SPATIAL ANALYSIS OF BLUE CARBON IN A UK SALTMARSH: IMPLICATIONS OF CARBON DISTRIBUTION.

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Abstract

In recent years saltmarshes have been found to be significant stores of blue carbon with important links to the global carbon cycle. Saltmarshes have the ability to sequester a significant amount of carbon with long residence times once buried. In this investigation, the spatial distribution of organic carbon of surficial sediments and the factors driving its production and preservation were studied at Biggar Saltmarsh, situated on Walney Island, west of Barrow-in-Furness on the north side of Morecambe Bay, England. Thirty-three sediment samples were collected from the surface (0-3cm depth) layer of the marsh along a linear transect extending from the highest marsh to the seawards limit of vegetation. Random spatial sampling was undertaken to ensure different marsh sub-environments were effectively sampled. Precise elevation data was collected for all sediment samples. Laboratory tests of samples included; TOC, TN, LOI, pH, conductivity and grain size analysis. Three silt-dominated marsh zones were defined with an upper high marsh comprising *Phragmites australis* (Zone 1), a mid-marsh area (Zone 2) with vegetation including *Triglochin maritima, Puccinellia* sp.*,* and a low marsh area (Zone 3) characterised by *Spartina alterniflora*. Organic matter, carbon and nitrogen decreased from high to low marsh. The highest values were in high marsh/elevations (TOC: 26.6 $\pm$ 7.84%, Organic matter: 49 $\pm$ 14.49%, TN: 1.9 $\pm$ 0.55%) and the lowest values found within low marsh/ elevations (TOC: 3.5 $\pm$ 7.84%, Organic matter: 8 $\pm$ 14.49%, TN: 0.35 $\pm$ 0.55%). Organic carbon, organic matter and nitrogen were found to have a significant relationship to elevation; $r= 0.931$, $p<0.05$; $r=0.834$, $p<0.05$; $r=0.942$, $p<0.05$ respectively, indicating that elevation, controlled by tidal inundation and subsequently establishment of less salt tolerant vegetation, is one of the main controls of organic carbon burial. No correlations were established between organic geochemical results and grain size indicating the latter parameter is not a major driver of carbon preservation at Biggar. High C/N ratios were found with highest in the high marsh (16.85) decreasing seaward (11.85), C/N values indicate a high influence of terrestrial vegetation input of organic matter. Based on sea-level rise data it has been estimated that 67% of carbon will be lost from Biggar Saltmarsh with a sea-level rise of 7.1mm/yr. The high amounts of organic carbon found within Biggar Saltmarsh highlights the importance of these blue carbon environments and the need to protect them in relation to future sea-level rise and anthropogenic impacts.

Chapter 1- Introduction

1.1 Global climate change

The widespread use of fossil fuels (coal, oil and natural gas) since the industrial revolution (1760-1830) has caused significant increases in the concentration of carbon dioxide (CO_2) within the atmosphere (Grace, 2013). Mean atmospheric CO_2 concentrations have increased by 40% from 278ppm to > 400 ppm today from the pre-industrial levels (Zarch et al. 2017). There has been a global acceptance that anthropogenically released CO_2 has triggered the increased greenhouse effect, causing global warming (Grace, 2013). Between 1880 and 2012 there has been a global rise in average surface air temperature of 0.85°C, and is estimated by the end of the 21st century there will be a global temperature increase of 1.2-1.5 °C relative to 1850-1900 (Zarch et al. 2017). Since 1971-2010 ocean warming has dominated the increases of energy stored within the climate system, with the ocean having absorbed 90% of all new thermal energy created, with only 1% stored in the atmosphere (IPCC, 2014; Thomas, 2014). The oceans remove around 2.3 Gt of carbon from the atmosphere each year, accounting for 27% of carbon released via fossil fuel burning (Grace, 2013). This has caused ocean warming, which is greatest within the uppermost 75 m which has seen temperature rises by 0.11 °C. This uptake of CO_2 within the ocean since the industrial revolution has resulted in acidification with a decrease in pH of 0.1 in surface water (IPCC, 2014).

One of the impacts of climate change is sea-level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC, 2014) stated that from 1901 to 2010 there was a rise in global sea-level of 0.19 m. The rate of SLR since the mid-19th century is greater than during the last two millennia. There are many uncertainties around the future of climate change, which the IPCC (2014) report tried to address. They argue that from 2016-2035 there will be a global mean surface temperature rise between 0.3-0.7°C with the artic region continuing to receive the most rapid rates of warming. This increase in temperature will result in further increases of ocean acidification by 15-17%, with the pH range of ocean surface falling a further 0.06-0.07 by the end of the 21st century. Increased temperatures will also result in the continuation of SLR with global sea-level continuing to rise at a faster rate during the 21st century than between 1971 and 2010. By 2081-2100 global sea-level will have risen by 0.26-0.55 m. SLR is not uniform over the ocean surface, with some areas experiencing greater rises then others (Mitrovica et al. 2001). These future projections of climate change highlight the importance of trying to mitigate climate change now and begin to attempt to reverse its effects.

1.2 Global Carbon Cycle

The global carbon cycle is comprised of a series of processes where carbon flows between the Earth's reservoirs in either gaseous (e.g. CO_2) or solid forms (e.g. coal) *(Figure 1.1)*. There are three main reservoirs to the global carbon cycle; the atmosphere, oceans and terrestrial systems (Grace, 2001). Carbon can either be transferred from one reservoir to another, either in a few seconds (photosynthesis) or over a millennia (fossil fuel creation) (Houghton, 2003). Terrestrial systems are comprised of a variety of stocks including sediments, soils and forests. The terrestrial biosphere is the largest reservoir of organic carbon within the global cycle, with the atmosphere being the smallest reservoir of carbon (Post et al. 1990). Yet, even though the atmosphere is the smallest reservoir, it has important roles in relation to links between the other two systems (Houghton, 2003). The other reservoirs (terrestrial, ocean and rivers) primarily interact with each other by trading carbon via the atmosphere even though the atmosphere only holds a small proportion of the Earths carbon (currently, 780 G ton C) (Archer, 2010).

Oceans are the second largest reservoir of organic carbon within the global carbon cycle and are important in relation to helping regulate atmospheric CO_2 (Post et al. 1990). The majority of carbon within the ocean is in the form of inorganic carbon. These inorganic compounds are oxidised rather than 'reduced' like for organic carbon. This does not require photosynthetic energy to carry out this process, it relies on pH changes within the ocean (Archer, 2010). The majority of the Earths carbon is stored within sedimentary rocks such as limestone ($CaCO_3$ and $CaMg(CO_3)_2$) and fossil fuels/Kerogen. These rocks are originally formed within the oceans, then were uplifted to the Earth's surface including to the top of mountain ranges (Archer, 2010). Organic carbon within the terrestrial biosphere is stored within all living things but most abundantly, organic carbon is stored within plants and soils. This is predominantly gathered via photosynthesis, where inorganic CO_2 is taken from the atmosphere and turned into organic compounds and stored (Archer, 2010; Hedges and Keil, 1995). However, there are large uncertainties regarding the total amount of carbon in the terrestrial reservoir. The majority of carbon budgets only take into account large terrestrial areas such as forests, but fail to account for smaller scattered areas of wetlands such as mangroves, saltmarshes and swamps, due to these environments only recently being recognised as major sinks/stores of organic carbon (Pendleton et al. 2012). This could be cause for carbon budgets of the terrestrial reservoir to be severely underestimated, as wetlands have been found to represent the largest component of the terrestrial carbon pool (Chmura, 2003). Even though coastal wetlands such as saltmarshes are classified as marine environments, they still belong within the terrestrial biosphere in relation to the global carbon cycle. This is due to them being transition zones between marine and non-marine environments. This is why this study is of such importance, as it highlights how coastal wetlands are overlooked ecosystems in relation to carbon burial and the global carbon cycle. More research needs to be undertaken within coastal environments in order to distinctively classify these ecosystems in relation to the global carbon biospheres (Allen, 2000).

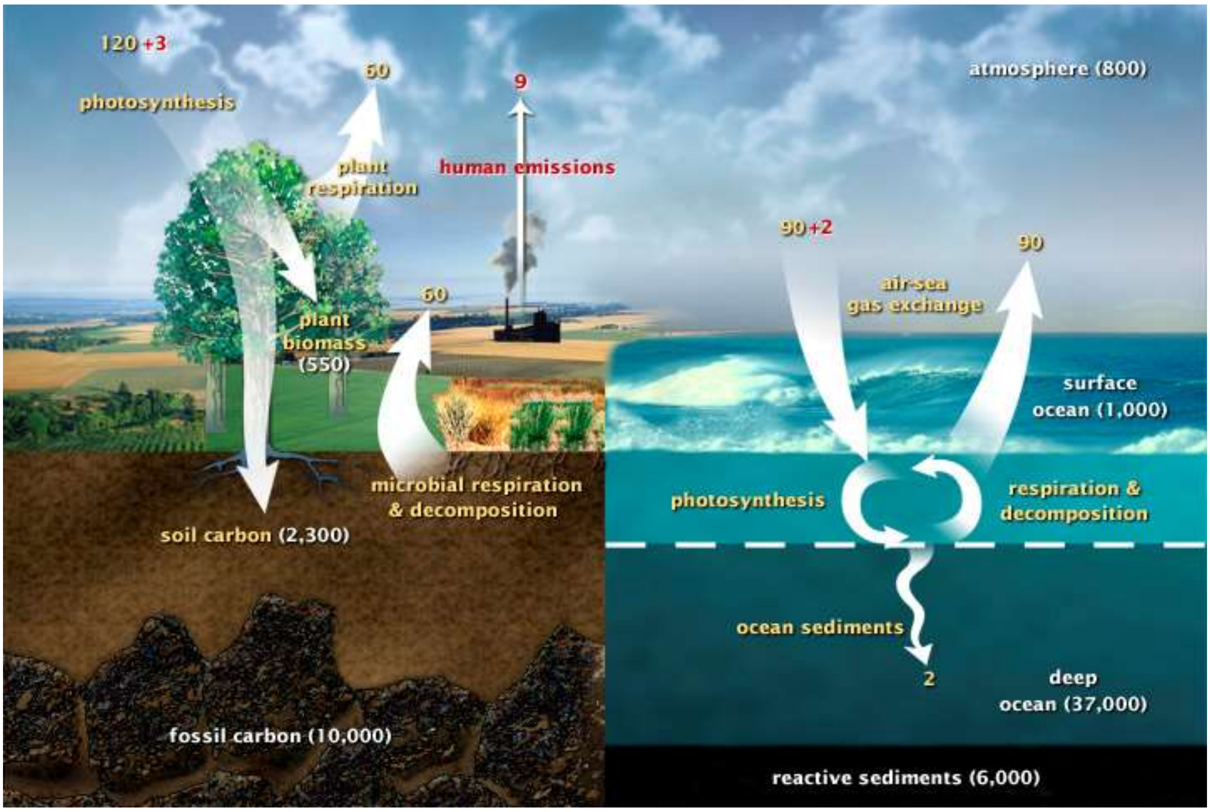

Figure 1.1: Diagram of the global carbon cycle. Sourced from (https://earthobservatory.nasa.gov/features/CarbonCycle)

1.3 Blue carbon in coastal wetlands

Blue carbon (Carr et al. 2018) is carbon that has been sequestered and stored in coastal and marine ecosystems. These ecosystems are vegetated coastal habitats, which include: mangrove forests, seagrass meadows and tidal salt marshes (Carr et al. 2018; Thomas, 2014). Blue carbon ecosystems only cover 2% of global area which equates to around 20 million hectares globally (Kirwan, 2013; Lau, 2013; Wylie et al. 2016). Even though coastal wetlands only occupy a small area globally, they are amongst the most productive ecosystems on Earth, being ten times more effective at sequestering CO_2 than terrestrial ecosystems such as tropical rainforests, boreal and temperate forests (Wylie et al. 2016), and have the capacity to store carbon for up to a millennia if left undisturbed. It is estimated that blue carbon habitats sequester carbon at a rate in excess of 100 Tg C yr^{-1} making up the largest proportion of carbon pools within terrestrial biological ecosystems (Hopkinson et al. 2012). As well as storing large amounts of carbon, these ecosystems also release negligible amounts of greenhouse gases such as methane. This is due to anaerobic methanotrophy which hinders the flux of methane gas, thus they emit much lower amounts than terrestrial ecosystems (Carr et al. 2018; Luisetti et al. 2013).

Blue carbon ecosystems have some of the highest loading rates of carbon and nitrogen on earth (Hopkinson et al. 2012). Mangrove forests are typically located in warm temperate to wet tropical climates between the latitudes 30°N and 38°S. They can be found along open coasts as well as in sheltered estuaries and located in tidal ranges between < 1 m and > 4 m. The carbon stored in mangroves represents around 15% of marine carbon stored in sediments (Livesley and Andrusiak, 2012). Saltmarshes by comparison can be found in all regions from wet and warm tropics to colder higher latitudes, they span between the latitudes 55°N and 45°S (Livesley and Andrusiak, 2012; Pendleton et al. 2012). Saltmarshes are typically located within sheltered estuaries typically at the mouths of rivers (Hopkinson et al. 2012). Globally carbon sequestration rates for these wetlands are estimated to be 210 g CO_2 m^{-2} yr^{-1} (Chmura, 2003). These ecosystems provide vital connections between the marine and terrestrial environments. They serve as sinks of sediments for both marine and terrestrial habitats as well as being a crucial source of marine carbon and nutrients supporting marine productivity and biodiversity (Livesley and Andrusiak, 2012).

Blue carbon habitats are also important for ecosystem services such as shoreline protection and water filtration. However, despite the importance of these habitats more than 50% of blue carbon ecosystems have been lost within the last half a century (Thomas, 2014; Wylie et al. 2016). Once these habitats have been disturbed they no longer act as a carbon sink and turn into a source. A global area loss of 0.17-7% has seen the release of 0.15 and 1.02 billion tons of carbon into the atmosphere, further accelerating anthropogenic climate change (Wylie et al. 2016). In 2010, the United Nations set up the blue carbon initiative with non-government partners. The aim was to promote climate change mitigation via the restoration of blue carbon ecosystems. However, the capacity of these habitats to sequester carbon appears to be lower in disturbed habitats than in undisturbed habitats (Thomas, 2014). Burden et al. (2013) compared the ability of restored saltmarshes to sequester carbon in comparison with natural saltmarshes. After 15 years of inundation sediment in restored sites followed trends in carbon storage from high to low marsh. The low marsh accumulated less carbon in comparison to the high marsh at both restored (10.9 Kgm^{-3}) and natural sites (13.7 Kgm^{-3}). However, there was a large difference between the carbon accumulation within high marsh. The natural high marsh site had carbon pools of 31.1 Kgm^{-3} in comparison to the restored marsh sites, which had carbon pools of 22.1 $\pm$ 20.7 kgm^{-3}. It was estimated that it will take 100 years for the restored saltmarsh sites to accumulate carbon at similar rates to the natural site (Burden et al. 2013). This highlights the importance of preserving these ecosystems and preventing ones that are still in a natural state from being lost.

1.4 Saltmarshes

Saltmarshes are vegetated areas covered by halophytic vegetation that are regularly inundated by the sea (Allen, 2000). They exist within the transition zone between the terrestrial environment and the marine environment, where the accumulation of marine and/or freshwater sediments enables the formation of soils. These soils receive prolonged salt water saturation triggering the transition from terrestrial ecosystems into marine ones (Ferronato et al. 2018). In low energy environments such as estuaries and embayments the formation of tidal mudflats occurs, produced predominantly from the accumulation of fine muddy sediments. This can only occur in areas where tidal currents and wind-wave action is limited (Foster et al. 2013). Both inorganic and organic sediment must also be supplied in sufficient quantities, in order for the mud flats to maintain their elevation via vertical accretion to keep pace with changes within relative sea level (Hughes, 2004). Halophytic vegetation will then colonise the upper intertidal mud flats where elevation is highest, to create saltmarshes (Foster et al. 2013). As vegetation continues to colonise and raise marsh elevation, new species will also begin to take hold so vegetation develops into successional zonations along the marshes elevation in relation to their salinity tolerances (Roner et al. 2016). The marsh will also be dissected by a network of branching tidal creeks, which supply fresh sediment to the marsh and saltpans and facilitate drainage (Foster et al. 2013). Saltmarshes are responsive to environmental changes, for instance sea-level changes, salinity, species invasion and other disturbances, which can all effect the system and vegetation zonation (Tanner et al. 2010).

Saltmarshes provide many important services for humans as well as many other species and organisms. One of the services they provide humans is the ability to act as a natural sea defence against flooding. If in enough abundance, marsh vegetation is able to prevent significant coastal flooding by attenuating the wave height and energy so reducing the ability of the waves to move inland (Foster et al. 2013). They also provide important habitats for species of vegetation, birds and mammals (Chmura, 2013). Marshes are considered particularly important for many species of migratory or over-wintering birds and waterfowl. These birds rely on marsh habitats for food, nesting and roosting before migrating back in the spring (Foster et al. 2013). However, most importantly saltmarshes are one of the most important environments on Earth in relation to blue carbon burial and the global carbon cycle (Lau, 2013). Hence, they could potentially provide a vital role for climate change mitigation (DeLaunne and White, 2012; Hopkinson et al. 2012).

1.5 Saltmarshes under threat

Saltmarshes around the world are currently under threat from many issues with the foremost reasons being as a result of sea-level rise and human activities in the form of land reclamation. 25% of lost intertidal areas and estuaries globally can be accounted for via land reclamation (Burden et al. 2013), causing the release of 0.15-1.02 Pg of CO^2 annually. In the Forth Estuary in Scotland, 51% of saltmarsh and mud flat area has been lost over the last 400 years through land reclamation for agriculture and industrial uses (Beaumont et al. 2014). Since the 1800s the UK has seen a 25% loss of its saltmarsh area from landscape conversion for industry, housing and farming. This is leading to ancient carbon stocks that have been buried for a long time, to begin to enter the atmosphere as CO^2 (Macreadie at al. 2013). It is estimated that there will be a further loss of 30-40% of global saltmarsh area within the next 00 years if the current rates of loss are maintained (Pendleton et al. 2013).

Sea-level rise is probably the biggest problem faced by saltmarshes in the future. Rising sea-levels and the reduced availability of sediment will be a key issue in the drowning and disappearance of saltmarshes globally, if marsh elevations are unable to keep pace with rises (Hopkinson et al. 2012; Roner et al. 2016). Although, Kirwan and Mudd (2012) suggest if there are only moderate rates of sea-level rises coupled with increases of CO^2 and temperature increases, this will lead to increases of plant productivity and therefore accretion. This would enable the marsh to survive sea-level rise. However, the majority of models predict that if a rise in sea level of over 1 m occurs by 2100, even marshes that have survived past sea-level rise will end up submerged or undergo productivity losses (Horton et al. 2018). Sustainable coastal management principles aim to encourage natural processes, and as such, restoration of coastal marshland has become a national priority, driven by government policy incentives such as ‘making space for water’. This is a UK government initiative set up by the Department of Environment, Food and Rural Affairs (DEFRA), and provides some mitigation for saltmarsh lost due to erosion and climate change processes, but also has potential to offset carbon emissions by carbon burial in the sediment. There is therefore an urgent need to improve understanding of carbon flux in and out of coastal wetlands by collecting spatially detailed baseline information from saltmarshes.

1.6 Aims and objectives

The aim of this study is to investigate the spatial distribution of organic carbon in surface saltmarsh sediments and the controls surrounding organic carbon distribution within contrasting saltmarsh sub environments.

In order to achieve this the main objectives for this study are;

1. Define the different saltmarsh vegetation zones with the use of high-resolution spatial analysis from GIS and field mapping.
2. Assess the spatial distributions of organic carbon throughout the marsh, and the relationship with environmental variables (including conductivity, grain size, organic content).
3. Define the relationship between organic carbon and elevation in relation to tidal inundation from the use of sediment conductivity.

