Environmental factors affecting chick diet of colonial auks at South Stack, NW Anglesey.

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Running head page: Environmental factors impacting colonial auk populations

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Abstract

The marine ecosystems of the world are facing increasing challenges due to climate change and human activities. Rising carbon dioxide levels and resulting oceanic changes have significant effects on marine organisms and ecosystems. Breeding colonies of common guillemots (*Uria aalge*) and razorbills (*Alca torda*) at South Stack, North Wales, play a vital role in coastal regions. The study investigates the complex relationship between environmental variables and chick diet composition in these colonial auks. The results revealed that common guillemots preferentially fed their chicks clupeids, while razorbills primarily fed their young with sandeels. The study examined the correlation between the time of day and the preference for sandeel and clupeid as prey, demonstrating a potential correlation, with a p-value of 0.05819. There was a strong negative correlation between sea surface temperature and week number, indicating declining SST over time. This SST decline was mirrored in a negative relationship between SST and prey abundance, suggesting that lower SST is linked to increased prey availability for common guillemots and razorbills in the study area. Wind speed (WS in mph) showed a positive correlation with both clupeid and sandeel abundance, suggesting that stronger wind speeds could influence the chicks' dietary requirements, potentially an increase in calorie intake. High and low tides did not significantly differ in mean prey abundance values, suggesting the tidal cycle did not substantially impact prey variation. These findings provide crucial insights into the potential changes of environmental factors on prey abundance dynamics within the studied site, with particular emphasis on the potential roles of the oceanic conditions and weather patterns in influencing prey availability for common guillemots and razorbills.

Keywords: predator-prey, colonial auks, fish populations, foraging behaviour, prey availability.

1. Introduction

The world's marine ecosystems have faced major challenges due to human activities and the far-reaching effects of climate change. The rising levels of carbon dioxide in the atmosphere leads to increasing ocean surface temperatures and higher ocean acidification (Behrenfeld et al., 2006; Doney et al., 2012). These environmental shifts have a direct

impact on marine organisms, influencing their population dynamics and increasing the risk of potential loss within marine and coastal ecosystems (Harley et al., 2006; Portner & Farrell, 2008). The decline in some fish stocks is attributed to the alarming trend of "fishing down the food web" on a global scale (Pauly et al. 2002, Pauly & Palomares, 2005; Myers & Worm 2003). Seasonal and intraseasonal changes in environmental conditions and the local food availability often affect the foraging behaviour and dietary preferences of animals including various seabird species influencing their breeding success and overall population dynamics (Jakubas & Manikowska, 2011; Pearce-Higgins et al., 2022).

Colonial auks, such as common guillemots (*Uria aalge*) and razorbills (*Alca torda*), play a vital role in marine ecosystems as indicators of environmental health and contributors to nutrient cycling in coastal regions (Hodges et al., 2022; Pistorius et al., 2023). South Stack, situated along the northwestern shores of Holyhead, Wales, is an important breeding site for colonies of these seabirds in the United Kingdom during their nesting season (Hamer et al., 2020). This site offers a unique opportunity to investigate the complex relationship between environmental variables and chick diet composition in colonial auks. While previous studies have examined the foraging behaviour of auks and its relationship with environmental factors (Daunt et al., 2002; Harris et al., 2015), the influence of these factors on the chick diet during the critical period of growth and development remains limited (Kadin et al., 2015; Wanless et al., 2022).

Common guillemot (*Uria aalge*) is found along the southwest coasts of England, very locally on the cliffs and islands of Wales, and in a larger number in the north of England and Northern Ireland, most of the population breeding in Scotland (JNCC, 2020; Mitchell et al., 2004; Zador et al., 2009). These charismatic birds are primarily known for their breeding colonies that occur on the rugged cliffs of Wales. The conservation status of common guillemot is classified as a species of "Least Concern" globally, but in certain regions in NW Europe including parts of the British Isles, they face important threats. Climate change, overfishing, and habitat disturbances have led to a decline in their numbers. Breeding success in Wales, a stronghold for these birds, depends greatly on the availability of their preferred prey, which primarily includes sandeels, clupeids and other small fish. Fluctuations in prey populations can have a direct impact on chick survival rates (Monaghan **et al.,** 1994; Anderson et al., 2014), thus monitoring their breeding sites and ensuring sustainable fisheries management are critical steps in securing the future of their breeding success in their nesting sites in Wales (Power et al., 2021). Given that clupeids and sandeels serve as a crucial source of nourishment not only for guillemots but also for other seabirds, alterations in the abundance of these fish species resulting from fluctuations in oceanographic conditions, encompassing sea temperature and currents, can exert profound effects on breeding success (Huntington et al., 2004).

Razorbills (*Alca torda*), another prevalent auk species in the study site, exhibit a similar dietary preference, primarily feeding on small marine fish such as sandeels and small clupeids. Similar to common guillemots, razorbills are also subject to conservation concerns, particularly in their breeding colonies along the UK's coastal cliffs (Massimino et al., 2019). Previous research has shown a decline in the population numbers and breeding success of razorbill populations in the United Kingdom, with a shortage of sandeels being implicated as a key contributing factor (Mitchell et al., 2004; Wanless et al., 2005; Heath et al., 2009). The availability of these critical prey species fluctuates annually, subject to the influence of environmental factors such as sea temperature and species composition of plankton (Carroll et al., 2015; Major et al., 2021). These fluctuations ultimately impact the breeding success of razorbill populations.

For common guillemots and razorbills breeding in seasonal environments, such as those in the South Stack region, the timing of crucial life-history events such as reproduction is closely linked to the peak availability of their preferred prey. This synchronization of breeding and food availability ensures the successful rearing of their chicks. However, in the context of a changing climate, shifts in annual cycles of various organisms can disrupt this delicate balance. Climate-induced changes may lead to mismatches between predators and their prey, which could reverberate through the ecosystem's structure and function (Stenseth et al., 2002; Daunt & Mitchell, 2013)

In this study, the aim is to investigate the oceanographic conditions and prey diet of common guillemot and razorbill chicks in the South Stack region of Hollyhead, North Wales. By examining changes in diet and foraging behaviours, a better understanding is sought for the relationships between these seabirds and their prey in the face of evolving oceanographic and climatic conditions. This research contributes to our broader understanding of how environmental changes impact marine ecosystems and the species that rely on them, presenting the potential consequences for seabird populations and the larger ecological community.

2. Methods

2.1 Study site

Fieldwork was conducted at South Stack cliffs, north-west of Holyhead, North Wales (Figure 1), during late June and the first half of July, 2023. In preparation for the breeding season, protocols were devised to systematically collect data regarding the dietary habits of common guillemot (*Uria aalge*) and razorbill (*Alca torda*) chicks. This involved visiting the breeding colonies located in the breeding ledges and monitoring the birds daily.

2.3 Data Collection

The observer was directed to locate a safe monitoring point enabling the observation nest sites within 8 study plots (colonies 0-7) (Figure 2) maintaining a distance not exceeding 30 meters over a 12-day period. The observer was also encouraged to include any Atlantic puffin (*Fratercula arctica*) nests within the study area in the observation if such nests were present; however, puffin chicks were not presented during the study in the observed area.

To reduce potential biases related to temporal changes in sampled prey, data collection was conducted at various intervals throughout the day, encompassing both morning and afternoon observations during the chick-rearing period.

During data collection, the observer employed various tools including digital SLR camera, telescope, the naked eye and binoculars to scan the flying birds heading toward the colonies. The observer focused on identifying individuals carrying fish and then tracked them until they returned to their breeding site.

