some of the available data, but also that there are areas there that are still unsurveyed. For the former, this species is known to be in high density, but this has not been identified as suitable habitat in our models and for the latter the model had to rely on mostly opportunistic sightings rather than survey data. Our model outputs could be used to guide where future monitoring should occur (e.g., in areas where no sightings data exist, but modelled habitat suitability predictions are high, see Table 6).

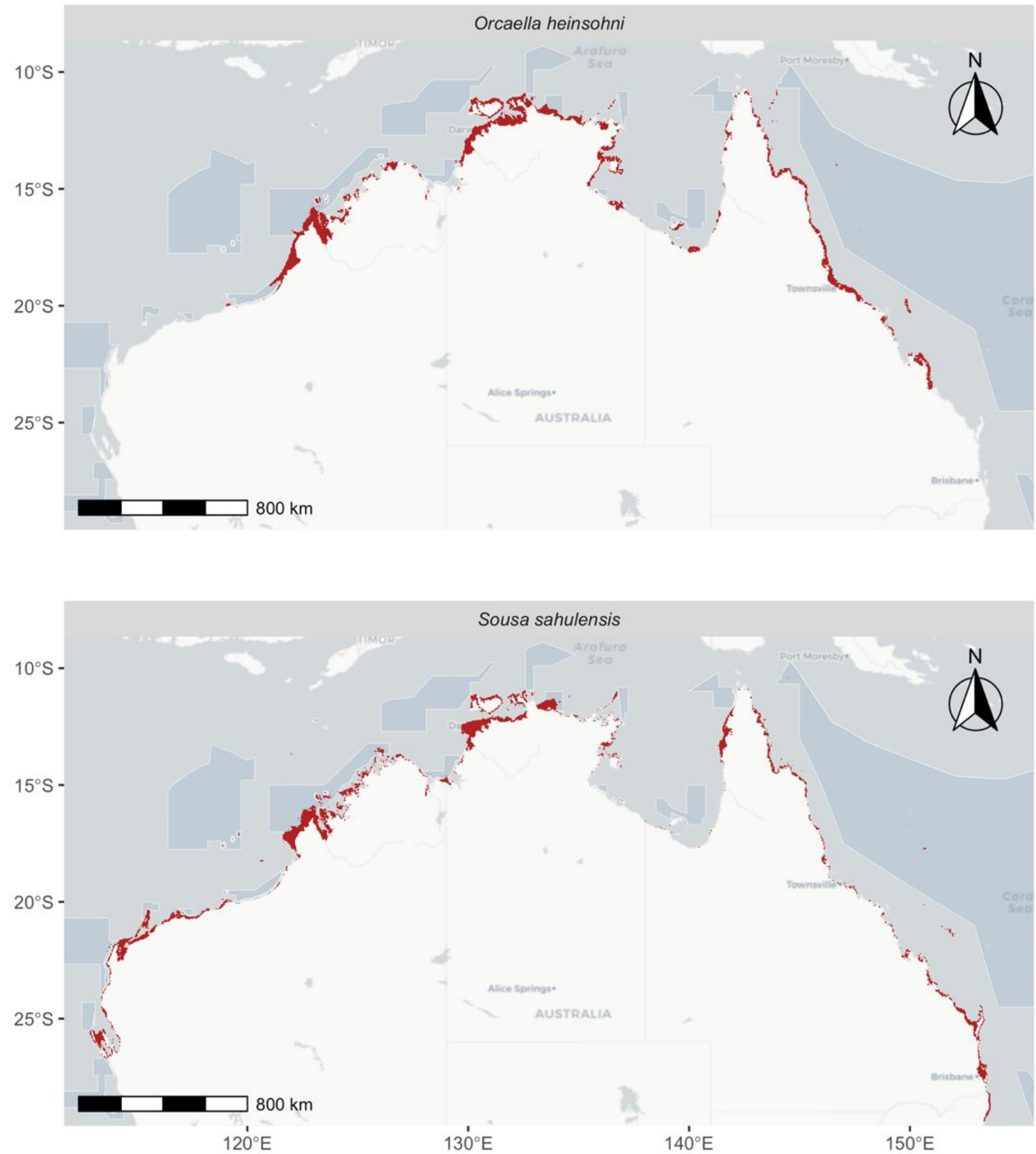

Figure 22 | Thresholded MaxEnt model predictions of habitat suitability (red) for (top) Australian Snubfin Dolphin (*Orcaella heinsohni*), and (bottom) Australian Humpback Dolphin (*Sousa sahulensis*) within Northern Australia. Models were constructed within the marine environment. Scaled model prediction of habitat suitability provided in Appendix 4. Response curves for model predictions provided in Appendix 9. Blue polygons represent Australian Marine Parks.

4. CONCLUSIONS AND RECOMMENDATIONS

In this report we identified and compiled 121 published and unpublished spatial datasets from structured and unstructured surveys, and combined it with freely available occurrence data to improve species distribution maps for 16 priority Threatened and Migratory species using habitat suitability modelling. In doing so, we identified many new datasets to inform species occurrence in areas where previously there were gaps or uncertainty. Such datasets are costly and difficult to obtain, so compiling and making use of existing data is prudent and habitat suitability modelling allows for prediction into data poor areas. For example, our habitat suitability predictions for river sharks and sawfishes (species with limited data) identified new locations with ideal habitat requirements for species occurrence. While the modelling approach has been useful for these species, it is worth noting that for river sharks and sawfishes in particular these distributions were built with some reliance on historical data and therefore there is now a need for updated information. In addition, the modelling approach provided some insight into the drivers of habitat suitability, identifying bathymetric and habitat associations as key determinants of suitable habitat for the 16 species (Appendices 5 – 9). Importantly, the modelling outputs can be used to prioritise locations for future surveys to obtain a more complete picture of species distributions (see Udyawer et al. 2020).

Although all species distributions were improved, some species still had data gaps, most notably, the river sharks, sawfishes and Hawksbill Turtles. The reason for the sawfish and river sharks having the most data gaps was largely due to the fact that most of the data for them are from discrete river systems and few data occur for them in the coastal and marine environments, especially for the river sharks. Similarly for Hawksbill Turtle, with most data informing the area used during the breeding season (nearshore) and although the post breeding distribution has been improved, there was only a relatively small sample size of satellite tracked turtles across the region to inform the model. For most of these species there is limited to no data coverage across all age and sex classes. Table 6 provides a summary of the key data gaps, and recommended future monitoring to focus effort and overcome the knowledge gaps that still persist for each species group.

In addition to filling the identified gaps in data collection highlighted by this project, the high-resolution distribution maps developed here provides an opportunity to conduct a comprehensive assessment of overlap with historic, current, and projected pressures within Northern Australia. Kyne et al. (2018) developed a complementary set of comprehensive maps, highlighting hotspots of potential pressures (e.g., resource extraction, pollution, habitat modification, climatic pressures) that threatened marine fauna are likely to interact with in the North Marine Region. Assessment of spatio-temporal overlap between key pressures and suitable habitats may identify key pathways for management and recovery efforts for key threatened marine species.

Although the project was initially scoped to include the North Marine Region only, we chose to expand it to other marine regions. This decision was made given that all the 16 species are distributed across all of Northern Australia, and for some (shorebirds), all of Australia, and as such, spatial modelling and mapping would ideally occur at that scale. However, we were unable to access many of the available datasets from Queensland. Some of these were not shared due to competing projects of the data custodians (and also competing demands). However, many of the datasets were collected with public funds and some with NESP/NERP funds. These latter datasets would ideally become publicly available once reporting is complete and a reasonable embargo period has elapsed for peer reviewed publication.

The focus of our modelling was at the regional and national scale and for many of these species there is a need to identify habitat suitability at finer scales. Although the environmental covariates are usually not available at finer scales, at least with most remote sensed products as used here, there are likely to be some opportunities for more local scale projects and these should be investigated.

This project has amassed a spatial dataset which has been made available to the DAWE for inclusion in the Species Profile and Threats (SPRAT) database that stores information on species and ecological communities listed under the EPBC Act for use in their future management of Threatened and Migratory marine species. This can be used by DAWE to improve future species distribution maps once more data become available to fill the gaps outlined here. This would ideally follow the modelling procedure (or similar) used here.

Table 6 | Summary of data gaps persisting upon updated habitat suitability modelling in the present study and recommended future directions for research and management of 16 species of Threatened and Migratory marine species in Northern Australia.

Species	Data gaps	Future directions
All Species	Assessment of protection available to species from the different Marine Protected Areas (MPAs) and spatial management zones	Overlay species distributions onto Australian Marine Parks (AMPs), state MPAs and Indigenous Protected Areas (IPAs) to calculate proportion of overlap in each spatial management zone including marine park zoning categories
	Assessment of threats to species	Overlay species distributions developed here with threat maps compiled in Project A12 – Australia's Northern Seascape (Phase 1) and assess overlap to identify intersection between high habitat suitability and high pressures
River sharks (*Glyphis garricki, Glyphis glyphis)*	Occurrence and habitat preferences in marine waters	Observer programs in commercial fisheries to identify coastal and marine records Acoustic and satellite tagging of large subadult Speartooth Sharks and adult Northern River Sharks
	Occurrence in unsurveyed rivers with predicted suitable habitat	Undertale surveys in the Moyle River (NT), estuarine creek systems in eastern Van Diemen Gulf (e.g., Murgenella Creek), Meda River (WA) and Mitchell and Normanby Rivers (Qld)
	Occurrence in historical locations now thought to be extinct (adequate surveys have not been undertaken to clarify this issue)	Survey Bizant River (QLD) for Speartooth Shark
Sawfishes (*Pristis clavata*, *P. pristis*, *P. zijsron*)	Occurrence in poorly surveyed regions with predicted suitable habitat	Survey coastal areas of the southern and south-eastern Gulf of Carpentaria and coastal areas of Joseph Bonaparte Gulf and the Kimberley.

Species	Data gaps	Future directions
		Survey streams in close proximity to the shore in the above listed regions (for Largetooth Sawfish)
Marine turtles (*Eretmochelys imbricata*, *Lepidochelys olivacea*)	Low sample size and limited spatial coverage of satellite tag deployments to robustly infer post breeding distribution for Hawksbill Turtles and to validate occurrence in poorly surveyed regions with predicted suitable habitat	Targeted satellite tag from areas where data are currently lacking, such as Ashmore Reef, Tiwi Islands and Arnhem Land. Search for and collate any satellite tracking data from Queensland (and potentially Western Australia) and South-east Asia and update models to potentially fill data gaps.
	Validate occurrence in poorly surveyed regions with predicted and unpredicted suitable habitat (offshore areas of Gulf of Carpentaria) for Olive Ridley Turtles	Deploy satellite tags at sites that may fill data gap in Gulf such as Groote Eylandt, western Cape York, and Wessel Islands.
	Fine-scale habitat preferences within and adjacent to key habitats	Assess species- and region- specific habitat associations from fine-scale telemetry data
	Data from adult males and other age classes and use of very offshore areas out to the EEZ	Increase deployment of satellite tags and include other sexes and age classes besides adult females of both species
Shorebirds (*Calidris canutus*, *Calidris ferruginea*, *Calidris tenuirostris, Charadrius leschenaultii*, *Charadrius mongolus, Numenius madagascariensis*)	Occurrence in poorly surveyed regions	Expand efforts to survey remote areas of the Gulf of Carpentaria and areas of the Kimberley
	Migration patterns	Collect movement data using telemetry where appropriate to define migratory pathways over and adjacent to marine habitats, and use of remote offshore islands

Species	Data gaps	Future directions
Dugong (*Dugong dugon*)	Occurrence in poorly surveyed regions with predicted suitable habitat	Fill in gaps in survey effort from Shark Bay to Eighty Mile Beach (WA).
	Habitat suitability and distribution across all of Northern Australia	Compile and include Queensland survey data (where possible) to extend habitat suitability models to whole Australian Dugong distribution
	Density of populations and seasonal occurrence within regions of high habitat suitability	Develop seasonal population density models within important regions of distribution (southern Gulf of Carpentaria, Shark Bay, Exmouth Gulf) Extend survey effort into the wet season in eastern Gulf of Carpentaria where possible
	Fine-scale movements and habitat associations	Compile existing and collect additional fine-scale movement data from satellite tag deployments on dugongs to assess habitat associations in areas with highest habitat suitability.
Inshore dolphins (*Orcaella heinsohni*, *Sousa sahulensis*)	Occurrence in poorly surveyed regions	Survey offshore areas of Dampier Peninsula, south-west of Darwin to the Joseph Bonaparte Gulf, Van Diemen Gulf to West Arnhem (for Australian Snubfin Dolphin) Survey coastal areas of the south-eastern and southern Gulf of Carpentaria (south-east) for inshore dolphins (in particular for Australian Humpback Dolphins*)*
	Occurrence in poorly surveyed regions with predicted habitat suitability	Survey coastal areas of southern Gulf of Carpentaria and north-west Queensland for inshore dolphins (in particular for Australian Snubfin Dolphins), to validate model findings.

Species	Data gaps	Future directions
		Survey offshore areas of the Admiralty Gulf, Kind Sound North and Yampi Sound for Australian Humpback Dolphins
	Occurrence and habitat suitability within river and freshwater systems	Compile and collect data to develop regional distributions for both species within important river systems (Prince Regent River WA, Daly and Alligator Rivers NT, Brisbane River QLD)

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APPENDICES

Appendix 1: Summary of occurrence data sources used to construct species distribution models

Species	Common Name	Data source	Data type(s)
All Species			
		Atlas of Living Australia (https://www.ala.org.au)	Sighting data, Museum records
		Global Biodiversity Information Facility (https://www.gbif.org)	Sighting data, Museum records
		WildNet – Queensland Wildlife Data (https://www.qld.gov.au/environment/plants-animals/species-information/wildnet)	Sighting data
		Natural Resource Maps (https://nrmaps.nt.gov.au/nrmaps.html)	Sighting data
		Northern Territory WildWatch (https://biocollect.ala.org.au/nt-wildwatch)	Sighting data, Stranding records
Elasmobranchs			
Glyphis garricki	Northern River Shark	NERP & NESP Marine Biodiversity Hub (Peter Kyne et al.; collaboration between CDU, CSIRO, NT Fisheries, Malak Ranger Group, Kakadu NP)	Catch records, Acoustic telemetry
		Murdoch University - David Morgan (unpublished data) - Jeff Whitty (unpublished data) - Morgan et al. (2004) - Morgan et al. (2011) - Thorburn (2006) - Thorburn and Morgan (2004)	Catch records
Glyphis	Speartooth Shark	NERP & NESP Marine Biodiversity Hub (Peter Kyne et al.; collaboration between CDU, CSIRO, NT Fisheries, Malak Ranger Group, Kakadu NP)	Catch records, Acoustic telemetry
		Lyon et al. (2017) via AODN (http://portal.aodn.org.au/)	Acoustic telemetry
		Dwyer et al. (2020) via AODN (http://portal.aodn.org.au/)	Catch data, Acoustic telemetry
Pristis clavata	Dwarf Sawfish	NERP & NESP Marine Biodiversity Hub (Peter Kyne et al.; collaboration between CDU, CSIRO, NT Fisheries, Malak Ranger Group, Kakadu NP)	Catch records, Acoustic telemetry
		Australian Museum (Amanda Hay)	Sighting data, Museum records

Species	Common Name	Data source	Data type(s)
		Ross Dwyer (unpublished data)	Catch records
		Barbara Wueringer (unpublished data)	Catch records
		University of Western Australia (Andrew Storey, unpublished data)	Catch records
		Murdoch University - David Morgan (unpublished data) - Jeff Whitty (unpublished data) - Morgan et al. (2011) - Thorburn (2006)	Catch records
		Fisheries agencies: - AFMA - WA Fisheries (Rory McAuley, Matias Braccini, Mathew Hourston) - NT Fisheries (Grant Johnson) - QLD Fisheries (Jason Stapley)	Catch records, Fisheries bycatch records
		Stevens et al. (2008)	Catch records
Pristis	Largetooth Sawfish	NERP & NESP Marine Biodiversity Hub (Peter Kyne et al.; collaboration between CDU, CSIRO, NT Fisheries, Malak Ranger Group, Kakadu NP)	Catch records, Acoustic telemetry
		Australian Museum (Amanda Hay)	Sighting data, Museum records
		University of Western Australia (Andrew Storey, unpublished data)	Catch records
		Devitt et al. (2015)(compiled from various sources, see Devitt et al. 2015 for details)	Sighting data, Catch records
		Murdoch University - David Morgan (unpublished data) - Jeff Whitty (unpublished data)	Catch records
		Fisheries agencies: - AFMA - WA Fisheries (Rory McAuley, Matias Braccini, Mathew Hourston) - NT Fisheries (Grant Johnson) - QLD Fisheries (Jason Stapley)	Catch records, Fisheries bycatch records
Pristis zijsron	Green Sawfish	Marine Biodiversity Hub (Peter Kyne et al.; collaboration between CDU, UWA, and Garig Gunak Barlu NP)	Drone survey
		Australian Museum (Amanda Hay)	Sighting data, Museum records
		University of Western Australia (Andrew Storey, unpublished data)	Catch records

Species	Common Name	Data source	Data type(s)
		Murdoch University - David Morgan (unpublished data) - Jeff Whitty (unpublished data) - Morgan et al. (2011) - Thorburn (2006)	Catch records
		Devitt et al. (2015)(compiled from various sources, see Devitt et al. 2015)	Sighting data, Catch records
		Fisheries agencies: - AFMA - WA Fisheries (Rory McAuley, Matias Braccini, Mathew Hourston) - NT Fisheries (Grant Johnson) - QLD Fisheries (Jason Stapley)	Catch records, Fisheries bycatch records
		Stevens et al. (2008)	Catch records
Marine turtles			
Eretmochelys imbricata	Hawksbill Turtle	Department of Environment, Parks and Water Security (Chatto and Baker 2008)	Beach and aerial surveys
		INPEX turtle monitoring (Cardno 2015)	Boat and aerial surveys, Beach surveys, Satellite Telemetry
		Charles Darwin University (Mick Guinea, unpublished data)	Satellite telemetry
		Whiting et al. (2006)	Satellite telemetry
		Hoenner et al. (2015)	Satellite telemetry
		Conservation International Timor-Leste (via OBIS; http://obis.org/)	Satellite telemetry
Lepidochelys olivacea	Olive Ridley Turtle	Department of Environment, Parks and Water Security (Chatto and Baker 2008)	Beach and aerial surveys
		INPEX turtle monitoring (Cardno 2015)	Boat and aerial surveys, Beach surveys
		Dwyer and Campbell (2016) via Zoatrack (http://dx.doi.org/10.4226/68/5701F923DB7E6)	Satellite telemetry
		McMahon et al. (2007)	Satellite telemetry

