Exploring the status of Western Australia's sea snakes

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Project Summary

All sea snakes are listed marine species under the EPBC Act and three Australian endemic species are listed as Critically Endangered or Endangered, and as such are a national conservation priority. Recent findings of two Critically Endangered sea snake species (*Aipysurus apraefrontalis* and *Aipysurus foliosquama*) in locations outside of their previously defined ranges have highlighted the lack of information on species distributions along the North West coast of Australia. Data on sea snake sightings on previously collected baited remote underwater video surveys (BRUVS) and fisheries independent trawl surveys were used to assess the utility of these methodologies to accurately define relative abundance and distribution patterns of sea snakes in the North West Marine Region (NWMR), including within Commonwealth Marine Reserves (CMRs), to refine species' status.

Presence/absence data from BRUVS were used to predict locations that are likely important habitats for sea snake populations within the NWMR, which included mid-shelf and oceanic shoals along the Kimberley and Pilbara coasts. Limited fisheries-independent trawl sampling data collected in Shark Bay and Exmouth Gulf highlighted patterns of interaction between sea snakes and trawl fishing, with survivorship curves indicating that most sea snake species encountered within these regions may be able to sustain low to moderate levels of trawl fishing. Trawl survey data also highlighted the need for additional fisheries interaction data to accurately assess the species-specific influence of fishing activities (e.g. trawl and trap fishing) on different life stages of sea snakes susceptible to incidental capture (bycatch). This project highlights the need for more data on sea snakes in regions lacking information (e.g. mid-shelf shoals of Kimberley coast, Pilbara coast and Rowley Shoals). In addition, further research is also required to assess the degree of connectivity between sea snake populations from offshore reefs that have seen recent declines, and those on adjacent mid-shelf and oceanic shoals.

Background

The North West Marine Region (NWMR) is considered a biodiversity hotspot for 'true' sea snakes (Elapidae, Hydrophiinae) within Australia and globally. Hydrophiine sea snakes contain three main genera, the *Aipysurus* (~11 species), *Emydocephalus* (1 species) and *Hydrophis* (> 50 species) genera (Lukoschek & Keogh 2006, Rasmussen et al. 2014). Species of *Aipysurus* and *Emydocephalus* are typically found in coral reef habitats, whereas species of *Hydrophis* more commonly occur in inter-reef soft sediment habitats, although there are exceptions to this pattern (Cogger 2000). All true sea snake species, with the exception of the pelagic yellow-bellied sea snake, *Hydrophis platurus*, are strongly associated with benthic habitats, and occur in coastal, shallow water habitats (typically <100 m depth), as they regularly need to come to the surface to breathe (Dunson 1975, Heatwole 1999).

Approximately 25 recognised species of sea snake occur off the coast of Western Australia, of which four are endemic to reef habitats in the remote NWMR (Table 1). Of the four endemic species, two are currently considered Critically Endangered (*A. apraefrontalis*, *A. foliosquama*) and *A. fuscus* is considered Endangered under the International Union for Conservation of Nature (IUCN) Red List Criteria. A large number of sea snake species (34% of known species) within Australian waters are classified as 'Data Deficient' under the IUCN criteria, where insufficient scientific information is available to make an accurate assessment of their population health and risk of extinction (Elfes et al. 2013). In Australia, all sea snakes are listed marine species under Australia's Environmental Protection and Biodiversity Conservation Act C'th, 1999 (EPBC Act). As many species of sea snake occupy turbid coastal waters they are infrequently encountered, and in many cases Data Deficient species are only known from a few specimens collected as fisheries bycatch and lack basic biological data. With little biological data available, the effects of anthropogenic threats (i.e. fishing, skin trade, coastal development) are unknown (Livingstone 2009). Basic biological and ecological data are urgently required to accurately assess the status of these species in the NWMR.

Sea snakes are a key management issue in the north within and beyond CMRs due to their EPBC status and their high biodiversity value. There is currently limited knowledge about the ranges and distribution patterns of sea snake species in the region, in addition to a lack of understanding of population status and threats. Remote reef systems in the NWMR (i.e. Ashmore and Hibernia, Scott Reef Complexes) have undergone recent declines in sea snake populations. 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. Sea snakes can be highly vulnerable to capture in some fisheries and are also used for their skin and flesh in some countries. Their interactions with Australian fisheries, particularly in Western Australia, are not well defined which also requires investigation. Data on biology, ecology, distribution, population trends and the cause/s of sea snake population declines are needed to underpin Conservation Advices, to define the status of these species under the EPBC Act and to fully define any required conservation action. An improved understanding of the distribution and status of sea snake populations within Australian waters is needed to accurately define any required conservation actions.

Table 1. Sea snake species of high conservation priority within Australian waters including current IUCN and EPBC status.

Species	Common name	IUCN status	EPBC status	Supporting information
Aipysurus apraefrontalis	Short-nosed sea snake	CR	CR, LM	Restricted range, coral dependent, recorded declines in the NW Shelf (Guinea 2013, Lukoschek et al. 2013)
Aipysurus foliosquama	Leaf-scaled sea snake	CR	CR, LM	Restricted to two reef areas in the NW Shelf, total area of occupancy < 10 km^2, recorded population declines over last 15 years (Guinea 2013, Lukoschek et al. 2013)
Aipysurus fuscus	Dusky sea snake	EN	LM	Restricted to a few reef areas in the NW Shelf, total area of occupancy < 500 km^2, population declines of at least 70% over 15 years (Elfes et al. 2013)
Hydrophis pacificus	Large-headed sea snake	NT	LM	Rare, restricted range in the Arafura sea, slow maturing, declines caused by trawl fisheries estimated at 20% over 25 years (Elfes et al. 2013)

CR: Critically Endangered, EN: Endangered, NT: Near Threatened, LM: Listed Marine

Past surveys for sea snakes in the North West Marine Region

The abundance and population health of sea snakes within the NWMR is of growing concern as a consequence of recent records of declines of populations on Ashmore and Hibernia Reef Complex (Guinea 2013, Lukoschek et al. 2013). Past surveys in the region have ranged from remote reef systems in the Timor Sea, to more recent surveys conducted in near-shore coastal habitats around Exmouth Gulf and Shark Bay (Fig. 1). Remote reef systems in the NWMR (Fig. 1b) have been the primary focus of the majority of research effort in the past, with the Ashmore and Hibernia Reef Complex being the longest surveyed reef system (surveyed on and off between 1978 and 2013) for sea snake populations (Guinea 2007, 2013, Lukoschek et al. 2013). Comparatively, little is known about the abundance, species richness and connectivity of populations between the remote reefs and adjacent mid-shelf shoals and coastal habitats along the Kimberley and Pilbara coasts (Moore & Richards 2014). Recent museum and field surveys reported by Sanders et al. (2015) and D'Anastasi et al. (2016a,b) have recorded populations of the two Critically Endangered endemic species (*Aipysurus apraefrontalis, A. foliosquama*) in coastal habitats farther south (i.e. Exmouth Gulf and Shark Bay) than previously recorded.

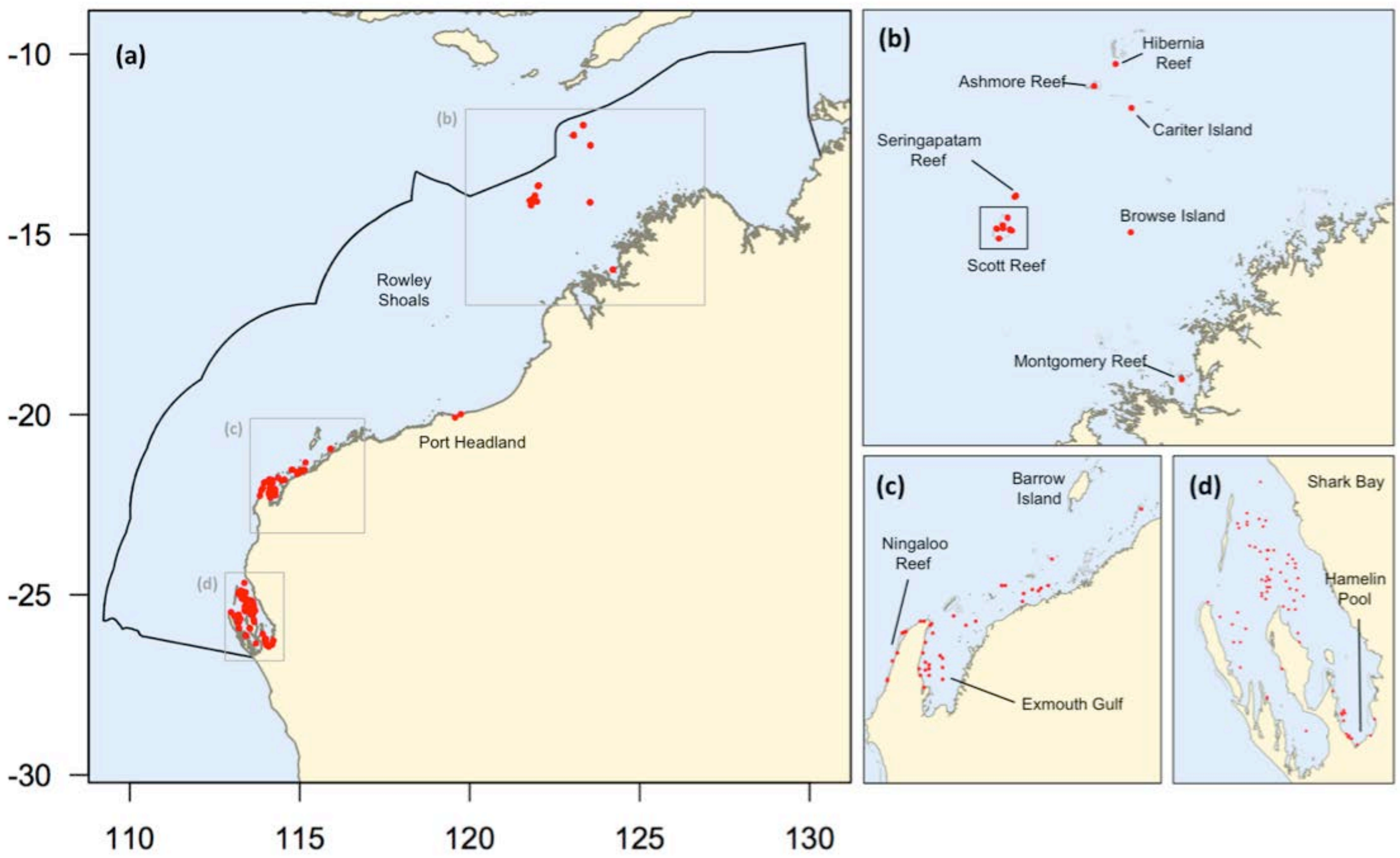


Figure 1. (a) Locations of geo-referenced surveys conducted focusing on sea snakes between 1973 and 2015. The surveys include snorkel, SCUBA, reef walks and trawl sampling conducted by multiple authors and institutions (Heatwole, Milton, Guinea, Lukoscheck, D'Anastasi, WA DPaW, WA DoF). (b) The remote reef systems around the Ashmore and Scott Reef Complexes of the NWMR have been the longest surveyed sites. Whereas, sites along the Ningaloo coast (c) and Shark Bay (d) are the most recently surveyed (D'Anastasi et al. 2016a, b).