The observer categorised the identified prey into one of five groups based on body shape and colour: sandeel, clupeid, gadid, other prey, or unknown (items not definitively identified due to unclear visibility or poor quality of the photograph). The "unknown" prey category was subsequently excluded from further analyses, ensuring no omission of significant prey types. There were 0.6% of “unknown” sampled prey in the diet of common guillemot. These unknown prey items could not be identified despite the photographs taken during the observation. Razorbills demonstrated a higher percentage of 3.2% of 'unknown'' fish in their diet, which the observer could not identify despite photographic documentation.

Common guillemots also may return to their breeding colonies carrying display fish, which are held prominently in their bills, making them easier to identify compared to the fish fed to chicks, which are swiftly swallowed. On the other hand, razorbills, with their larger beaks and ability to carry multiple fish at once, presented a more challenging task for the observer to identify their prey accurately. The larger beak size allowed razorbills to transport multiple smaller fish in a single trip, leading to less conspicuous displays of individual fish.

2.4 Data analysis

RStudio (R version 4.3 - 2023/2024) was used for statistical analysis. The data collected during the study were subjected to comprehensive data analysis to investigate prey preference between common guillemots and razorbills, as well as the influence of potential environmental determinants of variations in chick diet, such as time of day, tidal cycle, week number, wind conditions and sea surface temperature (SST).

To assess prey preferences, the identified prey items were categorised into different groups, including “sandeel”, “clupeid”, “gadid”, “other prey”, and “unknown prey”. The observed numbers of each prey type were then compared between common guillemots and razorbills using appropriate statistical methods, such as chi-square tests (Agresti & Finlay, 1992). These analyses aimed to determine whether there were significant differences in prey selection between the two species and whether any particular prey type was preferred by either bird species.

A contingency table was created to present the observed frequencies of sandeel and clupeid within the time periods that were taken during morning and afternoon monitoring. This table allowed one to investigate whether there was any significant relationship between the time of day and the presence of these fish species. Pearson's Chi-squared test was applied to this contingency table (Biswal, 2023). This test is commonly used to assess the association or independence between two categorical variables. In this study, the categorical variables were "Fish Species" (sandeel and clupeid) and "Time" (indicating the time of prey observation during a timed observation). The results include Yates' continuity correction to mitigate potential overestimation of statistical significance (Brown & Choi, 2001; Cohen, 2013).

The aim of this study was to examine the effect of potential environmental determinants and investigated the impact of ocean conditions on prey availability. Relevant oceanographic data was obtained, including sea surface temperatures (Celsius), week number, rainfall (mm), and wind speed (mph) from available online sources and analysed their association with the prey sample size. Correlation analyses and regression models were employed to identify any significant relationships between enviromental factors and prey abundance (Montgomery et al., 2012). This analysis was used to understand the ecological dynamics of the collected prey and their potential responses to changing environmental conditions. Prior to analysis, data were pre-processed to ensure accuracy and consistency. Correlation analysis was employed to assess the strength and direction of relationships between these variables, as it allows for the exploration of potential dependencies that may impact prey dynamics. This method was chosen for its ability to uncover patterns and associations in complex ecological systems. Additionally, this approach can aid in the identification of key environmental drivers that may influence the distribution and abundance of clupeid and sandeel populations.The method aimed to provide valuable insights into the ecological interactions and potential responses of these prey species to environmental changes in the study area. ANOVA (Analysis of Variance) was used to examine the relationship between the tidal cycle and prey abundance utilizing a general ANOVA model represented as:

```
aov2 <- aov(data = data, Prey ~ Height_high * Height_low)
```

This model allows for the assessment of how both high tide (Height_high) and low tide (Height_low) variables, as well as their interaction, influence prey abundance.

A Bayesian regression modelling analysis was used to extend regression by providing probabilistic estimates of parameters and exploring the relationships between various environmental factors (e.g. sea surface temperature, wind speed (WS)) and the abundance of clupeid and sandeel.In the Bayesian models, Gaussian distributions were used to model the relationships between environmental variables and the prey abundance, including estimates of model parameters, their standard errors, and 95% credible intervals (Montgomery et al., 2012; Gelman et al., 2013).

Throughout the data analysis, potential confounding factors were consideredand controlled for them to ensure the validity and reliability of our results (Rothman et al., 2012). The statistical significance levels were set at $p < 0.05$ to determine the significance of the findings. The study aimed to provide valuable insights into the prey preference between these seabird species and the environmental drivers that influence their foraging behaviours, contributing to a better understanding of the ecological dynamics in the study area.

3. Results

3.1 Breeding success and offspring survival

Between June – July of 2023, 36 common guillemot chicks and 13 razorbill chicks were observed for a total of 12 days (Figure 5). Seven unsuccessful offspring were monitored during the observation.

3.2 Chick diet composition

Clupeids, most likely of the species *Sprattus sprattus* (although a few young fish individuals, potentially representing another species such as young herring), were observed in the common guillemot chick diet (Figure 7). On average, there were about 9.67 clupeid fish observed in the sampled data (Figure 6). Sandeels dominated as the primary dietary component for razorbills' chicks, but the mean sandeel abundance was 2.5 in total observed fish daily.

A correlation between the time of day and the preference for sandeel and clupeid as prey were analysed (Figure 9). The results of the Chi-squared tests suggested a potential association between these factors. However, it is important to note that this association did not reach conventional levels of statistical significance (set at 0.05). While the p-value of 0.05819 (Table 1) falls slightly above the customary significance threshold, it indicates a trend toward an association between the time of day and prey preference.

3.3 Enviromental factors and prey availabilty

The correlation matrix (Fig.7) was computed to investigate potential relationships between environmental factors and the abundance of fish prey, clupeid and sandeel that were observed in the study. The results showed a strong negative correlation between sea surface temperature and week number, indicating a decrease in sea surface temperature as time progresses. Both coefficients suggest a negative relationship between the two variables, but the clupeid abundance coefficient (-0.414) is slightly stronger (closer to -1) than the sandeel abundance (-0.396).The correlation analysis found a negative correlation between sea surface temperature (SST) and prey abundance, indicating that lower sea surface temperatures are associated with increased prey availability for common guillemots and razorbills in the study site. The results of the Bayesian regression model for prey abundance also suggest the relationship between prey availability and sea surface temperature - SST (Figure 10). The coefficient SST is estimated to be 0.58 with a 95% confidence interval of (-1.26, 2.44). This positive coefficient indicates that as SST increases, the number of prey tends to increase, although the relationship is not statistically significant at the 0.05 level, as the confidence interval includes zero.

Wind speed (WS, in mph) showed a strong positive correlation with both clupeid and sandeel abundance, indicating that higher wind speeds may be associated with increased prey abundance.The results of the Bayesian regression model also do not provide strong evidence to conclude that changes in wind speed significantly impact clupeid and sandeel abundance (Figure 10), but the coefficient for WS is estimated to be 0.63 with a 95% confidence interval of (-0.04, 1.32), suggesting a positive relationship.

Rainfall (mm) showed a relatively weak positive correlation with all variables, indicating a modest influence on the observed relationships.The high tides variable has an F-value of 0.230 and a p-value of 0.646, while the low tides variable has an F-value of 0.721 and a p-value of 0.424 (Figure 11). The results suggest that there is no significant difference in the mean prey abundance values across different levels of high and low tides and the variation in observed fish cannot be attributed to differences in the tidal cycle.

These findings provide valuable insights into the potential impacts of environmental factors on the dynamics of prey abundance in the studied site.

