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Distribution, fisheries interactions and assessment of threats to Australia's sea snakes

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EXECUTIVE SUMMARY

Reported declines in sea snake abundance within multiple locations in Australia have increased concern about the status of sea snake species. Many regions of Australia, including the North-west shelf were once a global hotspot for sea snake abundance including the three endemic species that are listed as Endangered or Critically Endangered (*Aipysurus apraefrontalis*, *A. foliosquama* and *A. fuscus*). The extent and underlying causes of sea snake declines are still unknown, which hinders assessments of population status and development of management and recovery plans. Recent findings of new populations of species once thought locally extinct have made our current understanding of distribution patterns and their status outdated.

This project integrated existing sea snake occurrence data, field surveys and trawl interaction data to define the habitat suitability, distribution and area of occurrence of 27 species of sea snakes within the Australian Economic Exclusion Zone (EEZ). Areas of high diversity and endemism within the North-west and Northern Marine Region were defined, identifying south-west Gulf of Carpentaria as a region with the highest diversity, with the North-west Shelf region (i.e. Scott Reef and the north-west shoals) as a region of high sea snake endemism. Habitat suitability model spatial outputs were overlaid with annual fishing effort data using Automated Identification System (AIS) data from fishing vessels, to assess sea snake species exposure to trawl fishing. Overlap analysis identified regions along the Pilbara coastline and within the Gulf of Carpentaria as regions with significant overlap between trawl fishing effort and highly suitable habitats for sea snakes. Species with restricted ranges that fell within fishing grounds within the North-west marine region were identified to have high levels of spatial exposure to fishing activities.

Data obtained during field surveys and using fisheries-independent survey data identified high proportions of *A. apraefrontalis* and *A. foliosquama* within regional trawl surveys. Analysis of condition of encountered individuals from trawl surveys found that *Aipysurus* species had high survival rates in the surveys, whereas larger

bodied species of the *Hydrophis* lineage were more susceptible to mortality in trawl nets. Using updated information, including that generated from this project, recommendations are made to update the status of key species identified as vulnerable or of conservation priority within Australian waters. In summary, due to the lack of certainty of causes of extirpation in the two Critically Endangered species from Ashmore and Hibernia Reefs (*Aipysurus apraefrontalis* and *A. foliosquama*), and the high degree of overlap of their newly described coastal populations with trawl fisheries, we recommend these species remain as a conservation priority. Due to the significant reduction of geographic range, unknown causes of local extinctions of *Aipysurus fuscus* at Ashmore Reef, and mounting evidence of high rates of hybridisation within the surviving populations, we recommend that this species be considered for elevated conservation status, and be assessed for listing under the EPBC Act.

1. INTRODUCTION

Sea snakes are an ecologically diverse clade of more than 70 species globally, that represent the only truly marine reptiles (comprising ca. 90% of extant marine reptile species; Rasmussen et al. 2014). Of the >70 species described, ~27 are found within Australian waters and are listed marine species under the *Environmental Protection and Biodiversity Conservation Act* of 1999 (EPBC), with 2 endemic species (*Aipysurus apraefrontalis* and *A. foliosquama*) listed as Critically Endangered. Well documented declines in sea snake abundance in Western Australia, specifically within protected waters of the Ashmore Marine Park (Lukoschek et al. 2013), and the high representation of sea snakes in bycatch in coastal trawl fisheries have highlighted concerns about the status of sea snake species (Pears et al. 2012; Wassenberg et al. 2001). All the causes of the observed declines have not been defined, indicating an urgent need for research and exploration of the status of these species, in particular, knowledge on the distribution, threats and range of sea snake species in Northern Australia. These data are needed to define the status of these species to assist with updating EPBC listing status, as well as designing and implementing effective management and Recovery Plans.

This project aimed to compile existing information about sea snake occurrence, assemblages and bycatch rates from the northwest marine region, and collect additional data in regions with information gaps to; i) define sea snake distribution patterns, ii) identify key hotspots of high diversity and endemism, and iii) assess interaction rates and identify species vulnerable to fisheries bycatch. The new information generated will be discussed in the context of updating the status of key species that are identified as vulnerable or of conservation priority within Australian waters.

1.1 Current status of sea snakes in Australia

Over the last decade, molecular studies have continued to refine sea snake taxonomy, with new integrated assessment of genetic and morphological data

indicating that many widespread ‘species’ include multiple cryptic species, each with narrow distributions (e.g. *Emydocephalus* spp.: Nankivell et al. 2020; *Hydrophis* spp.: Ukuwela et al. 2013; Ukuwela et al. 2014). Additionally, recorded hybridization between closely related species with overlapping ranges is likely to affect the true diversity of sea snakes within Australia (Lukoschek 2018; Sanders et al. 2014). With increased molecular work and genetic assessments, it is estimated that there are likely an additional ~20 species that remain to be discovered, increasing global and Australian sea snake diversity (Udyawer et al. 2018).

Of the ~27 species of sea snakes currently described in Australia, seven species have highly restricted geographic ranges and are endemic to Australian waters (*Aipysurus apraefrontalis*, *A. foliosquama*, *A. fuscus*, *Hydrophis pacificus*, *A. pooleorum*, *A. tenuis*, and *H. donaldi*; see Appendix 1 for known distributions). Two of the six short-range endemics (*A. apraefrontalis* and *A. foliosquama*) are also currently listed as Critically Endangered under the International Union for the Conservation of Nature (IUCN) Red List criteria (Elfes et al. 2013). Until 2001, breeding populations of these two species were only known from Ashmore and Hibernia Reefs in the Timor Sea (Cogger 1975). However, neither species has been recorded at those two reefs since 2001, and both species were presumed extirpated, coinciding with a drastic decline in the overall sea snake assemblage in the area (Guinea 2013; Lukoschek et al. 2013; Sanders et al. 2015). Subsequently, breeding populations of both *A. apraefrontalis* and *A. foliosquama* were recently discovered in coastal Western Australia up to 800 km away from their previously known range in the Timor Sea (D'Anastasi et al. 2016b). *A. fuscus*, listed by IUCN as Endangered (Elfes et al. 2013), is historically recorded only from the Ashmore and Scott Reef complexes in the Timor Sea and has declined throughout that restricted range (Lukoschek et al. 2013). *Hydrophis pacificus* is currently listed by IUCN as Near Threatened (Elfes et al. 2013), and is primarily only known from bycatch records in the Northern Prawn Fishery (NPF) that operates within the Gulf of Carpentaria. The listing of this species as Near Threatened has been primarily due to its extremely localised catch distribution within the Gulf of Carpentaria, and their recorded declines in abundance of catch within fishing grounds (Milton et al. 2008).

Three species, *A. tenuis*, *A. pooleorum* and *Hydrophis donaldi*, are among the least-studied species, and are currently categorised as Data-Deficient and unassessed by IUCN, due to the lack of information on their geographic ranges and population trends (Elfes et al. 2013). Although *A. pooleorum* forms a closely related subpopulation of the more widely studied *A. laevis*, very little is known about this highly localised species, currently only recognised from Shark Bay in Western Australia (D'Anastasi et al. 2016a). Similarly, *H. donaldi* is a recently described species, and has only been recorded within estuarine habitats of Weipa, northeast Gulf of Carpentaria (Ukuwela et al. 2012).

2. DISTRIBUTION OF SEA SNAKES WITHIN AUSTRALIAN WATERS

A significant challenge in conserving rare species, and managing threats to populations of conservation priority, is accurately identifying suitable habitats and distributions of populations (Hoffmann et al. 2008). Long-term monitoring datasets are key to understanding spatial distributions and population trends, however for rare species like some short-range endemic species of sea snake, this information is often lacking. Systematic sampling is the most reliable way of filling knowledge gaps relating to the spatial distribution of species. However, achieving adequate spatiotemporal replication over large geographical areas or in difficult to survey habitats is impractical and inefficient. Correlative models linking species presence records to a set of environmental characteristics of those locations (hereafter species distribution models; SDMs; Peterson et al. 2011) are a practical and efficient tool that can be used to inform data collection strategies (Jackson and Robertson 2011), improve estimates of species distributions (Gherghel et al. 2018) and identify suitable habitats (Guisan et al. 2006). When applied to understanding the distributions of rare or information-deficient species, SDMs can identify geographic regions that have similar habitats to those known to be occupied, but that have no known records (Maycock et al. 2012). These areas represent high priority targets for future survey efforts and for consideration when planning for conservation management.

2.1 Species habitat suitability modelling

2.1.1 Species occurrence records

We compiled occurrence records for sea snakes found within Australian waters from four sources: (a) Records of sea snake sightings from one national (The Atlas of Living Australia; www.ala.org.au) and one international (Reef Life Survey; www.reeflifesurvey.com) data repository, (b) snorkel, SCUBA and boat-based day and night-time surveys conducted by Hub researchers and project partners (collected between 2014 and 2017), (c) sightings on baited remote underwater video stations collected by the Australian Institute of Marine Science (BRUVs; collected between

1999 and 2016), and (d) fisheries-independent trawl bycatch data collected between 2016 and 2017 by Hub Researchers in collaboration with the Western Australian Department of Fisheries (Figure 1, Appendix 1). Each occurrence record was quality checked to remove duplicated records, suspect or imprecise data, and verify the identification of species where photographic or video records were available (i.e. BRUVs and fisheries data). Together, we assembled a total of 8,359 records from 27 species (Appendix 1). Confirmed sea snake sightings and occurrence data were used to construct species distribution models (SDMs) within the Australian Exclusive Economic Zone to assess the extent of occurrence of all sea snake species where sufficient data was available.

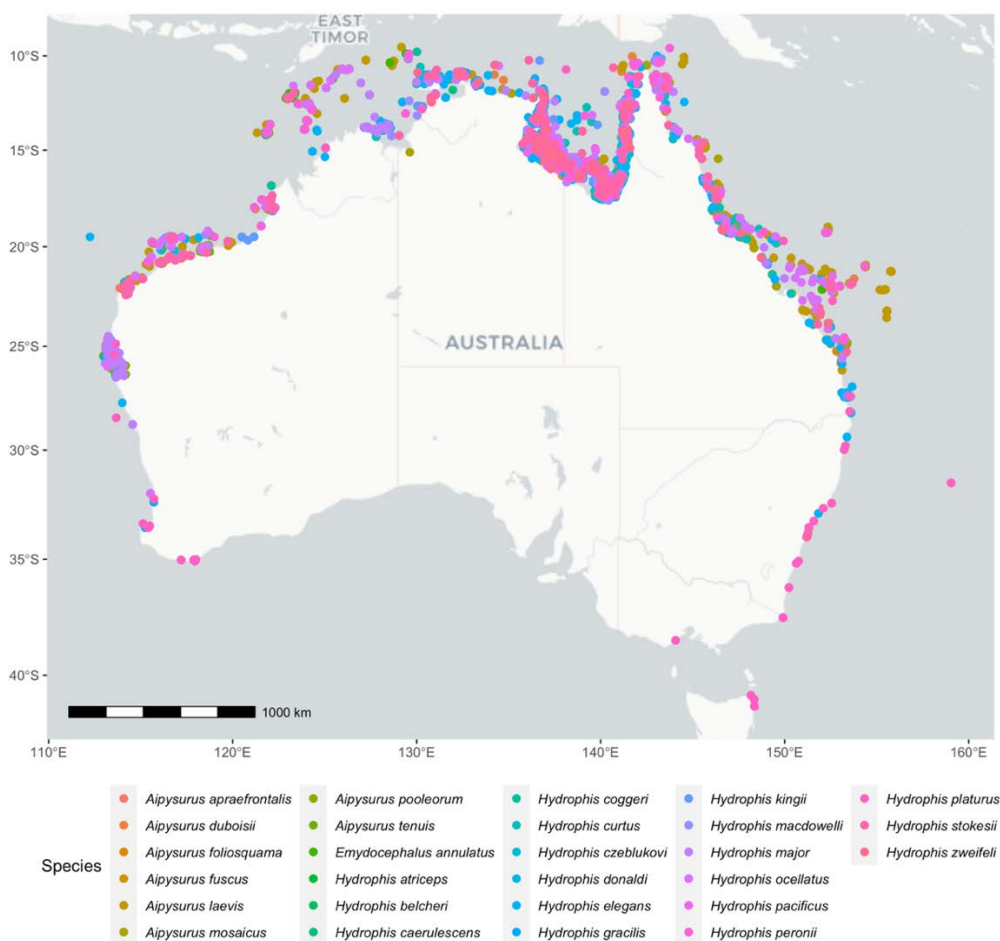


Figure 1. Locations of geo-referenced occurrences of 27 species of sea snakes used to build species distribution models. Data were run through a quality check by removing duplicated records, and potential misidentifications. Where video/photographs were available (i.e. BRUVs footage, fisheries photographs), these were used to verify occurrence records.

2.1.2 Environmental, biophysical and habitat variables

A wide array of climatic, habitat and geomorphological correlates were compiled to model species distributions within the Australian EEZ. Expert opinion and knowledge of sea snake ecology was used to make an *a priori* selection of 16 variables relating to oceanic climate, geophysical and habitat conditions (Table 1). Environmental data was standardised to the highest spatial resolution available (0.0083 degrees; 30 arc-seconds).

Table 1. Environmental, biophysical and habitat parameters used as covariates to model sea snake distribution.

Environmental Variable	Variable name	Source	Range	Mean \pm SD
<i>Oceanic climatic variables</i>				
Mean annual sea surface temperature ($^{\circ}$ C)	sst_mean	AODN	9.9 – 28.8	21.7 \pm 0.5
Mean sea surface temperature during coldest month ($^{\circ}$ C)	sst_cold_mnth	AODN	-1.7 – 26.7	19.3 \pm 5.1
Mean sea surface temperature during warmest month ($^{\circ}$ C)	sst_warm_mnth	AODN	11.1 – 32.1	24.1 \pm 5.0
Mean annual salinity (psu)	sal_mean	AODN	33.9 – 36.3	35.2 \pm 0.4
Mean salinity during wettest month (psu)	sal_fresh_mnth	AODN	32.2 – 36.1	34.9 \pm 0.6
Mean salinity during driest month (psu)	sal_salt_mnth	AODN	34.7 – 36.1	35.4 \pm 0.2
<i>Seabed geomorphology</i>				
Proportion of gravel substrate (%)	gravel	GA	0 – 88.1	7.4 \pm 7.7
Proportion of mud substrate (%)	mud	GA	0 – 99.1	50.3 \pm 26.3
Proportion of sand substrate (%)	sand	GA	0.8 – 100	42.1 \pm 22.6
<i>Seabed topography</i>				
Bathymetry (m)	bathy	GA	0 – 6878	2309.1 \pm 1996.7
<i>Habitat variables</i>				
Proximity to the coast (km)	dist_to_land	Calculated from GeoData Coast 100K	1 – 616	210.9 \pm 140.7
Proximity to reef systems (km)	dist_to_reef	Calculated from Seamap habitat layer	0 – 16855	444.9 \pm 469.1
Proximity to seagrass habitats (km)	dist_to_seagrass	Calculated from Seamap habitat layer	0 – 940.5	212.1 \pm 183.1
Proximity to mangrove habitats (km)	dist_to_mangrove	Calculated from Seamap habitat layer	0 – 1124.0	367.6 \pm 250.2
<i>Geographic position</i>				
Longitude	lon		109.23 – 163.18	
Latitude	lat		-8.88 – -47.18	

Note: Data were sourced at 30 arc-second resolutions from the Australian Ocean Data Network (AODN; <http://portal.aodn.org.au/>), Geosciences Australia (GA; <https://www.ga.gov.au/data-pubs>) or calculated using habitat distribution spatial layers from Seamap Australia (<https://seamapaustralia.org>).

2.1.3 Modelling framework

A correlative modelling approach was used to identify suitable habitats for each species using maximum entropy modelling (MaxEnt [version 3.4.1]; Phillips et al. 2006). Sufficient occurrence data was available for 23 out of the 27 species to produce suitability models. For these 23 species models, the default settings were used for fitting models. Correlative modelling is subject to biases from ‘*ad hoc*’ sampling (e.g. some museum records or opportunistic sightings), and 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 projection (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. This bias grid was used for selecting pseudo-absence points from within the model space.

The background used to generate pseudo-absences for all models was defined to within the Australian EEZ. 10,000 pseudo-absence points were randomly selected at the same spatial density as the bias grid for each species model. Model projections 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 Development Core Team 2019). Model tuning was undertaken using the ‘*ENMeval*’ R package (Muscarella et al. 2014), which undertakes a maximum likelihood process to estimate ideal hyperparameters for models.

2.1.4 Model evaluation and influence of environmental covariates

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 background points. An AUC score ranges between 0 and 1, where a score of 0 represents a complete mismatch between the model projection and actual occurrence data, while a score of 1 represents a perfect alignment between the projection and occurrence data. The true skill statistic (TSS) accounts for both model omission and commission 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). AUC and TSS scores across all species models were high (> 80) indicating all model projections matched well with the occurrence records for species on which they were trained (Table 2). Variable contributions were used to identify key environmental covariates that influence species-specific habitat suitability. Bathymetry, distance to reef systems and water temperatures contributed significantly to most species models overall (Figure 2).

