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Submitted for the degree of

MSc Marine Environmental Management

University of York

Environmental Department

# Barnacle Population Dynamics: Measuring Future Climate Change Impacts on Alderney

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**Abstract**

Climate change is a global issue that influences the marine environment, such as rocky shores, in which organisms are already exposed to extreme conditions which they are highly adapted to survive. With the added pressure of rapidly changing conditions, exhibited by climate change, the ability for organisms to be able to adapt is highly speculative. In order to monitor rapidly changing conditions and organism responses, indicators have been selected. One such indicator is barnacle populations, but in areas where resources and funding is limited, little is known about such indicators, such as Alderney in the Channel Islands. Therefore, the aim of this study was to provide a baseline for monitoring changes within the barnacle population, in order to provide an indicator for future environmental impacts such as climate change. Sampling was carried out at three sample sites, following the MarClim survey protocol, at high, mid and low tidal heights. In order to determine population dynamics, densities of adults and juveniles of each species were recorded along with predator presence and percentage cover of bare rock. Three species were found to occur, *Semibalanus balanoides, Chthamalus stellatus* and *Chthamalus montagui.* The more exposed site favoured *C. stellatus* whilst the more sheltered site favoured *C. montagui.* Higher densities of the two juvenile *Chthamalus* species were observed at a lower tidal height which have been found to then be outcompeted by *S. balanoides,* therefore it was surprising to find that adult *C. stellatus* was also found to have a higher density at both mid and low tidal heights. Bare rock was found to have a negative relationship with *S. balanoides,* which could be a determining factor for its abundance on Alderney. However, no predators were recorded in any of the samples, but *Nucella lapillus* was observed to be present at all sample sites. Although the aim of this study was to provide a baseline of barnacle population dynamics, further studies may also take into

consideration other factors such as substrate type, barnacle size and factors which have the potential to affect the larval stage of development.

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**Introduction**

Climate change has increasingly become a topic of concern in the biological world, especially with regards to marine ecosystems, with literature increasing exponentially since 1993 (Harley *et al.,* 2006). Projections under various climate change scenarios show no immediate signs of relief in increasing greenhouse gas emissions (IPCC, 2013) with no instant halt within the next 100 years at least, indicating that mitigation is needed to help reduce the effects on marine ecosystems (Harley *et al.,* 2006). Impacts include sea level rise, ocean acidification and increases in sea surface temperature (Harley *et al.,* 2006), which all have profound effects on both marine and terrestrial habitats.

Intertidal rocky shores are just one of the many diverse marine ecosystems that are affected by the effects of climate change. Fundamentally they are harsh ecosystems that support a large variety of organisms including macroalgae, crustaceans and molluscs (Little & Kitching, 1996), and act as a net exporter of energy for both terrestrial and marine ecosystems (UK Marine, 2001). They are naturally exposed to extreme conditions (Little & Kitching, 1996) with distribution and zonation influenced by a range of environmental factors (Jones & Demetropoulos, 1968). Such conditions, including variation in temperature with exposure at low tide, changes in salinity, desiccation, sedimentation and the physical force of the incoming tide (Little & Kitching, 1996); vary vertically along the shore, resulting in zonation (Woodroffe, 2002). These factors, along with added anthropogenic induced impacts such as trampling (Brosnan & Crumrine, 1994) and exploitation, result in highly adapted organisms within this ecosystem. Coupled with this enigmatic environment, climate change has induced considerable deviations within the intertidal environment with regards to diversity, abundance, species distribution, productivity and microevolutionary processes (Harley *et al.,* 2006). But in order to evaluate the true extent of any changes that may have occurred as a result of such impacts, it is imperative that the current community assemblages within ecosystems are known. In many regions, intertidal rocky shore ecosystems are highly studied and ongoing monitoring programmes are already established, such as those carried out by PISCO (Partnership for Interdisciplinary Studies of Coastal Oceans) in California (PISCO, 2016). However, not all regions contain the resources to be able to execute such monitoring programmes, for example small islands such as Alderney, which is situated in the Channel Islands.

Monitoring changes in annual temperature, determining temperature anomalies, recording shifts in species distribution and monitoring increases in extreme weather events are just several ways in which the consequences of climate change have being monitored (IPCC, 2014). In 2003 a review of the UK Climate Change Indicators was undertaken and 34 indicators were selected encompassing both marine and terrestrial systems (DEFRA). Five marine indicators were chosen in total, sea surface temperature, the occurrence of bottom living fish, barnacle abundance, plankton abundance and phytoplankton colour (DEFRA, 2003). Macroalgae has also previously been used as an indicator due to their sensitivity and ability to adapt to subtle changes in environmental conditions both in the short and long term (Tiernan, 2006). For this study however, barnacles, which have been identified as a suitable indicator of climate change (DEFRA, 2003; Mieszkowska[1] *et al.,* 2006), were used to assess current population dynamics, in order to identify potential future environmental impacts. With temperatures in the Channel Islands set to increase between 1.5 and 5 degrees centigrade in the next 100 years (Philippart *et al.* 2011), it is imperative that the current abundance and distribution of indicator species, such as barnacles, are known, to determine any changes that may occur. Barnacles are crustaceans with highly modified bodies, which are enclosed in calcareous plates, and are attached to the substratum by the anterior part of the head (Hayward *et al.,* 1996), but currently, little information exists on the barnacle community on Alderney, therefore, this study will aid in filling in these gaps.

Shifts in climatic envelopes are coupled with the changes in physical environmental conditions. This shift can be both polewards in latitude and upwards in elevation, with the limiting factors being dispersal and resource availability (Walther *et al.,* 2002). In the marine environment, it is thought that there has been a retreat in coldwater species while warmer water species are expanding in both range and abundance (Hawkins *et al.,* 2008). As a result of this shift, non-native or alien species are introduced into ecosystems, potentially resulting in the disruption of native species at either the same or adjacent trophic levels (Walther *et al.,* 2002). An example of this is the Californian gastropod *Kelletia kelletii,* which has been found to have shifted its distribution in response to seawater temperature and oceanic currents (Zacherl *et al.,* 2003). This shift is inevitably going to affect ecosystem communities both where it has shifted from and to. With regards to Alderney's barnacles, little is known about the species and communities on the island, but due to its position and climatic conditions, this would suggest that the native species would be *Semibalanus balanoides.* In addition, *Chthamalus stellatus* and *Chthamalus montagui* are also known to be present. The occurrence of these two species in Alderney could be due to either a shift in climatic envelopes, opening up new habitats to colonise due to climate change, or due to the accidental introduction by humans. The effects and distribution of these species in Alderney are unrecorded and unknown; they do however have spatial differences in species distribution along the shore. *Semibalanus balanoides* occupies the mid tidal level on moderately sheltered shores and shits up the shore with increased exposure (Hayward *et al.,* 1996). This differs to the distribution of *Chthamalus montagui* which occurs higher up the tidal zone and is suggested to be outcompeted by *Semibalanus balanoides* and therefore occurs lower down the shore when this species is not present (Hayward *et al.,* 1996). And finally, the distribution of *Chthamalus stellatus* differs again and is present above and below the mid tidal level on exposed rocky shores (Hayward *et al.,* 1996). Barnacles are a particularly appropriate species to monitor climate change in the Channel Islands region due to these three species being at the edge of their geographic distribution range on UK shores (DEFRA, 2003). If sea surface temperatures continue to increase as predicted, it is suggested that the two warmer occurring species *C. stellatus* and *C. montagui* will dominate over *S. balanoides* in regions southwest of the UK (DEFRA, 2003).