Species	Common Name	Data source	Data type(s)
		Whiting et al. (2007)	Satellite telemetry
		Department of Environment and Science (Col Limpus, unpublished data)	Satellite telemetry
Shore birds			
Calidris canutus	Red Knot	eBird	Sighting data
		BirdLife Australia (Australian Shorebird Monitoring, Birdata)	Sighting data
		Chatto (2003)	Survey Records
		Monash University (Rohan Clarke, unpublished data)	Survey Records
		Queensland Wader Study Group (Peter Driscoll)	Survey Records
Calidris ferruginea	Curlew Sandpiper	eBird	Sighting data
		BirdLife Australia (Australian Shorebird Monitoring, Birdata)	Sighting data
		Chatto (2003)	Survey Records
		Monash University (Rohan Clarke, unpublished data)	Survey Records
		Queensland Wader Study Group (Peter Driscoll)	Survey Records
Calidris tenuirostris	Great Knot	eBird	Sighting data
		BirdLife Australia (Australian Shorebird Monitoring, Birdata)	Sighting data
		Chatto (2003)	Survey Records
		Monash University (Rohan Clarke, unpublished data)	Survey Records
		Queensland Wader Study Group (Peter Driscoll)	Survey Records
Charadrius leschenaultii	Greater Sand-Plover	eBird	Sighting data
		BirdLife Australia (Australian Shorebird Monitoring, Birdata)	Sighting data
		Chatto (2003)	Survey Records
		Monash University (Rohan Clarke, unpublished data)	Survey Records
		Queensland Wader Study Group (Peter Driscoll)	Survey Records
Charadrius mongolus	Lesser Sand-Plover	eBird	Sighting data
		BirdLife Australia (Australian Shorebird Monitoring, Birdata)	Sighting data

Species	Common Name	Data source	Data type(s)
		Chatto (2003)	Survey Records
		Monash University (Rohan Clarke, unpublished data)	Survey Records
		Queensland Wader Study Group (Peter Driscoll)	Survey Records
Numenius madagascariensis	Eastern Curlew	eBird	Sighting data
		BirdLife Australia (Australian Shorebird Monitoring, Birdata)	Sighting data
		Chatto (2003)	Survey Records
		Monash University (Rohan Clarke, unpublished data)	Survey Records
		Queensland Wader Study Group (Peter Driscoll)	Survey Records
		Charles Darwin University (Amanda Lillyman, telemetry data via ZoaTrack)	Survey Records
Marine mammals			
Dugong dugon	Dugong	Charles Darwin University - Whiting (1999) - Whiting (2009)	Aerial survey sightings
		Department of Biodiversity, Conservation and Attractions, WA - Hodgson et al. (2008) - Gales et al. (2004) - Holley et al. (2006) - Preen et al. (1997)	Aerial survey sightings
		Department of Environment, Parks and Water Security - Groom et al. (2015) - Groom et al. (2017)	Aerial survey sightings
		Bayliss et al. (2019)	Aerial survey sightings
		INPEX dugong monitoring (Cardno 2015)	Aerial and boat surveys
		James Cook University - Marsh et al. (2000) - Marsh et al. (2008) - Marsh et al. (1995)	Aerial survey sightings
		Western Australian Marine Science Institution (Bayliss et al. 2017)	Aerial survey sightings
Orcaella heinsohni	Australian Snubfin Dolphin	Department of Environment, Parks and Water Security - Palmer et al. (2017) - Brooks et al. (2017)	Aerial and boat survey sightings

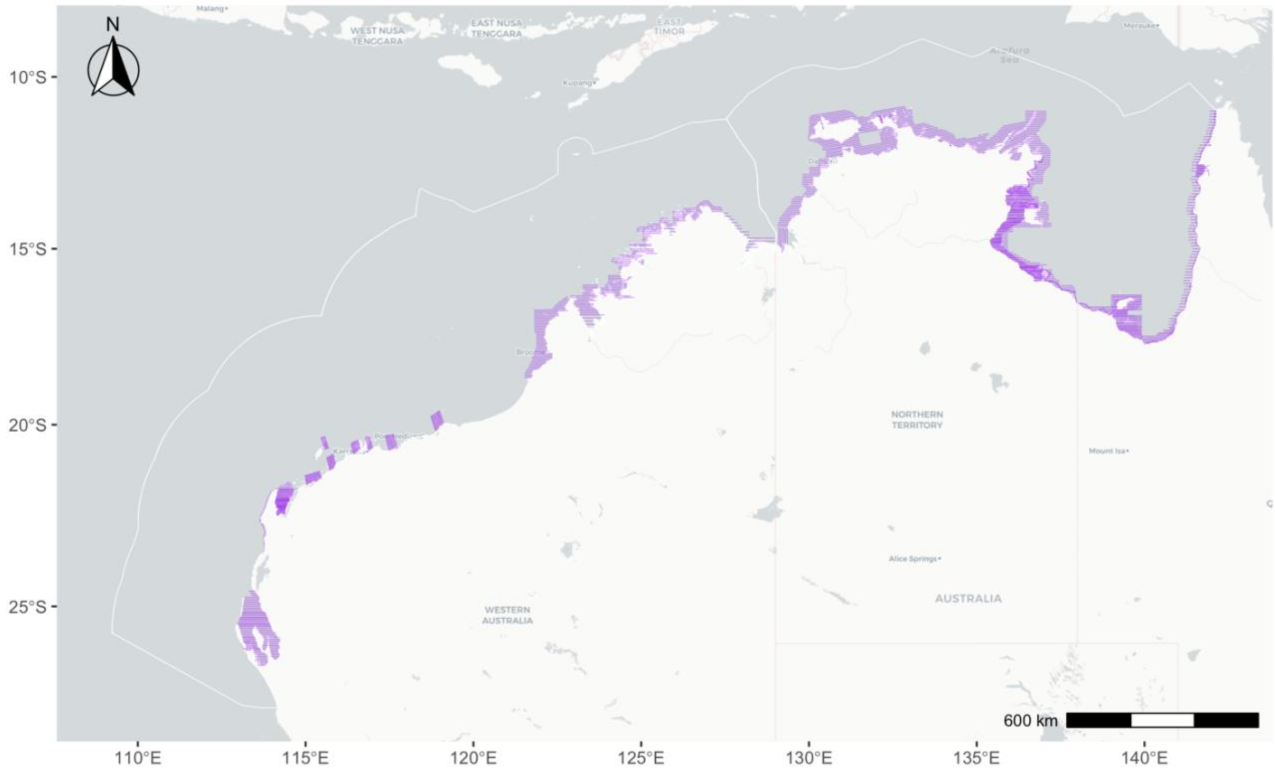
Species	Common Name	Data source	Data type(s)
		Department of Biodiversity, Conservation and Attractions, WA - Hodgson (2007)	Aerial and boat survey sightings
		Allen et al. (2012)	Aerial and boat survey sightings
		Entanglement dataset with sensitive data removed (Tulloch et al. 2020; Tulloch et al. 2018)	Sightings, stranding observations
		Western Australian Marine Science Institution - Bayliss et al. (2017) - Brown et al. (2017)	Aerial and boat-based survey sightings
		Center for Whale Research (Curt Jenner unpublished data)	Aerial and boat-based sightings
		Southern Cross University (Cagnazzi 2016, 2017)	Boat-based survey sighting
		Rio Tinto (GHD 2015)	Boat-based surveys, sighting observations
		Kimberly Whale Watching (Costin and Sandes 2009, 2011)	Boat-based surveys
Sousa sahulensis	Australian Humpback Dolphin	Ray Chatto (unpublished data)	Sighting and boat-based observations
		Department of Environment, Parks and Water Security - Palmer et al. (2017) - Brooks et al. (2017)	Aerial and boat survey sightings
		Department of Biodiversity, Conservation and Attractions, WA - Hodgson (2007) - Brown et al. (2012) - Allen et al. (2012) - Hunt et al. (2017)	Aerial and boat survey sightings
		Allen et al. (2012)	Aerial and boat survey sightings
		Entanglement dataset (Tulloch et al. 2020; Tulloch et al. 2018)	Sightings, stranding observations
		Western Australian Marine Science Institution - Bayliss et al. (2017) - Brown et al. (2017)	Aerial and boat-based survey sightings

Species	Common Name	Data source	Data type(s)
		Center for Whale Research (Curt and Micheline Jenner unpublished data)	Aerial and boat-based sightings
		Southern Cross University (Cagnazzi 2016, 2017)	Boat-based survey sighting
		Dolphin Research Australia (Liz Hawkins)	Boat-based surveys, sighting observations
		Rio Tinto (GHD 2015)	Boat-based surveys, sighting observations

Appendix 2: The repository housing all spatial model outputs including continuous optimal model predictions, prediction variance, and model evaluations (AUC, TSS) is accessible through the following link. Spatial model outputs (optimal model prediction and prediction variance) are provided in a GeoTiff format, model evaluation scores are provided as a CSV file, and response curves are provided as PNG files for each model:

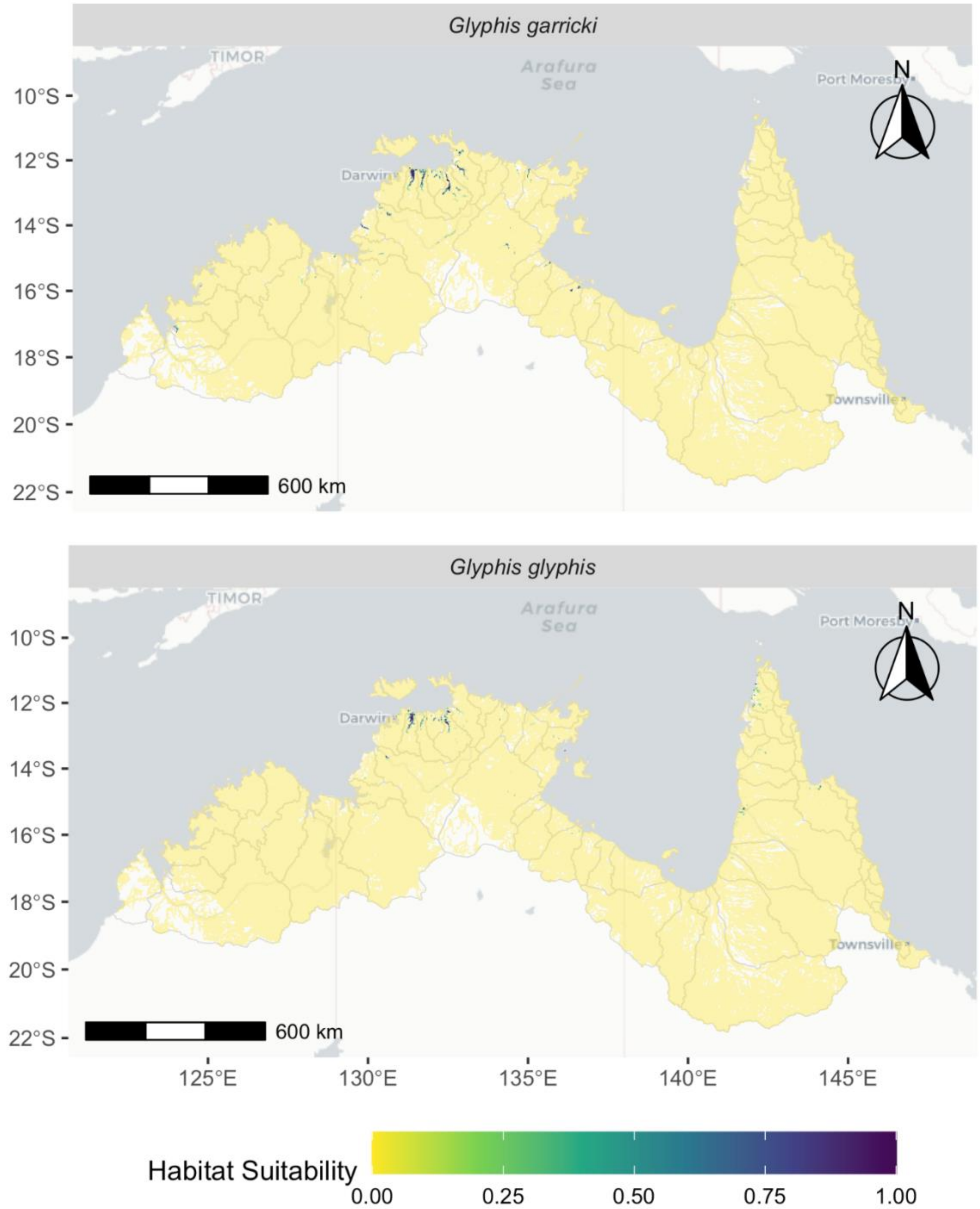
https://www.dropbox.com/sh/5jmdihvaqtjfeer/AADFaOBiGX2SmQ5gFmo6f2_ia

Appendix 3: Coastal aerial survey transects conducted by data contributors (see Appendix I) between 1997 – 2018 to collect occurrences of Dugong (*Dugong dugong*) within the North and North-west Marine Region.

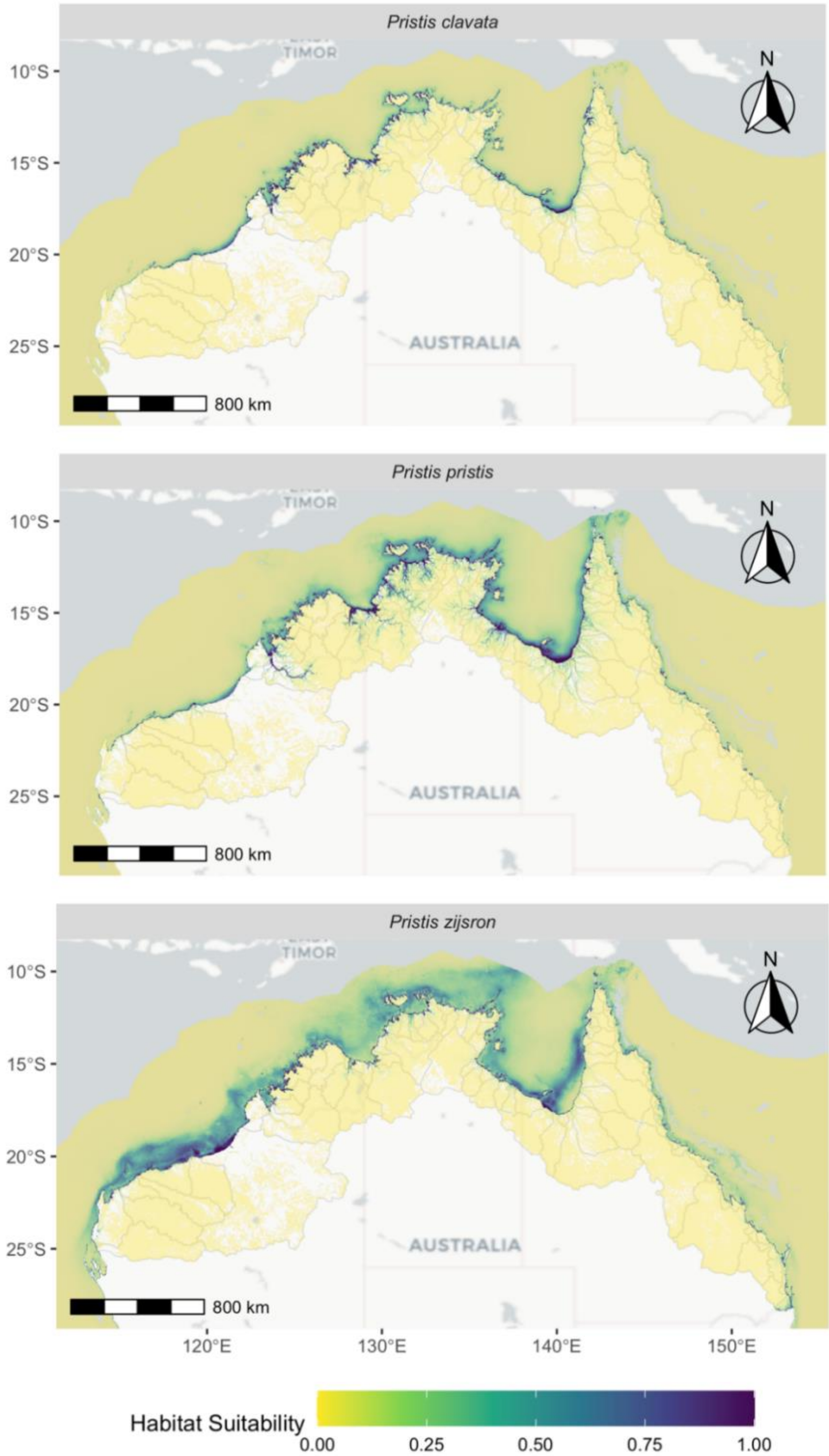


Appendix 4: Species habitat suitability predictions for the 16 shortlisted threatened species across northern Australia. Thresholded models and their interpretation are provided in the main manuscript.