A more detailed assessment of habitat suitability, distributions and effectiveness of current Marine Protected Areas has been conducted for a subset of short-range endemic species of high conservation priority within the North-west Shelf (*Aipysurus apraefrontalis*, *A. foliosquama*, *A. fuscus*, *A. pooleorum*, *A. tenuis*), with follow up field validation conducted as part of this project by Hub Researchers and collaborators in Udyawer et al. (2020).

Table 2. Summary table of model evaluation scores including the area under the receiver operating curve (AUC) and true skill statistic (TSS). AUC scores range between 0 and 1, where a score of 0 represents a complete mismatch between the model projection and actual occurrence data, while a score of 1 represents a perfect alignment between the projection and occurrence data. The true skill statistic (TSS) ranges from -1 to +1, where +1 indicates perfect agreement and values of zero or less indicate a performance no better than random

Common Name	Species	AUC	TSS
Short-nosed sea snake	<i>Aipysurus apraefrontalis</i>	0.867	0.904
Reef-shallows sea snake	<i>Aipysurus duboisii</i>	0.978	0.855
Leaf-scaled sea snake	<i>Aipysurus foliosquama</i>	0.989	0.969
Dusky sea snake	<i>Aipysurus fuscus</i>	0.943	0.999
Olive sea snake	<i>Aipysurus laevis</i>	0.981	0.885
Mosaic sea snake	<i>Aipysurus mosaicus</i>	0.991	0.918
Shark Bay sea snake	<i>Aipysurus pooleorum</i>	0.999	0.977
Brown-lined sea snake	<i>Aipysurus tenuis</i>	0.934	0.959
Turtle-headed sea snake	<i>Emydocephalus annulatus</i>	0.993	0.914
Dwarf sea snake	<i>Hydrophis caeruleus</i>	0.999	0.988
Slender-necked sea snake	<i>Hydrophis coggeri</i>	0.981	0.881
Spine-bellied sea snake	<i>Hydrophis curtus</i>	0.993	0.941
Geometric sea snake	<i>Hydrophis czelbukovi</i>	0.996	0.995
Elegant sea snake	<i>Hydrophis elegans</i>	0.987	0.906
Spectacled sea snake	<i>Hydrophis kingii</i>	0.991	0.935
Small-headed sea snake	<i>Hydrophis macdowellii</i>	0.987	0.881
Greater sea snake	<i>Hydrophis major</i>	0.987	0.898
Spotted sea snake	<i>Hydrophis ocellatus</i>	0.982	0.879
Large-headed sea snake	<i>Hydrophis pacificus</i>	0.999	0.983
Horned sea snake	<i>Hydrophis peronii</i>	0.983	0.881
Yellow-bellied sea snake	<i>Hydrophis platurus</i>	0.979	0.843
Stokes' sea snake	<i>Hydrophis stokesii</i>	0.986	0.896
Beaked sea snake	<i>Hydrophis zweifeli</i>	0.986	0.911

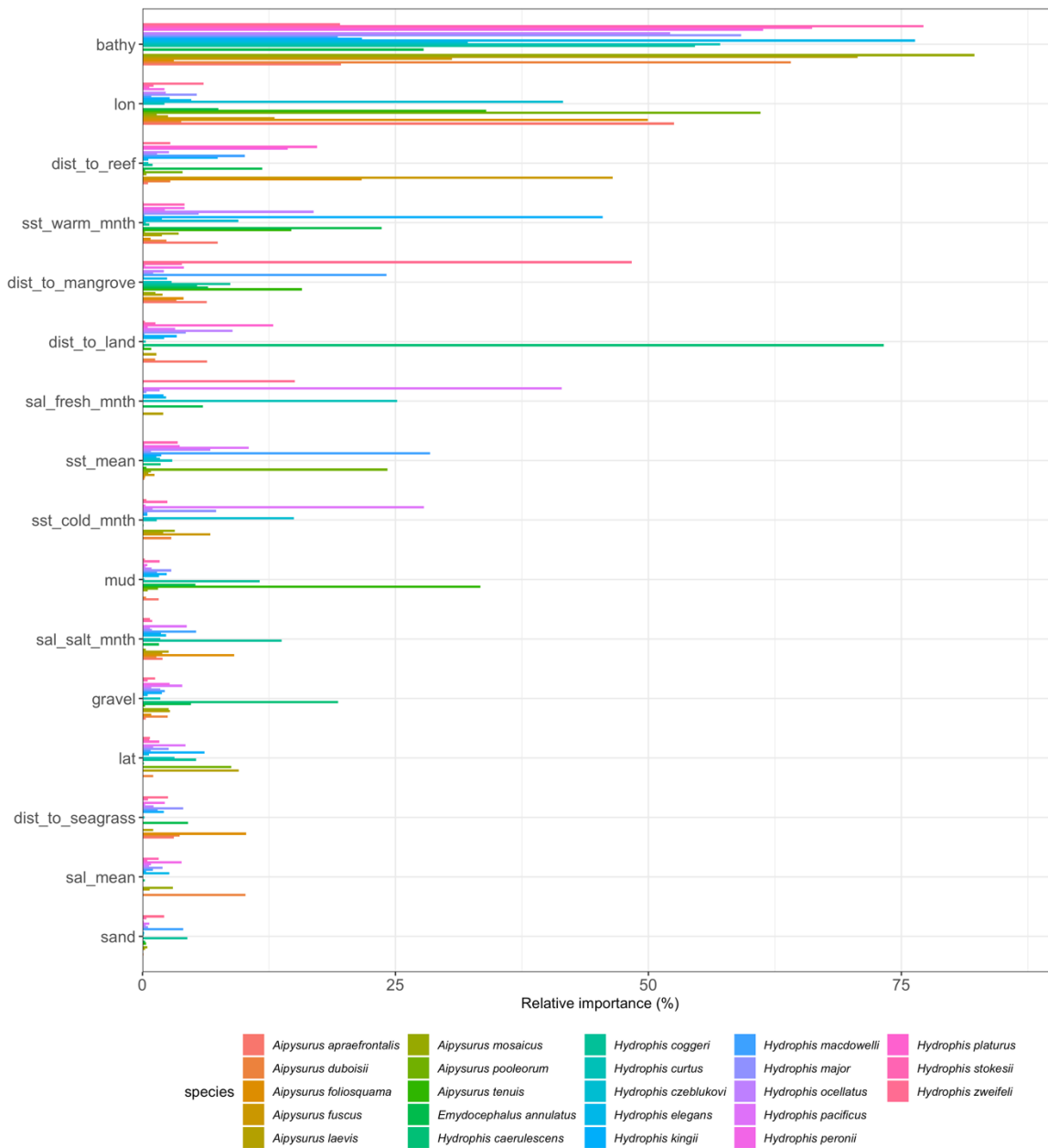


Figure 2. Summary of the relative variable contribution for each environmental variable used in optimal MaxEnt model for each of the 23 species for which sufficient data was available. Variable contribution was calculated for each tuned model. Variable on the y-axis are ranked in decreasing order based on average overall variable importance across all species models.

2.1.5 Identification of suitable habitats

To quantify ‘suitable’ and ‘unsuitable’ habitats, thresholds are often applied to model outputs to simplify continuous outputs into binary maps, which often aids in validating and interpreting SDMs (Peterson et al. 2011). We defined the threshold level as the lowest predicted value associated with any of the occurrence records, also known as the ‘lowest presence threshold’ (LPT; Pearson et al. 2007). This threshold is considered a conservative estimate of a species’ tolerance to each environmental variable and can provide an ecological basis to habitat suitability (Peterson et al. 2011). We created binary maps to identify suitable habitat based on this threshold value. A complete record of all species model outputs are provided as Appendix 1.

2.2 Identifying hotspots of sea snake biodiversity and endemism

A spatially explicit species assemblage modelling framework was utilised to quantify indices of species diversity (α -diversity) and endemism (Schmitt et al. 2017). Individual species-specific continuous predictions were used to calculate an index of species diversity using a probability stacked species distribution model (pSSDM). This consisted of a simplified index of summing the continuous species-specific habitat suitability model predictions across the Australian EEZ model space. Regions with larger diversity indices indicated regions suitable to more sea snake species and are likely to support a larger local diversity of species (Figure 3a). In addition to species diversity, habitat suitability outputs were used to calculate an index of local species endemism. The Weighted Endemism Index (WEI) was calculated for each pixel (c) within the model space (30 arc-second resolution within the Australian EEZ), by summing the inverse of the geographical range size (r_i) for each species (n) using the formula (Schmitt et al. 2017):

$$WEI_c = \sum_{i=1}^{n_c} \frac{1}{r_{i,c}}$$

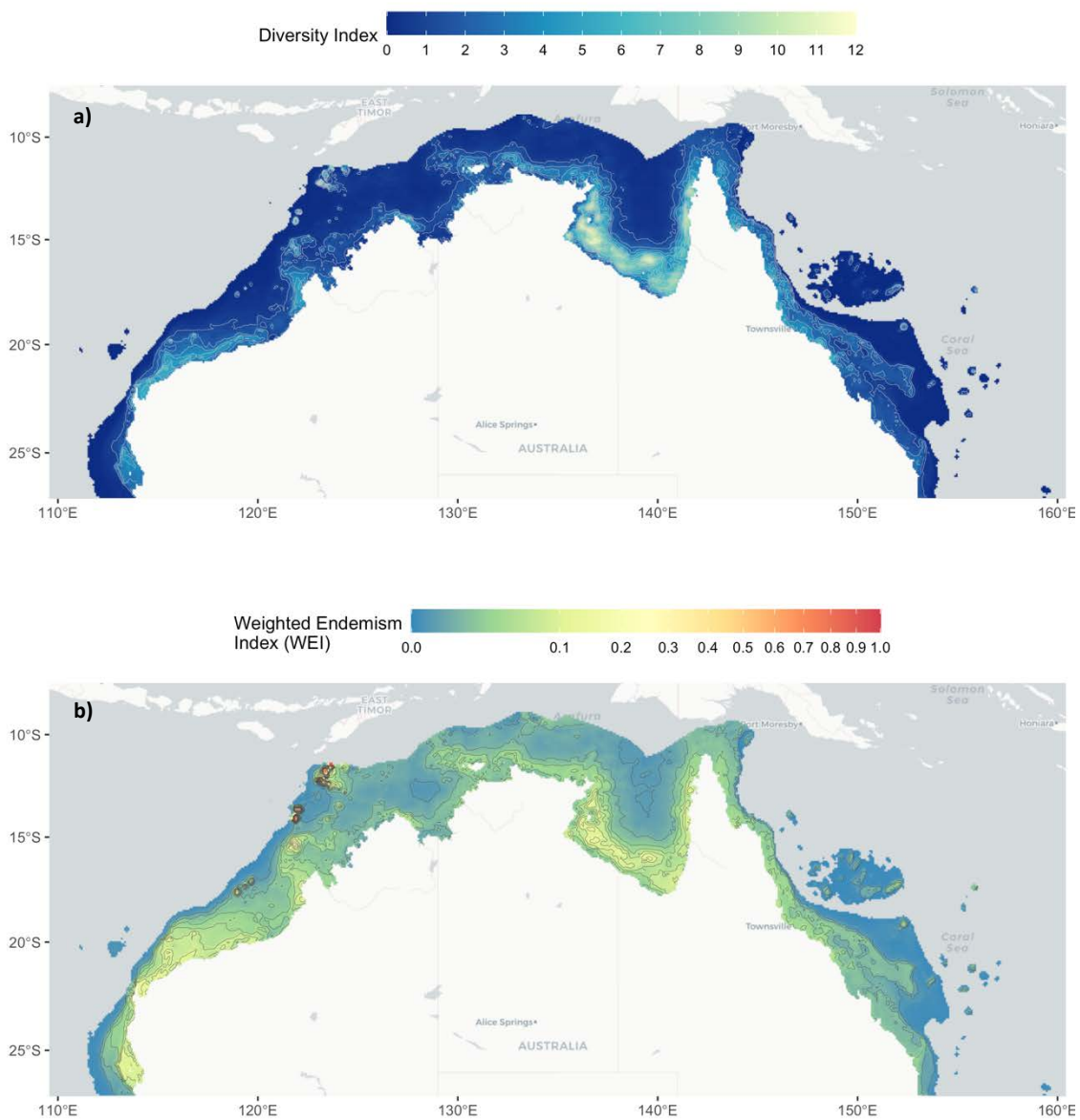


Figure 3. Spatially explicit species diversity (a) and endemism (b) maps for sea snake species across Northern Australia, within the Australian EEZ and in regions shallower than 1000 m. Note the colour scale in panel b is log scaled to highlight regions of high WEI within the North-west Shelf.

2.2.1 Diversity and Endemism of sea snakes within Marine Protected Areas

Spatial outputs of sea snake species diversity and endemism were intersected with two types of marine spatial planning units; i) Marine Protected areas; including Australian Marine Parks (AMPs) managed by Parks Australia and the Great Barrier Reef Marine Park (GBRMP) managed by the Great Barrier Reef Marine Park Authority, as well as ii) currently declared Indigenous Protected Areas (IPAs) managed by seven Indigenous Land Councils across Western Australia (Nyangumarta Warram and Yawuru), Northern Territory (Dhimurru and Anindilyakwa) and Queensland (Thuwathu/Bujimulla, Eastern Kuku Yalanji and Giringun). This assessment identified regions under federal and regional/local management that contained high diversity of sea snake species, or protected areas that have highly endemic species (Figure 4).

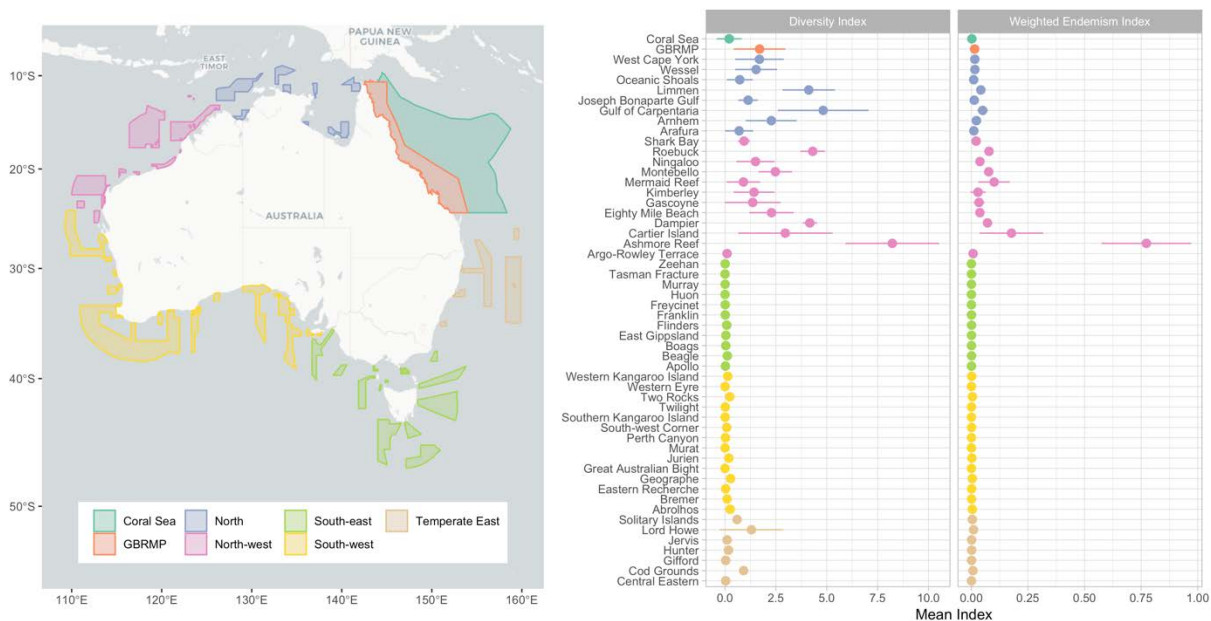


Figure 4. Diversity and endemism index of sea snake species within Marine Protected Areas (left panel) identified the North and North-west networks to have the highest diversity and endemism (right panels). Points in the right panel represent mean index values within AMPs, with error bars representing standard error of index values. Ashmore Reef Marine Park in the North-west network, and Gulf of Carpentaria Marine Park in the North network had the highest levels of species diversity and endemism.

The North-west and North networks were Parks with the highest rates of sea snake diversity and endemism. Ashmore Reef Marine Park was highlighted as the Park with the highest diversity and endemism index as the assessment included occurrences of sea snakes before the declines recorded at this location (Guinea 2013; Lukoschek et al. 2013), with low sea snake sighting rates from recent surveys (i.e. CSIRO Ashmore Reef Survey 2019; Somaweera et al. in review). Therefore, it is likely that the level of endemism and diversity has drastically reduced at Ashmore Reef Marine Park in light of recorded extirpation events of multiple species, and subsequent low numbers of individuals sighted in recent surveys (Guinea 2013; Somaweera et al. in review).

The overlap between sea snake diversity and endemism maps with declared IPAs highlighted that sea country within the Anindilyakwa IPA in the Northern Territory had the highest levels of sea snake diversity and endemism, with Thuwathu/Bujimulla and Dhimurru IPAs also displaying high levels of diversity within the Gulf of Carpentaria (Figure 5). The Yawuru IPA within Roebuck Bay was also highlighted as a region with high sea snake endemism in Western Australia. Hub Researchers worked with the Anindilyakwa Land and Sea Rangers to conduct preliminary surveys within the Anindilyakwa IPA to obtain additional information on sea snake assemblages within the western Gulf of Carpentaria, and is discussed in section 3.3 of this report.