Aims

Recently reported declines in sea snake abundance in Western Australia have increased concern about the status of sea snake species in this region. As all sea snakes in Australian waters are listed marine species under the EPBC Act, with two endemic species in the NWMR also classed as Critically Endangered, and a third listed as Endangered under the IUCN Red List, understanding the status of sea snakes in the NWMR is a national conservation priority. This project examines the current state of knowledge on sea snakes in Western Australian waters to define what is currently known and identify data and knowledge gaps.

This project analysed data already collected by the Australian Institute of Marine Science and the Western Australian Department of Fisheries to:

- Define the range and distribution of key sea snake families in the North West Marine Region (NWMR)
- Examine how oceanographic and environmental factors shape sea snake assemblages across all habitats within the NWMR
- Use previously collected data to produce predictive models to assess likelihood of occurrence maps within the NWMR for major families of sea snakes
- Use fisheries-independent data collected by the Western Australian Department of Fisheries to assess any patterns in incidental capture of sea snakes in trawl fishing gear within select coastal habitats along the west coast of Australia
- Identify gaps in knowledge, locations of interest and research priorities to accurately assess the status of sea snakes within the NWMR

Approach

Review, assimilation and analysis of existing baited remote underwater video survey (BRUVS) data was conducted to help define range and produce distribution maps of sea snakes found within the NWMR. Analysis was focused on identifying patterns in assemblages of sea snakes within all habitats in the region. Attempts were made to identify sea snakes sighted on BRUVS to species level and identify any patterns of presence and distribution of three priority species (i.e. *A. apraefrontalis*, *A. foliosquama*, *A.fuscus*). However, reduced resolution, lighting and visibility in some videos prevented accurate identification of sea snakes to species level. Data were still assessed at the genus level, to identify areas that are important to *Aipysurus* species and identify locations within the NWMR that have ideal environmental and oceanographic parameters to support healthy sea snake populations. At the genus level, four species of *Aipysurus* (*A. laevis, A. duboisii, A. tenuis* and *A. pooleorum*), the sole species in *Emydocephalus* (*E. annulatus*) and three species in *Hydrophis* (*H. major, H. ocellatus* and *H. peronii*) were positively identified. Although none of the three priority species were sighted on the BRUVS dataset, information from other species within the *Aipysurus* provided new information on the environmental and physical predictors important for the genus.

Data from other geo-referenced sources (e.g. Atlas of Living Australia, Reef Life Survey, previously conducted surveys, fisheries-independent trawl surveys) were pooled to assess ranges and distribution patterns of sea snakes that were positively identified to species-level and recorded within the NWMR, including the three priority species (*A. apraefrontalis*, *A. foliosquama*, *A.fuscus*). Confirmed records were used to construct predictive models to map the probability of presence of the three priority species within the NWMR to highlight locations that are likely to be ideal for the presence of these species, and require additional targeted surveys.

BRUVS deployments and setup

A total of 2290 BRUVS were deployed between November 1999 and April 2016 at sites spanning a range of latitudes (9.87˚S - 25.67˚S) and longitudes (112.91˚E - 129.59˚E) of the NWMR (Fig 2a). BRUVS were deployed at depths of 3 to 120 m (mean ± se; 38.25 ± 0.43 m). Each BRUVS consisted of a galvanised, steel frame with a detachable arm (20 mm plastic conduit), which positioned a 350 mm plastic mesh canister containing 1 kg of crushed oily sardines (*Sardinops* or *Sardinella* spp.) as bait on the sea floor (Fig. 2b). A simple camera housing made from PVC pipe with acrylic front and rear ports was situated inside the frame to deploy either a HandiCam recording on tape, or GoPros recording digitally. Single and stereo camera setups were used in this dataset at different BRUVS deployments. Wide-angle lens adapters were fitted to the cameras, and provided at least an hour (60.6 ± 0.6 min) of filming around the bait (Fig. 2b). A total of 2308.29 hours of footage was captured in the complete survey dataset with 582 snakes sighted on 482 out of the 2290 BRUVS.

Data analysis

Interrogation of each video was conducted using a custom interface (BRUVS2.1.mdb, Ericson and Cappo, unpublished, Australian Institute of Marine Science 2006) to store data from field operations and video interrogation, to capture the timing of events, and reference images of the sea snakes and seafloor habitat in the field of view. The maximum number of snakes seen together at any one time (*MaxN*) was recorded at each site, for each species sighted on the BRUVS. Whilst the use of *MaxN* potentially underestimates the numbers of individuals per species at each site, it overcomes the potential for double counting individuals within the same tape. For example, if five individuals are passing back and forth through the field of view, but only three are visible at one time, then *MaxN*=3.

Seafloor reference images at each BRUVS site were used to visually score percentage cover of six epibenthic cover types (i.e. Marine Plant/Algae cover, Hard Coral cover, Soft Coral cover, Filter feeder cover, Bare Mud/Sand cover and Encrusting algae/rubble cover). Reference images were also used to score a subjective habitat complexity index ('CI') based on rugosity and type of the substratum. The CI ranged from 1, representing the least complex habitat (single substratum/ flat sandy habitats) to 4, representing the most complex habitat (multiple substrata/ high relief reef habitats). The depth ('Depth') of each BRUVS site was also recorded in the field by echosounder. The shortest distances from the BRUVS to islands or the mainland ('DistCoast'), the closest exposed reef edge ('DistReef'), closest seagrass habitat ('DistSeagrass'), closest mangrove habitat ('DistMan') and closest source of freshwater ('DistFW') were calculated using customized scripts in the *R* environment (R Development Core Team 2016). Data on mean annual sea surface temperature ('SST') and Chlorophyll a concentration ('Chlor') at each BRUVS site were obtained from remote sensing datasets (http://www.oceancolor.gsfc.nasa.gov/; http://www.nodc.noaa.gov/SatelliteData). The BRUVS footage was also interrogated to provide measures of numbers of fish ('Fish Abundance') and numbers of species of fish ('FishSpRichness') at each BRUVS deployment. A full list of environmental and habitat parameters measured at each BRUVS deployment can be found in Table 2.

Issues with species identification using BRUVS

The capacity to use BRUVS footage to identify sea snakes to species level varied depending on a range of factors. Primarily, the resolution of videos restricted the level of detail available for identification of most sea snakes to species level. Older BRUVS deployments that were recorded on magnetic tapes had low resolution, with just over half of sea snake sightings (51.7%) having enough detail to positively identify to species level. The remainder of snakes on older tapes were either identified to genus level where possible, or classed as unidentifiable. Newer BRUVS deployments that were filmed digitally using GoPros had higher resolutions, and allowed for a larger proportion (82.1%) of sighted sea snakes to be positively identified to species level (Fig. 3). Nevertheless, identification of sea snakes in the *Aipysurus* and *Hydrophis* genera to species level using external characteristics alone is difficult without closer inspection of scalation around the body and head (Rasmussen et al. 2014). To avoid misidentification and subsequently, inaccurate analyses of occurrence and distribution pattern, plotting and analyses of BRUVS data were restricted to the genus level (i.e. *Aipysurus* sp., *Emydocephalus* sp. and *Hydrophis* sp.) with an additional category for sea snakes that were unidentifiable due to low resolution or reduced visibility in video footage (Fig. 4).

Table 2. Environmental and physical parameters measured at each BRUVS site, and used as predictor variables in Multivariate regression tree analyses, gradient boosted models and subsequent predictive models.

Environmental/Physical Parameter	Range	Mean ± SD
Depth (m)	3.70 – 120	38.24 ± 20.34
Latitude (decimal degrees)	-25.6 – -9.87	
Longitude (decimal degrees)	112.9 – 129.6	
Sea surface temperature (˚C)	22.88 – 30.43	27.81 ± 2.11
Chlorophyll a concentration (mg m^{-2} day^{-1})	0 – 4.07	0.31 ± 0.35
Proximity to the coast (m)	0 – 248600	66470 ± 62613
Proximity to reef systems (m)	0 – 246900	45980 ± 67363
Proximity to seagrass habitats (m)	0 – 351400	124200 ± 106802
Proximity to mangrove habitats (m)	2340 – 295200	172900 ± 79030
Proximity to freshwater source (m)	4605 – 365600	213500 ± 98402
Abundance of fish in BRUVS	1 – 5232	78.51 ± 136.33
Species Richness of fish in BRUVS	1 – 77	20.1 ± 14.64
Habitat Complexity Index (1-4)	1 – 4	
Marine Plant / Algae cover (%)	0 – 100	5.21 ± 15.28
Soft coral cover (%)	0 – 100	3.47 ± 10.78
Hard coral cover (%)	0 – 100	11.54 ± 25.98
Filter feeder cover (%)	0 – 90	3.82 ± 9.51
Bare sand / mud cover (%)	0 – 100	32.07 ± 38.07
Encrusting algae / rubble cover (%)	0 – 90	7.20 ± 14.87

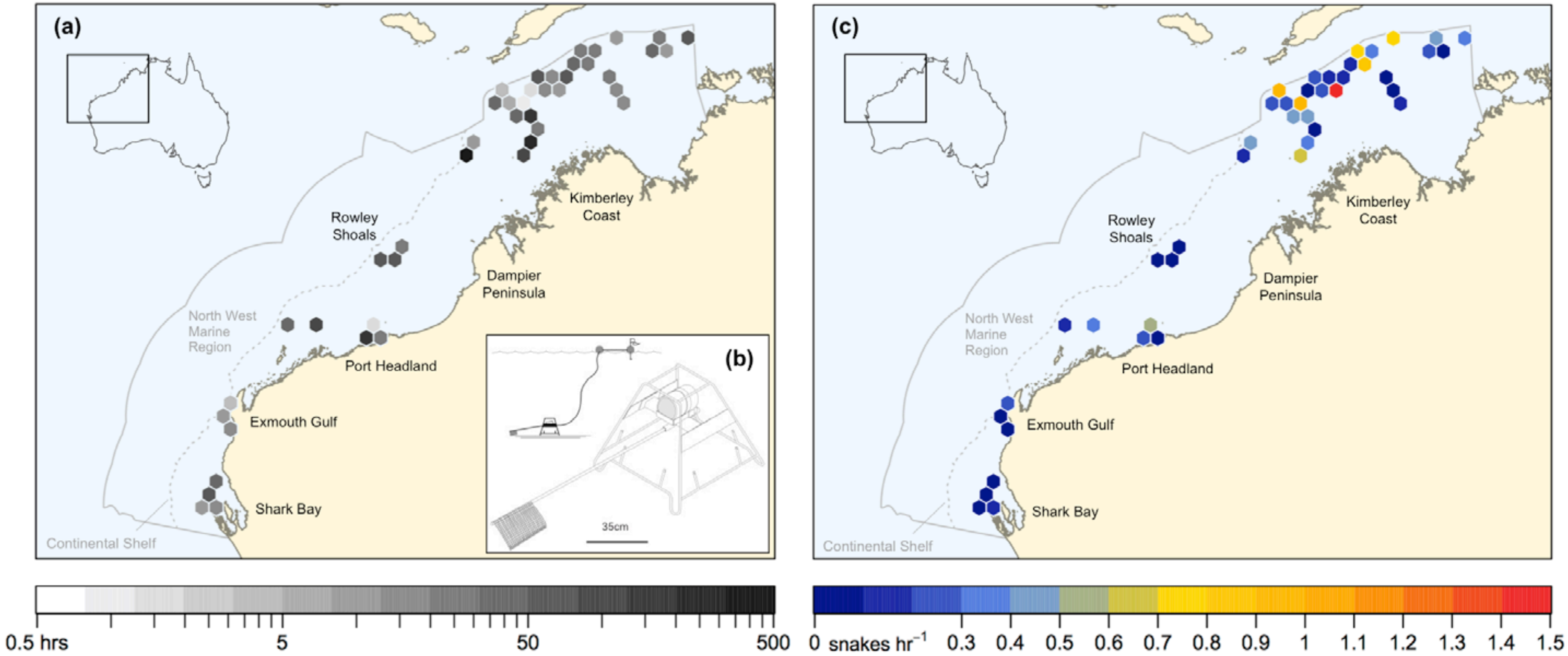


Figure 2. (a) Locations of baited remote underwater video station (BRUVS) deployments along the West Coast of Australia. Researchers from the Australian Institute of Marine Science conducted BRUVS deployments from 1999 – 2016. (b) An example of the set-up of single camera BRUVS used to sample the presence of marine fauna. (c) Sightings of sea snakes per hour of video footage within the NWMR, with sites in the Northern Oceanic Shoals recording high rates of sea snakes. A total of 2290 BRUVS were deployed in the region, with 582 sea snakes sighted on 482 BRUVS.

