Investigating the links between Geological Complexity and Biodiversity along a Geologically Heterogeneous Coastline

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Abstract

Heterogeneous coastlines support a wide variety of lithologies with different levels of complexity. An increase in geological complexity results in an increase in the number of species co-existing within a particular micro-site by providing protection from disturbance and predation. Habitat complexity influences feeding surfaces, size of living space and provides an increase in attachment sites, which all encourage species biodiversity. Research was carried out on the North Coast of Ireland, and three different rock types; Upper Basalt Formation, Lower Basalt Formation and Ulster White Limestone, were sampled. Systematic sampling techniques were used to collect field data on rocky shore biodiversity. Faunal species were identified and counted, and algal abundance was recorded as a percentage. Complexity data was collected by placing a rope alongside the 10m transects and pushing the rope into any cracks and crevices, then recording the length of the rope. A longer rope indicates higher complexity, which was quantified using the Rugosity index (C). To verify the validity of field complexity data, rugosity was also calculated on a kilometric scale using GIS software. The Shannon Diversity Index was used to calculate species biodiversity. Results were analysed using SPSS to conduct ANOVA, Pearson’s Correlation and Linear Regression tests. It was found that there was a significant difference in genera richness, species abundance and diversity between the three sites. Abundance was highest at the Upper Basalt Formation, but genera richness and diversity were highest at the Lower Basalt Formation. A strong significant difference in complexity was found, with the Upper Basalt Formation being the most complex. Results show a positive relationship between species diversity indices and geological complexity.

1. Introduction

There's no biological interface more evident than the boundary between the ocean and land. Around 33% of the coastline is made up of rocky shores regularly in contact with water from the sea. The geology exposed to seawater provide many different niches for colonization by marine flora and fauna and are imperilled by severe conditions such as intermittent exposure to high energy waves. The biological and physical controls on present-day rocky shores have been the key focus of many marine scientists. In rocky-shore environments, the ecology is comprised of many communities where different species are interrelated by their response to physical surroundings and their effects on each other (Broitman *et al.,* 2008, Cartwright and Williams, 2012, Helmuth *et al.,* 2006, Johnson and Baarli, 1999). Few studies acknowledge that species abundance also depends on local patchiness of rocky shore communities; where complexity of the habitat has an effect on the processes and interactions of species (Eriksson *et al.,* 2006). Previous species diversity pattern models have presumed that habitats are all spatially homogeneous (Hutchinson and MacArthur, 1959). However, structurally complex heterogeneous habitats are vital as they offer a wider variety of microhabitats and niches, which contributes to the diversity within individual habitats by allowing species to co-exist. (Kostylev *et al.,* 2005, Pianka, 2011). Heterogeneity within an environment encourages a wide range of resources, which leads to co-existence of competitors, something which wouldn't be possible in a homogenous environment. Therefore, it's undeniable that heterogeneity is important for the maintenance of biodiversity (Kostylev *et al.,* 2005, Levin, 1981, Levin, 1992).

This study looks at the complexity of the lithology along a heterogeneous coastline. It's been found that a lithological mix is an important factor and coastlines with homogenous lithology tend to be straighter than coastlines of varied lithology (Porter-Smith and Mckinlay, 2012). Different rock types will be more complex than others; complexity includes all the minor features of a habitat, such as the shape, degree of angularity, size and texture of a substrate and its relationship with the surrounding environment (Gee and Warwick, 1994). There's been a clear general trend, explaining that an increase in habitat complexity will show an increase in the biodiversity and abundance of organisms in a community due to an increase in living space, suitable feeding surfaces, modification of environmental conditions, increase in the variety of food organisms, increase in protection from predators and disturbances, as well as providing an increase in attachment sites. (Coull and Wells, 1983, Fretter and Manley, 1977, Gee and Warwick, 1994, Morse *et al.,* 1985). Most research looking at links between biodiversity of assemblages and structural complexity has related to interference, however, in more recent years, studies have focused on looking at habitats with varied structural complexity and evaluating its ability to survive disturbance, predation and competition (Coull and Wells, 1983).

The main drivers of heterogeneity in coastal type habitats are climate, oceanography and patterns in regional geology (Harris *et al.,* 2012, Johnson *et al.,* 2003). Scientists have proposed that rocky shore morphology is a result of the physical strength of the lithology and the effect of hydraulic stress from the waves. Others have assigned shoreline complexity to the connection of the bathymetric profile and the sea surface, describing complexity as being a two-dimensional representation of uneven shelf topography. Another factor that needs to be taken into consideration when explaining coastline complexity is long-term terrestrial erosion. There is no individual definite reason to explain why some coastlines are complex, but all factors contribute to heterogeneity (Thompson *et al.,* 1996). Studies have used different methods to quantify complexity. Kostylev *et al.,* (2005) used fractal dimensions (D) to represent rocky shore complexity whilst other studies have used the rugosity index (C) (Fuad, 2010).

MacArthur and MacArthur (1961) found a positive relationship between species diversity and geological complexity. Topographically complex surfaces may have more species present due to increased habitat diversity or because of an increase in surface area. Effects of increasing area and heterogeneity can be difficult to separate (Gee and Warwick, 1994, Whittaker and Fernández-Palacios, 1998). In most studies, the effects of geological complexity and surface area are confounded because surface area increases with increasing topographic complexity (Kostylev *et al.,* 2005). There's often a link between species richness associated with topographic variation and an increase in range of ecological niches (Debski *et al*, 2002). Rocky shores undertake a role for geological complexity by creating microclimate variation and dealing with biological interactions (Fairweather, 1988).

Thompson *et al*. (1996) carried out a study in the Isle of Man on the diversity and abundance of intertidal organisms found on biologically generated complex habitats and less complex habitats, looking at bare rocks and barnacle covered rocks. It was found that abundance of individuals was much greater in the sites with pits (more geologically complex) than the sites located on flat areas (less complex). There is a dynamic balance between fucoids, limpets and barnacles; all co-existing in the rocky shore environment. Increased surface complexity will ease the environmental stress marine species experience during low tide. Organisms found on complex rocky shores can benefit each other in many ways. For example, fucoid algae provide shelter for limpets from desiccation stress whilst other invertebrates benefit from mussel shells which provide a refuge from wave action. Species found on less complex areas along the coastline wouldn’t receive these benefits (Thompson *et al.,* 1996).

Menge *et al.* (1985) found that many organisms depend on high habitat complexity, using the holes and crevices in the rock as protection from consumers. Mortality rates are high and constant on open surfaces as there is no protection from predators but differs with time and space in more complex environments where holes and crevices are present. It was found that in a heterogeneous environment, stability is higher than in homogenous environments. There seems to be a gap in many studies, where the complexity is classified as being qualitative rather than quantitative. Menge *et al*. (1985) classifies complexity on a scale of 1 to 5, 1 being a nearly uniform and flat surface and 5 showing an extremely complex rock structure, with the presence of pits and crevices. Wilding *et al,* (2010) assess three techniques for quantifying topographic complexity: Chain, divider and wheel. He found that the distance-wheel was quick and easy to use and much quicker than the chain method on large scales but at small scales, all of the techniques took around the same time to use.

Aim: To use appropriate scientific methodology to determine links between geological complexity and biodiversity of a heterogeneous rocky shore.

Objectives:

1) Collect field data on the geological complexity and biodiversity of the study area
2) Calculate the diversity indices (Species Abundance, Genera Richness and Shannon Biodiversity index) of three rock types.
3) Calculate percentage algal cover for the three rock types by analysing images of quadrat samples
4) Analyse rocky shore rugosity using complexity data and the rugosity index (C) on both a metric and kilometric scale
5) Statistically analyse results using SPSS and compare data to assess the relationships between Geological Complexity and Biodiversity

Hypotheses to be tested:

H_{01}: There is no difference in habitat biodiversity of the different rock types found along the North Coast of Ireland

H_{02}: There is no difference in the geological complexity of the different rock types found along the North Coast of Ireland

H_{03}: There is no relationship between the complexity of a coastline and the biodiversity of that coastline located along the North Coast of Ireland

2. Material and Methods

2.1. Study Area

Northern Ireland is located within Western Europe and is bordered by the North Atlantic Ocean and the Irish Sea, which separates it from mainland Britain. The geology has been influenced by successive glaciations over a long period of time. The geology of the North Coast was assessed using an online geology index (Mapapps2.bgs.ac.uk) in order to determine the rock types that would be used for the study.