Figure 5. Diversity and endemism index of sea snake species with declared Indigenous Protected Areas (left panel) identified that sea country within the Gulf of Carpentaria, and within Roebuck Bay had high levels of sea snake diversity and endemism (right panels). Points in right panel represent mean index values within IPAs, with error bars representing standard error of index values.

3. SEA SNAKE INTERACTIONS WITH FISHERIES IN NORTHERN AUSTRALIA

Sea snakes are vulnerable to capture in trawl fisheries and represent a large component of bycatch in the trawl sector across Australia (Wassenberg et al. 2001; Zhou et al. 2012). Interactions with fishing activity remain a critical concern for sea snake populations in Australian waters (Milton et al. 2009), however species-specific assessments have been limited across the different trawl sectors across Northern Australia. Hub Researchers compiled data from fisheries observer programs and used modelled habitat suitability to conduct a high-level assessment of exposure to fishing pressures across the North-west and North marine region.

3.1 Fishing effort information

Spatial information on fishing effort was obtained from two sources; i) the Automatic Identification System (AIS) data from vessels flagged as ‘fishing’ vessels within the Australian EEZ stored by the Australian Maritime Safety Authority on the Craft Tracking System (<https://www.operations.amsa.gov.au/Spatial/DataServices/DigitalData>), and ii) the Global Fishing Watch (<https://globalfishingwatch.org>). Where recorded, tracks from vessels associated with trawl or squid-jiggers were retained for the spatial analysis as these gear types have the highest interaction with sea snakes. Gear type information was not available for AIS data from the AMSA Craft Tracking System, therefore only tracks from known trawl fishing grounds were included (i.e. Gulf of Carpentaria, Shark Bay, Exmouth Gulf). AIS data for fishing vessels prior to 2012, and within Queensland waters was sparse, and likely represented an incomplete dataset available from these open access databases, therefore this spatial analysis was restricted to the North-west and Northern marine region between 2012 – 2016 where fishing effort data was most complete.

Tracks were gridded to the same spatial resolution as the sea snake habitat suitability spatial outputs. AIS data was used to estimate mean fishing hours for each raster pixel based on the estimation method by Kroodsma et al. (2018). Briefly, yearly AIS data was binned to the same grid resolution of the sea snake habitat models

(0.0083 degrees; 30 arc-seconds), with time associated to each AIS detection; i.e. time between consecutive positions within each grid plus half the time to the next AIS position if it fell in another grid. To obtain an overall effort raster, estimated fishing time was summed across all tracks per year, and then averaged across the five years for which reliable data was available (Figure 6).

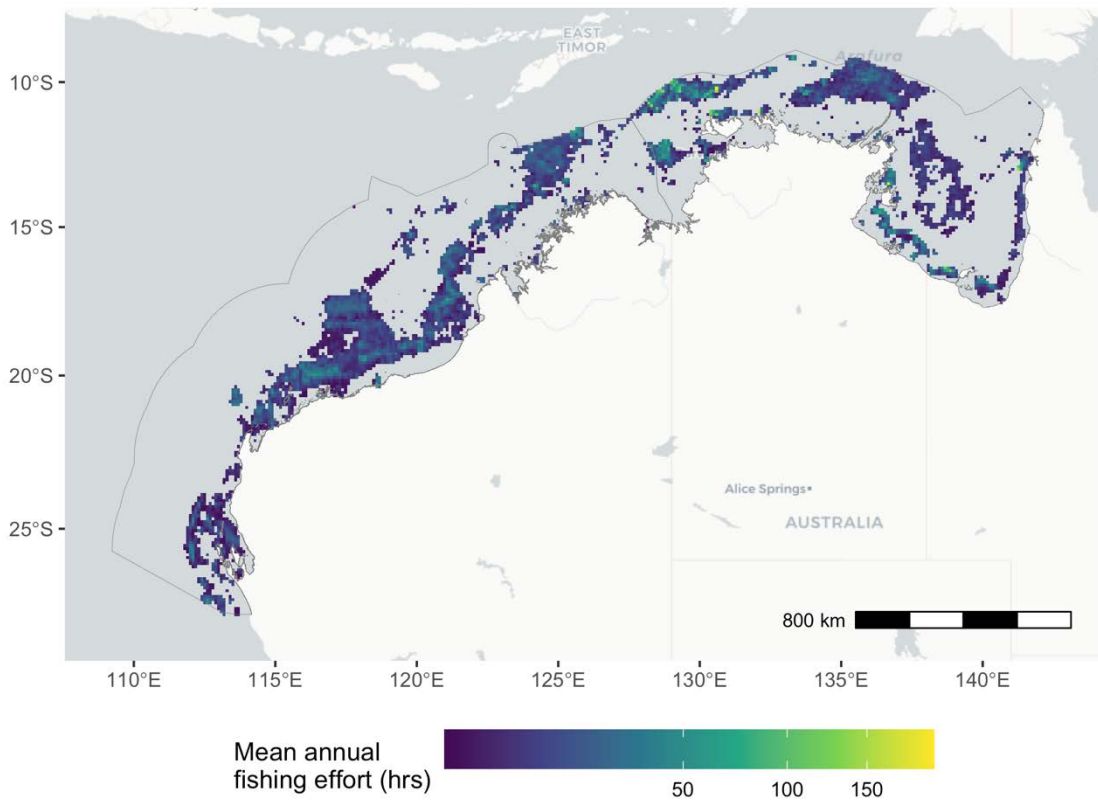


Figure 6. Estimated mean annual fishing effort in hours between 2012 – 2016 within the North-west and Northern marine region. Annual fishing effort was estimated using AIS data from the AMSA Craft Tracking System and Global Fishing Watch datasets. Note colour bar on the bottom is log scaled to highlight regions with high mean annual fishing effort.

A spatially explicit co-occurrence index (coined here as Fishing Exposure Index; FEI) between fishing effort and habitat suitability was estimated to identify locations where habitats suitable for sea snakes are likely exposed to fishing efforts. The FEI was calculated for each species of sea snake using indices of co-occurrence modified from Queiroz et al. (2019) within the North-western and Northern marine region. Briefly, FEI was calculated for each pixel within the model space by adding the number of hours of fishing effort within each raster pixel (normalised to between 0 and 1), with the modelled projection of habitat suitability (between 0 and 1) above the lowest presence threshold (LPT) for each species, then dividing by 2. This produced a FEI that ranged between 0 and 1 with indices of 1 indicating complete overlap of highly suitable habitats to high levels of fishing effort, and 0 indicating no overlap at all. FEI outputs were averaged across all species to produce an overall fishing exposure map indicating regions with high overlap between fishing activity and suitable habitats for sea snake species (Figure 7).

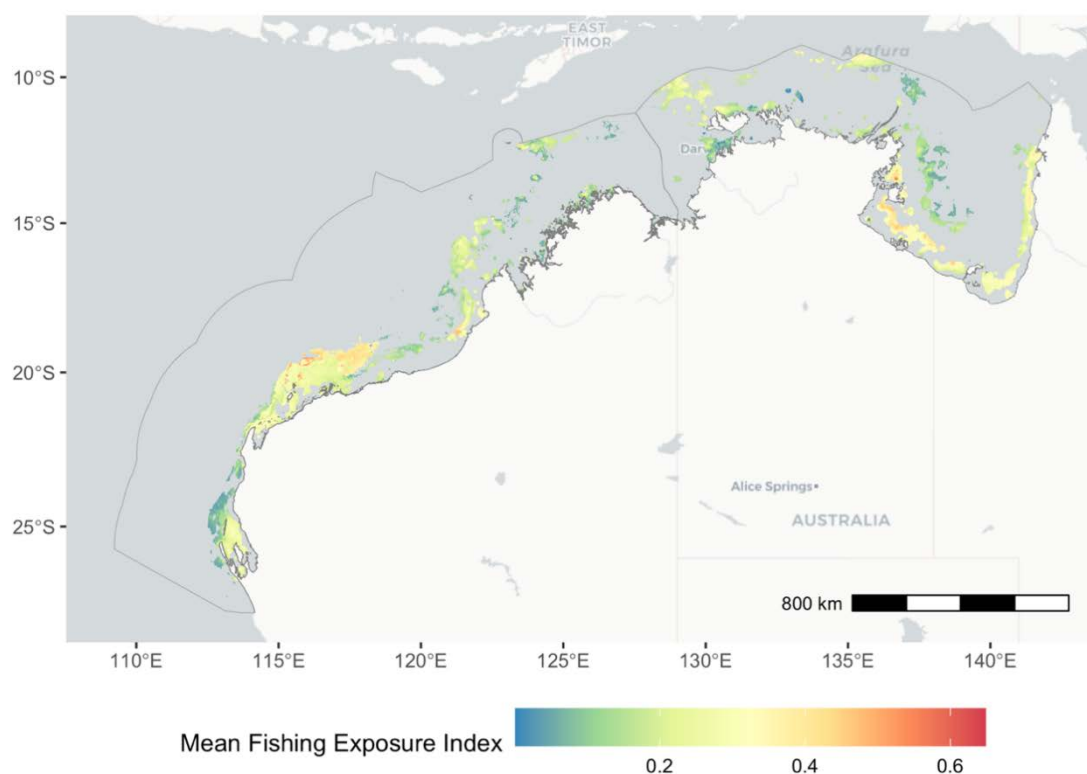


Figure 7. Mean Fishing Exposure Index across 23 species of sea snake highlighting regions with high fishing exposure of sea snakes to trawl fishing effort within the Australian EEZ.

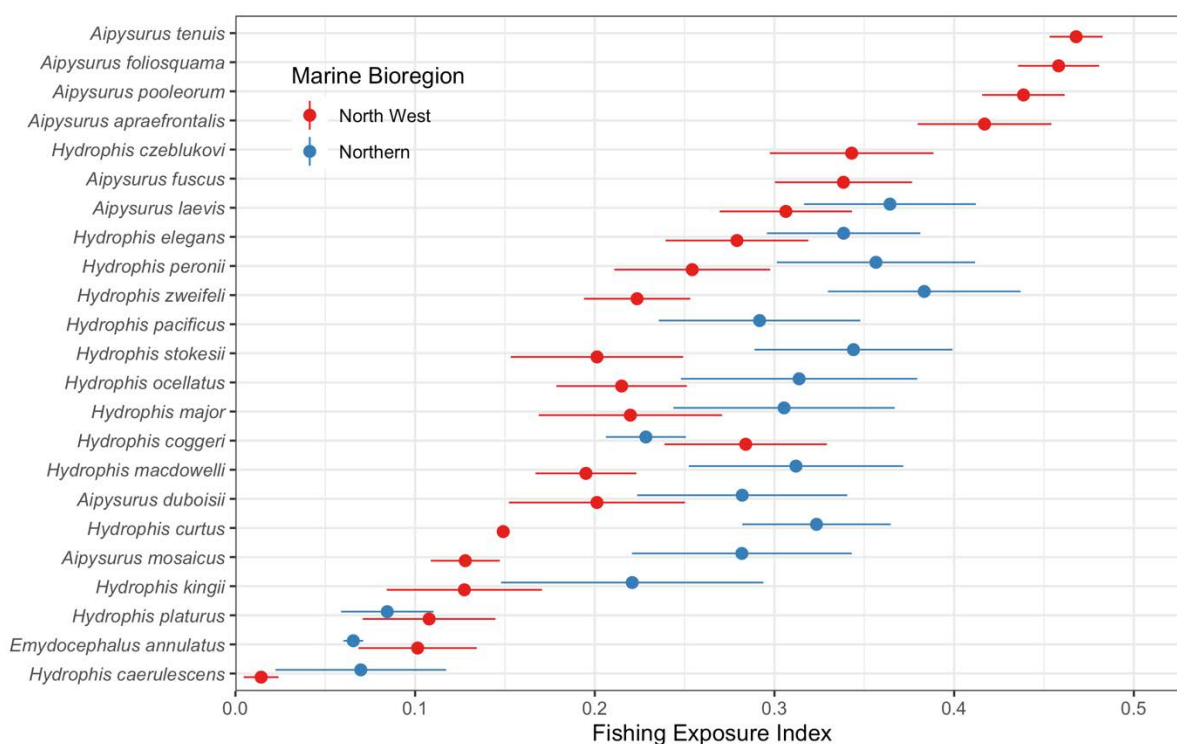


Figure 8. Mean and standard error of species-level fishing exposure index within the North-west and North marine region, highlighting high exposure indices for species with restricted ranges that fall entirely within highly productive trawl grounds within the Pilbara, Shark Bay and Exmouth Gulf regions.

FEI outputs were also used to assess overlap of fishing activities to species-specific suitable habitats within each of the marine regions (Figure 8). Regional and species-level FEI indicated short-range species on the West coast that have highly suitable habitats within known fishing grounds (i.e. *A. tenuis*, *A. foliosquama*, *A. pooleorum*) were likely to have higher exposure to coastal trawl fishing. Within the Northern marine region, species that had highly suitable habitats within the Gulf of Carpentaria displayed high exposure to fishing efforts, and represented species that are known to frequently occur as bycatch within the Northern Prawn Fishery (e.g. *A. laevis*, *H. elegans*, *H. stokesii*, *H. peronii*; Milton 2001). FEI calculated here does not incorporate measures of interaction rates and mortality with each fishing sector as this data was not recorded or available at species levels across all fisheries. Nevertheless, patterns in FEI calculated here broadly show similar patterns in regional fisheries assessments (Milton 2001; Zhou et al. 2012).

3.2 Species assemblages and interactions rates with fisheries on the North West Shelf

Sea snake interaction was used to conduct a preliminary assessment of species-specific interaction rates within four coastal areas of Western Australia; Shark Bay, Exmouth Gulf, Pilbara and the Kimberley (Figure 9). Data used in this assessment were collected by the scientific observer program of the Western Australian Department of Fisheries (WA DoF) in collaboration with Hub Researchers on the RV Naturalist between 2014 and 2018. Surveys consisted of research trawls conducted within trawl fishing grounds within Shark Bay (118 trawls between 20 – 60 min), Exmouth Gulf (34 trawls between 15 – 150 min), Pilbara region between Onslow and Broome (96 trawls between 10 – 120 min), and the Kimberley region north of Broome (73 trawls between 20 – 60 min). Sea snakes captured in these surveys were photographed and identified to species level and live snakes were released in healthy condition. Data were used to assess the assemblage of snakes encountered in these surveys and conduct a preliminary assessment on survival of sea snakes that interact with trawl gear within these four broad coastal regions.

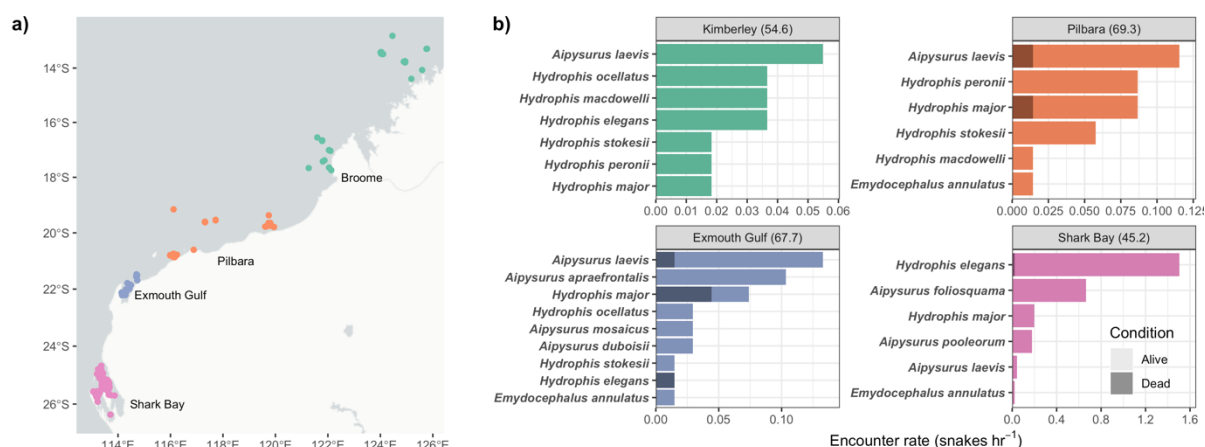


Figure 9. (a) Map of locations of trawl surveys conducted on the RV Naturaliste where sea snakes were captured within the four broad regions. (b) Species-specific encounter rates and condition of sea snakes within the four broad regions with total duration of trawls conducted (hrs) in parentheses in graph titles.