Chapter 2- Literature review

2.1 Carbon sequestration in saltmarshes

There is little understanding of the way that carbon is stored and the factors surrounding its sequestration within individual saltmarsh sub-environments (Lovelock et al. 2014). To date the processes involved in the storage and preservation of organic carbon and matter are well-known, but how individual environments within saltmarshes such as high and low marsh store carbon relative to each other are not. Each environment is thought to have different potential and capacity to sequester and store organic carbon. Yet, saltmarshes are thought to be more productive than tropical rainforests, with carbon sequestration rates being ~55 times faster, and capacity to store this carbon for up to a millennium if left undisturbed, compared to just decades in rainforests (Howe et al. 2009; Lau et al. 2013). The initial global estimate of the total amount of carbon stored by saltmarshes is suggested to be around 87.2 $\pm$ 9.6 Tg C yr^{-1}, significantly higher than rainforests (53 $\pm$ 9.6 Tg C yr^{-1}) (Macreadie at al. 2013). This estimate of carbon burial in saltmarshes may not be applicable globally due to variations within coastal wetlands, which differ with climate. The majority of studies are of North American and Southern Canadian saltmarshes. These marshes have different environmental characteristics resulting in different sequestration rates in comparison with Northern European marshes. North American and Southern Canadian marshes accumulate sediment under different climatic conditions resulting in differences of vegetation and sedimentation patterns. (Beaumont et al. 2014; Bouchard and Lefeuvre, 2000). This potentially could affect the preservation of organic matter and consequently carbon sequestration. For instance, North American and Southern Canadian saltmarshes typically tend to be organic rich with more acidic peaty soils, which helps to preserve organic matter. By comparison, UK marshes tend to be more mineral rich indicating that they are not as good at preserving organic matter than North American and Southern Canadian marshes (Allen, 2000). This suggests that the initial global carbon burial estimates may be too high if European saltmarshes are in fact storing less carbon.

2.2 Organic matter and organic carbon preservation in saltmarshes

Marsh zonation is an integral aspect of every saltmarsh, as zone margins are the transition zone between different vegetation species, which are a function of elevation within the tidal frame (Roner et al. 2016). Saltmarshes receive organic matter from two main sources, autochthonous and allochthonous. Autochthonous sources are derived from *in-situ* sources such as saltmarsh vegetation. Allochthonous sources are derived from organic material being transported from elsewhere, by rivers or ocean (Lamb et al. 2006). The majority of organic matter found within saltmarshes comes from the colonising vegetation in the marsh. Vegetation sequesters organic carbon via fixing atmospheric carbon through photosynthesis and storage as plant biomass (Hedges and Keil, 1995; Owers et al. 2016). When the plant dies some of this carbon is subsequently stored within the marsh sediments for extensive time periods until broken down by microbes (Allen, 2000; Day et al. 2008; Macreadie et al. 2013) and aided by oxygen via aerobic decomposition. This decomposition occurs slowly once buried due to less oxygen penetrating the waterlogged sediments (Elsey-Quirk et al. 2011). The accumulation of organic matter is dependent upon the balance between the production and decomposition of below ground biomass as well as the import/export of above ground biomass which is determined by the hydrological regime (Ougang et al. 2017).

2.3 Previous studies

There have been a number of studies investigating carbon sequestration and spatial distribution of carbon throughout wetlands. A similar study to this research project was undertaken by Roner et al. (2016) who conducted a study on the Venice lagoon, Italy on two saltmarsh sites (San Felice and Riga). Thirty three samples were collected over three 40 m transects. Two of the transects were in San Felice saltmarsh and one was in Riga saltmarsh. Both of the study sites started along the marsh edge close to the main channel and finished close to an inner creek. Roner et al. (2016) found over the two sites there was an average soil density of 0.044 g C cm^{-3} with an average accumulation rate of 132 g C m^{-2} y^{-1}. This study gave a good indication of carbon storage in different saltmarshes, however, the transects did not sample different zones across the marsh. Only the tidal creek area was sampled. High marsh was not sampled, which is where the highest values of carbon would be expected. Other spatial sampling features such as elevation data was collected but vegetation cover change were not measured. These are important aspects of spatial carbon burial within saltmarshes.

A number of different studies have been carried out on North American and Southern Canadian saltmarshes. Connor et al. (2001) researched saltmarshes within the Bay of Fundy in New Brunswick, Canada. They found that carbon densities for the marsh ranged from 0.009 to 0.055 g C m^{-3}, with the highest values located within high marsh and the lowest values within low marsh. Carbon accumulation rates for the surface where calculated as 95 g m^{-2} yr^{-1}. Ardenne (2018) carried out a similar study. They investigated two marshes in the Gulf of St. Lawrence, Canada and one marsh on the Southern coast of Maine, USA. Cores where taken along transects from upland (high marsh) towards the seawards edge (Low marsh), with spacing intervals to reflect the marsh geomorphology. Average carbon stocks within all three of the marshes was calculated as being 26.13 $\pm$ 17 kg C m^{-2} which is higher than the global average of 16.2 kg C m^{-2}. This high average was pushed up from the high values found at the USA Maine marsh (51.4 $\pm$ 30.3 kg C m^{-2}) in comparison to the St. Lawrence

Canadian marshes. Their results show that carbon density averages should not be used to estimate regional carbon values due to the individuality of individual saltmarshes. If resources allow sampling of individual marshes, then this approach should be taken.

Zhou et al. (2007) researched the spatial variability of elements within a saltmarsh including carbon. The study was carried out on a saltmarsh on the eastern coast of Chongming Island, China. Fifteen surface samples at a depth between (0 and 5 cm) were collected for one wet season and one dry season on the marsh. Additionally three core samples were collected at the high, low and unvegetated flats within the marsh, these cores where collected away from tidal creeks in order to prevent tidal influence. Average total carbon ranged from 0.1-0.7% with the core samples being 0.54% (high marsh), 0.2% (low marsh) and 0.17% (unvegetated flats). Annual carbon accumulation rates for the whole marsh were calculated between 1.1 and 1.5 $x10^{10}$ g C yr^{-1}. Using similar methodology Owers et al. (2016) looked at the spatial variability of carbon storage of the Currambene Creek, Jervis Bay, Australia. A total of twelve sediment cores were taken; each core sample location was selected in order to capture the spatial variability of vegetation structure. This included position in the landscape and changes within environmental gradients such as elevation. From these cores, it was estimated that for the upper 30 m, soil carbon density was 3933 $\pm$ 444 Mg C. These studies are useful in looking at the spatial distribution of carbon throughout the marsh in relation to marsh zonation and features. By not sampling linear transect changes from high to low marsh, changes in relation to vegetation cover change or elevation changes cannot be seen. Even though elevation was not a useful component for these studies, it is important in relation to carbon burial in saltmarshes when using a linear transect.

Chapter 3- Study site

Biggar Saltmarsh *(Figure 3.1)* was the selected marsh for this study. Biggar is situated on Walney Island west of Barrow-in-Furness on the north side of Morecambe Bay (Northwest England). The bay is situated on the eastern coast of the Irish Sea, between the Lake District to the north and the Fylde Peninsula to the south. The bay is a macro-tidal embayment and is the largest intertidal area in Britain with an area estimated to be 34339 ha in 1999 (Mason et al. 1999; 2010). The bay is shallow, with 68% of the area comprised of intertidal sand and mud banks with the remainder of the area consisting of saltmarsh (Sloan and Aldridge, 1981). Four main rivers feed into the bay; the Kent and Leven to the North and the Wyre and Lune in the South (Thornhill et al. 2012). Morecambe Bay has mean high water springs of 4.6 m (Newlyn, Ordnance Datum) with low springs of -3.6 m. The tidal ranges vary within the Bay due to its size and configuration. The Bay can be classified as tide-dominated with wave heights of only around 0.5m for 75% of the year. The bay is exposed to prevailing winds from the Irish Sea, but due to sheltering, the fetch of the waves is limited, causing the small waves seen (Mason et al. 1999).

This location was selected as the area is relatively mature marsh, and also because the area has been used previously in other sedimentary studies (Rahman et al, 2013). The marsh was well-suited to addressing the aims of this study, having a gently seawards sloping gradient, clearly defined vegetation zones and contrasting marsh sub-environments (e.g. creeks, pans etc). The mean spring tidal range was reported as 8.15 m (Rahman et al. 2013). Whilst aspects of the marsh appear relatively pristine, there is a road adjacent to the high marsh which may impact marsh hydrology and environmental conditions, and also truncates the upper boundary, preventing any inland roll-over.

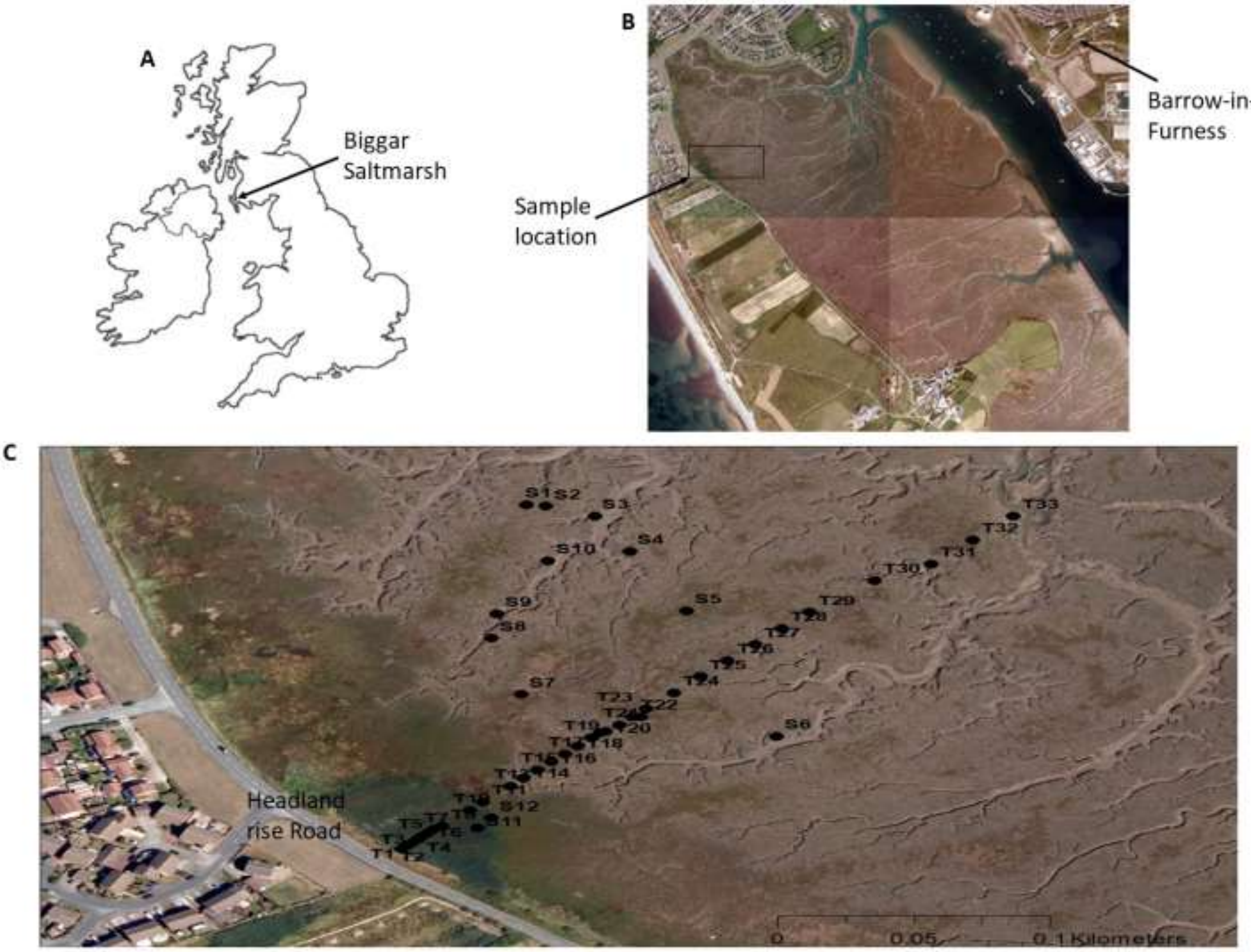

Figure 3.1: Location maps of Biggar Saltmarsh including: The location of Biggar Saltmarsh in the UK (A), Aerial map of Biggar Saltmarsh with sample location within the marsh (B) and the sample locations within the sampling site within Biggar Saltmarsh (C).

Chapter 4- Methodology

4.1 Field methods

Thirty-three surface (approximately 0-3 cm depth) sediment samples were collected from the initial top organic layer of the marsh in order to sample recent cumulative deposition or changes within the marsh where erosion is occurring at the surface rather than sediment deposition (Horton et al. 2006). Two spatial sampling strategies where adapted; First, samples were collected along a 210 m linear transect across the different vegetation zones of the marsh *(Figure 2.1)*. This transect covered the main marsh sub environments from high to low marsh and was employed to link organic carbon values with elevation and distance from the highest point. This is a commonly applied sampling strategy used in other studies of saltmarshes, to effectively capture the range of sub-environments along an environmental gradient such as Roner et al. (2016). Sampling intervals were designed to effectively capture all marsh zones as defined by vegetation change. Hence, the narrow *Phragmites australis* (approximately 90 m width) dominated high marsh was sampled every 5 m, then sample spacing increased to every 10 m and 15 m as the vegetation cover changed and different species became more widespread from each other. The change in distance between each sample was varied to ensure each vegetation zone along the marsh was sampled.

Samples were also collected randomly away from the transect in order to limit problems with spatial auto-correlation within the analysis to limit instance independence and dependencies within the data, and to capture features of the marsh such as areas of vegetation change and around tidal creeks (Roner, 2016). Thirteen of these surface sediment samples were collected. The co-ordinates of each sample were noted in order to plot the locations spatially. *(Figure 3.1)*.

A digital laser total station was used to measure the elevation of each sample collected along the transect and for each of the random samples. This provided a point of elevation relative to the top of the saltmarsh just above the high marsh (assumed to approximate highest astronomical tide). These data points provide a cross sectional transect for the marsh to see the changes in elevation as well as comparing the elevation of the random samples to the transect. The elevation of the sample locations are important in order to link in variables such as tidal inundation (hydroperiod) to elevation and carbon sequestration (Zhou et al. 2007).

A combined sampling strategy (using linear transect and random spatial sampling) method was chosen to overcome the limitations of other studies which typically collect samples randomly thus only targeting specific marsh zones, not the full marsh zonation. For example, Lovelock et al. (2014)

collected three sediment samples from each of the chosen sampling locations. This provides useful baseline data, but is insufficient to take into account different successional zones within the marsh or the full spatial variability in such environments as it does not measure widespread distribution data within the marsh.

4.2 Laboratory

Laboratory geochemical analysis included: loss on ignition (LOI), total organic carbon (TOC), nitrogen (N), inorganic carbon (IC), grain size analysis, soil conductivity and pH. Samples were first dried at room temperature, then ground using a mortar and pestle. Samples were then sieved to 2mm so that they could be analysed for total carbon and grain size.

4.2.1 Grain size analysis

Grain size analysis was completed using laser granulometry (Ryzak, 2011) to determine the different grain sizes (<2mm diameter) present throughout the sediments of the marsh in order to determine their relationship to carbon contents. Testing was carried out following standard procedures as set out by Gray et al. (2010) involving pre-treating samples with hydrogen peroxide (H_2O_2) in order to remove organic material. Approximately 10 g of sediment was used for the analysis. 10 ml of water was used with 10 ml of H_2O_2 for the initial reaction and left overnight. Then a further 15 ml of H_2O_2 was added to the samples and was put on a hot plate until the reaction of the H_2O_2 with the organic matter had finished. A few drops of Calgon (dissolved sodium hexametaphosphate, $Na_6O_{18}P_6$) was added to each sample before analysis to defloccuate the clay particles.

Allen et al. (2004) state that H_2O_2 removes most if not all organic content within a sample. However, samples have an increased reduction in mean and median values in grain size in relation to untreated samples but the mode will see little effect, indicating that there are no real advantages to pre-treating samples unless interested in the mode. On the other hand, Grey and Scott (2010) suggest that H_2O_2 pre-treatment needs to be carried out when samples contain moderate-high levels of organic material. They found textural ratios and measures of central tendency of particle size distributions including mode can be heavily impacted by the presence of organics. For this study digestion was undertaken to avoid potential problems due to the high levels of organics present within all samples (see results). The data obtained by the laser granulometer was analysed through the GRADISTAT program to obtain statistics for grain size statistic (Blott and Pye, 2001).

4.2.2 Carbon

Total organic carbon was measured using the Shimadzu TOC-VSSI solid sample analyser for both sediments and vegetation, as it is one of the most accurate ways of measuring carbon. This is important as a limitation of other studies including Owers et al. (2016); Chmura et al. (2003) and Roner et al. (2016), is that they only estimate the amount of carbon in a sample via the LOI equation (organic carbon = (0.04)LOI + (0.0025)LOI^2). Although, this method does give indicative results, the carbon values are not as precise as those collected from carbon analyser machines. IC was also measured for the sediments using the Shimadzu TOC-VSSI analyser so that a more precise amount of total overall carbon in the marshes could be calculated. As well as helping to identify important correlations with other key features within the marsh such as elevation and grain size. Organic carbon was also determined for sampled vegetation. Vegetation samples collected from the field were frozen so that they could be freeze dried before analysis. Samples were then ground into a powder using an agate mortar and pestle in order to be able to be run through the carbon analyser. Each sample weighed between 30-40 mg.

4.2.3 Loss on ignition

Loss on ignition testing was carried out in order to gain a measure of the amount of organic matter present within the marshes sediment as organic matter provides valuable links with organic carbon burial (Shennan et al. 2015). LOI followed the standard procedures as set out by Konare et al. (2010). Crucibles where weighted empty and then again with the sediment in order to determine the weight of sediment. They were then placed in a 105°C oven overnight for 12 hours and cooled in a desiccator before being reweighed. Samples were then placed in the muffle furnace overnight for 6 hours at 475° and again cooled in a desiccator before being weighed. In order to gain the percentage of organic matter present in each sample this equation was used for each sample: $\%\,Organic\ matter = \frac{\text{mass 105°C} - \text{mass muffle}}{\text{mass 105°C}} \times 100$. However, not all of the sample locations could be tested for LOI due some samples having insufficient sediment to enable testing.

4.2.4 Nitrogen

Nitrogen was measured for both sediment and plant samples on order to try and provide links with organic carbon and to try and understand where organic matter had come from, from the use of molar C/N ratios. Nitrogen was analysed using the Skalar Primax SNC 100-IC-E analyser. Each sample was weighed to between 150-200mg as a minimum sample size necessary for nitrogen detection.

4.2.5 Environmental variables

Environmental variables such as pH and salinity were measured in order to determine if there was any relationship between these and organic matter preservation and organic carbon burial. For the determination of pH, the sampled sediment was mixed into a paste by adding deionised water at a ratio of 1:2.5 for sediment to deionised water. This enabled pH to be measured using paper pH strips .The final test was to test the sediment for salinity. This was measured by the use of a calibrated conductivity probe. The ratio of 1:2.5 had to be changed to 1:5 as the conductivity probe wasn't able to pick up a reading for a 1:2.5 ratio.

4.3 Data analysis

Data obtained from the lab was statistically analysed via SPSS. Shapiro-Wilk normality testing was used due to the sample size being < 50. As the results of the normality test were all normal, Pearson's correlation was used to test for correlations between the variables, with the significance at the 0.05 level. The creek sample was removed from all correlations due to being a sub-environment to the marsh, only the distinguished vegetation zones were relevant. T33 was also removed from all correlations as this was suspected to be an outlier value, due to the values given for this location during analysis. Linear regression was then carried out in order to obtain the R squared values.

In order to acquire molar C/N ratios the equation C/N ratio = (C*14)/(N*12) was used due to this being the standard equation for this calculation (Perdue, 2007). Maps were produced in Arc GIS 10 to show relationships and spatial distributions of variables by carrying out Kriging analysis. Kriging is a geostatistical tool which enables the spatial interpolation of results to predict values of unknown points based on statistical likelihood from known values (Kumar, 2007). This data is then plotted spatially to predict carbon distribution and other variables across the site. The areas within the predicted map surface which do not have any data points could not be clipped, this would have been desirable.

Elevation data were collected in the field relative to each other and then adjusted to more realistic values that have been based off local tidal levels obtained from local tide gauge data. The highest marsh vegetation limit within the *Phragmites australis* zone of the marsh was used as the mean high water spring tide (MHWS)/ highest astronomical tide (HAT) boundary. The highest astronomical spring tide value was used from Heysham tide gauge for the 28th April 2017 as this was the closest date for when field work was carried out (http://www.ntslf.org/tides/hilo?port=Heysham). However, this data was chart datum, so was adjusted into Ordnance Datum by subtracting 4.9 from the Heysham tide gauge data in order to convert the values from chart datum into ordnance datum (http://www.ntslf.org/tides/datum).

Chapter 5- Results

This chapter displays all of the analysed data collected from Biggar Saltmarsh. The results are split into multiple sections consisting of marsh morphology, sedimentology, environmental data, organic geochemistry and statistical processing.