Considering this, the aim of this study therefore, was to collect quantitative information on the current population of barnacles by measuring species presence, density and age structure in order to analyse community structure. In addition to this, the presence of the predator, *Nucella lapillus* (dog whelk), was also recorded to determine any influence on barnacle assemblages. This information can then be used as a baseline for monitoring changes within the barnacle population, in order to provide an indicator for future environmental impacts such as climate change.

## Methodology

*Site Descriptions*

Sampling was carried out on the northernmost Channel Island Alderney. It is relatively small with a width of one and a half miles and a length of three and a half miles; however, it is the third largest island within the Channel Islands (Alderney[1], no date). Three sites were selected for data collection Clonque Bay, Longis Bay and Braye Bay, during July and August 2016.

Clonque Bay is situated to the north west of the island and is located within the Alderney West Coast and the Burhou Islands Ramsar site. The site was designated in 2005 (JNCC, 2008) and spans an area of 15,629 hectares (Ramsar, 2006). It encompasses a range of habitats including pebble beaches, rocky shores and rocky offshore islands, and was designated due to its large colony of gannets along with over one hundred species of seaweeds which play a vital role in the survival of the gannet population (Ramsar, 2006). Although limitations are in place for fishery exploitation and access to Burhou during breeding season (JNCC, 2008), there is currently no protection in place in the area in which the barnacles are situated.

Clonque Bay consists of several substrate types including bedrock, boulders, and a mixture of coarse substrates including rocks, pebbles, sand and gravel (Broadhurst, 2015). Barnacle populations at this site were mainly distributed on both stable bedrock and boulders, which were clustered into two patches at either side of the bay, as illustrated in figure 1 which shows the sample points for this site. Biotope surveys have categorised the bay as a high to moderate energy site (Broadhurst, 2015), with the addition of the fast flowing and complex current system which proceeds the bay, resulting in harsh conditions and the steady input of nutrients, also contributing towards this energy classification.

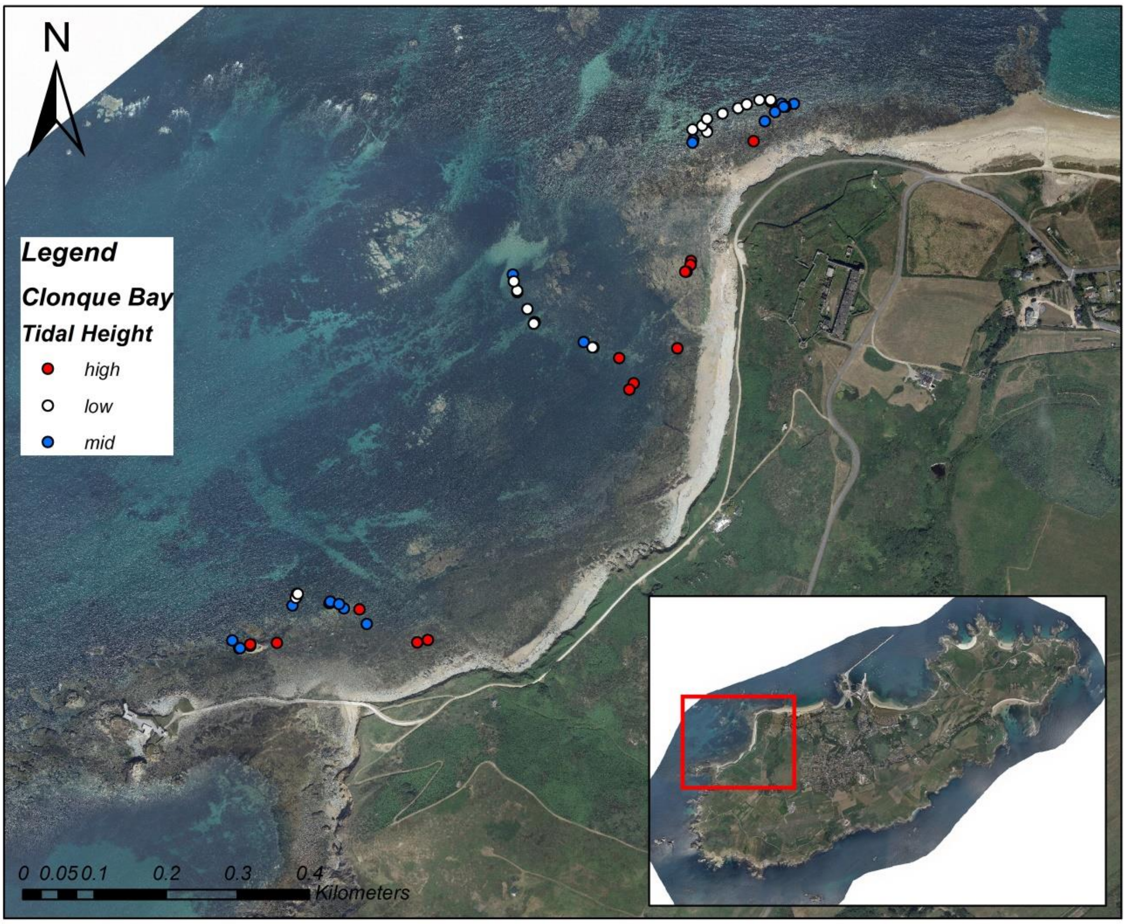


Figure 1: Clonque Bay survey site presenting high (red), low (white) and mid (blue) sample points.