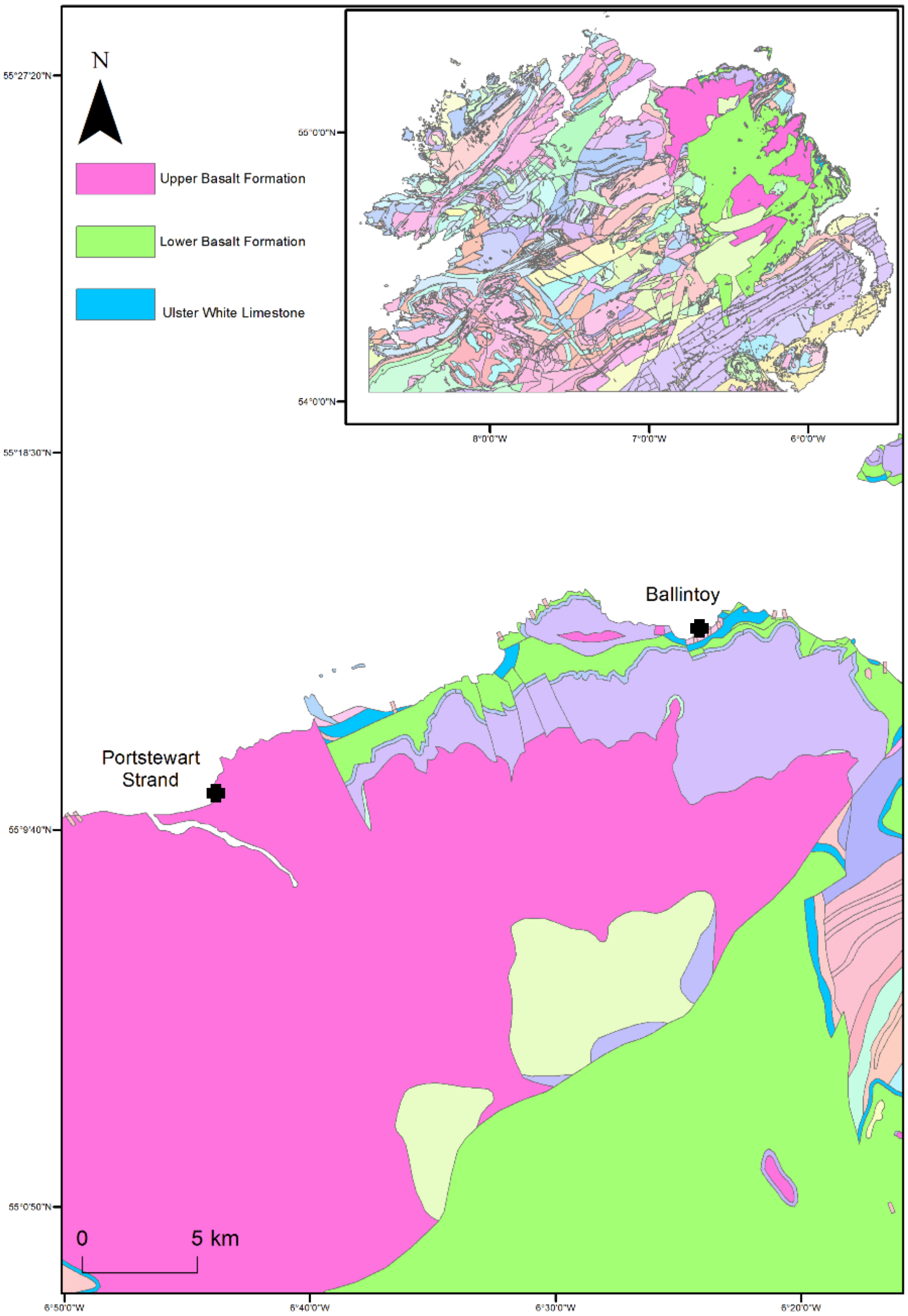

Figure 1 - Geology Map of the North Coast of Northern Ireland, highlighting the sample sites: Ballintoy and Portstewart Strand

The northern-facing shoreline is moderately open and linear, made up of cliffs and rocky headlands with gravel and sandy beaches (Quinn *et al.,* 2000, Westley *et al.*, 2011). Tides are semi-diurnal, and the tidal range is relatively small (<1m). Around 54% of all winds are from between west and south with a mean of 57.4 days with gales over the period 1975-1986 (Rohan, 1986, Wilson *et al*., 2004). The study sites are affected by micro tidal environments and the wave regime is swell-dominated with high wind and wave energy. Wave heights along the North Coast range from around 15m-25m (Fig.1) (Jackson *et al., 2005).*

Figure 2 - Maps produced using ArcMap 10.3.1 showing the location of the 15 transects sampled in the study area. A) Upper Basalt Formation, B) Lower Basalt Formation and C) Ulster White Limestone

The first location sampled was Portstewart Strand, a two-mile-long beach with sand dunes (55° 10' 26''N, 6° 43' 28''W), where the geology was composed of the Upper Basalt Formation (UBF) (Fig. 1). Data was collected from the northern side of the beach at a moderately exposed area where Upper Basalt rock formations are found (fig.2.A). Ballintoy Harbour (55° 14' 28''N, 6° 22' 53''W) is where the other two rock types were found; Ulster White Limestone (UWL) and Lower Basalt Formation (LBF) (fig. 1). Ballintoy harbour is known to have a well raised shoreline and changes in sea levels are associated with its creation. Some of the geology found at Ballintoy Harbour has been eroded into arches and caves by the sea. Data was collected from a moderately exposed area of Ballintoy Harbour where both LBF and UWL are found along the shore (Fig.2.B, Fig.2.C).

2.2. Field Methodology

Scientific methods were used along the North Coast of Northern Ireland to investigate the relationship between geological complexity and biodiversity along a heterogeneous coastline. Three rock types were sampled to distinguish differences in geological complexity and links between how complex an area is and its biodiversity. Tide times were considered; collecting data from the lower intertidal before it's submerged in water if the tide was coming in, and from the upper intertidal first if the tide was going out. Tide times were checked online, and data was collected accordingly. The UBF site at Portstewart Strand was sampled on Monday 9th October 2017 and the LBF and UWL sites at Ballintoy Harbour were sampled on Monday 23rd October 2017. All rock types were sampled during low tide therefore data was collected from the lower intertidal first during daylight hours.

2.2.1. Rocky Shore Biodiversity

A systematic sampling technique was used to collect primary, quantitative data on the biodiversity of the area. 10m transects were measured out and were placed randomly along the rocks facing northwards (fig. 2). A 50cmx50cm quadrat, divided into 25 smaller squares, was placed every 2m along the transect. There were five quadrat readings taken for each transect, hence a total of 25 quadrat readings for each rock type (Menge *et al.,* 1985*).* This was a sufficient sample size to compare and contrast between the results. A photograph was taken of each quadrat and all algal and faunal species visible to the naked eye were identified and counted as a percentage and the total number respectively, using the quadrat grid (Sterry and Cleave, 2012). This included molluscs and arthropods. The GPS coordinates for each quadrat was recorded for all transects. This method is similar to that used by Bloch and Klingbeil, (2015) and Kostylev *et al.*, (2005).

2.2.2. Geological Complexity

Geological complexity differed within sample sites, ranging from rough areas with lots of cracks and crevices to very smooth surfaces. To collect data on the geological complexity of the area the same transects facing northwards were used (fig. 2). A rope was placed alongside the transect and pushed into all the holes and crevices in the rock and held in place on contact points, starting at the 0m mark and finishing at the 10m mark on the measuring tape. The rope was then measured, and the length was recorded. The longer the rope was after being pushed into the crevices of the rocks, indicated a higher geological complexity. Barnacles were not excluded when measuring complexity as the presence of these individuals made little difference to the topographic complexity of transects. Five transects were taken for each rock type in order to record the complexity (Johnson *et al.,* 2003). Taking this amount of repeat results makes the data more valid. This method was similar to the chain method analysed in Wilding *et al., (*2010*),* and was suitable as it's being used on small scale transects.