5.1 Morphology

Figure 5.1 illustrates the three different marsh zones along the transect, with the dominant vegetation species present within each of the marsh zones. The marsh zones have been established as zone 1, being high marsh, zone 2 as middle marsh and zone 3 as lower marsh. Elevation change appears as a large fall from the beginning to the end of the transect, although the change in total elevation is only 1m excluding the tidal creek. Zone 1 has the sharpest decline in elevation, falling from 5.42 m to 5.09 m over 12 m. This area is the only area within the marsh where *Phragmites australis* occurs. Zone 2 extends over a 68m, where elevation falls from 5.09 m to 4.63 m. After the tidal creek lower marsh (zone 3) extends for 130 m where the marsh elevation falls from 4.63 m to 4.52 m, at 150 m there is a sudden fall and rise in elevation from 4.5 m to 4.4 m as it is on the edge of a tidal creek.

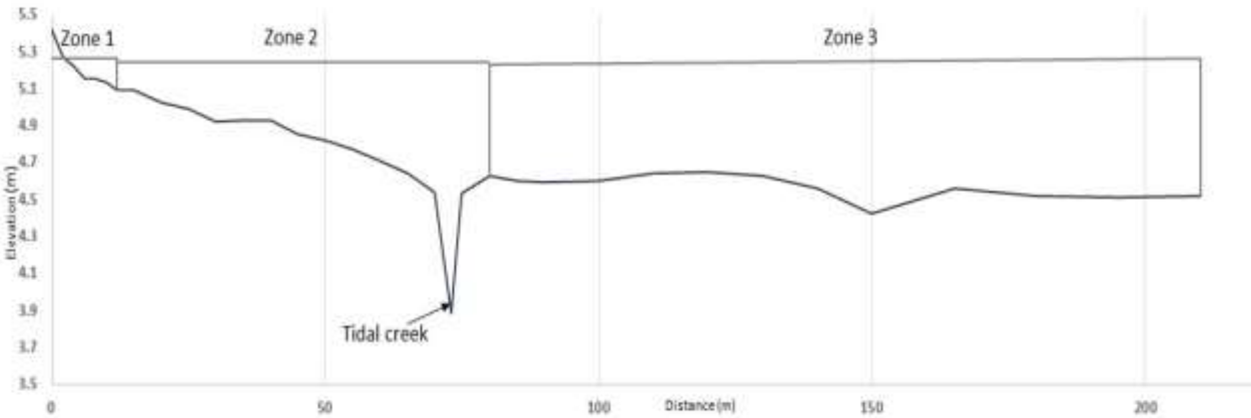

Figure 5.1: Elevation (relative to tide gauge data) transect of the Biggar Marsh with corresponding marsh zonations with vegetation present within each of the marsh zones defined as; Zone 1 (0-12 m): Phragmites australis. Zone 2 (12-80 m): Limonium, Triglochin maritima, Puccinellia sp., Carex salina. Zone 3 (80-210 m): Halimilone portulacoides, Armeira maritima, Spartina alterniflora, Plantago maritima.

5.2 Sedimentology

5.2.1 Grain size

Mean grain size has been used as an approximation for the coarseness of the sediments at Biggar Saltmarsh. *Figure 5.2* shows the variation in mean grain size against distance along the sampled transect from high to low marsh. The results for mean grain size range from 5.6 µm to 20.48 µm *(Table 1)* in the high marsh (zone 1), 7.0 µm to 22.1 µm in the middle marsh (zone 2) and from 8.44 µm to 19.04 µm in the low marsh (zone 3). The largest mean grain sizes occur at distinct peaks at 55, 65 and 140 meters where values reach 9.46 µm, 22.1 µm and 19.04 µm in the silt size fraction. This peak at 65 m coincides with a location close to a tidal creek *(Figure 5.1)*.

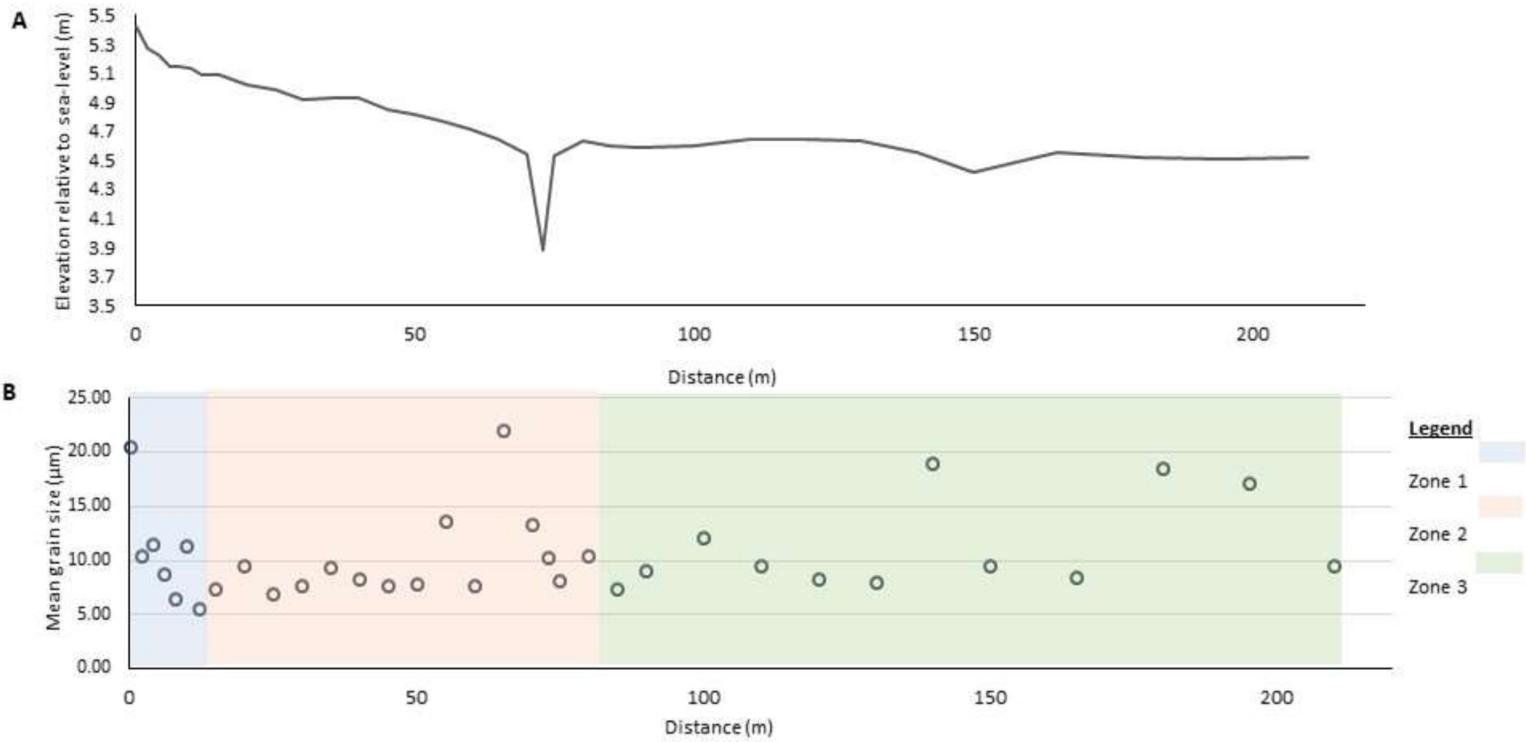

Figure 5.2: Biggar Saltmarsh elevation (A) in relation to mean grain size over distance (B) with shaded vegetation zones.

Millimeters (mm)		Micrometers (μm)	Phi (φ)	Wentworth size class	
	4096		-12.0	Boulder	Gravel
	256		-8.0	Cobble	Gravel
	64		-6.0	Pebble	Gravel
	4		-2.0	Granule	Gravel
	2.00		-1.0	Very coarse sand	Sand
	1.00		0.0	Coarse sand	Sand
1/2	0.50	500	1.0	Medium sand	Sand
1/4	0.25	250	2.0	Fine sand	Sand
1/8	0.125	125	3.0	Very fine sand	Sand
1/16	0.0625	63	4.0	Coarse silt	Silt
1/32	0.031	31	5.0	Medium silt	Silt
1/64	0.0156	15.6	6.0	Fine silt	Silt
1/128	0.0078	7.8	7.0	Very fine silt	Silt
1/256	0.0039	3.9	8.0	Clay	Mud
	0.00006	0.06	14.0		

Table 1: Went Worth grain size classification. Table obtained from (http://www.planetary.org/multimedia/space-images/charts/wentworth-1922-grain-size.html)

There does not appear to be much of a spatial trend in grain size distribution *(Figure 5.3).* Grain size is predominantly within the range of 6.5-6.9 µm *(Table 1)* for the majority of the marsh, this range is the same for the areas of the marsh dominated by tidal creeks. There is an area within the high marsh that has values of 7-7.1 µm. This area is on the edge of the *Phragmites australis* adjacent to the tidal creek systems.

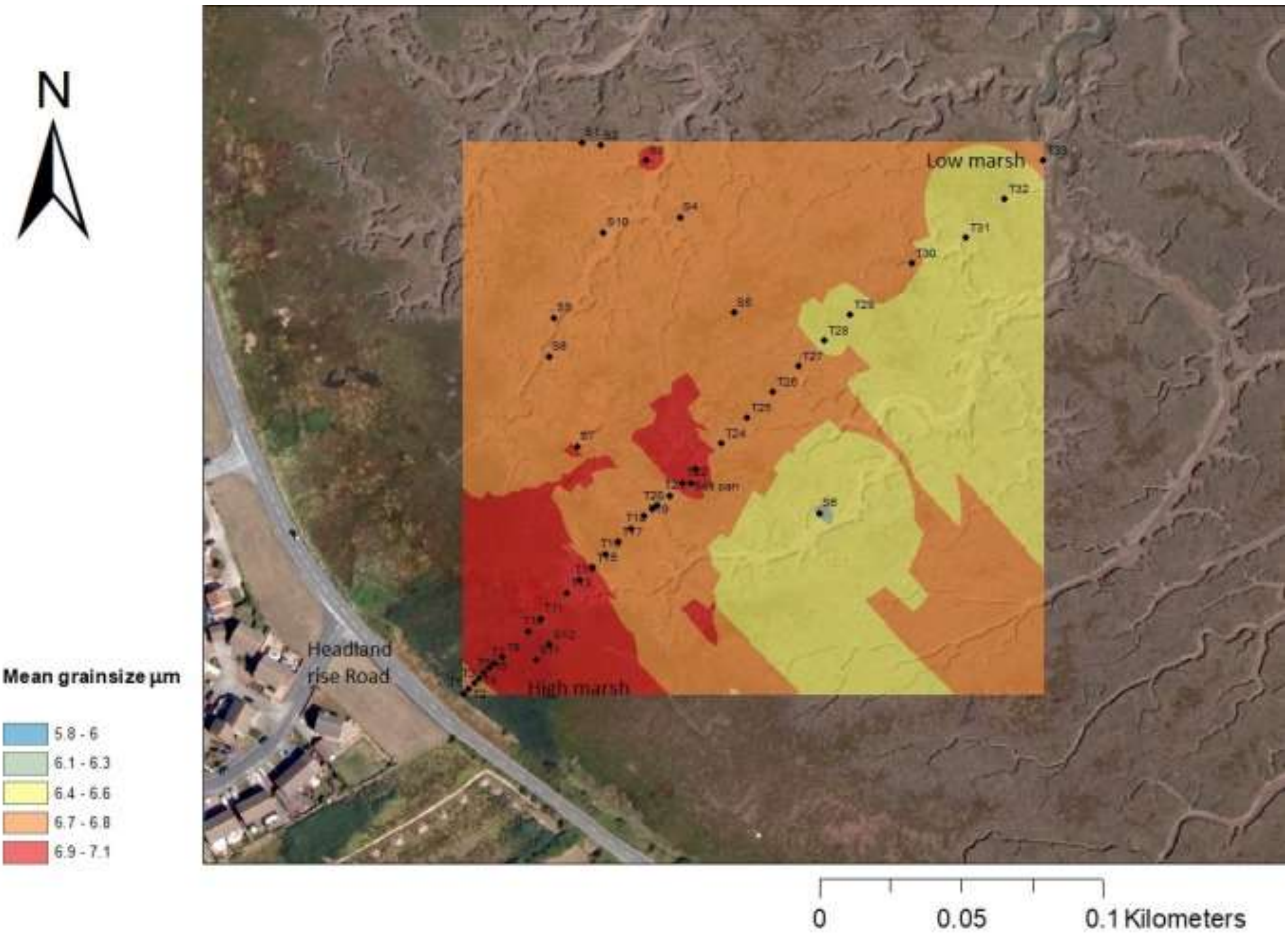

Figure 5.3: Spatial distribution of grain size throughout the sampled area of Biggar Saltmarsh. Map created via Kriging in Arc GIS 10 using both transect and spatial sampling data.

The sediment in the Biggar Saltmarsh mostly consists of very coarse to medium silt *(Figure 5.4)* making up between 50-70% of the sediment. Very fine sand and clay does not appear to make up a significant proportion of the sediment, with the majority of the marsh not containing any fine sand. Apart from very coarse to medium silt, the very fine sand contributes a maximum of 10% in samples at 65 m, 140 m and 180-195 m. This coincides with proximity to tidal creeks and vegetation cover change *(Figure 5.1)*.

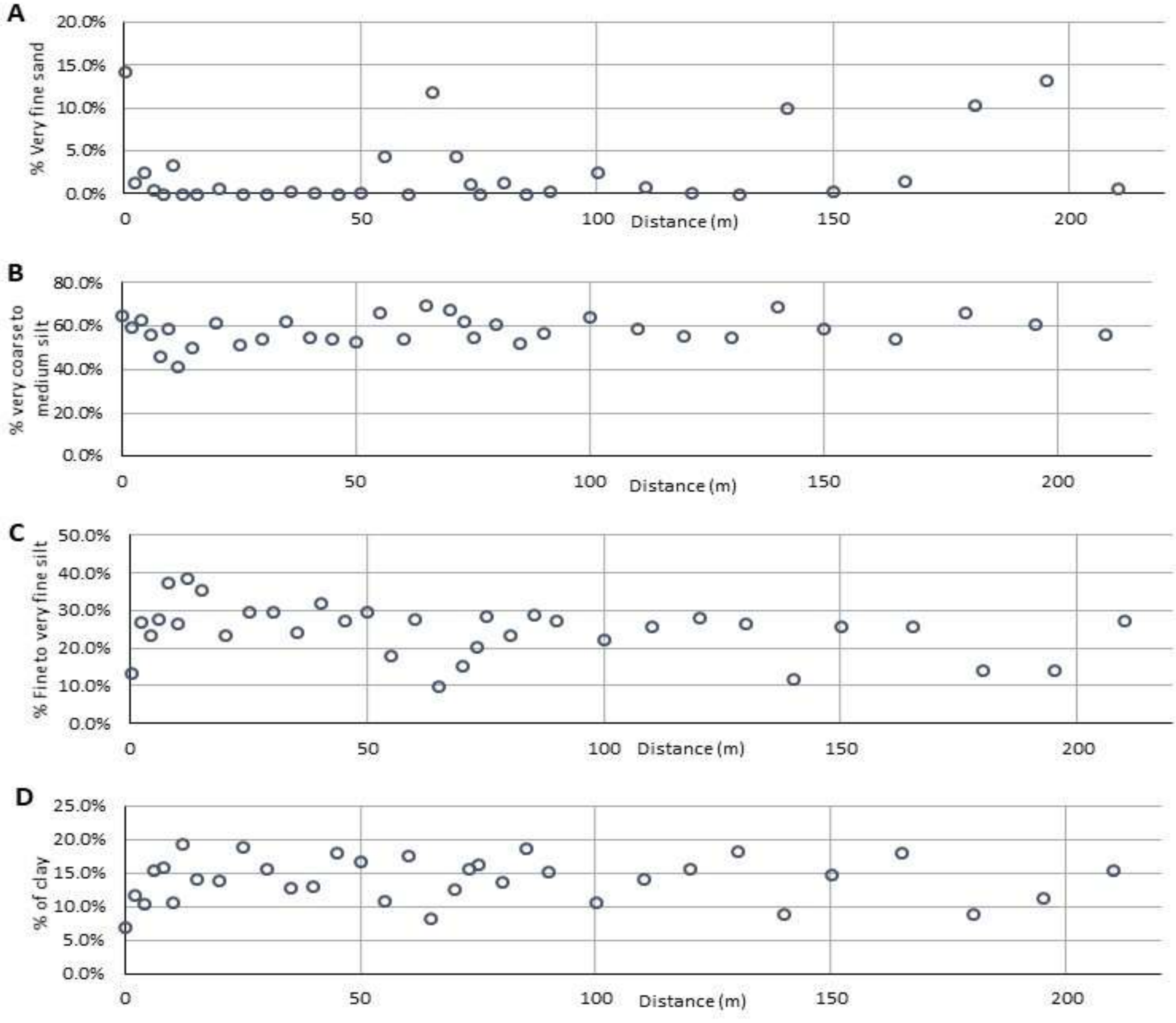

Figure 5.4: Comparison of the percentage of sediment from different grainsize fractions over distance. A is percentage of very fine sand. B is the percentage of very coarse to medium silt. C is the percentage of fine to very fine silt and D is the percentage of clay.

5.2.2 Correlations

To establish whether elevation exerted any control over mean grain size variability, a Pearson's correlation was undertaken to determine the significance of any relationship after normality testing. *Figure 5.5* shows there is some correlation between mean grain size and elevation. There is a weak negative correlation between mean grain size and elevation r = -0.158, $p > 0.05$ with $R^2 = 0.02$.

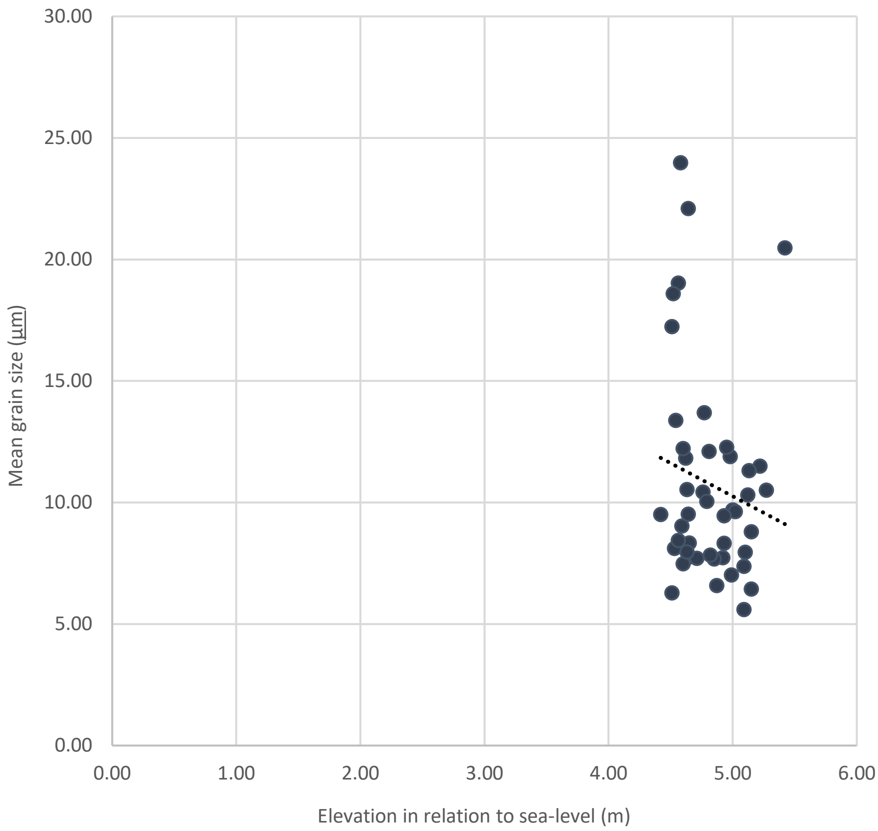

Figure 5.5: Correlation between elevation and mean grain size. r = -0.1158, $p > 0.05$ with $R^2 = 0.02$. Creek sample was removed from correlation due to being a sub environment to the marsh as well as T33 as this is an outlier value.

To determine if there was any correlation between mean grain size and distance along the transect a Pearson's correlation was carried out after normality testing *(Figure 5.6)*. There does not appear to be any correlation between mean grain size and distance, $r = 0.291$, $p > 0.05$ with $R^2 = 0.08$.