Longis Bay is situated to the south east of Alderney and is part of the Longis nature reserve (Alderney[2], no date). The bay consists of sandy beaches, bedrock and cobble fields with barnacles distributed in one continuous patch along the bedrock, as illustrated in figure 2, which shows the sample points for this site. Longis Bay has previously been defined, from biotope surveys, predominantly as a high energy site (Broadhurst & Salado, 2011), again due to the strong current systems that surround Alderney, therefore providing ideal conditions for barnacle populations. Although designated as a reserve, it holds no international designation and during the summer months is highly used for recreational purposes (A. Balding, personal observation). It is also worth noting that there is also an outflow pipe situated to the west of the bay, which could have potential impacts to the intertidal environment.

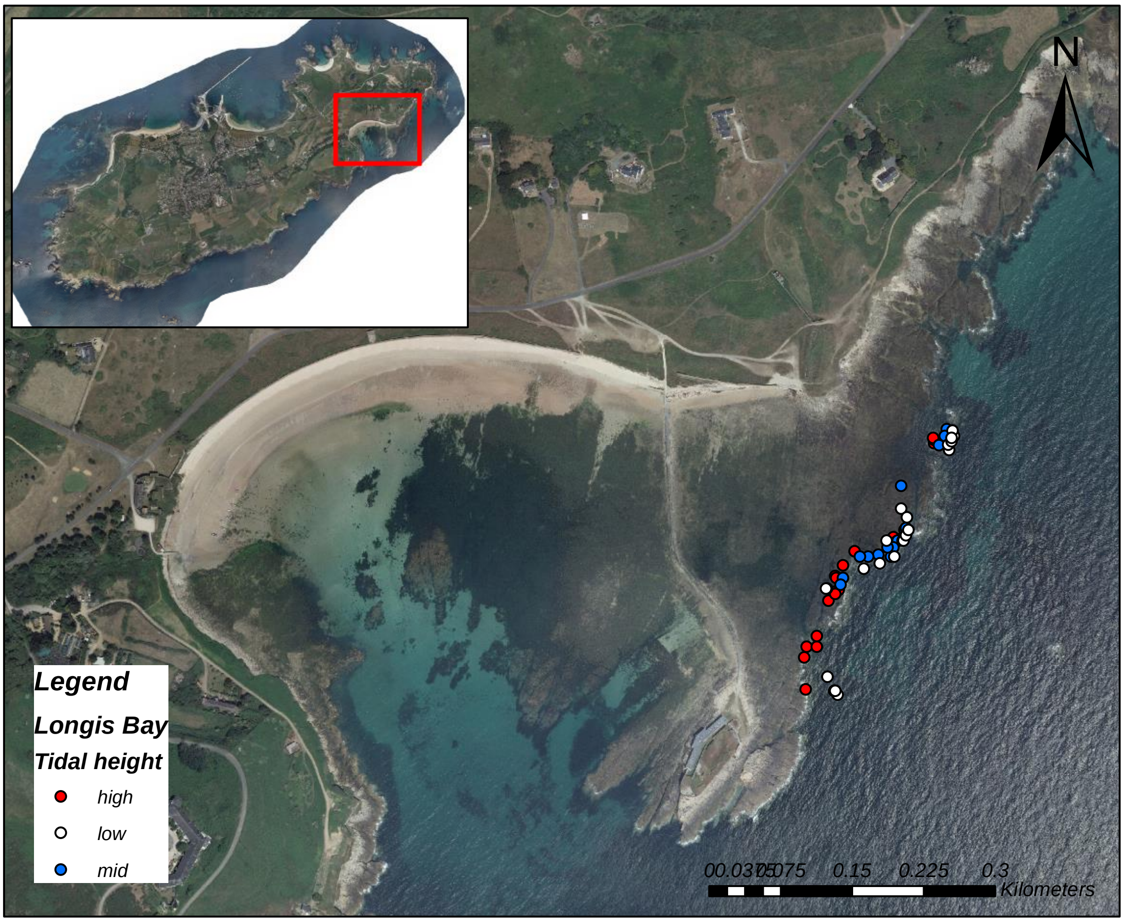


Figure 2: Longis Bay survey site presenting high (red), low (white) and mid (blue) sample points.

And finally Braye Bay is situated in the centre of the north side of the island and consists of sandy beach, cobble fields and stable bedrock. Barnacles at this site are distributed in two small patches on bedrock and boulders which are situated close together, as illustrated in figure 3, which shows the sample points for this site. The bay is not protected and is highly likely to be subject to anthropogenic impacts from the harbour, adjacent to the sample site.

The harbour is the only one on the island and therefore is highly active, although the bay is artificially sheltered from the breakwater which protects the harbour, potentially impacting barnacle populations and deeming the site as a moderately exposed energy site according to the JNCC classification system (Connor *et al.,* 2004).


Figure 3: Braye Bay survey site presenting high (red), low (white) and mid (blue) sample points.

*Sampling methodology*

Surveys at all sites were carried out following the MarClim survey protocol (MarClim, 2008), which is the Marine Biodiversity and Climate Change Project. It was a multi-funded project which ran for four years with the aim to investigate marine biodiversity and the effects that climate warming were having (Mieszkowska[2] et al., 2006). Following the protocol laid out by this project, twenty quadrat samples, 10 $cm^2$, were surveyed at each tidal height, upper, mid and lower, at each of the sample locations. The upper tidal height was defined as approximately one metre from the top of the barnacle zone, lower was one metre from the bottom of the barnacle zone and mid was at a height in between these two points. For each quadrat sampled the parameters recorded were density of Semibalanus balanoides, Chthamalus stellatus and Chthamalus montagui, with density of adults and juveniles recorded separately, presence and density of the barnacle predator Nucella lapillus, and the percentage cover of bare rock. The position of the samples was also recorded as a GPS coordinate and a photograph taken for reference. The error of the GPS coordinate monitor used could be up to 18 metres at some sites, which therefore accounts for the overlap between low, mid and high sample points in figures 1, 2 and 3. Juvenile barnacles were identified by their smaller size, the lack of erosion and by the lighter colour of the more recently laid down shell (Burrow et al., 2010). Samples were chosen at random using a chalk ball that was thrown into the area of the shore height being sampled. If it landed on an area in which barnacles were not present, it was re thrown. Although the protocol states that two independent patches at each shore height should be sampled, this was not possible at the sample sites chosen, due to sites being reasonably small and so random sampling along the shore was carried out instead.