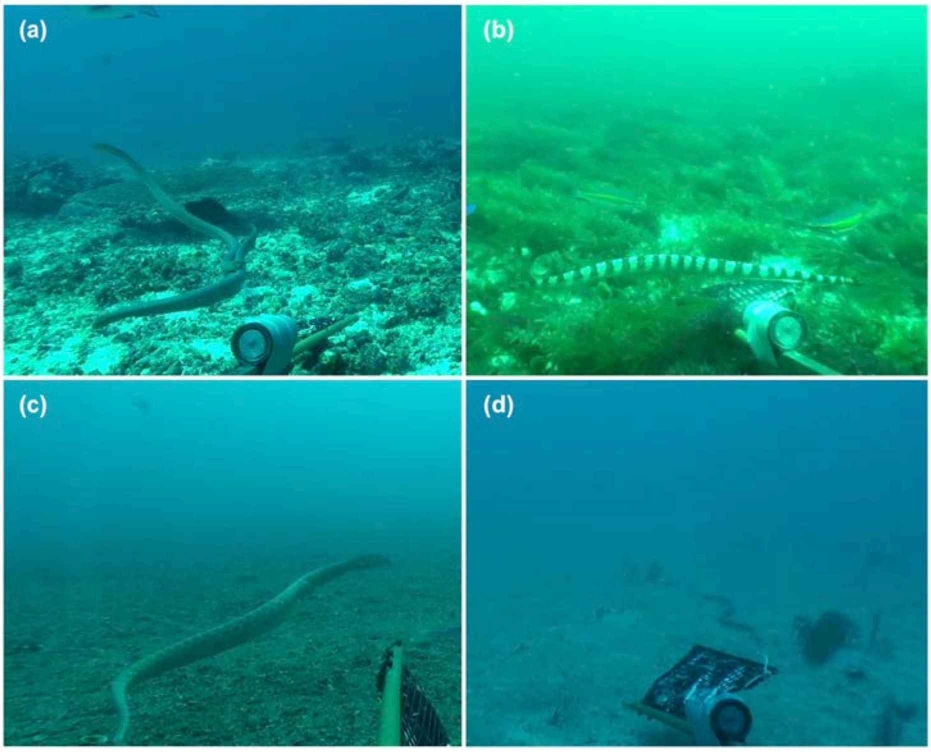


Figure 3. Screen-captures of sea snakes observed on BRUVS (a) two individuals of *Aipysurus laevis* displaying courtship behaviour, (b) *Emydocephalus annulatus*, (c) *Hydrophis ocellatus*, (d) 'other species', category for unidentifiable snakes.

Factors influencing sea snake assemblage within the NWMR

Occurrence and relative abundance (*MaxN*) of sea snakes recorded from BRUVS footage were used to conduct a multivariate analysis to examine how environmental and physical covariates influenced the assemblage of sea snakes within the NWMR. A multivariate regression tree analysis (MRT; De'ath 2002) was used to determine the influence of 19 factors (Table 2) on the assemblage of four groups of sea snakes (*Aipysurus* genus, *Emydocephalus* genus, *Hydrophis* genus and other unidentifiable sea snake species) and identify which genera were indicator group responsible for the MRT groupings, which represent assemblages. Indicator groups are species (or genera in this case) that characterise a given assemblage, and often represent the group that influence the diversity and assemblage of animals encountered within a habitat (Dufrêne & Legendre 1997).

Multivariate regression tree analyses are a useful tool for analysing complex ecological data with high order interactions and non-linear distributions while producing models that are easy to interpret (De'ath 2002). The MRT attempts to explain the variation in the response variable (*MaxN* of each sea snake category) by repeatedly partitioning the data into homogeneous groups based on a single explanatory variable (e.g. depth, proximity to closest reef). In this analysis, group and site variables were standardised to the same mean to increase the strength of the relationship between group dissimilarity and ecological distance gradients (see De'ath 2002). A Dufrêne-Legendre index (DLI) was calculated for each group at each node of the resulting tree (Dufrêne & Legendre 1997). The group with the largest DLI at each node can be considered as the indicator group for that assemblage. MRT analyses were conducted using all BRUVS samples (n=2290). The MRT analyses were conducted using the 'mvpart' package in the *R* environment (R Development Core Team 2016).

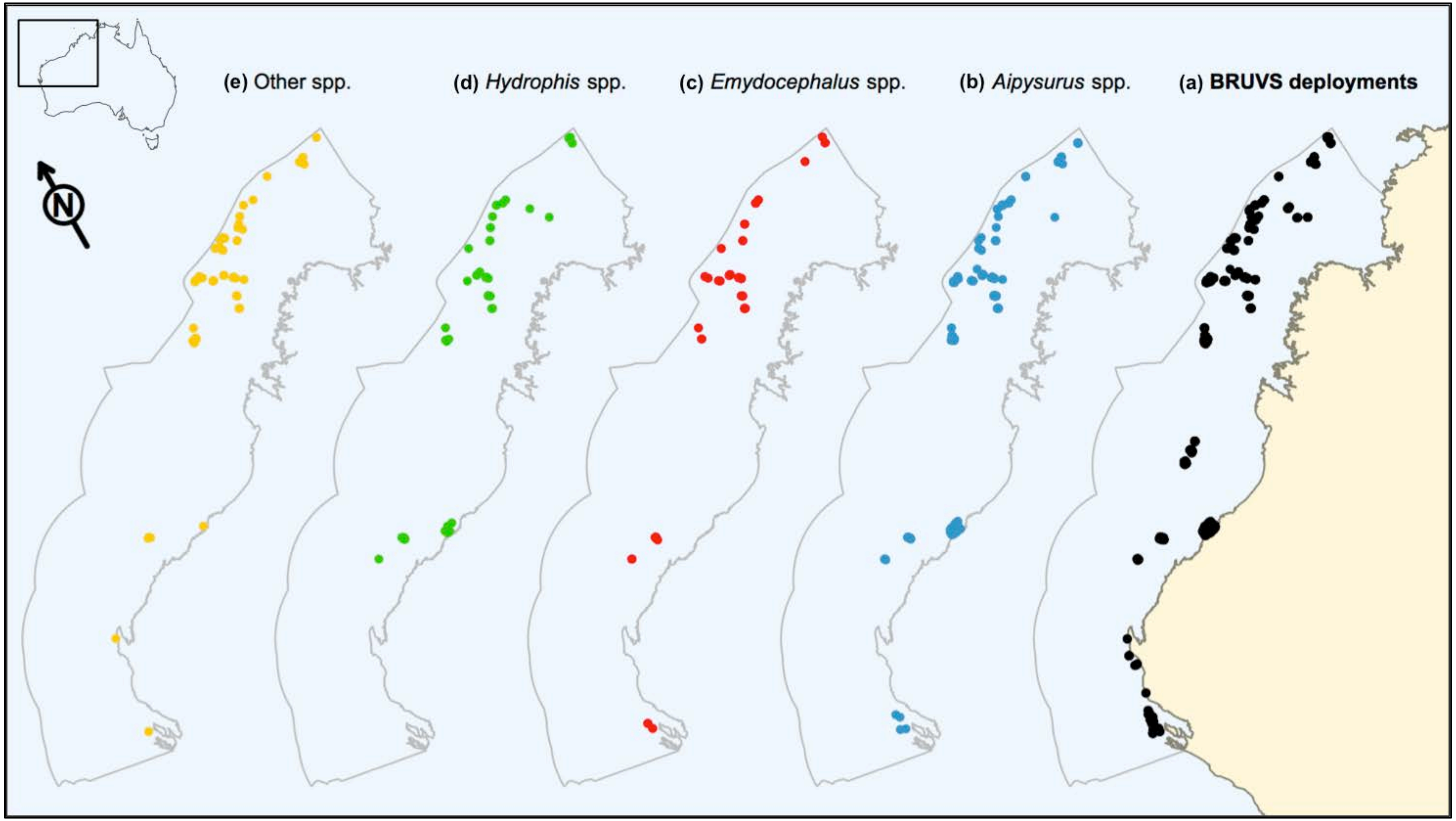


Figure 4. Sequential plots (from right to left) of (a) sites of all BRUVS deployments within the NWMR. Subsequent plots represent locations of BRUVS where sea snakes of the respective groups were sighted (b) *Aipysurus* species, (c) *Emydocephalus* species, (d) *Hydrophis* species and (e) other unidentified species.

The majority of identifiable sea snakes sighed in the BRUVS dataset were in the genus *Aipysurus* (63%) followed by *Hydrophis* (12%) and lastly *Emydocephalus* (11%). Unidentifiable sea snakes comprised 14% of all sightings, with the majority of them detected between 1999 and 2004 when the BRUVS deployments employed magnetic tapes and older video recording devices. The MRT analysis resulted in an optimal tree of four splits (Fig. 5) with a cross-validation relative error of 0.84. The optimal tree grouped the results based on the proximity of BRUVS deployment to seagrass habitats ('DistSea') and proportion of hard coral cover at the BRUVS site. The primary split was based on the distance the BRUVS was from seagrass habitats, with sites less than 56 km from seagrass habitats dominated by *Aipysurus* species. This assemblage represents inshore BRUVS sites within Shark Bay and the Pilbara coast, which were in close proximity to sea grass meadows. The secondary split was based on the hard coral cover at each BRUVS site. As expected, sites with more than 5% coral cover were dominated by reef-associated species in the *Aipysurus* genus, with this genus identified as the indicator group in sites with high coral cover. Sea snakes in the *Hydrophis* and other groups dominated in sites with less than 5% coral cover, with sea surface temperature playing a significant role in defining assemblages in non-reefal habitats.

