Understanding seabird and marine mammal occupancy of tidal stream environments at annual and seasonal scales.

A dissertation in partial fulfilment of the requirements
for the degree of Master of Science (MSc) in Marine Biology
at Bangor University

PRIFYSGOL
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Submitted in September 2021.

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Understanding seabird occupancy of tidal stream environments.

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Abstract

Many seabirds and marine mammal populations across the globe are declining as a result of climate change and anthropogenic practises such as over-fishing. With these threats already facing the animals and the shifting of energy resources into marine renewables due to climate change ever approaching, it is important that devices such as tidal stream turbines do not cause further harm. It is known that both disturbance and displacement are both risks to the animals along with collision with the turbine blades which can cause serious harm and even death. These risks are even greater as there is an overlap between the areas suitable for tidal stream turbines and suitable conditions for the birds and mammals. We use a unique nine-year dataset on seabird and marine mammals use of Bluemull Sound in Scotland, a tidal stream environment, to assess the occupancy patterns at annual and seasonal scales. There is a huge knowledge gap surrounding this topic however, by analysing a long-term data set using GAMs and quantitative plots, we answer the following questions – (1) Does animals' use of Bluemull Sound differ between years? (2) Does this depend upon shore of wide-ranging species? (3) Under what conditions are animals most at risk from turbines?

Key words: Tidal, seabird, Bluemull Sound, occupancy, tidal stream, Shetlands, guillemot, marine

1. INTRODUCTION

1.1. Need for alternative energy.

During the last century, the global climate has undergone an overall temperature increase of 0.6°C (Walther et al, 2002) with each of the previous four decades warmer than that before it and the temperatures are only expected to further increase with predictions of increases between 2.0 and 4.5°C during the coming 100 years (Sorte et al, 2010). Throughout the last 800 000 years, carbon dioxide existing in the Earth's atmosphere has reached levels greater than ever seen before (Lüthi et al., 2008) and in 2019 the levels were greater than any period observed in over two million years (IPCC, 2021).

Estimations show that they could surpass 800ppm by the end of this century resulting in the pH of surface water decreasing by 0.3 units (Feely et al, 2009). This decrease in pH, also known as ocean acidification, occurs due to the seawater absorbing atmospheric carbon dioxide, ultimately resulting in an increase in hydrogen ion concentrations (Caldeira & Wickett, 2003). Oceans are reported to absorb around thirty percent of the atmospheres carbon dioxide therefore, as the atmospheric carbon dioxide increases, the oceans absorb even more causing them to further acidify. Atmospheric methane conditions are also on the rise and are reported to have more than doubled since 1850 (Fraenkel, 2006).

Deforestation, industrialisation, burning of fossil fuels and land-use changes are directly responsible for the increasing concentrations of greenhouse gases present in the atmosphere today (Guinotte & Fabry, 2008, Feely et al, 2009). Greenhouse gas concentrations present in the atmosphere are predicted to continue rapidly increasing which will result in continued alarming increases in both ocean and atmospheric temperatures (Feely et al, 2009). Between 2011 and 2020 the yearly average Arctic Sea ice hit its lowest level recorded since 1850 and the late summer Arctic Sea ice area was recorded as the smallest in the last 10 centuries (IPCC, 2021). The year of 2020 also witnessed a host of extreme weather events and natural disasters. It is heavily acknowledged that hot extremes such as heatwaves, which can result in wildfires and droughts, have increased in frequency and intensity throughout the vast majority of land regions since the 1950s. Meanwhile, cold extreme events have decreased in frequency and intensity. It is reported with great confidence that these changes are the result of humans (IPCC, 2021).

These monumental environmental impacts alongside the status of 'peak oil' on the horizon demonstrate that the current energy production strategies are not sustainable due to the heavy focus on fossil fuels and other more developed alternative renewable energy resources are the only way forward (King, 2004). If this change is not undertaken rapidly, it is incredibly likely that the frequency and intensity of extreme weather events such as heavy precipitation alongside loss of land ice will only continue to increase (IPCC, 2021).

1.2. Marine renewable energy.

After many complaints over aesthetics of renewable resources, particularly wind farms, along with competition over land and space for their installation, focus for renewables has shifted offshore (Taylor, 2004). Currently the most underdeveloped energy sources in the world (Kumar et al, 2015), marine renewable energy sources consist of tides, offshore wind energy, waves, offshore solar energy and many more (Taveira-Pinto et al, 2020). All together they are theorised to have the prospect of sustainably meeting the global energy demand for power (Pelc & Fujita, 2002).

The United Kingdom is currently hosting the biggest marine energy resources with tidal lagoons within and tidal barrages across estuaries serving the potential to generate around 20% of the UKs electricity, meanwhile, harvesting energy from waves and projects using tidal current turbines have the possibility to generate another 20% if not more (Callaghan & Boud, 2006). Marine developing countries are said to be encountering a lack of sufficient energy resources resulting in the increased need for development of marine renewable energy resources. Their development would enhance these countries' economies whilst also providing protection under the circumstances of natural disasters and epidemics for example, COVID-19 or earthquakes during which they stand the chance of being cut off both accidentally and on purpose by developed countries which would result in an energy crisis (Ou et al, 2021, Aktas & Kircicek, 2020, Coughlan et al, 2020).

1.3. Tidal stream turbines.

With the increasing pressure to shift to marine renewable energy resources and with wind power being well developed already, focus is shifting towards tides in particular tidal stream turbines which are being increasingly discussed. Like wind turbines using air, they use the water to generate electricity (Fraenkel, 2006) however, due to water being 832 times less dense than air, the rotors on tidal turbines are smaller in size (Fraenkel, 2006). Generally, the turbines have two or three blades depending on the design and the model (Bryden & Melville, 2004, Fraenkel, 2006). These are attached to the rotor of the turbine resulting in the tips of the blades moving at the fastest rate escorted by the currents at speeds of up to 23 knots. Speeds greater than this can result in water cavitation and decreased efficiency (Wilson et al, 2006). When compared with the area the blades sweep, they are narrow allowing for each blade to cut through the water currents and shift the water along (Wilson et al, 2006). The majority (over 70%) of tidal turbine models utilise the gravity-base mounted horizontal-axis design which mimic a plane propellor, but there are a few turbines that are designed to float rather than being stationary in one spot (Fox et al, 2018). The turbines are strategically placed within rapid tidal streams, and it is forecast, based off present demands, that they could generate between 5 and 10% of the United Kingdom's electricity demand (Fraenkel, 2006). In comparison, it is predicted that tidal energy overall has the potential to provide 20% (Melikoglu, 2018).

Tidal stream energy is not a constant readily available resource as it is solely reliable on the tides which are in turn controlled by the gravitational interactions between the sun, earth and moon. However, these interactions are easily predicted, and it is well known that both neap and slack tides provide very little energy (Fraenkel, 2006). The predictability of these events allows for a contractable energy supply as the generators can be made aware in advance (Fraenkel, 2006).

As suggested by the name, these turbines can only be installed into tidal stream environments. These energetic zones occupy areas usually less than $10km^2$ (Waggitt et al, 2016), and are easily identified due to their fluctuating and frequent predictable currents that travel at a pace of over 1 m/s (Hughes et al, 2015). These environments are often found surrounding headlands, across banks and within straits (Couch & Bryden, 2006) as a result of the flow of water being constrained in turn resulting in a diverse set of flow features including but not limited to eddies, upwelling and boils (Hughes et al, 2015).

Currently, throughout the UK there are a total of five operational tidal stream turbines, each 600kW, installed by Nova Innovation at Bluemull Sound in the Shetland Islands. The initial turbine within the array was installed in 2016 and was the first in the world (Isaksson et al, 2020). This Shetland array has since provided power for the businesses and homes through the Shetland grid (Nova Innovation - https://www.novainnovation.com).

1.4. Impacts on seabirds and information needs.

Whilst tidal stream environments are key areas for the developments of marine renewable energy resources, they are also very important for diving seabirds pursuing their prey (Benjamins et al, 2015). The UK, Scotland in particular, is home to large seabird colonies which are of great international importance, many of which are protected under the EU Habitats Directive and the EU Birds Directive (European Commission, 2013, Michell et al, 2004). Despite these legal protections, the number of seabirds has been observed to decrease by 9% since 2000 (JNCC, 2007) due to increasing sea temperatures, over-fishing as well as predation from mammals such as the American mink (*Neovison vison)* (Frederiksen et al, 2004, Langston, 2010). The hydrodynamic attributes of tidal stream environments help to seabirds' prey species causing them to be more readily available. The predictability of these environments also allows for greater exploitation of the prey (Zamon, 2001, Johnston et al, 2005).

With human induced threats currently facing seabirds already, the addition of increased stress as a direct result of the installation of tidal stream turbines is of concern (Dias et al, 2019, Copping et al, 2016). The two main probable impacts of the turbines are collision of the pursuit diving birds into the blades causing death or severe injury, and displacement due to modification of the habitat and disturbance which has the potential to impact prey availability due to changes in water turbulence (Inger et al, 2009, Furness, 2012, O'Doherty et al, 2010). No marine mammal has been witnessed colliding with a tidal turbine blade yet however, it is still a risk, particularly to seals (Copping et al, 2017). Disturbance and displacement of seabirds is expected to take place during the installation of the turbines as a result of increased boat traffic transporting the turbines and noise pollution produced during their deployment (Fox et al, 2018, Frid et al, 2012) although, the scale of these disturbance will determine whether this displacement is only temporary or if they are permanently displaced (Jarrett et al, 2018). The same impacts will be likely during decommission (Isaksson et al, 2020). Black guillemots and European shags are classified as local bird species resident to Bluemull Sound, and it has been noted that these species have a greater risk of underwater collision with tidal stream turbines throughout the UK due to their preference for benthic and epibenthic prey (Furness et al, 2012). Atlantic puffins and Common guillemots have been reported to have a smaller visual field whilst underwater resulting in an increased risk of collision due to difficulty detecting obstructions (Katzir, 2003).

There is an overlap between both the suitable sites for the tidal stream turbines and the suitable feeding areas for diving seabirds at Bluemull Sound in Scotland therefore, it is vital to assess the interactions between diving seabirds and the tidal turbine site year-round across all different environmental conditions in order to minimise the risks facing the seabirds and prevent further species decline.

1.5. Knowledge Gap.

Before the large-scale installation of tidal stream turbines, it is crucial we know the likelihood of interactions between animals and these devices. Whilst there have been many studies monitoring seabirds' behaviour within the UK, they are the majority short term studies resulting in many contradicting results. For example, a study previously carried out at Bluemull Sound reported a decline in the number of black guillemots during high energy currents (Robbins, 2017) however a study published a few years earlier stated the opposite (Rodger, 2014). The current approach when monitoring sites in Scotland consists of baseline surveys being carried out once a month for two years (SNH, 2011 – http://www.nature.scot) however the seabird distribution is highly dynamic. These twenty-four snapshot surveys may not accurately capture the birds' occupancy resulting in an underestimated or overestimated frequency of encounters particularly in those wider-ranging species such as Atlantic puffin. We need to know (1) whether birds use of these sites is dynamic or consistent, within and amongst years and seasons, (2) is consistency of use greater in short-ranging local species as expected and (3) if inconsistent, what environmental factors could explain variations in animals use within and amongst years?

This study uses a unique nine-year dataset on seabird and marine mammals use of a tidal stream environment to assess the occupancy patterns at annual and seasonal scales at Bluemull Sound, Shetland. This location is suitable for these studies because it supports a diverse range of seabirds including short-ranging species like Black guillemot (*Cepphus grylle*) and European shag (*Phalacrocorax aristotelis*), and wider-ranging species like Atlantic puffin (*Fratercula arctica*), Northern gannet (*Morus bassanus*) and Common guillemot (*Uria aalge*). The site also experiences variations in sea surface temperature, salinity and wind due to its position to the north of the UK. Bluemull is much cooler than its surrounding waters resulting in warmer waters moving in and out of the channel in correlation with the tides. The predictability of the area stems from there being no cylindrical pattern between the cold and hot waters. At a local scale, the tides are very predictable and change daily (Nash et al, 2012). Here, we combine information on the presence and numbers of seabirds between 2010 and 2018 with environmental conditions to ask the following questions:

1. Does animals' use of Bluemull Sound differ between years?
2. Does this depend upon shore or wide-ranging species?
3. Under what conditions are animals most at risk from turbines?

2. METHODOLOGY

2.1. Data Collection

Study site.

The data for this study was collected from Bluemull Sound (60°41'50" N, 0°58'54" W) found in the Shetlands, Scotland from November 2010 until July 2018. It is located between the islands of Unst and Yell. The site is a tidal stream environment hosting average current speeds of over 2 m/s (Neil et al, 2017). The channel here is fairly narrow, but it is adjudged suitable for the installation of tidal energy technology and already is home to an ongoing project run by Nova. The tidal array found at Bluemull is currently made up of five Nova M100 tidal turbines and the installation of a final one is planned to take place within the next 24 months after the approval to extend the project was requested. At first, the project was planned to be decommissioned in 2035 following the installation of the fifth turbine however this has been postponed until 2038 due to the permitted extension for the sixth turbine. The first turbine was installed in 2016 (McPherson, 2018). Figure 1 shows the study site.