*Analysis*

Prior to analysis data exploration resulted in only one variable being transformed, bare rock (power 3), to minimise the effect of outliers and skew, to reduce curvature and to remove heteroscedasticity. Where this variable is mentioned in this report, this transformation applies. Using the R software package, intercorrelation between predictor variables was then investigated, with Pearson's Correlation Coefficient and Variance Inflation Factors (VIF). However, no covariation occurred (Pearson $r \geq 0.7$ and/or $VIF \leq 5$) (compromise between Montgomery & Peck (1992) and Zuur et al. as stated in Zuur et al., 2010). Six Generalised Linear Models (GLMs) were then employed to determine any relationships between adults and juvenile of each species, with the explanatory variables site, height, percentage cover of bare rock and predator presence. A negative binomial error function was used for all of the models due to over-dispersion, excluding juvenile C. montagui, as this response variable was not considered over-dispersed and so a Poisson error function was used. Full models were initially run, and then backwards-forwards stepwise selection based on Akaike Information Criteria was performed to produce minimum adequate models (MAM), in order to minimise the amount of Kullbal-Leibler information lost (Burnham et al., 2011). Over-dispersion was checked to ensure that variability was not greater than expected (residual deviance/degrees of freedom > 1.5) and analysis of deviance (likelihood ratio tests) were carried out to ensure that the probability of the amount of deviance explained had not decreased from the full model to the MAM. This resulted in a negative binomial error function being used for all the response variables excluding C. montagui. Residual plots and analysis of deviance plots were also checked to ensure that the correct GLM had been carried out. For 95% significance level, an alpha value of 0.05 was used.

**Results**

A total of 23,429 barnacles were sampled across a cumulative area of 18 metres squared, with 90.4% of these *S. balanoides,* 8.4% *C. stellatus* and the least abundant of only 1.2% *C. montagui. S. balanoides* was the most abundant across all tidal heights and sites, with the two warmer water *Chthamalus* species having considerably lower densities, with the absence of *C. montagui* from Longis Bay. This is presented in figures 4, 5 and 6 which show the densities for both adults and juveniles of all species, across all tidal heights at Braye, Clonque and Longis Bay respectively.

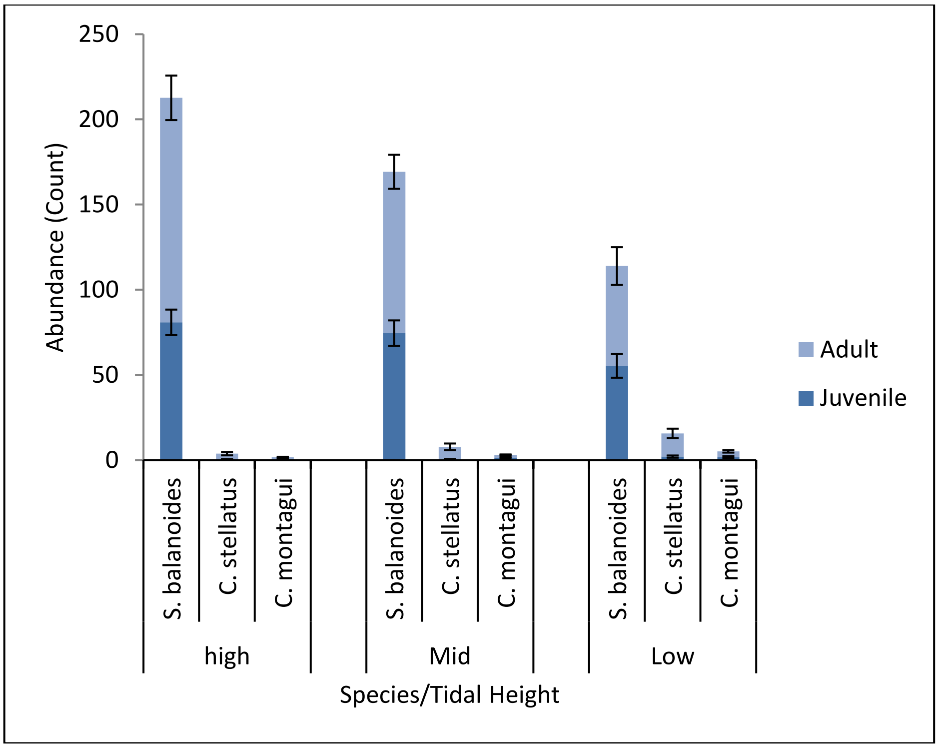


Figure 4: The density of all three species of barnacle, both adults and juveniles, across all tidal heights at Braye Bay, including standard error.

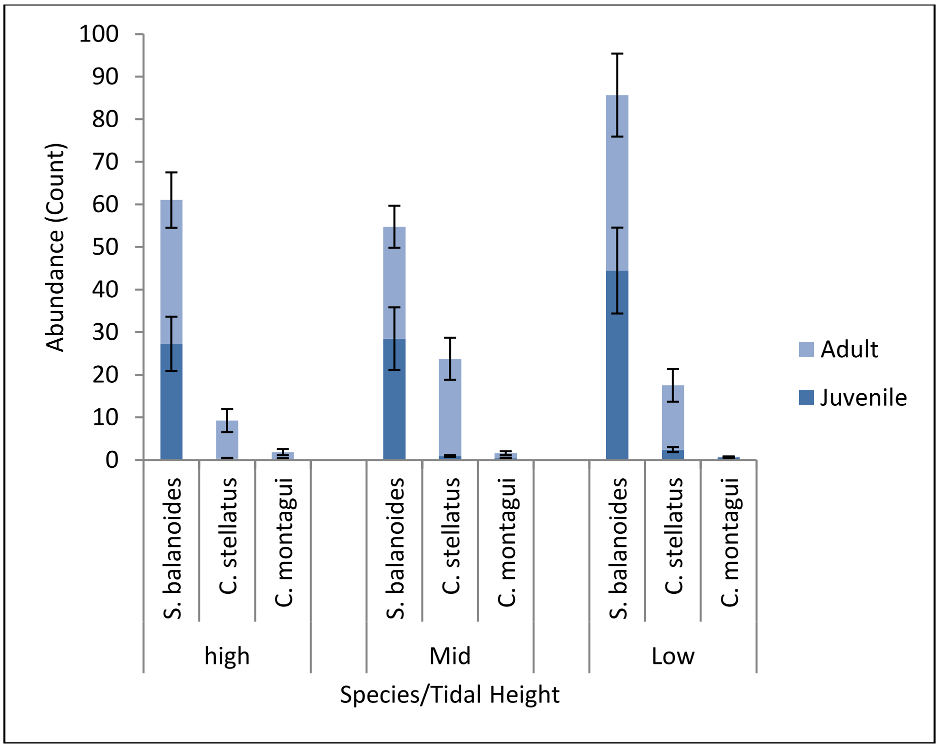


Figure 5: The density of all three species of barnacle, both adults and juveniles, across all tidal heights at Clonque Bay, including standard error.