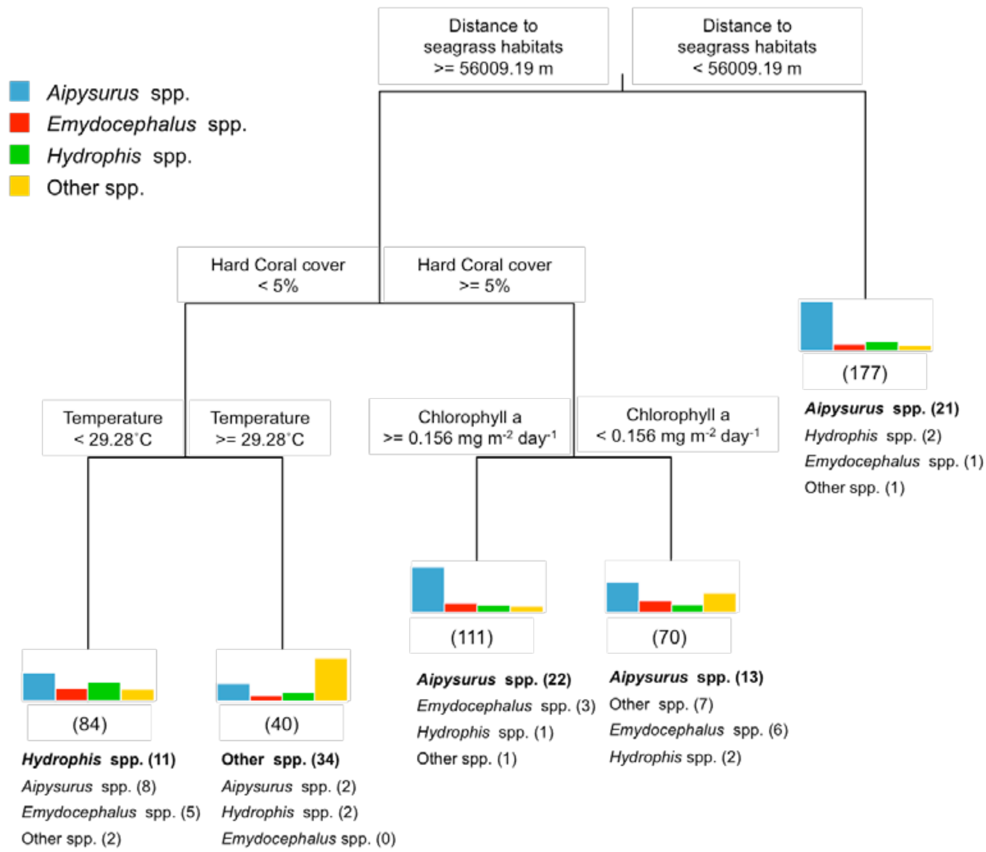


Figure 5. The optimal multivariate regression tree explaining the occurrence of sea snake groups explained by 19 environmental/physical predictors at each BRUVS deployment site.
Bar plots show the multivariate species mean at each node with the number of sites included indicated in parentheses below it. The DLI was calculated for each sea snake group at each node, with groups in bold representing the indicator group of each assemblage.

Factors influencing habitat associations and occurrence

The presence/absence of each species at each BRUVS was used to determine how environmental/physical factors influenced species occurrence. Boosted regression tree (BRT) analyses were used to examine how the measured spatial and environmental variables (Table 2) influenced the occurrence of each genus of sea snake within the NWMR continental shelf. The BRT analysis uses a tree based model that relates a response variable to multiple predictors using recursive partitioning with the added advantage of improved predictive performance achieved by boosting (De'ath 2007, Elith et al. 2008).

The BRT analysis fitted a proportion of the data (training set), into several initial models consisting of simple classification trees. The remaining data (testing set) were then run though the parameters of the initial model trees and at each stage of the analysis, each explanatory variable was weighted according to predictive error. The weighting of each variable was determined by a user-defined learning rate (*lr*). A large *lr* results in an over-fitted model and a small *lr* results in diminished model performance (Elith et al. 2008). Model performance was determined by cross validation of the training set and the optimal number of trees for each model. The BRT analysis then ran these models with the weighted data until the predictive error was at its minimum.

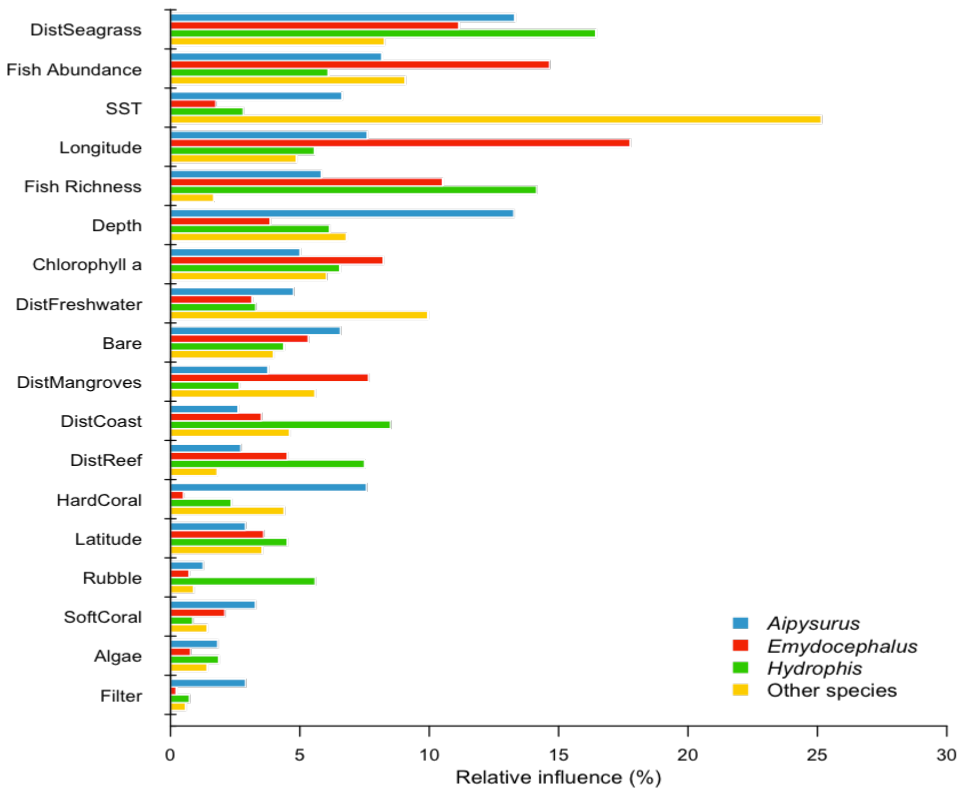


Figure 6. Relative influence of physical/environmental predictors on the presence/absence of each sea snake group based on 5-fold cross validated boosted regression tree model.

The relative influence of each predictor in the BRT analysis was calculated by the number of times the variable was selected for splitting and the squared improvements to the predicted values resulting from the splits (Friedman 2001). Higher percentages of relative influence indicate a stronger influence of predictors on the response variable. BRT analyses were run in the R environment using the 'gbm' and 'dismo' packages (Elith et al. 2008). The presence/absence of each group of sea snake was used as the response variable, a training set of 0.5 was chosen and a *lr* of 0.001, with a 5-fold cross validation used to find the optimal number of trees.

The BRT analysis of the BRUVS dataset collected within the NWMR (n=2290) showed that the presence of sea snakes was most strongly influenced on average by the proximity to seagrass habitats ('DistSeagrass'), followed by the abundance of fish recorded on each BRUVS ('Fish Abundance') and the sea surface temperature ('SST'; Fig. 6). The occurrence of sea snakes in the genera *Aipysurus* and *Hydrophis* were most strongly influenced by the distance to the closest seagrass habitats, whereas the presence of sea snakes in the genus *Emydocephalus* and 'other unidentified species' were most strongly influenced by longitude ('lon') and sea surface temperature ('SST') respectively (Fig. 6). Partial dependency plots of the four most influential factors in the BRT models suggested that *Aipysurus* species were most likely to be sighted on BRUVS closer to seagrass habitats (< 200 km) in depths less than 40 m, with moderate to low levels of fish abundance (Fig.7). In contrast, *Hydrophis* species were more likely to be sighted in areas further away from seagrass and reef habitats (> 200 km), with fewer numbers of species of fish sighted on BRUVS. These results are broadly consistent with the MRT analysis, where proximity to seagrass, fish abundance and fish species richness influences sea snake occurrence and diversity. The optimal BRT models were also used alongside multiple explanatory variables (Table 2) to predict the probability of occurrence of sea snakes over a spatial scale using the presence/absence data from the BRUVS dataset.

The BRT models were used to produce probability of occurrence maps for the four main groups of sea snakes assessed using the BRUVS dataset (Fig. 8) as well as an overall map to identify areas within the NWMR that comprise ideal environmental and physical parameters for sea snake occurrence (Fig. 9). These maps provide a 'snapshot' baseline view of sea snake distribution patterns and are based on the limited spatial coverage of BRUVS deployments (see Fig 2); therefore care must be taken when interpreting the results of the BRT predictive outputs. Increased information about sea snake assemblages and occurrence in locations with low BRUVS coverage is needed (i.e. central and southern NWMR, Kimberley and Pilbara coasts) to assess the accuracy and ground-truth these models. However, these models consistently show that locations along the mid-shelf shoals of the Kimberley coast and oceanic shoals north of the Ashmore/Hibernia reef complex have habitats that are likely to support sea snake populations (Figs. 8 and 9). These findings are consistent with previous observations made in these regions by Moore and Richards (2014), who found mid-shelf shoals along the Kimberley coast supporting healthy sea snake populations. Future surveys and long-term monitoring programs are required in these areas to assess and ground-truth model outputs, and examine in more detail how changes in environmental parameters (e.g. water temperatures and habitat quality) may affect sea snake assemblages and population health over seasonal and decadal time scales.