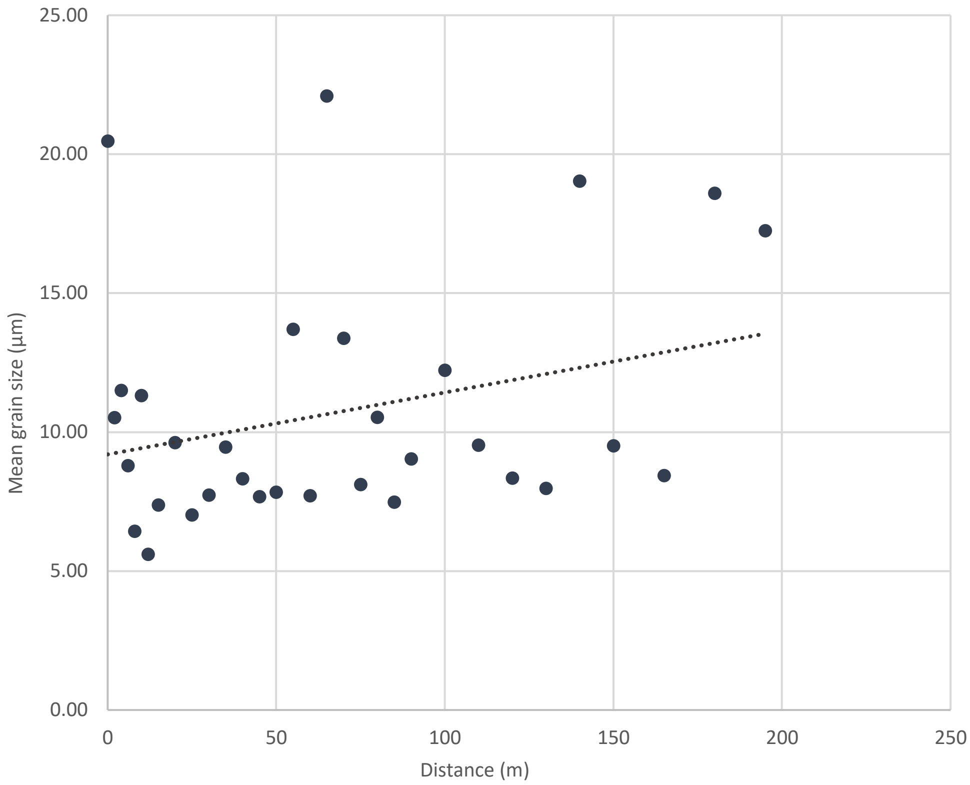

Figure 5.6: Correlation between distance and mean grain size. $r = 0.291$, $p > 0.05$ with $R^2 = 0.08$. Creek sample was removed from correlation due to being a sub environment to the marsh as well as T33 as this is an outlier value.

5.3 Environmental data

5.3.1 Conductivity

Figure 5.7 shows conductivity change from high to low marsh in relation to marsh elevation. Conductivity increases from high to low marsh, with high marsh values as low as 0.35 ms in comparison to low marsh having values up to 10.34 ms. There appears to be a relation between conductivity and elevation. When elevation decreases the conductivity increases. The conductivity of the sediment also increases within the tidal creek *(Figure 5.1)* seen at 73 m increasing from 9.2 ms up to 16.2 ms. Conductivity falls at 150 m meters from 14.05 ms to 9.15 ms when there is a light dip in elevation.

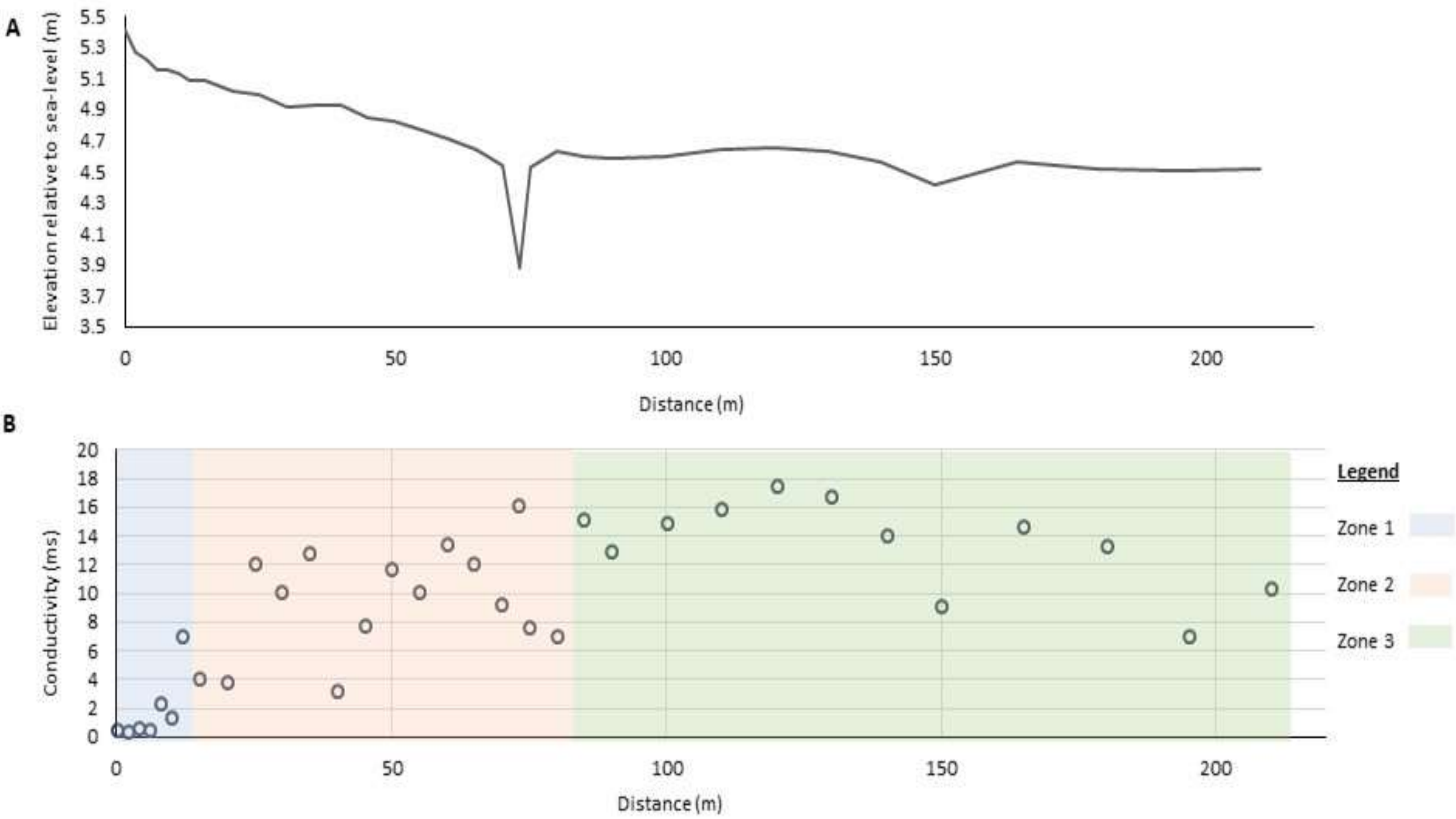

Figure 5.7: Biggar Saltmarsh elevation (A) in relation to conductivity of dry sediment (B with shaded vegetation zones).

There is a rise in conductivity from high to low marsh *(Figure 5.8)*, conductivity ranges from 0.53-2.2 ms in the high marsh to values of 9-11 ms in the low marsh. The highest conductivity values appear to be concentrated around the tidal creeks with values ranging from 12-16 ms in this area of the marsh. The lowest values of conductivity are within the *Phragmites australis* vegetated area of the marsh (0.53-5.5 ms) where there are no tidal creek influence.

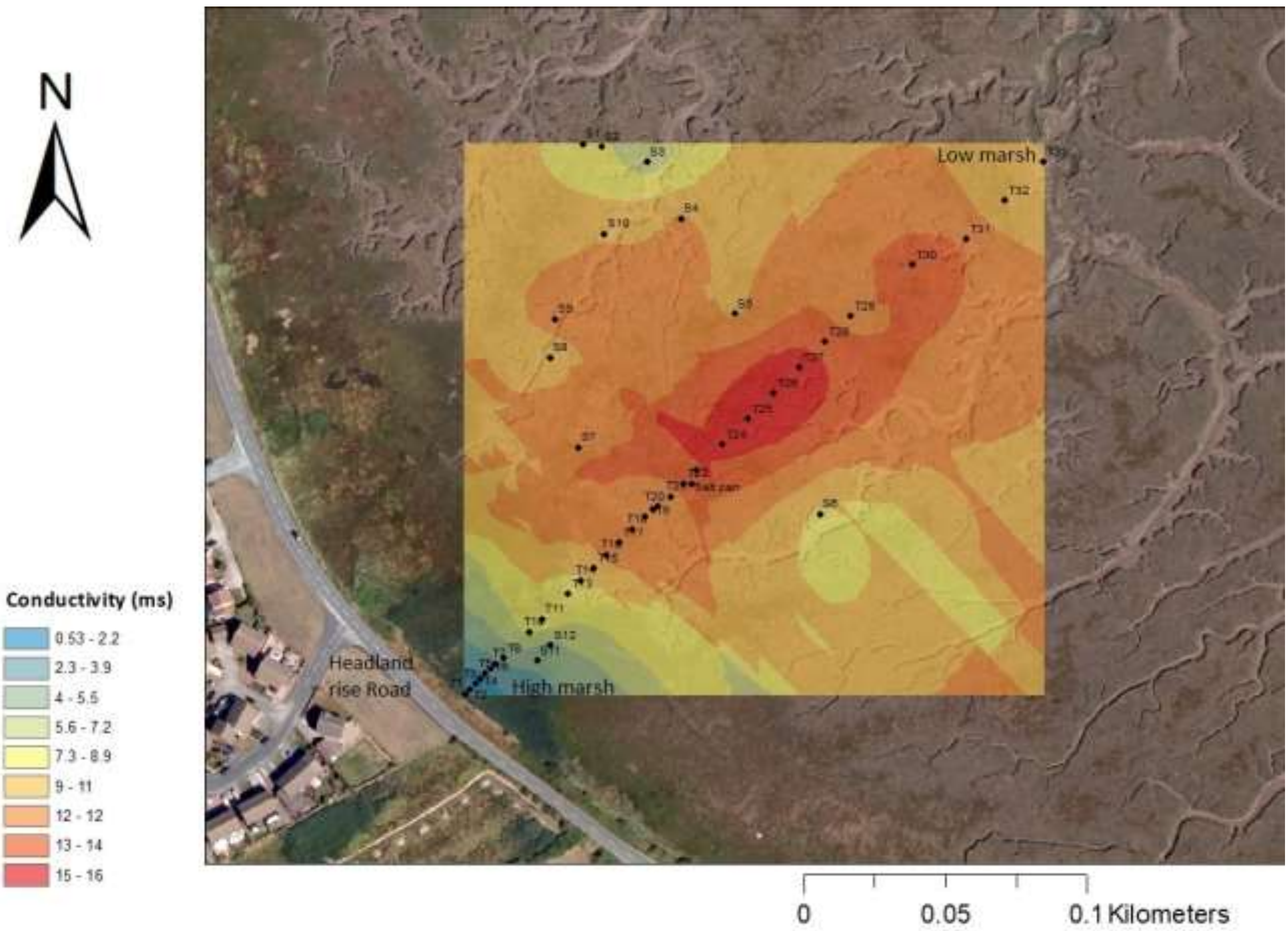

Figure 5.8: Spatial distribution of salinity to dry sediment throughout the sampled area of Biggar Saltmarsh. Map created via Kriging in Arc GIS 10 using both the transect and spatial sampling data.

5.3.2 pH

The pH of the marsh has a small range between 5.5 and 7 *(Figure 5.9).* There is a slight increase in pH from the start of the transect to the end, ranging from more acidic in the high marsh of 5.3, up to neutral (7) at the end of the transect. The tidal creek (73 m) also sees an increase of pH to 7 as well as the area surrounding the tidal creek *(Figure 5.1)*. The areas of the marsh adjacent to the tidal creeks are a dominant part of the sample area (high-initial/middle marsh) which have a pH range or 5.3-6.2 *(Figure 5.10)*. After this, the pH increases to 6.3-6.8 around the tidal creek systems.

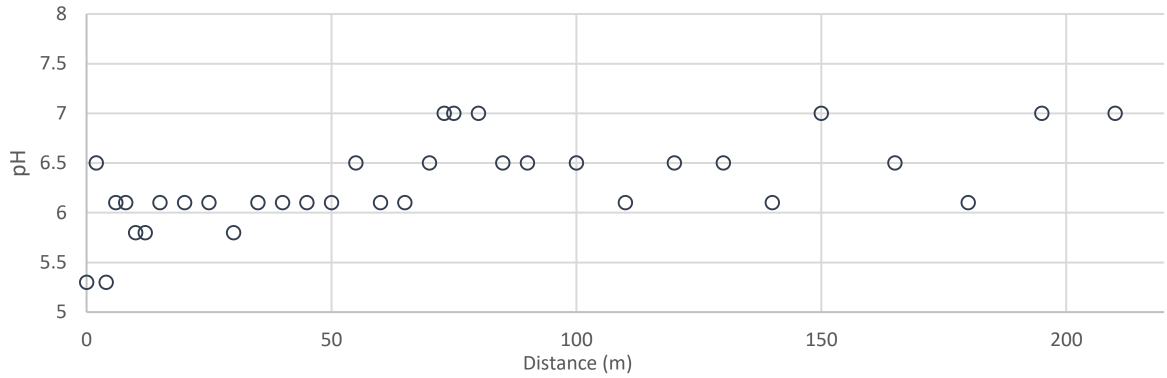

Figure 5.9: pH change of dry sediment over distance.

Figure 5.10: Spatial distribution of pH to dry sediment throughout the sampled area of Biggar Saltmarsh. Map created via Kriging in Arc GIS 10 using both the transect and spatial sampling data.

5.3.3 Correlations

After normality tests a Pearson's correlation was calculated for elevation and conductivity. The results in *(Figure 5.11)* show there is a negative correlation between elevation and conductivity r = -0.719, $p < 0.05$ with $R^2 = 0.52$.

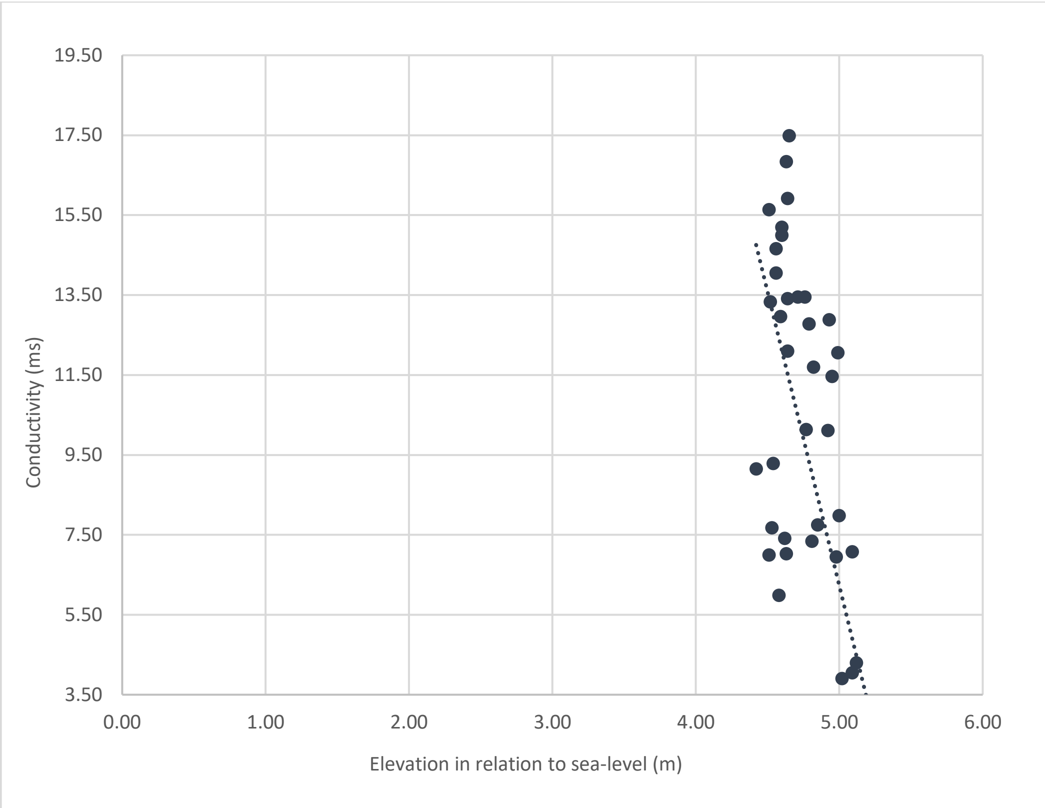

Figure 5.11: Correlation between elevation conductivity of dry sediment. r = -0.719, $p < 0.05$ with $R^2 = 0.52$. Creek sample was removed from correlation due to being a sub environment to the marsh as well as T33 as this is an outlier value.

5.4 Organic geochemistry

5.4.1 Organic matter

Organic matter decreases from high to low marsh, *(Figure 5.12)* with high marsh having values of up to 49% and low marsh having values as low as 8%. A data gap exists between 15 and 40 m due to insufficient sample. There is a spike of organic matter at 55 m from 20% up to 41% and then back down to 18%. This is the location on the transect where there is a vegetation cover change with the main dominating species being *Limonium* and *Halimione portulacoides (Figure 5.1)*. Organic matter appears to follow a similar trend as elevation. As elevation decreases so does the amount of organic matter. This is evident at 73 m within the tidal creek as organic matter drops down to 8%. This is also evident within the tidal creek area at 90 m, where the amount of organic matter drops down to 12% from 16%.

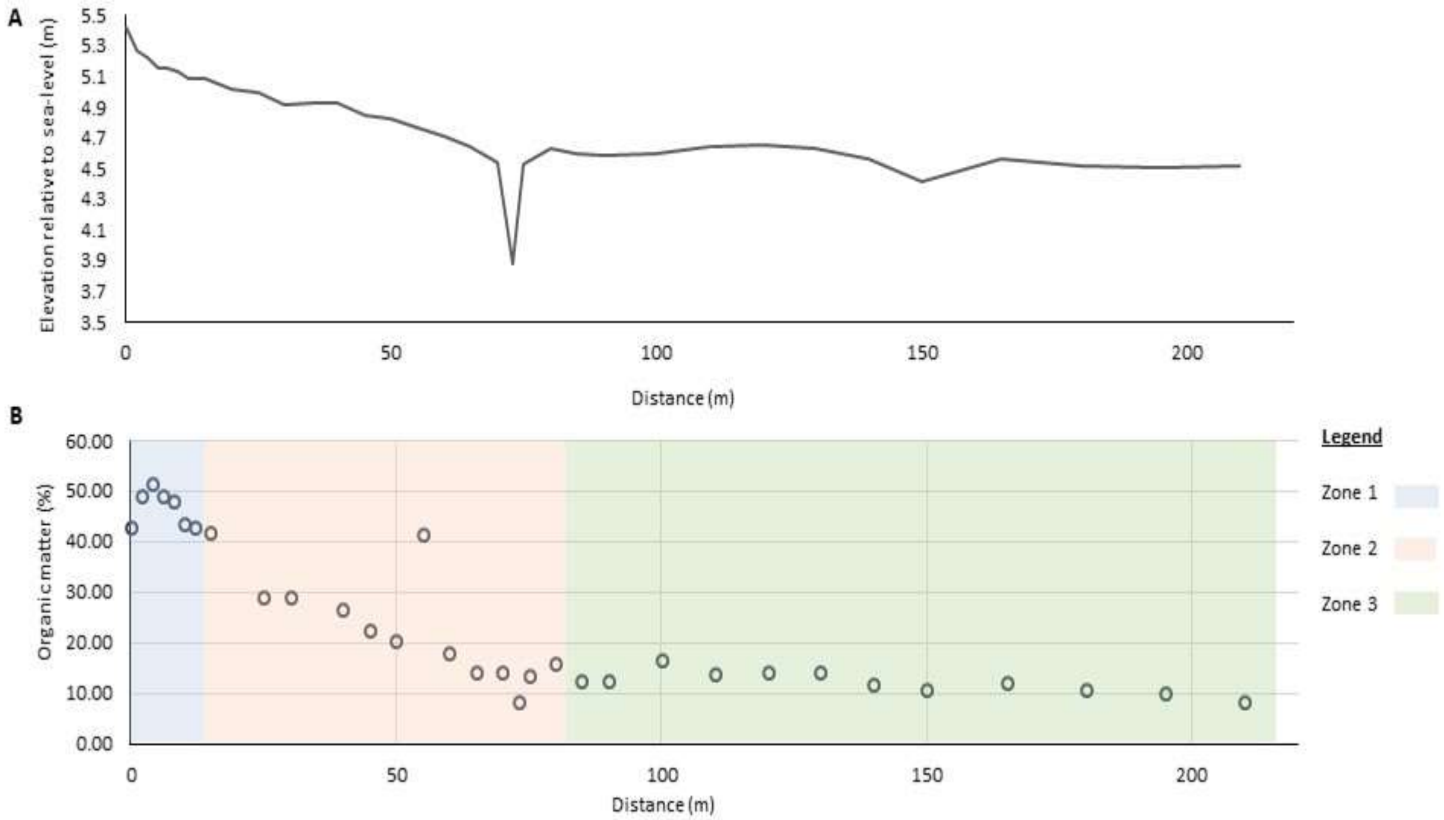

Figure 5.12: Biggar Saltmarsh elevation (A) in relation to % organic matter of dry sediment (B) with shaded vegetation zones.