4. Discussion

4.1 Prey availability

At South Stack, North Wales, common guillemots (*Uria aalge*) show a preference for feeding their chicks on clupeids, whereas razorbills (*Alca torda*) tend to feed their young with sandeel. The chick diet may vary from one year to another within the same colony and also differ between colonies at both regional and local levels (Chivers et al., 2011). During the observation period extending from June to July, a notable shift in dietary preferences among razorbills. As July progressed, sandeels showed reduced availability as they tend to bury themselves in the sand during this period (MCCIP, 2018). Consequently, a natural transition in prey preference from sandeels to clupeids was observed. With a p-value of 0.05819 (Table 1), the test suggests a trend toward association between the presence of fish species (sandeel and clupeid) and different time periods (morning and afternoon). While the p-value is not significant at the 0.05 level, it is close to this threshold. This suggests that there may be a potential relationship between the time of day and the presence of these fish species, but more data and further investigation may be needed to confirm this relationship.

During a 14-day monitoring period (in 2011), the proportions of different prey types fed to common guillemot chicks were analysed (Emery, 2011). It was observed that clupeid was the most frequently sampled prey at the South Stack colony during that specific year of monitoring. Sandeels were also present in the data, albeit in a much smaller numbers, while gadoids were not found there (Emery, 2011; Anderson et al., 2014). It is important to note that common guillemots predominantly consume single fish, while razorbills tend to capture multiple fish in each foraging trip due to their larger beakfuls. This behavioural difference could potentially affect the recorded the mean sizes of prey between the two species. These observations underscore the significance of clupeids as a dominant food source for common guillemot chicks at South Stack colony during the selected monitoring year, providing valuable context for understanding their feeding behaviour and prey preferences.

The breeding success of seabird species, including common guillemots and razorbills, is intricately linked to prey availability (Camphuysen et al., 2006; Chimienti et al., 2017). One of the key factors contributing to the past growth in the numbers of these species has been the presence of suitable nest sites and reasonably abundant prey availability. However, it is essential to recognise that the prey abundance can be vulnerable to shifts caused by rising temperatures and extreme weather events (Chimienti et al., 2017; Glew et al., 2017). Previous research has provided valuable insights into how common guillemots and razorbills respond to changes in prey encounter rates. These seabirds vary in their sensitivity to different aspects of prey availability, which can have profound implications for their breeding success (Jenkins & Davore, 2020; Pistorius et al., 2023).

There is a significant relationship between prey capture rates and environmental conditions for these seabirds during the chick-rearing period (Thaxter et al., 2013). Furthermore, the species-specific responses to varying prey characteristics. Predictions from the past study indicated that razorbills were more sensitive to decreases in sandeels. Common guillemots, on the other hand, were found to be more sensitive to prey patches that were more widely spaced. Both species responded similarly to reduced prey density.

This research presents the significance of understanding how changes in prey availability can impact the foraging ecology and ultimately the breeding success of common guillemots and razorbills. It provides a framework for assessing the potential consequences of environmental change on prey abundance, highlighting the need to consider seabird foraging behaviours and ecological dynamics in conservation and management strategies.

4.2 Wind conditions

Results of the present study indicate that local wind conditions significantly influence the prey availability and foraging behaviour. During higher wind speeds, auks increased their foraging trips compared with trips performed during low winds. In focusing on wind speed and prey abundance, it is important to note that while the research indicated a positive correlation between wind speed and prey availability, there are some limitations to consider. The data collected did not include days when the wind speed exceeded 26 mph, primarily due to safety concerns related to conducting observations on the cliff. It may therefore represent a potential bias in the dataset, as extreme wind conditions can have particular ecological effects that were not captured in the study.

The past literature suggested that the correlations between prey availability and wind conditions in auks and highlighted the intricate relationship between these factors in shaping the foraging strategies of these seabirds. When prey is abundant, auks are more efficient in their foraging efforts, spending less time searching for food (Jakubas et al., 2022; Piatt et al., 2007; Scott et al., 2000). However, when the number of local prey is low, seabirds must invest more time and energy in foraging (Fayet et al., 2021), potentially needing to travel longer distances to find sufficient food resources (Clay et al., 2023). Wind speed further complicates this dynamic, as strong winds can hinder auk flight and prey detection, disrupt prey distributions by mixing the water column, and create challenging wave conditions for capturing prey (Collins et al., 2020; Jakubas et al., 2022). Common guillemots are less successful in locating and catching fish in strong winds, illustrating the influence of wind conditions on prey capture rates (Piatt et al., 2007; Scott et al., 2000).

4.3 Sea surface temperature

The study demonstrated significant insights into the complex interplay of environmental factors in shaping the chick diet. The present research analysis found a negative correlation between sea surface temperature (SST) and prey abundance, indicating that lower sea surface temperatures are associated with increased prey availability for common guillemots and razorbills in the study site. This finding aligns with previous research highlighting the influence of environmental variables such as SST on the distribution and abundance of sandeels and clupeids, which are critical components of the auk chick diet (Cury et al., 2011; Henriksen et al., 2021). The decline in SST over the study period may have implications for the distribution and abundance of marine prey species (Rutterford et al., 2023), potentially affecting the foraging behaviour of common guillemots and razorbills.

Over recent years, there has been a gradual and consistent increasing trend in global temperatures (IPCC, 2023). The rise in sea-surface temperature (SST) in the North Sea, with an approximate 1°C increase since the early 1980s, has emerged as a significant environmental factor impacting seabird populations (Yumashev et al., 2017). The previous studies demonstrated that higher SST during winter months is associated with reduced over-winter survival of adult seabirds and decreased breeding success in the following year (Frederiksen et al., 2004). This finding underscores the influence of warming ocean conditions on seabird demography.

The consequences of rising SST extend beyond seabird populations, affecting the entire marine ecosystem. Shifts in the species composition and biomass of the plankton community can occur in response to warming sea temperatures (Beaugrand et al., 2003). Furthermore, the populations of the lesser sandeel *(Ammodytes marinus)*, an important prey species for razorbills, have been negatively impacted by warmer sea temperatures (Arnott and Ruxton, 2002). These ecological changes in prey availability reverberate through the food web, ultimately affecting the foraging opportunities and reproductive success of seabirds.

In addition to prey availability, SST is a critical component in understanding the ecological processes driving sandeel larval production and survival to the juvenile stage, known as recruitment. The relationships between prey abundance and climate factors including SST suggest the key determinants of sandeel recruitment (Lynam et al., 2013). This research underscores the pivotal role of SST in shaping the early life stages of sandeels, which in turn has far-reaching implications for the seabird species that rely on them as a primary food source.

The rise in sea surface temperature is a prominent factor impacting not only the survival and breeding success of auk chicks but also the fish populations. Changes in prey availability, driven in part by warming sea temperatures, have significant effects on seabird populations, highlighting the need for ongoing research to comprehensively understand and address the complex ecological interactions in this changing environment.

4.4 Breeding success

The breeding success of common guillemots (*Uria aalge*) and razorbills (*Alca torda*) at South Stack, Holyhead, during the recent breeding season, spanning from June to July, has garnered considerable attention due to a series of significant challenges observed in the colonies. The number of monitored chicks this year was relatively low, with 36 common guillemot chicks and 13 razorbill chicks observed (Figure 5) , indicating potential issues affecting the reproductive success of these seabird colonies. Additionally, there have been cases of unknown deaths within the observed colonies and instances of predatory attacks by seagulls during the last days of observations (Fig. S1), in the mid July. There were found 7 deceased chicks on the ledges and in the sea. These factors raise questions about the overall health and resilience of these populations in the face of changing environmental conditions.

To better understand the recent breeding challenges, it is important to consider the existing literature and research findings. Anderson et al. (2014) highlighted the impact of local food supply on seabird breeding success and population trends. The results suggest that changes in the common guillemot chick diet are likely influenced by a combination of climate and fisheries effects. Climate-related shifts in fish distribution and abundance, particularly temperature changes in the North Sea, appear to affect the availability of prey species.