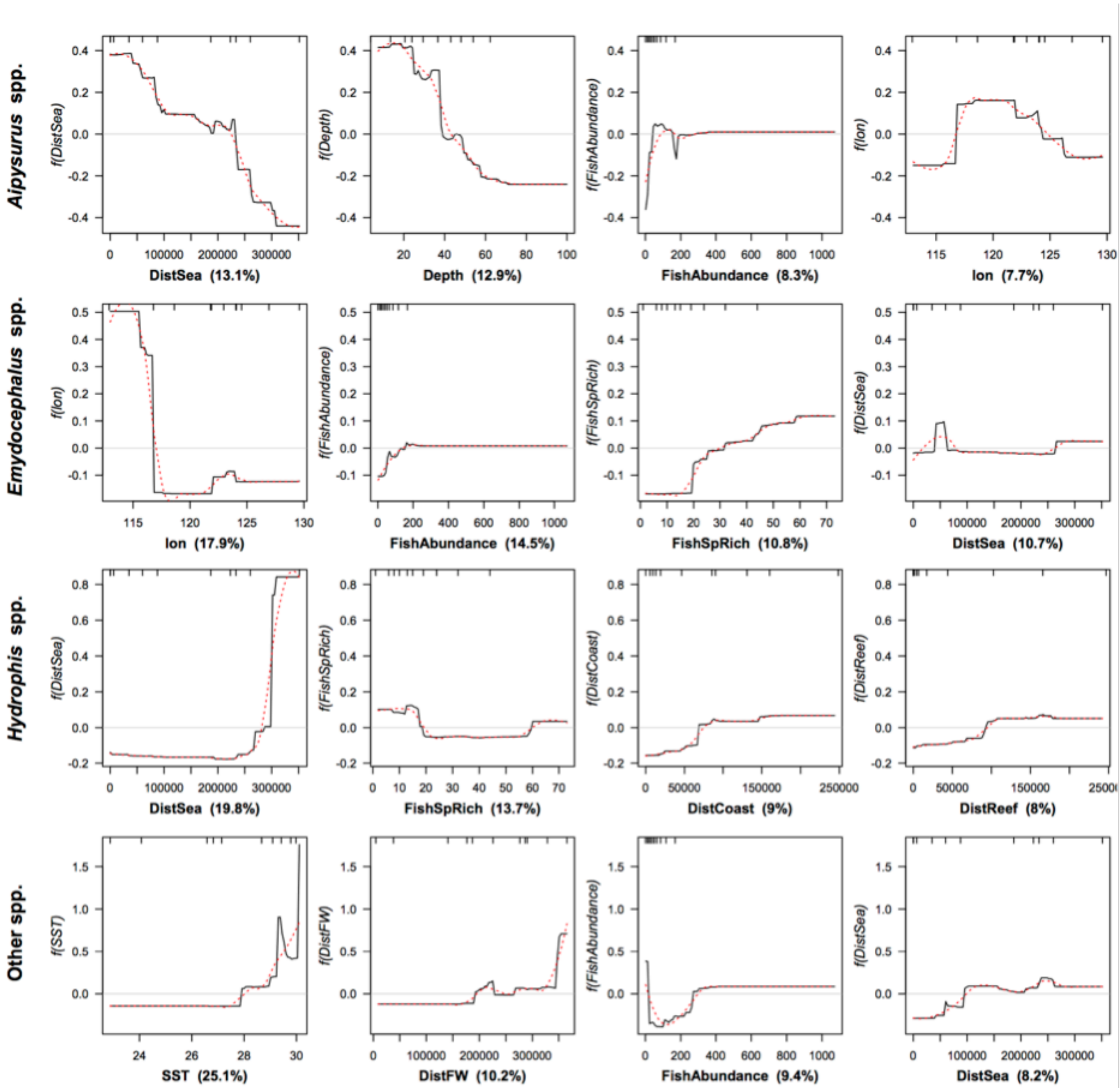


Figure 7. Partial dependency plots for boosted regression tree (BRT) analysis. Plots show the fitted functions of the probability of occurrence of sea snakes with the four most influential predictors for each group in the BRT model for all BRUVS deployed within the NWMR (n=2208). Broken red lines represent a smoothed line highlighting the trend in the probability of occurrence across each influential predictor. X-axes represent continuous variables: proximity to seagrass habitats ('DistSea', m), proximity to exposed reef edge ('DistReef', m), proximity to the coast ('DistCoast', m), proximity to freshwater sources ('DistFW', m), number of fish sighted on BRUVS videos ('FishAbundance'), number of species of fish sighted on BRUVS videos ('FishSpRich'), longitude of BRUVS deployment ('lon'), depth ('Depth', m) and mean annual sea surface temperature at BRUVS location ('SST', ˚C).

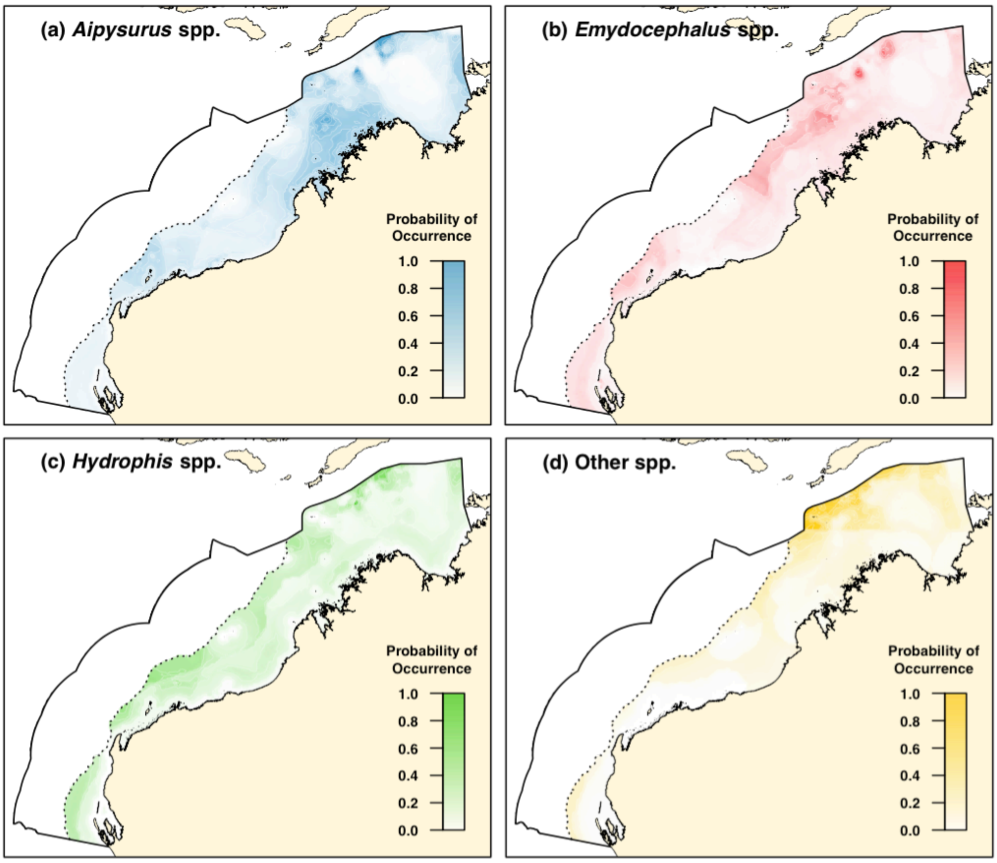
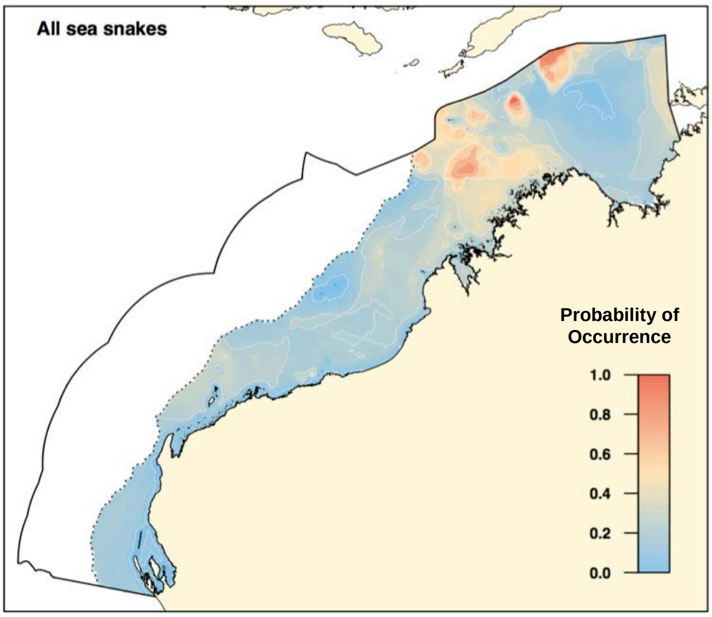


Figure 8. Probability of occurrence plots based on gradient boosted regression models for each sea snake group, assessed using 19 environmental/physical predictors (Table 2) from 2290 BRUVS deployments within the continental shelf (< 1000 m depth contour). Contours with darker shades indicate locations with a high probability of sea snake occurrence, indicating habitats and environmental parameters in those locations are ideal for the presence of sea snakes of that group. Caution should be taken when interpreting these maps, as models are unlikely to accurately predict the presence of sea snakes in regions with low BRUVS coverage (e.g. Shark Bay, Pilbara Coast).

Figure 9. Probability of occurrence of all sea snakes within the NWMR continental shelf (<1000 m depth contour) based on a BRT model using 2290 BRUVS deployments and 19 environmental and physical predictors (Table 2). Contours with warmer colours indicate regions with a higher probability of sea snake occurrence, and indicates habitats ideal for sea snake presence. Care should be taken when interpreting this map, as the model is unlikely to accurately predict the presence of sea snakes in regions with low BRUVS coverage (e.g. Shark Bay, Pilbara Coast, Southern NWMR).



Distribution and occurrence of conservation priority species

Limitations in species-level identification of sea snakes using BRUVS meant that information relating to the three priority species (i.e. *A. apraefrontalis*, *A. foliosquama* and *A. fuscus*) was inadequate. Therefore, other sources of data were used to identify patterns in distribution and occurrence for these three species. Data sources were selected based on the reliability of geo-referenced positions recorded for sea snakes within the NWMR, as well as sources that reported reliable species-level identification, which were corroborated by taxonomic specialists using either photographic evidence or physical specimens (e.g. museum specimens). Firstly, records of sea snakes obtained from the BRUVS data in the current project were used where positive species-level identification was possible. However, as the three priority species were not sighted in this dataset, other sources of data were also integrated. Other data sources included the Atlas of Living Australia ('ALA'), which collates geo-referenced reports of marine fauna including sea snakes collected by researchers and stored as museum specimens, or submitted by researchers that conducted field surveys. Sea snake sightings were also obtained from the Reef Life Survey ('RLS') program that catalogues the presence of marine life, including sea snakes, at surveyed reef systems around the world. Data from fisheries-independent trawl surveys conducted by the Western Australian Department of Fisheries ('Fishery') and past underwater visual census ('UVC') data from previous studies (D'Anastasi et al. 2016a) that recorded these species were also included to this analysis.

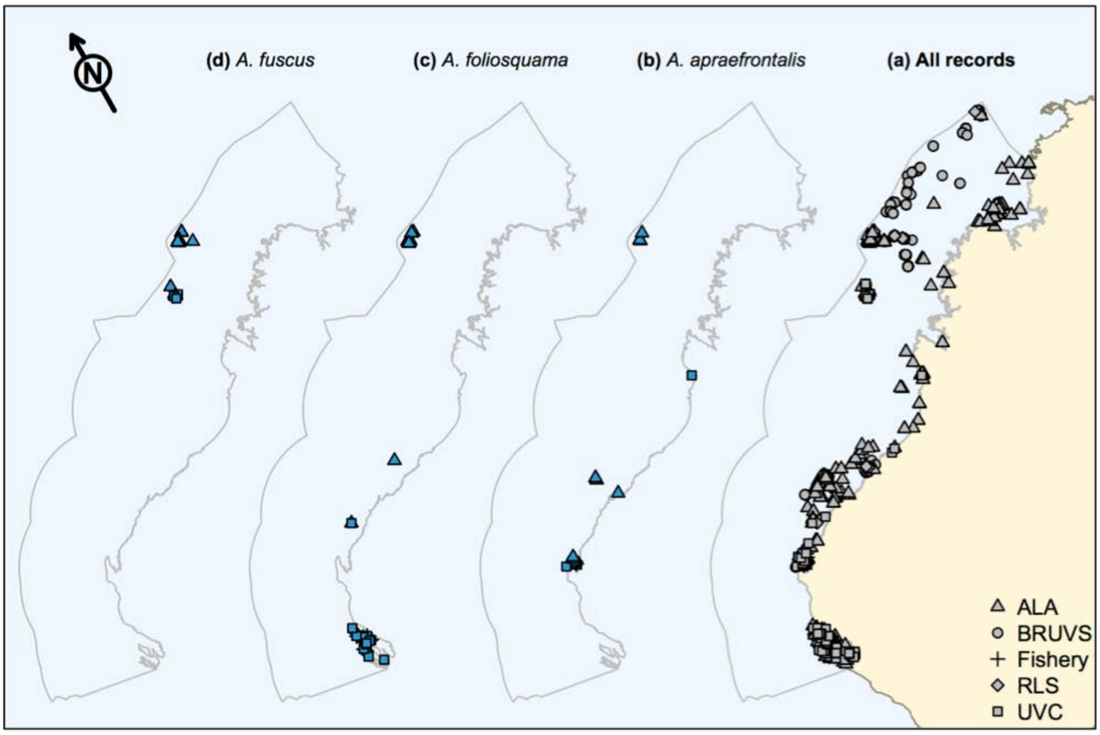


Figure 10. Sequential plots (from right to left) of (a) all geo-referenced records of sea snakes within the NWMR collected by multiple data sources ['ALA': Atlas of Living Australia; 'BRUVS': current study dataset; 'Fishery': Western Australian Department of Fisheries trawl surveys; 'RLS': Reef Life Survey program and 'UVC': past surveys conducted by D'Anastasi et al. (2016a)]. Subsequent plots show the distribution of the three priority species (b) *Aipysurus apraefrontalis* (c) *A. foliosquama* and (d) *A. fuscus*.