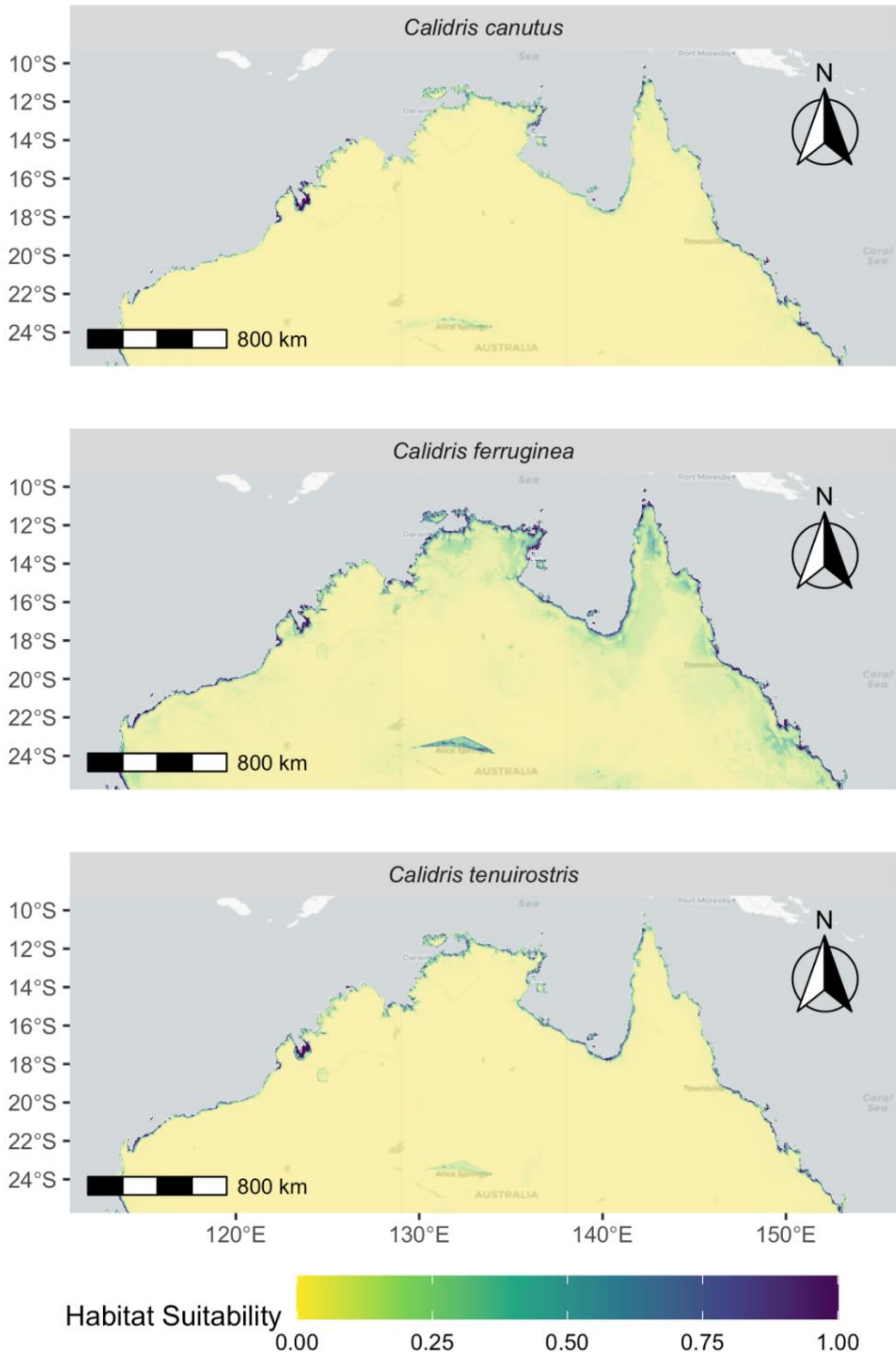
a. Northern River Shark (*Glyphis garricki;* top) and Speartooth Shark (*Glyphis glyphis*; bottom) model predictions:



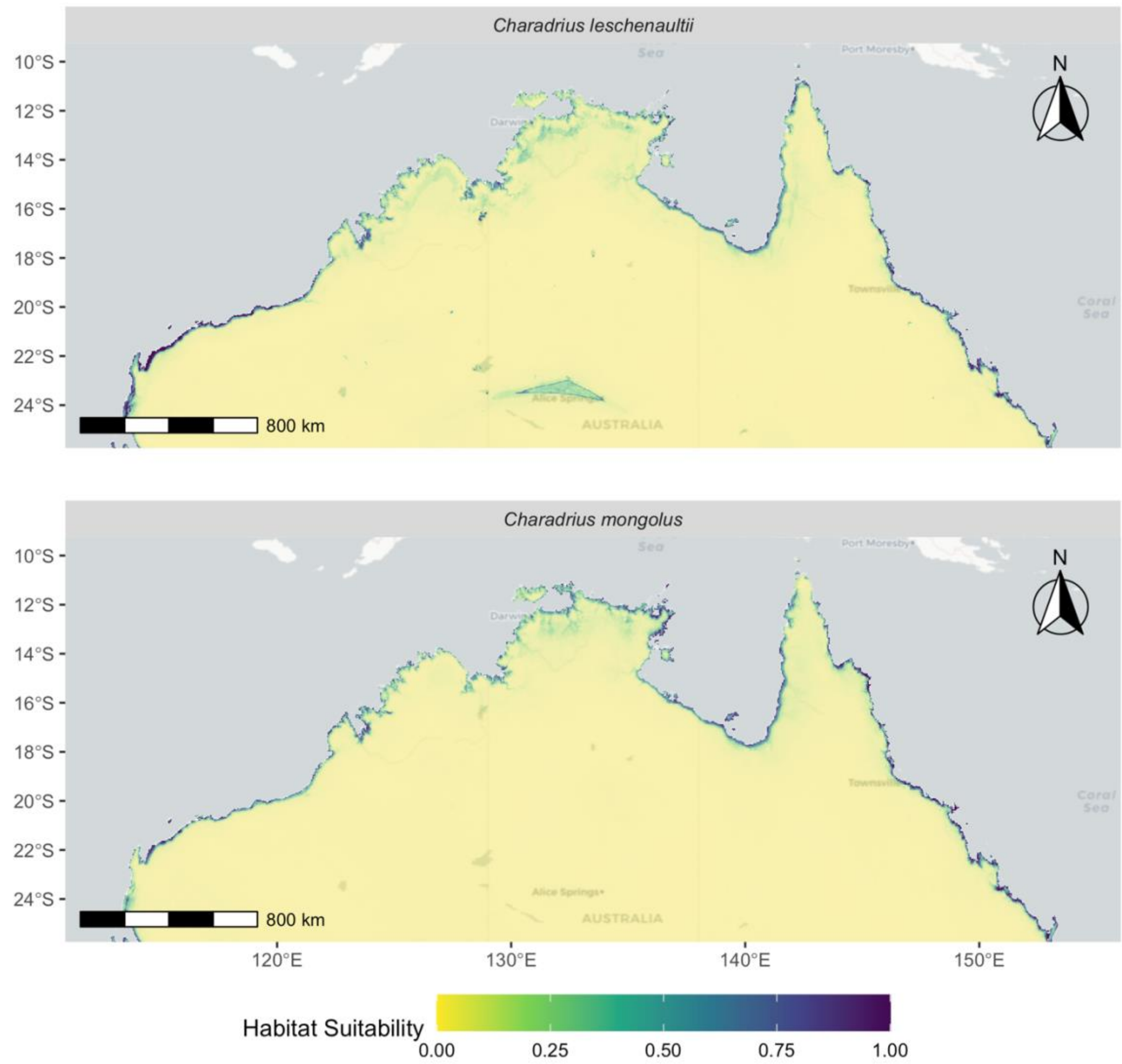
b. Dwarf Sawfish (*Pristis clavata*; top), Largetooth Sawfish (*Pristis pristis*; middle) and Green Sawfish (*Pristis zijsron*; bottom) model predictions:



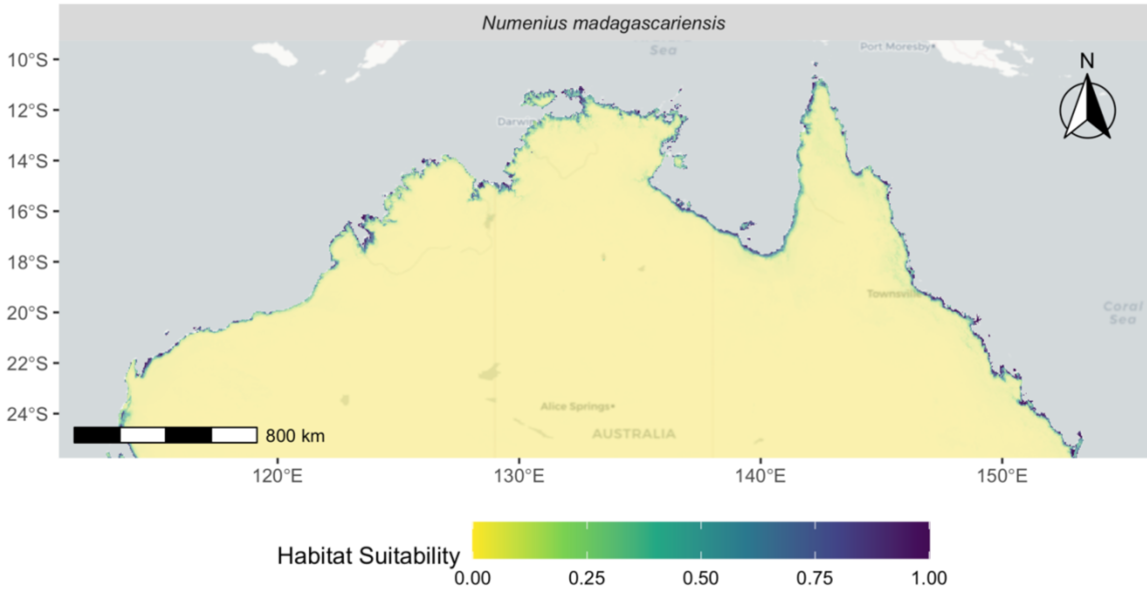
c. Red Knot (*Calidris canutus*; top), Curlew Sandpiper (*Calidris ferruginea*; middle) and Great Knot (*Calidris tenuirostris*; bottom) model predictions:



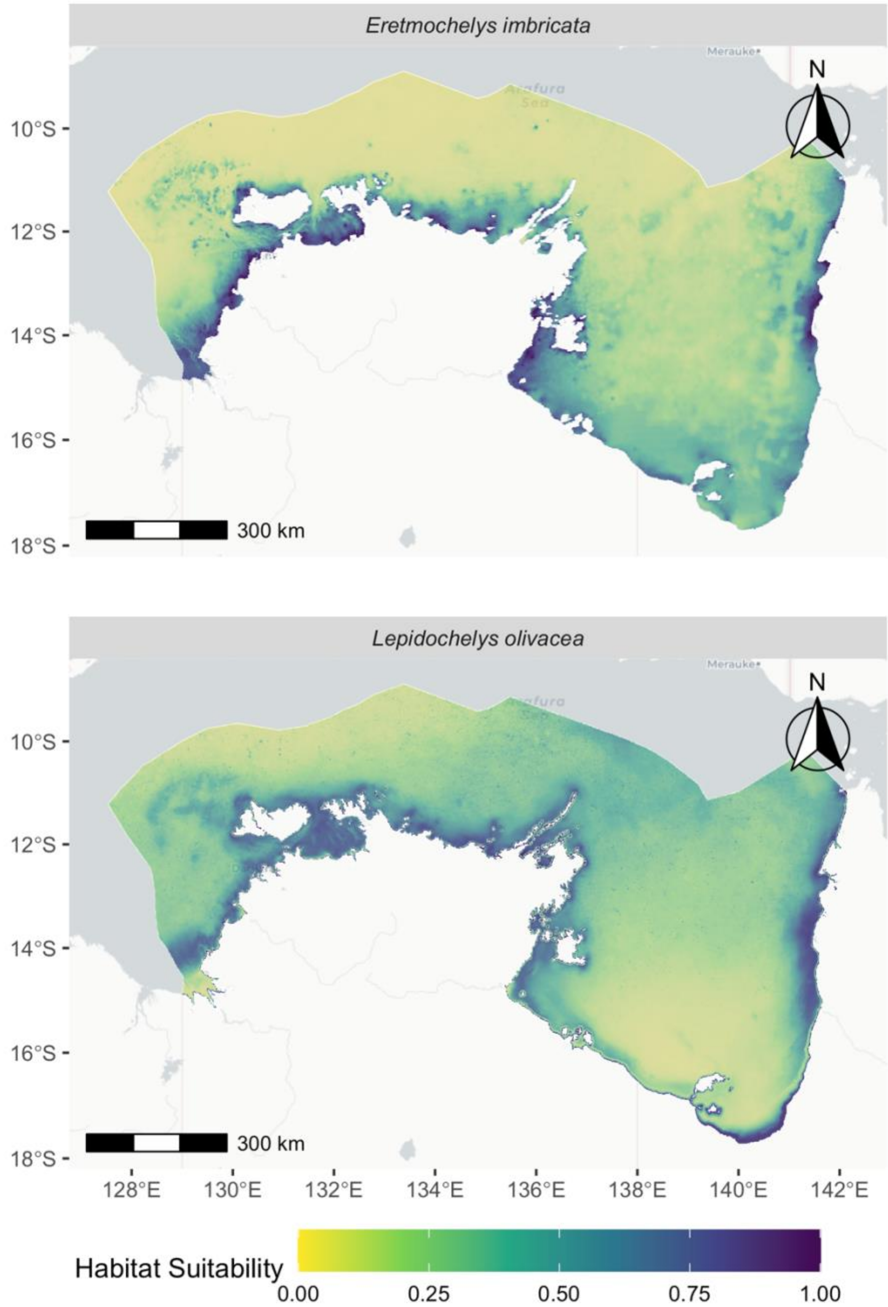
d. Greater Sand-Plover (*Charadrius leschenaultii*; top) and Lesser Sand-Plover (*Charadrius mongolus*; bottom) model predictions:



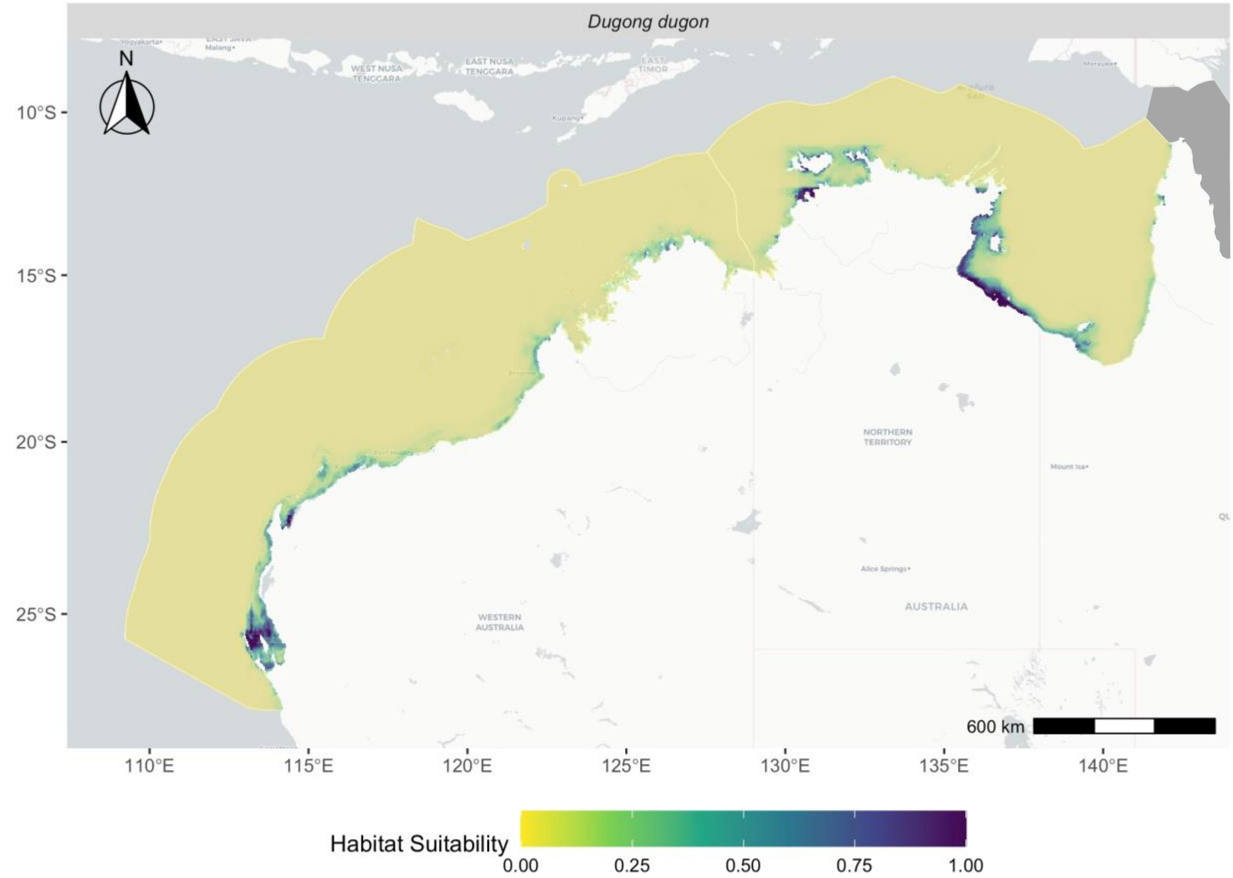
e. Eastern Curlew (*Numenius madagascariensis*) model prediction:



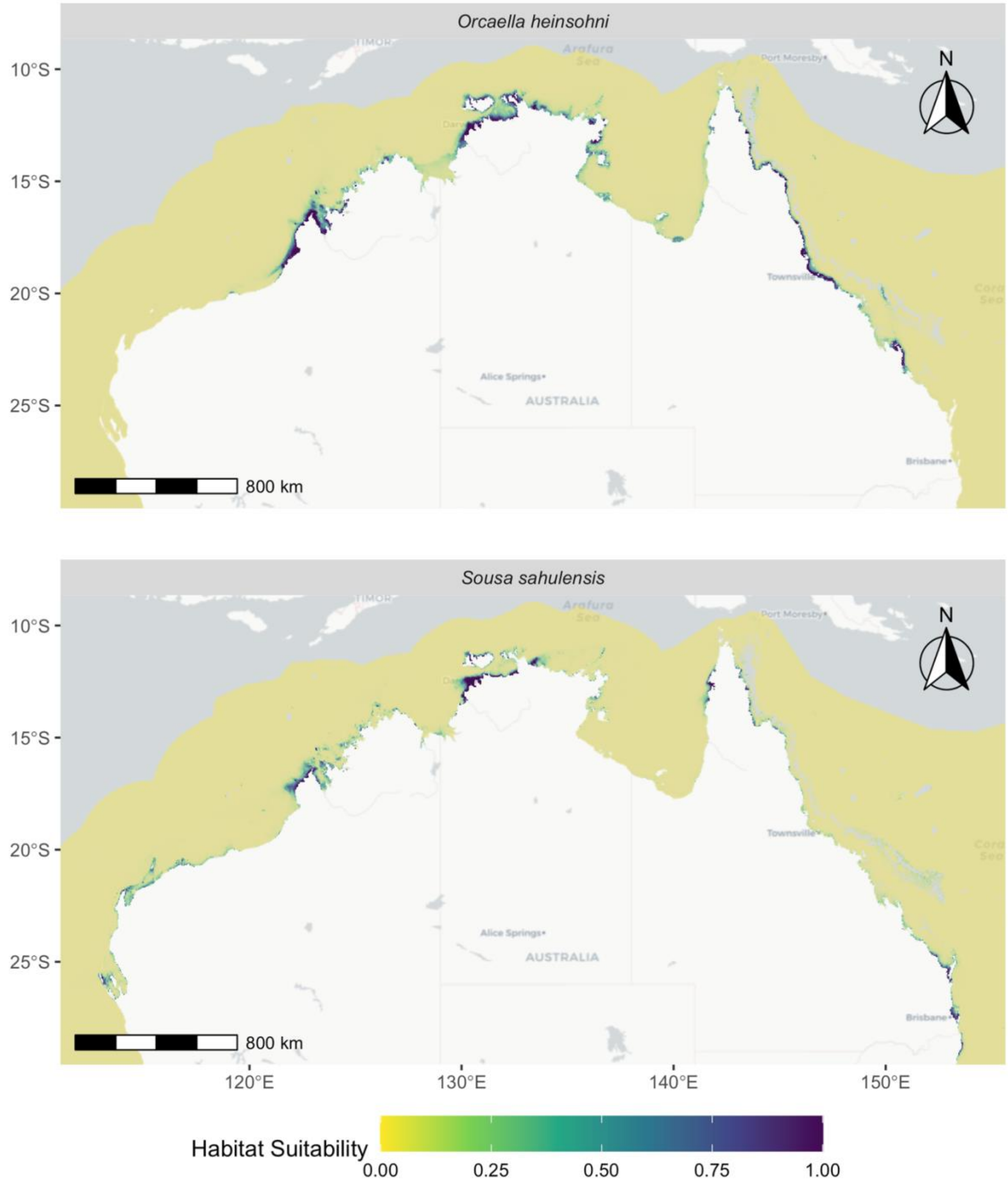
f. Hawksbill Turtle (*Eretmochelys imbricata*; top) and Olive Ridley Turtle (*Lepidochelys olivacea*; bottom) model predictions:



g. Dugong (*Dugong dugon*) model predictions:

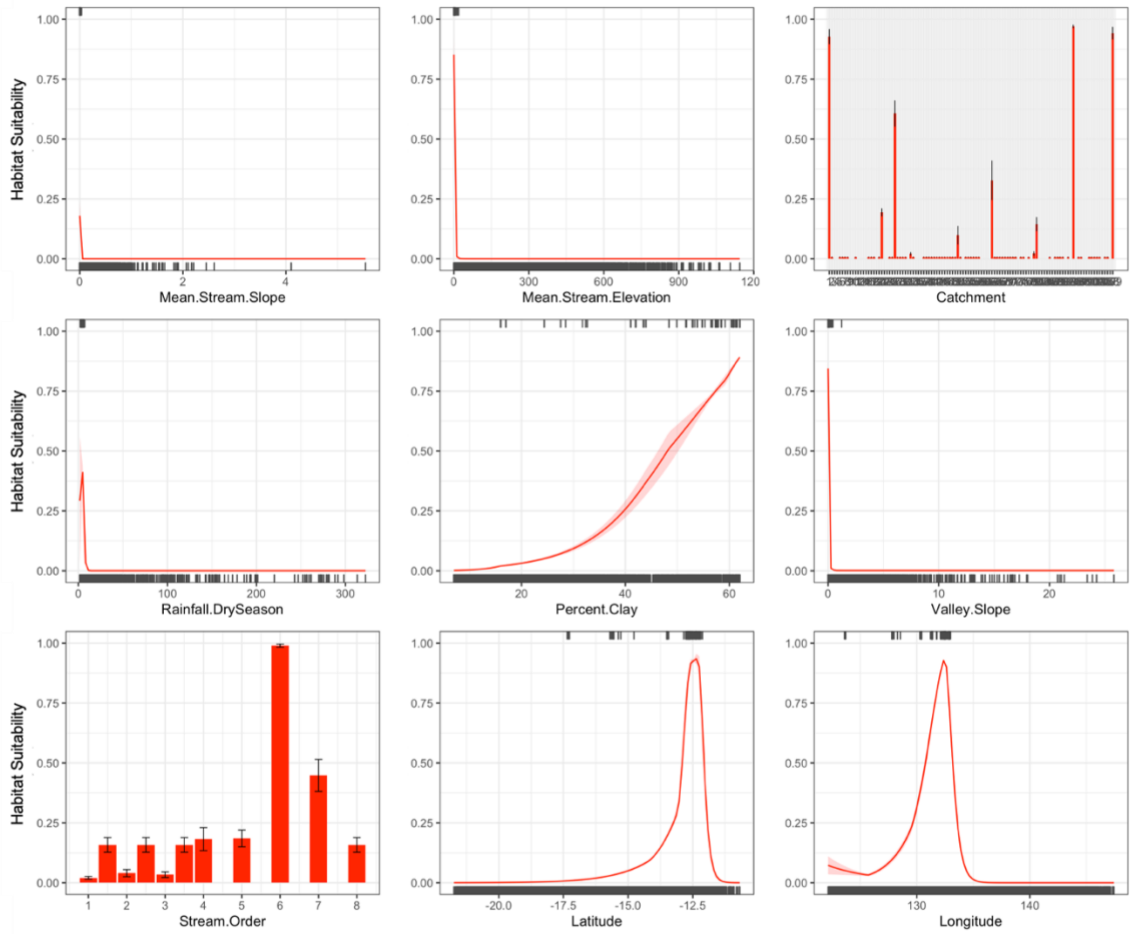


h. Australian Snubfin Dolphin (*Orcaella heinsohni*; top) and Australian Humpback Dolphin (*Sousa sahulensis*; bottom) model predictions:

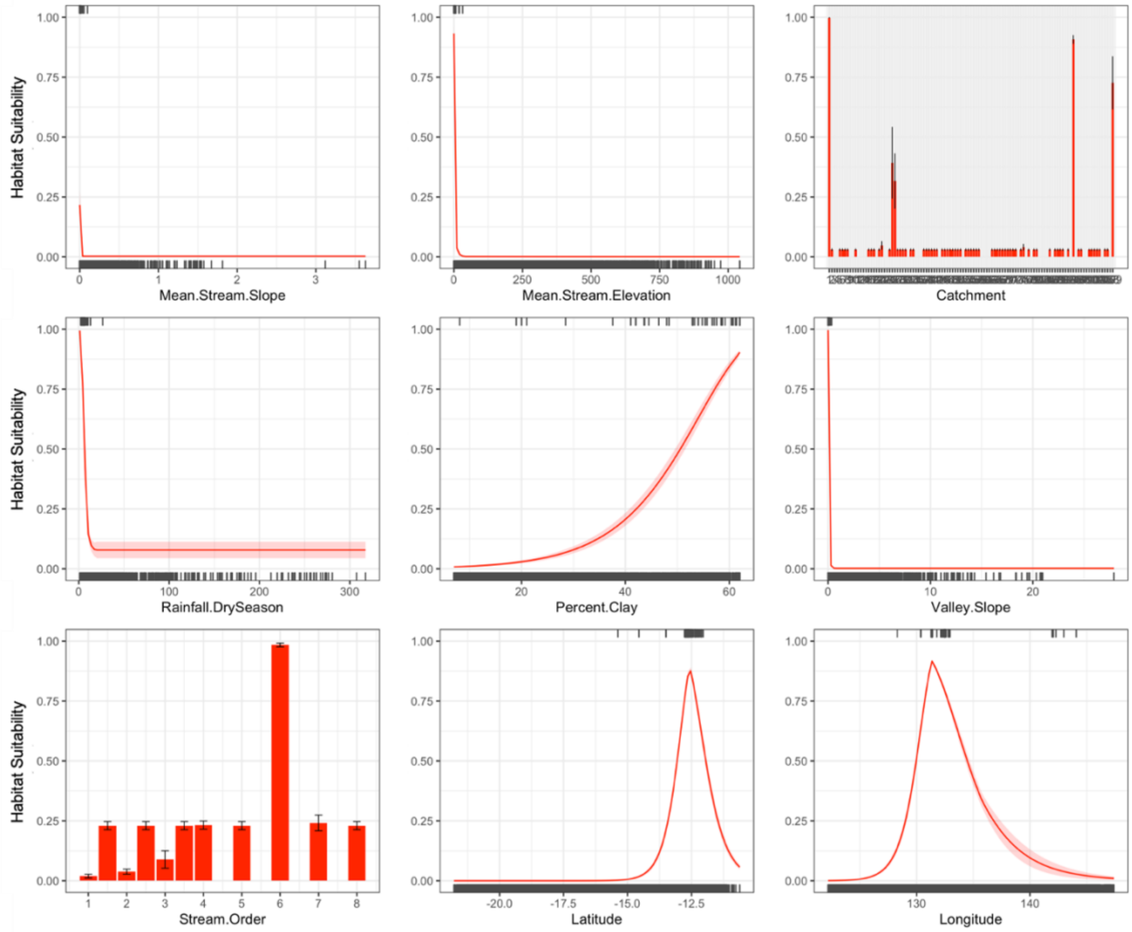


Appendix 5: Response curves for river shark models with rug plot in each panel identifying variables extracted from occurrence (top) and pseudo-absence(bottom) points.

a. Northern River Shark (*Glyphis garricki*)



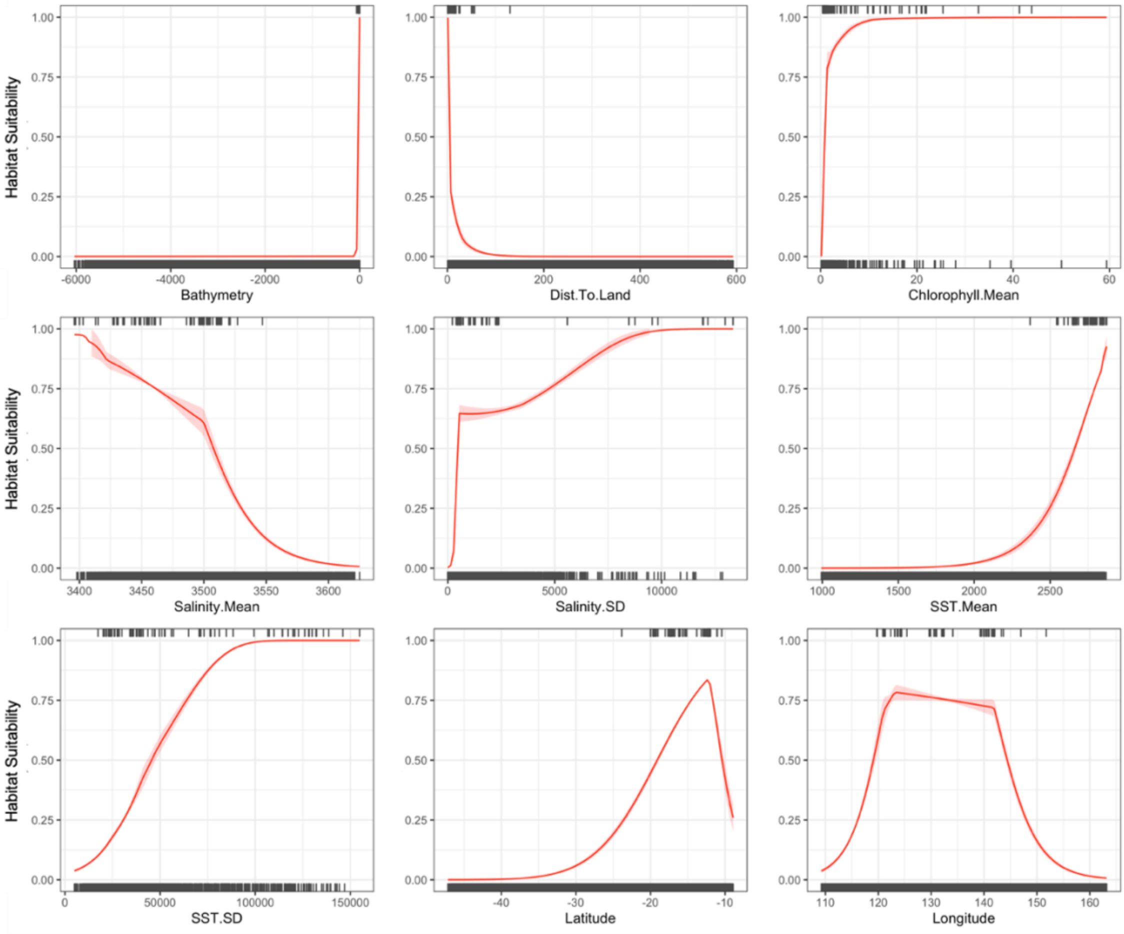
b. Speartooth Shark (*Glyphis glyphis*)



Appendix 6: Response curves for river and marine components of sawfish models with rug plot in each panel identifying variables extracted from occurrence (top) and pseudo-absence(bottom) points.

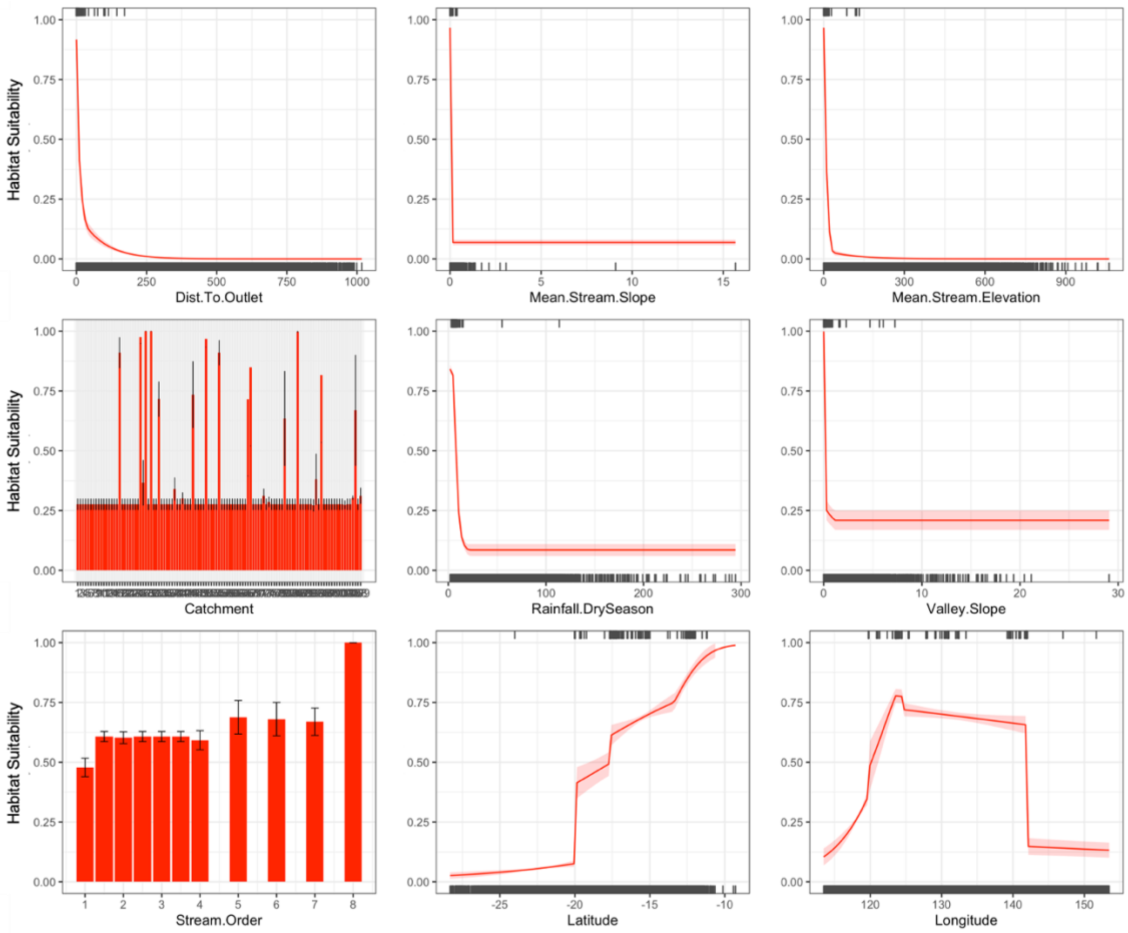
a. Dwarf Sawfish (*Pristis clavata*)

Marine Model:



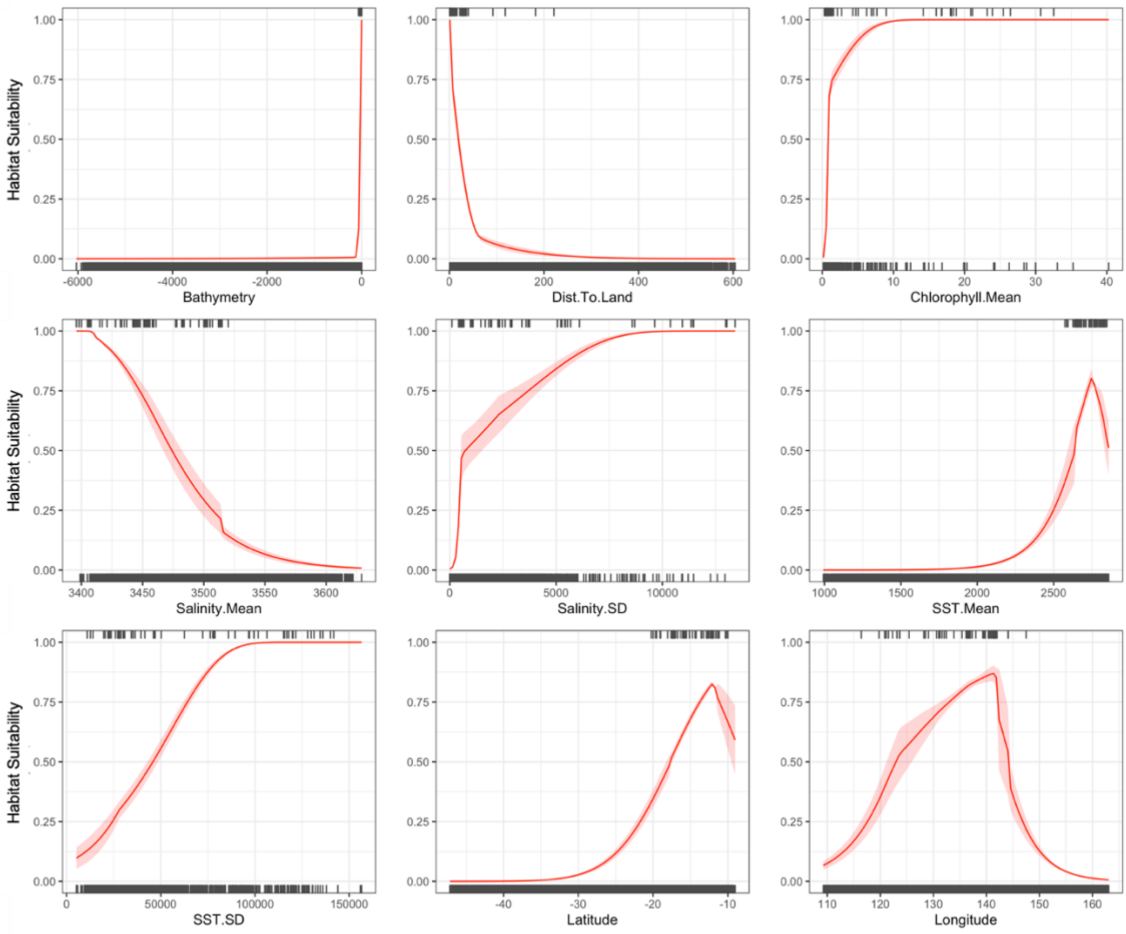
Dwarf Sawfish (*Pristis clavata*)