Figure 5.13 shows a decreasing trend in organic matter from high to low marsh, with high marsh sediment having a range of up to 47% organic matter and the low marsh having a range down to 9.1%. There are samples that are characterised by certain vegetation such as *Phragmites australis,* where organic matter is at its highest ranging from 32-47% *(Figure 5.1).* Low values are around tidal creeks which range from 11-14%.

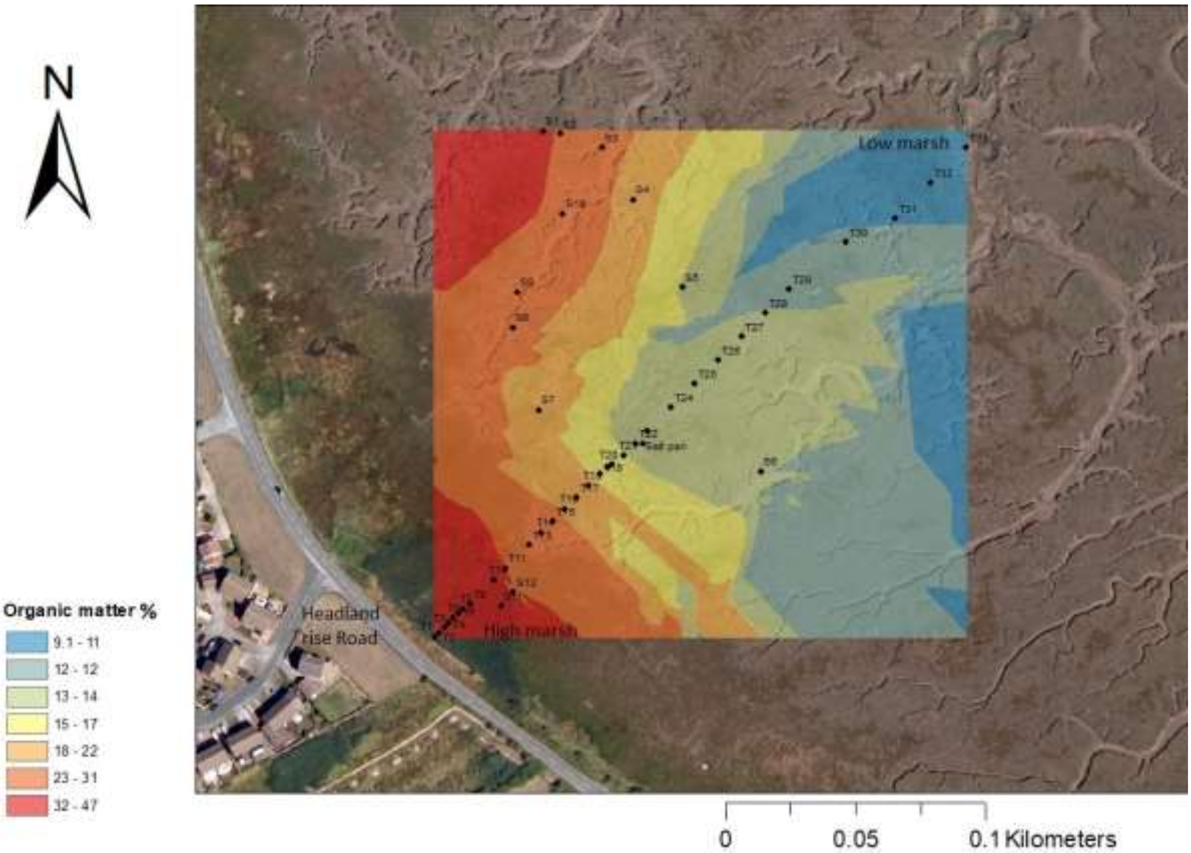

Figure 5.13: Spatial distribution of % organic matter of dry sediment throughout the sampled area on Biggar saltmarsh. Map created via Kriging in Arc GIS 10 using both the transect and spatial sampling data.

5.4.2 Total organic carbon

Organic carbon *(Figure 5.14)* decreases from high to low elevation, with the highest elevations having organic carbon values of up to 26.6% and lowest elevations having organic carbon values of 3.5%. The biggest change in organic carbon values occurs initially in the high elevations of the marsh as there is a sharp decrease from 23.7% down to 8.7% between 10 m to 45 m along the transect. This drop is in the area of the marsh changing from a *Phragmites australis* dominated area into a mixed zone, with of *Triglochin maritima* and *Carex salina (Figure 5.1).* The drop at 45 m from 8.7% down to 3% at 55 m is also in a zone of vegetation change with dominant vegetation species being *Limonium* and *Puccinellia*. Organic carbon decreases adjacent to tidal creeks, at 73 m. Organic carbon decreases to 2.6% from 5% in the tidal creek *(Figure 5.1)*. This can also be seen at 55 m in an area characterised by tidal creeks. Organic carbon decreases from 8% to 5%, but then increases back up to 6.5% after the creek area. 90 m also sees this trend of decreases of organic carbon with tidal creek proximity. Organic carbon drops to 4.5% from 6% then increasing up to 6.6% at 100 m.

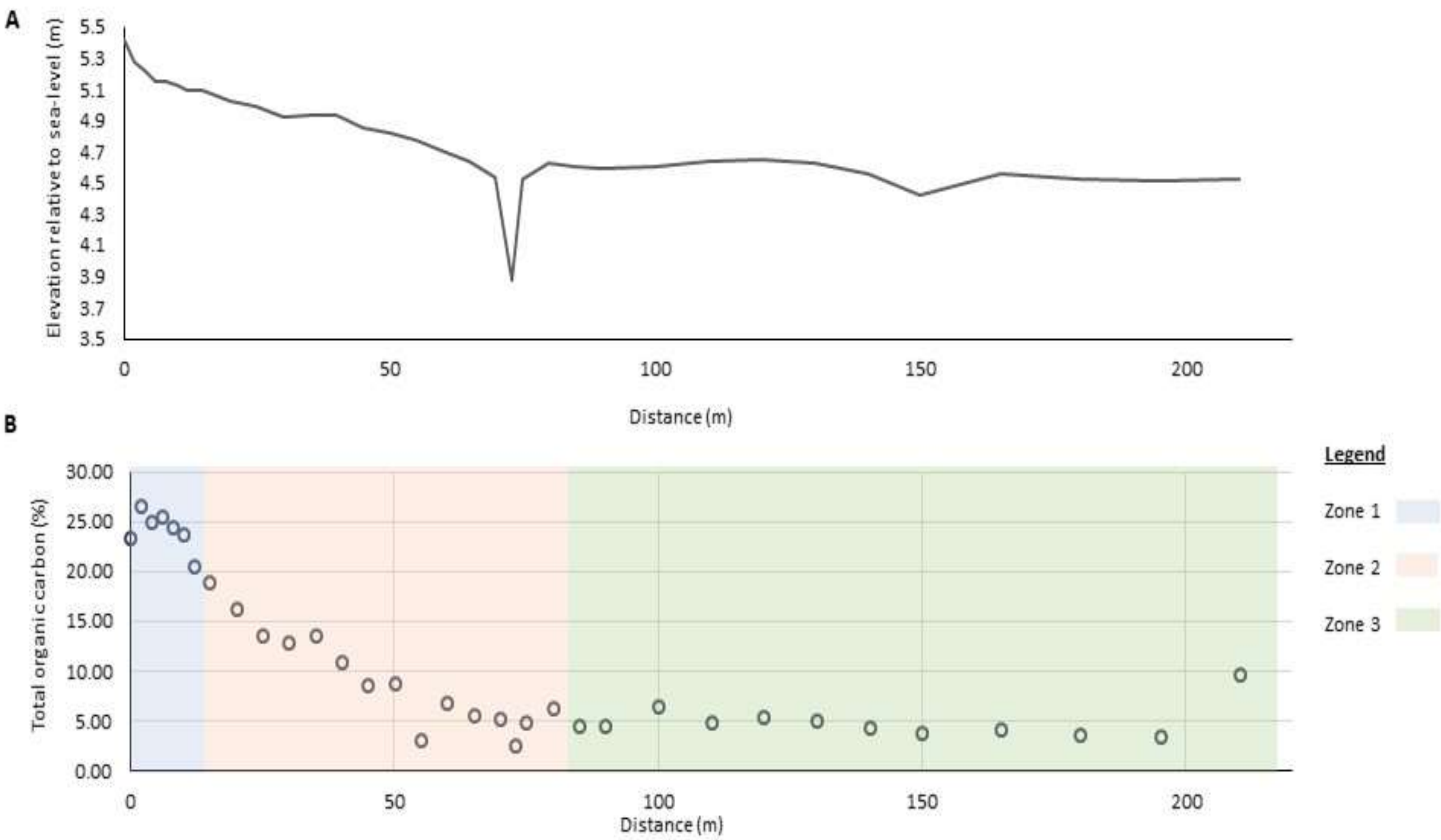

Figure 5.14: Biggar Saltmarsh elevation (A) in relation to % total organic carbon of dry sediment (B) with shaded vegetation zones.

A clear decreasing trend of organic carbon content from high to low marsh can be seen in *Figure 5.15*. Only in zone 1 amounts of organic carbon present in the sediments are high (23-25%). This is the *Phragmites austrslis* zone *(Figure 5.1)* at the highest point on the marsh. After this, there is a steady decline in the amount of organic carbon towards the low marsh. A large portion of the sampled marsh appears spatially to have low organic carbon values (3.3-5.7%), this area is predominantly low marsh, as well as the tidal creek zones throughout the sampled area. The areas adjacent to the tidal creeks rises to 5.8-8%.

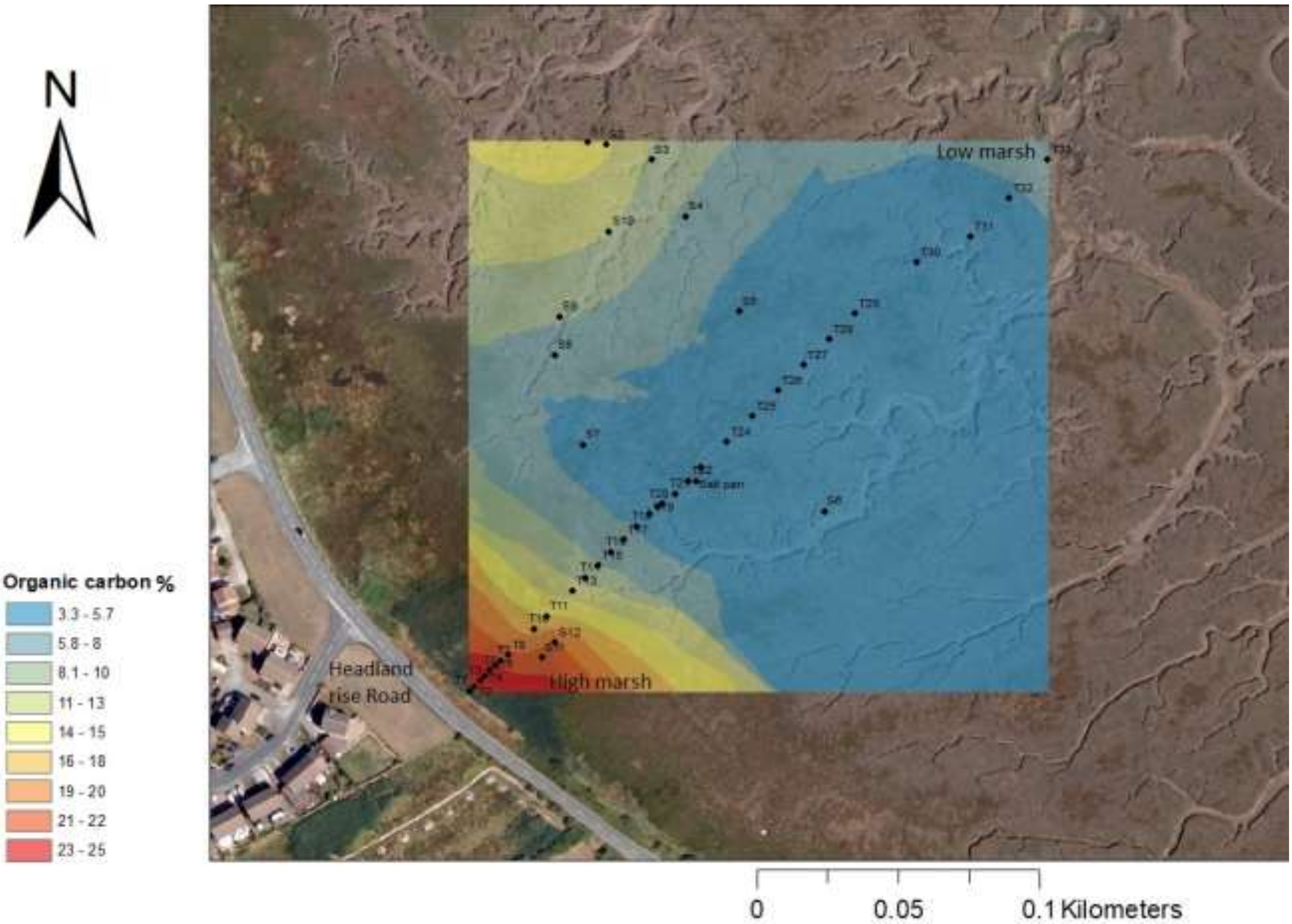

Figure 5.15: Spatial distribution of % total organic carbon of dry sediment throughout the sampled area Biggar Saltmarsh. Map created via Kriging in Arc GIS 10 using both the transect and spatial sampling data.

5.4.3 Total nitrogen

Total nitrogen (N) decreases from high to low marsh *(Figure 5.16)* with the high marsh having values of up to 1.9% and the low marsh having values as low as 0.35%. The greatest decrease in N can be seen from 15 m to 50 m where N falls from 1.5% to 0.8%. This area of decrease is in an area of vegetation change *(Figure 5.1)* from an *Phragmites australis* to an area of mixed vegetation with dominant species being *Triglochin maritima* and *Carex salina.* N appears to follow a similar trend to elevation. As elevation decreases so does N. There is a steady decrease from high elevation until the transect is approaching an area surrounded by tidal creeks at 55 m dropping from 0.8% to 0.3%, then again at 73 m where N drops down to the lowest value of 0.24% which is directly within the tidal creek *(Figure 5.1)*.

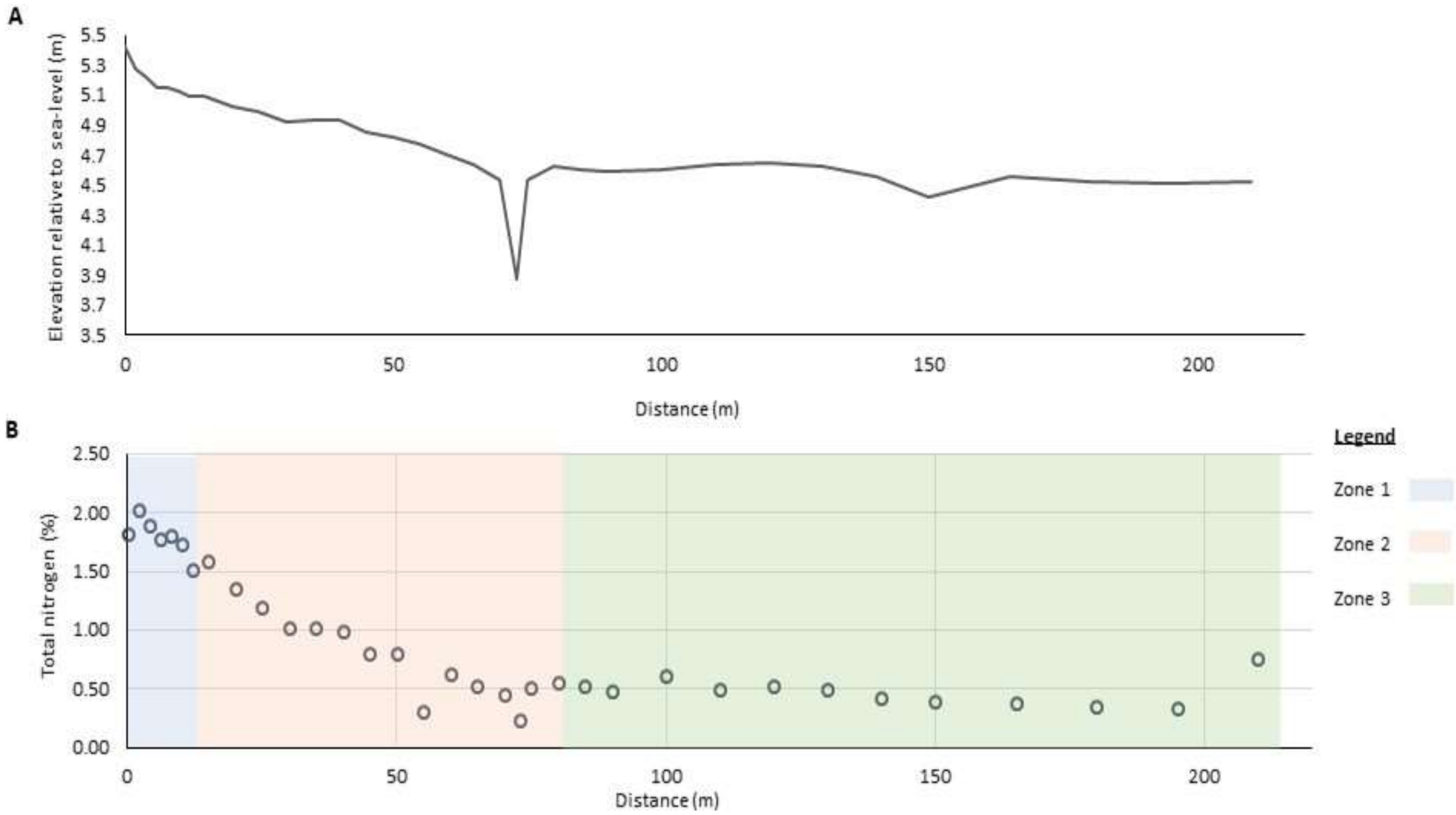

Figure 5.16: Biggar Saltmarsh elevation (A) in relation to % total nitrogen of dry sediment (B) with shaded vegetation zones.

The spatial mapping *(Figure 5.17)* shows a clear trend of decreased nitrogen with distance from the high marsh. The area of tidal creek sampling sees a decrease down to 0.3-0.47% but then increases back up to 0.48-0.65% again afterwards. This spatial view is very similar to the spatial distribution of organic carbon in *(Figure 5.15)* indicating a connection between the two elements.