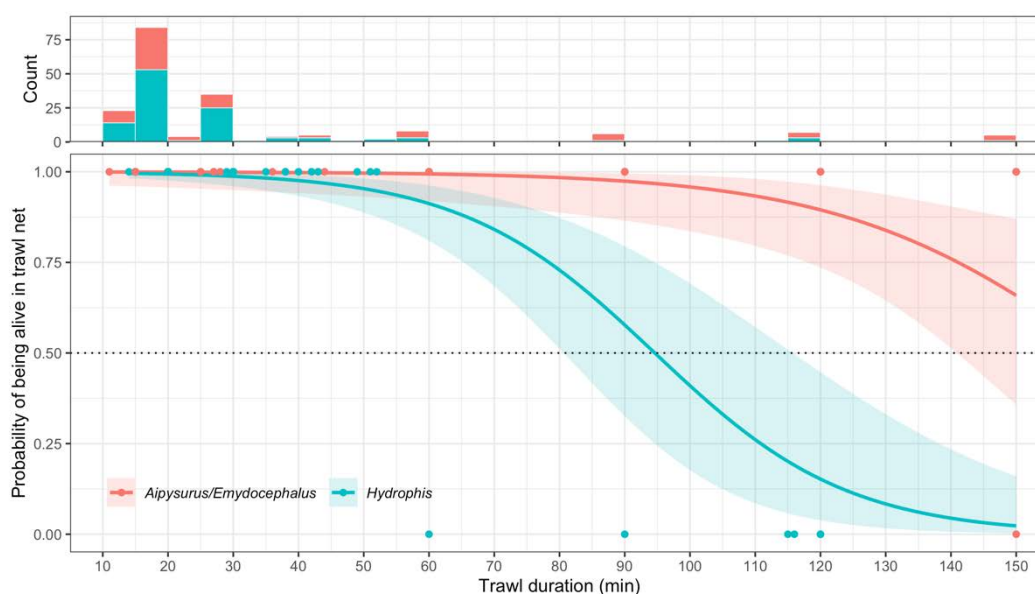


Figure 10. Survivorship curves for sea snakes encountered in trawl surveys broken down into the two main lineages (*Aipysurus/Emydocephalus* and *Hydrophis*). Species and regional level analyses was not possible due to limited regional and species-specific data. Histogram on the top highlights the counts of snakes within the two main lineages encountered across the full range of trawl duration.

Catch composition across all four regions highlighted that sea snakes are encountered in relatively low numbers, with the highest encounter rates of sea snakes within Shark Bay (Figure 9b). The two currently classified Critically Endangered species (*A. foliosquama* and *A. apraefrontalis*) were encountered within Shark Bay and Exmouth Gulf, respectively. Sea snake catch across all four regions was low despite longer trawls (> 60 min trawl duration) conducted in Exmouth Gulf and Pilbara regions. Relatively short trawls within Shark Bay (~20 min) yielded relatively high numbers of sea snakes (Figure 9).

Survivorship curves were constructed using a binomial logistic regression examining whether trawl duration influenced whether sea snakes were alive or dead upon landing on deck (Figure 10). Survivorship curves were constructed for both lineages of sea snakes (*Aipysurus/Emydocephalus* and *Hydrophis*), however sufficient data was not available to create species-specific or region-specific curves. The logistic regression showed that sea snakes in general had high rates of pre-release survival regardless of trawl duration, indicating that overall, snakes

encountered in these surveys were robust to short – moderate durations of trawls. Lineage-specific curves identified that the larger *Hydrophis* species (i.e. *Hydrophis elegans*, *H. major*; Figure 9b) were likely to be encountered dead in trawl nets in trawls longer than ~90 min (Figure 10), whereas *Aipysurus/Emydocephalus* species were comparatively more robust across the full range of trawl durations. Similar assessments within the Northern Prawn Fishery (Milton et al. 2008) and Queensland Trawl Fishery (Pears et al. 2012) have identified larger-bodied species within the *Hydrophis* genus (e.g. *H. pacificus*, *H. elegans*) to be highly susceptible to capture and mortality in nets.

Post-capture survival in sea snakes is variable among sea snake species and fishing practices, with most species encountered in commercial trawl fisheries within Australian waters displaying high short and long-term survival post capture (Milton et al. 2008; Wassenberg et al. 2001). However, sea snakes with larger body size (e.g. *H. elegans*, *H. stokesii*, *A. laevis*, and gravid females), and or less frequent reproduction (e.g. *A. laevis* and *H. elegans*, reproducing every 2 to 3 years) are likely to have higher susceptibility to capture and mortality in trawl and trap fisheries (Courtney et al. 2010).

3.3 Assemblage of sea snakes within coastal protected areas within the Gulf of Carpentaria

The Gulf of Carpentaria was identified as a region with high diversity of sea snakes (Figure 3a), and a region with high exposure to fishing impacts (Figure 7). This region is a highly productive trawl fishing ground, with high seasonal sea snake bycatch rates within the Northern Prawn Fishery (NPF) (Fry et al. 2018). Coastal areas protected from trawl activities can provide refugia to populations of sea snakes that interact with trawl fisheries (Udyawer et al. 2016). This project collaborated with the Anindilyakwa Land and Sea Rangers to collect preliminary survey data for sea snakes using opportunistic boat-based field surveys, and recorded sea snakes encountered during beach activities conducted by the Rangers (Figure 11). Diversity and endemism models identified the sea country of the Anindilyakwa Indigenous

Protected Area (IPA), in coastal waters of Groote Eylandt, as an important region for sea snakes (Figure 12).



Figure 11. Sea snakes recorded within the Anindilyakwa IPA by the Anindilyakwa Land and Sea Rangers during beach activities and during on-water activities. (Photo Credit: Katie Oxenham, Jeff Paul, Keith Lambert)

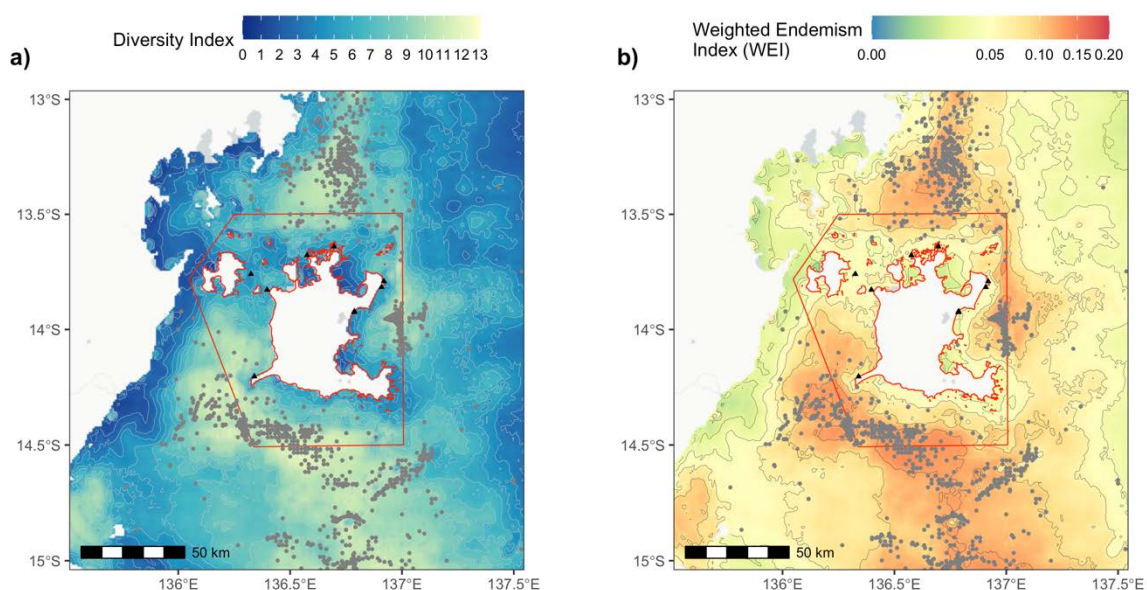


Figure 12. Distribution of records of sea snakes within the Anindilyakwa Indigenous Protected Area (IPA; red boundary), with maps highlighting the high diversity (a) and relative weighted endemism (b) of sea snakes in surrounding waters of the IPA. Black triangles represent coastal records of sea snakes recorded by the Anindilyakwa Land and Sea Rangers during marine operations and from sightings recorded by the Rangers and other Groote Eylandt residents on the Australian Sea Snakes page (<https://www.facebook.com/groups/australianseasnakes>). Grey points represent records from the Atlas of Living Australia and records from the NPF scientific observer program (Milton et al. 2008).

Occurrence records around Groote Eylandt and elsewhere in the Anindilyakwa IPA collected from the Anindilyakwa Land and Sea Rangers were compiled with other sources where species ID were verified (i.e. Atlas of Living Australia, NT Maps, community sighting records; <https://www.facebook.com/groups/australianseasnakes>) to assess the assemblage of sea snakes encountered within the Anindilyakwa IPA (Figure 13). The assemblage of sea snakes recorded within the IPA reflect commonly encountered species in adjacent fishing grounds (Fry et al. 2018). Species commonly encountered included *Hydrophis elegans*, *H. major*, *H. stokesii*, *Aipysurus laevis*, *A. mosaicus*. The movement and residence of these species in shallow habitats within the IPA may provide some protection from trawl interactions in the highly productive fishing grounds within and adjacent to the Anindilyakwa IPA. Future work in this region can utilise the baseline assemblage datasets and assess residency and movement patterns of sea snakes between those found within the IPA and those that interact with the NPF through a coordinated mark-recapture program, or through animal tracking studies. Understanding how vulnerable sea snake species use shallow habitats within the Gulf of Carpentaria, like IPAs and other marine protected areas (e.g. Marine Parks, AMPs) that have restricted trawl fishing activity, can help assess the impacts of the large bycatch rates of sea snakes on populations within the Gulf of Carpentaria (Udyawer et al. 2016). The data collected within this region highlight the importance of strong protections and limitations on fishing efforts within IPAs, that allow vulnerable species like sea snakes to recover from high interactions in adjacent trawl fishing grounds.

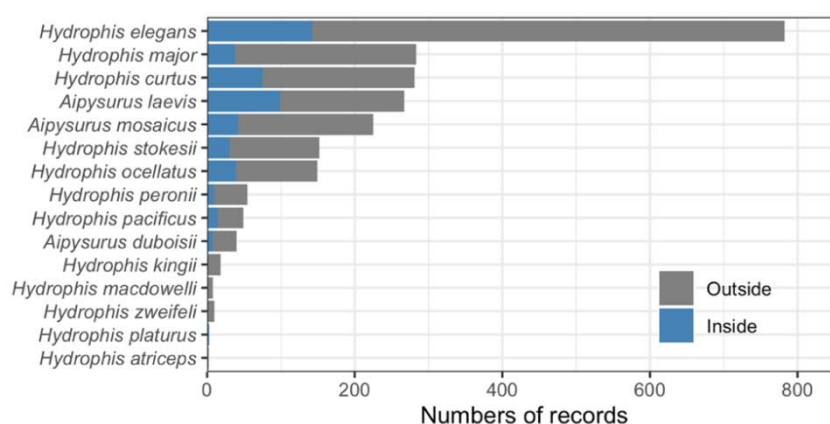


Figure 13. Assemblage of sea snakes recorded within and adjacent to the Anindilyakwa IPA.

4. CONCLUSIONS AND RECOMMENDATIONS

At an EEZ level the habitat suitability modelling highlighted baseline hotspots of species diversity and endemism within the North-west Shelf and western Gulf of Carpentaria. Local extirpation events and localised declines of sea snake populations in key locations along the North-west Shelf (i.e. Ashmore Reef Marine Park; Lukoschek et al. 2013) has highlighted the need for re-assessment of endemic species found in this region. The assessment of fishing exposure indicated regions within the western Gulf of Carpentaria, and areas along the Pilbara coastline that displayed significant co-occurrence of suitable habitat with high trawl fisheries effort. Trawl survey information from four regions across the Western Australian coastline highlighted that although sea snakes were captured in relatively short trawls within key fishing grounds like Shark Bay and Exmouth Gulf, they displayed a high survival rate in trawl nets. Larger-bodied species in the *Hydrophis* lineage (e.g. *H. elegans*, *H. major*) are likely to be more susceptible to mortality within trawl nets, however further research on post-release mortality, and re-capture rates within confined fishing grounds (e.g. Shark Bay, Exmouth Gulf) is required to assess population level, and long-term impacts of high bycatch rates. Although not tested in the present study, there is likely a significant influence of trawl gear type used, and application of bycatch reduction devices, to the catchability of sea snakes within these regional fisheries (Chandrapavan et al. 2012; Milton et al. 2009). Assessment of trawl bycatch indicate fewer snakes reported in the Pilbara fish trawl fishery and Shark Bay scallop fishery relative to the prawn trawls, which are likely due to differences in the gear selectivity/mesh size used within the different fisheries sectors (Evans and Molony 2010; Wassenberg et al. 2001).

The following section provides a summary of key recommendations to assist in updating conservation status of species currently listed as Critically Endangered under the EPBC Act (i.e. *Aipysurus apraefrontalis*, *A. foliosquama*), and species identified as conservation priority (i.e. *A. fuscus*). These recommendations are made based on the information on distribution, exposure to fishing pressures, and fisheries interactions generated in this project.

***Aipysurus apraefrontalis* (Short-nosed sea snake)** – This species was previously only known from Ashmore and Hibernia Reefs in the North West Shelf (Cogger 1975). This species is now considered locally extinct at Ashmore and Hibernia Reefs based on regular surveys not sighting this species in those locations since 2001 (Guinea 2013; Lukoschek et al. 2013). Recent surveys and genetic analyses have identified resident populations within coastal locations between Exmouth Gulf and Broome (D'Anastasi et al. 2016b; Lukoschek 2018; Sanders et al. 2015). The present project utilised habitat suitability models to refine the distributions of this species, and predicted locations around Exmouth Gulf, Barrow and Montebello Islands, and coastal areas North of Broome as highly suitable coastal habitats for this species.

Spatial analysis of habitat suitability identified 10% of suitable habitats are protected in current MPA networks along the west coast, with an additional 16% within multi-use areas under limited protection (Udyawer et al. 2020). Based on habitat suitability models and spatial patterns in fishing effort within the North-west marine region, this species has a potentially high exposure to trawl fisheries (Figure 7), and comprise a significant proportion of the sea snake bycatch species within the Exmouth Gulf sector (Figure 9b). Survival analysis for this lineage highlights that although this species interacts with trawl gear frequently, this species is highly robust to short – medium length trawls (Figure 10). Post-release survival and recapture rates of individuals within enclosed areas like Exmouth Gulf are currently unknown, and further long-term data is required to ascertain any long-term impacts of fishing activities to the newly discovered coastal populations. However, given the presence of the trawl fishery within Exmouth Gulf for more than 50 years, the current status is likely to represent the population in its affected state.

Based on the yet unknown causes of extirpation of this species at Ashmore and Hibernia Reefs, the high degree of overlap of the newly described coastal populations with trawl fisheries, and the yet unquantified long-term impacts of the high bycatch rate of this species within its current range, we recommend this species remain as a conservation priority. Focus of future research should include collection of information on post-release survival and long-term impacts of bycatch rates in

trawl fisheries to assess sustainability of populations within regions of high fisheries overlap.

***Aipysurus foliosquama* (Leaf-scaled sea snake)** – This species was also only previously known from Ashmore and Hibernia Reefs in the North West Shelf (Minton and Heatwole 1975). This species has not been sighted since 2001 at Ashmore and Hibernia Reefs and is now considered locally extinct from that region (Guinea 2013; Lukoschek et al. 2013). Recent surveys and fisheries bycatch data have identified resident populations within coastal locations between Shark Bay and Port Headland (D'Anastasi et al. 2016b; Lukoschek 2018; Sanders et al. 2015). The present project utilised habitat suitability models to refine the distributions of this species and predicted highly suitable habitats for coastal populations within Shark Bay, and between Exmouth Gulf and Port Headland.

Spatial analysis of habitat suitability identified 22% of suitable habitats are protected in current MPA networks along the west coast, with an additional 3% within multi-use areas under limited protection (Udyawer et al. 2020). Based on habitat suitability models and spatial patterns in fishing effort within the North-west marine region, this species has a high potential exposure to trawl fisheries (Figure 7), and are the second most abundant sea snake species within research prawn trawl bycatch from Shark Bay (Figure 9b), being captured in large numbers in relatively short trawls. Survival analysis for this lineage highlights that like *A. apraefrontalis*, this species is highly robust to short – medium length trawls (Figure 10). Post-release survival and recapture rates of individuals within enclosed areas like Shark Bay are currently unknown, and further long-term data is required to ascertain any long-term impacts of fishing activities to the newly discovered coastal populations. Also like *A. apraefrontalis*, the current population status is likely to be representative of an already altered state given the fishery's long history of operation in the area.

Based on the yet unknown causes of extirpation of this species at Ashmore and Hibernia Reefs, the high degree of overlap of suitable habitat for the coastal populations with trawl fisheries, and the yet unknown long-term impacts of the bycatch rate of this species within its current range, we recommend this species

remain as a conservation priority. Focus of future research for this species, like that of *A. apraefrontalis*, should include collection of information on post-release survival and long-term impacts of bycatch rates in trawl fisheries to assess sustainability of populations within regions of high fisheries overlap.