River Model:



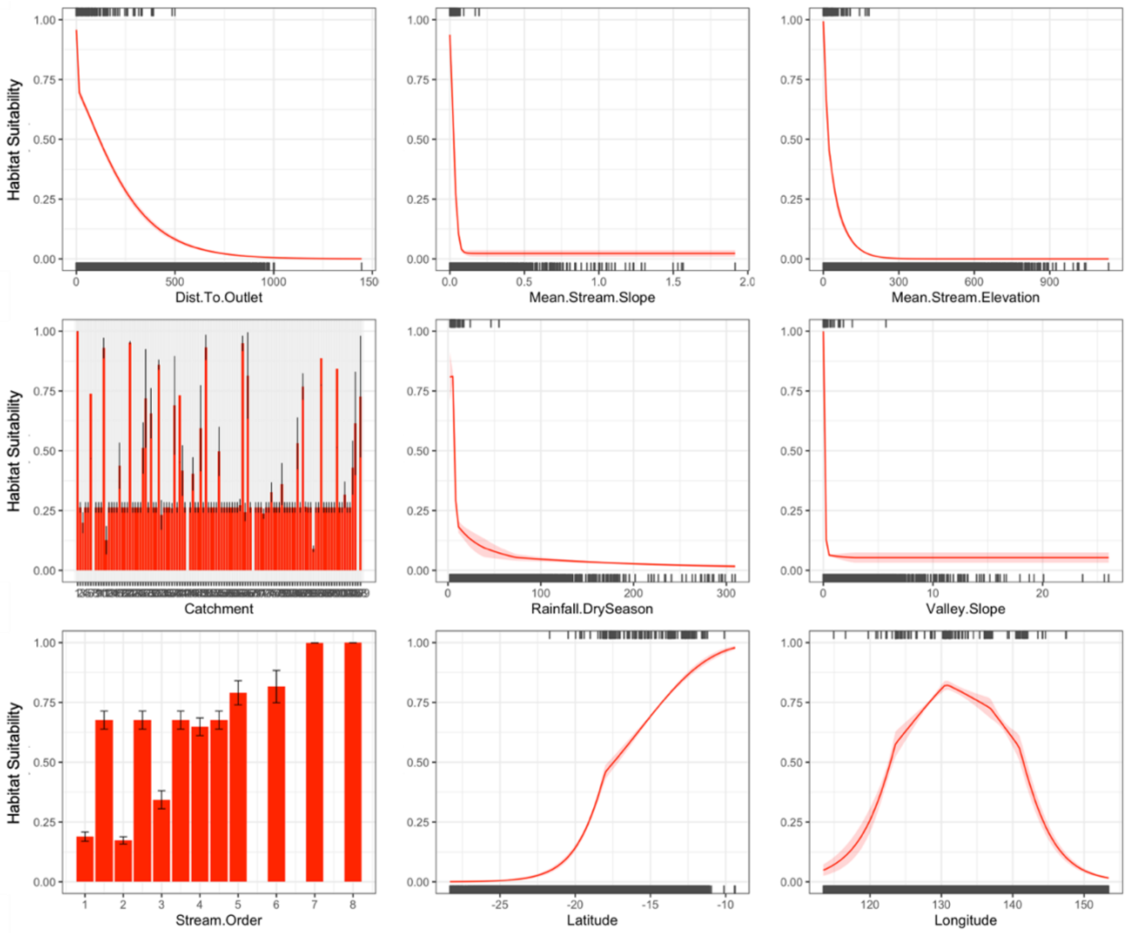
a. Largetooth Sawfish (*Pristis pristis*)

Marine Model:



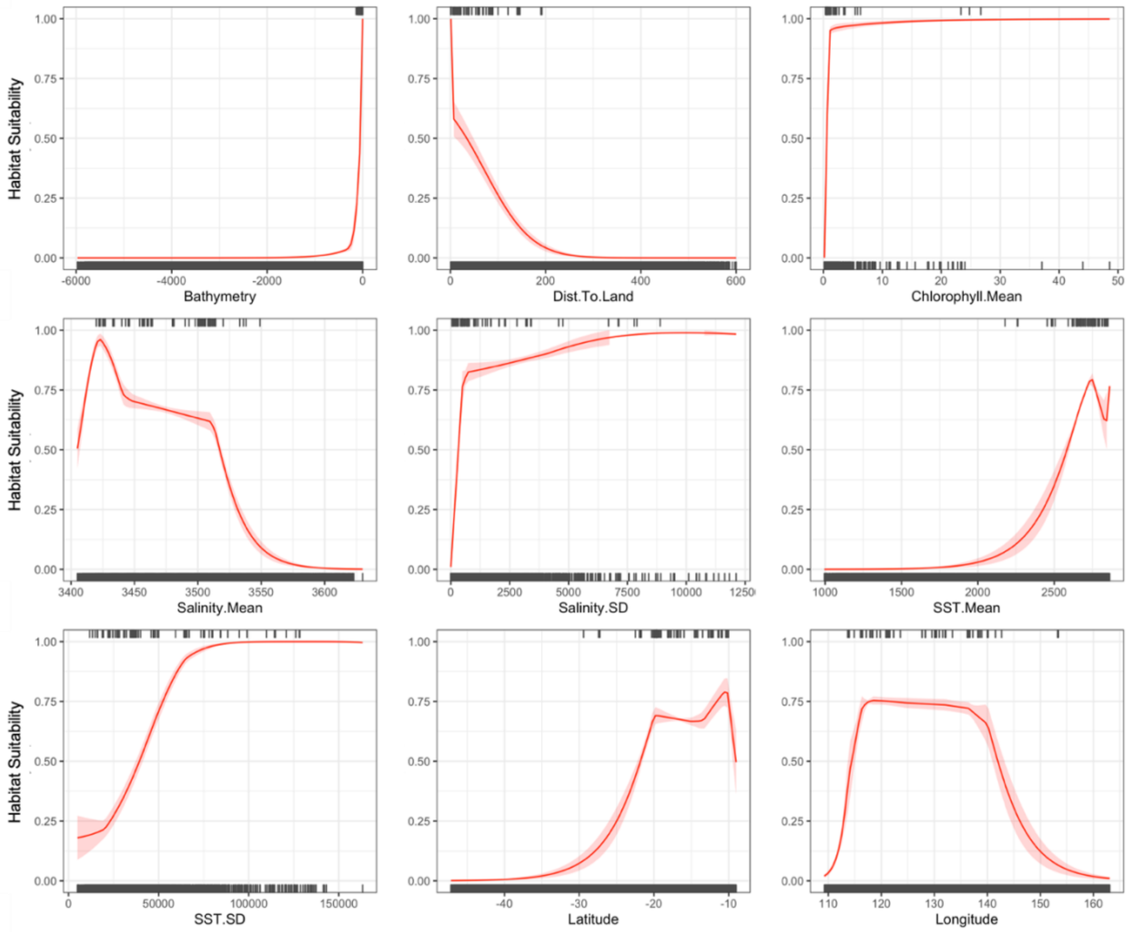
Largetooth Sawfish (*Pristis pristis*)

River Model:



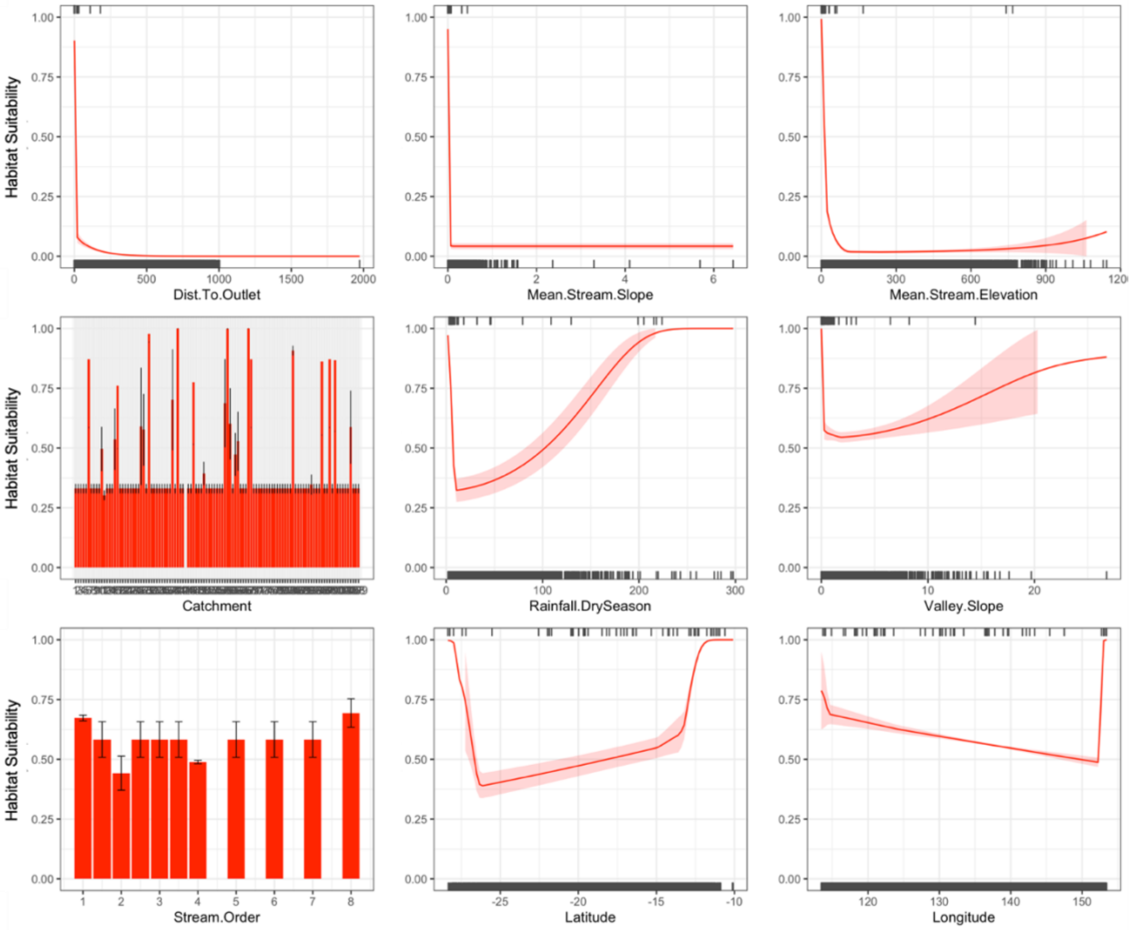
a. Green Sawfish (*Pristis zijsron*)

Marine Model:



Green Sawfish (*Pristis zijsron*)

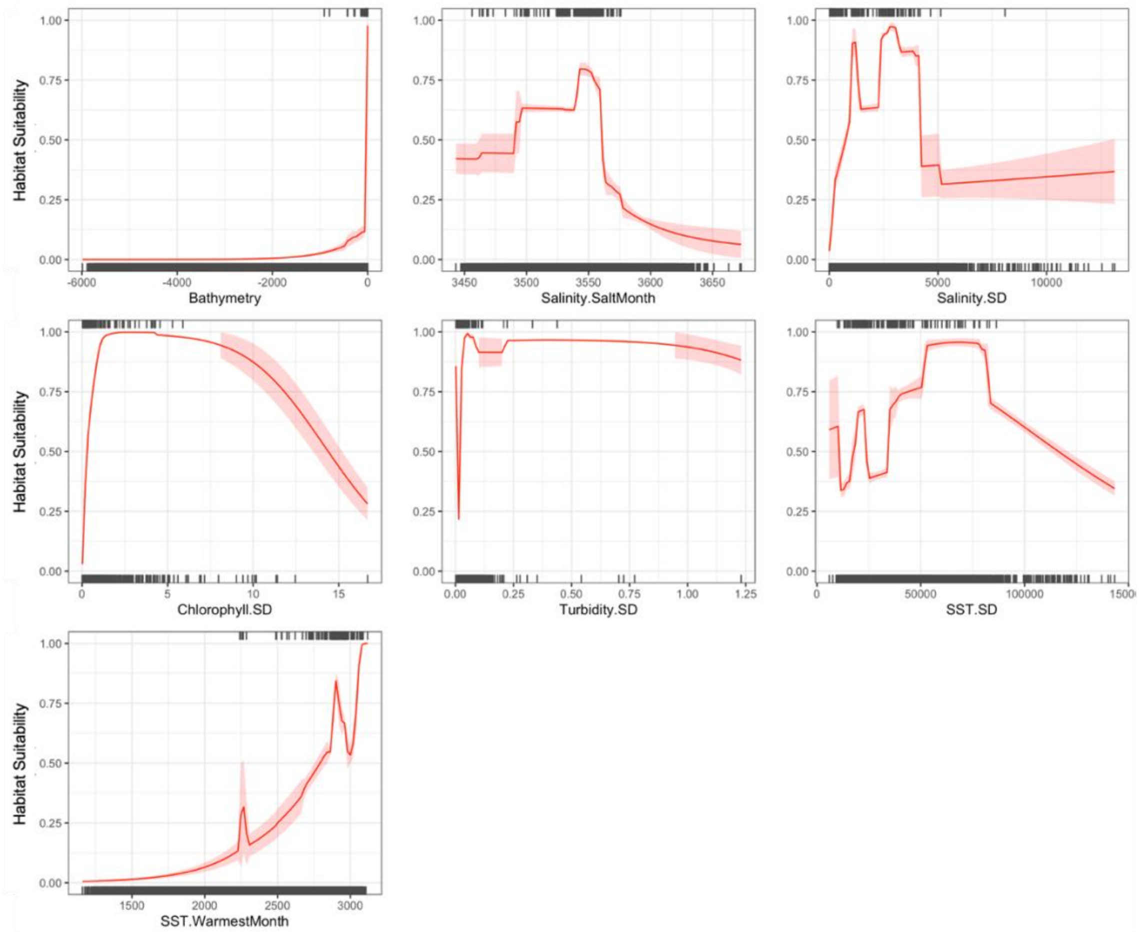
River Model:



Appendix 7: Response curves for marine turtle models with rug plot in each panel of Maxent models identifying variables extracted from occurrence (top) and pseudo-absence(bottom) points.

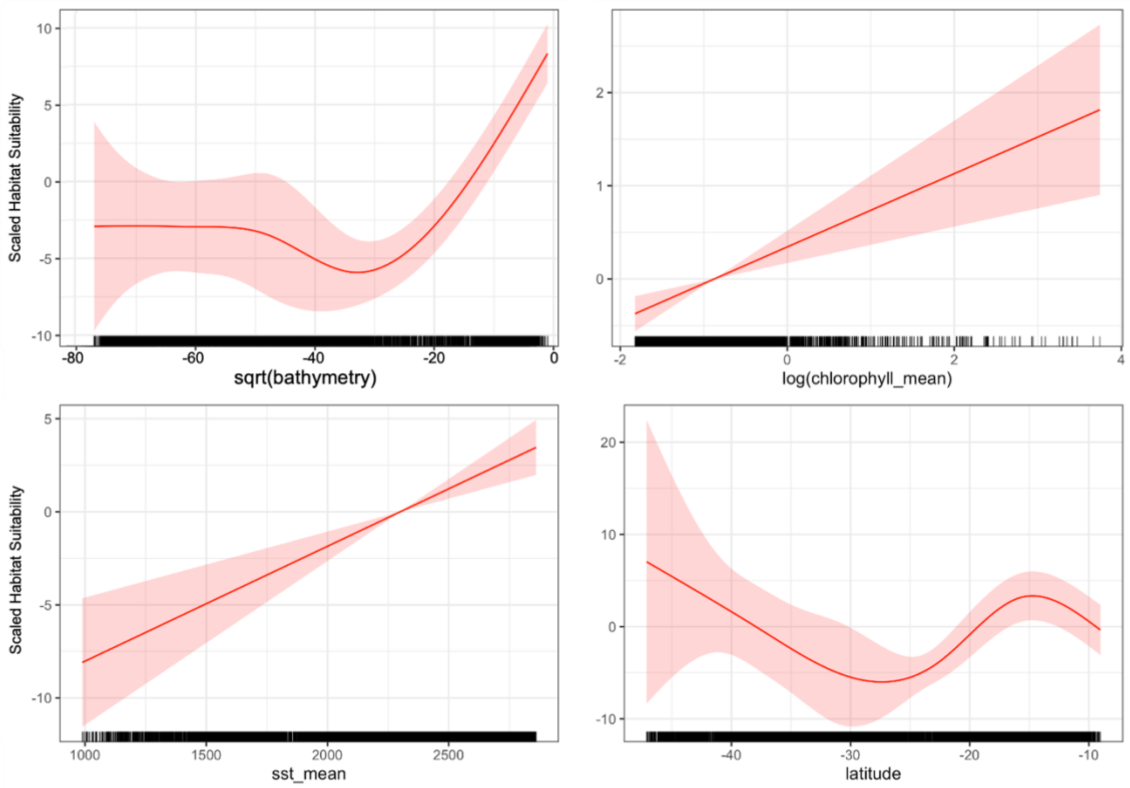
a. Hawksbill Turtle (*Eretmochelys imbricata*)

MaxEnt model response (presence only occurrence model)