In a more recent study by Bennett et al. (2022), the concept of the "buffer effect" in population regulation was explored, focusing on high-quality breeding sites as a limiting resource. This study suggests that the quality of breeding sites plays a crucial role in determining breeding success, and individuals tend to breed disproportionately at the highest quality sites. This finding may have implications for the observed decline in the number of nests at South Stack. If high-quality breeding sites are limited or degraded, it could contribute to reduced breeding success.

The past research also presented the idea of site-dependent regulation, where the quality of breeding sites influences population dynamics (Jeschke et al., 2007; Bennett et al., 2022). This concept aligns with the observation of low chick numbers this year, as it suggests that changes in site quality may affect breeding success. Factors such as the availability of suitable nest sites and food resources can directly impact the reproductive capabilities of seabirds. Furthermore, the previous findings highlight the importance of considering population trends. In cases where populations are recovering after a decline, the study suggests that new sites and previously occupied sites of varying quality may be occupied at similar frequencies. This could be relevant to South Stack if there has been a recent population decline or if there are changing dynamics within the colonies.

The presence of unknown deaths within the colonies and predatory attacks by seagulls underscores the vulnerability of these seabird populations. Predation can be a significant threat to breeding success, and addressing such challenges may require management strategies to protect nesting sites and chicks from potential predators (Williams, 1975; Camphuysen 2002). This year, throughoutthe UK, including Wales, there have been reported cases of avian influenza (bird flu) (Welsh Government, 2023). These cases have raised concerns about the health of avian populations in the region, given the potential risks associated with the spread of such diseases.

In our study area, we observed 7 cases of deceased chicks; however, these carcasses were not subjected to laboratory analysis to determine the cause of death. This lack of investigation leaves a gap in our understanding of the factors contributing to chick mortality within the colonies.

The presence of these unexplained deaths within the colonies, coupled with observed predatory attacks by seagulls, influencing the vulnerability of these seabird populations during the breeding season. Predation, especially by avian predators, can pose a significant threat to breeding success, as it can lead to the loss of both adult birds and their vulnerable chicks. Addressing these challenges requires the development and implementation of effective management strategies aimed at protecting nesting sites and chicks from potential predators.

4.5 Limitations

The assessment of the relationship between wind conditions and prey availability in this research is incomplete due to postponed observations on days when the wind speed (mph) was over 26 mph due to health and safety considerations. It is essential to recognise that the relationship between wind speed and prey abundance may be influenced by other environmental factors, such as average temperature and sea surface temperature. In many cases, higher wind speeds are associated with lower temperatures. This dynamic may lead to increased energy spending for the chicks, as they would need to maintain their body temperature and meet higher metabolic demands. Consequently, the observed positive correlation between wind speed and prey availability may be driven by the increased feeding effort of adult seabirds to meet the higher caloric requirements of their chicks during adverse weather conditions.

The past observations demonstrated that foraging effort tends to decrease during high winds among seabirds. Some pelagic seabird species, such as Procellariforms, may actually benefit from high wind speeds by using them to soar, thus reducing their foraging costs. However, this may have the opposite effect on species that are unable to soar and must expend more energy to navigate against strong winds. This is particularly relevant for auks, such as common guillemots and razorbills, which are known to have some of the highest recorded flight costs.

Furthermore, it should be acknowledged that the assessment of breeding success in this research is incomplete. This limitation arises from the fact that the present observations did not include data from the incubation period in early June. The incubation phase is a crucial aspect of understanding breeding success in avian species, as it directly impacts chick survival and overall reproductive outcomes (Verhulst & Nilsson, 2007). Given this limitation, it is important to recognise that the scope of our analysis is limited, and further research is needed to obtain a more comprehensive understanding of the factors influencing breeding success in the studied auk populations. Future investigations should aim to incorporate data from the incubation phase to provide a more relevant assessment of breeding success and its underlying determinants.

5. Conclusions

In conclusion, this study provides baseline data highlighting relationships between environmental factors and prey availability in common guillemots (*Uria aalge*) and razorbills (*Alca torda*) at the study side of South Stack, North Wales. Prey abundance plays a critical role in shaping breeding success (Wanless & Daunt, 2023). While the statistical analysis did not show a significant p-value, the close proximity to the 0.05 threshold suggests a potential relationship between the time of day and the presence of specific fish species (sandeel and clupeid). The dominance of clupeids as a food source for common guillemot chicks and sandeel in the razorbill chick diet during the monitoring period underscores the importance of understanding their dietary preferences.

The negative correlation between sea surface temperature (SST) and prey abundance indicates that lower SST is linked to increased prey abundance for common guillemots and razorbills. This finding underscores the impact of warming ocean conditions on the distribution and abundance of critical prey species and, consequently, the foraging opportunities for seabirds.

The breeding success of auk populations at South Stack may potentially face challenges in recent years. Several factors, including a low prey sample size, the possibility of avian influenza, and predation, have emerged as potential contributors to lower chick numbers and the presence of unexplained chick deaths. Moreover, the concept of site-dependent regulation implies that site quality may play a pivotal role in influencing breeding success, highlighting the need for further exploration in future studies.

It is important to acknowledge the limitations of this research. The exclusion of extreme wind conditions and the absence of data from the incubation period are important considerations. Future investigations should aim to address these limitations and provide a more comprehensive understanding of the factors influencing the breeding success of common guillemots and razorbills at South Stack.

These findings hold significant implications for auk populations, particularly in the face of ongoing climate change (Amélineau et al., 2019). As climate change alters prey distribution and abundance, and leads to more extreme weather events, the foraging behaviour and reproductive success of auks may be at risk (Pearce-Higgins, 2021). Understanding the complex interplay between environmental factors and auk foraging behaviour is crucial for predicting how these seabird populations will respond to changing conditions and for implementing effective conservation measures (Piatt et al., 2007).