Observational data.

Land-based vantage point surveys first commenced at Bluemull Sound in November 2010 prior to the tidal turbines being installed. The aim of these surveys was to monitor the distribution and attendance of both marine mammals and diving seabirds inhabiting the waters. In 2019 the surveys were stopped due to the modification of their design in order to explore new objectives. The observation point chosen for these surveys is found on Ness on Cullivoe, a coastal headland (figure 2). This is a raised vantage point allows clear visibility spanning across the entire area. The method of surveying involved splitting the survey area into two separate zones. Zone 1 covered the area nearest to the location of the tidal turbines meanwhile, zone 2 consisted of the greater stretch of Bluemull Sound. The surveys were split into intervals of three months (February until April, May until July, August until October and November until January) in order to allow for stratification. In total, nine surveys were conducted during each three-month interval, each lasting four hours and spanning across a variety of tidal states. These methods were replicated each year for a total of nine years. Winter daylight hours were noted to be a limiting factor causing a decrease in the number of surveys conducted before 09:00 and after 15:00 (Cooper et al, 2020).

Each individual four-hour survey consisted of twenty-four scans for seabirds occupying the waters and twelve scans for marine mammals with each scan carried out in the form of a 'single sweep' in order to capture a single moment of the day. Every ten minutes a scan for seabirds was conducted whilst a scans for marine mammals were carried out every twenty minutes. Zone 1 was the focus of the first three minutes of each scan and all birds were identified down to species level and counted excluding those just flying through. The number of birds sitting on the water's surface, the number of birds seen diving and the count of marine mammals were all noted. Movement of any marine mammals along with foraging behaviours were also recorded. For the remaining minutes of each scan, the focus shifted to zone 2 and the same observations were recorded. Finally, the scans were carried out scanning into the direction of the tide when it was observed to be running in order to minimise the risk of double counting individuals (Cooper et al, 2020).

2.2 Environmental data.

Wind speed.

The wind speed (m s^{-1}) data for the weather conditions at Bluemull Sound between 2010 and 2018 was extracted from the Copernicus ERA5 database (https://climate.copernicus.eu/climate-reanalysis). This data supplies hourly estimates for a variety of atmospheric, land and oceanic variables every day.

Sea surface temperature and salinity.

Data for the sea surface temperature (K) and salinity (ppt) were obtained online using E.U. Copernicus Marine Service Information (https://climate.copernicus.eu/climate-reanalysis The dataset chosen was the Atlantic-European North West Shelf-Ocean Physics Reanalysis consisting of metadata provided by CHEMS. This data is constructed using an ocean assimilation model called NEMO (Nucleus for European Modelling of the Ocean) including tides at 7km horizontal resolution. The variables extracted from this data set are 'sea_water_salinity (S)' and 'sea_water_potential_temperature (T)'.

Productivity.

E.U. Copernicus Marine Service Information (https://climate.copernicus.eu/climate-reanalysis) was used to source productivity data (NPP). The database chosen was the 'Atlantic-European North West Shelf-Ocean Biogeochemistry Reanalysis' produced using metadata given by CHEMS. The dataset extracted for use in this study is 'net_primary_production_of_biomass_expressed_as_carbon_per_unit_volume_in_sea_water (PP)'.

2.3. Data Analysis

Does animals' use of Bluemull Sound differ between years?

The total species count data at Bluemull for all the birds excluding the red throated diver were used in this study along with the total counts for the common seal, Atlantic grey seal and harbour porpoise from the Bluemull marine mammals' dataset. The bird data was then divided into the breeding season (months April through to August) and the non-breeding season (September until March) whilst the marine mammal data was split into winter (May through until September) and summer (June until August). The next step involved calculating the probability of encounter for each species and the average number if encountered for every year. These were also calculated for each tidal state.

In order to calculate the probability of encounter, presence or absence was analysed. If at least one individual was counted a 1 was inputted however, if no individuals were spotted this was replaced with a 0. Averages of the presence and absence were then calculated for each year resulting in eight values (between 0 and 1) for each year (2011-2018) and then six values, one for each tidal state. The winter and non-breeding season datasets also included data from 2010 however there were still 8 values calculated marked as 2011-2018 however the values were calculated for that winter season including the beginning of winter which began in the previous year. For example, the 2011 data point is calculated using data recorded from November of 2010 until May 2011. These values were then plotted onto bar charts with year or tidal state on the x-axis and probability of encounter on the y-axis.

The average number of individuals if encountered involved deleting the data points where zero total sightings of the species were recorded. Averages for each species were then recorded same as with the probability of encountering and again these data points were illustrated with year or tidal state along the x-axis and number if encountered on the y-axis.

Does this depend upon shore or wide-ranging species?

For the bird species, some are shore based and are found to be present in the waters at Bluemull sound year-round whilst others are wider-ranging species with numbers fluctuating throughout the year. In this study, the European shag and the Black guillemot are the shore-based species whilst Atlantic puffin, Northern Gannet and Common guillemot are the wider-ranging species. Qualitative and quantitative comparisons were made by inspecting the plots.

Under what conditions are animals most at risk from turbines?

R Studio was used to understand the impact of the sea surface temperature, wind speed, salinity and productivity on the seabird and marine mammal species across years. Season was listed as a factor variable and the others numerical. Exploratory plots were formulated between the species and the environmental variables for both seasons. These plots allow for any obvious relationships to emerge. The next step is to subset the data points into the two different seasons. The mgcv package (Wood & Wood, 2015) was used for this analysis. This package allows the calculation of general linear models and general additive modelling. Standard linear models are not suitable for use on this data as they assume that the data is a normal distribution and that the values can be positive or negative and typically, with count data a poisson or over dispersed distribution is observed. Also, the probability of species encounter points are bound between 0 and 1 so will certainly not produce a normal distribution. As an alternative, a general linear model was trialled as this allows for non-normal distributions. The dispersal family selected for the probability data was binomial whilst tweedy was selected for the numbers if encountered as this is more flexible. Despite the exploratory graphs suggesting some significant relationships, the GLMs determined they were in fact non-significant. This is potentially due to a small sample size as the nine years of data has been condensed down into only eight data points for each species.

General additive models (GAMs) were then used which account for the fact that some relationships may not be linear. A GAM states the certain percentage of the variation which that environmental variable is responsible for. These models were then conducted for each species for both probability or encounter and number if encountered across both seasons against each of the four environmental variables. The dispersal families chosen were binomial for the probability data and tweedy for the number data. k was inputted as 8 for all models unless when plotted it did not display a linear relationship. In these instances, k was constrained to 3. The effect size was calculated for each model which was then alongside the deviance explained and the relationship displayed on the plot. These tables were then analysed, and the strong relationships determined using a colour coding system.

3. **RESULTS**

3.1. Does animals' use of Bluemull Sound differ between years?

Seabirds.

As seen in figures 3 to 18, more specifically plots A and C, all species have experienced some form of fluctuation over the years even if only minor. During the European shag breeding season (figure 6A), the probability of encounter fluctuated between 0.72 in 2011 and 0.40 in 2017 with the highest number of individuals if encountered recorded in 2013 at 9.89 (figure 6C). The Atlantic puffin displays lower probabilities of encounter than the European shag during this season with the highest chances of sighting reported in 2012 and 2018, both around 0.42 (figure 3A). The lowest probability was in 2013 (around 0.25) corresponding with the lowest number if encountered also reported in 2013 (figure 3C) at 2 individuals. Years 2011 and 2012 on figure are similar to 2017 and 2018 which could suggest a pattern for the puffins. The greatest number if encountered was reported in 2016 at 6 individuals closely followed by 5.87 in 2012 however in 2013 a low of 2.26 was counted and a steady decline from 2015 onwards. In contrast, the Black guillemot shows for the most part consistent probabilities of encounter never falling below 0.92 meaning there's a very high chance of seeing these birds at Bluemull during the breeding season (figure 4A). The number if encountered for black guillemots was highest in 2011 with 16.4 and lowest in 2012 with less than half that (6.297) counted before peaking again in 2015 with 12.87 counted illustrating a large amount of inter-annual variation (figure 4C). The common guillemot (figure 5A) also displays some consistency with the probability of encounter remaining at around 0.15 until 2017 when it declined to a low of 0.071 before recovering and climbing to a high of 0.253 in 2018. These animals were usually seen in alone or in very small groups across all years with numbers not exceeding 1.7 (2016) (figure 4C). The probability of encountering a Northern gannet was greatest in the 2011 breeding season at 0.464 (figure 7A). This then fluctuated with a low of 0.095 reported in 2018 after a decline from 2015 onwards. Gannets were seen in small groups of between 1 and 3 individuals most years however a peak of 6.12 in 2012 was reported (figure 7C).

During the non-breeding season, the highest probability of encounter for the European shag was reported in 2011 at 0.939 (figure 11A), same as the breeding season. Unlike the breeding season, the lowest probability of encounter was in 2013 at 0.671. This season displays a lot of fluctuation over the years with peaks again in 2016 (0.913) before declining again in 2017 prior to recovering in 2018. Variation is also observed in the numbers encountered with a high of 10.255 in 2015 (figure 11C) and low of 5.1 in 2017. During the non-breeding season these seabirds are usually seen in groups with years 2012, 2013, 2017 and 2018 all having averages of around 5 individuals. Atlantic puffins were only witnessed at Bluemull in years 2011 and 2014 during the non-breeding season (figure 8A). The number encountered was 1 both years (figure 8C). In contrast, Black guillemots were present all years during the non-breeding season with probability of encounter never below 0.92 (figure 9A) mirroring the breeding season. They were always spotted in groups with the largest witnessed in 2012 and 2017 at around 12.2. only 7.12 were observed in 2013 (figure 9C). The common guillemot display slightly more fluctuation in probability of encounter than the black guillemot with a range of 0.011 in 2012 to 0.18 in 2013 (figure 10A). These birds were seen in small groups across all years (figure 10C) like the breeding season. Northern gannet probability of encounter underwent a lot of fluctuation over the years during the winter season. In 2011 the probability was extremely low just like during breeding at 0.00379 however this had increased to 0.158 by 2012 (figure 12A). Another dip was recorded in 2014 (0.0662) before a spike in 2015 and another low in 2016. The highest probability was recorded in 2017 (0.314). The numbers of gannets if encountered remain fairly consistent across years except in 2015 when an average of 3.917 was recorded in comparison to the other years which were all below 2 (figure 12C).

Marine mammals.

During the summer season, the probability of encountering a common seal at Bluemull was incredibly low between 2011 (0) through until 2015 (0.00926) (figure 14A). In 2016 there was a drastic increase to 0.135 probability before a slight decline to 0.111 in 2017 prior to the highest chance of 0.236 measured in 2018. This trend was also mirrored during the winter season for the common seal (figure 17A) with the probability of encountering one never reaching above 0.142 until 2016 when it jumped to 0.201 before reaching 0.321 in 2018. When the seals were encountered, they were usually seen alone however, there were rare cases when 2 were observed in the summer seasons of 2016 and 2018 (figure 14C & 17C) and the winter season of 2017 when the number was 2.424. In contrast, the Atlantic grey seal saw a probability of encounter of 0.146 in summer 2011 (figure 13A) however, this dropped to 0 in 2012 and remained very low with 0 also reported in 2014. The chances were still low in 2017 at 0.0185 but in 2018 they had recovered to 0.0972. This same pattern is observed in the winter season for the grey seals (figure 16A). The numbers if encountered generally remained around 1 across the years for both seasons never exceeding 1.2 (figures 16C & 13C). The probability of encountering harbour porpoise at Bluemull Sound remained low across all years for both the winter and summer seasons (figures 15A & 18A). During summer the highest probability was found in 2018 at 0.125 whilst the lowest of 0.0303 in 2014. To compare, 2016 had the highest probability during the winter at 0.108 whilst 2014 also reported the lowest probability of 0.0233. These animals were always spotted in groups during the winter season with the largest observed in 2013 consisting of an average of 7.05 individuals (figure 18C).

3.2 Does this depend upon shore or wide-ranging species?

The European shag and black guillemot are the local ranging birds in this study. When compared to the other birds, the Black guillemot has the greatest probability of encounter over the years, never dropping below 0.90. As well, as holding a high presence in summer, it also maintains this during the winter months when the wider- ranging species', such as the Atlantic puffin, probabilities drop significantly. The European shag also maintains a higher probability of encounter than the wider-ranging species during the non-breeding season, even higher than the breeding season during some years including for example during 2016. In contrast, whilst the common guillemot displays low probabilities of encounter during both the breeding and non-breeding season, they are visibly lower during the breeding season with years 2011, 2012 and 2015 falling extremely low. The Northern gannet visibly displays similar amounts of fluctuation over the years in both the breeding and non-breeding season. The wider-ranging species do not appear to experience any more or less inter-annual variation than the local species. The marine mammal species all display low probabilities of encounter during both the summer and winter seasons. The numbers if encountered also remain consistent.