The rugosity index (C) was used to calculate rugosity using the equation:

$$C=1-d/l \qquad (1)$$

where d represents the distance covered by the rope when pushed into the contours and crevices of the rock and l is the length of transect.

To compare validity of the metric scale field rugosity, rugosity was also calculated on a kilometric scale. Using ESRI ArcMap 10.3.1, the draw tool was used to draw 1km transects around the coastline at a 1:4000m scale. Using the same start and end points, another line was drawn at a 1:800m scale, where contours of the shore were much more visible. The rugosity index (C) was calculated where d represented the line drawn at 1:800m, which considered contours of the shore and l represented the 1km transect (Fuad, 2010).

2.3. Quantitative Analysis

2.3.1. Species Biodiversity Data

Biodiversity was analysed using percent algal cover and biodiversity indices (species abundance, genera richness and Shannon diversity index). The Shannon index provides a quantitative calculation and considers variation in richness and evenness (Nagendra, 2002, Scrosati *et al.,* 2010). Species abundance was calculated by counting all individual faunal species in the study area samples. Genera richness was calculated by counting all individual genera that were recorded in the study area samples. Shannon diversity index was calculated using the formula:

$$H=-\sum p_i \ \ln p_i \qquad (2)$$

where p_i is the number of individuals of one particular species found, divided by the total number of individuals found.

2.3.2. Statistics

The difference in genera richness, species abundance and diversity were tested using analyses of variance (ANOVA) using IBM SPSS Statistics 24. This tested if the diversity indices were homogeneous between rock types. The difference in percent algal abundance between sites was tested using ANOVA. Relationships between the individual diversity indices and rugosity were tested using Pearson’s correlation and linear regression, to distinguish if relationships were correlated or significant. Pearson’s correlation and linear regression analysis methods were also used to test the relationship between percent algal cover and rugosity.

3. Results

3.1. Richness

Genera richness was calculated by counting all individual genera present in each quadrat along all transects. A total of 15 faunal taxa were identified on the three shores; three species of limpets, eight periwinkles, one species of anemone, one type of barnacle, one crab and one combtooth blenny. The average genera richness found per sample in the study area was 6.53±3.0 (Mean±SD). Richness was lowest at the UWL site and highest at the LBF. The average genera richness for the sites was 6.4±2.4 for UBF, 9.6±1.67 for LBF and 3.6±2.3 for UWL (fig.3.A).

ANOVA analysis shows that there is a significant difference in genera richness between the three sites ($p<0.01$).

3.2. Abundance

Total of 2524 individual faunal organisms were counted and recorded for the three sites. The average species abundance found per sample in the study area was 169.27±197.09 (Mean±SD). The results show that UBF has a higher average species abundance per sample (395±113.7) compared to LBF (70±20.45) and UWL (40±51.2). The high species abundance recorded for the UBF site is due to the large presence of *Chthamalus stellatus* which are present in abundance of up to 445 per individual quadrat sample. There is one sample that has a low abundance at the UBF site, namely sample five with a value of 220. One sample has a high abundance at the UWL site, namely sample 13 with a value of 127 (fig. 3.B).

Species abundance is highest at the UBF site and ANOVA analysis shows that there is a highly significant difference in species abundance between the three sites ($p<0.001$)

3.3. Diversity

Species diversity differed among the three locations. The Shannon diversity index was used to describe the diversity of faunal species in the study area. Diversity was highest at the LBF site (1.76±0.19 (Mean±SD), followed by the UWL (0.87±0.58) and UBF (0.45±0.15). The average diversity index for the entire study area is 1.03±0.67. There is one sample with a low diversity value at the UBF site, namely sample four with a value of 0.19 (fig. 3.C).

ANOVA analysis shows that there is a high significant difference in species diversity between the three sites ($p<0.001$).

Table 1 - Faunal Species Recorded (Mean±SD) for the three shores sampled

Taxon	Upper Basalt Formation	Lower Basalt Formation	Ulster White Limestone
Actina equina	0.60 ± 1.34	14.60 ± 12.86	
Cancer pagurus	0.20 ± 0.45		
Chthamalus stellatus	354.40 ± 98.87	1.60 ± 3.58	
Patella pellucida	3.80± 5.22	3.80 ± 2.95	1.60 ± 2.61
Patella ulyssiponensis	3.60 ± 3.29	2.40 ± 1.67	
Patella vulgata	21.80 ± 13.16	12.60 ± 7.67	6.20 ± 8.32
Lipophyrs pholis	0.20 ± 0.45		
Littorina littorea	5.40 ± 7.09	17.40 ± 12.90	19.60 ± 23.96
Littorina mariae	1.60 ± 2.19	0.8 ± 1.10	4.20 ± 7.82
Littorina neglecta	1.00 ± 1.73	2.00 ± 1.58	
Littorina nigrolineata		1.80 ± 3.49	0.40 ± 0.89
Littorina obtusata	0.40 ± 0.89	3.20 ± 1.10	0.40 ± 0.89
Littorina rudis	1.00 ± 2.24	0.80 ± 0.84	
Littorina saxatilis	1.20 ± 1.64	3.40 ± 2.88	6.80 ± 8.41
Melahaphe neritoides		2.80 ± 4.38	0.80 ± 1.79

The dominant species at the UBF was *C. stellatus,* found in mean abundances of 354.40. C. *stellatus* was not recorded for the UWL. The most abundant species at the UWL was *L. littorea,* which was also found at the other two sites. The same number of genera were found at UBF and LBF with fewer being recorded at the UWL (Table 1).

Table 2 - Average Mean Percent Cover of Algal Species on the three shores sampled

Taxon	Upper Basalt Formation (%)	Lower Basalt Formation (%)	Ulster White Limestone (%)
Asophyllum nodosum		1.32	
Ceramium virgatum		3.72	5.44
Chondrus crispus	0.88		
Cladophora rupestris		2.04	0.6
Codium tomentosum	2.88	0.32	0.88
Corallina officinalis			0.12
Dictyota dichotoma	2.16	1.08	0.76
Fucus serratus	16.24	28.6	12.8
Fucus spiralis	2.44	3.84	2.2
Fucus vesiculous	3.4	1.08	0.16
Himanthalia elongata		3.56	0.32
Lithophylum incrustans	0.48	0.12	
Palmaria palmata			0.52
Pelvetia canaliculata	15.88	18.64	0.12
Phycodrys rubens		0.16	3.88
Plumalia plumosa			0.24
Polysiphonia lanasa	0.4		
Pterothamnion plumula		0.2	
Saccharina latissimi			0.2
Ulva lactuca	1.76	1.2	8.04

Fucus serratus covered the largest percentage of space at all sites. High percent cover of *P. canaliculata* was recorded for both the UBF and LBF, but not for the UWL. The largest number of algal species was recorded at the UWL, followed by the LBF and then UBF (Table 2).