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9. Figures

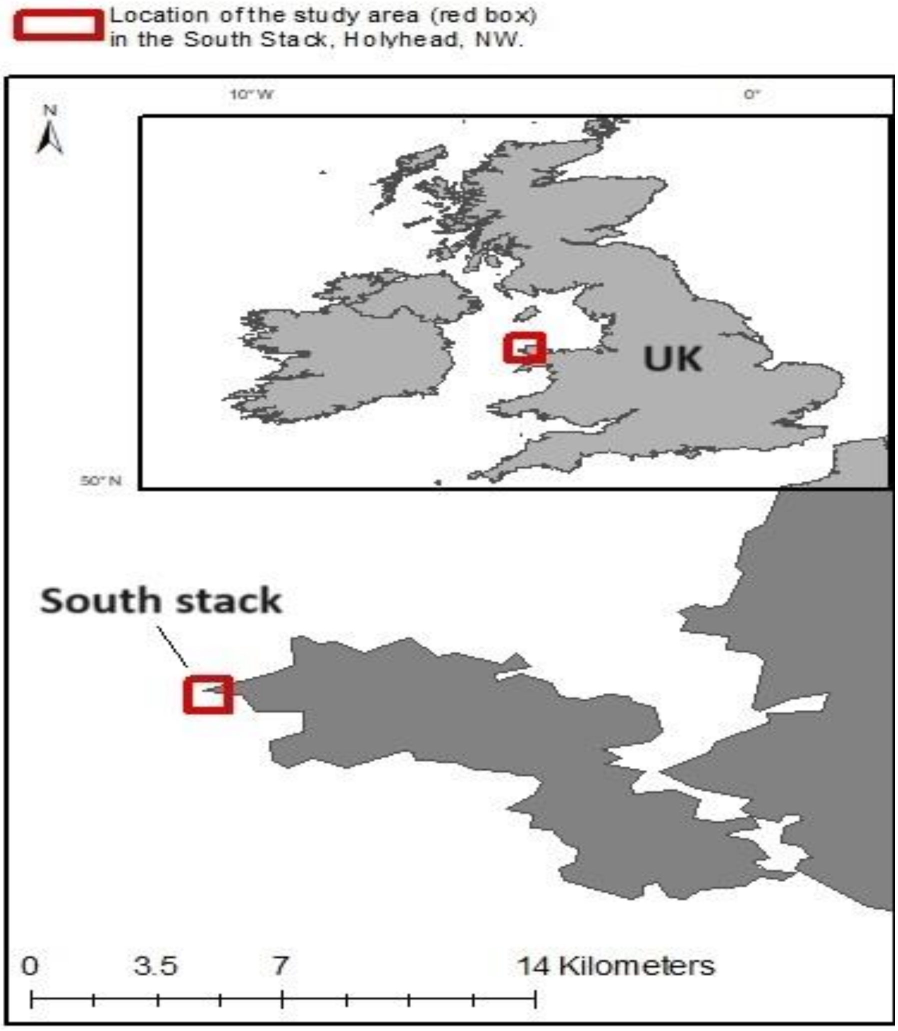

Figure 1. The map shows the study site location.

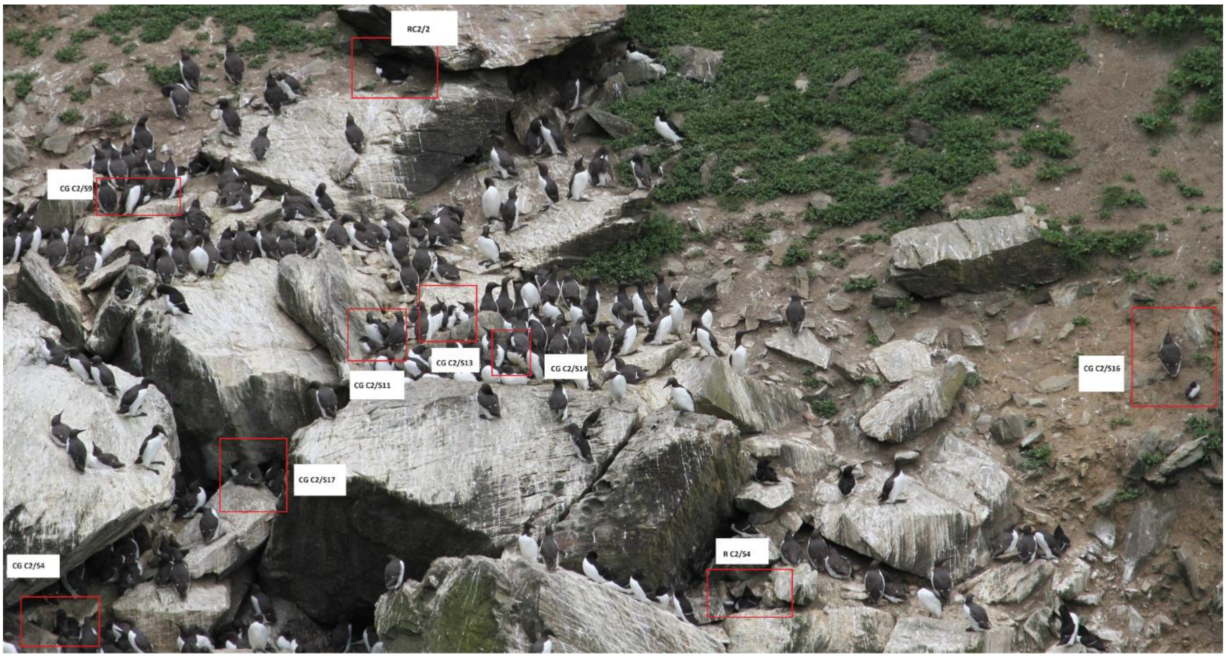

Figure 2. Common Guillemot *Uria aalge* breeding success and feeding watch study plot of colony 2, South stack, July 2023.

Figure 3. Observations of Common Guillemot (*Uria aalge*) feeding behaviour at South Stack, June-July 2023. The left photograph presents a common guillemot individual carrying clupeid prey. The right image shows an adult CG carrying prey (sprat) to its chicks and other chicks within the same colony on the ledge.

Figure 4. Observations of Razorbill (*Alca torda*) feeding behaviour at South Stack, June-July 2023. The left photograph presents a razorbill individual carrying sandeel prey. The right image shows an adult razorbill to its chick on the ledge.

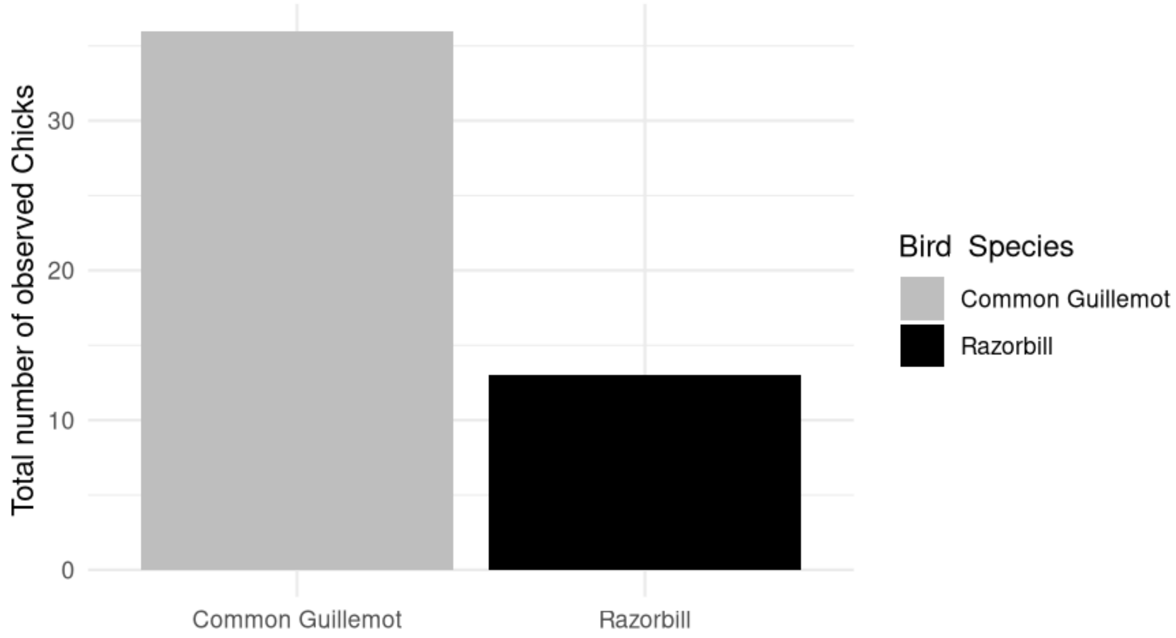

Figure 5. The monitoring of chicks in the site area during late June and July 2023, with a total number of 36 Common Guillemot chicks and 13 Razorbill chicks observed