3.3 Under what conditions are animals most at risk from turbines?

Tables 1 and 2 display the green-green relationships between each of the seabird and mammal species (highlighted in blue) and each of the environmental variables – sea surface temperature, wind speed, salinity and productivity. Overall, a total 15 green-green relationships were identified (12 identified for probability of encounter and 3 identified for average number of individuals if encountered).

The relationships identified are:

1. Atlantic puffin in winter, with more likelihood of encounters during cooler winters.
2. Atlantic grey seal in winter, with increased likelihood of encounters in cooler winters.
3. Northern gannets in winter, with increased likelihood of encounters in warm winters.
4. Atlantic puffin in winter, with more likelihood of encounters during periods of strong winds.
5. Common seal in winter, with increased likelihood of encounters during periods of slower winds.
6. Harbour porpoise in winter, with more likelihood of encounters during slower winds.
7. Common seal in summer, with increased likelihood of encounters when salinity is lower.
8. Atlantic grey seal in winter, with more likelihood of encounters when salinity is greater.
9. Atlantic Puffin in winter, with increased likelihood of encounters when salinity is greater.
10. Atlantic puffin in winter, with more likelihood of encounters when productivity is lower.
11. Harbour porpoise in winter, with more likelihood of encounters when productivity is lower.
12. Northern gannet in winter, with increased likelihood of encounter when productivity is greater.
13. Common seal in summer, with greater numbers of individuals generally encountered during stronger winds.
14. Atlantic puffin in winter, with greater numbers encountered during stronger winds.
15. Northern gannets in summer possessed a strong non-linear relationship between the number of individuals encountered and salinity.

Seasonality.

There are a lot of green-green relationships identified during winter, primarily in the probability of encountering the animals whilst there are fewer green-green in summer and in numbers of animals if encountered. This shows that the environmental drivers have greater impacts during the winter seasons and on the occupancy of the animals in the tidal stream rather than their numbers if encountered.

Species.

The Atlantic grey seal, Gannet, Porpoise and Atlantic puffin commonly had green-green relationships. All these species could be considered wide-ranging and some potentially migratory with them choosing to occupy Bluemull Sound in summer when the environmental conditions are ideal.

Environment.

There are contrasting green-green relationships across the environmental variables with some positive and others negative. This shows that there are species specific responses to the environment with lots of green-green relationships across all environmental variables. This explains the shifts in community composition over the years as the presence and number of each species depends on the environmental conditions.

3.4 TIDAL STATE ANALYSIS

Seabirds.

During the breeding season, the probability of encountering a European shag at Bluemull was greatest during the max flood at 0.61 closely followed by the inc ebb with 0.59 probability. The other tides remained consistent with probabilities ranging between 0.515 to 0.535 (figure 6B). The number if encountered was much greater during inc ebb than any other tide with an average of 7.5 birds (Figure 6D). In contrast, the probability of seeing an Atlantic puffin during was breeding season was greater during flood tides than the ebb tides (figure 3B). The numbers were also greater during the flood tides with dec flood hosting the most with 5.29 birds (figure 3D). The black guillemot possesses the highest probability of encounter of the seabirds with it never dropping below 0.92 across all tidal states during summer (figure 4B). The lowest probability was during max flood with 0.928 meanwhile inc flood inc ebb had a 99% chance. The common guillemot also did not encounter any major fluctuations across the tidal states during the breeding season (figure 5B). The greatest probability was during max flood (0.219) and the smallest 0.127 during dec ebb. The numbers if encountered never reached about 1.8 with these birds seen mostly solo or in pairs during all tides (figure 5D). The Northern gannet’s probability of encounter was consistent ranging only between 0.26 (inc ebb) and 0.323 (dec ebb) (figure 7B).

The non-breeding season saw the probability of encountering a European shag never below 0.72 (max ebb) (figure 11B). The dec ebb tide had the greatest probability at around 0.82. The ebb tides saw greater numbers if encountered than the flood tides and overall, the max flood had the lowest number with an average of 4.69 birds whilst the other tides saw larger groups. The Atlantic puffin was only encountered during flood tides in the non-breeding season with the greatest probability during inc flood (0.00549) however, it was still very low (figure 8B). Only single birds were observed (figure 8D). As seen during the breeding season, the probability of encountering a black guillemot remained high across all tidal states during the non-breeding season, never dropping below 0.95 (figure 9B). These birds were observed in groups across all tides with the largest number of 11.59 observed during dec ebb tide and the smallest at 8.2 during max flood (figure 9D). In contrast, the common guillemot displayed low probabilities of encounter across all tidal states (figure 10B). The highest was observed during inc flood at 1.11 whilst the lowest of 0.06 during inc ebb. These birds were also observed in very small groups never exceeding 2.5 or solo across all states (figure 10D). Northern gannets also displayed little fluctuation in numbers across tidal states (figure 12D).

Marine mammals.

The probability of encountering a common seal at Bluemull was low during both seasons across all tides, even more so in summer where it did not exceed 0.09 (figure 14B). In winter, the greatest probability of encounter was during dec flood at 0.178. They were also only seen solo or in pairs across both seasons (figures 14D & 17D). Like the common seal, the probability of encountering an Atlantic grey seal also remained low across all tides (figures 13B & 16B) however during the summer the probability was greatest at max ebb (0.0588) and lowest during dec ebb (0.0154). Individuals were commonly spotted solo (figures 13D & 16D) however, during dec ebb the average was 1.5 and inc ebb 1.167. During winter, the probability of encounter for the grey seal was greatest during dec flood (0.0510) and lowest during inc flood (0.0280). Finally, the harbour porpoise had low probability of encounter across all tides during both seasons (figures 15B & 18B). Larger groups were observed during winter with the largest during dec ebb with an average of 6 mammals (figure 18D).

4 DISCUSSION

There is a lack of long-term studies monitoring occupancy of tidal stream environments, they are usually only carried out over several months therefore, findings regarding inter-annual variation from reliable sources are few and far between demonstrating the severity of the knowledge gap. A previous study carried out at Bluemull Sound found that there was an increase in the number of black guillemots during fast-flowing currents (Rodger, 2014) however, a study conducted a few years later reported the opposite (Robbins, 2017). The birds breeding season has been found to impact the importance of the tidal stream environments to seabirds (Waggitt et al, 2014) with auks including the Atlantic puffin (Waggitt et al, 2014), gulls like the black legged kittwake (Drew et al, 2013) and terns such as the Arctic tern (Lieber et al, 2019) reported to move in and exploit these environments due to the ideal environments for nesting and feeding being present. These findings support those from this study with the migratory species, particularly the Atlantic puffin, moving into Bluemull Sound during the breeding season. It’s also previously reported that Black guillemots and European shags were the two primary species observed in the tidal streams during the non-breeding season (Waggitt et al, 2016). These two species use the tidal stream environments to forage all year round. This study concurs with the Waggitt et al, 2016 report findings as the probability of encountering a Black guillemot at Bluemull sound remained high during both seasons. The European shag also maintained a high probability of encounters year-round in comparison to those migratory species.

Regarding the impact of environmental variables on the occupancy and numbers in tidal stream environments, this is a large part of the knowledge gap again, due to a lack of long-term data sets. The main findings from this study were that most green-green relationships were identified during the winter and non-breeding season illustrating that the occupancy of animals in Bluemull is more heavily impacted by the environmental variables during the winter season, the species’ considered wide-ranging possessed a number of green-green relationships supporting the theory that they choose to visit Bluemull Sound in the summer when the environmental conditions are preferable and finally, the green-green relationships for the environmental variables show that there are species specific responses to the environment.

5 CONCLUSION

Overall, this study has contributed to decreasing the knowledge gap surrounding seabird and marine mammal occupancy of tidal stream environments with some conclusive results, some new and others supporting previous studies. The further analysis of long-term data sets is crucial to find out more, particularly with the environment continually changing.

6 ACKNOWLEDGEMENTS

Thank you to Dr James Waggitt for supervising the project and NOVA for allowing use of the dataset

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Table 1. The status of the relationships between the numbers if encountered for birds and marine mammal species and the environmental variables, alongside the deviance explained, which were determined using GAMs, and the effect size of each model. The values are colour coded (dark green - effect size > 1 or deviance explained >25%, orange – effect size between 0.5 and 1 or deviance explained 10-25% and light green – effect size >0.5 or deviance explained >10%) in order to identify the strong relationships which are highlighted in blue. Summer is defined as the breeding season (months April – August) and winter as non-breeding season (September – March) for seabirds. For the marine mammals winter season is the months September until May and summer June until August.

Species	Season	Sea surface temperature			Wind			Salinity			Productivity		
AGS	summer	0.22	negative linear	0.093	9.41	negative linear	0.8214	0.757	negative linear	0.1729	11.9	negative linear	0.7552
AP	summer	8.41	negative linear	0.321	0.21	negative linear	0.0597	5.78	positive linear	0.2539	32.4	positive linear	0.6499
BG	summer	1.4	positive linear	0.09	18.6	negative linear	0.2659	10.8	positive linear	0.2588	6.29	negative threshold	0.1115
CG	summer	66.1	negative threshold	0.218	15.7	negative threshold	0.117	12.6	positive linear	0.1133	9.31	positive linear	0.1094
CS	summer	2.51	negative linear	0.214	74.6	positive threshold	1.1895	28	negative linear	0.7072	0.00028	positive linear	0.0024
ES	summer	7.4	negative linear	0.405	11.7	positive linear	0.6922	29.1	non-linear U	0.8167	0.523	negative linear	0.1139
HP	summer	46	positive linear	0.671	0.513	positive linear	0.0955	0.12	negative linear	0.0333	0.022	positive linear	0.0171
NG	summer	28.6	positive threshold	0.555	19.8	positive threshold	0.4698	85.5	non-linear U	1.4403	36.5	positive linear	0.8754
AGS	winter	47.5	non-linear U	0.07	0.0158	negative linear	0.0022	27.6	non-linear hump	0.054	23.1	negative threshold	0.0553
AP	winter	18.7	negative linear	2.152	50.2	positive linear	4.1662	8.98	positive linear	1.4111	16.3	negative linear	1.9251
BG	winter	23.2	positive linear	0.278	28.6	negative linear	0.3164	44.2	non-linear U	0.3805	51.3	positive threshold	0.3668
CG	winter	37.5	negative linear	0.521	33.5	positive linear	0.5274	39.1	positive linear	0.547	28.6	negative linear	0.4636
CS	winter	24.3	positive linear	0.437	44.5	negative linear	0.7866	94.4	negative threshold	0.9723	30.2	negative threshold	0.3574
ES	winter	8.64	negative linear	0.238	27	positive linear	0.4313	14.4	non-linear U	0.1513	20.9	negative linear	0.3659
HP	winter	57	negative linear	0.488	4.44	negative linear	0.1841	23.6	non-linear U	0.2077	59	negative threshold	0.5082
NG	winter	58.2	positive threshold	0.852	9.22	positive linear	0.4227	2.81	negative linear	0.2274	57.8	positive threshold	0.7383

Table 2. The status of the relationships between the probability of encounter for birds and marine mammal species and the environmental variables, alongside the deviance explained, which were determined using GAMs, and the effect size of each model. The values are colour coded (dark green - effect size > 1 or deviance explained >25%, orange – effect size between 0.5 and 1 or deviance explained 10-25% and light green – effect size >0.5 or deviance explained >10%) in order to identify the strong relationships which are highlighted in blue. Summer is defined as the breeding season (months April – August) and winter as non-breeding season (September – March) for seabirds. For the marine mammals winter season is the months September until May and summer June until August.