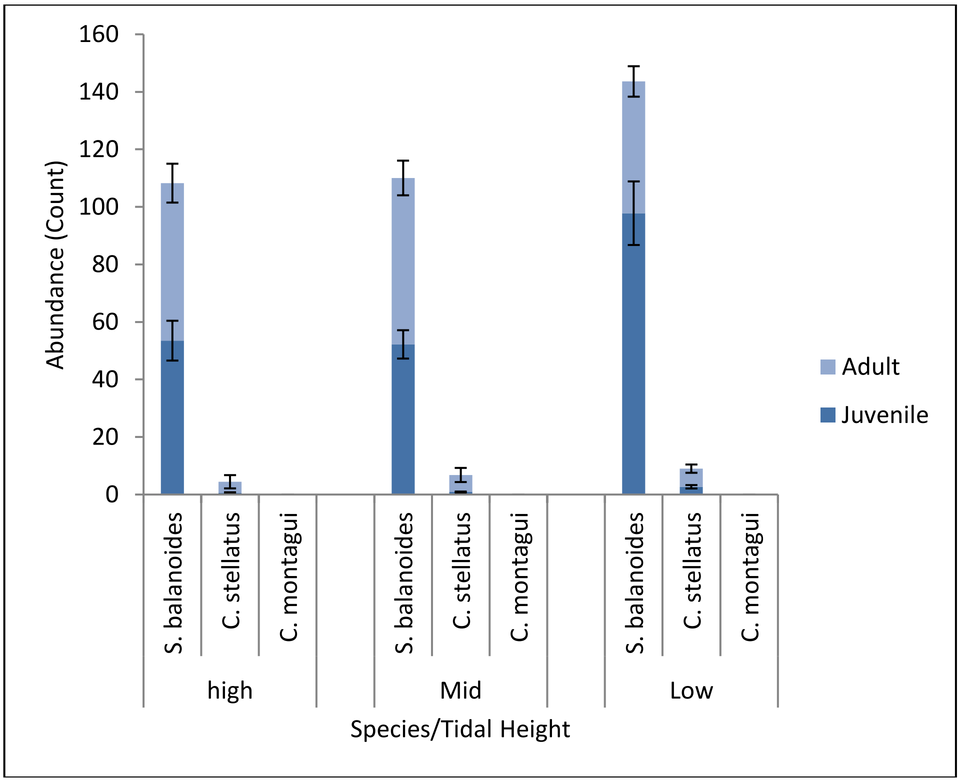


Figure 6: The density of all three species of barnacle, both adults and juveniles, across all tidal heights at Longis Bay, including standard error.

From Pearson's Correlation it was concluded that there was no correlation between predictor variables. Therefore full models containing all variables were able to be carried out, which are presented in table 1, along with the results from the minimum adequate models produced by the backward-forwards stepwise selection. As stated, all of the models produced a significant result for over-dispersion excluding juvenile *C. montagui* and all diagnostic plots were deemed acceptable.

Table 1: Generalise linear models of adult and juvenile barnacles of each species, *Semibalanus balanoides, Chthamalus stellatus* and *Chthamalus montagui* against environmental parameters with a sample size of 180. Statistics presented are probability of deviation (p), the direction of the gradient of the trend (positive or negative) where applicable, percentage deviance explained by each variable (%D) total deviance explained (T%D), probability of decreased deviance explained from the full model (p[D]) and the degrees of freedom for each model (df), with variables in bold demonstrating significant variables (alpha=0.05).

| Model name and variables tested | Minimum adequate models |
|---|---|
| Model 1:<br>Juvenile *Semibalanus balanoides*, site, height, bare rock | **Site: p<0.05, %D=5.87**<br>**Bare Rock (negative): p<0.05, %D=15.53**<br>AIC=1768.4, T%D=24.83, p[D]=0.460, df=176 |
| Model 2:<br>Adult *Semibalanus balanoides*, site, height, bare rock | **Site: p<0.05, %D=8.29**<br>**Height: p<0.05, %D=6.28**<br>**Bare Rock (negative): p<0.05, %D=27.72**<br>AIC=1726, T%D=45.95, p[D]=0, df=174 |
| Model 3:<br>Juvenile *Chthamalus stellatus*, site, height, bare rock | **Height: p<0.05**<br>AIC=508.01, T%D=21.24, p[D]=0.777, df=177 |
| Model 4:<br>Adult *Chthamalus stellatus*, site, height, bare rock | **Site: p<0.05, %D=8.67**<br>**Height: p<0.05, %D=5.43**<br>AIC=1141.9, T%D=14.22, p[D]=0.519, df=175 |
| Model 5:<br>Juvenile *Chthamalus montagui*, site, height, bare rock | **Site: p<0.05, %D=34.16**<br>**Height: p<0.05, %D=6.11**<br>AIC=308.12, T%D=40.27, p[D]=0.047, df=175 |
| Model 6:<br>Adult *Chthamalus montagui*, site, height, bare rock | **Site: p<0.05, %D=43.91**<br>Bare Rock: p=0.12260, %D=0.93451<br>AIC=403.58, T%D=44.87, p[D]=0.048, df=176 |

From the results obtained from the GLMs, the only significant differences, with regards to site, were found at Clonque and Braye Bay. Clonque had a significantly higher density of adult *C. stellatus* and a significantly lower density of juvenile *S. balanoides* compared to both Longis and Braye as presented in figures 7 and 8 respectively. Braye on the other hand, had a significantly greater density of adult *S. balanoides,* and both adult and juvenile *C. montagui* as presented in figures 9, 10 and 11 respectively.

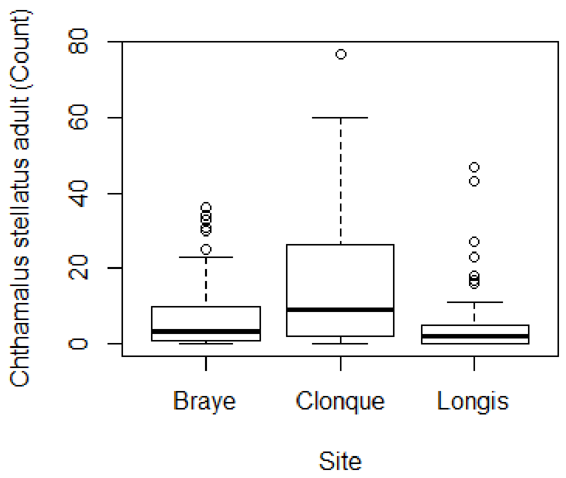


Figure 7: The density of adult *Chthamalus stellatus* at all three sample sites Braye, Clonque and Longis

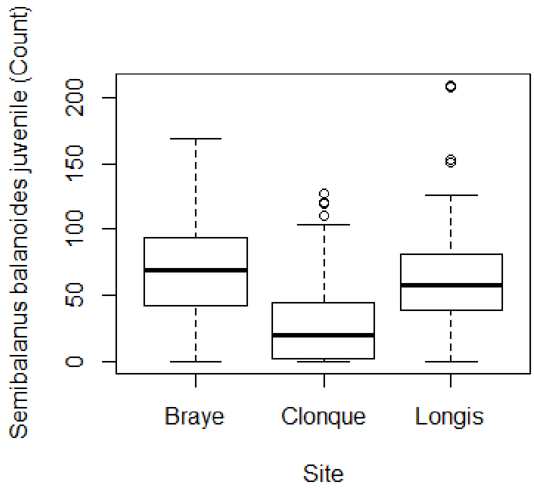


Figure 8: The density of juvenile *Semibalanus balanoides* at all three sample sites Braye, Clonque and Longis.