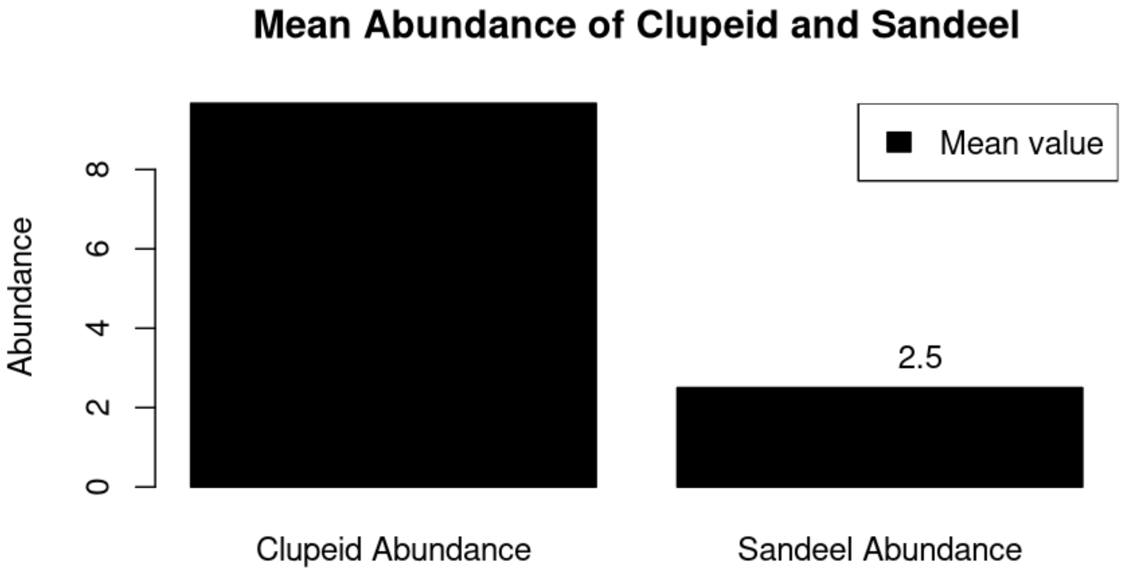

Figure 6. The mean sizes of prey sampled for both clupeid fish and sandeels as observed in our study. In the sampled data, there was recorded an average of approximately 9.67 clupeid fish and the abundance of sandeels among all observed fish was 2.5.

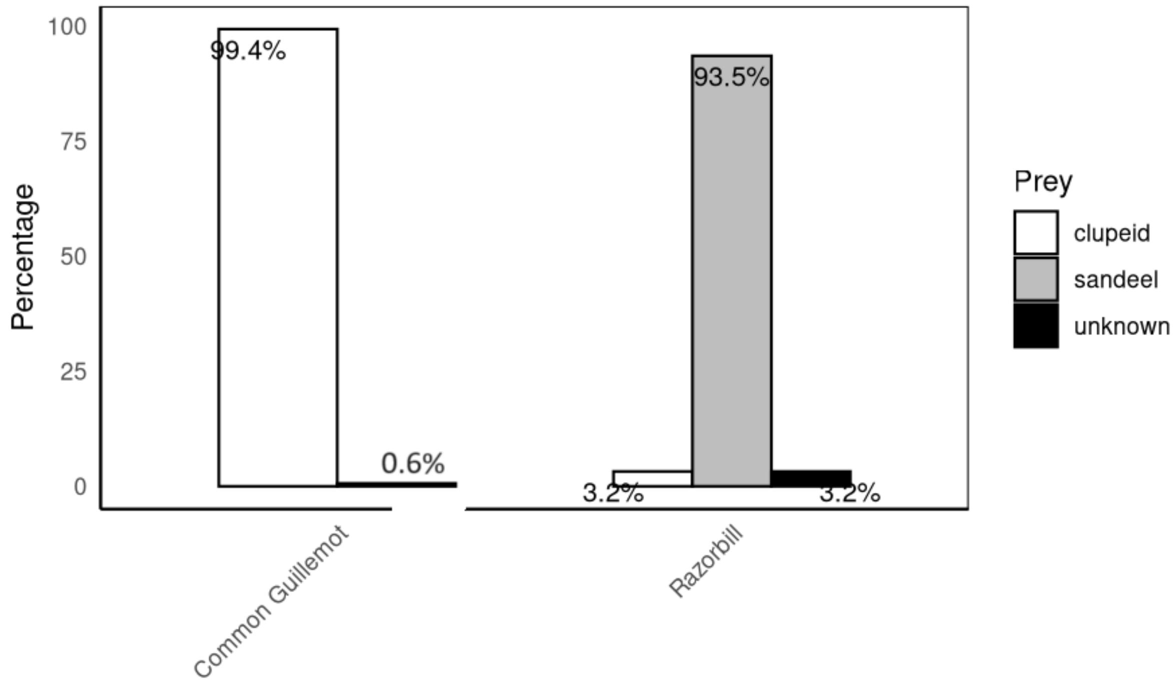

Figure 7. This figure presents the percentage composition of chick diets for Common Guillemot and Razorbills observed at South Stack during the months of June to July 2023. The prey compositions present prey fish, including clupeid, sandeel, and an "unknown" category (used when photographic evidence of the prey did not provide sufficient information for precise identification). The graph provides insights into the dietary preferences and variations in the diets of these seabird species over the monitoring period.