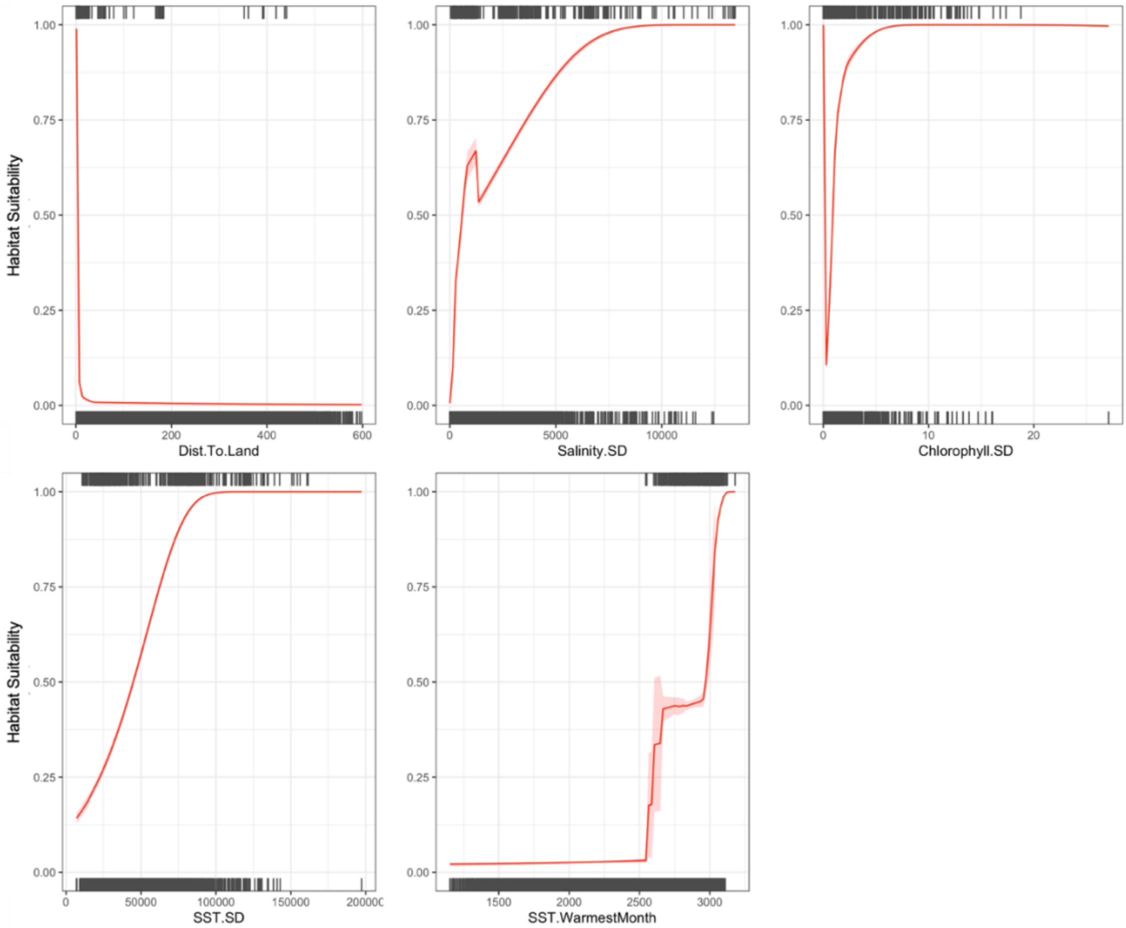
Hawksbill Turtle (*Eretmochelys imbricata*)

GAMM model response (satellite telemetry model)



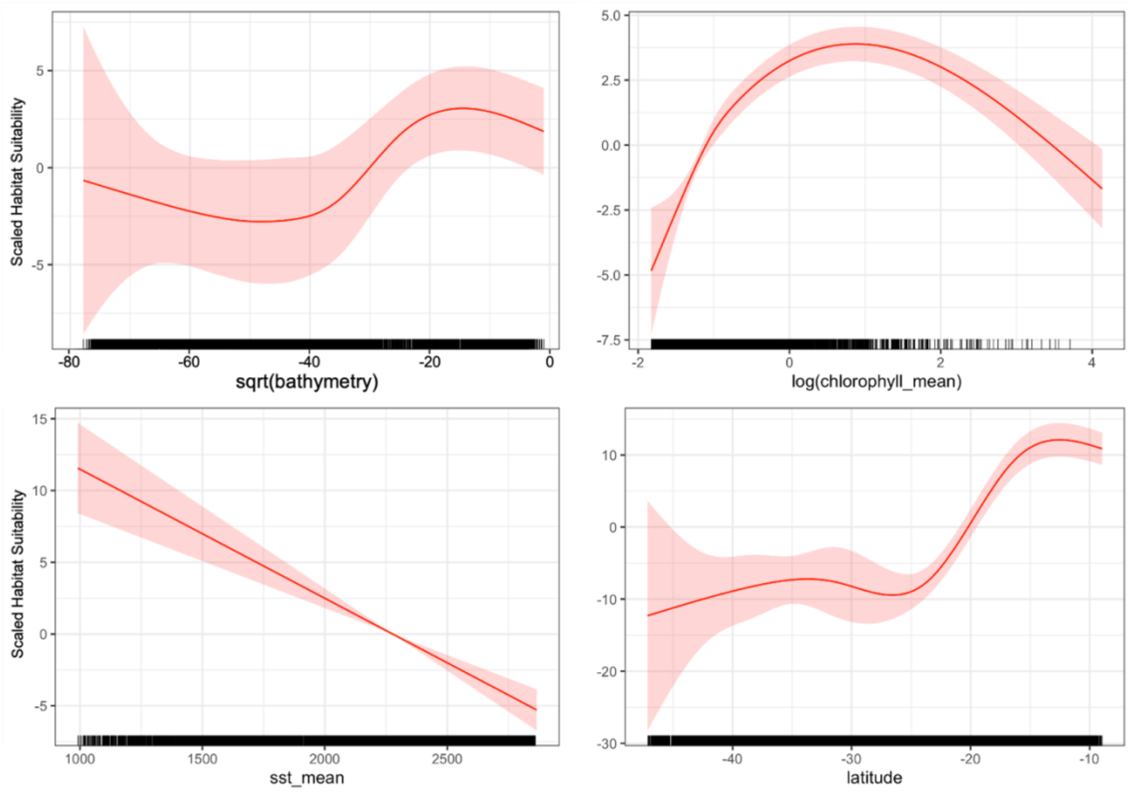
b. Olive Ridley Turtle (*Lepidochelys olivacea*)

MaxEnt model response (presence only occurrence model)



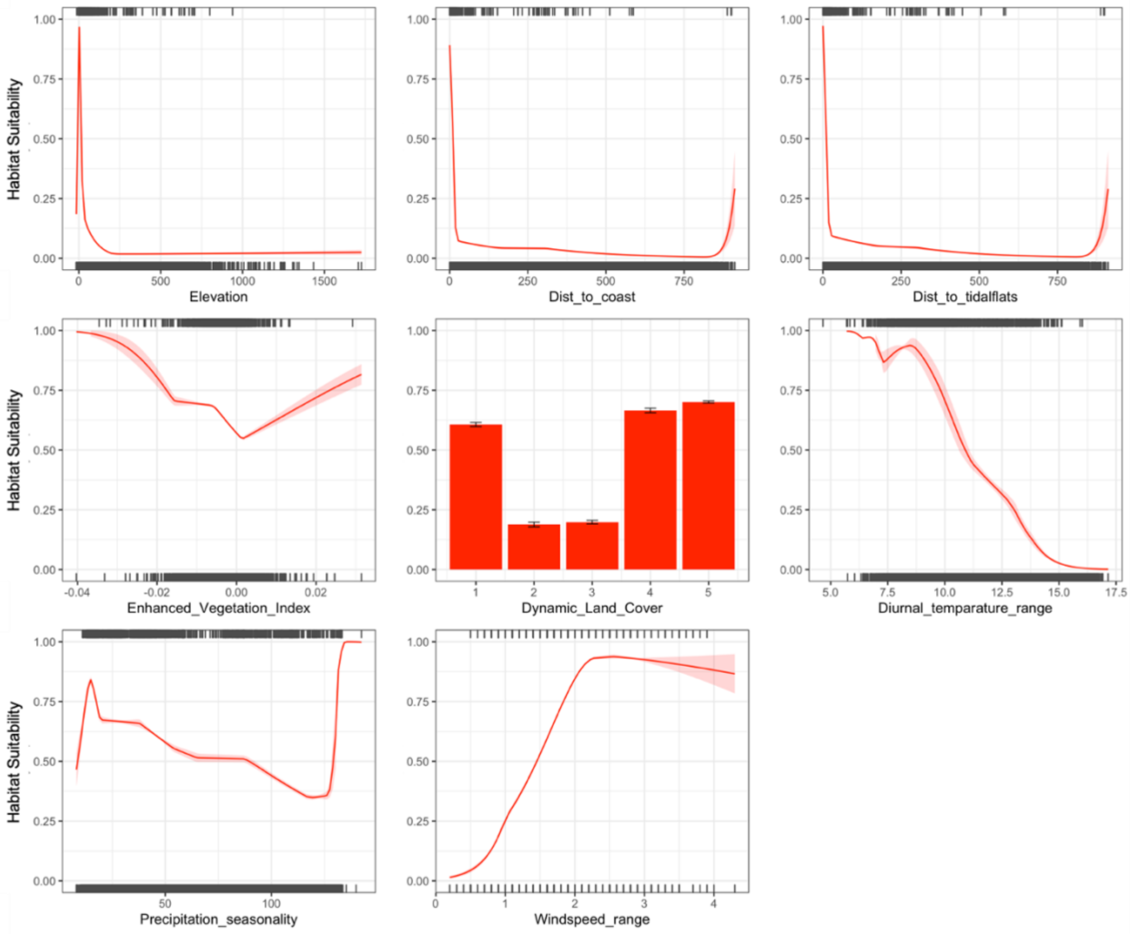
Olive Ridley Turtle (*Lepidochelys olivacea*)

GAMM model response (satellite telemetry model)

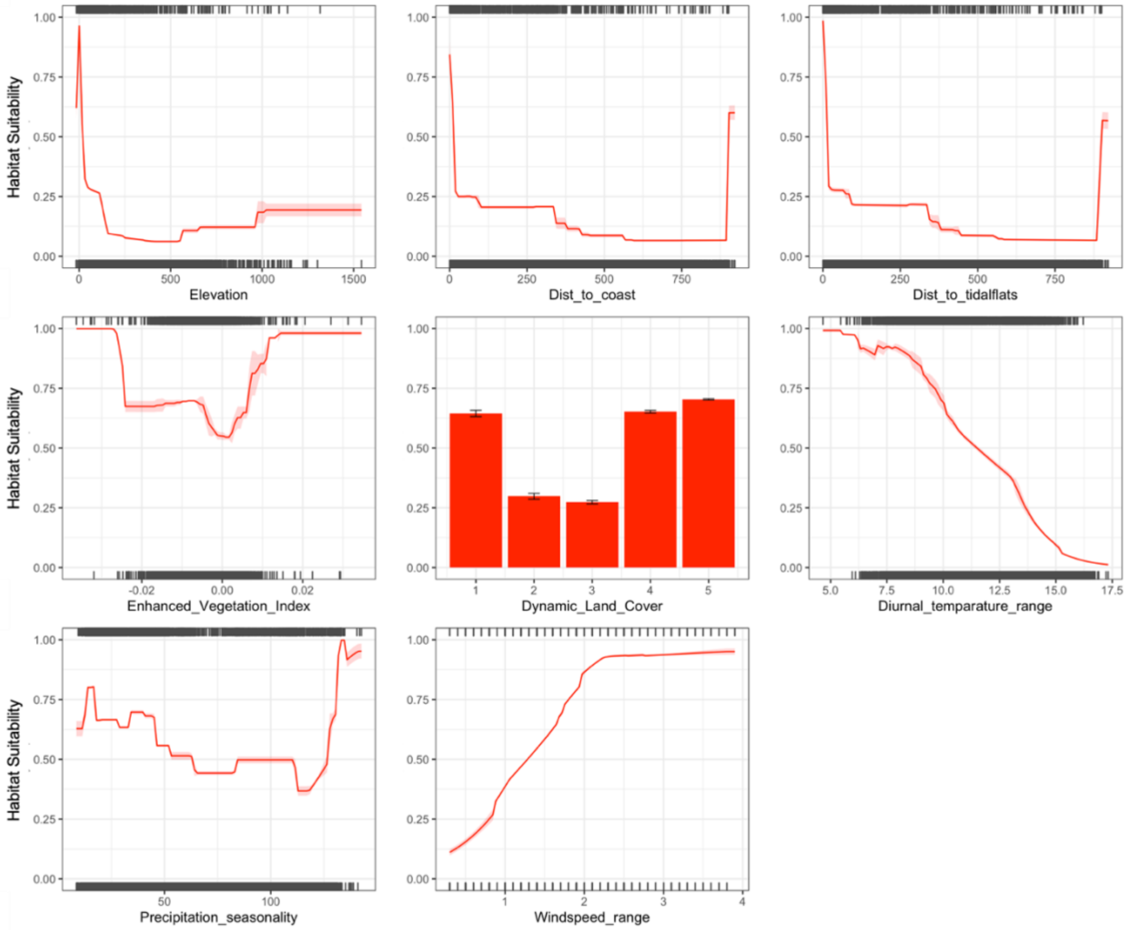


Appendix 8: Response curves for shorebird models with rug plot in each panel identifying variables extracted from occurrence (top) and pseudo-absence(bottom) points.

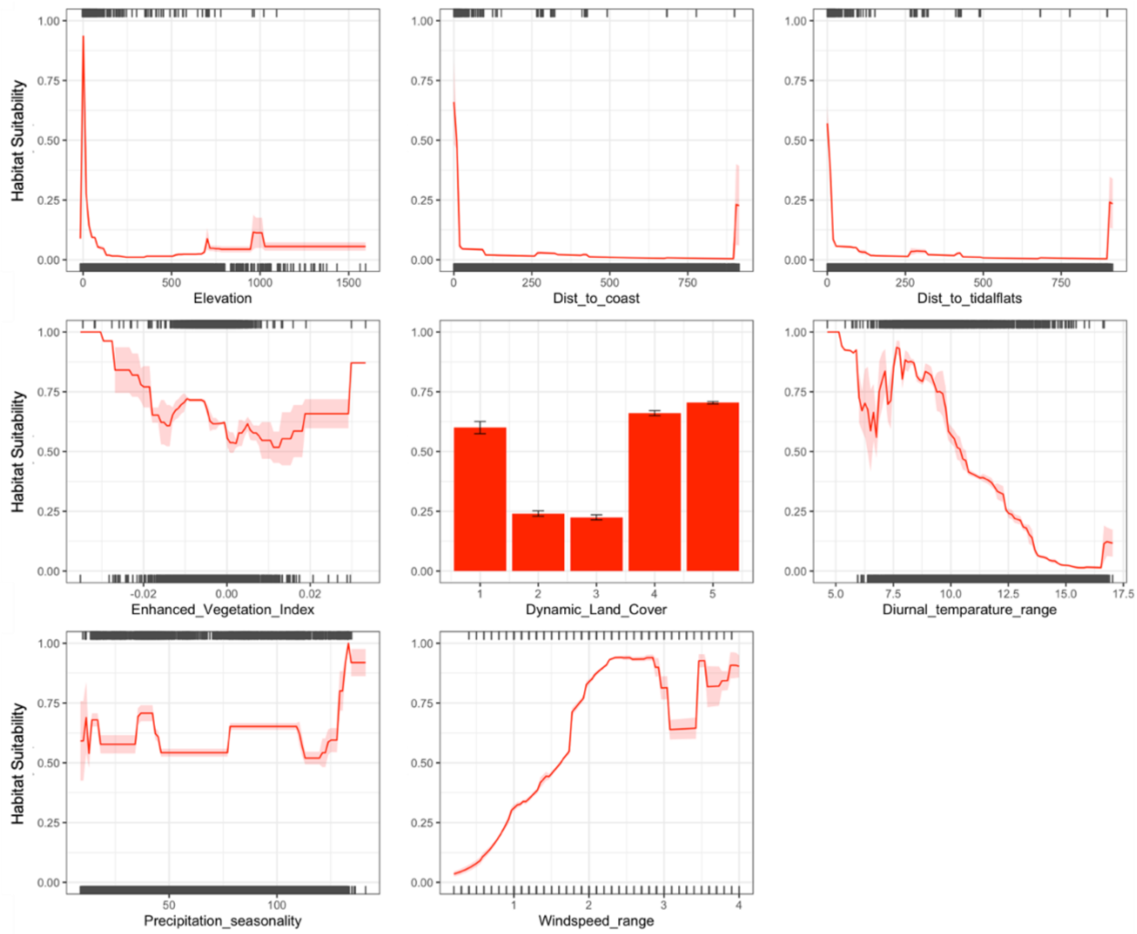
a. Red Knot (*Calidris canutus*)



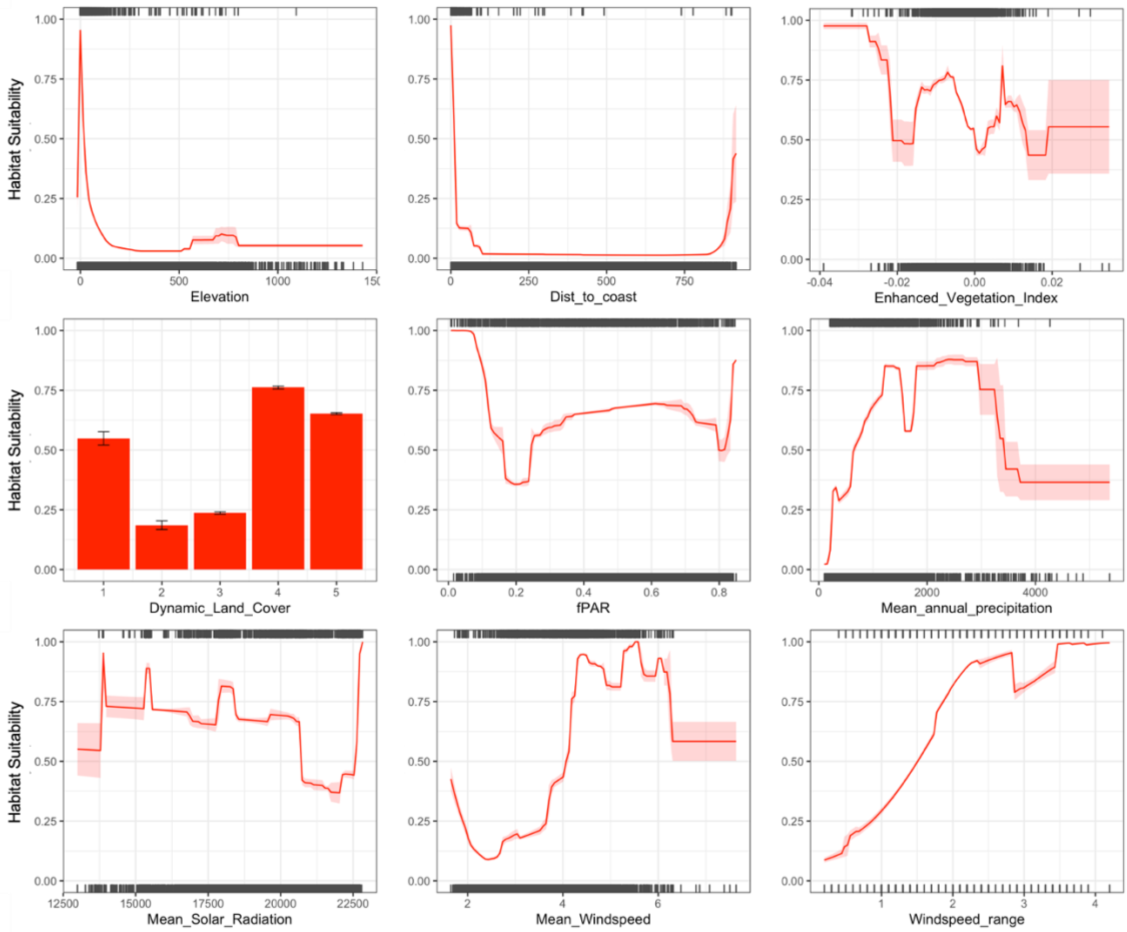
b. Curlew Sandpiper (*Calidris ferruginea*)