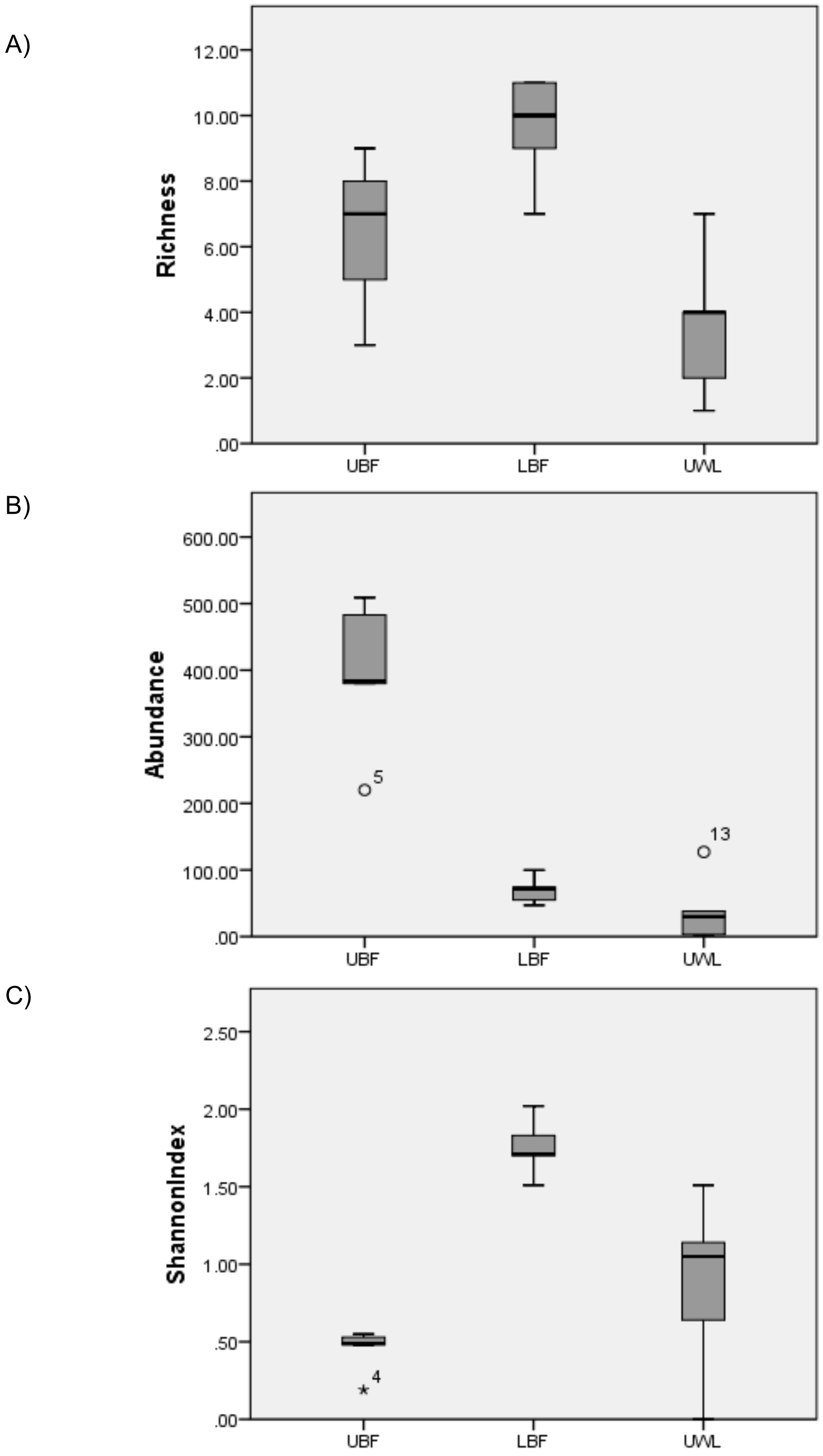

Figure 3 - Comparisons of A) Genera Richness, B) Species Abundance and C) Shannon Diversity Index for the three rock types

3.4. Algal Cover

Percent algal cover in the study area ranges between 10.6%-83.2% with an average of 49.2%±20.4 (Mean±SD). The highest percent cover was found at the LBF site with an outlier value of 83.2% at sample eight. The average percent algal cover found the LBF site was 66%±11.61. There is one sample that had a low percent cover at this location, namely sample two with a value of 51.6%. Percent algal cover ranges between 20.2%-64.4% (sample one and two respectively) with an average value of 45.64%± 16.05 (fig.4). The UWL had the lowest algal cover with an average value of 35.96%±21.83. There is one sample that had a high percent cover, namely sample 12 with a value of 69.6%.

ANOVA analysis shows that there is a significant difference in percent algal cover between the three rock types (p=0.05).

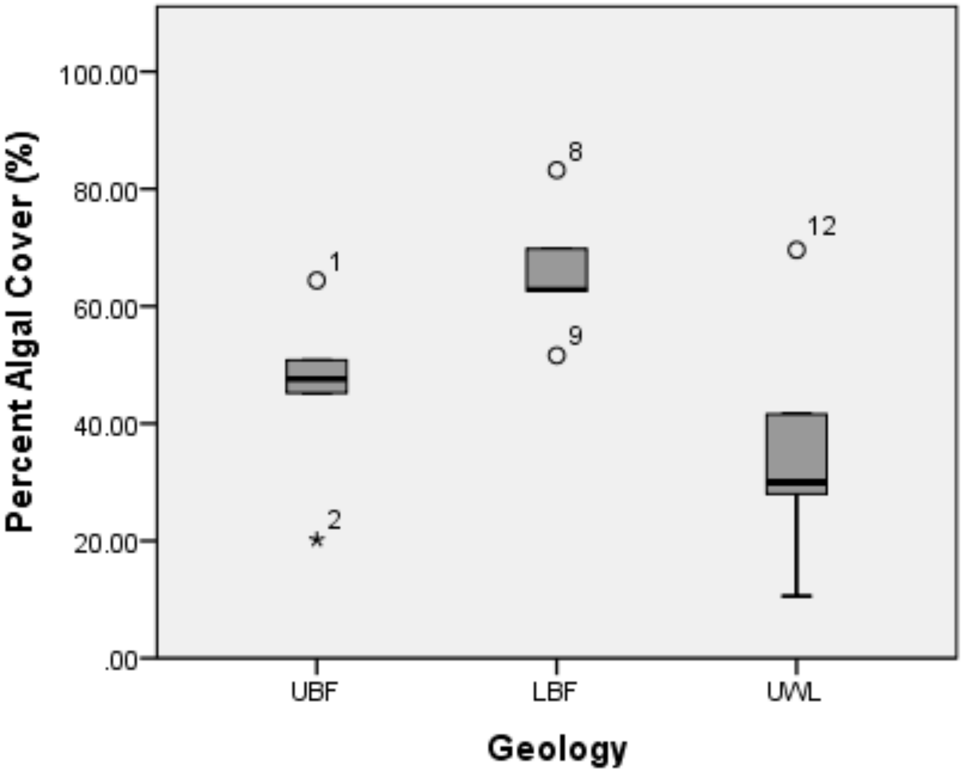

Figure 4 - Comparison of Percent Algal Cover between the three rock types

3.5. Rocky Shore Rugosity

Rocky shore rugosity ranges from 0.03 to 0.35 in the 15 locations within the study area, with an average of 0.23±0.09. The highest rugosity index was recorded at the UBF site, where the average was 0.33±0.02. UBF rugosity ranges between 0.31-0.35. The average rugosity value for the LBF site is 0.21±0.03 and there is one sample, namely sample eight with a value of 0.27, which has a higher rugosity value than other samples at this location. The lowest rugosity was recorded for at the UWL location, representing the lowest surface complexity. Average rugosity at the UWL site is 0.14±0.07. There is one sample, namely sample 12 with a value of 0.21, which has a higher rugosity value than other samples at this location (fig. 5).

Rugosity was investigated on both a metric and kilometric scale. This ensured that the rugosity values collected out in the field were a true representation of the complexity of the three rock types. Table 3 highlights the validity of the rugosity values found for UBF, LBF and UWL.

Table 3 - Rugosity Index on Metric and Kilometric Scale

	Metric Scale Rugosity	**Kilometric Scale Rugosity**
Upper Basalt Formation	0.33	0.31
Lower Basalt Formation	0.21	0.2
Ulster White Limestone	0.15	0.14