***Aipysurus fuscus* (Dusky sea snake)** – This Australian endemic species has a very restricted range within the offshore reef and shoals of the North West Shelf (Minton and Heatwole 1975). This species was previously abundant at Ashmore and Hibernia Reef, with populations recorded within the Scott and Seringapatam Reef complex. This species has not been sighted since 2005 at Ashmore and Hibernia Reefs and is now considered locally extinct from that region (Guinea 2013; Lukoschek et al. 2013), with a contraction of its known global range by ~40%. Currently, this species does not have a Listing Advice on the EPBC, however is listed as Endangered under the IUCN Red list (Elfes et al. 2013). The present project utilised habitat suitability models to refine the distributions of this species and predicted highly suitable habitats for this species within the known range (Scott Reef Complex), but also identified some mid-shelf Shoals as additional locations with highly suitable habitats (i.e. Heywood, Vulcan Shoals). Validation of these models identified potentially new localities for this species on Heywood Shoal (Udyawer et al. 2020).

Concerningly, spatial analysis of habitat suitability identified only 2.1% of suitable habitats are protected at any level within current MPA networks along the west coast (Udyawer et al. 2020). This species had a comparatively lower fishing exposure index than other short-range endemics of the North-west shelf (Figure 7), and was not recorded as bycatch in the trawl survey data (Figure 9b), likely due to their association with highly complex habitats and hard structures (D'Anastasi et al. 2016a) where trawl surveys were not conducted. Apart from their considerably reduced geographic range, there is evidence of high rates of hybridisation of this species with the more commonly occurring sister species *Aipysurus laevis* within the surviving populations at Scott Reef (Sanders et al. 2014). The reduced genetic diversity within this species, and high levels of introgression ('reverse speciation') into *A. laevis* are significant concerns that affect their status as a species.

Based on the significant reduction of geographic range, the yet unknown causes of local extinctions at Ashmore Reef, and ongoing impacts of the high rates of hybridisation within the currently surviving populations, we recommend this species be considered for elevated conservation focus, and be assessed for listing under the EPBC Act. Focus of future research to understand this species should include increased surveying effort in regions identified as suitable habitats (Udyawer et al. 2020) and to assess the genetic diversity of newly located populations. The species' restricted range, and limited dispersal capacity makes them highly vulnerable to changing climate. Additionally, a lack of ecological information on this species makes it difficult to assess their functional utility to reef systems and understand the ecological impact of losing this species through increased hybridisation within their shrinking geographic range.

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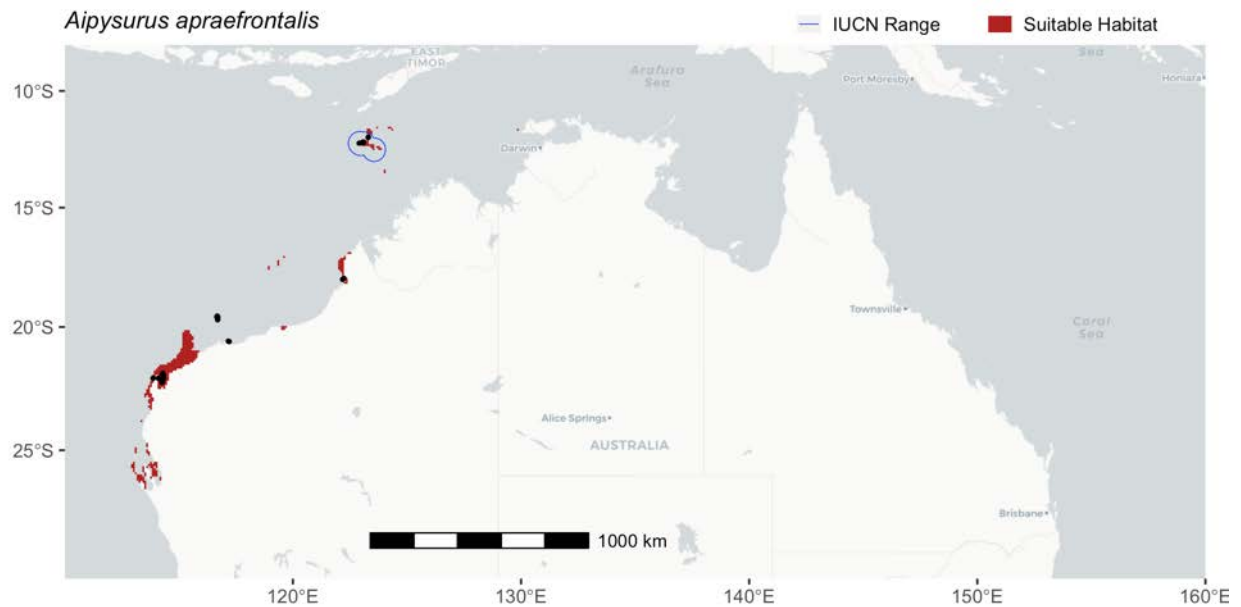
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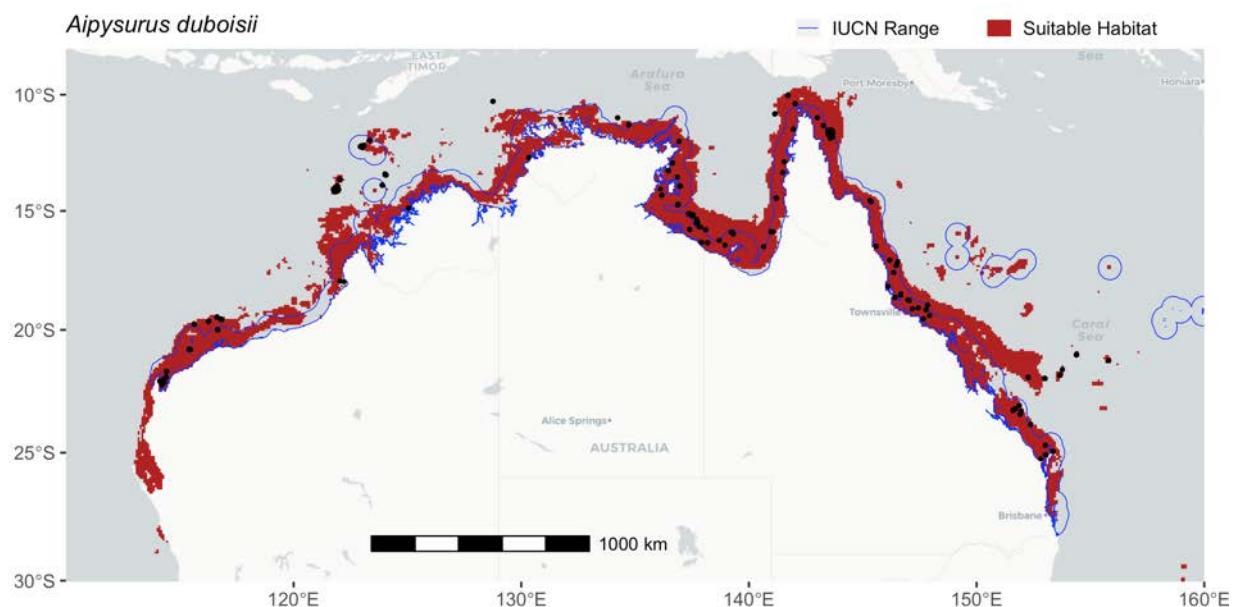
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APPENDICES

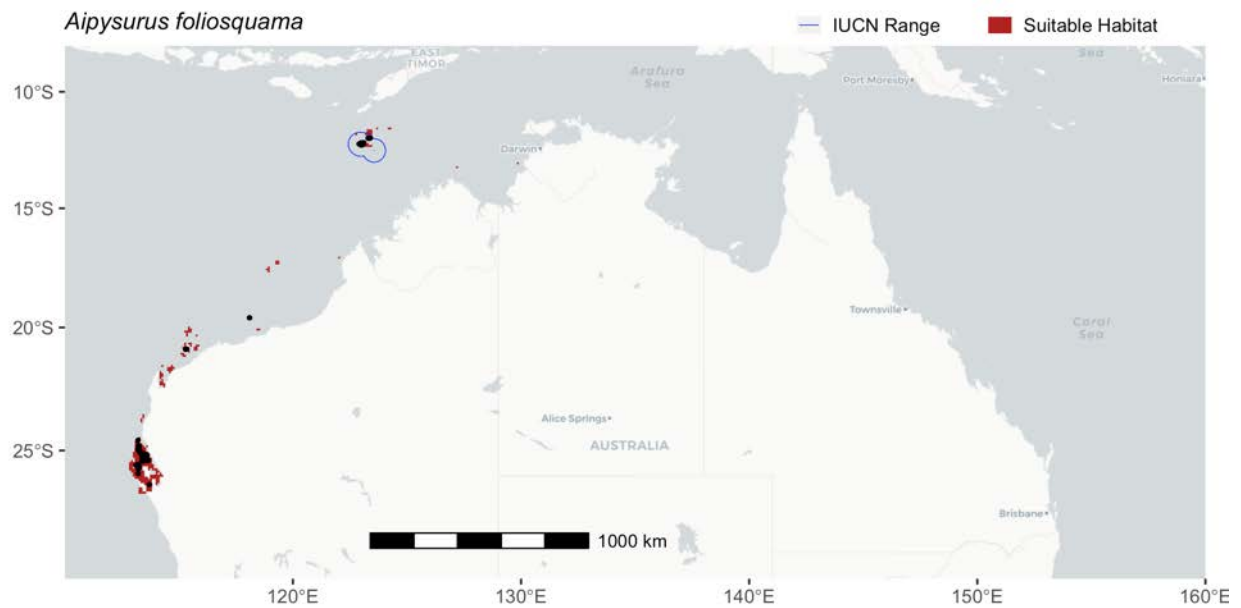
Appendix 1: Binary outputs of all MaxEnt models. Thresholding conducted using lowest presence thresholds calculated for each model.



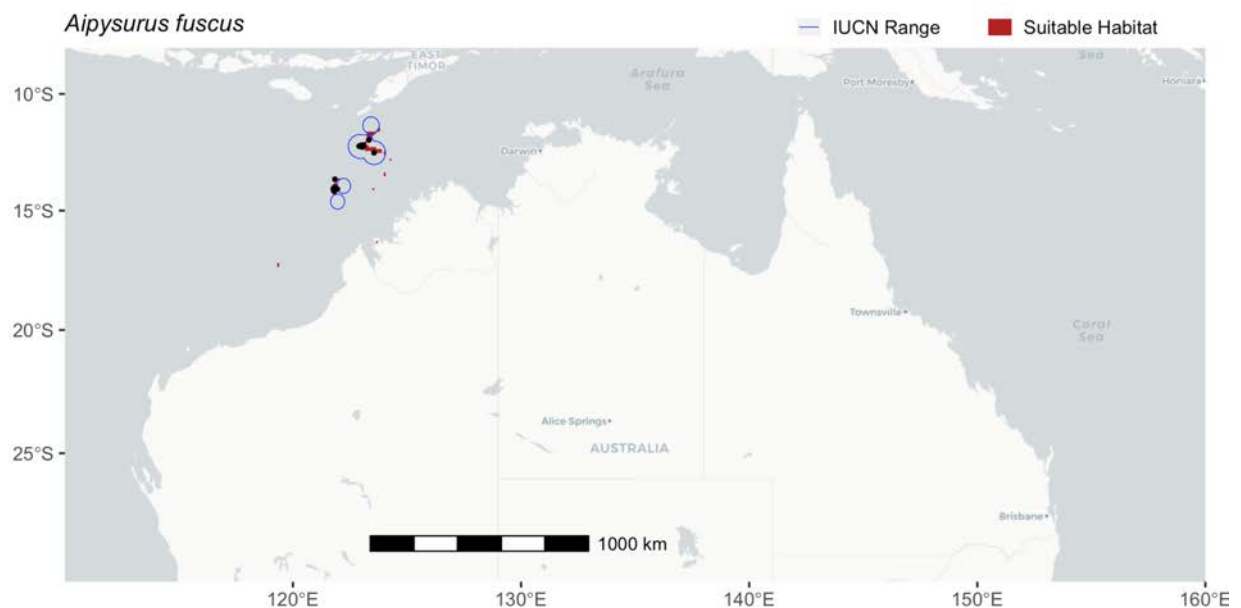
FigA1. Modelled suitable habitat for *Aipysurus apraefrontalis*, Short-nosed sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



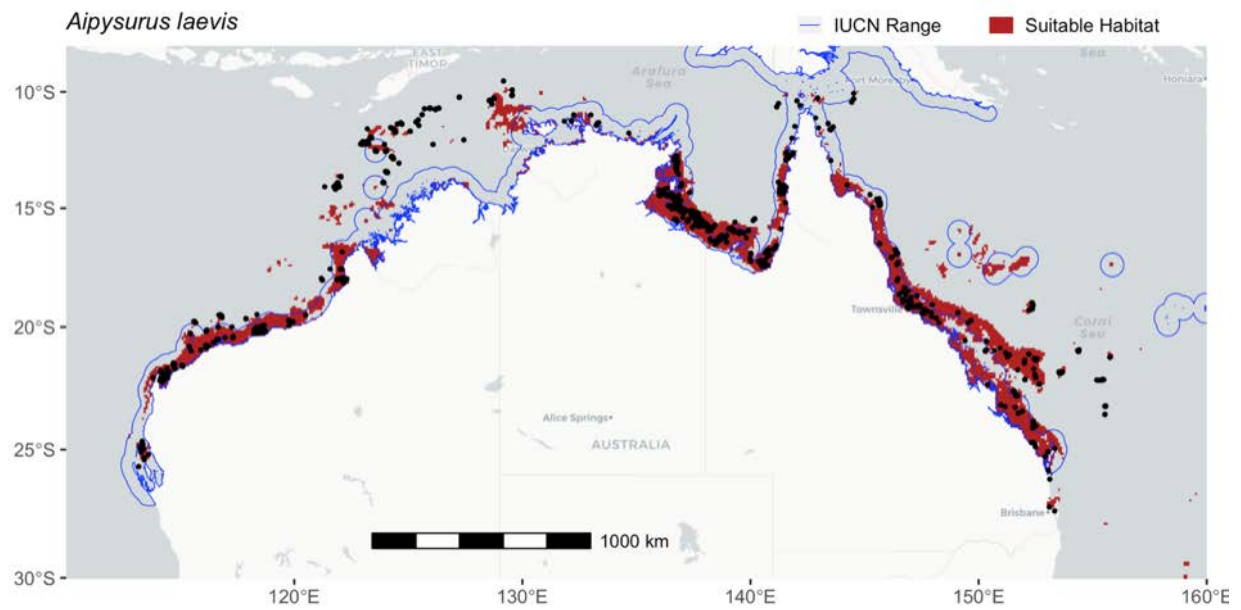
FigA2. Modelled suitable habitat for *Aipysurus duboisii*, Dubois' sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



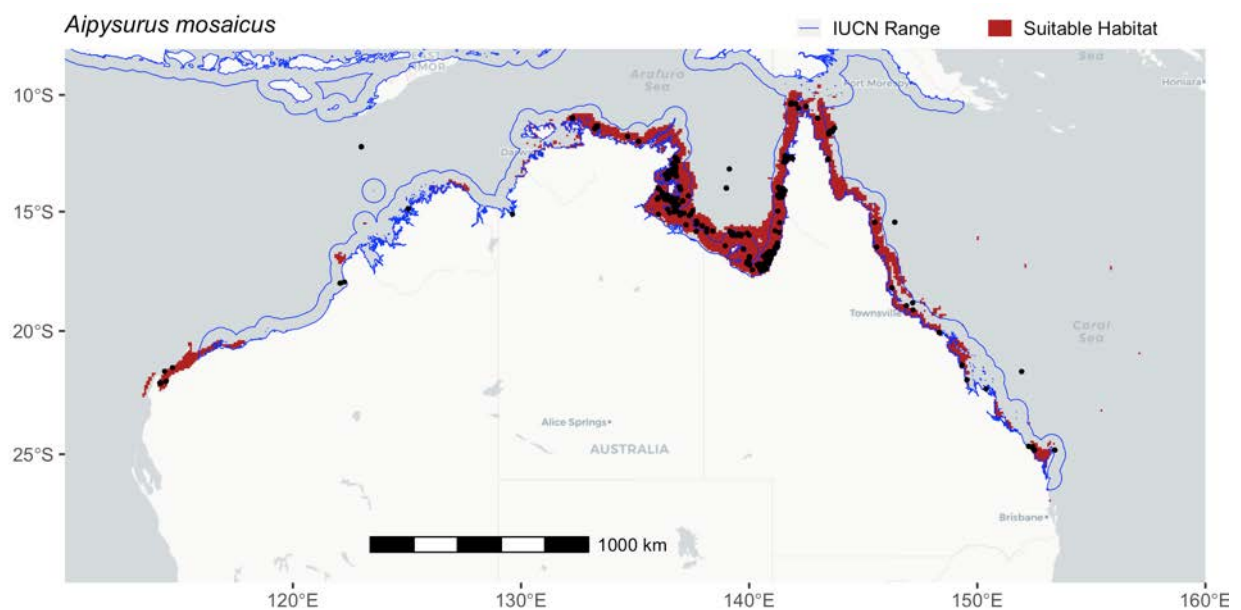
FigAS3. Modelled suitable habitat for *Aipysurus foliosquama*, Leaf-tailed sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