Records of 1849 sea snakes from 21 species within the NWMR were used to produce occurrence and distribution maps (Fig. 10 a; see Appendices for maps for each species). BRT models were also constructed using the records of the three priority species (Fig. 10 b,c & d) to produce probability of occurrence maps to identify potential habitats and areas within the NWMR continental shelf where these species are likely to occur. Models used 10 out of the 19 environmental and physical predictors used previously (Table 2), such as epibenthic composition (i.e. Coral cover, Habitat complexity index) and fish species richness and abundance were not available for the majority of the recorded locations. The resulting model outputs showed that the Northern oceanic shoals, the remote northern reef systems (e.g. Ashmore and Scott Reef Complexes) and mid-shelf shoal habitats along the Kimberley and Pilbara coasts were likely ideal habitats for *A. apraefrontalis* and *A. foliosquama* (Figs. 11 a & b), with the Northern oceanic shoals important habitats for *A. fuscus*. The model for the full dataset showed that in general, coastal and mid-shelf regions along the Kimberley coast are important habitats for sea snake populations, with a large proportion of records along the northern Kimberley coast, central Pilbara coast and Shark Bay (Fig. 11d). Increased resolution of regional data on habitat coverage, fish abundances are required to re-evaluate and refine models for sites with high occurrences of these species (i.e. Shark Bay and Exmouth Gulf) to more accurately assess habitat associations and probability of presence of sea snakes at a finer scale.

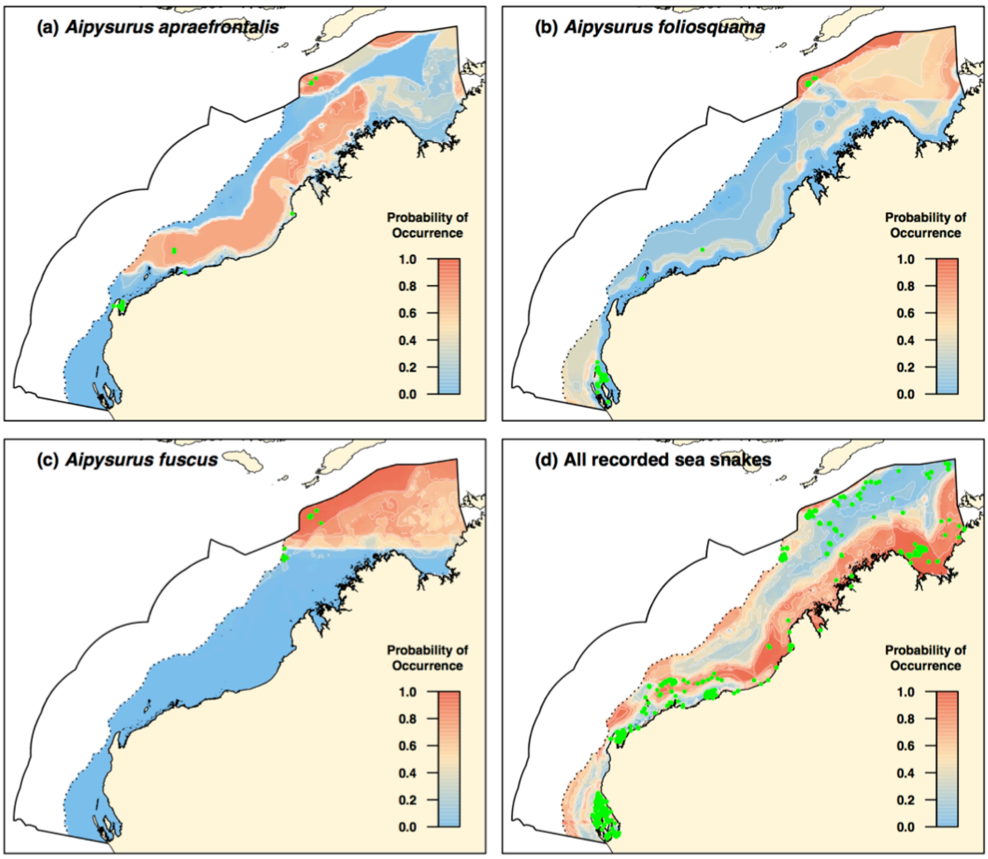


Figure 11. Probability of occurrence plots based on gradient boosted regression models for the three priority species (a) *A. apraefrontalis*, (b) *A. foliosquama* and (c) *A. fuscus* and (d) for all records within the NWMR. Models were assessed using 10 environmental/physical predictors sourced from remote sensing data within the continental shelf (< 1000 m depth contour). Contours with warmer colours indicate regions with a high probability of occurrence, indicating habitats and environmental parameters in those locations are ideal for the presence of that species of sea snake. Green points indicate locations where sea snakes were recorded.

Assessing sea snake interactions with trawl fishing activity

Interactions with fishing activity remain a critical concern for sea snake populations in Australian waters (Milton et al. 2009), however limited data are available to assess what impact current fishing activities have on sea snake populations within the NWMR. Preliminary analyses were conducted on data from scientific demersal trawl surveys conducted by the Western Australian Department of Fisheries (WA DoF) within two coastal sites, Exmouth Gulf (August and October 2014; March – May and September-October 2015) and Shark Bay (August and November 2014; February – June, August and November 2015; February – May 2016)(Fig. 12). Surveys consisted of a total of 15 trawls within Exmouth Gulf that ranged from 60 – 150 min (total effort 23.7 hrs) and 80 short trawls within Shark Bay, ranging from 20 – 30 min (total effort 29.4 hrs). Sea snakes captured in these surveys were photographed and identified to species level and live snakes were released in healthy condition. Trawl survey data provided critical information on the range extension of two of the Critically Endangered species found within the NWMR (*A. apraefrontalis* and *A. foliosquama*) (D'Anastasi et al. 2016b).

Catch composition from both bays indicated that sea snakes were caught in low numbers within Exmouth Gulf (16 sea snakes) as compared to Shark Bay (109 sea snakes); nevertheless, the two priority species were encountered in both coastal habitats (Fig 13). Sea snake catch in Exmouth Gulf was low despite longer trawls, whereas relatively short trawls within Shark Bay (~20 min) yielded similar numbers of sea snakes (Fig 14 a). Survivorship curves were constructed using a binomial logistic regression examining whether trawl duration influenced if sea snakes were alive or dead upon landing on deck (Fig. 14 b). 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

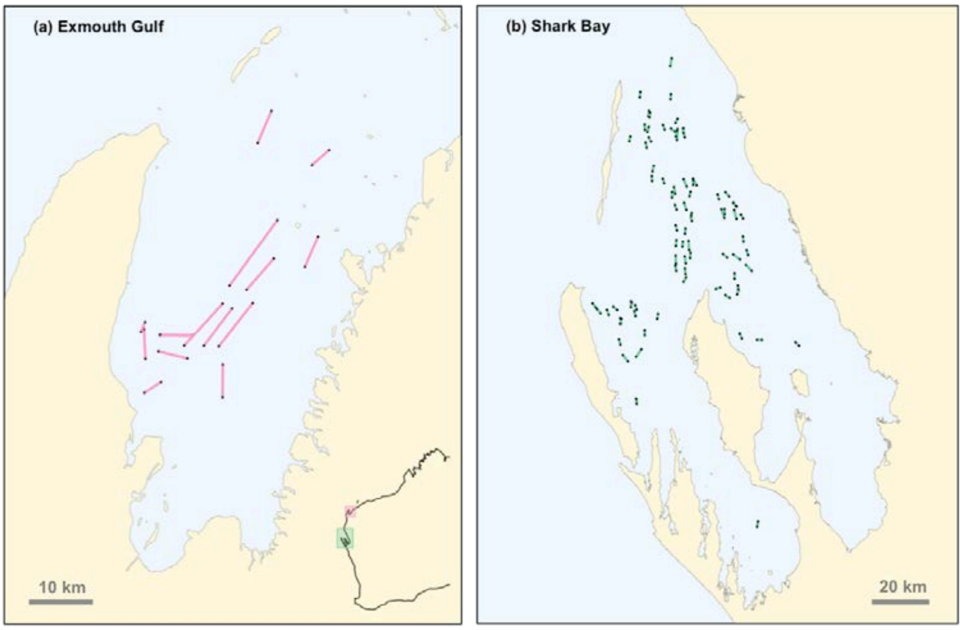


Figure 12. Locations of demersal trawl surveys conducted by WA DoF within (a) Exmouth Gulf and (b) Shark Bay. Lines indicate tracks of trawls conducted within each site.

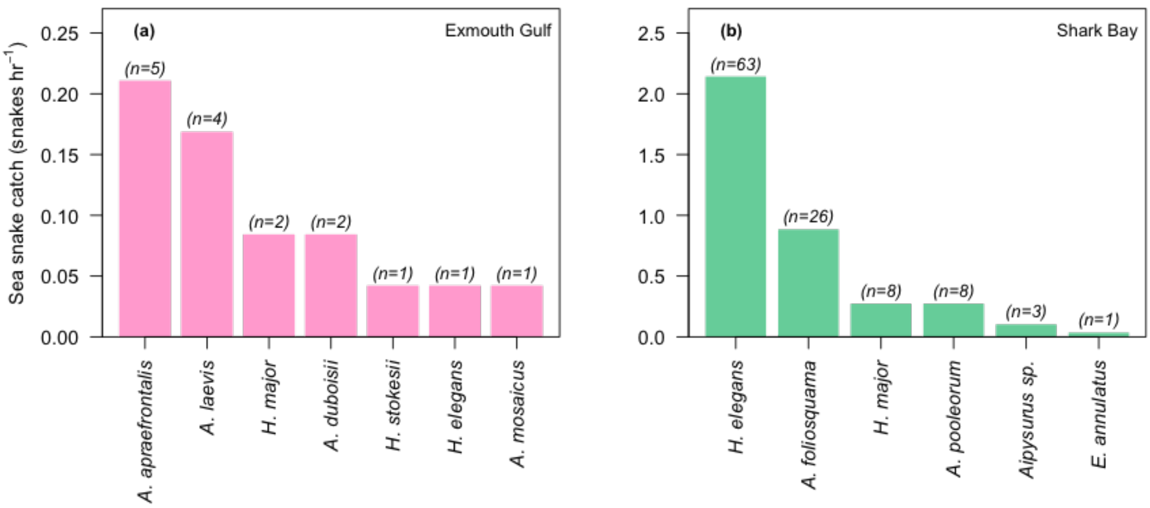


Figure 13. Catch rate and species composition of sea snakes in trawl surveys within (a) Exmouth Gulf and (b) Shark Bay. Numbers of each species is represented within parentheses above each bar.

surveys could be robust to short to moderate durations of trawls. Post-capture survival in sea snakes is extremely variable depending on the species and fishing practices, with most species encountered in commercial trawl fisheries within Australian waters displaying high short and long-term survival post capture (Wassenberg et al. 2001, Milton et al. 2008). 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). Life-history information of commonly encountered sea snakes in fisheries within the NWMR and estimates of maximum sustainable yield is needed to assess how fisheries interactions may affect population structure and identify particular species or life-stages that may be vulnerable to increased fishing efforts in particular habitats (Pears et al. 2012).