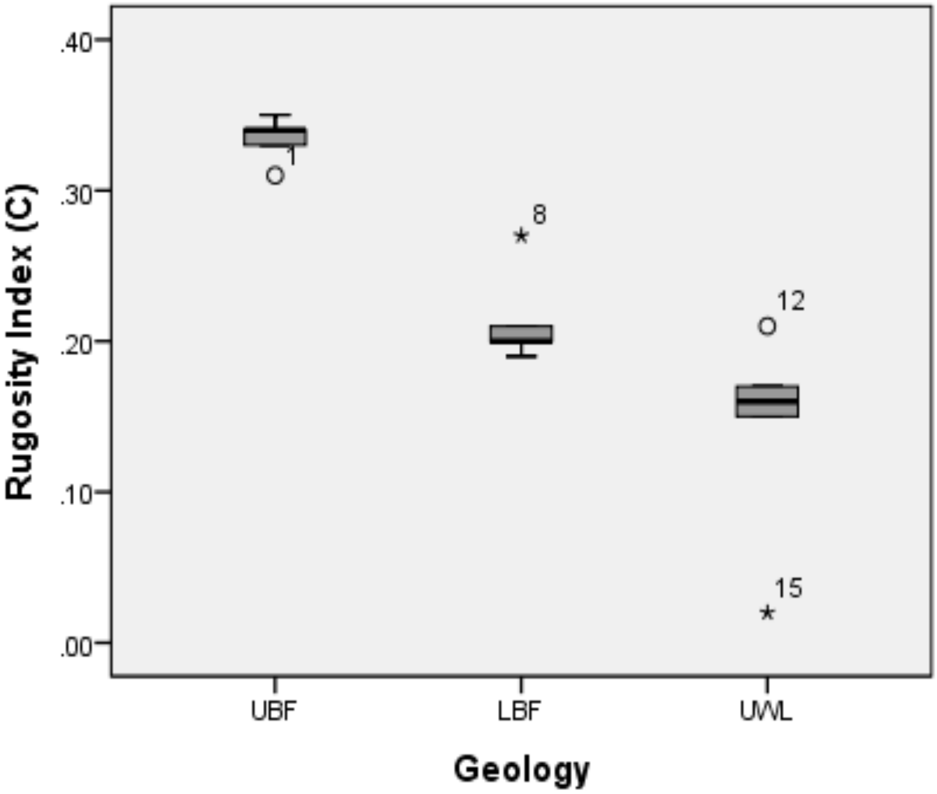

Figure 5 - Comparison of Rugosity Index between the three rock types

ANOVA analysis shows that there is a highly significant difference in rugosity between the three lithologies ($p<0.001$).

Rugosity was classified into three groups: low (<=0.170), medium (0.171-0.275) and high (>=0.275). Based on the classification, 47% of the rocky shore in the study area has medium rugosity, 33% has high rugosity and 20% has a less complex surface (Table 4).

Table 4 - Classification and Proportion of Rugosity Index (Classification Classes taken from Fuad 2010)

Rugosity Index Class	**Value**	**Upper Basalt Formation**		**Lower Basalt Formation**		**Ulster White Limestone**		**Total**	
		n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Low	<=0.170	0	0	0	0	3	66	3	20
Medium	0.171-0.275	0	0	5	100	2	33	7	47
High	>=0.275	5	100	0	0	0	0	5	33

3.6. Relationship between Rugosity and Species Biodiversity

The relationship between species biodiversity and rugosity was analysed using Pearson's correlation test and linear regression analysis.

3.6.1. Rugosity-Fauna Genera Richness Relationship

Overall, there was a positive correlation between genera richness and rugosity (r=0.393). Linear regression analysis highlights that the relationship is not significant (t=1.542, p=0.147). For the UBF, the correlation was weak, and the linear regression shows no significance in the relationship (r=0.014, t=0.024, p=0.983). There was a positive correlation at the LBF site, but the linear relationship was not significant (r=0.642, t=1.452, p=0.242). Rugosity and genera richness was positively correlated at the UWL, but the linear regression shows that the relationship is not significant (r=0.847, t=2.762, p=0.07) (fig. 6).

3.6.2. Rugosity-Species Abundance Relationship

Overall, rugosity was positively correlated with species abundance (r=0.872) and the relationship was very significant (t=6.43, p<0.001). The UBF shows a strong correlation between rugosity and abundance with the linear regression showing a significance in the relationship (r=0.949, t=5.217, p<0.05). There was a strong positive correlation between rugosity and abundance at the LBF site and the linear regression shows a significance in the relationship (r=0.913, t=3.885, p<0.05). UWL shows a positive correlation between abundance and rugosity but the relationship was not significant (r=0.69, t=1.65, p=0.198) (fig. 7).

3.6.3. Rugosity-Species Diversity Index Relationship

Overall, the Shannon diversity index was negatively correlated with rugosity (r=-0.141). Pearson's correlation analysis shows a weak correlation and linear regression shows that the relationship is not significant (t=0.512, p=0.617). When looking at the individual locations, the UBF shows a weak correlation between rugosity and the diversity index and the relationship is not significant (r=0.229, t=3.697, p=0.711). The LBF site shows a very strong correlation between the diversity index and rugosity and a significant relationship is shown by the linear regression analysis (r=0.906, t=3.697, p<0.05). UWL shows a very strong correlation and a high significance in the relationship (r=0.962, t=6.145, p<0.01) (fig. 8).

3.7. Relationship between Rugosity and Algal Cover

The relationship between percent algal cover and rugosity was investigated using Pearson's correlation analysis and linear regression. Overall, there is a weak correlation between rugosity and algal cover and a linear regression shows that there is no significant relationship (r=0.196, t=0.72, p=0.48). UBF site displayed a weak correlation between rugosity and algal cover, and no significant relationship (r=0.3, t=0.55, p=0.62). There is essentially no correlation between rugosity and species abundance at the LBF location and the linear regression is not significant (r=0.09, t=0.01, p=0.89). The UWL site presents a positive correlation between rugosity and species abundance but no significant relationship (r=0.51, t=1.028, p=0.38) (fig. 9).

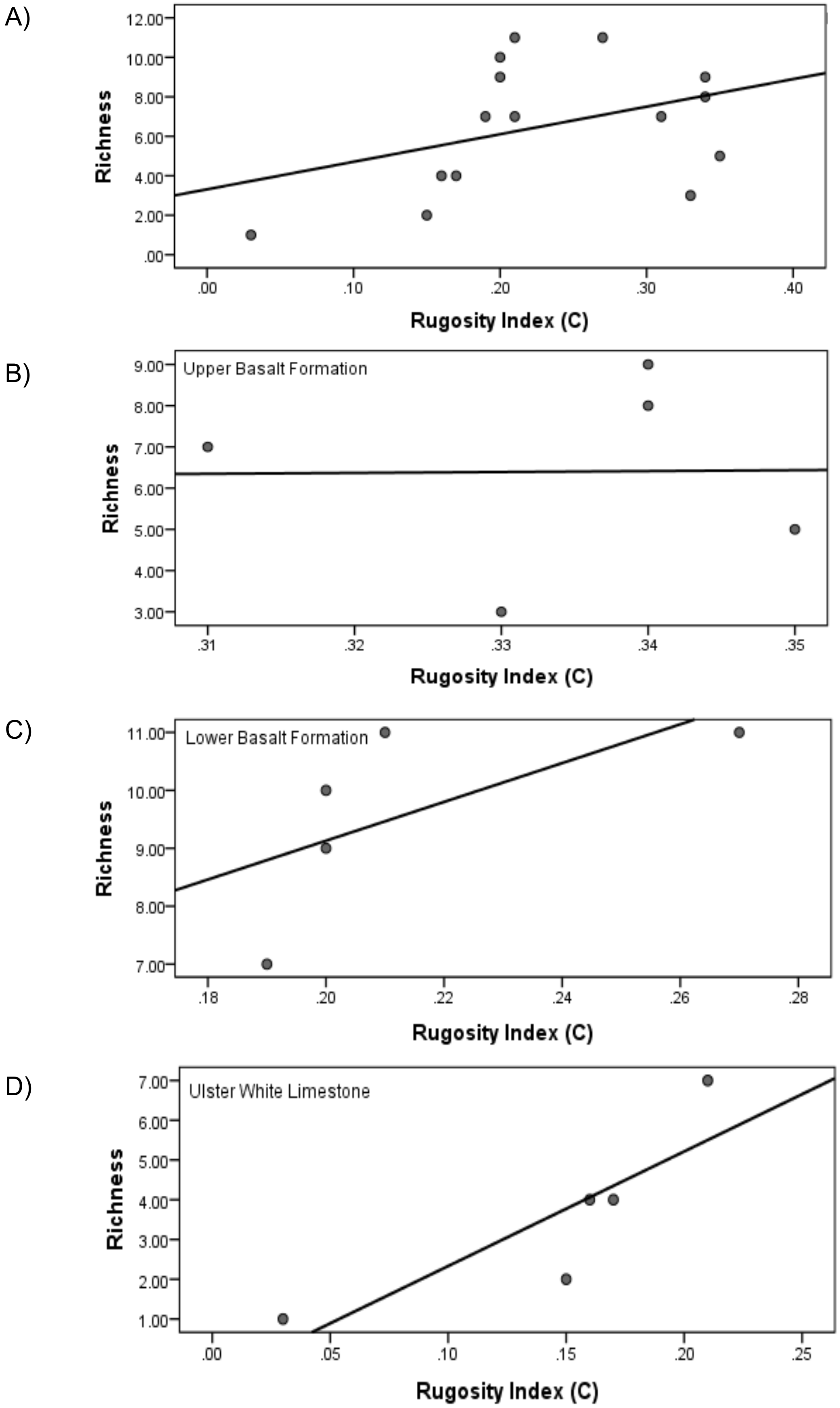

Figure 6 - Rugosity - Genera Richness Relationship. A) Entire study area (r^2=0.155), B) Upper Basalt Formation (r^2=1.874E-4), C) Lower Basalt Formation (r^2=0.413) and D) Ulster White Limestone (r^2=0.718)