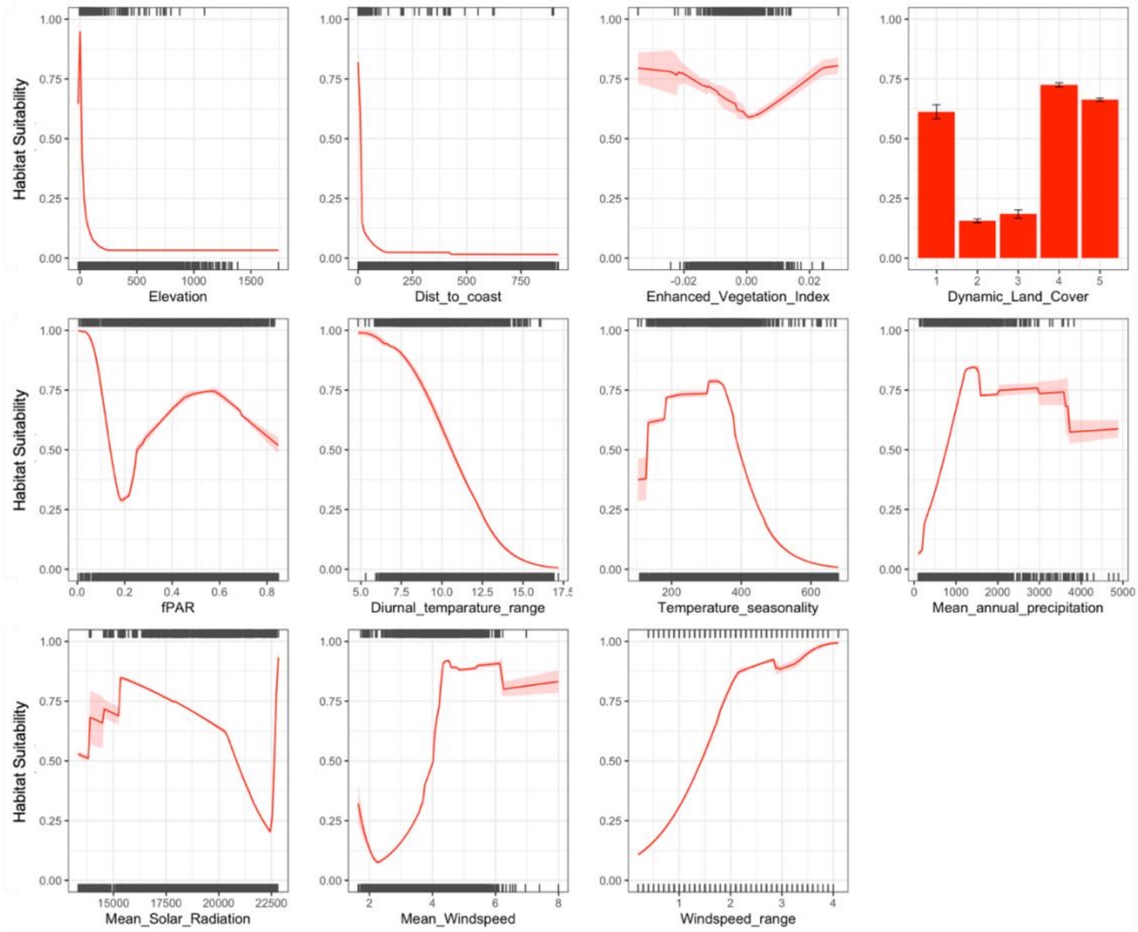
c. Great Knot (*Calidris tenuirostris*)



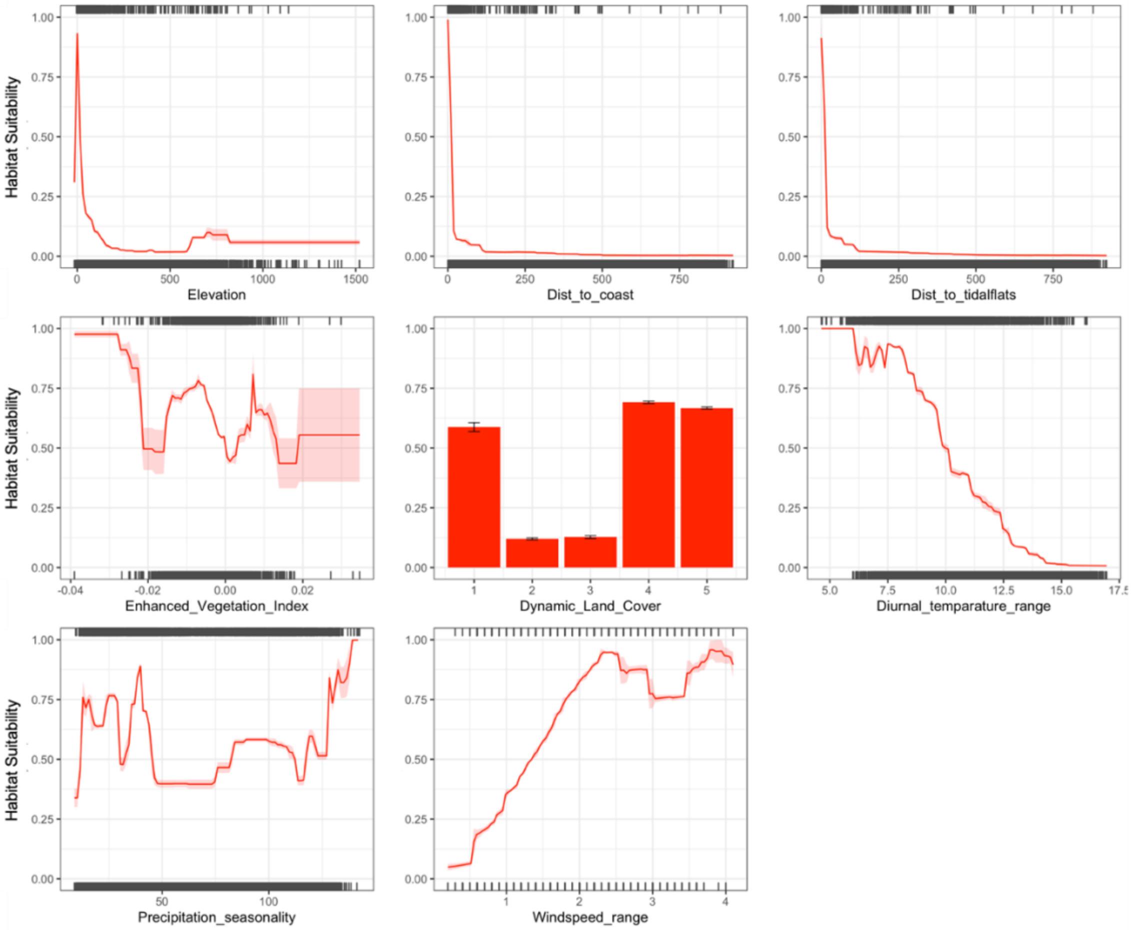
d. Greater Sand-Plover (*Charadrius leschenaultii*)



e. Lesser Sand-Plover (*Charadrius mongolus*)



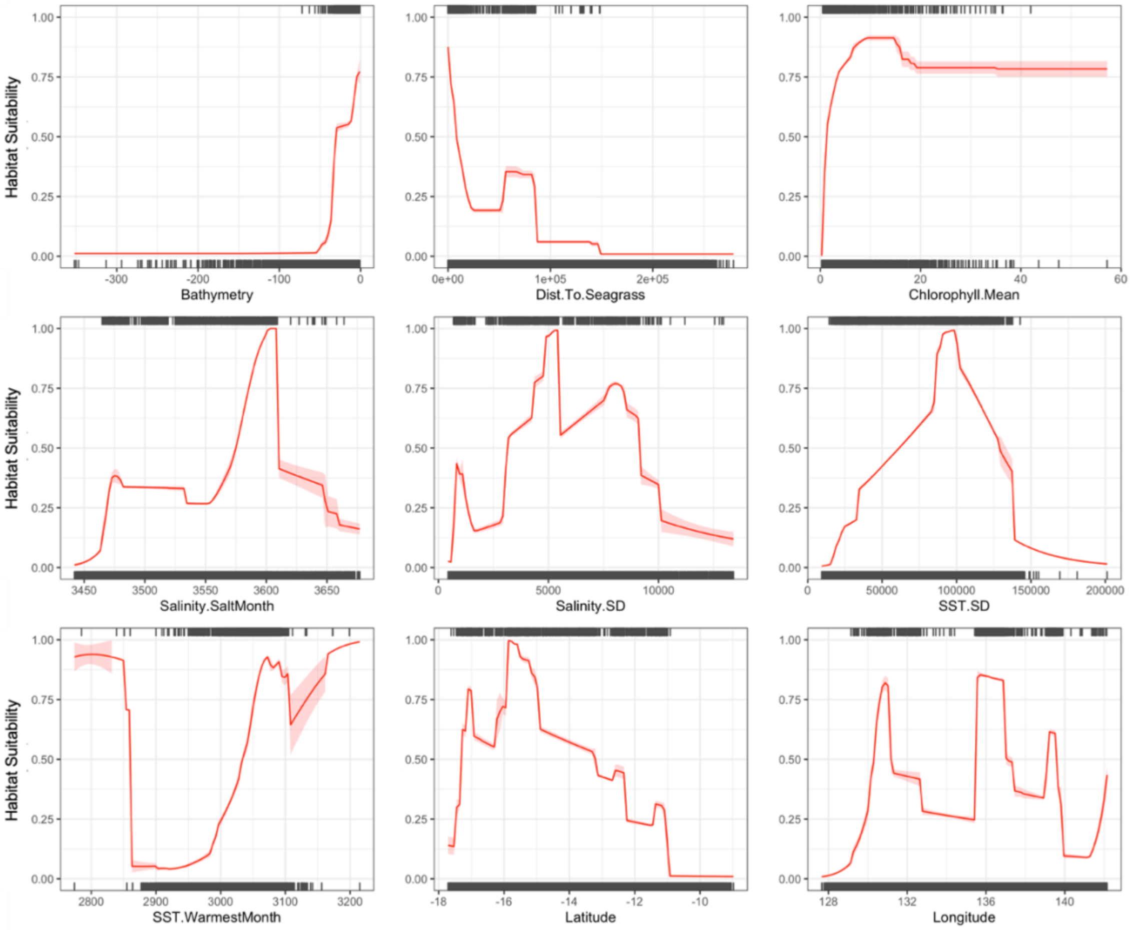
f. Eastern Curlew (*Numenius madagascariensis*)



Appendix 9: Response curves for marine mammal models with rug plot in each panel identifying variables extracted from occurrence (top) and pseudo-absence(bottom) points.

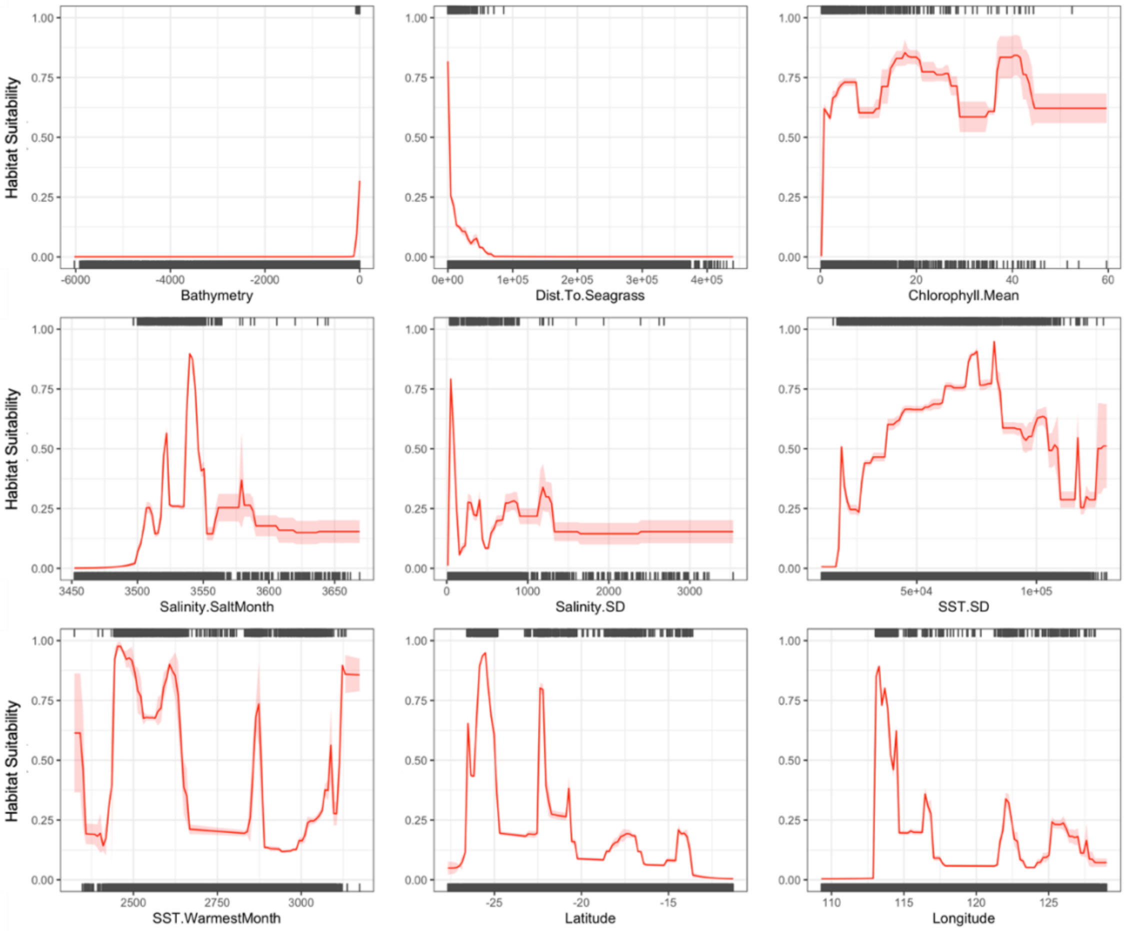
a. Dugong (*Dugong dugon*)

North Marine Region

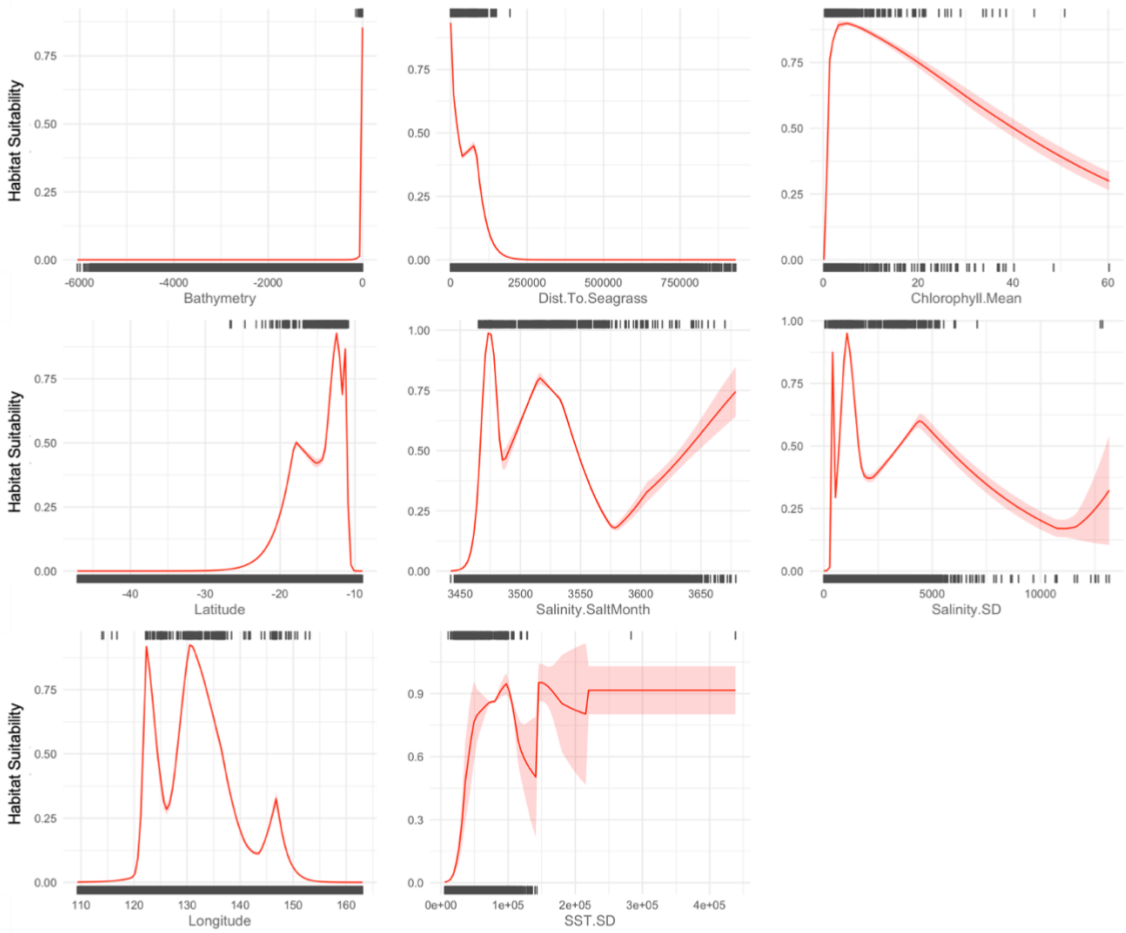


Dugong (*Dugong dugon*)