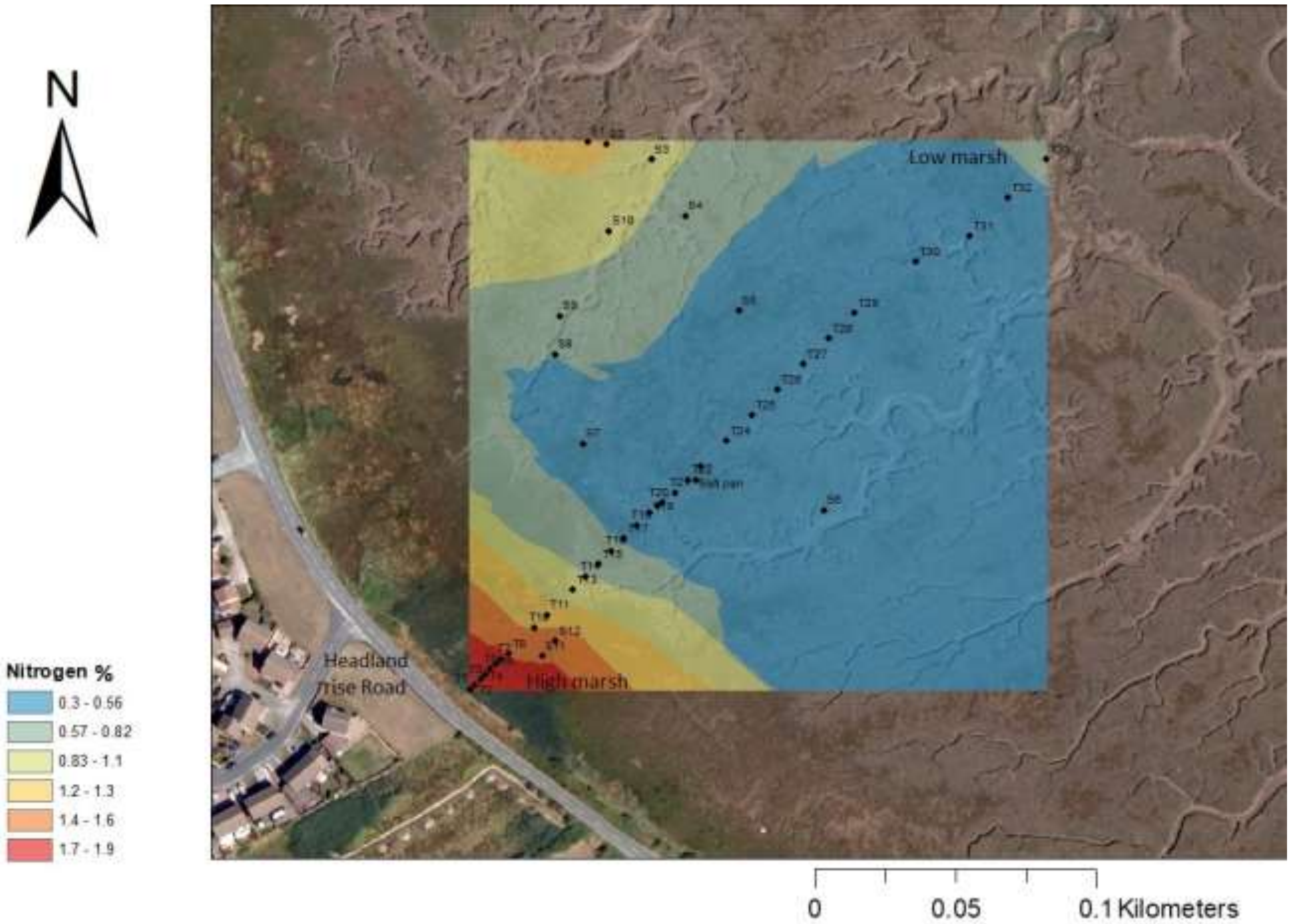

Figure 5.17: Spatial distribution of % total nitrogen of dry sediment throughout the sampled area Biggar Saltmarsh. Map created via Kriging in Arc GIS 10 using both the transect and spatial sampling data.

5.4.3 Molar C/N ratios

The molar C/N ratio decreases from high to low marsh, *(Figure 5.18)* with the high marsh having a ratio of up to 16.9 and the low marsh having a ratio down to 11.9. The highest molar ratios are found within the *Phragmites australis* zone *(Figure 5.1)*, which is at 0-12 m with another high peak at 35 m of 15.7, which is an area of mixed vegetation and dominated by species such as *Triglochin maritima and Carex salina*. Overall there is a decreasing trend in molar C/N ratio from high to low marsh *(Figure 5.18)*. An area in the middle marsh has values of 10.9-11.6 and 11.6-12.4. This is within the tidal creek zone with the lowest values of 10.9-11.6 being within the actual tidal creek itself. The end value has a sudden increase from 11.9 to 14.9 would appear to be an outlier value as this sudden rise at the end of the transect also occurs for total organic carbon *(Figure 5.14)* and total nitrogen *(Figure 5.16)* but not for organic matter *(Figure 5.12)*.

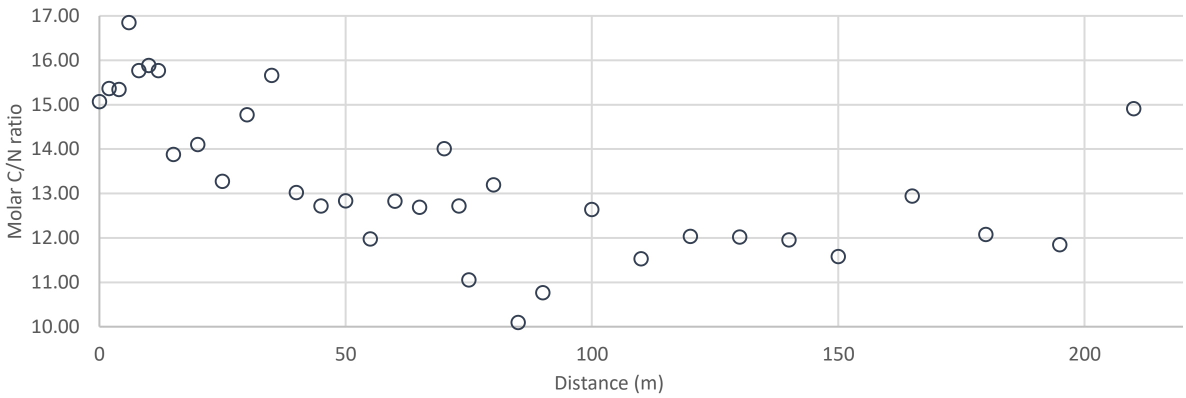

Figure 5.18: Molar C/N ratio of dry sediment vs distance.

Figure 5.19 shows the C/N ratio of different marsh species in comparison to the C/N ratio of the sediment at the corresponding position on the marsh. *Phragmites austrslis* has one of the lower C/N ratios in contrast to the other species, averaging 17.6. However, the molar ratio does not see any change relative to the sediment, with the sediment having an average molar ratio of 17.6. *Spartina alterniflora* in comparison sees the highest C/N ratios averaging 30 but sees the biggest change in the ratio when compared to the sediment, which averages 16.4. The ratio is almost half of the ratio for the vegetation.

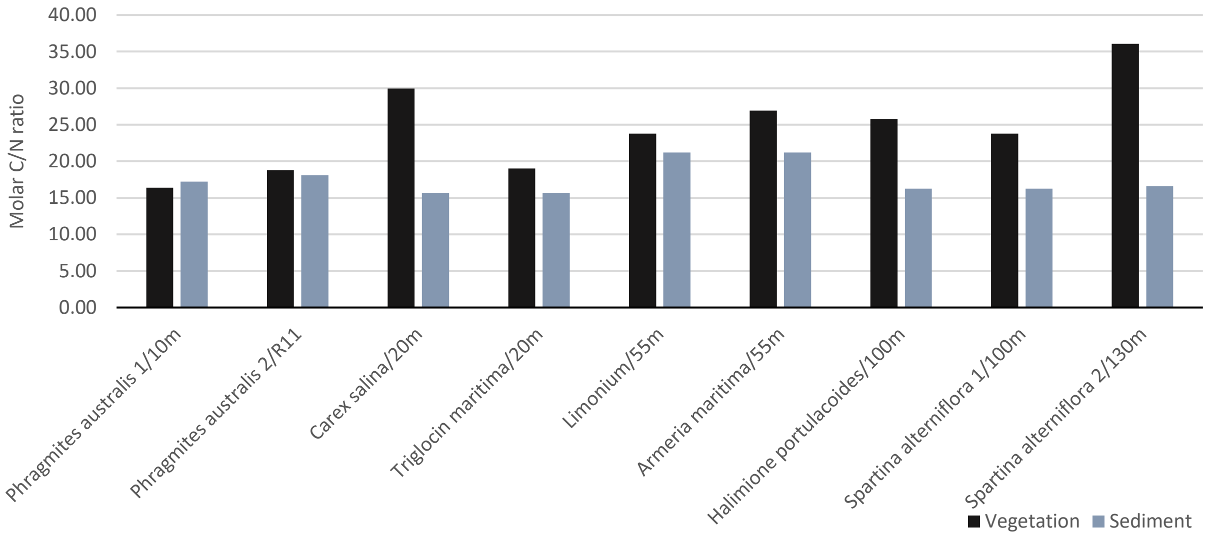

Figure 5.19: Molar C/N ratio for organic carbon and organic nitrogen of vegetation in comparison to corresponding locations of dry sediment from the same sample locations on the marsh.

5.4.4 Correlations

In order to examine any relationship between organic matter and elevation after normality testing a Pearson's correlation with R squared was carried out to see how close of a relationship there where between these two factors. As seen from the results of this test in *Figure 5.20* there appears to be a strong correlation between organic matter and elevation. There is a positive correlation between organic matter and elevation r = 0.834, $p < 0.05$ with $R^2 = 0.70$.

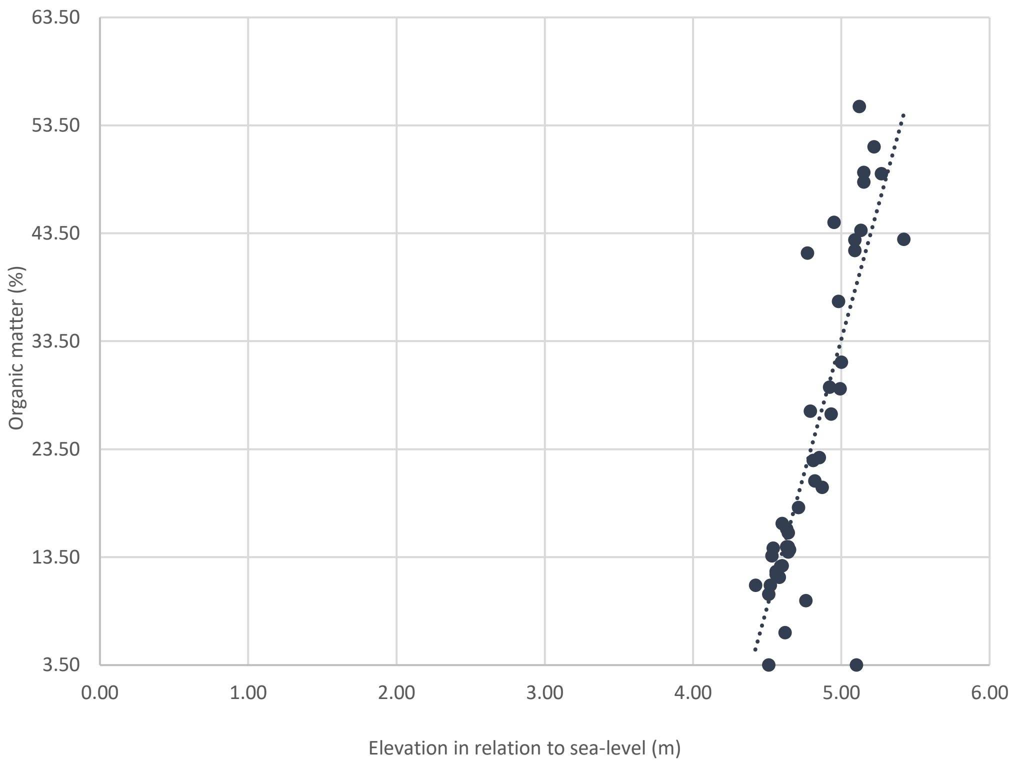

Figure 5.20: Correlation between elevation and % organic matter of dry sediment. r = 0.834, $p < 0.05$ with $R^2 = 0.70$. Creek sample was removed from correlation due to being a sub environment to the marsh as well as T33 as this is an outlier value.

After normality tests were carried out a Pearson's correlation with R squared was tested. The results of this test *(Figure 5.21)* show a strong correlation between organic carbon and elevation. There is a strong positive correlation between organic carbon and elevation $r = 0.931$, $p < 0.05$ with $R^2 = 0.87$.

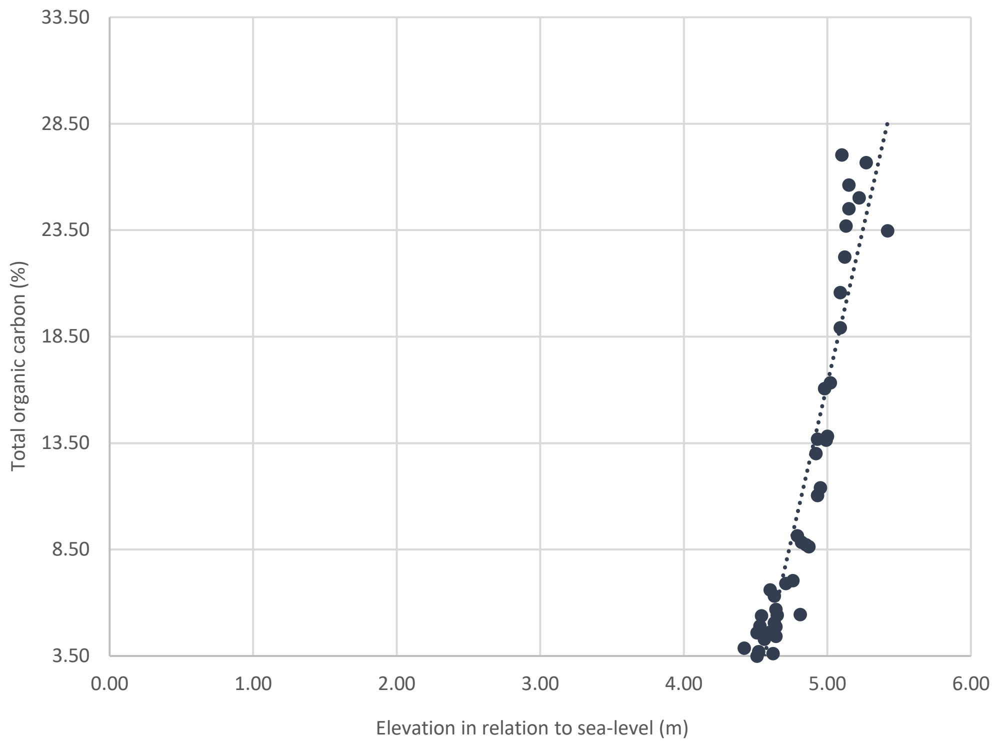

Figure 5.21: Correlation between elevation and % total organic carbon of dry sediment. $r = 0.931$, $p < 0.05$ with $R^2 = 0.87$. Creek sample was removed from correlation due to being a sub environment to the marsh as well as T33 as this is an outlier value.

A Pearson's correlation with R squared was carried out after normality testing *(Figure 5.22).* There is of a strong correlation between nitrogen and elevation r = 0.942, $p < 0.05$ with $R^2 = 0.89$.

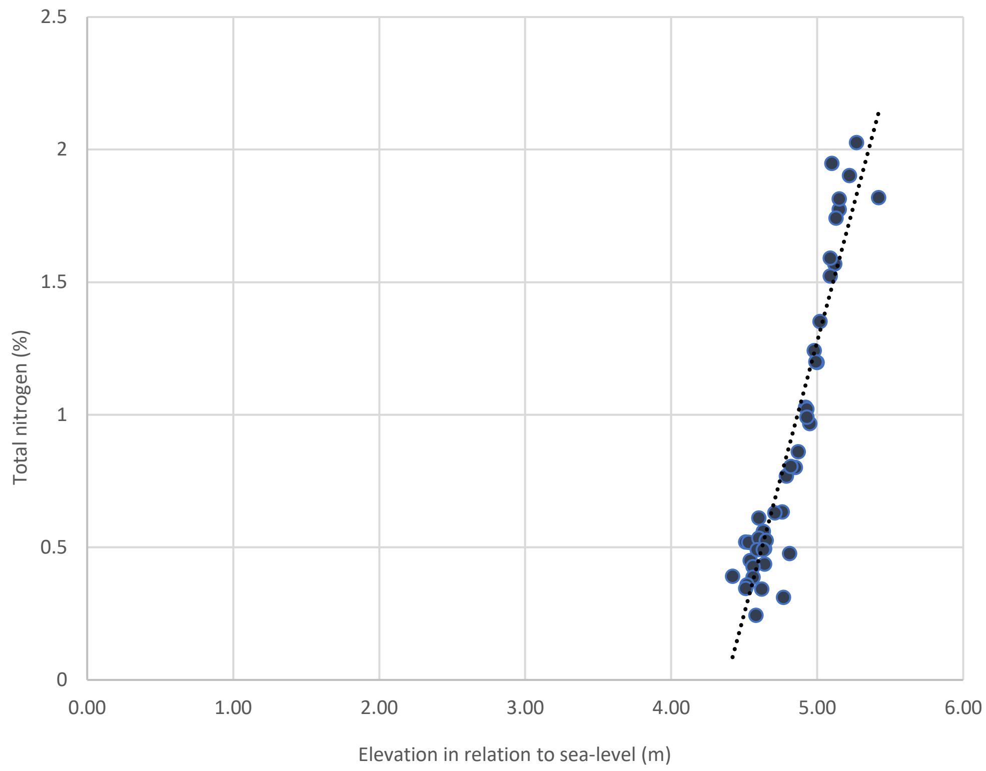

Figure 5.22: Correlation between elevation and % total nitrogen of dry sediment. r = 0.942, $p < 0.05$ with $R^2 = 0.89$. Creek sample was removed from correlation due to being a sub environment to the marsh as well as T33 as this is an outlier value.

5.4 Statistical processing

In order to better understand the relationship between total N and organic carbon a Pearson's correlation as carried out. The test results shown in *Figure 5.23* show a strong correlation between nitrogen and organic carbon. There is a strong positive correlation between nitrogen and organic carbon r = 0.994, $p < 0.05$ with $R^2 = 0.99$. The Y intercept of the trendline was used to estimate the organic nitrogen of the samples. The trendline equation was used to determine this. 0.1352% is the value of the inorganic nitrogen so this can be subtracted from the results to give organic nitrogen.

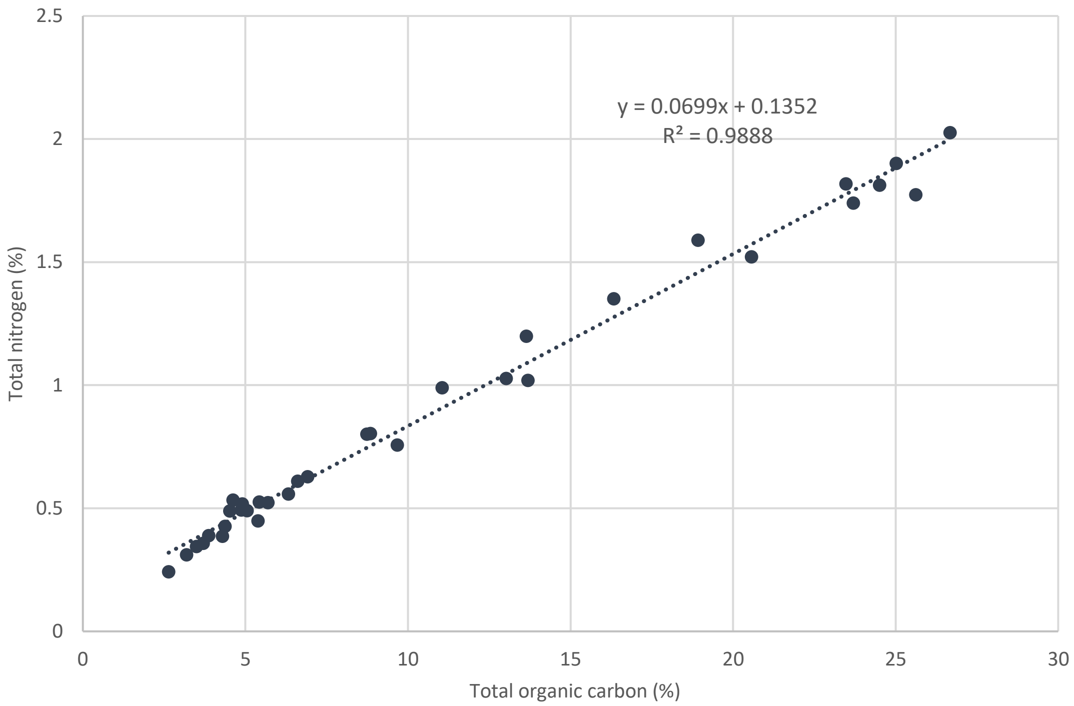

Figure 5.23: Correlation between % total nitrogen and % total organic carbon of dry sediment. r = 0.994, $p < 0.05$ with R^2 = 0.99. Creek sample was removed from correlation due to being a sub environment to the marsh as well as T33 as this is an outlier value.

Mean grain size and organic carbon was tested for normality before having a Pearson's correlation with R squared. The results of this test as shown in *Figure 5.24* indicate there is a weak correlation between total organic carbon and mean grain size. There is a weak positive correlation between mean grain size and total organic carbon with $r = -0.196$, $p > 0.05$ with $R^2 = 0.04$.