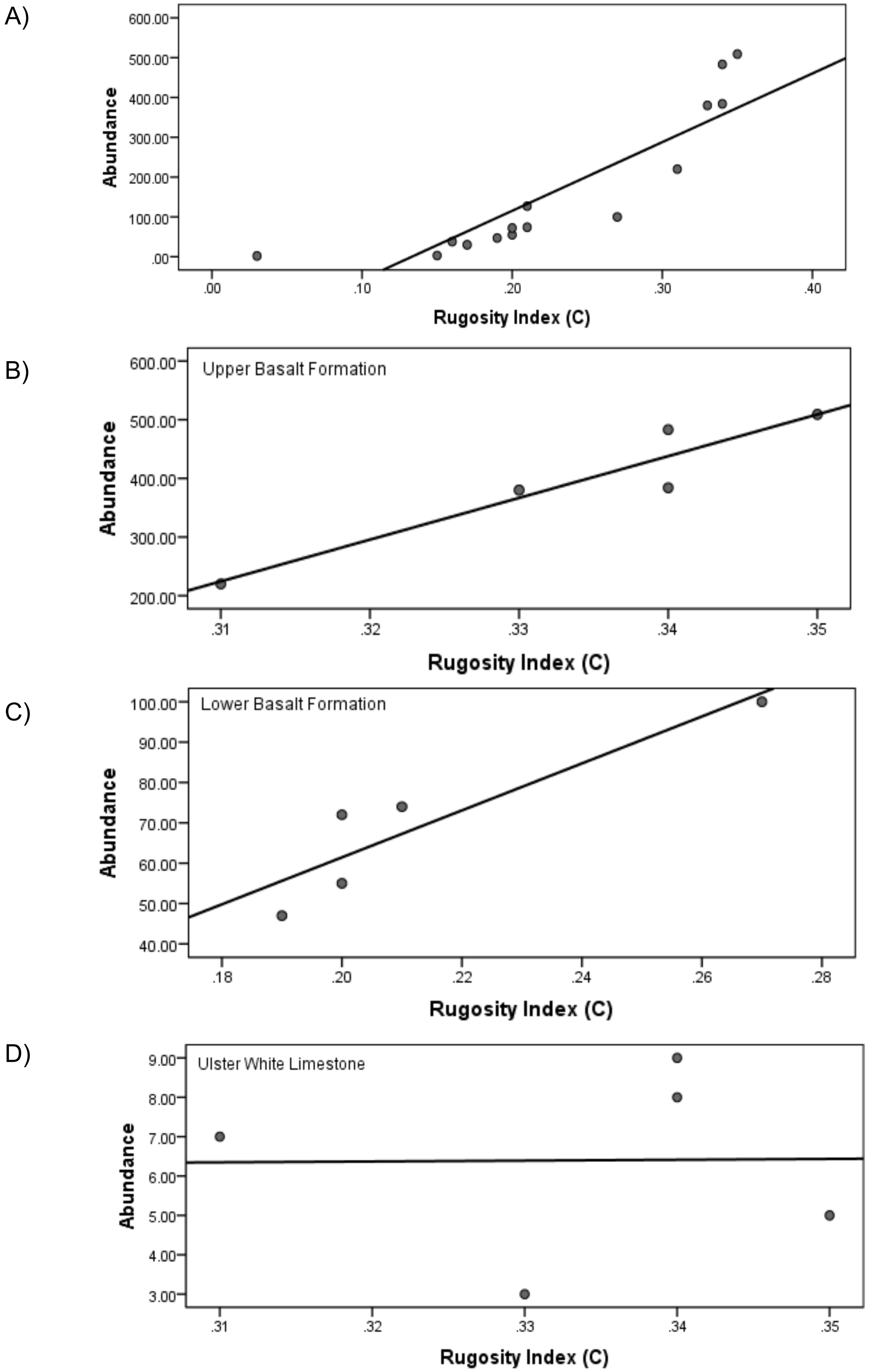

Figure 7 - Rugosity – Species Abundance Relationship. A) Entire study area (r^2=0.761), B) Upper Basalt Formation (r^2=0.761), C) Lower Basalt Formation (r^2=0.834) and D) Ulster White Limestone (r^2=0.476)

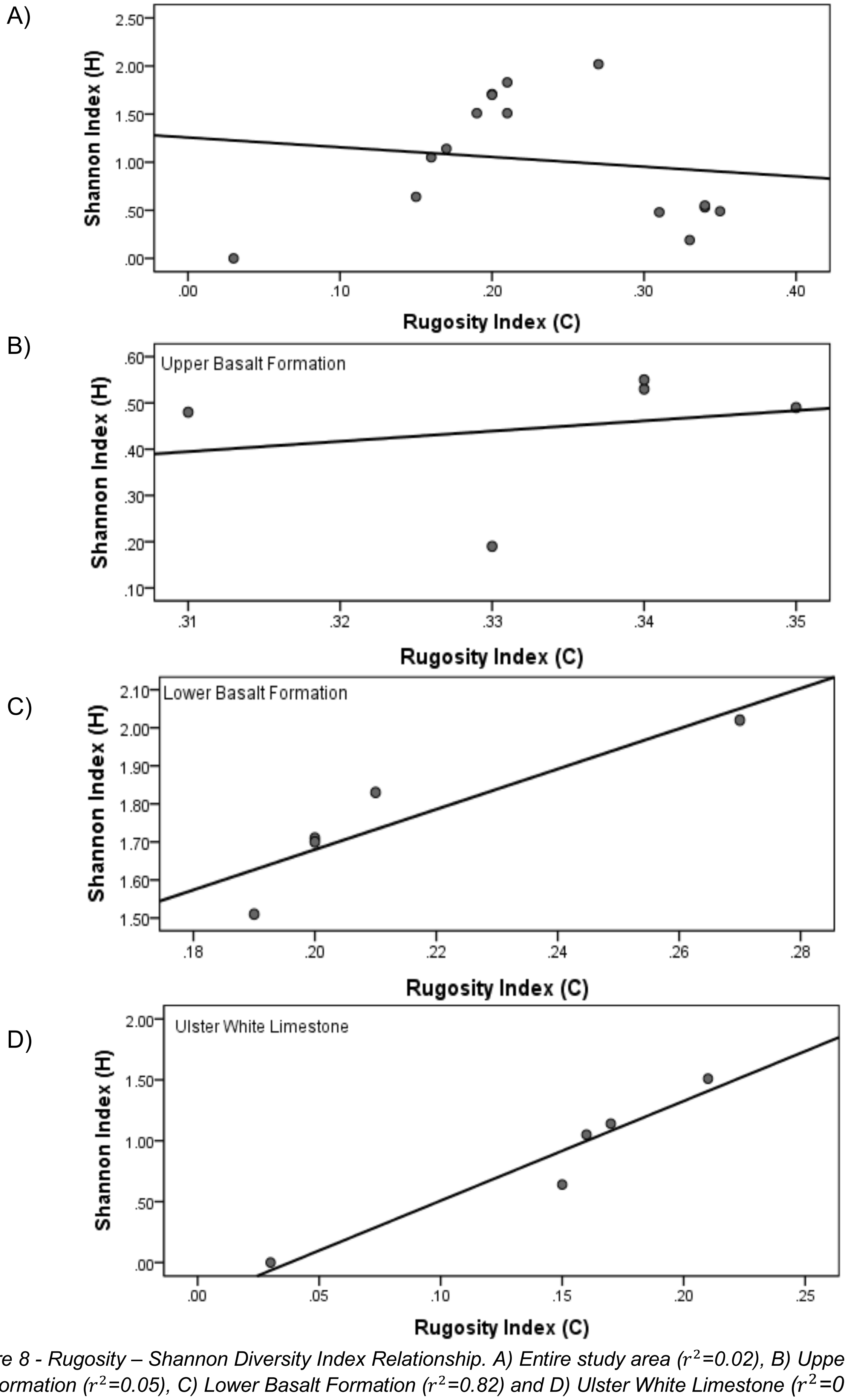

Figure 8 - Rugosity – Shannon Diversity Index Relationship. A) Entire study area (r^2=0.02), B) Upper Basalt Formation (r^2=0.05), C) Lower Basalt Formation (r^2=0.82) and D) Ulster White Limestone (r^2=0.09)