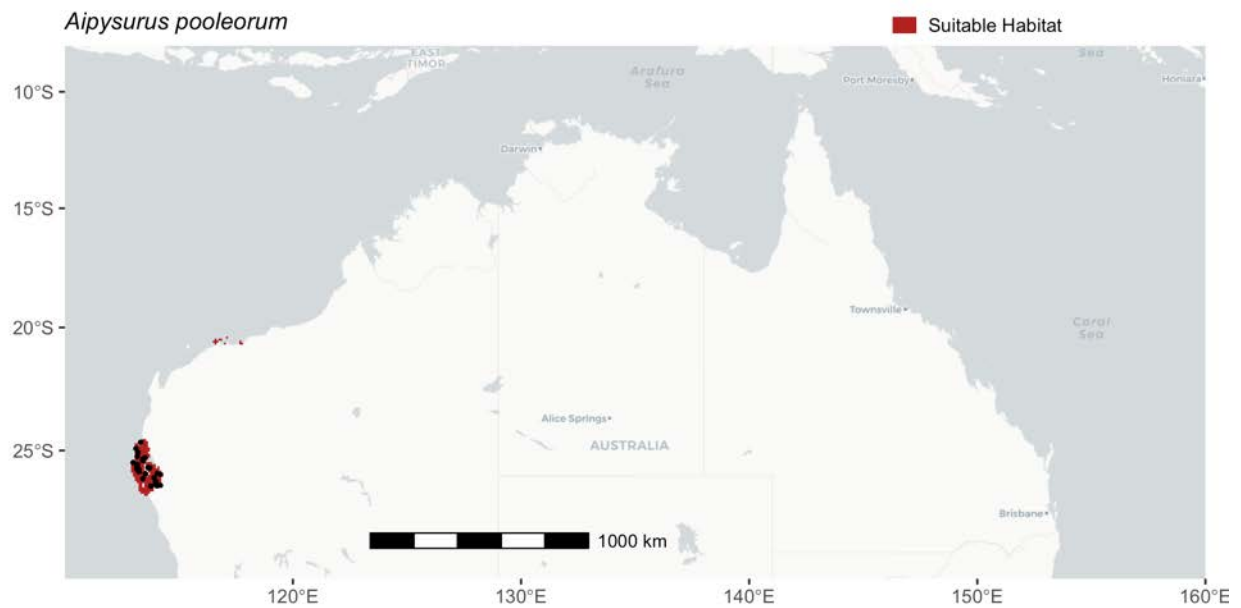
FigA4. Modelled suitable habitat for *Aipysurus fuscus*, Dusky sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



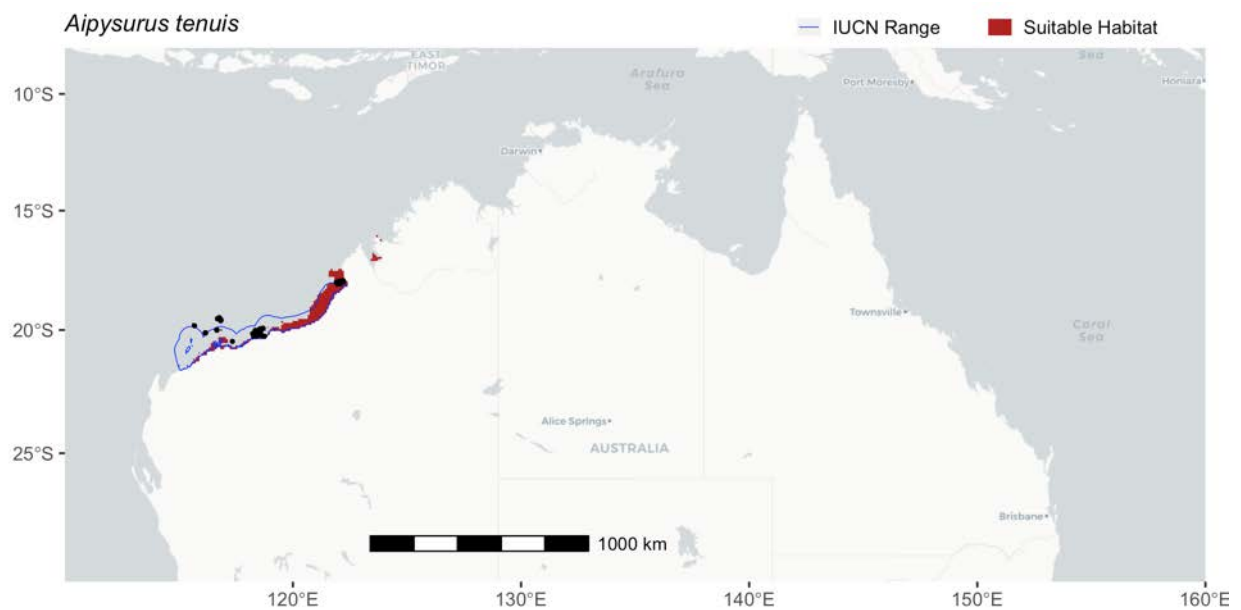
FigA5. Modelled suitable habitat for *Aipysurus laevis*, Olive sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



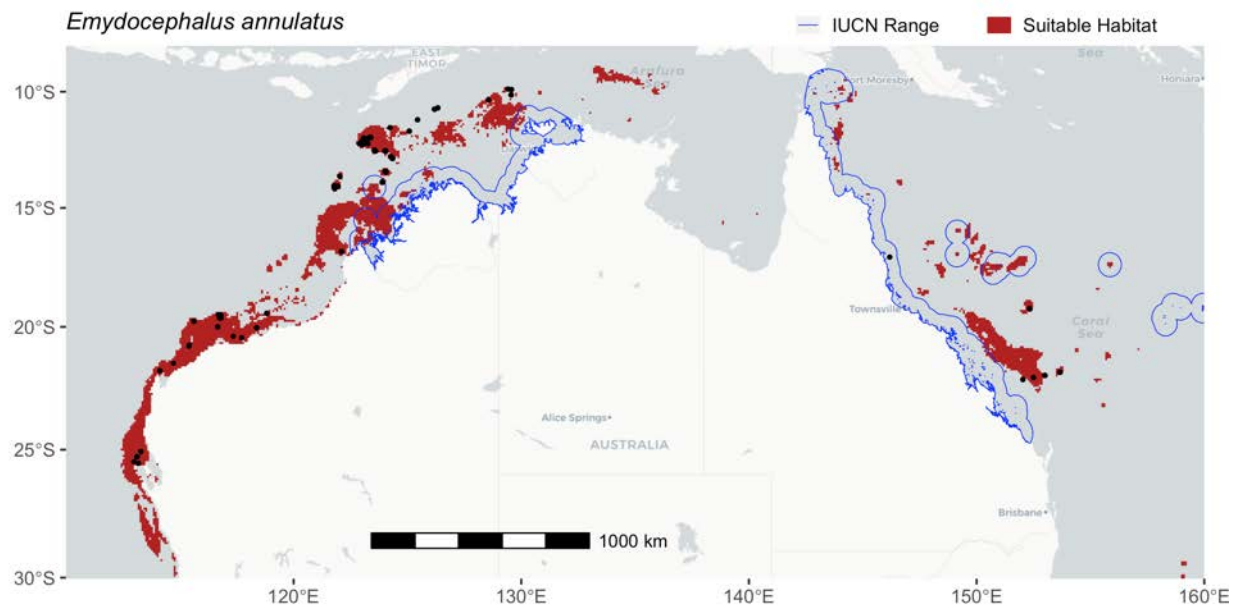
FigA6. Modelled suitable habitat for *Aipysurus mosaicus*, Mosaic sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



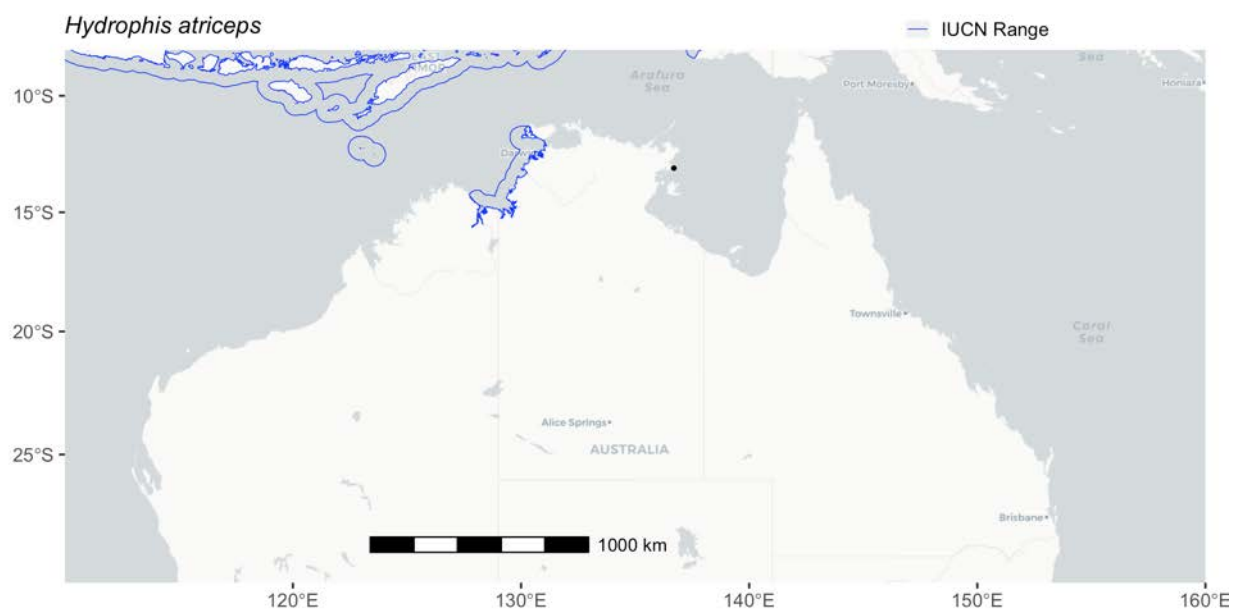
FigA7. Modelled suitable habitat for *Aipysurus pooleorum*, Shark Bay sea snake, within the Australian EEZ (red areas) using occurrence records (black points), this species has not been assessed currently under the IUCN Red List.



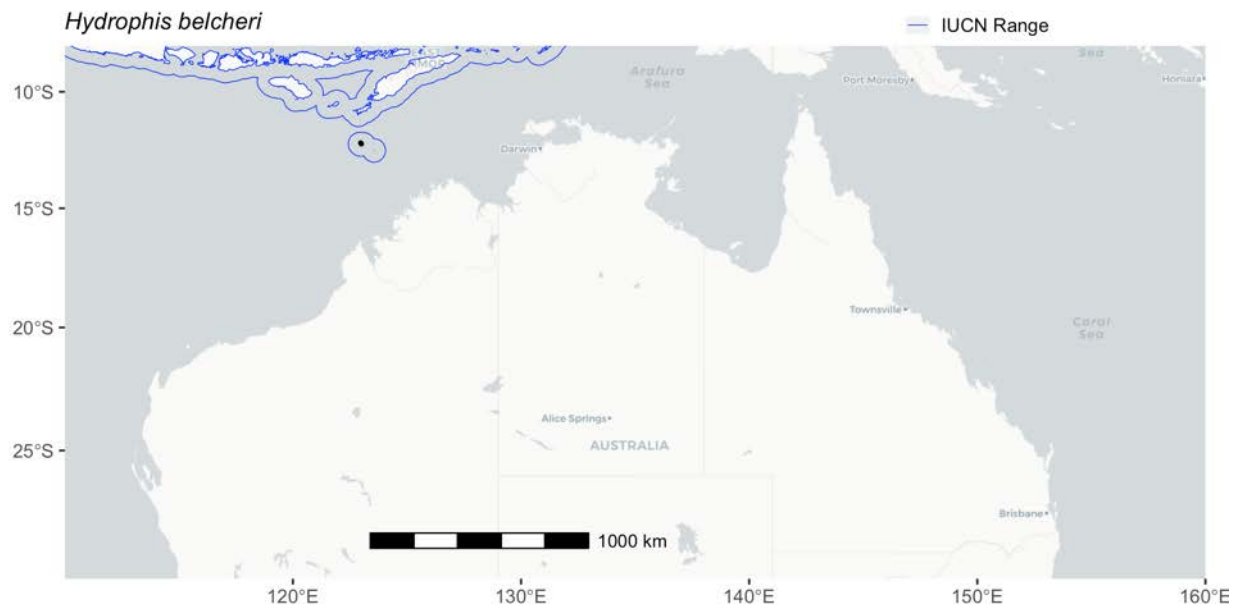
FigA8. Modelled suitable habitat for *Aipysurus tenuis*, Brown-lined sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



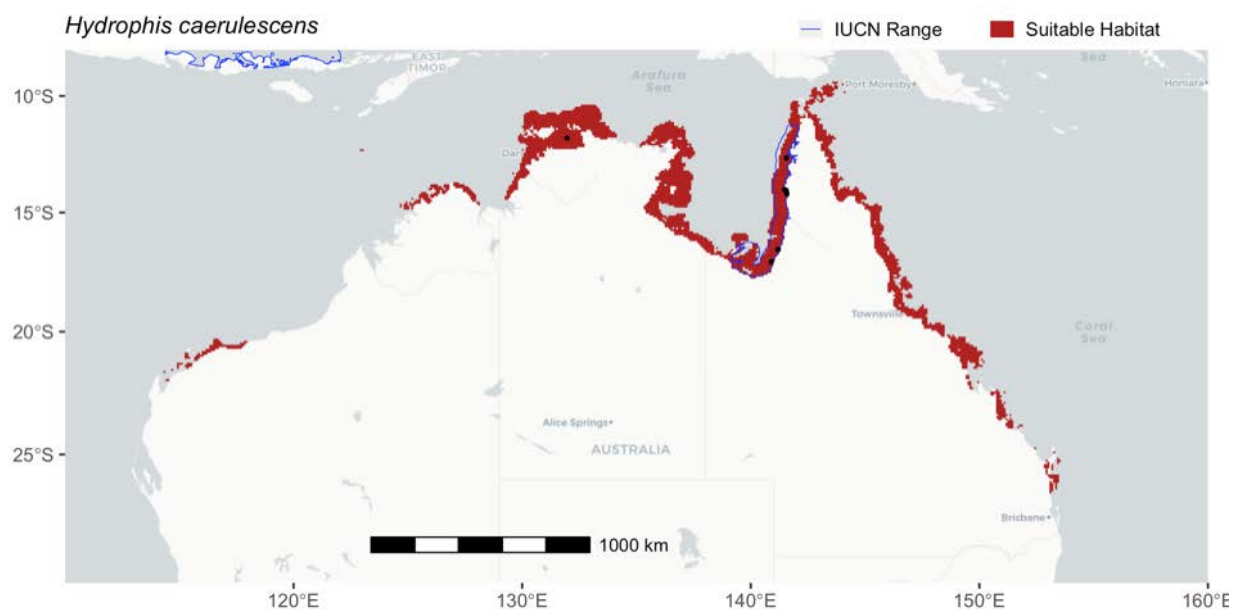
FigA9. Modelled suitable habitat for *Emydocephalus annulatus*, Turtle-headed sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons). Individuals from the west-coast have been recently classified as a separate species to the east coast (Nankivell et al. 2020), however currently been assessed as a single species.



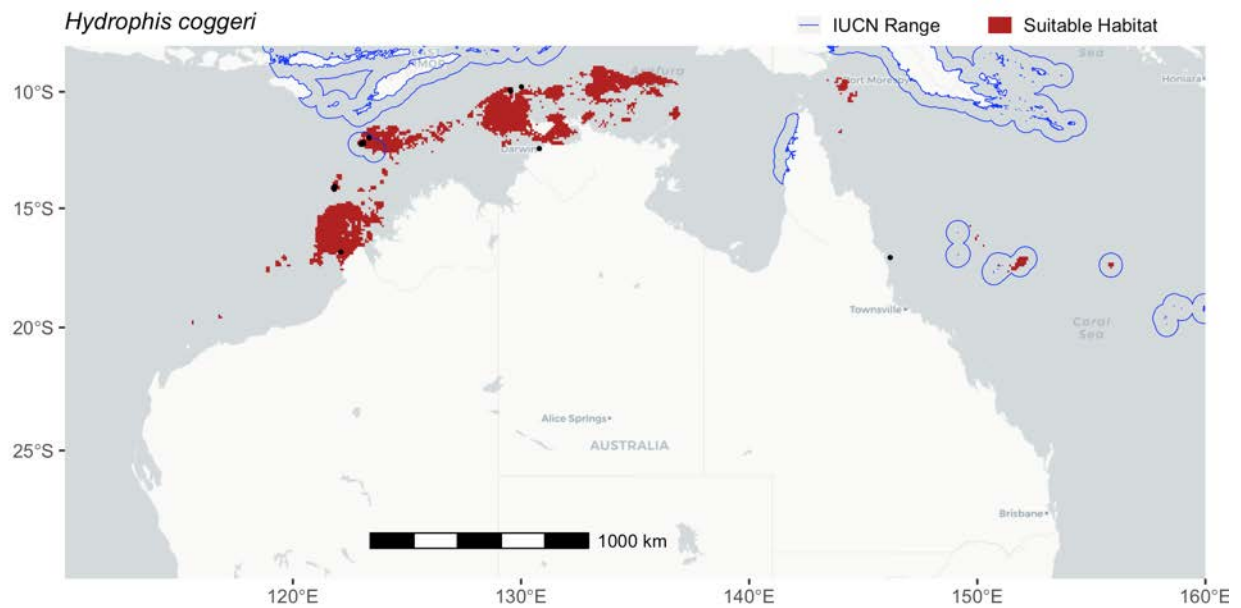
FigA10. Occurrence data for *Hydrophis atriceps*, Black-headed sea snake, within the Australian EEZ (black points), with current global range recognised by the IUCN Red List (blue polygons). Insufficient occurrence data was available to model suitable habitat.