Estimating species-level short- and long-term survival was not possible with the current dataset, and more data from similar fisheries-independent and fisheries-dependent records are needed to assess how much variation there is in survival rates within and between commonly encountered species in the NWMR and between different fishing practices (e.g. trawl fishing, trap fishing). As two of the three priority sea snake species were encountered in the present dataset, further analysis of fisheries data is necessary to assess what impact fishing activities have on these species, and specifically to look at short and long-term post capture survival in these species. Increased fisheries-independent and dependent data is also required to assess if the preliminary results from the present study still hold true over the wider fisheries within the NWMR, and identify any particular species or life-stages that may be susceptible to fishing activity in these regions.

The present trawl survey dataset has highlighted the importance of fisheries-independent and dependent sampling to understand the spatial distribution of rare sea snake species, otherwise difficult to survey using other methodologies (e.g. BRUVS or UVC). The presence of populations of *A. apraefrontalis* and *A. foliosquama* within coastal WA, in previously unknown habitats in the case of *A. foliosquama*, from the WA DoF dataset has necessitated

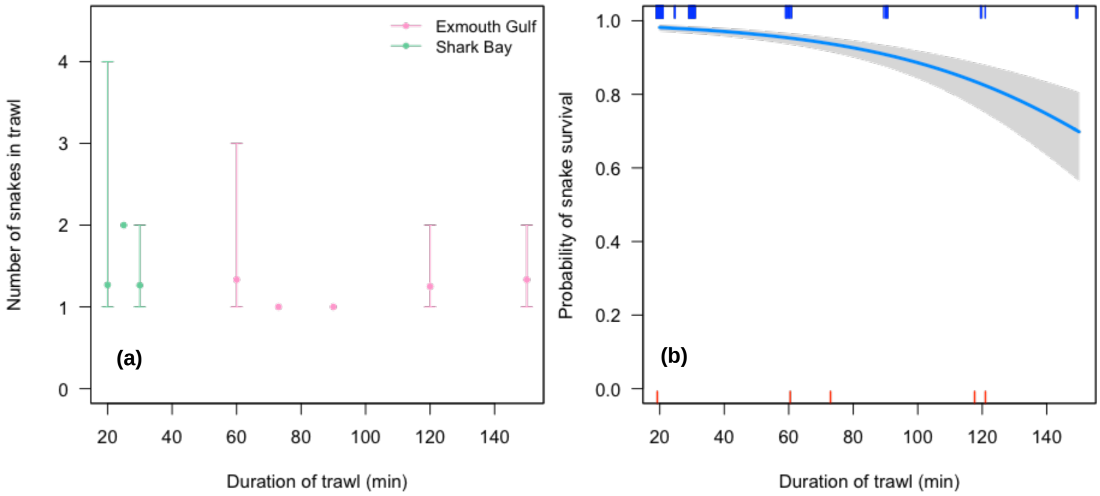


Figure 14. (a) Sea snake catch within Shark Bay and Exmouth Gulf was high despite short trawl durations. Points represent mean numbers of snakes; with whiskers representing the range. (b) Survivorship curves for full dataset showed that the majority of sea snakes encountered survived regardless of trawl duration.

a re-evaluation of the spatial distribution and habitat use of these species which were previously only associated with coral reef habitats around Ashmore Reef. This new information will potentially have implications when re-evaluating their conservation status.

Conclusions and recommendations

An accurate assessment of the status of Western Australia's sea snakes will require a significant amount of additional data. Synthesis and analyses of available BRUVS and fisheries-independent data on sea snakes within the NWMR has highlighted the scarcity of comparable spatial data for priority sea snake species in the region. The analyses of BRUVS data identified important environmental and physical parameters that influence sea snake assemblages within all habitats in the NWMR. Predictive modelling highlighted the importance of mid-shelf and oceanic shoal habitats for sea snake populations, with regions along the Kimberley coast and within the Northern Oceanic Shoal CMR as locations that are likely to support healthy sea snake populations. However, low coverage of BRUVS in some areas limited the capacity of predictive models to accurately predict sea snake presence in known sea snake hot spots, such as Shark Bay.

Based on the available BRUVS data and analyses conducted we provide some recommendations for future research and data collection to effectively explore the status of sea snakes within the NWMR, including the three species considered high priority (*A. apraefrontalis*, *A. foliosquama* and *A. fuscus*):

- Increased survey effort (using BRUVS or other means) is needed along the mid-shelf shoals along the Kimberley coast as models show these areas are potentially important habitats for sea snakes, particularly for three critical species in the region (Figures 8, 9 and 11)

- Baseline and long-term surveys are needed in important seagrass habitats in shallow coastal habitats around Exmouth Gulf, Shark Bay and elsewhere.
- Increased data are needed from the Northern Oceanic Shoal CMR within the northern sector of the NWMR, as these areas have high abundances of sea snakes.
- Increased information on the connectivity of sea snake populations between remote reef systems and adjacent coastal habitats are required to understand if declines observed in Ashmore and Scott Reef Complexes have influenced sea snake assemblages in adjacent shoal habitats, using genetic approaches (mitochondrial DNA and Single Nucleotide Polymorphisms, preferably using DARTseq for comparability with existing data sets collected by B. D'Anastasi and V. Lukoschek).
- Increased information on sea snake assemblages is required within Rowley Shoals and the central Pilbara coast of the NWMR as currently there is very little data in that region, and is needed to highlight connectivity between high abundance sites in the north and coastal habitats in the south.
- Water temperature was an important environmental parameter that influenced sea snake assemblages in coastal habitats. Behavioural and physiological data is required to assess how variable temperature regimes and heat waves in coastal WA (e.g. the 2010 marine heatwave; Pearce et al. 2011) may influence sea snake persistence and population health. Sea snakes in coastal WA live in habitats close to their thermal maxima (Heatwole et al. 2012). Rising water temperatures and predicted increases in the frequency of heatwaves may play a significant role in deteriorating sea snake population health, with evidence of heatwave induced sea snake population decline observed in Shark Bay (D'Anastasi et al. 2016a).

Interactions of sea snake populations with fishing activity is a primary concern within the NWMR, and there is a need for more fisheries-dependent and independent data to accurately define the status of sea snakes in the NWMR. The preliminary analysis of trawl survey data collected by WA DoF highlighted the importance of such data in identifying spatial distribution patterns of rarely encountered species of sea snake. The collection of species-specific catch data and estimation of maximum sustainable yield for sea snakes within the wider fishery is needed for defining distribution patterns and evaluating the vulnerability of priority species to fishing activities. Scientific and Crew Member Observer programs in trawl and trap fisheries (such as those successfully run in the Commonwealth-managed Northern Prawn Fishery); or photographic records of catch can provide valuable information to help define sea snake catch composition and highlight locations along the NWMR with high overlap between sea snake populations and fishing activity (Courtney et al. 2010). Short and long-term post-release survival rates of sea snakes (particularly the three priority species) are also not well known and should be explored. Further analysis of the spatial extent of fishing activities is needed to understand the extent of interaction between fisheries and the three priority species within the NWMR, and evaluate fishing practices in locations where these interactions may be elevated.