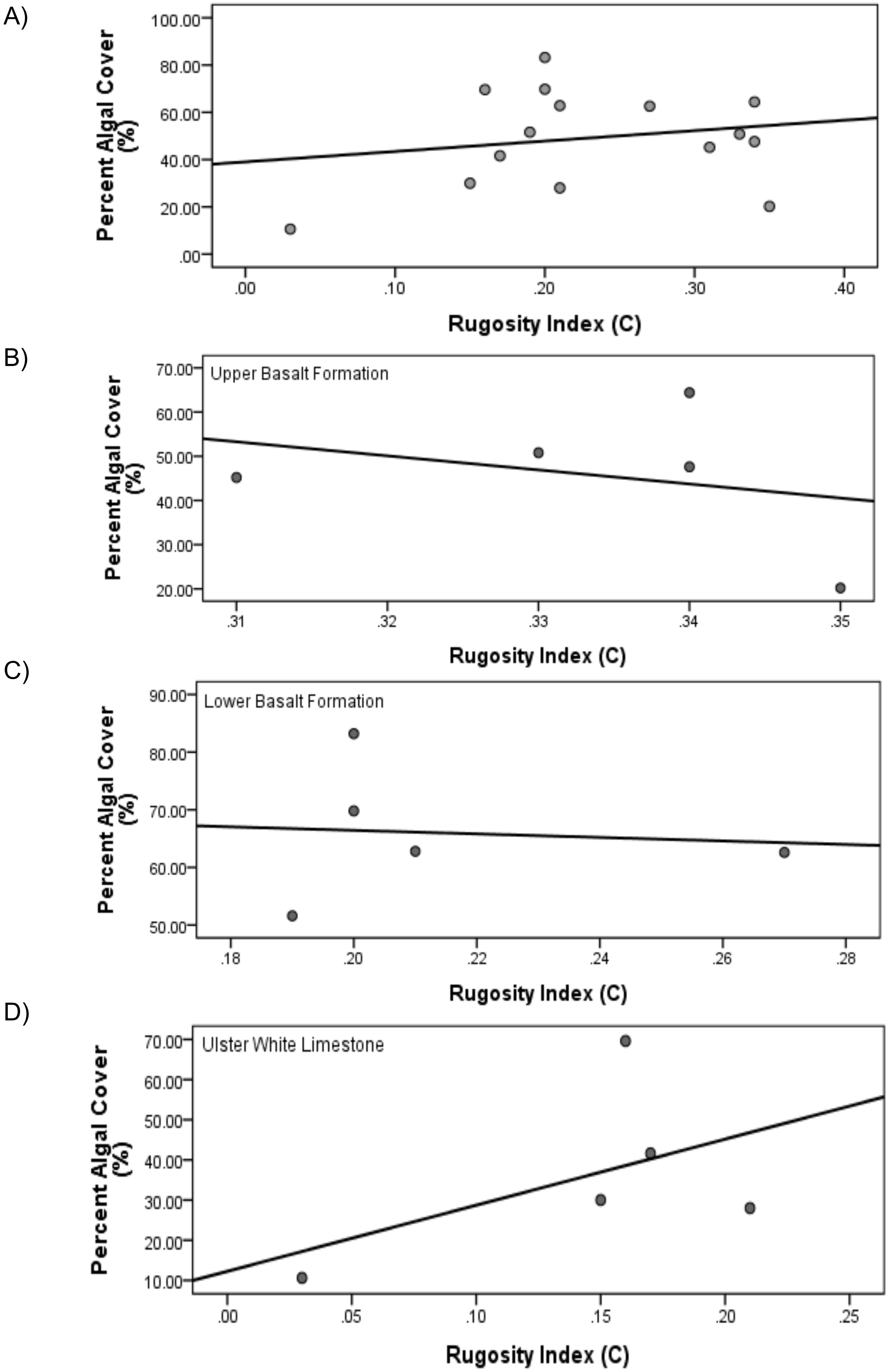

Figure 9 - Rugosity – Percent Algal Cover. A) Entire study area (r^2=0.04), B) Upper Basalt Formation (r^2=0.01), C) Lower Basalt Formation and D) Ulster White Limestone (r^2=0.26)

4. Discussion

4.1. Geological Complexity

The study covered a variety of rock types found along the heterogeneous North Coast of Ireland. Rocky coastlines provide an array of habitat types and levels of heterogeneity (Kostylev *et al.,* 2005). Previous studies have shown that regions with a heterogeneous lithology tend to have more complex coastlines with softer material being easiest to erode (Davidson *et al.,* 2002, Porter-Smith and McKinlay, 2012). Coastline complexity is characterised by lithological factors and wave action (Porter-Smith and McKinlay, 2012).

The rugosity index (C) was used to quantify the complexity of the lithologies found along the coastline. The highest rugosity value was recorded for the UBF, where the average was 0.33. The UWL site was the least complex, with an average rugosity value of 0.14. This can be explained by the effects of wave action and the structural strength of the rocks (Fairbridge, 2004, Porter-Smith and McKinlay, 2012). Both sites, Portstewart Strand and Ballintoy Harbour, are north-facing and are subject to similar conditions impacting the geology, however, the UWL is more easily eroded due to a softer, chalk structure in comparison to the hard, basalt lithologies. UWL has a much greater hardness and a lower porosity compared to typical chalk due to the rapid thermal and burial loading of tertiary basalts on top of the limestone and is more complex than expected (Maliva and Dickson, 1997, Simms, 2000). Both the LBF and UBF are similar in terms of chemical and physical composition, however, the UBF is located at the Portstewart Strand site, where there is less shelter in comparison to the Ballintoy site; where the LBF and UWL lithologies are found. For heterogeneous coastlines, waves will erode the weaker substrate first, which in this case is the UWL (Porter-Smith and McKinlay, 2012). It's clear that geological control is the dominant factor, as similar marine processes are acting along the coastline. Wave action is effective in eroding sections along the coastline, but the scale of erosion is dependent on the geological makeup of the lithology found along the coast. From the results and observations, it appears that the UWL is a much flatter, less complex surface compared to the two basalt substrates (fig. 5). To ensure validity of complexity data collected in the field, rugosity was also calculated on a kilometric scale (Table 3). From the results, it's clear that rugosity values on both scales support each other, and therefore represent the complexity of the coastline accurately. Rugosity was classed into 3 categories; Low, Medium and High (Table 4). From the field data collection, 33% of the coastline had a high rugosity index, representing all samples taken from the UBF site, and 20% has a low rugosity index, representing the majority of samples taken at the UWL site. ANOVA shows that there is a significant difference in the geological complexity of different rock types.

4.2. Species Biodiversity and Algal Abundance

Species richness was significantly different for the three sites. LBF had the greatest species richness. There was a high significant difference in species abundance between the three sites, with the greatest number being recorded at the UBF. There was a high abundance of the species *Chthamalus stellatus* at this site, a barnacle species that occupies small crevices on rocky shores, protecting them from predators and can endure long periods of exposure (Johnson and Baarli, 1999). There was a high significant difference in species diversity between the three sites. Diversity was greatest at the LBF, followed by UWL. The low species diversity at the UBF location is due to the large abundance of *Chthamalus stellatus,* which will have skewed the evenness and therefore the diversity index, however, species richness was high at this site. *Patella vulgata* is the dominant species at the UBF and has a role in structuring the community. Limpet density declines with an increase in shelter, which explains the greater abundance of limpet species at the UBF, compared to the sheltered LBF and UWL sites (Table 1) (Jenkins and Hartnoll, 2001). Barnacle patches provide species with refuge, allowing species to co-exist within the available space and reduce the risk of mortality for predatory snails (Kostylev *et al*., 2005). This also explains the increase in faunal species at UBF compared to UWL, where there are no barnacle species present (Table 1). The periwinkle, *Littorina littorea,* was highly abundant at both the LBF and UWL sites, where barnacle species were either not present or present in low abundances but was not abundant at the UBF (Table 1). This suggests that survival rates of *L. littorea* are low in the presence of *C. stellatus*.