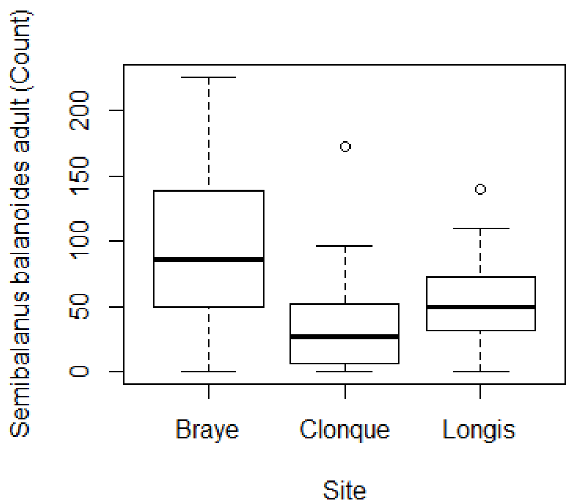


Figure 9: The density of adult *Semibalanus balanoides* at all three sample sites Braye, Clonque and Longis.

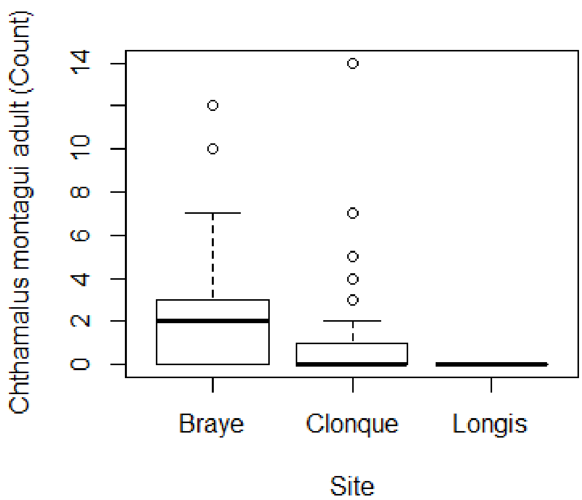


Figure 10: The density of adult *Chthamalus montagui* at all three sample sites Braye, Clonque and Longis.

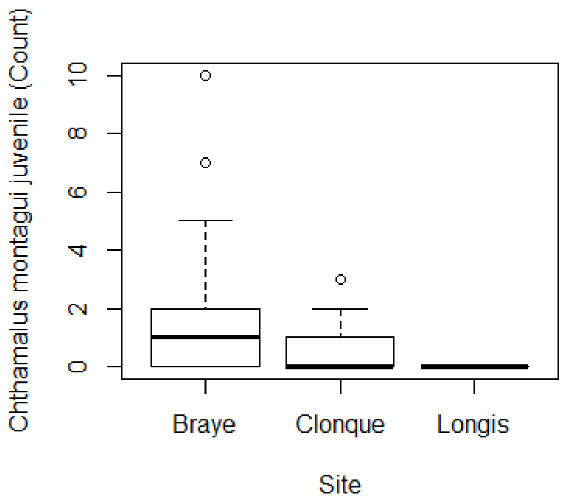


Figure 11: The density of juvenile *Chthamalus montagui* at all three sample sites Braye, Clonque and Longis.

Differences in tidal heights were also observed from the GLMs. Juvenile *C. stellatus* and *C. montagui* were both found to have a great density at a lower tidal height compared to mid and high, with adult *C. stellatus* being significantly greater in density at both mid and low compared to a high tidal height, as illustrated in figures 12, 13 and 14 respectively.

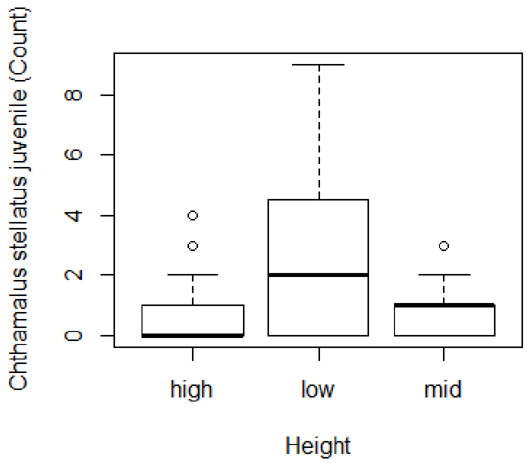


Figure 12: The density of juvenile *Chthamalus stellatus* at all tidal heights high, low and mid.

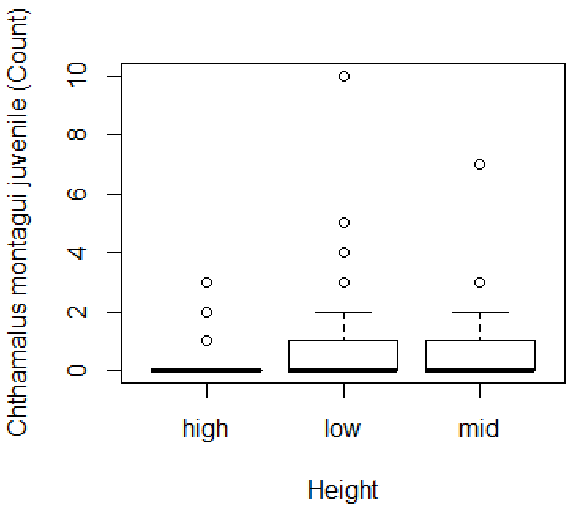


Figure 13: The density of juvenile *Chthamalus montagui* at all tidal heights high, low and mid.