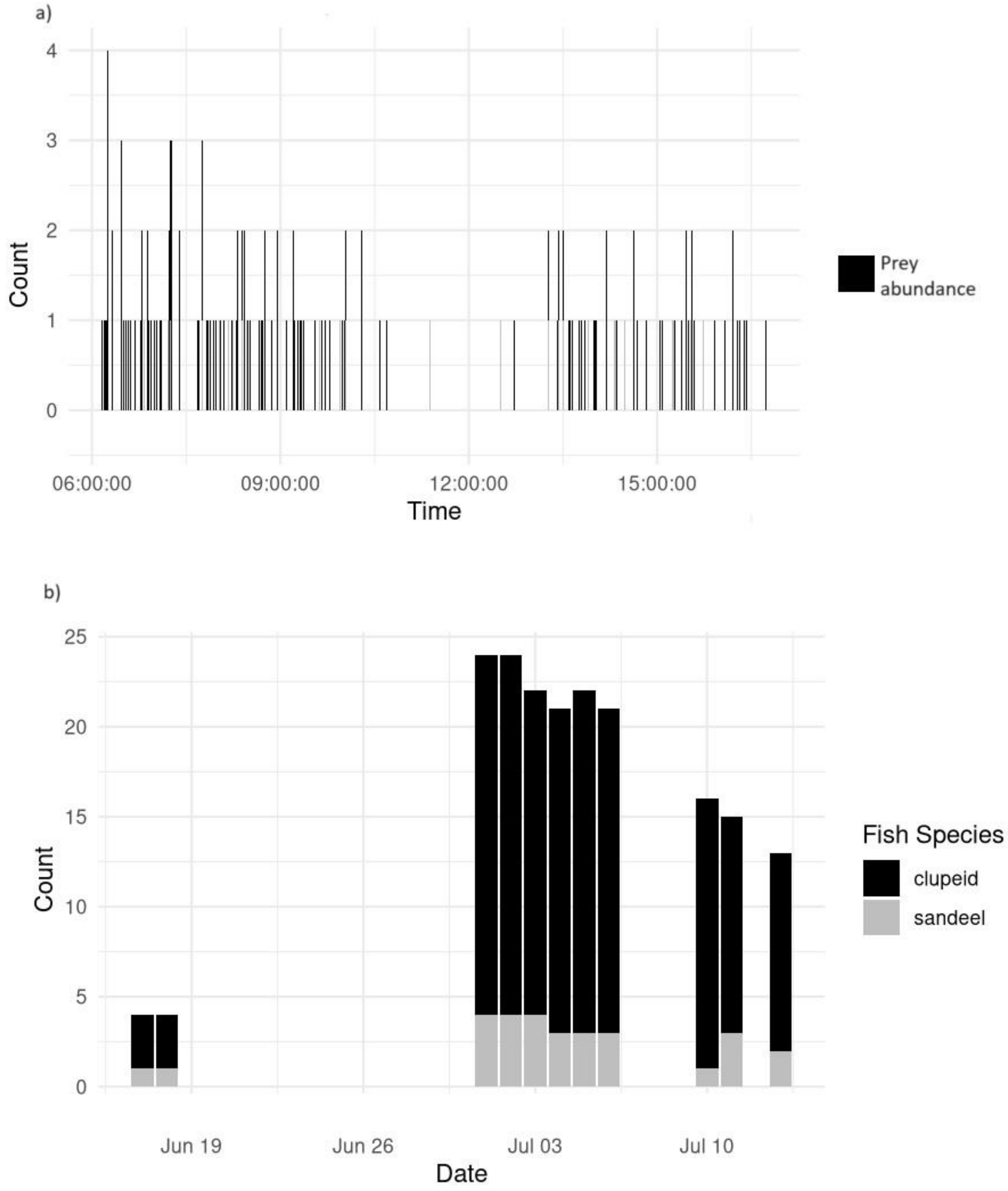

Figure 8. The figure provides insights into the changing prey preferences/ abundance and foraging behaviour of the monitored seabirds during June and July at South Stack, North Wales. a) This figure illustrates the relationship between the time of day and the success of prey to the observed chicks of Common guillemots and Razorbills during the months of June to July 2023. The observations were conducted in the morning (6:00 to 11:00) and afternoon (12:00 to 17:00) to capture when these seabirds were most active in foraging for prey. As depicted, mornings were the peak activity periods for these birds in successfully obtaining prey. b) This graph shows the relationship between monitoring dates in the months of June and July 2023 and the preferences of the observed seabirds for prey. The activity levels of the birds were relatively low in June. However, from the beginning of July, there was a significant peak in prey consumption, which gradually decreased over time.

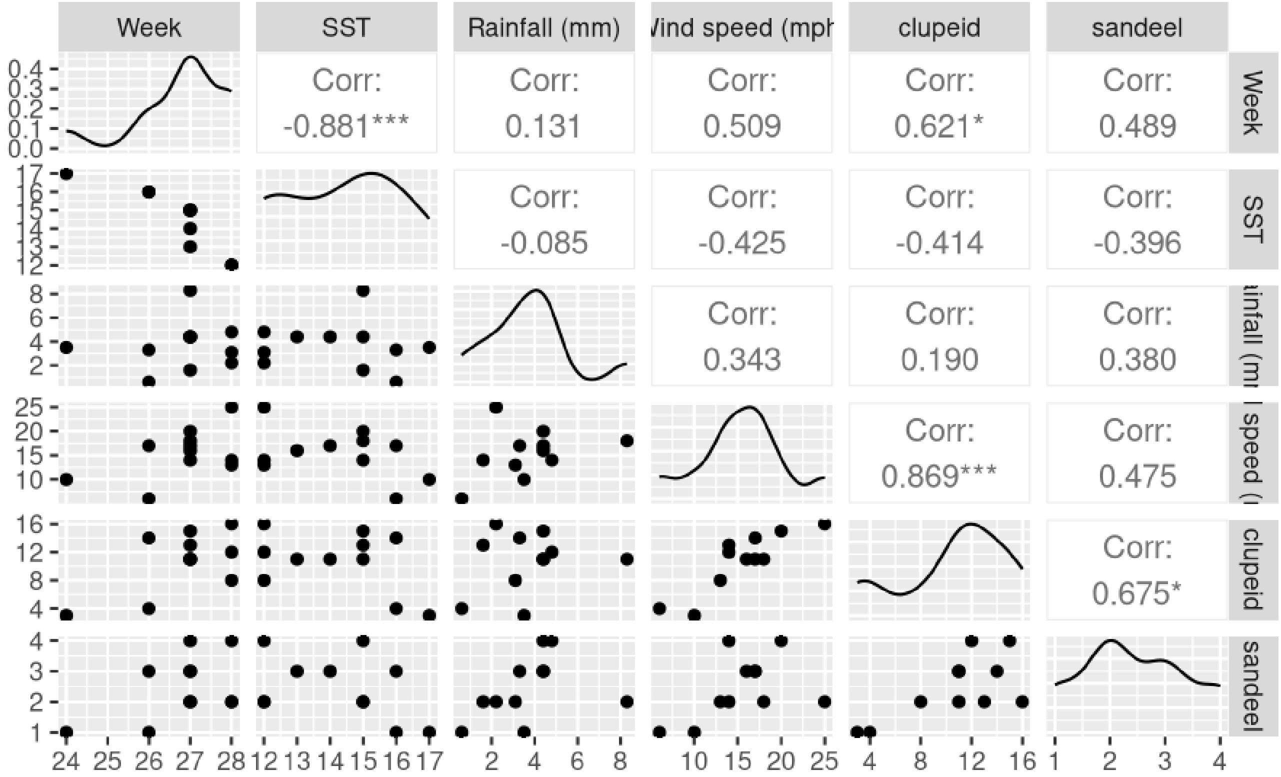

Figure 9. Correlation matrix analyzing the relationship between prey abundance (clupeid and sandeel) and environmental factors to quantify the strength and direction of this correlation between various variables.

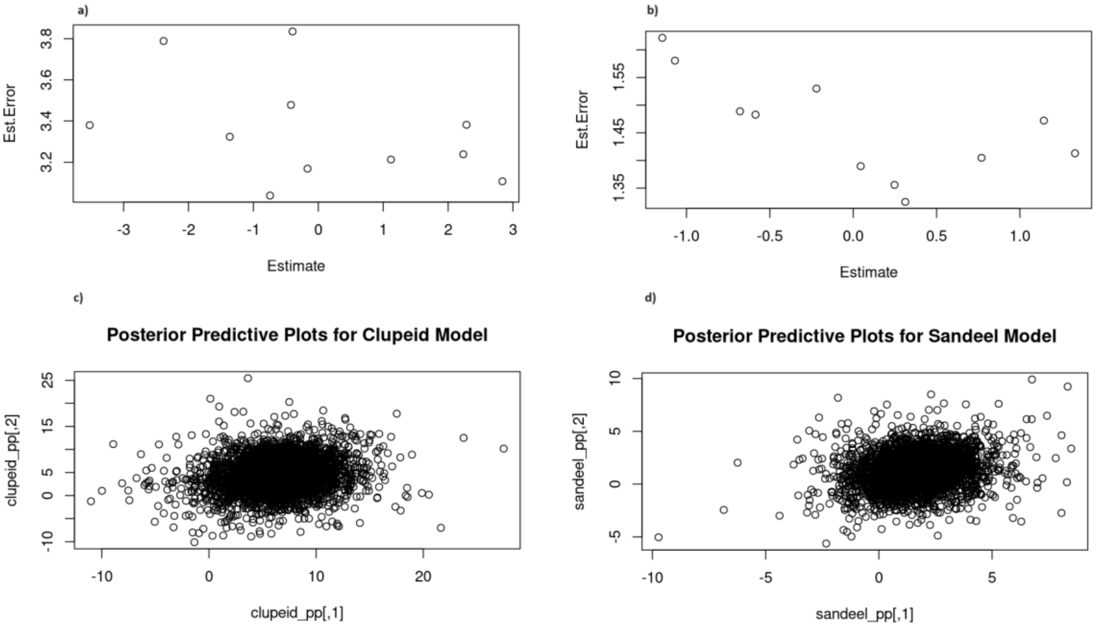

Figure 10. The plots provide information about the estimated coefficients, their uncertainty, and the convergence of the Bayesian regression model to assess the relationships between predictors (sea surface temperature and wind speed) and the response variable (prey abundance) and provide a measure of how confident the results can be in the estimated values. a) The residual plot was generated to assess the model fits for clupeid abundance using Bayesian regression. Residuals are randomly scattered around zero with no clear pattern. This suggests that the model is capturing the underlying relationships in the data well, and the discrepancies between observed and predicted values are random and unbiased b) The residual plot was generated to assess the model fits for sandeel abundance using Bayesian regression. Residuals are randomly scattered around zero with no clear pattern. This suggests that the model is capturing the underlying relationships in the data well, and the discrepancies between observed and predicted values are random and unbiased c) In the plot, which corresponds to the clupeid abundance model, the residuals are displayed. d) The plot corresponds to the sandeel abundance model. Similar to the clupeid model. The plot performs adequately in capturing the underlying relationships between predictors and response variables. (c), the residuals for the sandeel model are examined. The plot displays residuals against their corresponding observations. A visual inspection reveals that the residuals in this plot also exhibit a reasonably random distribution around zero, indicating that the model provides a satisfactory fit to the data.