20 algal species were found during the field data collection. The average percent algal cover for the study area was 49.2%. The highest algal abundance was recorded at the LBF, which can be explained by the increase in attachment sites compared to the UWL, where the lowest percent algal cover was recorded. The high faunal species abundance and diversity found at the LBF, can be explained by the large presence of *Fucus serratus,* as it's understood that *Fucus* seaweeds can provide a refuge for many species, by providing protection from extreme temperatures and desiccation stresses. Barnacle settlement is greater on open substrates compared to under *Fucus,* explaining the increase in C. stellatus at the UWL, where *Fucus* abundance is poorer (Table 2) (Hawkins, 1983**,** Grant, 1977, Menge, 1976, Thompson *et al*., 1996). ANOVA determined that there is a significant difference in percent algal cover between the three rock types. Physical and biological factors are known to increase the rock area and are more likely to tolerate a larger biomass of algae, which will then support a greater number of grazing species (Kostylev *et al.,* 2005). It's thought that the presence of algae can promote species evenness and elevate diversity (Eriksson *et al*., 2006). There may be an increase in diversity with decreasing human population density, as algae often decline in areas where human activity is high (Addessi, 1994, Bloch and Klingbeil, 2016). This may explain why algal

abundance was much higher at the LBF compared to the UBF, as the location of the UBF is subject to more visitors than the other site. On rocky shores, periwinkles (*Littorina* spp.) are essential consumers. The most abundant periwinkles, *Littorina littorea* feed on the green algae *Ulva lactuca*, which was most abundant at the UWL, where a large number of *L. littorea* were recorded (Table 1 and Table 2) (Bloch and Klingbell, 2016, Scrosati *et al*., 2010)

4.3. The relationship between biodiversity and geological complexity

The physical structure of a coastline can alter the vulnerability of intertidal fauna to wave exposure, desiccation stress and predation by creating different microhabitats (Sebens, 1991). Complex surfaces can provide a variety of niches for animals of different size, allowing many species to co-exist within the same site (Kostylev *et al.,* 2005). The relationships between rugosity and the diversity indices were investigated using linear regression and pearsons correlation test. In the study area, the diversity indices that have the highest correlation with rugosity are species abundance and genera richness. There is a positive correlation between genera richness and rugosity. The lowest genera richness was found for the UWL site, where geological complexity was also lowest. It's understood that surface complexity is relative to the amount of available space and microhabitats for benthic species, which can then influence the genera richness of a habitat (Kostylev *et al.,* 2005). Rugosity, and therefore complexity, was positively correlated with species abundance and the relationship was highly significant. An increase in geological complexity reduces the chances of predation on abundant prey in intertidal habitats (Coull and Wells, 1983). Consumer pressure on rocky heterogeneous coasts tends to be less intense compared to homogenous coasts, therefore the animals have a better survival rate (Menge *et al.,* 1985). Overall, Shannon index was negatively associated with rugosity. The relationship between the Shannon index and rugosity was most significant at the UWL ($r=0.962$, $p<0.01$), but was not significant for the UBF ($r=0.229$, $p>0.05$). The high abundance of *C. stellatus* skewed the evenness and therefore the diversity of the UBF and the overall study area. The relationship between species diversity was significant for the LBF location, where there was a strong correlation ($r=0.906$, $p<0.05$). Linear regression models show the relationship of rugosity with the diversity indices (fig. 6, fig. 7, fig. 8 and fig. 9).

There is a positive relationship between diversity and complexity at different scales. Complexity is vital for species co-existence by creating a variety of niches and micro-habitats with a diverse range of resources (Kostylev *et al.,* 2005). This study shows that the presence of a dominant species (*C. stellatus*) can have a strong effect on the diversity of a habitat.

A study by Palmer (1992), found that an increase in complexity allows more species to co-exist per microsite and Johnson *et al*. (2003) found a positive relationship between genera richness and complexity (Kostylev *et al.,* 2005). This study supports these findings, with species abundance and genera richness increasing with increasing complexity. Results are similar to that found in many other studies, where variables reflecting habitat complexity, such as algal cover and surface complexity, were positively associated with richness or diversity. It's understood that surface complexity, especially in the form of cracks or crevices, provide a vital refuge to many species from predation (Bloch and Klingbeil 2016, Menge and Lubchenco 1981). Increased complexity can provide micro-sites, which protect organisms from severe temperatures and desiccation stress, therefore promoting the settlement and perseverance of species (Bloch and Klingbel, 2016, Scrosati *et al.,* 2010).

4.4. Limitations

Limitations of the study include how intertidal range was not considered. Different species are more abundant at different levels of the intertidal zone and this may help explain results by looking at the location of samples in relation to the lower, middle and upper intertidal zones (fig. 2). The upper limits of zonation of rocky shore species can be set by desiccation and thermal stresses (Connell, 1972, Davenport and Davenport, 2005, Helmuth *et al.,* 2006, Johnson and Baarli, 1999, Somero, 2002). Species may then be excluded from an intertidal region by changes in oxygen levels or water temperatures (Helmuth *et al.,* 2006, Leslie *et al.,* 2005, Scrosati *et al.,* 2010, Service, 2004).

Presence of the species *C. stellatus* impacted the diversity index results for the UBF. To prevent this, barnacle species could be removed from sampling sites before counting and recording species. For further investigation, other rock types found along the North Coast of Ireland could be considered, such as "Waterloo Mudstone Formation" or "Barony Glen Formation", to provide more validity to the results and test differences in biodiversity and complexity even further. The effects of Storm Ophelia may also have impacted the results. Storm Ophelia hit Ireland on 16th October 2017. Data was collected from Portstewart Strand before the storm on Monday 9th October, however, the Ballintoy Site, where both the LBF and UWL are located, was sampled after the storm on Monday 23rd October. Weather systems such as storms can intermittently tear out areas of overgrowth where species are well established and reopens the substrate to colonization by other species and therefore affects results (Johnson and Baarli, 1999). Sampling occurred during autumn, where species are subjected to colder temperatures compared to spring/summer. It may be worthwhile to conduct the same study during a period where temperatures are warmer and when there would be more hours of daylight. An increase in attachment strength in autumn/winter has been found in response to an increase in hydrodynamic loading related with these seasons, and therefore increasing survival rates during physically stressful periods (Carrington, 2002). Sea surface temperature will be higher in summer and therefore effects on what species can survive. Fauna can be influenced by stormier periods in autumn and winter followed by calm periods in the summer, which influences the diversity at certain periods of the year (Carrington, 2002).

Temporal replications will allow for comparisons in changes in disturbance regimes, environmental conditions or interspecific interactions which change community structure (Adams, 2001, Bloch and Klingbell, 2016)

5. Conclusion

A total of 15 faunal taxa were found in the study area. Statistical analyses show that there is a highly significant difference in genera richness, species abundance and species diversity between the three rock types and therefore the null hypothesis, H_{01}, can be rejected. A significant difference in percent algal cover was also found. A strong significant difference in rugosity was found between the three shores ($p<0.001$), showing that there is a difference in geological complexity and therefore allowing the null hypothesis, H_{02}, to be rejected. No significant relationship was found between genera richness and rugosity. A significant relationship was found between rugosity and species abundance for all sites sampled except for the UWL. A significant relationship was only found for the LBF and UWL regarding rugosity and species diversity index. The UBF did not show a significant relationship, which has been explained by the large abundance of the barnacle species *C. stellatus* skewing the evenness and therefore the diversity of this site. Therefore, the null hypothesis, H_{03} , has to be accepted for the UBF but can be rejected for both the LBF and UWL.

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