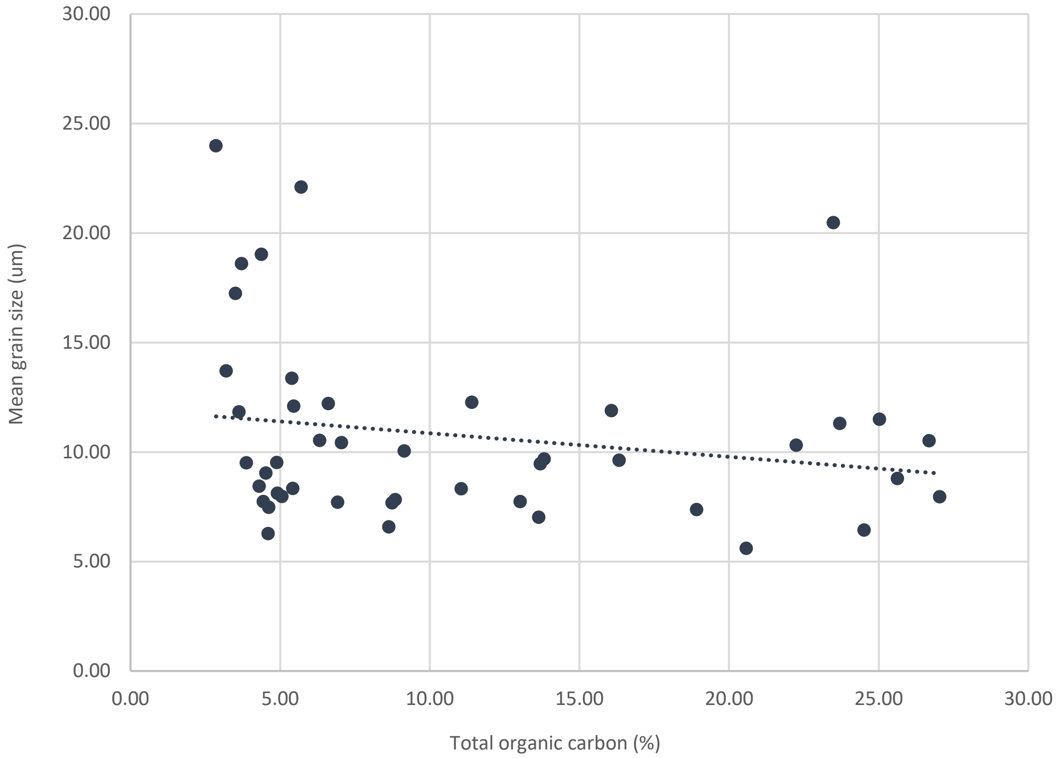

Figure 5.24: Correlation between mean grain size and % total organic carbon of dry sediment. $r = -0.196$, $p > 0.05$ with $R^2 = 0.04$. Creek sample was removed from correlation due to being a sub environment to the marsh as well as T33 as this is an outlier value.

Chapter 6- Discussion

6.1 Morphology and vegetation

The first main objective of this study was to *"Define the different saltmarsh vegetation zones with the use of high-resolution spatial analysis from GIS and field mapping"*. In order to fulfil this objective marsh zonation of Biggar has been defined from vegetation distribution along the transect and elevation changes across the marsh. This enabled the identification of three distinct marsh zones.

Vegetation zonation can largely be attributed to salinity tolerance of specific species, which relates to elevation height. The initial 12 m of the transect *(Figure 5.1)* has been designated as zone 1 (high marsh), due to *Phragmites australis* being the dominant vegetation species. This zone has the highest elevations within Biggar Marsh (5.2 m $\pm$ 0.85 m mean tide mark), and is a suitable habitat for *Phragmites australis,* typically receiving infrequent tidal inundations, with full submergence only occurring during the highest astronomical tides and storm events (Carter, 1991: 335 - 346). The low salinity of the sediment pore waters in that zone *(Figure 5.7)*, is consistent with this species (low salinity tolerances) (Burdick, 2001; Vasquez, 2006). Zone 2 (12-80 m) is considered as middle marsh; this zone includes the tidal creek *(Figure 5.1)*. Elevation is still relatively high (4.77 m $\pm$ 0.14 m mean tide mark) to the end of the zone, where elevation levels are comparable to the low marsh. There is a more diverse vegetation species characterising this area of the marsh; species change in dominance from the top of the middle marsh to the seaward margin. *Puccinellia* sp., is more dominant vegetation species at upper middle marsh, with *Triglochin maritima* becoming the dominant species towards the seaward end *(Figure 5.1)*. These species are more salt tolerant than *Phragmites australis,* therefore, they can survive more frequent tidal inundations (Cooper, 1982; Gray, 1967).

The seaward marsh zone is zone 3 (low marsh), which is the largest zone (80-210 m). This area of the marsh has the lowest elevations, with little variation in elevation (4.57 m $\pm$ 0.07 m mean tide mark). The vegetation changes with *Halimione portulacoides* and *Spartina alterniflora* dominating. The lower elevations of the low marsh result in a greater hydroperiod (Ferronato, 2018), meaning that this zone is frequently inundated resulting in more saline sediment pore waters *(Figure 5.7)* in comparison with the rest of the marsh along with poorly drained sediments. This is seen in Biggar as low marsh has the highest conductivity values *(Figure 5.8)*. *Halimione portulacoides* and *Spartina alterniflora* are able to survive in saline environments with frequent sea water inundations (Jensen, 1985).

Roner et al. (2016) carried out a study on saltmarshes in the Venice lagoon in Italy, and found *Spartina alterniflora* characterised low elevations. The study found that there was a strong dependence of vegetation on sediment elevation, and that the higher the elevation the lower the salinity. This is in agreement to the results for this study as there is a significant negative relationship between elevation and conductivity at Biggar ($r=-0.719$, $p<0.05$), *(Figure 5.11)*. Different species have a preferred elevation within the marsh, but this changes between different sites due to marsh variability (Silvestri et al. 2005).

6.1 Sedimentation and sedimentology

The spatial distribution of grain size was studied in order to determine links between grain size and carbon distribution. Mean grain size does not appear to have a strong or significant relationship with elevation ($r=-0.1158$; $p>0.05$), *(Figure 5.5)* indicating that elevation is not one of the main drivers of sediment distribution. Yet, grain size does appear to increase towards the seaward edge of the marsh *(Figure 5.3)*, as well as within and around tidal creeks at Biggar. However, the data in *Figure 5.6* does not suggest that mean grain size has a strong or significant relationship to distance along the marsh transect ($r=0.291$; $P>0.05$). However, grain size distribution is typically non-uniform over a marsh (Roner et al. 2016). Even though grain size does not have a strong relationship with distance, the spatial distribution *(Figure 5.3)* indicates increased grain size with proximity towards tidal creeks as well as towards the seaward edge of the marsh, where greater and more frequent tidal flows are experienced.

The highest rates of deposition occur within the areas where there is the largest tidal dampening effect. The more vegetated the marsh area, the greater the dampening effect is causing waves to lose energy and deposit sediment (Moller and Spencer, 2002; Reef et al. 2018). The largest grain sizes within middle to high marsh are found around the tidal creeks at Biggar Marsh *(Figure 5.3)*. The areas around the creeks are all vegetated causing a dampening effect, resulting in the large grain size of the sediments within the water column to be deposited in the near vicinity (Perry, 2007). Furthermore, as water spills over the edge of the creek onto the marsh surface, there is a sudden drop in energy of the water as the water is no longer in a confined area (e.g. tidal creek channel) causing the sediment load to be deposited as particles fall out of suspension (Carter, 1991: 335 - 346). This sudden drop means that the over spilled water has relatively low energy and finer sediments fall out of suspension as the water moves away from the tidal creek (Perry and Taylor, 2007). This indicates that tidal creeks and tides/waves exert control over sediment distribution throughout the marsh than elevation. Elevation is also controlled by vegetation trapping sediment, which helps to raise the marsh elevation relative to sea-level (Wilson et al. 2014). These findings are similar to those of Roner et al. (2016) on the San Felice and Riga saltmarshes in the Venice Lagoon in Italy. There, there was also an increase in mean grainsize seawards *(Figure 5.3)*. The same authors also found that around the tidal creeks there was coarser sediment deposition along channel edges with grain size decreasing away from the creek edges, indicating the influences of these features to the development of the saltmarsh and the distribution of sediment.

Typically, UK saltmarshes are thought to be clay rich environments (Beaumont et al. 2014), however, the sediments of Biggar saltmarsh are predominantly made up of silts, with clay only making up around 10-20% of the total marsh sediment (*Figure 5.4*). There appears to be no trend to the amount of clay along the transect at Biggar. Allen (2000) investigated Zeeland saltmarsh in the Netherlands finding that with increased distance from tidal creeks clay increases rapidly. This is opposite to the findings for Biggar Saltmarsh where there is no rapid increase of clay seawards. The low amounts of clay within the Biggar Saltmarsh could be explained by the dynamics of clay deposition. Clay particles settle very slowly and are usually kept in suspension within the water column. Saltwater amplifies the surface attraction of the particles, however, this electrolytic binding will only increase enough for particles to adhere to each other with the addition of freshwater. As particles continue to aggregate, the settling weight of the particles increases so clay sediments can settle/be deposited (Perry and Taylor, 2007). This could explain the low amounts of clay within Biggar Marsh as there is not enough fresh water influence to allow clay particles to adhere to each other. Alternatively, there may not be a lot of clay particles already in suspension within the saline water, so when fresh water enters there are not enough particles to adhere to each other to increase setting weight so particles remain suspended within the water column.

6.3 Organic matter

The preservation and sequestration of carbon within saltmarsh environments is of great importance to the global carbon cycle and potential climate change mitigation due to the potential for carbon sequestration and low greenhouse gas emissions (Chen et al. 2017). The understanding of the processes behind this is the aim of this study *"To investigate the spatial distribution of organic carbon in surface saltmarsh sediments and the controls surrounding carbon distribution within contrasting saltmarsh sub environments*". The low percentage of sand within the sediments at Biggar Saltmarsh and the high amount of silt *(Figure 5.4)* within the majority of the sediments, leads to better preservation conditions for organic matter within the marsh (Ruiz-Fernandez et at. 2018), due to silt having smaller pore spaces making it more resistant to oxygen penetration (Howarth and Hobbie, 1993; Mayer, 1994). Sediment accumulation is one of many environmental variables which help the preservation and reactivity of organic matter. The deposition and accumulation of sediments help to bury organic matter and prevents oxidising agents dissolved in marine waters from accessing organic matter (Hedges and Keil, 1995). Waterlogged sediment reduces the ability of oxygen to penetrate via diffusion throughout the sediment column helping to create anaerobic conditions which leads to lower decomposition rates of organic matter (Howarth and Hobbie, 1993). There is no significant relationship between mean grain size and organic carbon (r=-0.196, p>0.05); *(Figure 5.24)* indicating that the grain size of sediments at Biggar, which is related to surface area (e.g. Mayer, 1994; Hedges and Keil, 1995) has little control in the preservation of organic carbon. Burial control however, has not been assessed as only surficial samples were collected for this study. Work on sediment cores would help to clarify the relationship between carbon burial and grain size.

The amount of organic matter and organic carbon at Biggar are highest at high elevations in the marsh, with the highest values located within the high marsh (zone 1), then decreasing seawards to lowest values at lowest elevations in the low marsh (zone 3) *(Figure 5.12 & Figure 5.14)*. Strong and significant correlations where found between elevation and organic matter (r= 0.834, p= $\leq$0.05), *(Figure 5.20)* and elevation and organic carbon (r= 0.931, p= $\leq$0.05), *(Figure 5.21)*. This indicates that elevation is one of the main controls for generation of organic matter. One of the main reasons for this could be the distribution of vegetation at Biggar. Vegetation is distributed within the tidal frame based on salinity preferences and marsh elevation (Crosby et al. 2016; Lamb et al. 2006). The upper 20 m of the high marsh at Biggar is dominated by *Phragmites australis (Figure 5.1),* this is a larger plant than those found lower in the marsh, meaning that there will be more above and below ground biomass produced due to larger roots (Reef et al. 2018). The organic matter produced from vascular plants is enriched in ligneous and phenolic compounds that are recalcitrant, and difficult to decompose (Ruiz-Fernandez et al. 2018). This results in the production/preservation of high amounts of organic matter, which helps to raise marsh elevation, in turn resulting in greater amounts of organic carbon sequestration (Kirwan and Megonigal, 2013). Zone 2 (middle marsh) still has ligneous vegetation, however it is not dominant and tend to be smaller species such as *Puccinellia* sp., which produces less above ground biomass in comparison to *Phragmites australis*.

The reduction of below ground production could also be a determining factor. Increased tidal inundation could result in roots being washed away by tides and run off after death. This results in lower organic matter production so causes a reduction in elevation gain, as well as reduced organic carbon burial in comparison to the high marsh (Zone 1). As the plants in Biggar become smaller and less ligneous towards the lower marsh (Zone 3) (*Halimilone portulacoides, Spartina alterniflora* and *Plantago maritima*) they become easier to decompose (Ruiz-Fernandez et al. 2018), less organic matter is preserved resulting in low elevations and low organic carbon content, which is the case at Biggar. Saltmarsh productivity rates have been found to range from 64-219 g C $m^{-2}yr^{-1}$ in UK saltmarshes, with average figures of 120-150 g C $m^{-2}yr^{-1}$ for most UK saltmarshes (Beaumont et al. 2014). However, the rates of organic matter production have not been measured for this study so this cannot be known. This is an element that could be measured in further study upon this marsh.

The type of organic matter may be another factor controlling carbon burial. At Biggar this will likely have been produced from both above and below ground by terrestrially derived vegetation. Above ground is typically surface leaf litter which surrounds the vegetation during dieback, getting trapped with mineral grains. Below ground productivity is predominantly in the form of roots, rhizomes and tubers (Allen, 2000). Below ground production of organic matter is a greater contributor to organic matter than above ground production in the majority of saltmarshes, largely due to the material being less readily available for export from the marsh system, as well as being harder to decompose (Chmura, 2013; Ougang et al. 2017). However, little is known about below ground productivity especially in UK and Northern European saltmarshes (Allen, 2000). Most studies focus on above ground biomass production via vascular plants missing out on belowground production of roots, rhizomes and microflora (Chmura, 2013). Here only surface samples were collected, and only above ground biomass will have been sampled. Deeper sediment cores could have improved this.

The uptake of nitrogen by vegetation is a key component of the nitrogen cycle, with vegetation able to take up nitrogen in many different forms, from inorganic chemical compounds including ammonium and nitrate to organic forms such as proteins (Nasholm et al. 2009). Soils contain a large amount of organic nitrogen compounds with free amino acids accounting for a small fraction of soil nitrogen and peptide and protein bound amino acids accounting for over half the organic nitrogen sediment pool (Nasholm et al. 2009). Nitrogen and organic carbon at Biggar are strongly and significantly correlated ($r= 0.994$, $p<0.05$), (*Figure 5.23)* indicating that nearly all nitrogen in the top sediment is organic. The strong and significant correlation of organic nitrogen and elevation ($r=0.942$, $p<0.05$), *(Figure 5.22),* similarly to organic carbon, suggests that similar controls are responsible for its distribution in Biggar Saltmarsh.

Nitrogen-rich organic compounds are typically considered the first components of organic matter to be broken down (Lamb et al. 2006). Lamb et al. (2006) explains how nitrogen is lost more rapidly than carbon in the initial stages of organic matter decomposition so increases C/N ratios. However, once microbial decay takes over decomposition, the proportion of nitrogen increases as inorganic nitrogen is introduced via external nitrogen fixation. Carbon is lost at a faster rate than nitrogen initially due to respiration causing C/N rations to be lowered. During the last stages of decomposition carbon and nitrogen losses stabilise, and they are lost at the same rate to each other. This limits the use of C/N ratios as a proxy for organic matter source. Bouchard and Lefeuvre (2000) found that the rate of litter decomposition was slowest in the high marsh with a rapid rate of nitrogen leaching from decayed litter from middle to low marsh. After a 30 day period, only 1-5% of nitrogen remained within the decayed litter whereas approximately 60% of nitrogen remained within the decayed litter of the high marsh. A study by Chen et al. (2017) on saltmarshes in the Yangtze Estuary, China concluded that the storage of soil nitrogen was less than the soil carbon storage. They suggest that this could be due to the decomposition of surface litter and roots, which preferentially enriches carbon over nitrogen. The study also found that around 22-55% of organic carbon and 0.6-35% of nitrogen within the marsh sediments is derived from terrestrial vegetation. This highlights how the leaching of nitrogen from decaying vegetation increases from high to low marsh and could be a reason for the low levels of nitrogen seen at Biggar *(Figure 5.16)*, due to the organic matter decay only being in the initial stages. The values of organic nitrogen obtained at Biggar Saltmarsh will therefore, presumably derive from different types of organic matter (e.g. vegetation, algae) and/or the different decomposition rates of organic matter that contain nitrogen.

The type of sedimentary organic matter can be characterised by molar C/N ratios i.e. terrestrial or marine sources. Terrestrial vegetation typically have high C/N ratios of greater than 12, with marine organic matter having values less than this. The C/N ratio of vegetation can be highly variable within a small area due to large variations of nitrogen within the plants (Lamb et al. 2006). The molar C/N ratio at Biggar decreases from high to low marsh *(Figure 5.18)* with the values indicating that the major source of organic input of the marsh is derived from terrestrial vegetation sources, especially in the high marsh, with marine sources increasing towards the lower marsh. However, it is hard to distinguish the origin of organic matter using only C/N ratios as only surficial sediments were collected for this study, so the C/N ratios obtained may not be an full representation of the marsh. In order to gain a more detailed understanding of the type of organic matter within the marsh, or to verify the C/N ratios obtained for this study further research is needed. Core samples should be taken with the implementation of other indicators such as lipid biomarkers or isotopic analysis to further understanding on the type of organic matter found within Biggar Saltmarsh. The highest values found within Biggar for organic matter and carbon are within the high and middle marsh *(Figure 5.13 & Figure 5.15)*, indicating that these are the areas where the preservation of organic matter is the most effective. As discussed above, further study would help to clarify the areas of best organic matter preservation. For the majority of the marsh vegetation species *(Figure 5.19)* preservation of organic matter in the sediment appears to be high due to the C/N ratio of the vegetation compared to the corresponding sediment locations (e.g *Phragmites australis*) having similar values. The vegetation species that have high C/N ratios, but then much lower C/N ratios for the corresponding sediment locations (e.g. *Spartina alterniflora*) could still have good levels of preservation of the vegetation even though they are located in low marsh. The lowered C/N ratio within the sediment could be due to high inputs of algae in the surface sediments. Algal inputs are known to cause the lowering of C/N ratios of sediments (Li et al. 2016).

Due to the low marsh receiving regular tidal inundations, this allows for high amounts of algae to be deposited or grow on the surface of the sediment resulting in the lowering of the C/N ratio of the sediment. Lower C/N ratios are also found within the tidal creek at Biggar, this is where the lowest C/N ratio within the marsh is located *(Figure 5.1 & Figure 5.18)*, suggesting higher inputs of algae than higher up in the marsh. However, due to algae decomposing quickly by comparison to ligneous vegetation, this makes it hard to distinguish if they are the source of the organic matter (Lamb et al. 2006) and ratio lowering within these areas of the marsh, rather than just the poor preservation of organic matter. Yet, the material within the tidal creek could not be contemporary, the sediments could have been deposited a number of years ago resulting in lowered C/N ratios. In order to assess the contributions of marine algae matter to carbon burial at Biggar further research should be done. Again the use of sediment cores with biomarkers and isotopes would help to distinguish algal inputs into the marsh, as well as over a temporal scale from the use of sediment cores.

Another cause for low organic content within the lower marsh could be due to increased flooding of marsh sediments which may enhance organic matter decay rates due to oxygenated tidal waters covering the sediments, which could result in poor preservation (Ruiz-Fernandez et al. 2018). No oxygen measurements were carried out in this study but the high levels of salinity *(Figure 5.7 & Figure 5.8)* in the low marsh pore waters at Biggar and the lowered organic matter rates *(Figure 5.12)* provide support for this hypothesis. This could be one of the causes as to why organic matter and organic carbon values are decreasing from high to low marsh *(Figure 5.13 & Figure 5.15)* and within/around the tidal creeks. Due to increased tidal inundations within middle to low marsh causing organic matter to decompose at a faster rate, resulting decreases in of organic carbon burial.

6.4 Implications for the understanding in saltmarshes

As discussed above, elevation is an important factor for blue carbon burial and helping the preservation of organic matter in relation to tidal inundation amongst other variables. Elevation will become more important for saltmarshes over the next 25 years due to sea-level rise relative to marsh's ability to maintain their elevation in relation to sea-level. Saltmarshes are vulnerable to sea-level rise as they occupy a narrow elevation range (Horton et al. 2018). This is obvious at Biggar *(Figure 5.1)* as there is not a large change in the range of elevation values from high to low marsh. The ability of saltmarshes to maintain their elevation with respect to rising sea-levels, and hence their ability to store carbon, depends upon the amount of available suspended sediment that can lead to marsh accretion. Kirwan et al. (2010) modelled different rates of sea-level rise for a number of different coastal wetland systems and found that marsh survivability largely depends on available sediment supply. A marsh with a low sediment supply will only be able to survive a few millimetres of sea-level rise per year, in comparison to a marsh with has a high sediment supply which could survive up to a few centimetres sea-level rise a year. Many marshes are under threat of reduced sediment supply as a result of human activities and influence, for example, the building of dams within river catchments (Schuerch et al. 2018) and canalisation/stabilisation of rivers. The majority of saltmarshes will be able to withstand low rates of increase (millimetres) in sea-level rise by maintaining a stable profile, however, many saltmarshes will be lost if there are high rates within sea-level rise (centimetres) (Best et al. 2018).