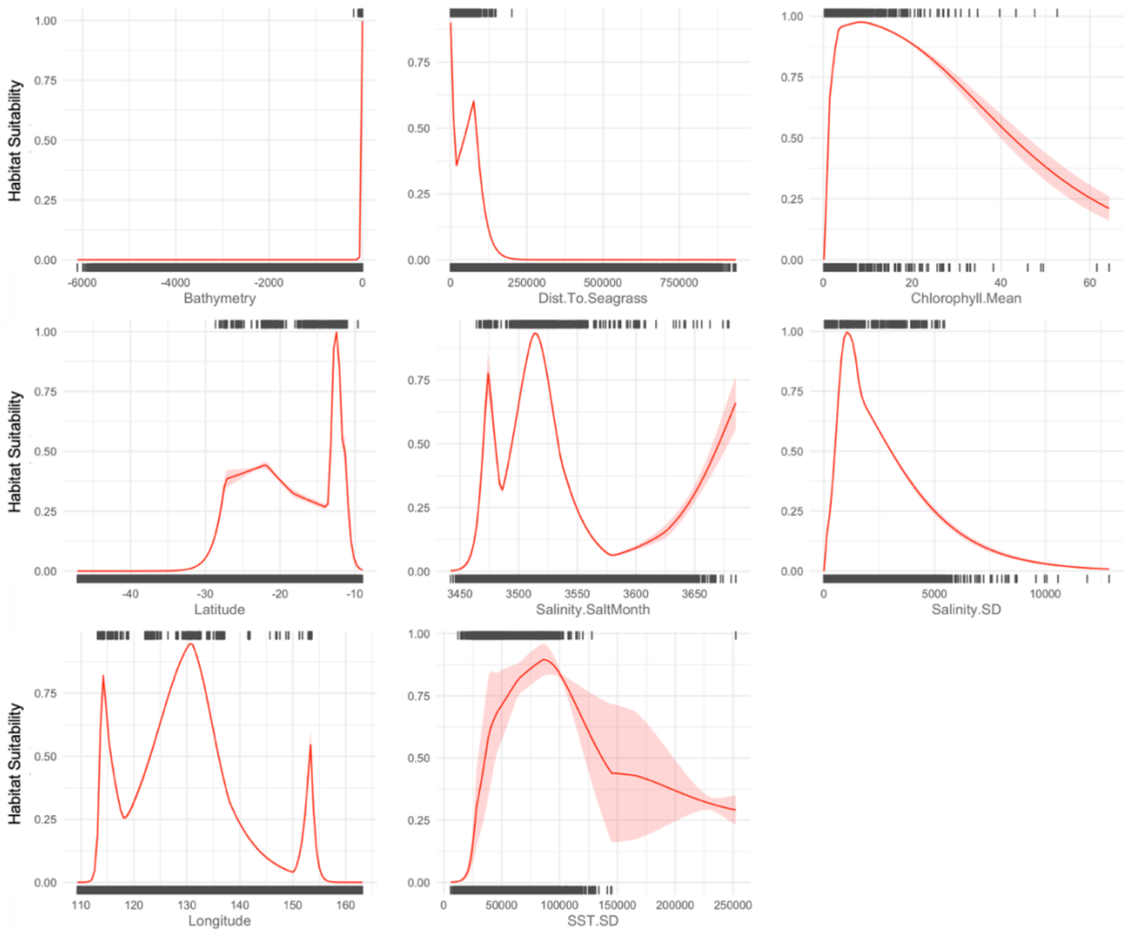
North-west Marine Region



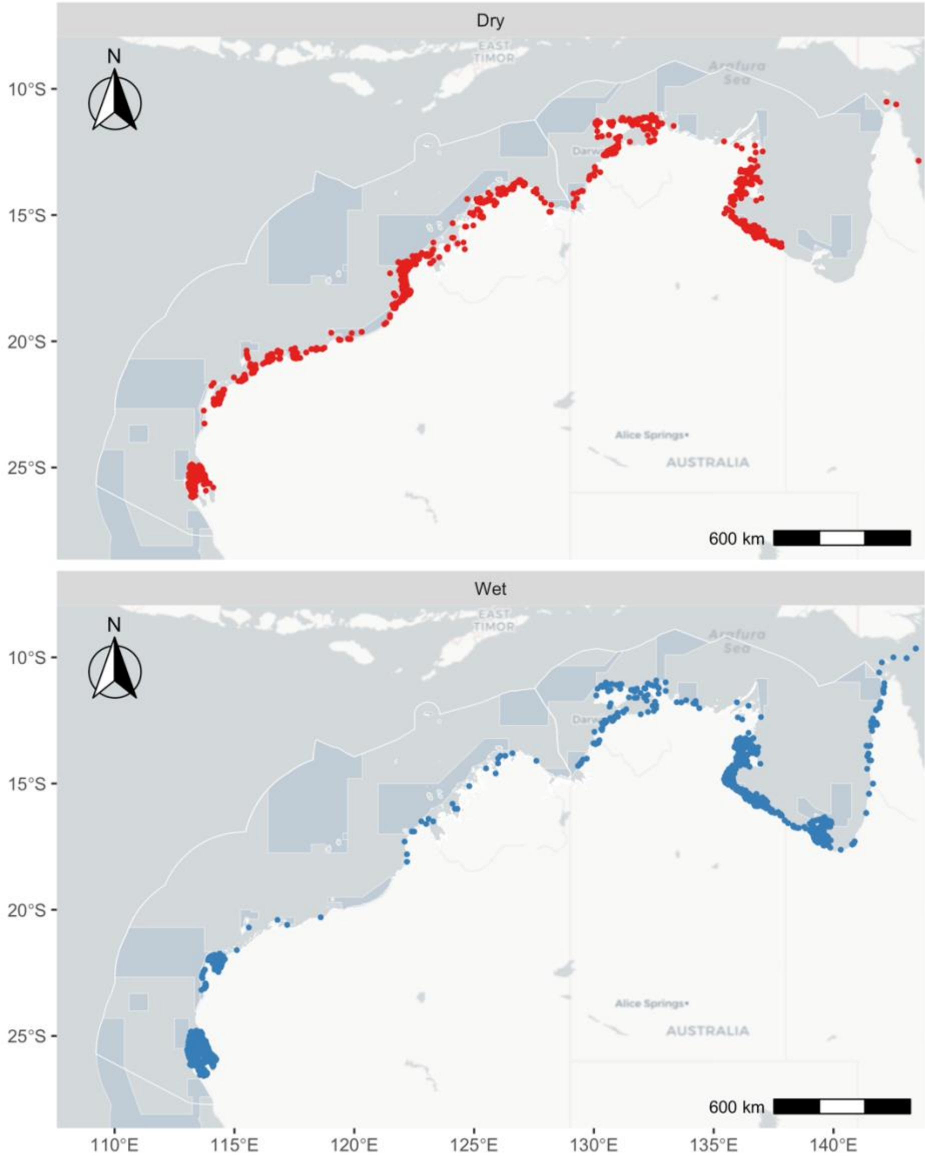
b. Australian Snubfin Dolphin (*Orcaella heinsohni*)



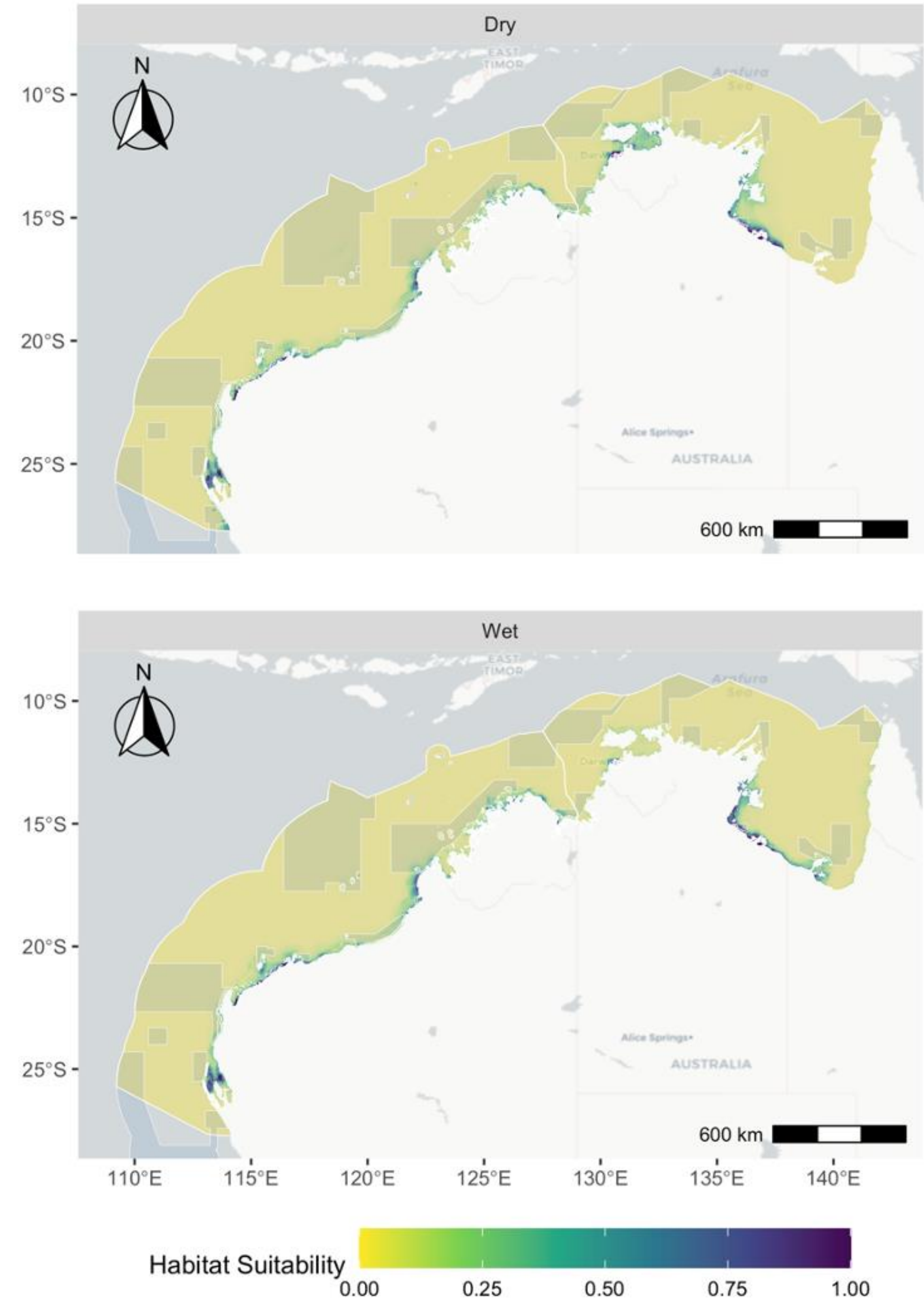
c. Australian Humpback Dolphin (*Sousa sahulensis*)



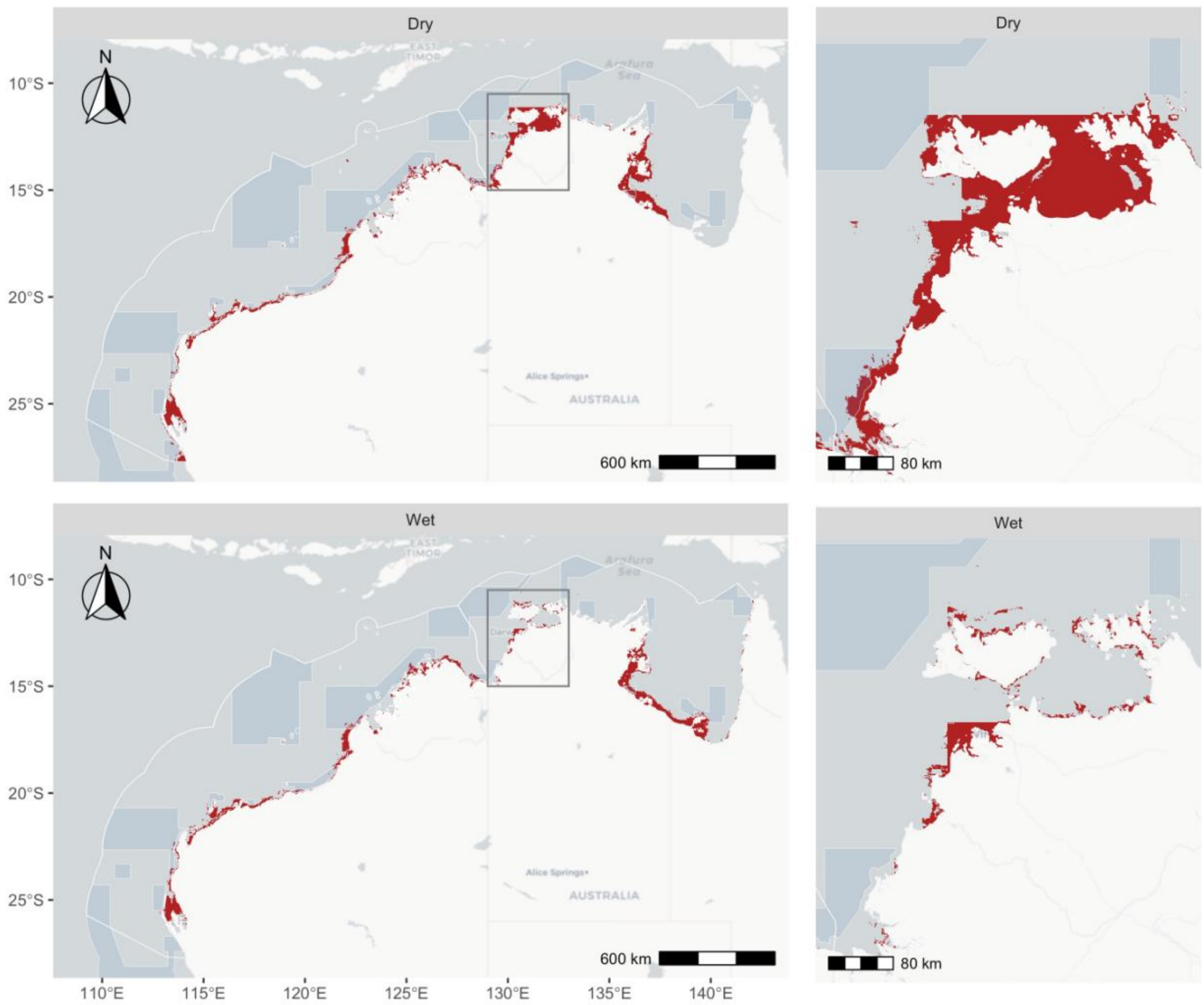
Appendix 10: Seasonal habitat suitability modelled for Dugong (*Dugong dugon*) across the North and North-West Marine region. Separate models were constructed for the Wet (November - April) and Dry (May - October) seasons based on recorded date of observation in occurrence record (where available), and seasonal predictor variables.



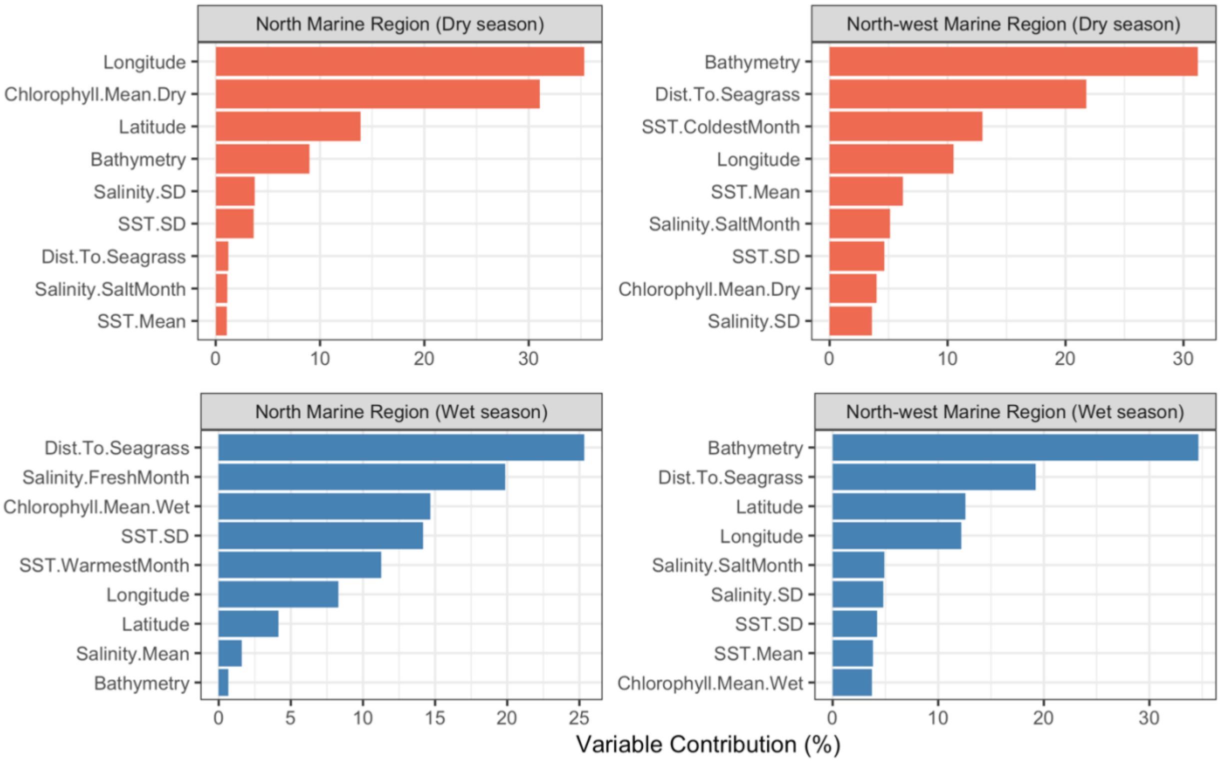
Appendix 10a | Occurrence data used to model seasonal distribution patterns of Dugong (*Dugong dugon*) across the North and North-west Marine Region of Australia (outlined in white) during the [top] dry season (May – October) and, [bottom] wet season (November – April). The majority of occurrence data compiled was from standardised aerial surveys with date of collection associated with each occurrence record. Australian Marine Parks highlighted as blue polygons.



Appendix 10b | Seasonal MaxEnt model predicts for Dugong (*Dugong dugon*) across the North and North-west Marine Region of Australia (outlined in white) during the [top] dry season (May – October) and [bottom] wet season (November – April). Australian Marine Parks highlighted as blue polygons.



Appendix 10c | Seasonal thresholded models Dugong (*Dugong dugon*) identifying suitable habitats across the North and North-west Marine Region of Australia (outlined in white) during the [top row] dry season (May – October) and [bottom row] wet season (November – April). Panels on the right display zoomed in model outputs adjacent to Darwin, NT. Australian Marine Parks highlighted as blue polygons.



Appendix 10d | Summary of the relative contribution of each variable used in optimal models for regional (North and North-west Marine Regions) and seasonal (dry and wet seasons). Variable contribution was calculated for each tuned model. Variables on the y-axis are ranked in decreasing order based on average overall variable importance across each model.

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