Species	Season	Sea surface temperature			Wind			Salinity			Productivity		
AGS	summer	0.41	positive linear	0.22	75.10	negative linear	0.10	18.00	positive linear	1.50	0.08	positive linear	0.11
AP	summer	0.89	negative linear	0.04	39.90	negative linear	0.31	7.37	positive linear	0.11	7.50	positive linear	0.13
BG	summer	8.13	negative linear	0.02	43.30	negative linear	0.06	12.60	negative linear	0.02	33.90	negative linear	0.04
CG	summer	43.50	negative linear	0.58	15.60	negative linear	0.38	0.00	negative linear	0.00	13.00	positive linear	0.33
CS	summer	16.20	negative linear	1.10	4.65	negative linear	0.84	35.00	negative linear	1.60	0.26	positive linear	0.16
ES	summer	0.03	negative linear	0.01	9.96	negative linear	0.17	21.70	positive linear	0.21	2.89	positive linear	0.09
HP	summer	3.74	negative linear	0.21	9.72	negative linear	0.46	0.57	negative linear	0.08	2.15	positive linear	0.18
NG	summer	8.13	positive linear	0.34	1.62	negative linear	0.17	45.40	positive linear	0.77	8.88	positive linear	0.38
AGS	winter	29.20	negative linear	1.43	17.90	positive linear	1.41	30.90	positive linear	1.56	9.15	negative linear	0.83
AP	winter	39.40	negative linear	3.38	71.30	positive linear	5.35	25.60	positive linear	2.37	31.50	negative linear	2.71
BG	winter	1.74	negative linear	0.01	13.10	negative linear	0.03	29.70	negative linear	0.04	3.02	negative linear	0.01
CG	winter	2.29	negative linear	0.33	20.60	negative linear	1.00	15.30	negative linear	0.89	1.54	negative linear	0.27
CS	winter	0.36	positive linear	0.10	81.30	negative linear	1.95	29.80	negative linear	0.92	18.90	negative linear	0.75
ES	winter	35.50	negative linear	0.25	1.44	positive linear	0.05	17.20	positive linear	0.18	35.50	negative linear	0.26
HP	winter	6.71	negative linear	0.37	48.00	negative linear	1.27	35.40	negative linear	0.85	51.10	negative linear	1.04
NG	winter	48.10	positive linear	1.60	13.50	negative linear	0.85	14.80	negative linear	0.90	52.80	positive linear	1.71

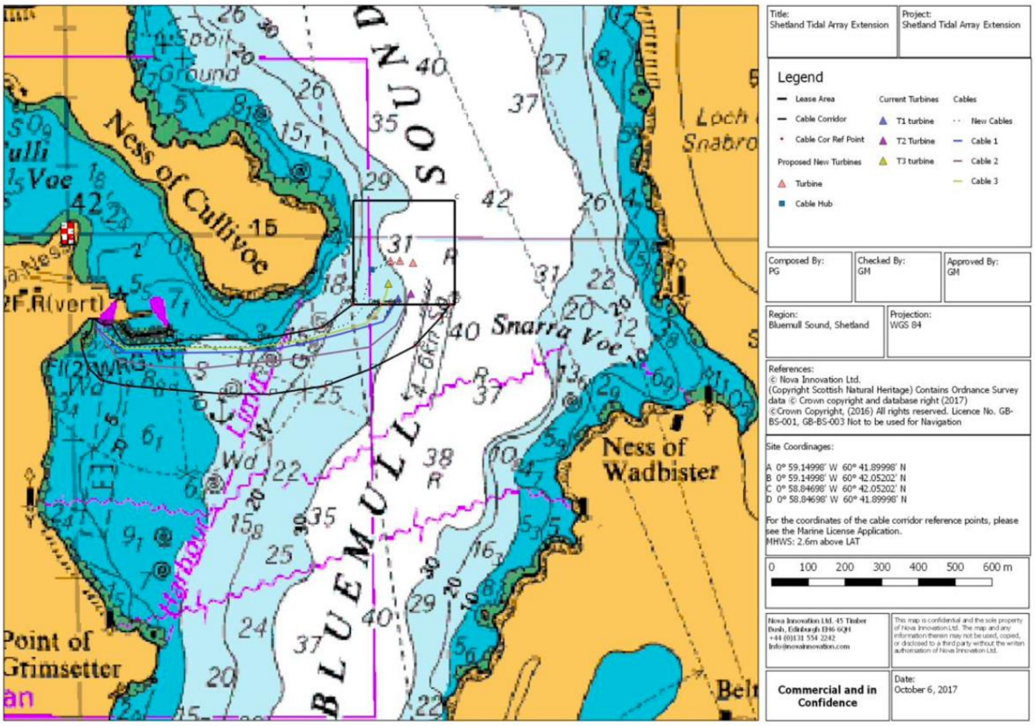

Figure 1. Location of the Shetland Tidal Array in Bluemeull Sound [Nova Innovation Ltd – McPherson, 2018]

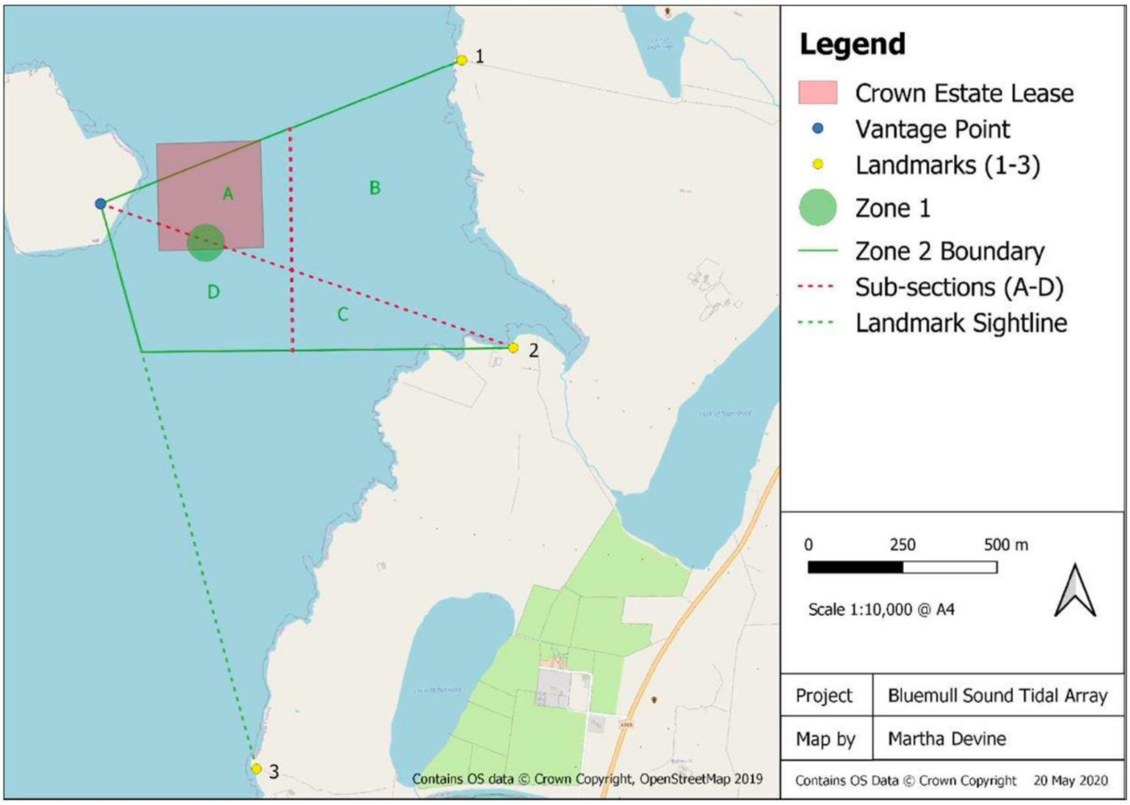

Figure 2. The location of the survey zones and vantage point at Bluemull Sound. [Source: Nova Innovation 2020 – Cooper et al, 2020].

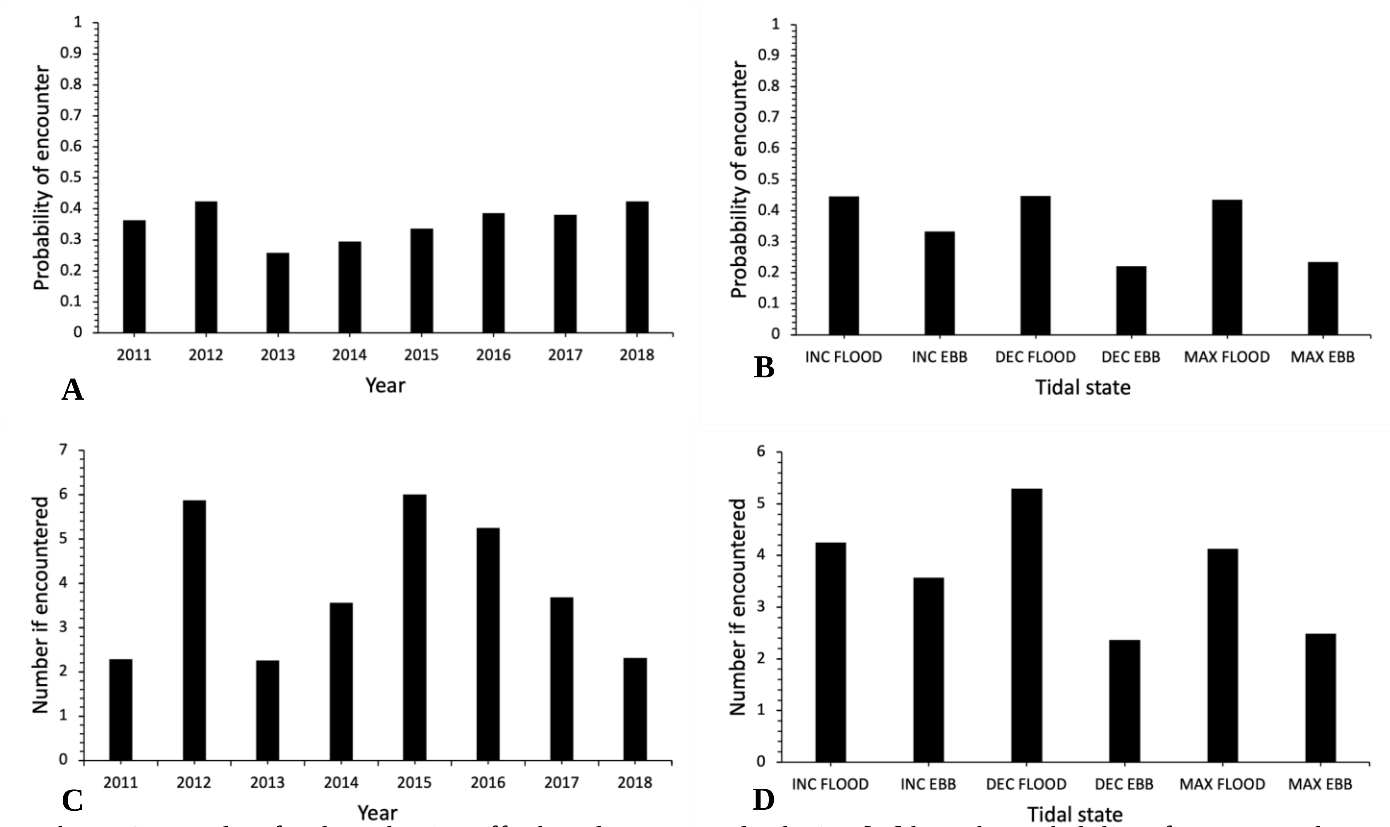

Figure 3. Bar plots for the Atlantic puffin breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

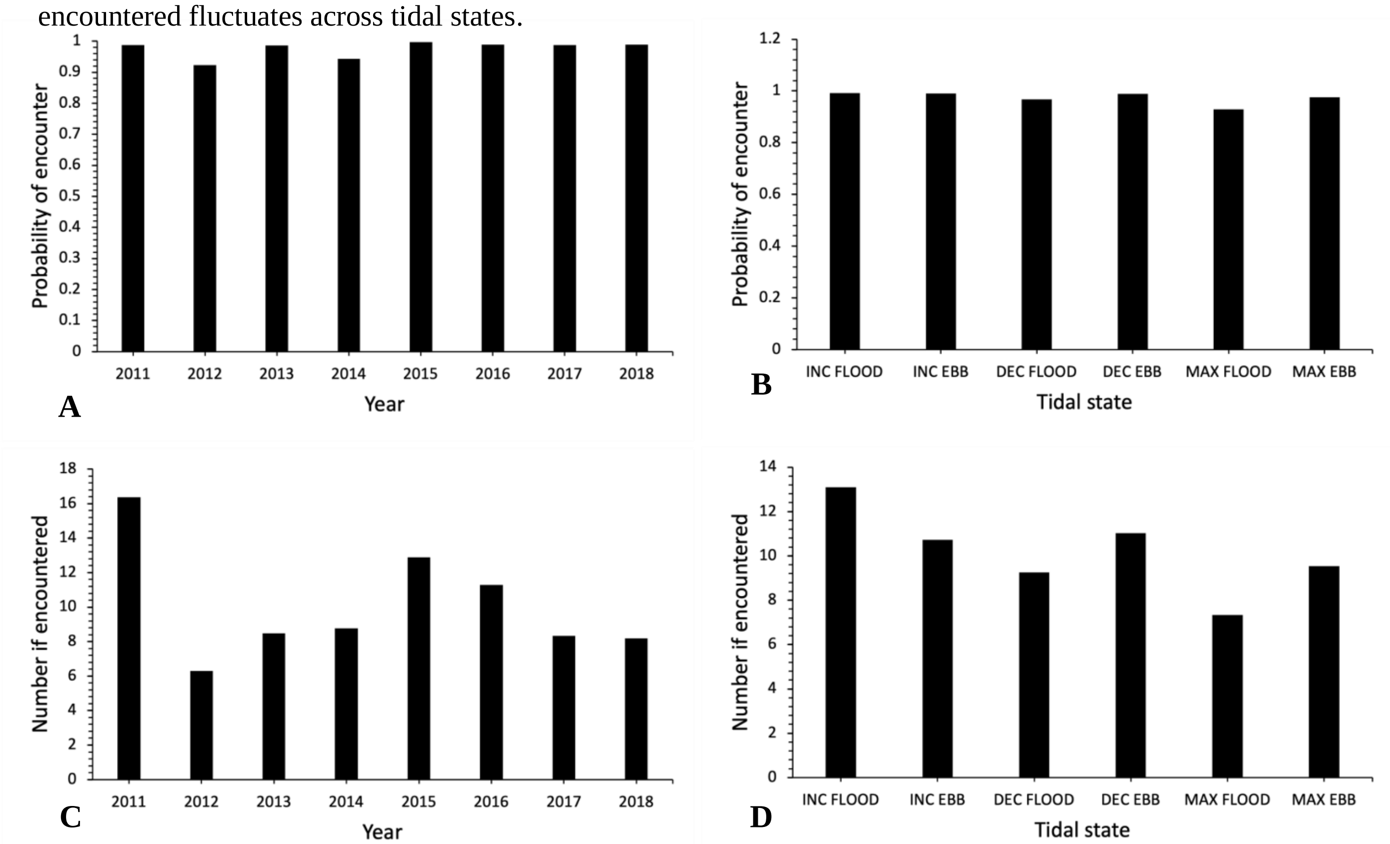

Figure 4. Bar plots for the Black guillemot breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