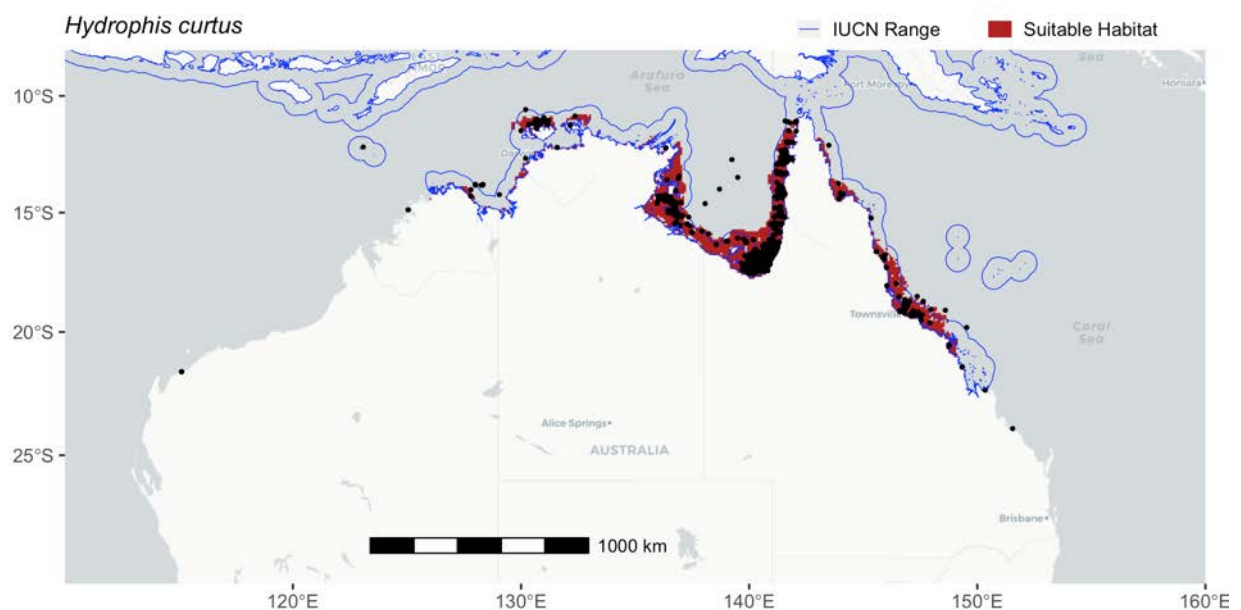
FigA11. Occurrence data for *Hydrophis belcheri*, Faint-banded sea snake, within the Australian EEZ (black points), with current global range recognised by the IUCN Red List (blue polygons). Insufficient occurrence data was available to model suitable habitat.



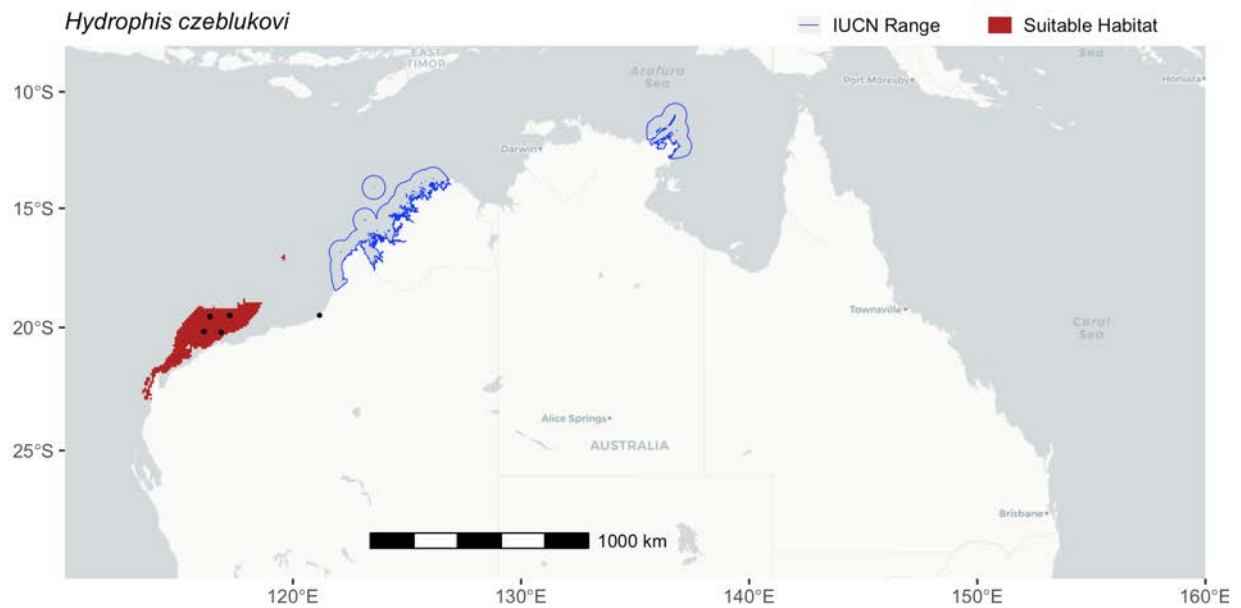
FigA12. Modelled suitable habitat for *Hydrophis caeruleus*, Dwarf sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



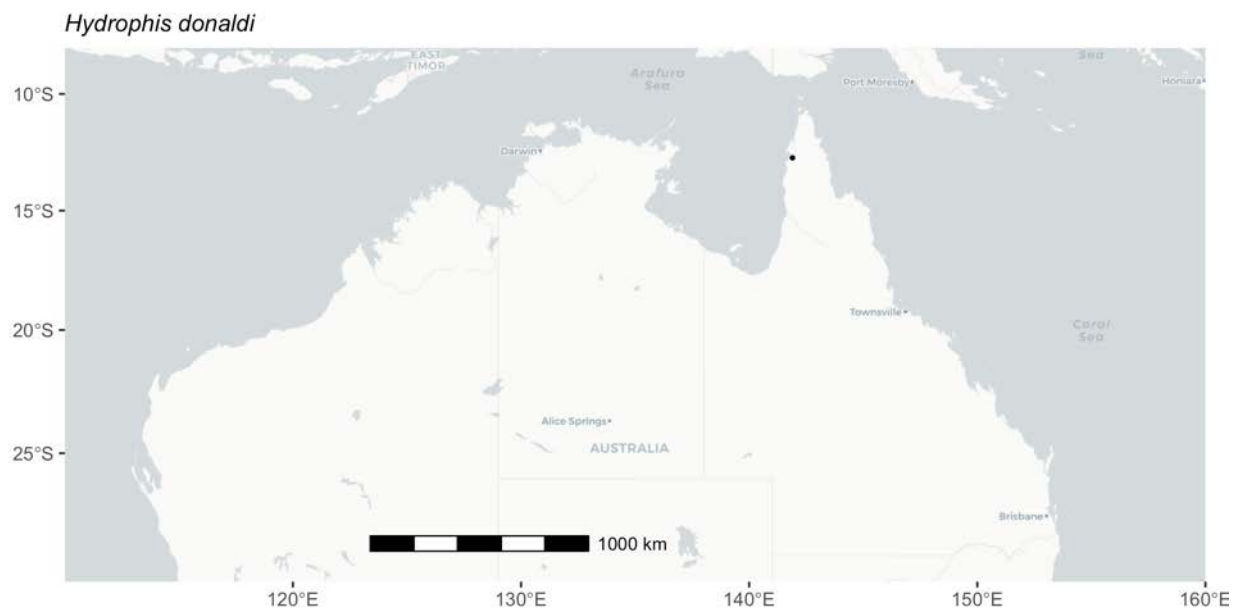
FigA13. Modelled suitable habitat for *Hydrophis coggeri*, Cogger's sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



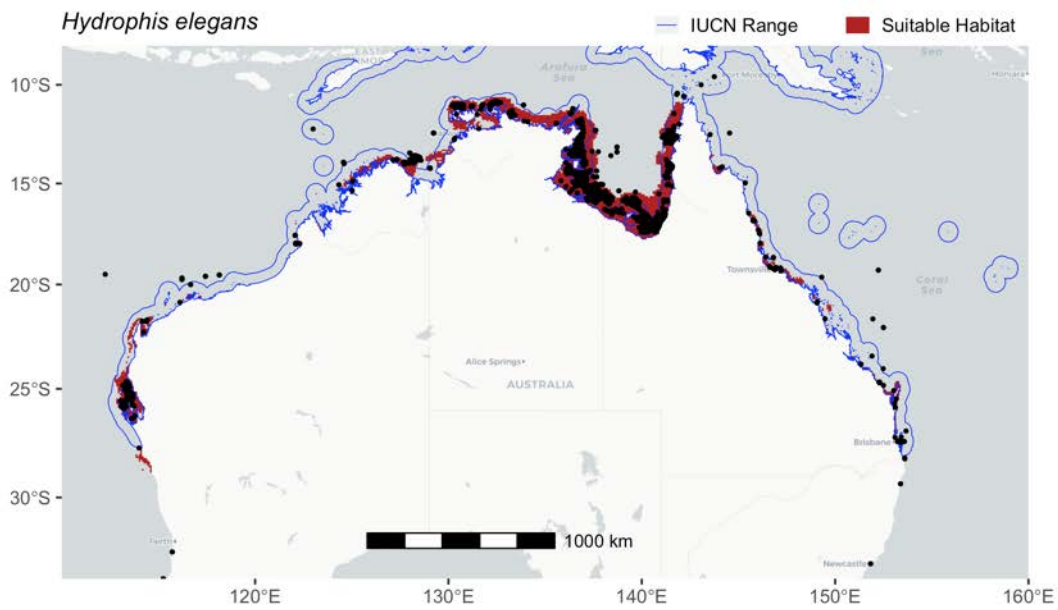
FigA14. Modelled suitable habitat for *Hydrophis curtus*, Spine-bellied sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



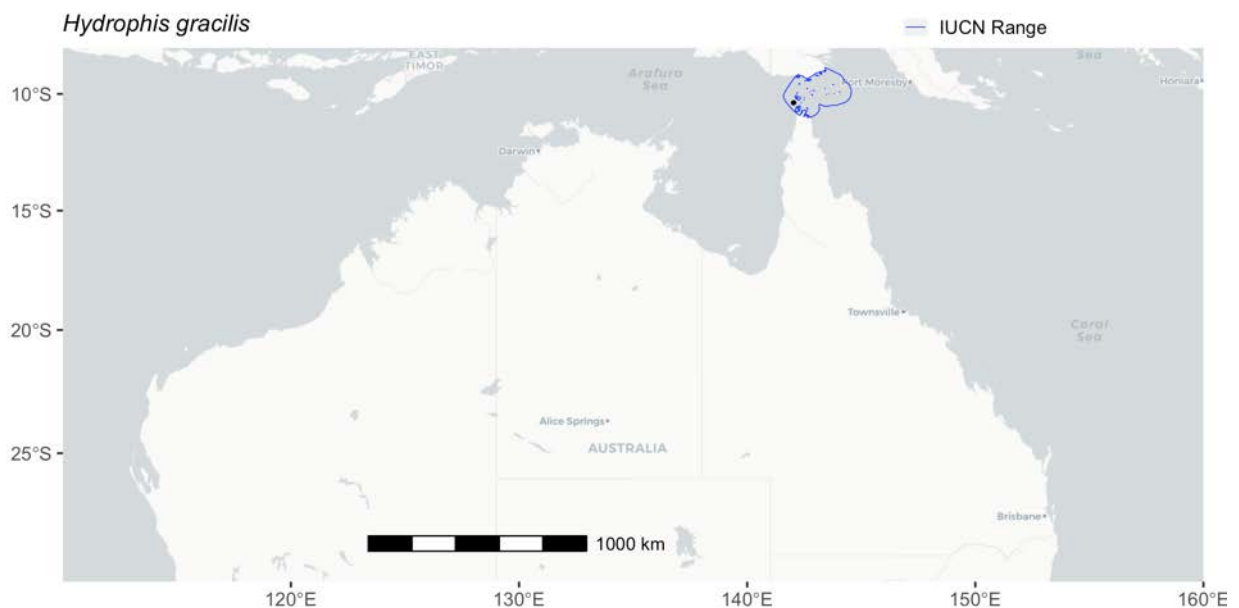
FigA15. Modelled suitable habitat for *Hydrophis czeblukovi*, Geometrical sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



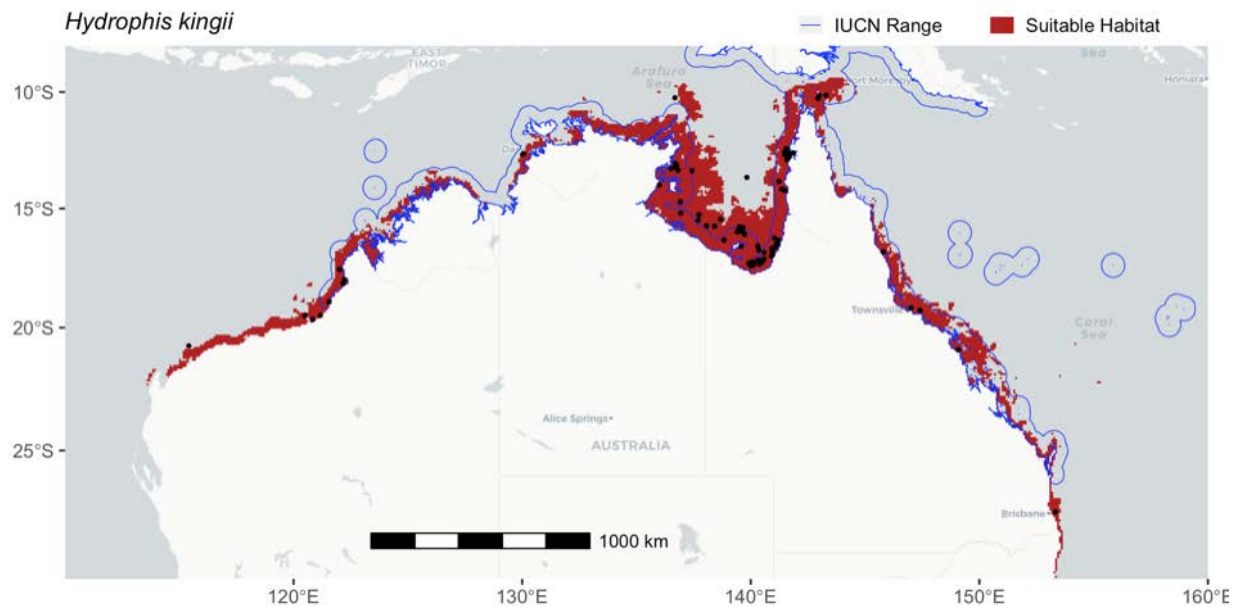
FigA16. Occurrence data for *Hydrophis donaldi*, Rough-scaled sea snake, within the Australian EEZ (black points). This species has not been currently assessed under the IUCN Red List, and insufficient occurrence data was available to model suitable habitat.