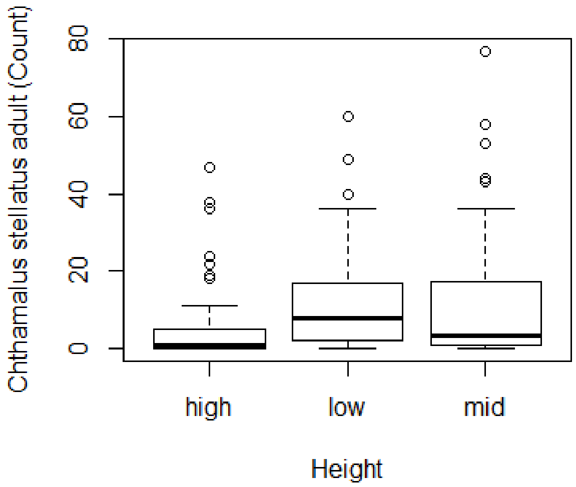


Figure 14: The density of adult *Chthamalus stellatus* at all tidal tights high, low and mid.

The factor bare rock was only found to have a relationship with *S. balanoides* with both adults and juveniles. These were both negative, non-linear, second order, quadratic relationships, as presented in figures 15 and 16 respectively.

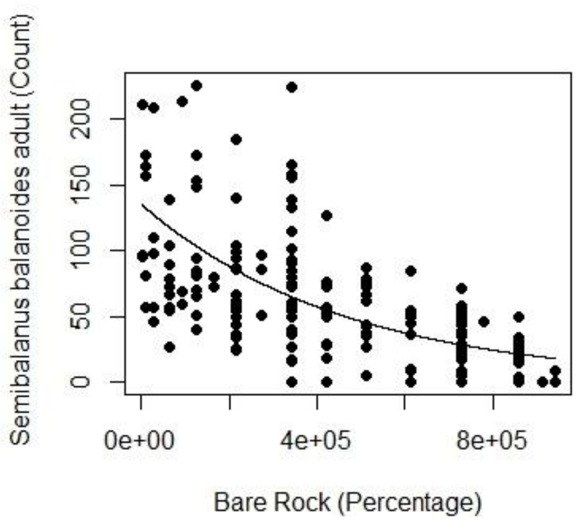


Figure 15: Relationship between the density of adult *Semibalanus balanoides* and percentage cover of bare rock (Bare Rock: power 3). The trend is from a univariate Negative Binomial Generalised Linear Model (AIC=1726, %D=27.72, $p<0.05$).

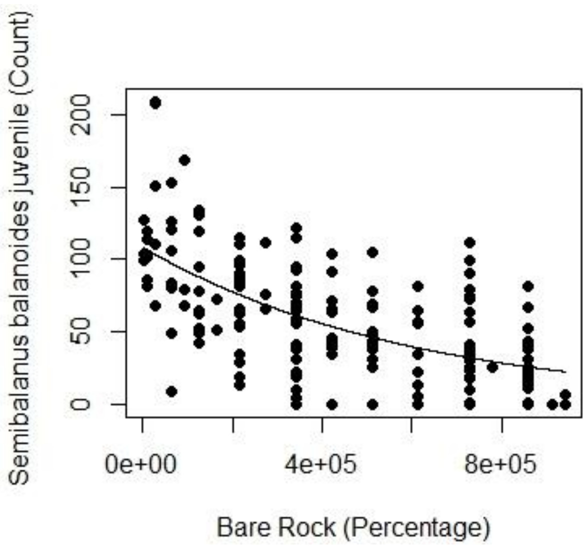


Figure 16: Relationship between the density of juvenile *Semibalanus balanoides* and percentage cover of bare rock (Bare Roc: power 3). The trend is from a univariate Negative Binomial Generalised Linear Model (AIC= 1768, %D=15.53, $p<0.05$).

No predators were recorded in any of the quadrats sampled and so no relationship was able to be determined with this factor. Although, the barnacle predator dog whelk (*Nucella lapillus*) was observed to be present at all sample sites, with a particularly high density at the Clonque Bay sample site.

**Discussion**

From the GLMs employed on the data collected, results indicated that site, tidal height and percentage cover of bare rock did have some influences on the population dynamics of barnacles. A higher density of *C. stellatus* was found at Clonque compared to the other two sample sites Braye and Longis. As stated, this site is considered to be high energy, due to the fast flowing and complex current systems that precede the bay, and as it has been suggested that with an increase in wave exposure there is an increase in the production of *C. stellatus* larvae (Burrows *et al.,* 1992), this could account for the higher density of this species observed at Clonque. In contrast, Braye had a higher density of *C. montagui*, which prefer more sheltered conditions for higher larval production. Due to the breakwater which protects the harbour adjacent to Braye Bay, conditions are a lot more sheltered in comparison to Clonque and Longis, and therefore this higher production in larvae could account for the higher density of both adult and juvenile *C. montagui* at this site. In addition, anthropogenic impacts from the harbour could also be affecting barnacle populations, such as pollution. Pollution, resulting from heavy boat activity, has been found to decrease genetic diversity in other *Balanus* species (Ma *et al.,* 2000), and therefore a reduction in genetic diversity could result in a decreased ability for species to adapt to environmental changes, such as those arising from climate change. The impacts of pollutants could also have an indirect effect on barnacle dynamics due to the impacts on the barnacle predator dog whelks. Although they were not recorded in any of the samples, *Nucella lapillus* was observed to be present in all of the bays studied, which are affected by high concentrations of tributyltin (TBT) found in antifouling paint used on vessels (Bryan *et al.,* 1987). TBT causes imposex, which is the process in which females grow male sex organs, which ultimately results in females to become sterile and therefore results in population declines (Bryan *et al.,* 1987). And although TBT was prohibited in the UK from 1987 (Santillo *et al.,* 2001), and under aerobic conditions only takes approximately three months to degrade and therefore is not likely to still be present in the environment (EXTOXNET, 1993), other pollutants which have not been studied at depth, could result in similar or greater impacts such as these. As a result, predation levels on the barnacle populations could be affected, due to the high harbour activity at Braye and therefore an increase in pollutants, which could alter barnacle population dynamics.

The differences in densities at both Clonque and Braye could also have been due to the types of substrate which the barnacles occurred on. At both of these sites, populations were observed to be present on both stable bedrock and boulders, whereas at Longis barnacles only occurred on stable bedrock. Substrate type has been found to influence settlement in other *Chthamalus* species, in which settlement rates increased on natural compared to smooth granite substrate types (Raimondi, 1990). Explanations for this selection include the decreased risk of removal from harsh environmental conditions and to decrease the susceptibility to desiccation and thermal stress (Raimondi, 1990). By selecting surfaces that contain pits and depressions, this increases the availability of shaded and damp surfaces, helping organisms to cope with extreme weather conditions, but this also gives rise to great variability within sites (Raimondi, 1990).