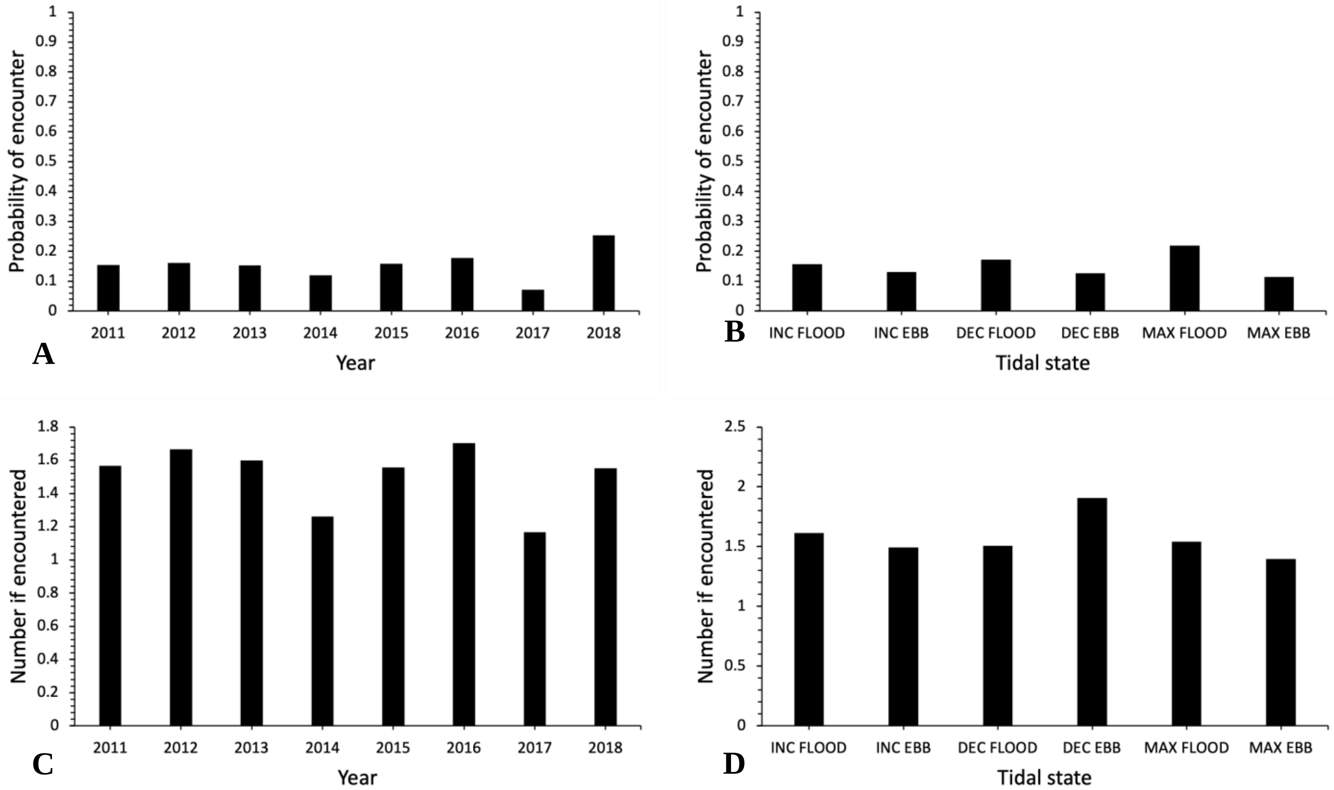

Figure 5. Bar plots for the Common guillemot breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

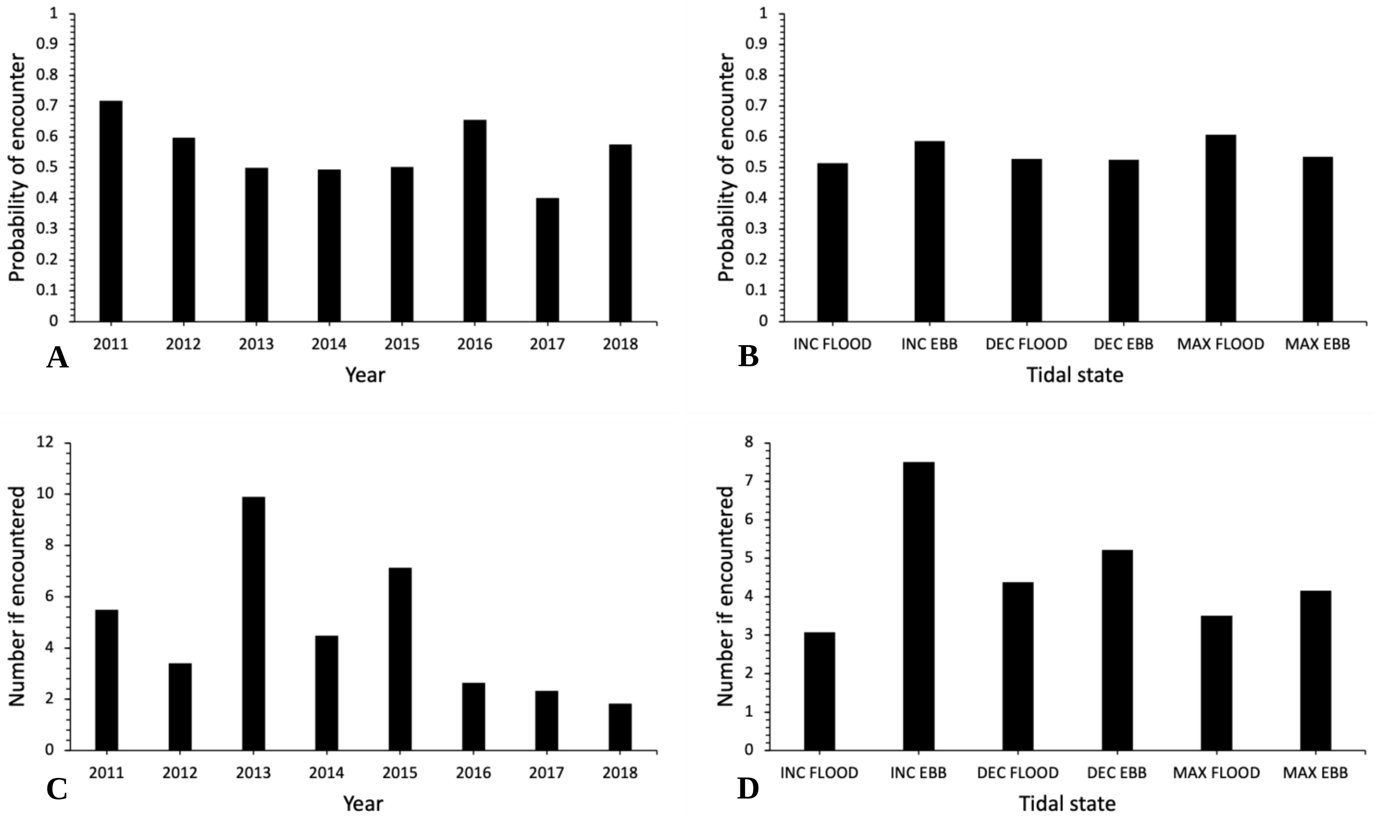

Figure 6. Bar plots for the European shag breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

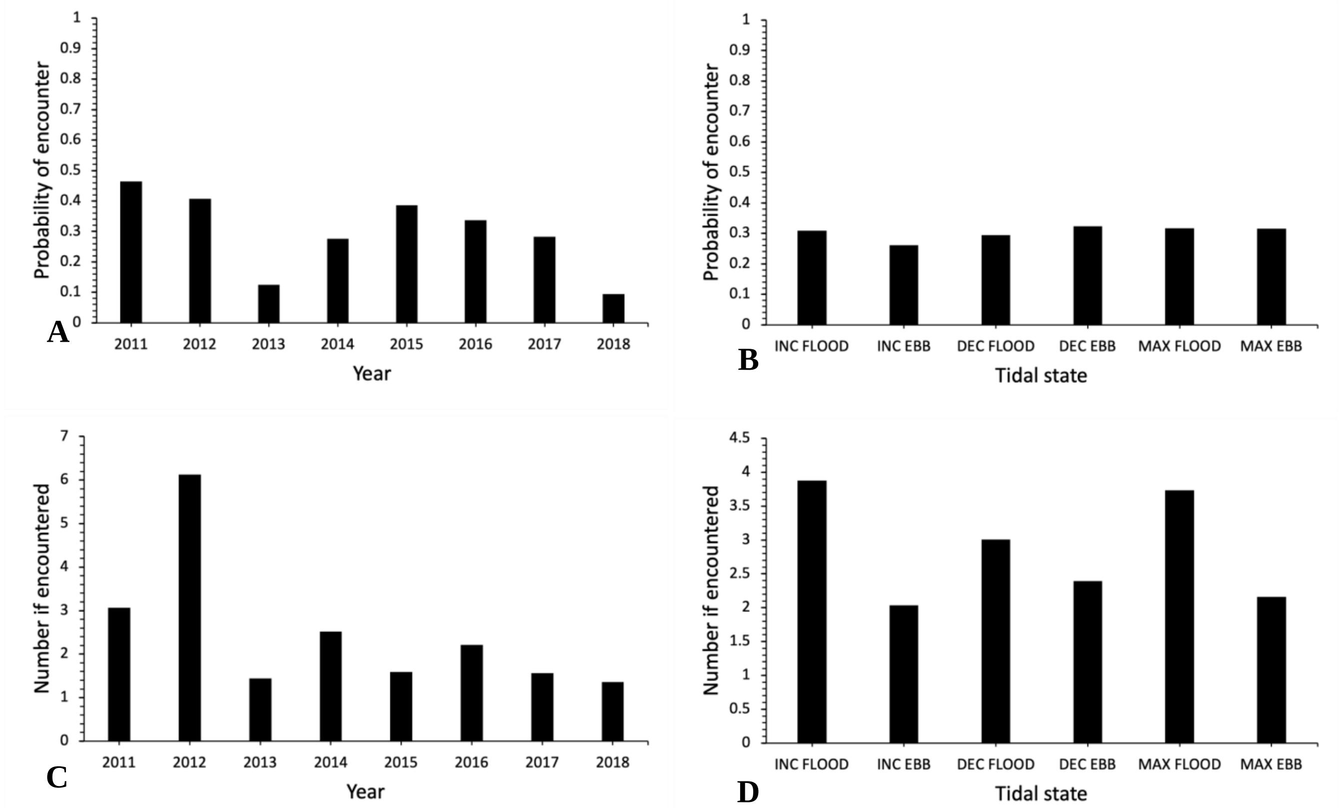

Figure 7. Bar plots for the Northern gannet breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