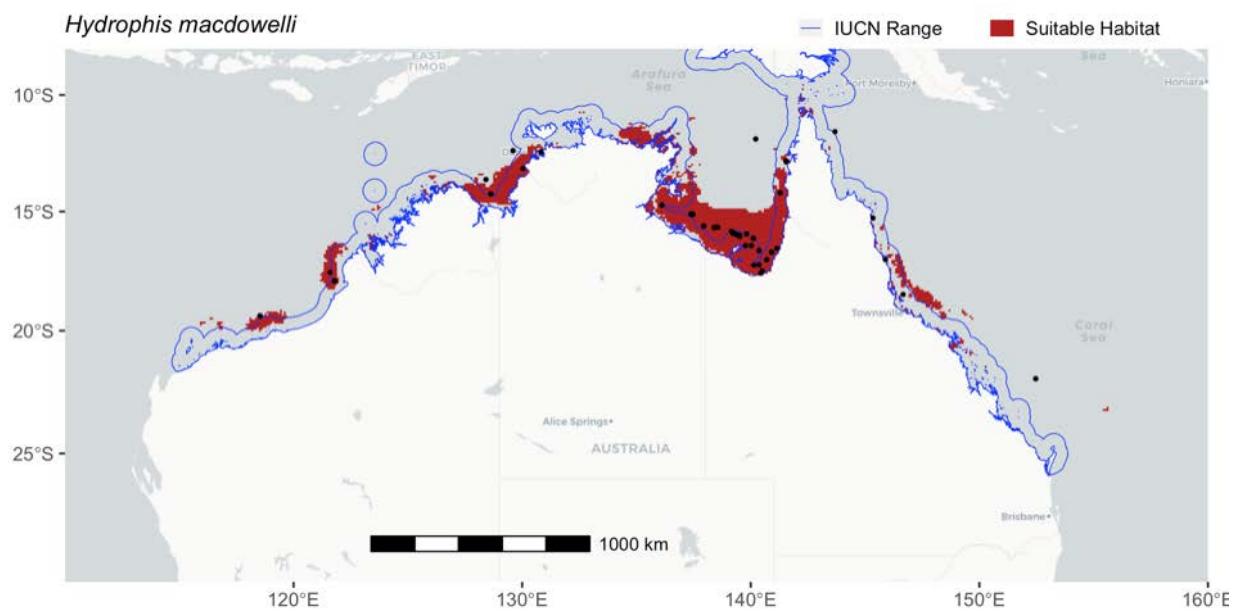
FigA17. Modelled suitable habitat for *Hydrophis elegans*, Elegant sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



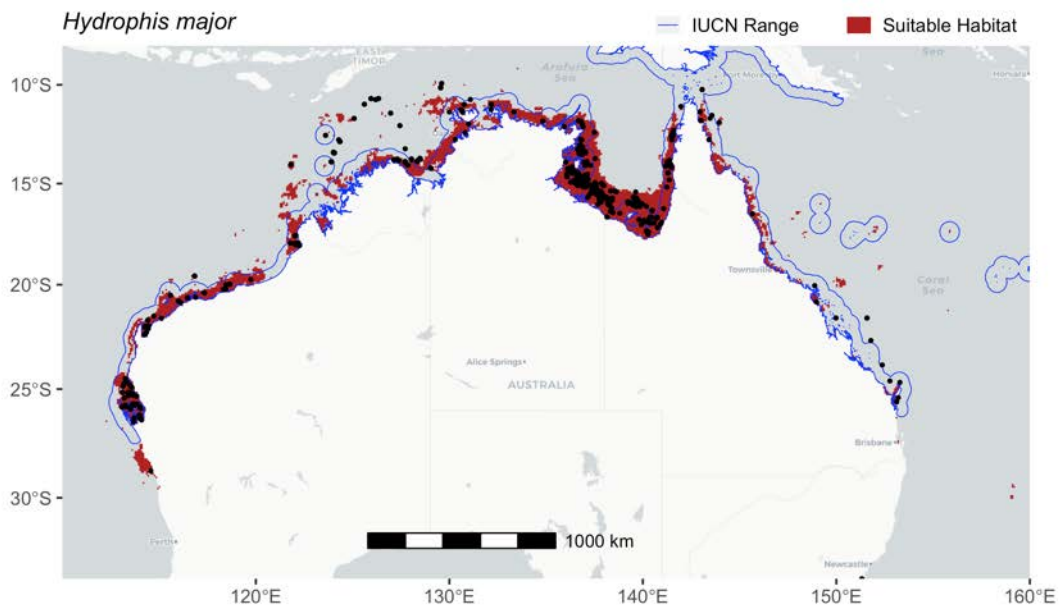
FigA18. Occurrence data for *Hydrophis gracilis*, Slender sea snake, within the Australian EEZ (black points), with current global range recognised by the IUCN Red List (blue polygons). Insufficient occurrence data was available to model suitable habitat.



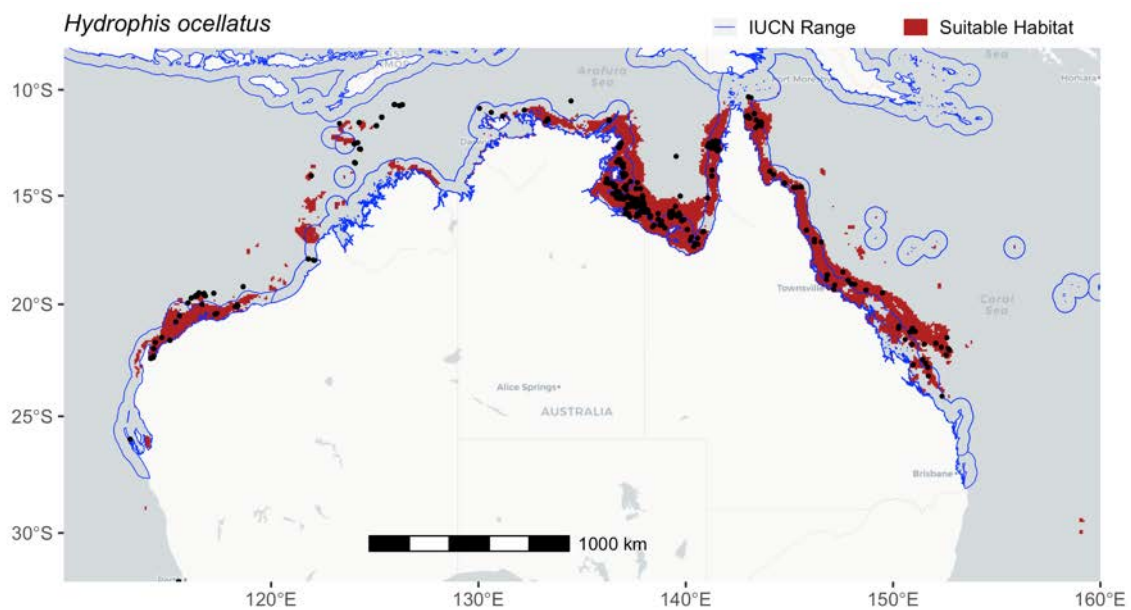
FigA19. Modelled suitable habitat for *Hydrophis kingii*, Spectacled sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



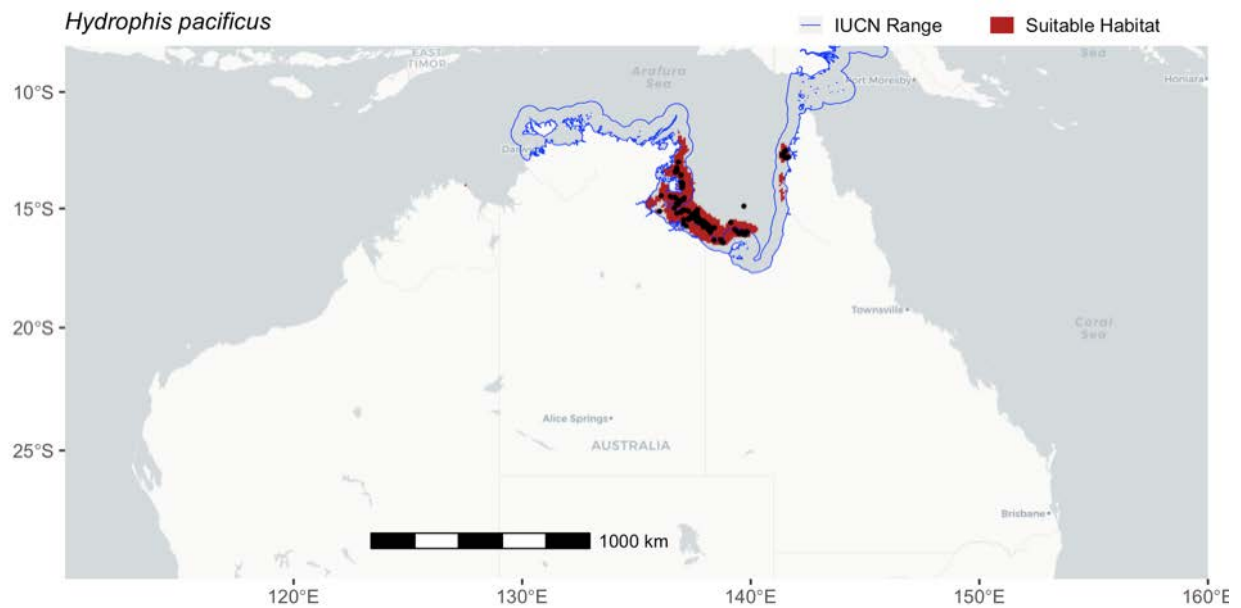
FigA20. Modelled suitable habitat for *Hydrophis kingii*, Spectacled sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



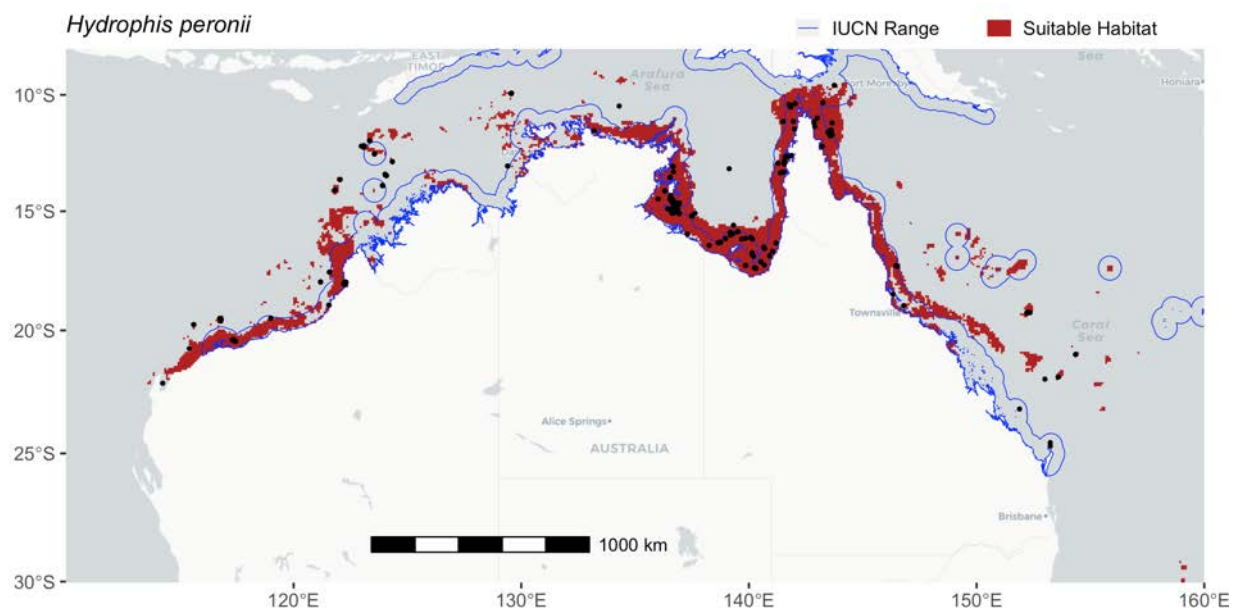
FigA21. Modelled suitable habitat for *Hydrophis major*, Greater sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



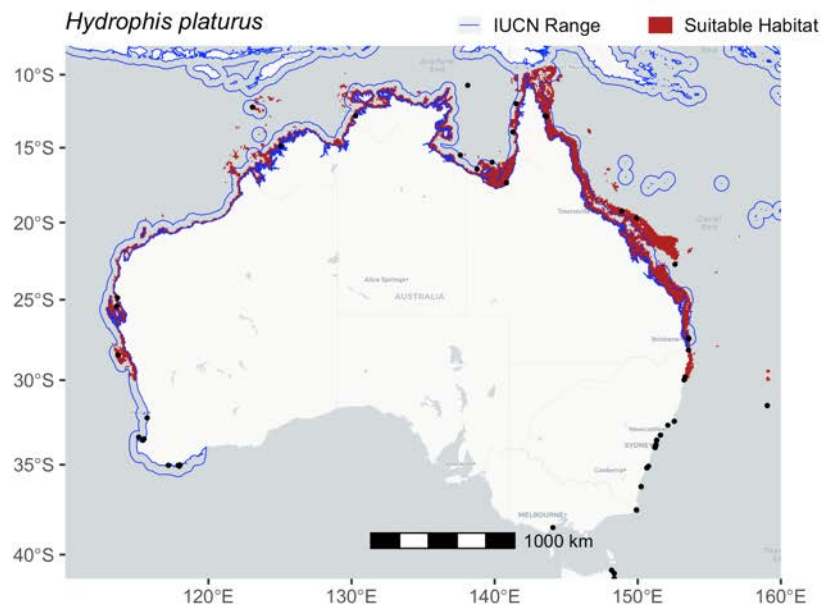
FigA22. Modelled suitable habitat for *Hydrophis ocellatus*, Spotted sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



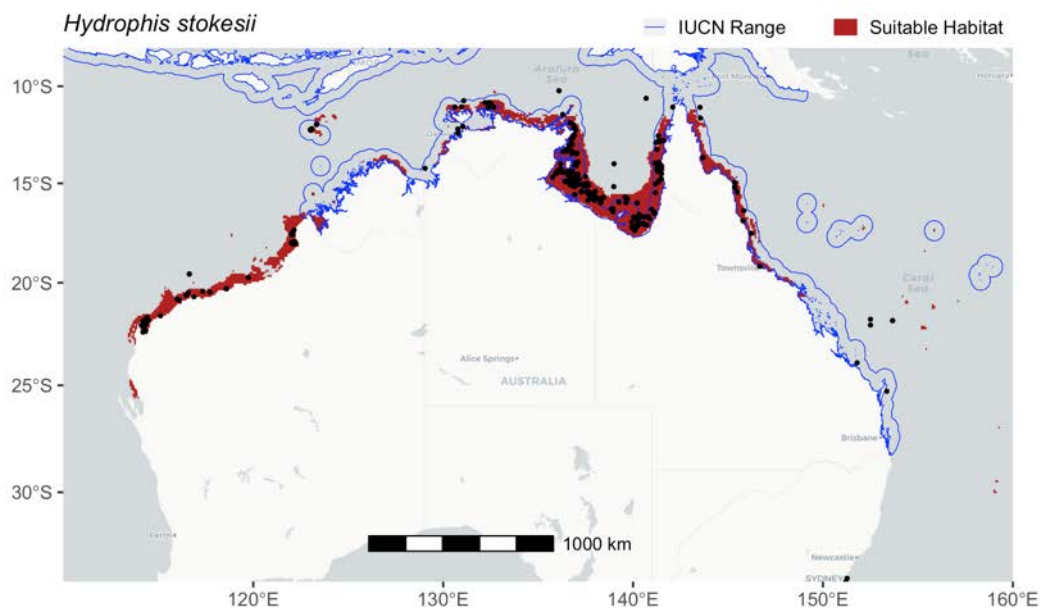
FigA23. Modelled suitable habitat for *Hydrophis pacificus*, Large-headed sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



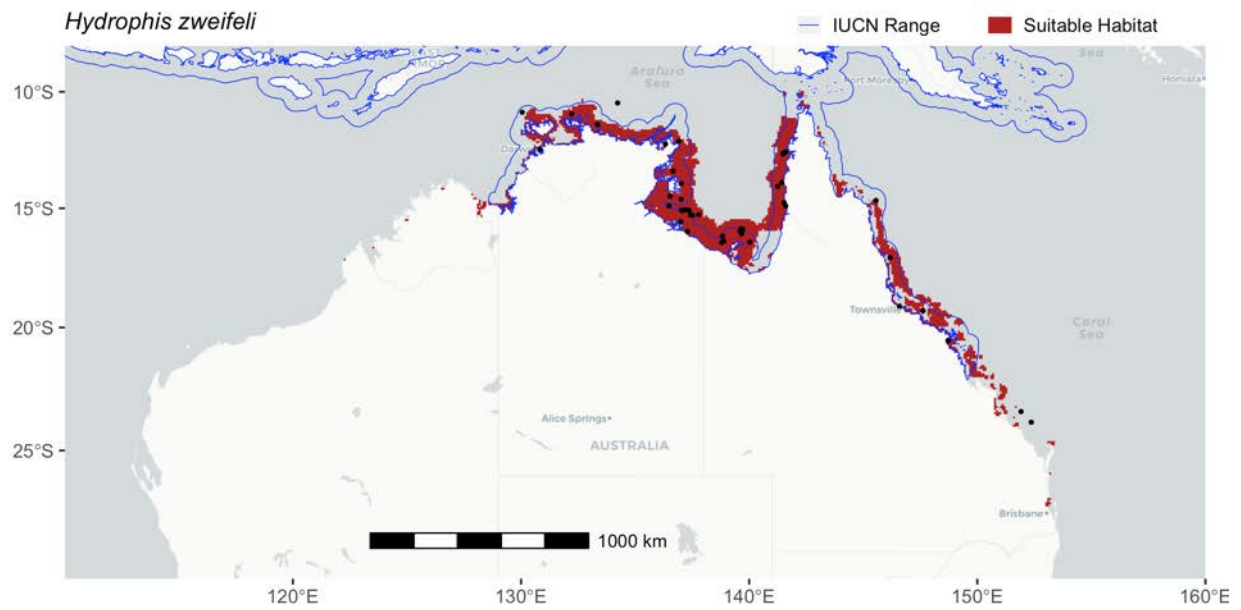
FigA24. Modelled suitable habitat for *Hydrophis peronii*, Horned sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



FigA25. Modelled suitable habitat for *Hydrophis platurus*, Yellow-bellied sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



FigA26. Modelled suitable habitat for *Hydrophis stokesii*, Stokes' sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



FigA27. Modelled suitable habitat for *Hydrophis zweifeli*, Beaked sea snake, within the Australian EEZ (red areas) using occurrence records (black points), with current global range recognised by the IUCN Red List (blue polygons).



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