Tidal height often plays an important role in the distribution of organisms along the shore due to an organisms ability to be able to survive harsh conditions with the receding tide. Although

*C. stellatus* has been found to occur at all tidal heights, *C. montagui* favours the lower shore but is often outcompeted, due to overcrowding by *S. balanoides* (Hayward *et al.,* 1996). Therefore, although a higher density of juvenile *C. stellatus* and *C. montagui* were observed to be present at a lower tidal height, these populations of juveniles have been observed to be outcompeted by *S. balanoides* on other shores (Connell[2], 1961). This could consequently explain why this relationship is not reflected in the adult population of *C. montagui,* however *C. stellatus* was unexpectedly found to be higher in abundance at both low and mid tidal heights. Although this finding could be the norm on Alderney, it could also be due to other factors, and therefore further studies are needed to examine this result.

Although a negative relationship was found between both adult and juvenile *S. balanoides* and bare rock, no relationship occurred between this factor and the two warmer water species of *Chthamalus*. This would suggest that bare rock could potentially be an important determining factor for the abundance of *S. balanoides* on Alderney. However, to examine this relationship in more detail, studies that include clearing areas and monitoring recovery rates could be carried out (Raimondi & Ambrose, 2006). This finding could also indicate that *S. balanoides* is more selective, and only settles in areas in which no other organisms occur. Therefore, this could suggest that the two *Chthamalus* species are less selective and are more likely to co-occur with other organisms, but again more research is needed in order to investigate this relationship.

As stated, the barnacle predator *Nucella lapillus* was not present in any of the quadrats and therefore no relationship with this factor was able to be determined. Although, dog whelks were observed to be present at all sample sites and therefore could still have an impact on barnacle population dynamics. *N. lapillus* is an intertidal species which is distributed from mean high water neap to mean low water spring (Hayward *et al.,* 1996) but has also been found to vary in distribution between adults and juveniles (Feare, 1970). Juveniles are thought to migrate up the shore, in order to reduce the risk of predation by crabs at lower shore (Feare, 1970), and as the size of dog whelk has been correlated with the size of its prey (Crothers, 1985), this would suggest that a greater proportion of juvenile barnacles are predated upon at a higher tidal height, and a greater proportion of adults are predated upon at a lower tidal height. In addition to this, *N. lapillus* has also been found to only be able to predate on a certain number of barnacles a day (Connell[1], 1961), and therefore this could account for the higher density of juvenile *C. stellatus* observed at low tidal heights. If juvenile dog whelks migrate up the shore, they will be predating the smaller juvenile *C. stellatus*, while the larger adult dog whelks will be optimising consumption by actively selecting larger barnacles (Connell[2], 1961), therefore resulting in a higher abundance of juveniles of both *Chthamalus* species at a lower tidal height. The higher abundance of *S. balanoides* at all sites however, cannot be accounted for by the presence of dog whelks. This is due to *N. lapillus* actively selecting *S. balanoides* over *Chthamalus* species (Crothers, 1985), and therefore must be accounted for by other environmental factors.

By examining the densities of all species, across all sites and heights, it is clear that the dominant species is *S. balanoides,* with the two warmer water *Chthamalus* species being far less abundant. With increased impacts from climate change, such as increases in annual temperatures (Harley *et al.,* 2006), what we would expect to observe from future monitoring is a decrease in *S. balanoides* and an increase in the two *Chthamalus* species. Although it could be argued that this has already started to occur at Clonque Bay, due to the significantly lower density of juvenile *S. balanoides* and a significantly higher density of *C. stellatus,* it could just be due to the more favourable conditions of *C. stellatus* (Burrows *et al.,* 1992). Therefore, further monitoring is needed.

In addition to barnacles acting as an indicator of climate change, they could also be used as an indicator of other environmental impacts such as pollution. At Longis Bay, an outflow pipe is present which, if water exiting the pipe is not treated correctly, could result in negative impacts on the intertidal ecosystem in this area. Therefore, by knowing the current population dynamics of barnacles at this site, it could be vital if accidents were to occur, in measuring impacts and recovery rates. This could also be the case at the other two sample sites, if future impacts, both natural and anthropogenic, were to occur.

Surveys in this study followed the MarClim protocol, which has provided a baseline of data investigating barnacle population dynamics, but improvements to this methodology could be made in order to investigate these populations further. Although species were divided into adult and juvenile populations, size was not measured. As a result of decreased pH from ocean acidification, it has been found that there has been compensatory calcification, resulting in an increase in basal shell diameter, but that central shell wall plates were weaker and therefore more easily predated (McDonald *et al.,* 2009). Therefore it would be beneficial to monitor changes in barnacle size as an indicator of the effects of ocean acidification. In addition to size, as discussed substrate type can also influence settlement rates and survival; therefore, this variable could also be recorded during surveys in order to determine any relationship with this factor. Although this study focused solely on the settlement stage of the barnacles' life cycle, this is highly dependent on the success of recruitment and the larval stages of development. Factors which have been found to effect the larval stage include larval input, predation, physical environmental parameters and food availability (Barnes, 1956), which can all have potential impacts on the density of juveniles present. Therefore, although this study does not directly measure larval populations, it would be worth considering and monitoring environmental factors such as these in future studies.

**Conclusion**

To conclude, a baseline has been established for monitoring changes within the barnacle population, in order to provide an indicator for future environmental impacts such as climate change, on Alderney. Differences between the three sample sites were observed with Clonque Bay harbouring a greater density of adult *C. stellatus* but a significantly lower density of juvenile *S. balanoides.* This could be due to the more favourable exposed conditions which are preferred by *C. stellatus* which are present at this site. Braye on the other hand was found to possess a higher density of *C. montagui* compared to the other sample sites which could be accounted for by the more sheltered conditions provided by the breakwater, which protects the harbour adjacent to this bay. With regards to tidal height, both species of *Chthamalus* were found to have a higher density at a lower tidal height, which are often then outcompeted by *S. balanoides,* therefore it was surprising to discover that this was also the case for adult *C. stellatus* which were found to have a higher density at both mid and lower tidal heights. Bare rock was only found to have a relationship with *S. balanoides* which was a negative relationship, suggesting that this could be an important factor for its abundance on Alderney. And finally there were no recordings of the barnacle predator dog whelk in any of the quadrats sampled; therefore no relationship with this factor was able to be determined. Although a baseline has been established, other factors such as barnacle size, substrate type and factors affecting the larval stage of development could also be considered in future monitoring, to further extend the knowledge of population dynamics on Alderney.

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