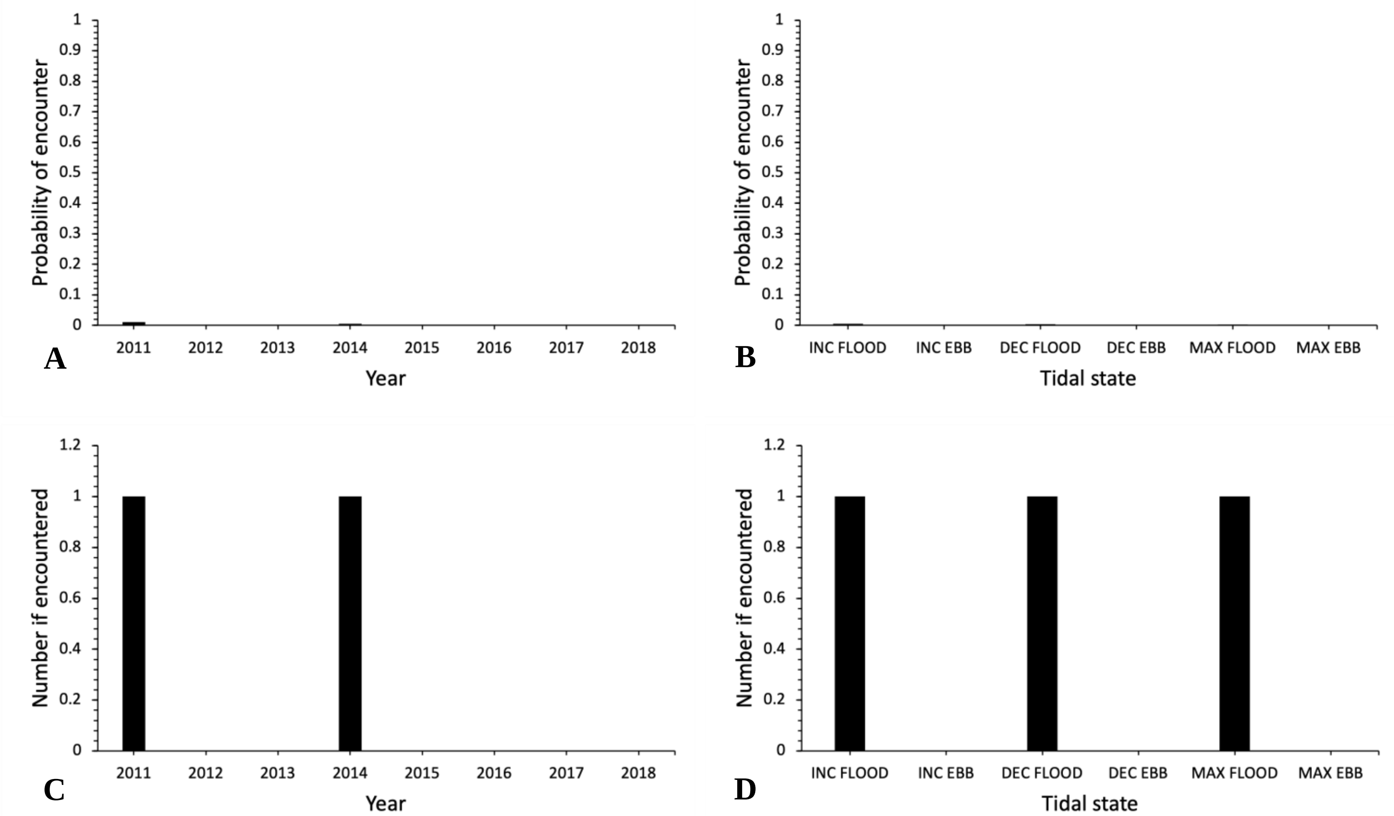

Figure 8. Bar plots for the Atlantic puffin non-breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

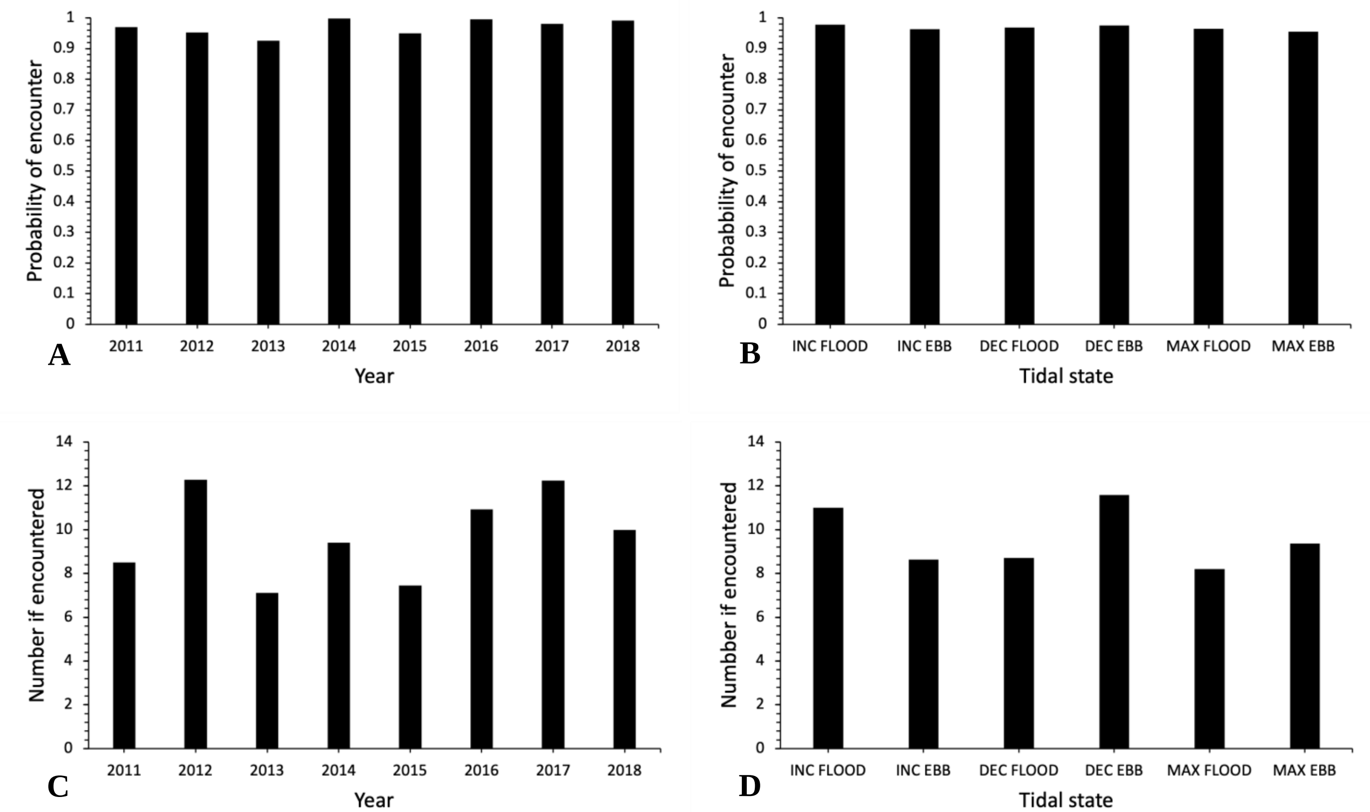

Figure 9. Bar plots for the Black guillemot non-breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

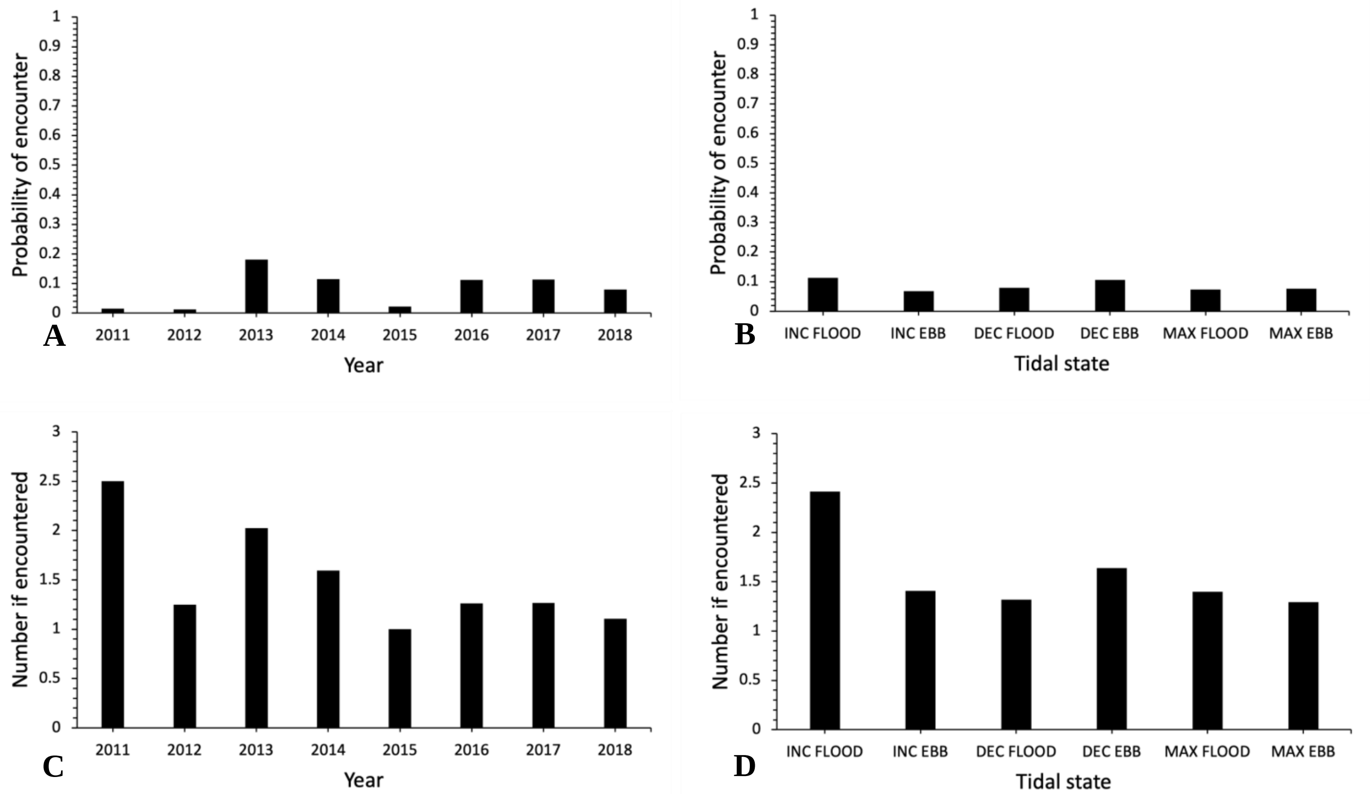

Figure 10. Bar plots for the Common guillemot non-breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

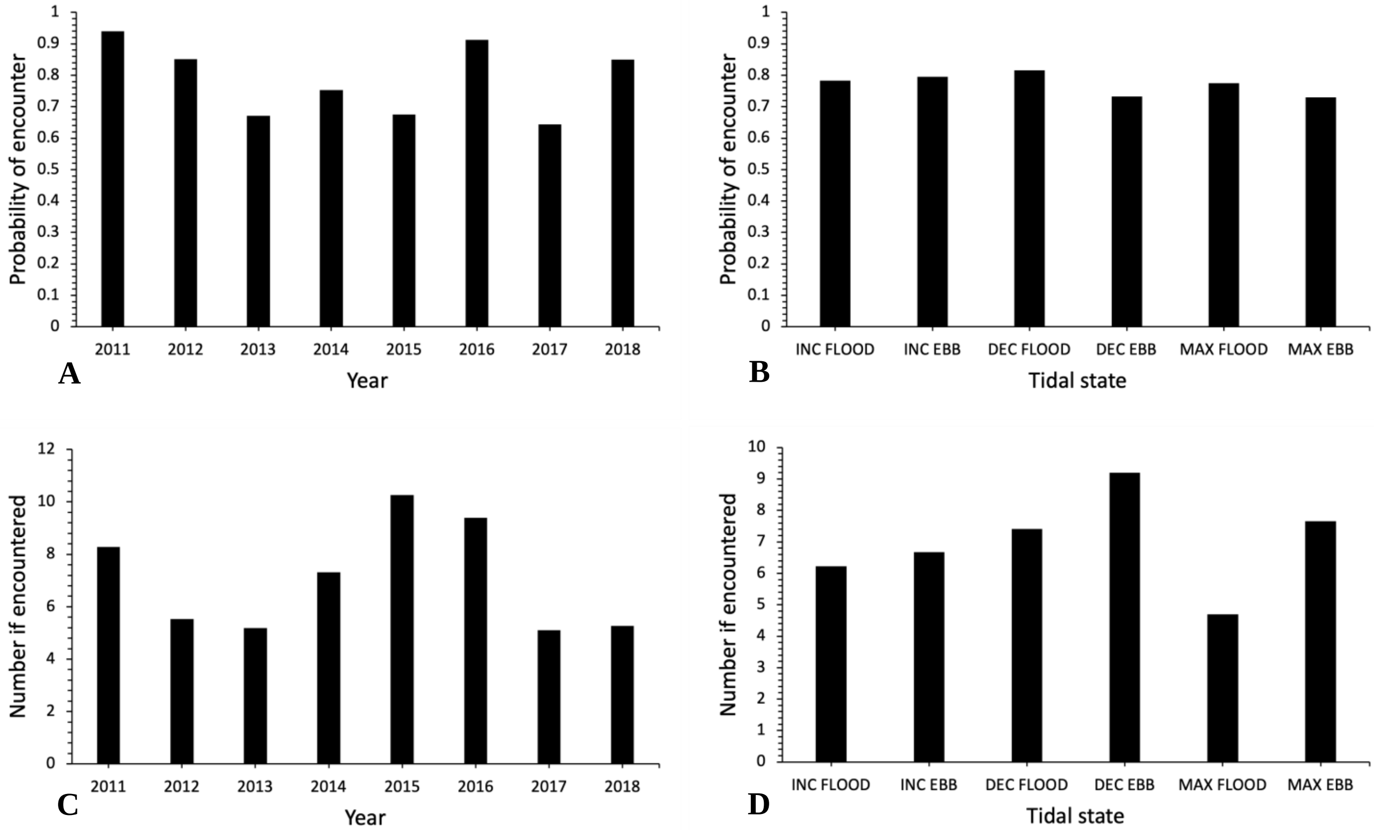

Figure 11. Bar plots for the European shag non-breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