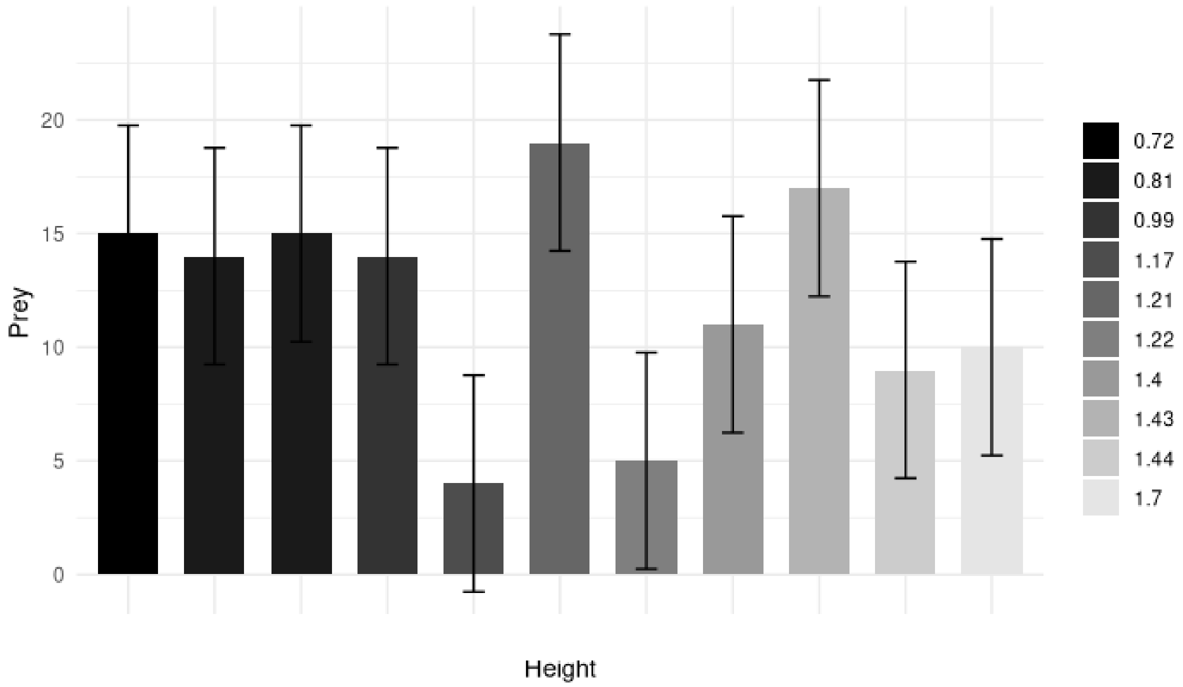

Figure 11. The ANOVA pesents the results of an analysis of variance, which assesses whether there are statistically significant differences in the response variable the prey abundance (Prey) across different levels of the tidal cycle. A p-value of 0.646 is relatively high, indicating that there is no strong evidence to suggest that high tides have a significant effect on prey abundance. The low tides have p-values greater than the commonly chosen significance level of 0.05.

10. Tables

Table 1. Pearson's Chi-squared test with Yates' continuity correction was performed to examine the association between the time of day and the success of prey. The analysis was conducted using RStudio, a statistical analysis software.

Test Statistic (X-squared)	**3.5883**
Degrees of Freedom	**1**
P-Value	**0.05819**

11. Supplementary material

Table S1. This table provides a chronological overview of the developmental stages of Common Guillemot (*Uria aalge*) chicks. The table presents information on key aspects of chick development. The table was used torecognise the age/ stage development of the observed chicks of Common guillemots and Razorbills.

Age	Plumage	Size	Beak	Behaviour
0-7 days	Downy feathers	Tiny/ small	Soft, not fully developed	Newly hatched chicks depend on parents for warmth and food.
7-10 days	Downy feathers	Rapidly increasing	Soft, short, and pointed	Chicks grow rapidly, dependent on parental care.
10-14 days	Down feathers	Medium	Slightly more curved	Parents continue feeding fish to the growing chicks.
14-18 days	Contour feathers emerging, black and white feathers	Larger with well-defined body	Straighter and firmer	Chicks become more active, strengthen wing muscles, and prepare for first flights.
18-25 days	Developing adult plumage, darker feathers	Larger with well-defined body	Adult-like beak structure	Chicks leave nesting site, make their first flights by diving from cliffs or ledges.

Table S2. These statistics provide valuable information about the estimated coefficients, their uncertainty, and the convergence of your Bayesian regression model to assess the relationships between predictors (sea surface temperature and wind speed) and the response variable (prey abundance) and provide a measure of how confident the results can be in the estimated values. The estimated coefficients, including intercept (-4.84), sea surface temperature (0.54), and wind speed (0.61), reveal relationships with prey abundance. The narrow credible intervals (-36.47 to 27.77 for intercept) and low standard errors indicate precise estimates. Rhat values of 1.00 demonstrate excellent convergence, supported by Bulk Effective Sample Sizes (Bulk_ESS) and Tail Effective Sample Sizes (Tail_ESS). Family-specific parameters, such as sigma (4.65), capture data variability. Posterior Predictive Plots and Residual Plots visually illustrate model fit and data relationships, facilitating a comprehensive understanding of predictor-response dynamics, enhancing result confidence.

```
Population-Level Effects:
                        Estimate Est.Error l-95% CI u-95% CI Rhat
Intercept                  -4.84     16.06   -36.47    27.77 1.00
Sea_surface_temperature     0.54      0.92    -1.33     2.40 1.00
Wind_speed                  0.61      0.34    -0.10     1.27 1.00
                        Bulk_ESS Tail_ESS
Intercept                   1993     2164
Sea_surface_temperature     2202     1930
Wind_speed                  2063     1779

Family Specific Parameters:
      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma     4.65      1.24     2.90     7.73 1.00     2420     2656
```

Table S3. The ANOVA table shows the results of an analysis of variance, which assesses whether there are statistically significant differences in the response variable the prey abundance (Prey) across different levels of the tidal cycle. A p-value of 0.646 is relatively high, indicating that there is no strong evidence to suggest that high tides have a significant effect on prey abundance. The low tides have p-values greater than the commonly chosen significance level of 0.05.

```
                       Df Sum Sq Mean Sq F value Pr(>F)
Height_high             1   6.52   6.523   0.230  0.646
Height_low              1  20.43  20.427   0.721  0.424
Height_high:Height_low  1   1.68   1.683   0.059  0.814
Residuals               7 198.28  28.325
```

Figure S1. Predatory attack - Great Black-Backed Gull (Larus marinus) attacking a Common Guillemot chick, July 2023.