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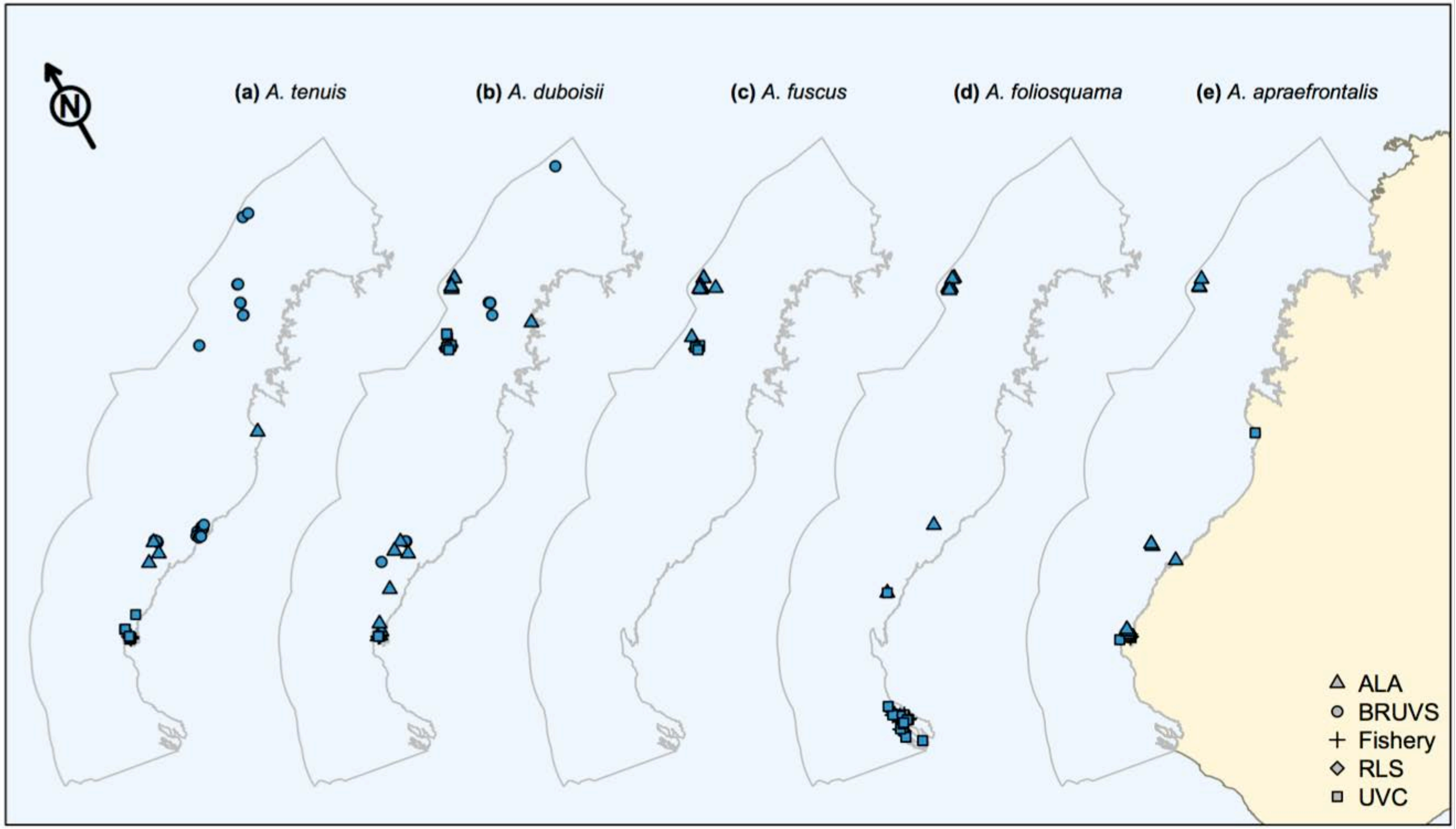
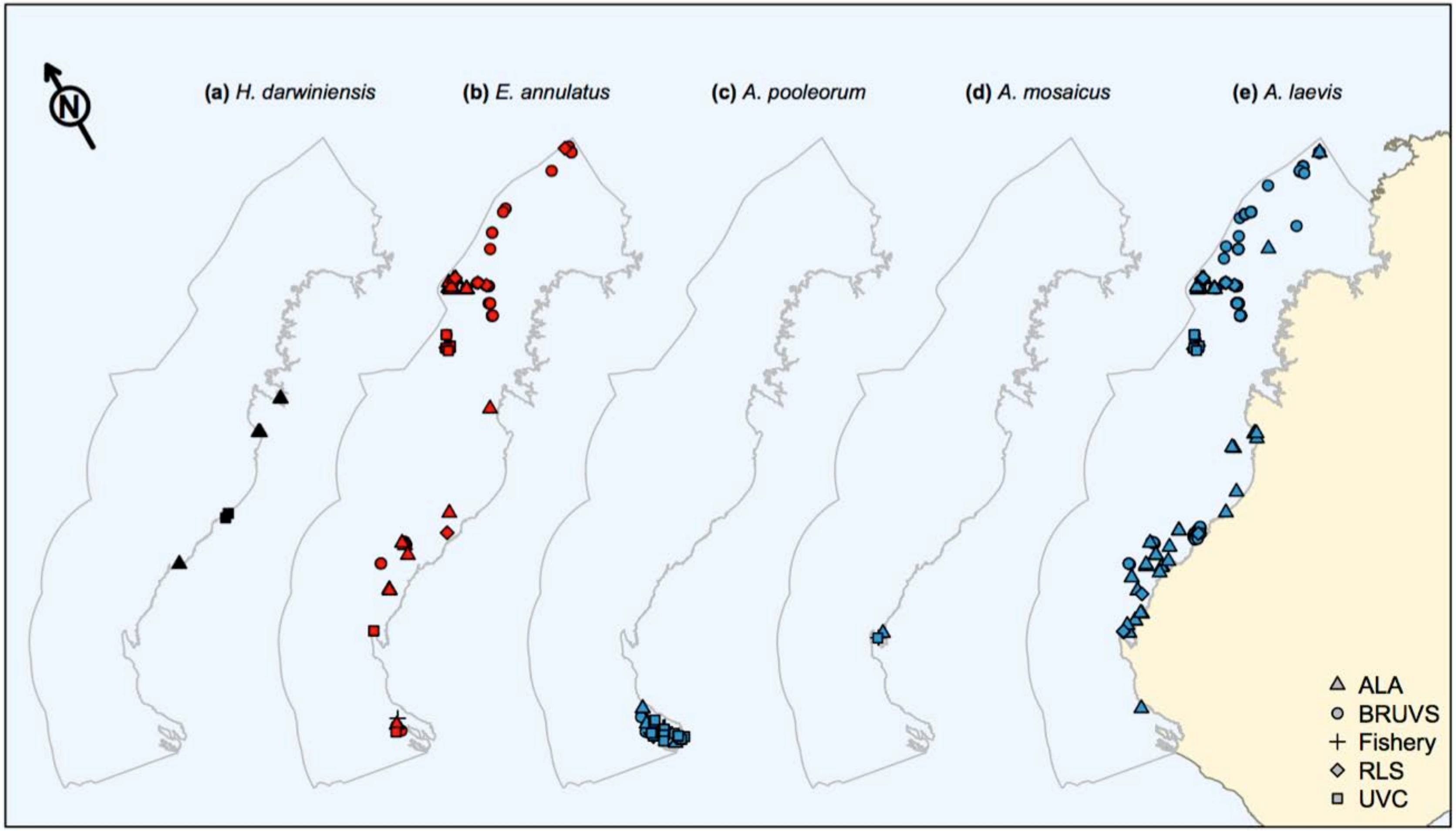
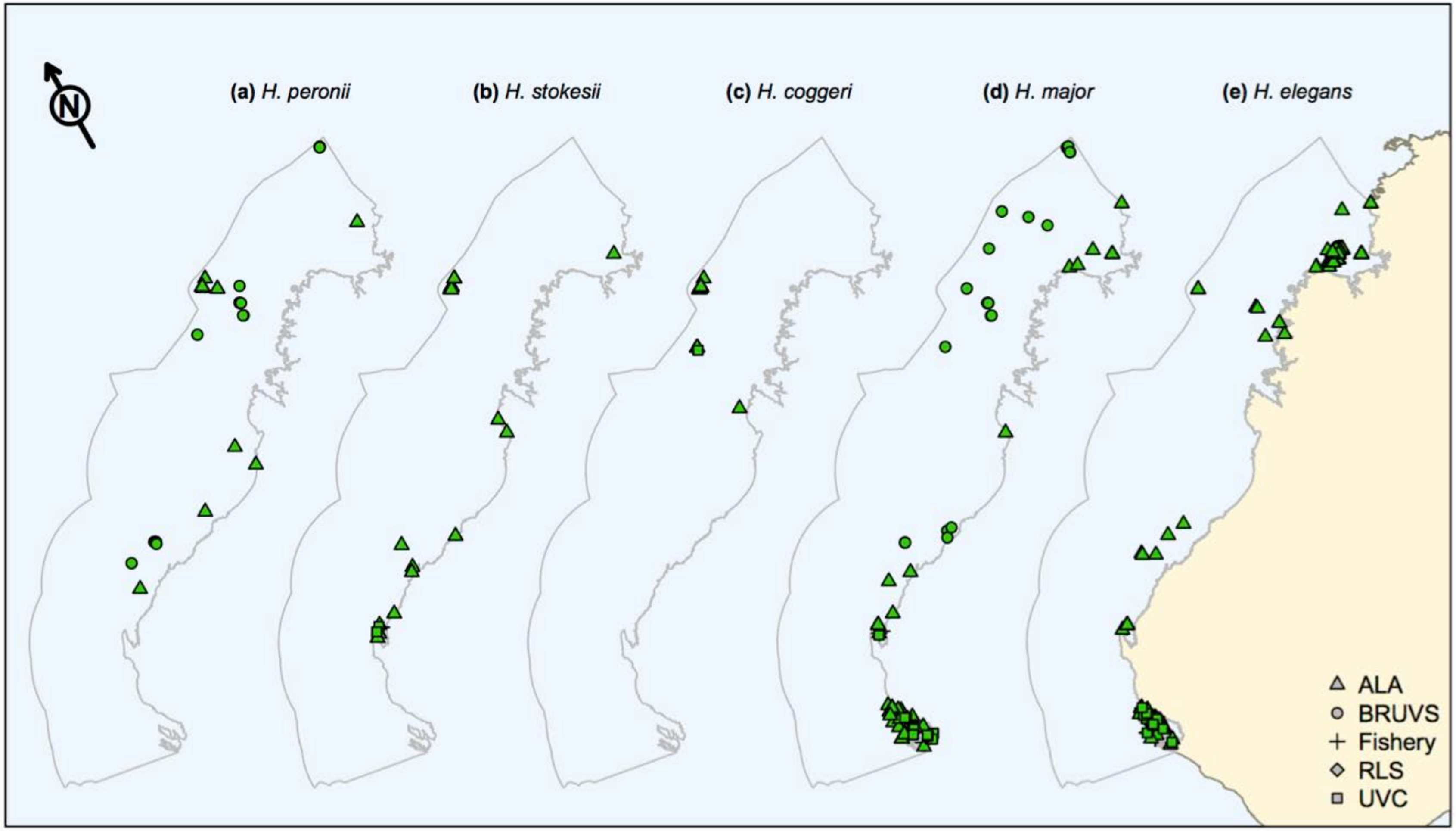
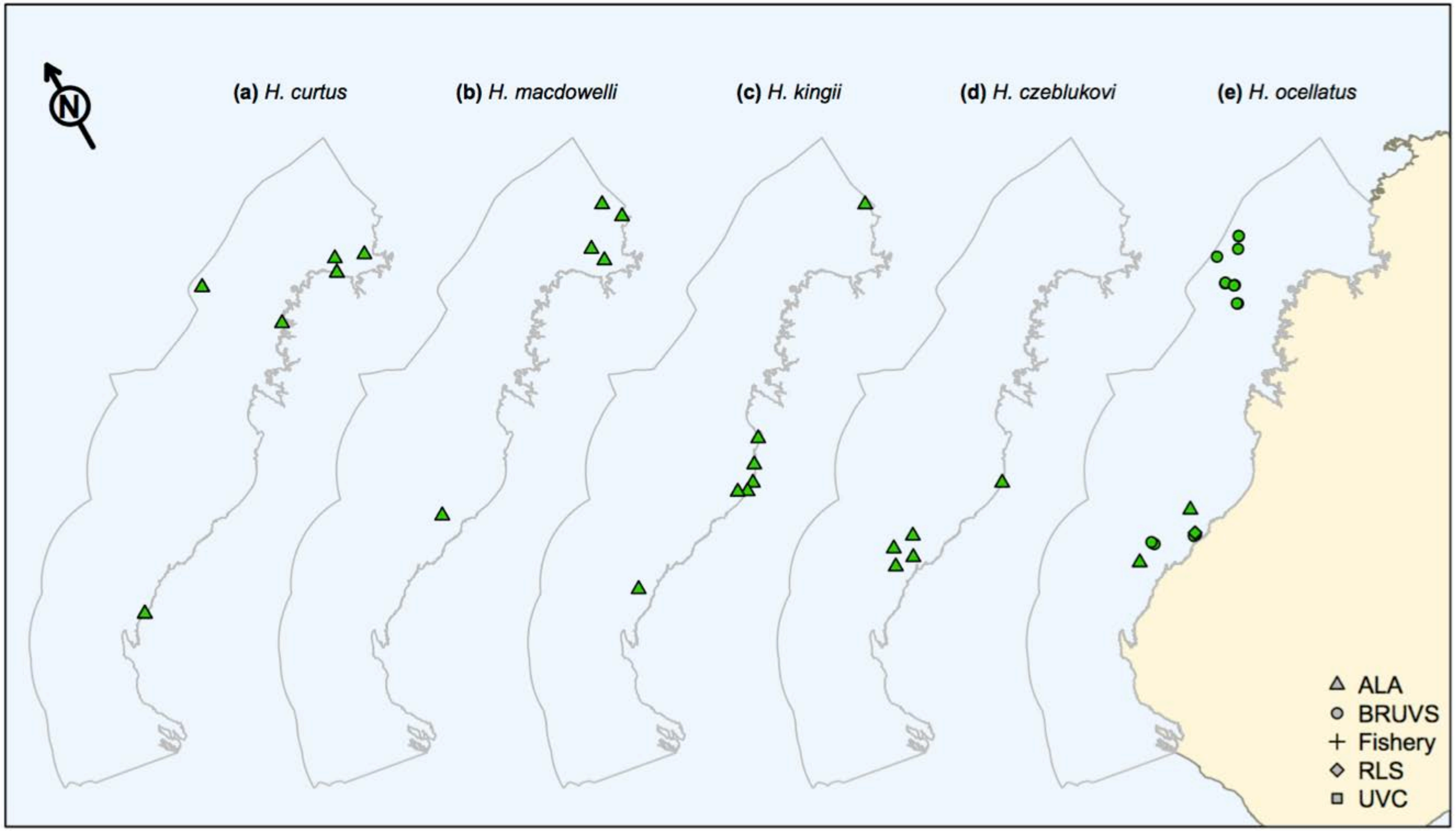
Appendices: Species-specific distribution maps using data from multiple sources within the North West Marine Region




N
(a) H. darwiniensis
(b) E. annulatus
(c) A. pooleorum
(d) A. mosaicus
(e) A. laevis
ALA
BRUVS
Fishery
RLS
UVC


N
(a) H. peronii
(b) H. stokesii
(c) H. coggeri
(d) H. major
(e) H. elegans
ALA
BRUVS
Fishery
RLS
UVC


N
(a) H. curtus
(b) H. macdowelli
(c) H. kingii
(d) H. czeblukovi
(e) H. ocellatus
ALA
BRUVS
Fishery
RLS
UVC

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