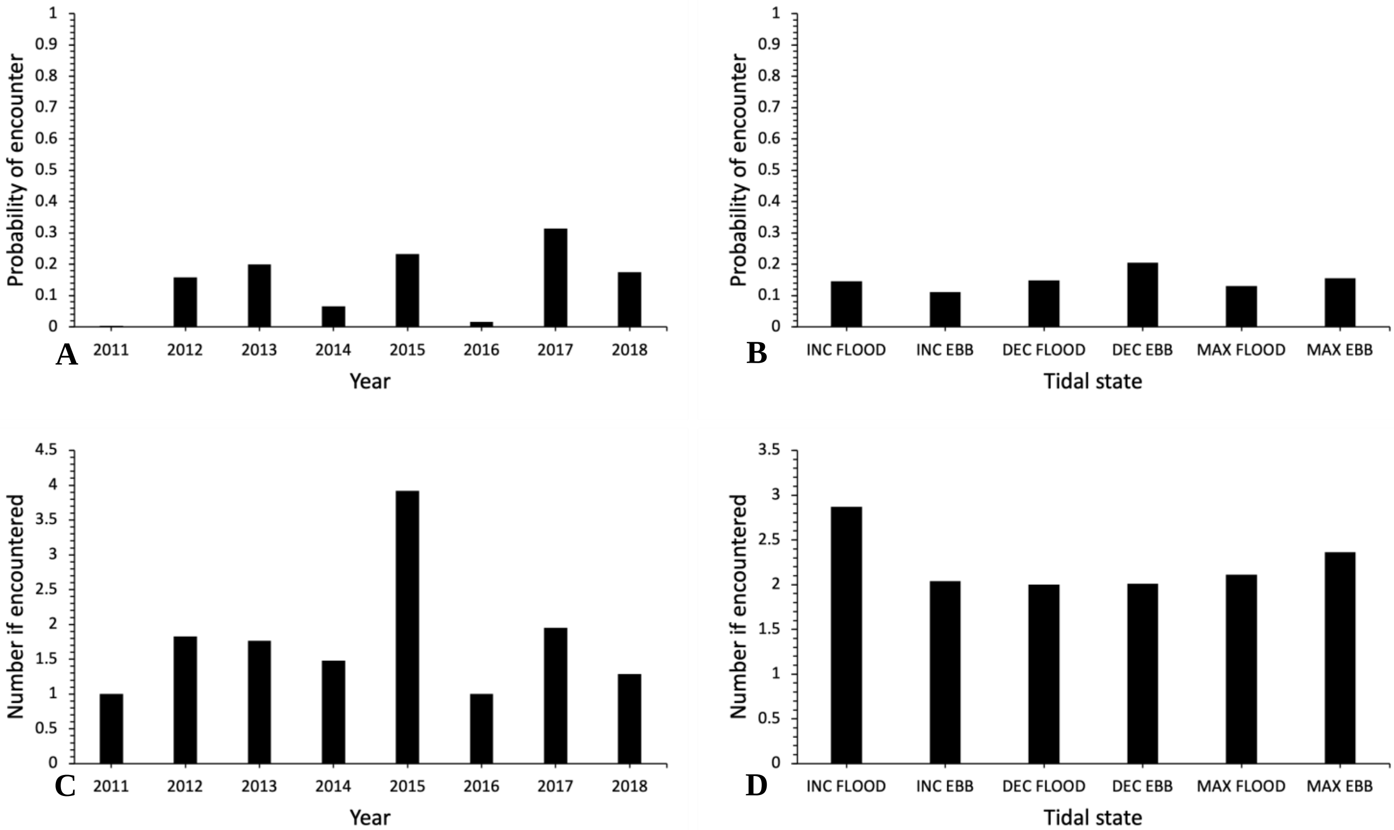

Figure 12. Bar plots for the Northern gannet non-breeding season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

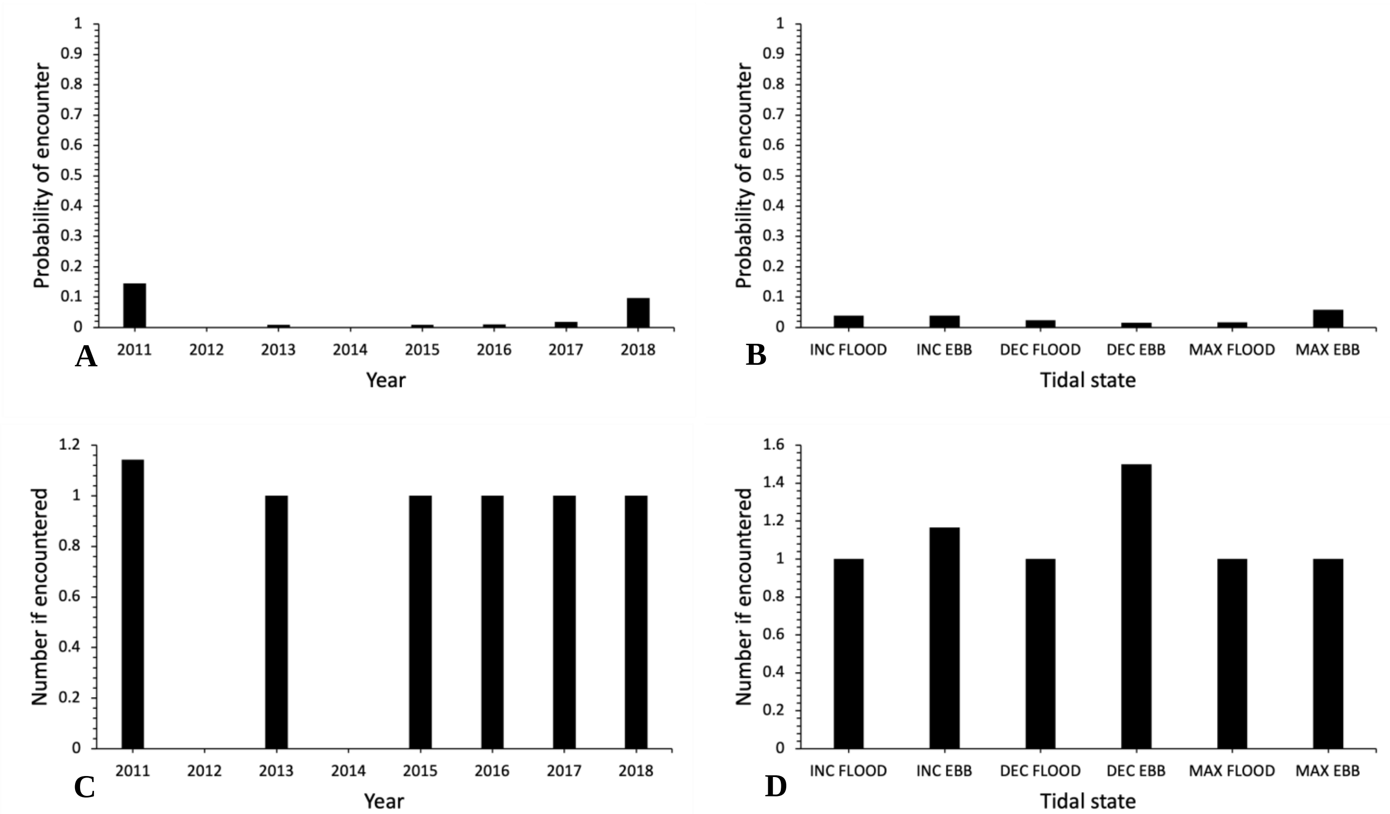

Figure 13. Bar plots for the Atlantic grey seal summer season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

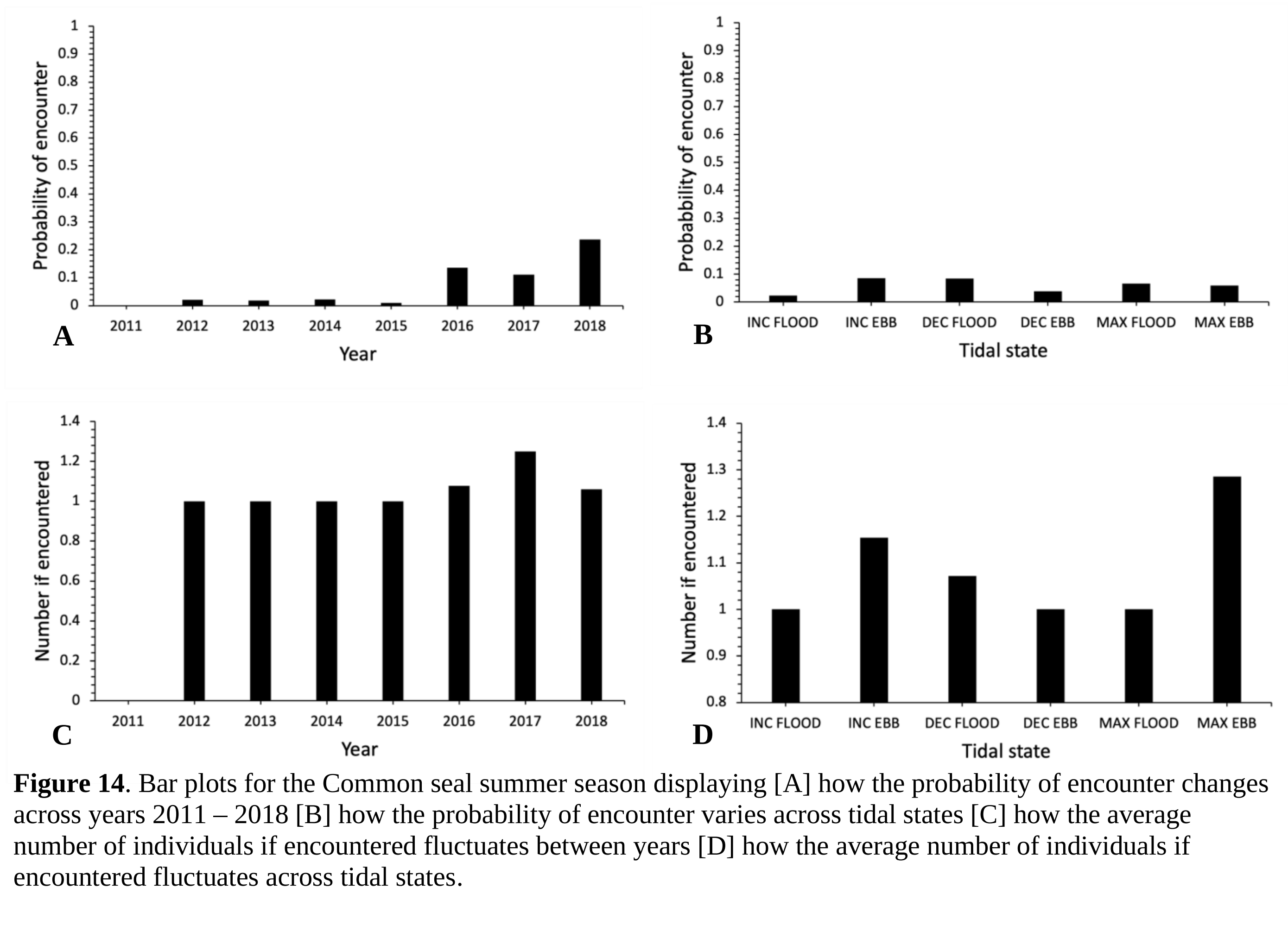

Figure 14. Bar plots for the Common seal summer season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

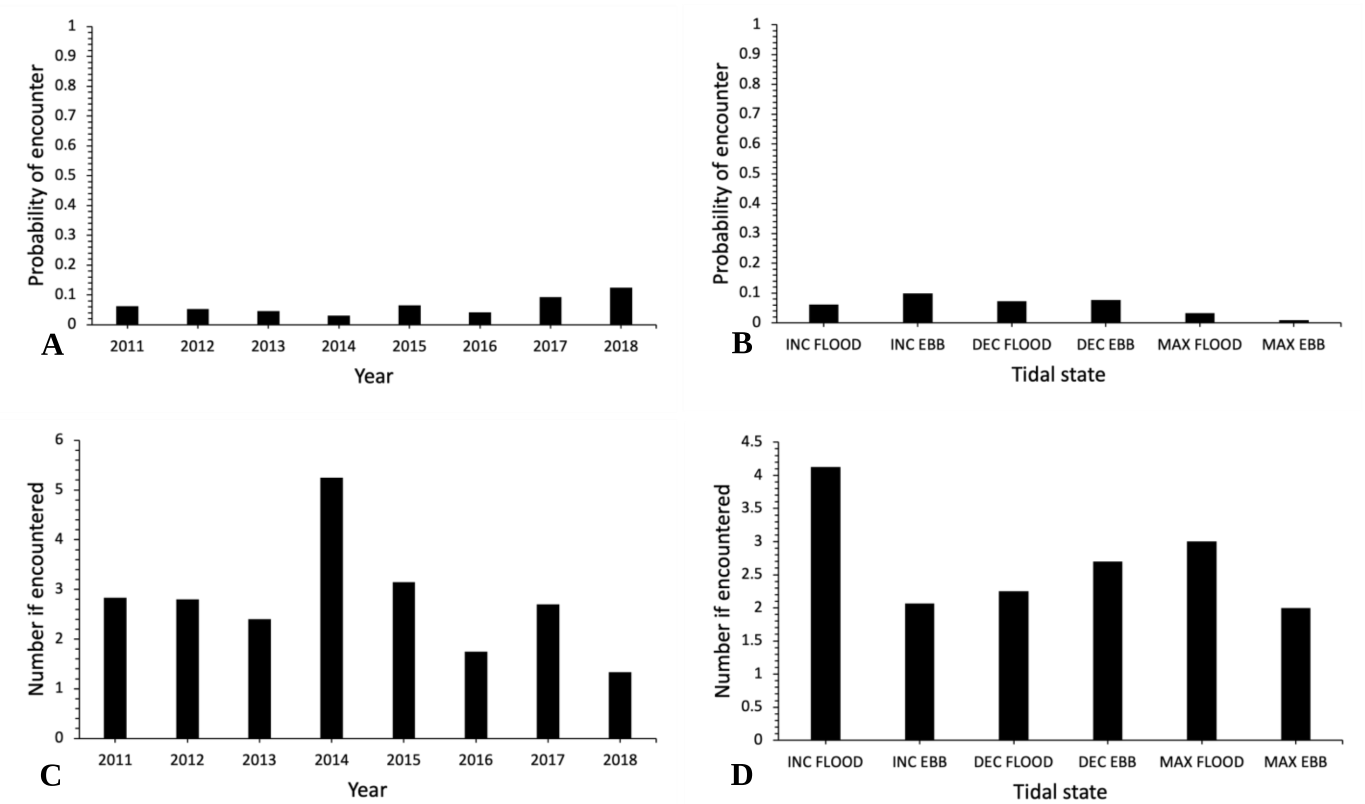

Figure 15. Bar plots for the Harbour porpoise summer season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

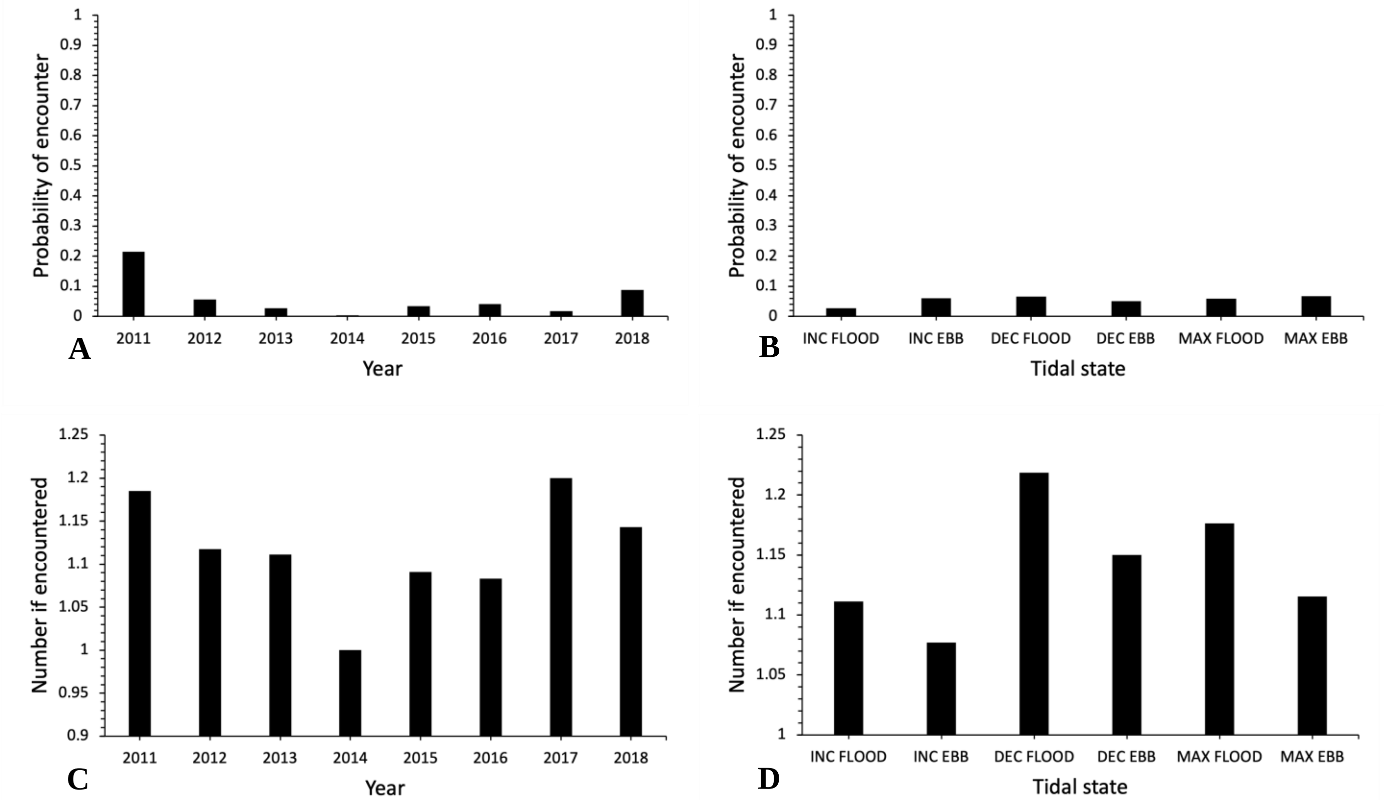

Figure 16. Bar plots for the Atlantic grey seal winter season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

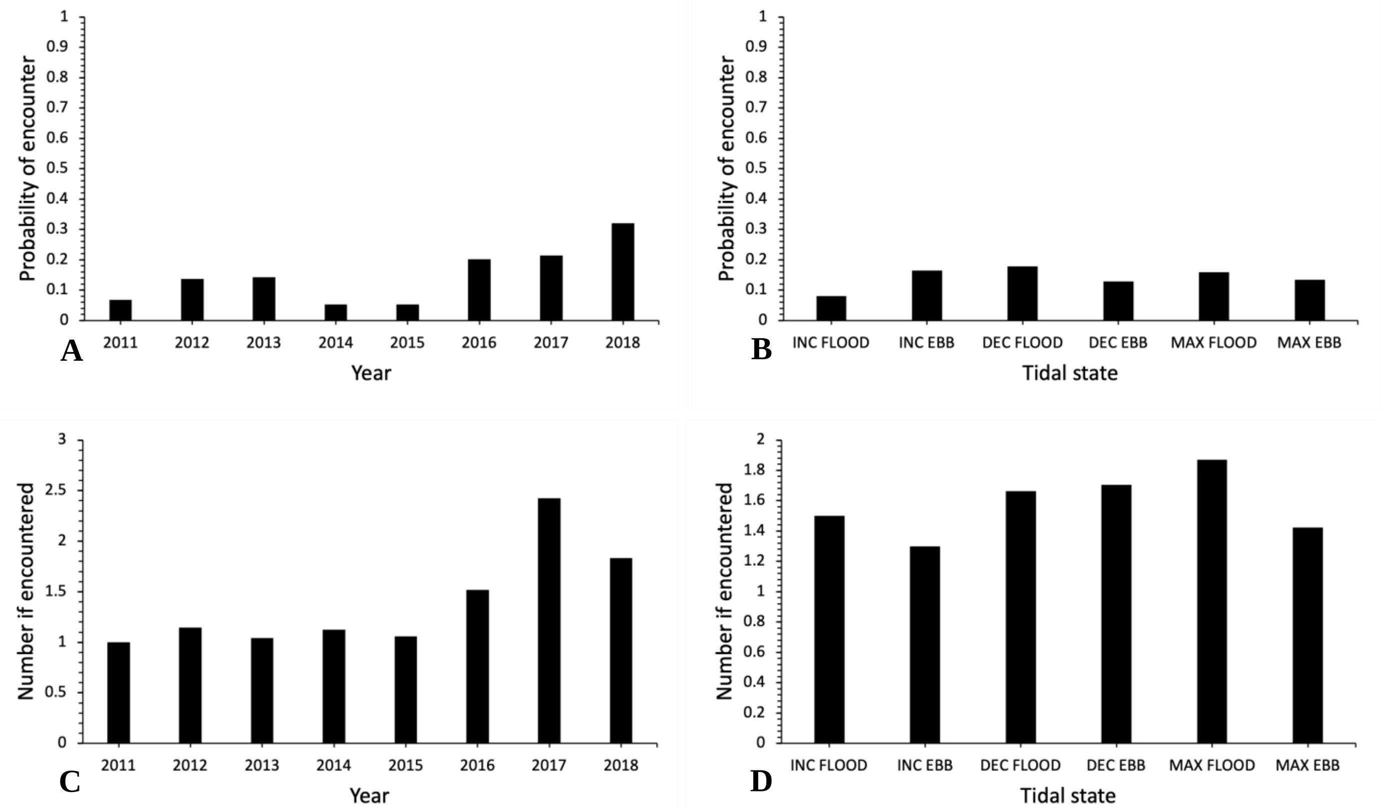

Figure 17. Bar plots for the Common seal winter season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.

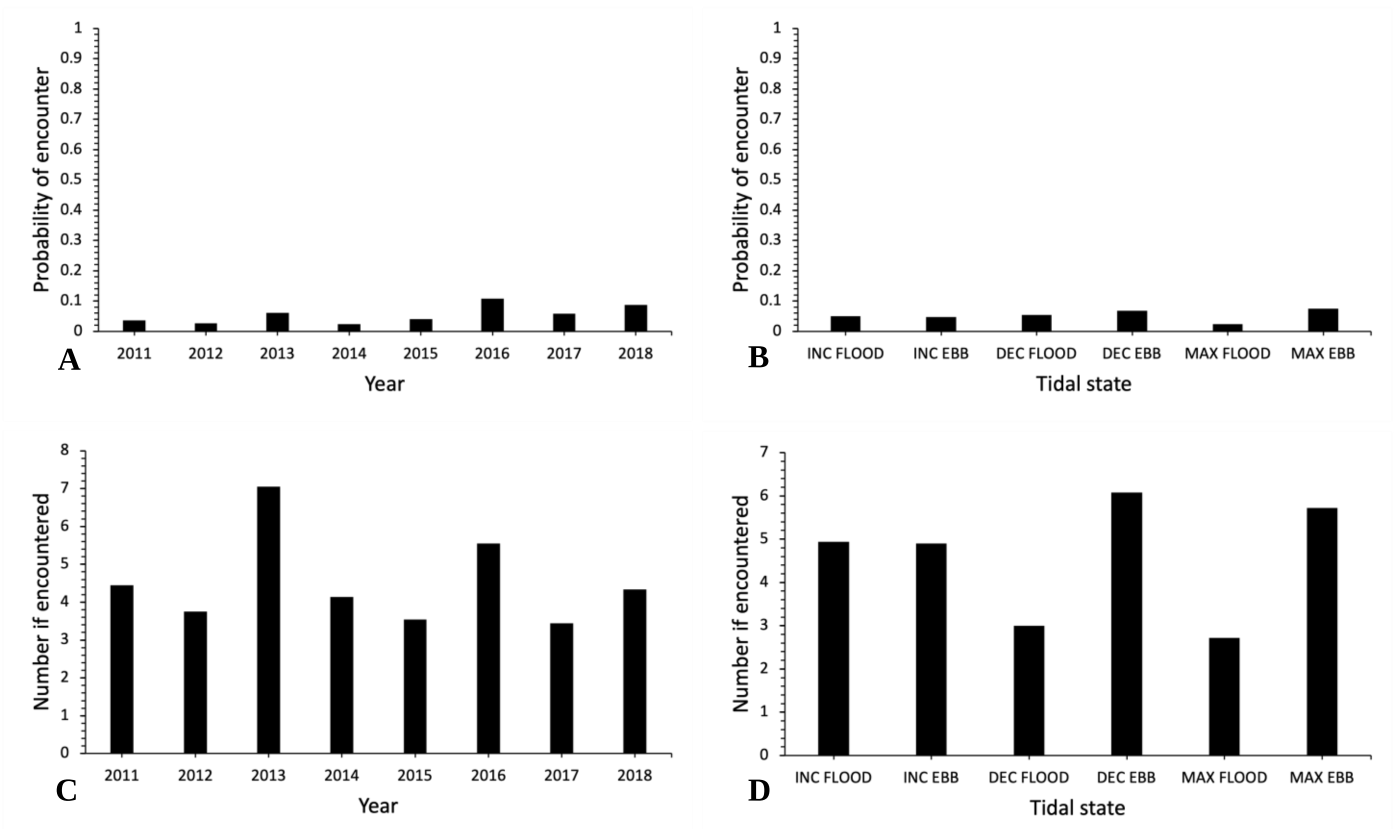

Figure 18. Bar plots for the Harbour porpoise winter season displaying [A] how the probability of encounter changes across years 2011 – 2018 [B] how the probability of encounter varies across tidal states [C] how the average number of individuals if encountered fluctuates between years [D] how the average number of individuals if encountered fluctuates across tidal states.