Once a marsh loses its ability to keep pace with sea-level rise, this leads to loss of vegetation, further reducing marsh elevation within the tidal frame and results in the submergence of the marsh, and the formation of un-vegetated subtidal environments (Kirwan et al. 2010). If Biggar undergoes a sea-level rise of 7.1mm y^{-1} based on sea-level rise data from Horton et al. (2018) then this will result in a 67.25% loss of carbon content within Biggar saltmarsh on submergence and erosion of the marsh. The only part of the marsh to survive sea-level rise will be the uppermost area of high marsh. However, this will see vegetation change from high marsh of *Phragmites australis*, dominance *(Figure 5.1)* to low marsh species such as *Halimione portulacoides* and *Spartina alterniflora* which will further reduce organic carbon contents *(Figure 5.15)*. There are limitations to this calculation, as it assumes that there is no sediment accretion. Secondly, it assumes that decomposition rates will stay the same, which will not be the case if there is a change in dominant vegetation from high marsh species to low marsh species (Eagle-Gonneea, 2019; Stagg et al. 2016). This calculation also assumes that the eroded sediment is not redistributed throughout the marsh, or that there are no ocean inputs of carbon (Chmura, 2004).

Studies of saltmarshes on the South Coast of the UK have found that modern day accretion rates result in elevation gain of 4-8 mm/yr in areas of low elevation where tidal inundation is frequent, in comparison to areas of high marsh which only build elevation by < 3 mm/yr. If a sea-level rise of 7.1 mm/yr was to occur, then this would result in the drowning of these marshes (Horton et al. 2018). The ability of Biggar Saltmarsh to survive sea-level rise over the next 25 years is unsure. This study has not measured long-term sedimentation/accretion rates, or measured the yearly sedimentation rates in relation to rising sea-level. However, mean yearly sedimentation rates for Biggar can be estimated from those calculated by Rahman et al. (2013) as being 0.75 cm yr^{-1} and 0.45 cm yr^{-1}. If a sea-level rise of 7.1 mm/yr was to occur based on Horton et al. (2018) estimates, then Biggar saltmarsh will be able to keep pace with sea-level rise based on a sedimentation rate of 0.75 cm yr^{-1}. However, if Biggar saltmarsh sedimentation rates are based on the low end of 0.45 cm yr^{-1} then Biggar risks submergence if a 7.1 mm/yr rise in sea-level occurs, as the marsh will be unable to keep pace with sea-level rise. Based on these sedimentation rates, some areas of Biggar saltmarsh will be able to keep pace with sea-level rise, but not the whole marsh. Some areas of this marsh has the risk of being submerged/eroded with sea-level rise. However, this may help to further raise marsh elevation of surviving areas of the marsh may continue if sediment is redistributed (Rahrahman et al. 2013). This will require further study in order to determine the survivability of Biggar saltmarsh in regards to the marsh being able to maintain its elevation in relation to sea-level rise, via sedimentation rates. These are important questions that have arisen during this study, and should be researched further in future studies in order to answer these uncertainties.

Once saltmarshes become submerged erosion will occur (Kirwan and Megonigal, 2013). Erosion rates will increase with sea-level rise in areas where the environments are shallow. Hence the depth of the water over the marsh and reduces the marshes ability to dissipate waves moving along the marsh surface (Kirwan and Megonigal, 2013). Marsh erosion will result in these ecosystems becoming carbon sources rather than sinks due to the disturbance of the sediments. When sediments are eroded from the marsh, this allows oxygen to enter into buried sediments causing the anoxic zone to become oxic (Macreadie et al. 2013). This could result in large amounts of buried carbon to be released back into the atmosphere as carbon dioxide, resulting in large scale impacts on the global climate (Ardenne et al. 2018; Arriola and Cable, 2017).

However, Kirwan and Megonigal (2013) suggests that the erosion of saltmarshes may not be completely negative. The erosion within one area of the marsh could help the rest of the marsh survive sea-level rise if the eroded sediments being deposited in a struggling area of the marsh, which helps to raise the elevation profile of the marsh. The same concept also apply to the expansion of tidal creeks; the material produced from this expansion will help to raise elevation if redistributed elsewhere on the marsh. Although individual marshes could survive sea-level rise, this will still result in the release of organic carbon that has been stored for hundreds/thousands of years to be released into the atmosphere. As oxygen enters the newly eroded sediment that has been buried for long scale time periods, this begins the process of oxic decomposition and the conversion from a site of carbon burial into a carbon source (Macreadie et al. 2013).

The creation of seawalls or other man made obstacles that prevent the landward migration of saltmarshes (Valiela et al. 2018) is also detrimental to saltmarshes survivability of sea-level rise and erosion, contrary to Kirwan and Megonigal (2013) view. The erosion of saltmarshes results in the loss of vegetation cover of the eroded area, which leaves low lying areas susceptible to the full impact of tidal wave/storm surges resulting in the loss of even more area (Best et al. 2018). As the marsh edges erode, vegetation will tend to migrate to higher elevations, however, obstacles such as seawalls will prevent the inland migration of vegetation resulting in the loss of species that are unable to tolerate prolonged inundation times (Best 2018 et al.; Rosencranz et al. 2018). This will result in the loss and drowning of the marsh as sea-level and erosion overtakes the marshes ability to migrate in a process known as 'coastal squeeze' which is a major threat to the survival of UK saltmarshes (Pontee, 2013).

The drowning and disappearance of saltmarshes via these processes is a problem that could be faced at the Biggar Saltmarsh in the near future. Along the edge of the marsh there is a road with housing developments behind *(Figure 3.1)*, this development and road has the potential to result in coastal squeeze occurring at Biggar Saltmarsh. The potential loss of Biggar saltmarsh highlights the importance of understanding the environmental consequences of loss of saltmarshes that have the potential to sequester large amounts of carbon, such asmBiggar Saltmarsh *(Figure 5.15)*. If these saltmarshes turn from carbon sinks into carbon sources this could have devesting effects for the environment especially in relation to the climate and global warming from the large amounts of carbon dioxide that would be released into the atmosphere. Further study is required within Biggar saltmarsh to assess the full carbon stocks within the marsh and the rates of potential loss. This knowledge could be gained by taking multiple core samples along multiple marsh transects, as well as random spatial sampling in order to gain temporal scales on carbon sequestration rates. This could then also be used to determine the total amount of carbon within the marsh as this study cannot determine total carbon estimates due to only surface samples being collected for this study. This would enable a more detailed understanding of carbon sequestration within Biggar Saltmarsh, and of the potential future threats faced by Biggar saltmarsh in relation or sea-level rise/erosion, potentially then trying to mitigate these threats.

Chapter 7- Conclusion

The main aim of this study was *"to investigate the spatial distribution of organic carbon in surface saltmarsh sediments and the controls surrounding carbon distribution within contrasting saltmarsh sub environments".*

This aim was achieved, as Biggar Saltmarsh has been shown to vary spatially in organic carbon contents of surface sediments. Marsh zonation was established based on vegetation patterns. High marsh, an area with the highest elevations furthest from the sea has been shown to have highest amount of organic carbon. Middle and low marsh have decreasing organic carbon contents. The controls on carbon distribution of saltmarsh surficial sediments have been explored in the following objectives;

The first objective to *"define the different saltmarsh vegetation zones with the use of high-resolution spatial analysis from GIS and field mapping"* was accomplished with three different zones within Biggar saltmarsh being defined. This determination was based on vegetation cover change observed during field sampling, aided by the collected marsh elevation data. The use of elevation data coupled with vegetation cover change enabled three distinctive marsh zones to be identified. Elevation also provided important links to organic carbon content, indicating that the mechanisms that control it are the main/important drivers in relation to organic carbon burial. This has been one of the first studies to provide a transect of elevation in order to determine if there are links to organic carbon burial which were found.

The second objective of the study was to *"assess the spatial distributions of organic carbon throughout the marsh, and the relationship to environmental variables (including conductivity, grain size, organic content)"*. Grain size did correlate with organic carbon indicating that this is not one of the main drivers of organic carbon burial within Biggar. Conductivity correlated with organic carbon content indicating that this is a controlling factor in relation to organic carbon distribution. Both conductivity and organic matter content also provided links to elevation, further supporting the importance of elevation within saltmarshes and the potential importance that elevation has for organic carbon burial.

The third objective was to *"define the relationship between organic carbon and elevation in relation to tidal inundation from the use of sediment conductivity"*. Thus, links between conductivity in relation to organic carbon and elevation were explored. Areas of low conductivity where found to have the higher organic carbon values indicating that these were areas of low tidal inundation due to low conductivity being related to low tidal inundations.

The potential of saltmarshes to survive sea-level rise within the next 25 years will largely depend on sediment accretion rates and the impacts of humans on the saltmarsh environment. If sea-level rise drowns saltmarshes or causes severe erosion, this will have the potential to turn saltmarshes from carbon sinks into harmful carbon sources, which could have devastating effects to global climate. Further research needs to be carried out on sediment deposition and organic matter accretion rates in relation to sea-level rise in order to assess the potential threat Biggar saltmarsh faces from future sea-level rise. The burial of organic carbon in saltmarshes is an understudied area, that would significantly benefit from further research in order to fully understand the processes that cause carbon burial in saltmarshes.

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Appendix

Table 2: Sample ID with T being transect data and S being spatial data, with distance along the transect and field coordinates used to produce GIS maps.

Sample ID	Distance (m)	X Coordinates	Y Coordinates
T1	0m	318231	467205
T2	2m	318233	467207
T3	4m	318235	467209
T4	6m	318237	467211
T5	8m	318239	467213
T6	10m	318241	467215
T7	12m	318243	467217
T8	15m	318246	467219
T9	20m	318251	467224
T10	25m	318256	467229
T11	30m	318261	467234
T12	35m	318266	467239
T13	40m	318271	467244
T14	45m	318276	467249
T15	50m	318281	467254
T16	55m	318286	467259
T17	60m	318291	467264
T18	65m	318296	467269
T19	70m	318301	467274
Creek	73m	318304	467277
T20	80m	318306	467278
T21	85m	318311	467282
T22	90m	318316	467287
T23	95m	318321	467292
T24	100m	318331	467302
T25	110m	318341	467312
T26	120m	318351	467322
T27	130m	318361	467332
T28	140m	318371	467342
T29	150m	318381	467352
T30	165m	318405	467372
T31	180m	318426	467382
T32	195m	318441	467397
T33	210m	318456	467412
Salt pan	-	318319	467287
S1	-	318277	467419
S2	-	318284	467418
S3	-	318302	467412
S4	-	318315	467390

S5	-	318336	467353
S6	-	318369	467275
S7	-	318275	467301
S8	-	318264	467336
S9	-	318266	467351
S10	-	318285	467384
S11	-	318259	467218
S12	-	318264	467224

Table 3: Elevation data collected from the field, which was converted based off of Heysham tide gauge data then converted into Ordnance datum from chart datum.

Field elevation (m)	Elevation (difference) (m)	Elevation based on tide gauge data (m)	Final elevation converted (m)
80.33	-	10.32	5.42
80.18	0.15	10.17	5.27
80.13	0.05	10.12	5.22
80.06	0.07	10.05	5.15
80.06	0	10.05	5.15
80.04	0.02	10.03	5.13
80	0.04	9.99	5.09
80	0	9.99	5.09
79.93	0.07	9.92	5.02
79.9	0.03	9.89	4.99
79.83	0.07	9.82	4.92
79.84	-0.01	9.83	4.93
79.84	0	9.83	4.93
79.76	0.08	9.75	4.85
79.73	0.03	9.72	4.82
79.68	0.05	9.67	4.77
79.62	0.06	9.61	4.71
79.55	0.07	9.54	4.64
79.45	0.1	9.44	4.54
78.79	0.66	8.78	3.88
79.44	-0.65	9.43	4.53
79.54	-0.1	9.53	4.63
79.51	0.03	9.5	4.6
79.5	0.01	9.49	4.59
79.51	-0.01	9.5	4.6
79.55	-0.04	9.54	4.64
79.56	-0.01	9.55	4.65
79.54	0.02	9.53	4.63
79.47	0.07	9.46	4.56
79.33	0.14	9.32	4.42
79.47	-0.14	9.46	4.56
79.43	0.04	9.42	4.52
79.42	0.01	9.41	4.51
79.43	-0.01	9.42	4.52

Table 4: Laboratory results for Total organic carbon, Inorganic carbon, Loss of ignition, mean grain size, conductivity and pH for both transect and spatial samples.

Sample ID	TOC %	IC %	TN %	LOI %	Mean grain size µm	Conductivity (ms)	pH
T1	23.48	0.00	1.82	42.93	20.48	0.5267	5.3
T2	26.68	0.00	2.03	49.03	10.52	0.3523	6.5
T3	25.02	0.00	1.90	51.52	11.50	0.6643	5.3
T4	25.62	0.06	1.77	49.14	8.800	0.5199	6.1
T5	24.51	0.00	1.81	48.25	6.440	2.36	6.1
T6	23.70	0.00	1.74	43.76	11.32	1.457	5.8
T7	20.57	0.03	1.52	42.89	5.603	7.078	5.8
T8	18.92	0.00	1.59	41.91	7.382	4.052	6.1
T9	16.33	0.51	1.35	-	9.626	3.905	6.1
T10	13.64	0.00	1.20	29.10	7.024	12.06	6.1
T11	13.02	0.01	1.03	29.24	7.736	10.11	5.8
T12	13.69	0.00	1.02	-	9.463	12.88	6.1
T13	11.05	0.01	0.99	26.75	8.330	3.265	6.1
T14	8.74	0.05	0.80	22.74	7.682	7.749	6.1
T15	8.85	0.00	0.80	20.55	7.836	11.7	6.1
T16	3.19	0.67	0.31	41.67	13.70	10.14	6.5
T17	6.92	0.00	0.63	18.09	7.714	13.45	6.1
T18	5.70	0.13	0.52	14.44	22.10	12.1	6.1
T19	5.39	0.22	0.45	14.33	13.38	9.292	6.5
Creek	2.64	0.67	0.24	8.46	10.34	16.2	7
T20	4.91	0.52	0.52	13.63	8.117	7.676	7
T21	6.32	0.29	0.56	16.11	10.53	7.031	7
T22	4.62	0.36	0.53	12.70	7.480	15.2	6.5
T23	4.52	0.04	0.49	12.63	9.040	12.96	6.5
T24	6.61	0.39	0.61	16.61	12.22	15	6.5
T25	4.88	0.01	0.49	13.99	9.532	15.92	6.1
T26	5.43	0.23	0.53	14.19	8.342	17.49	6.5
T27	5.06	0.31	0.49	14.46	7.975	16.84	6.5
T28	4.38	0.27	0.43	11.89	19.04	14.05	6.1
T29	3.87	0.50	0.39	10.90	9.511	9.149	7
T30	4.29	0.01	0.39	12.18	8.440	14.66	6.5
T31	3.71	0.47	0.36	10.89	18.60	13.33	6.1
T32	3.50	0.82	0.35	10.06	17.25	7	7
T33	9.68	0.01	0.76	8.38	9.482	10.34	7
Salt pan	4.596	0.22	0.52	3.51	7.352	15.64	7
S1	16.07	0.03	1.24	37.18	6.491	6.95	6.5
S2	13.82	0.00	1.2	31.55	6.778	7.985	6.1
S3	8.633	0.38	0.86	19.96	7.291	3.155	6.5
S4	7.05	0.04	0.63	9.46	6.686	13.45	6.5
S5	3.624	0.41	0.34	6.51	6.485	7.416	7
S6	2.857	0.70	0.24	11.63	5.480	5.988	7

S7	4.436	0.02	0.44	15.77	7.067	13.41	6.1
S8	5.454	0.19	0.48	22.47	6.483	7.344	7
S9	9.148	0.16	0.77	27.02	6.734	12.78	6.1
S10	11.4	0.03	0.97	44.51	6.515	11.47	6.1
S11	22.24	0.02	1.57	55.25	6.711	4.299	6.5
S12	27.04	0.00	1.95	3.51	7.070	0.7789	6.1

Table 5: Vegetation Total organic carbon and Total nitrogen data with sampled locations.

Sample location	Vegetation species	TOC %	TN %
10m	*Phragmite australius* 1	20.62	1.605
S11	*Phragmite austalius* 2	31.14	2.068
20m	*Carex salina*	29.67	1.291
20m	*Triglocin mairitima*	28.64	1.893
55m	*Armeria maritima*	19.17	0.966
55m	*Limonium*	22.71	1.249
100m	*Halimione portulacoides*	25.99	1.311
100m	*Spartina alterniflora* 1	30.64	1.638
130m	*Spartina alterniflora* 2	30.55	1.123

Table 6: Grain size data produced from gradisat of the sediment fractions of transect data.

Sample ID	% MUD:	% V fine sand	% V coarse-medium silt	% Fine-V fine silt	% CLAY:
T1	85.6%	14.4%	65.0%	13.7%	7.0%
T2	98.7%	1.3%	59.9%	27.0%	11.8%
T3	97.4%	2.6%	63.2%	23.6%	10.5%
T4	99.5%	0.5%	56.2%	27.7%	15.6%
T5	100.0%	0.0%	46.6%	37.4%	16.0%
T6	96.6%	3.4%	59.2%	26.6%	10.7%
T7	100.0%	0.0%	41.8%	38.7%	19.5%
T8	100.0%	0.0%	50.2%	35.5%	14.3%
T9	99.2%	0.8%	61.8%	23.6%	13.9%
T10	100.0%	0.0%	51.5%	29.6%	18.9%
T11	100.0%	0.0%	54.5%	29.7%	15.8%
T12	99.6%	0.4%	62.2%	24.5%	12.9%
T13	99.9%	0.1%	54.8%	31.9%	13.2%
T14	100.0%	0.0%	54.4%	27.4%	18.2%
T15	99.8%	0.2%	53.4%	29.7%	16.7%
T16	95.5%	4.5%	66.6%	18.0%	10.8%
T17	100.0%	0.0%	54.5%	27.8%	17.7%
T18	88.1%	11.9%	69.7%	10.1%	8.3%
T19	95.5%	4.5%	67.7%	15.2%	12.6%
Creek	98.7%	1.3%	62.4%	20.5%	15.8%
T20	100.0%	0.0%	55.0%	28.5%	16.5%
T21	98.6%	1.4%	61.3%	23.5%	13.8%
T22	99.9%	0.1%	52.4%	28.9%	18.7%
T23	99.6%	0.4%	56.9%	27.3%	15.4%
T24	97.4%	2.6%	64.5%	22.3%	10.6%
T25	99.1%	0.9%	59.0%	26.0%	14.1%
T26	99.8%	0.2%	55.7%	28.3%	15.8%
T27	99.9%	0.1%	54.9%	26.7%	18.3%
T28	90.0%	10.0%	69.1%	11.9%	9.1%
T29	99.6%	0.4%	59.0%	25.8%	14.8%
T30	98.5%	1.5%	54.5%	25.9%	18.1%
T31	89.6%	10.4%	66.3%	14.3%	9.0%
T32	86.8%	13.2%	61.1%	14.3%	11.3%
T33	99.3%	0.7%	56.5%	27.4%	15.4%

Table 7: Grain size data obtained via gradistat

Sample ID	Sediment type:	Sorting:	Mean (phi):	Mean (µm):	Sorting	Skewness
T1	Coarse Silt	Poorly Sorted	5.61	20.48	1.900	1.395
T2	Medium Silt	Poorly Sorted	6.57	10.52	1.854	0.777
T3	Medium Silt	Poorly Sorted	6.44	11.5	1.813	0.909
T4	Medium Silt	Poorly Sorted	6.83	8.8	1.910	0.601
T5	Fine Silt	Poorly Sorted	7.28	6.44	1.607	0.518
T6	Medium Silt	Poorly Sorted	6.47	11.32	1.778	0.608
T7	Fine Silt	Poorly Sorted	7.48	5.6	1.685	0.485
T8	Fine Silt	Poorly Sorted	7.08	7.38	1.707	0.637
T9	Medium Silt	Poorly Sorted	6.7	9.63	1.906	0.958
T10	Fine Silt	Poorly Sorted	7.15	7.02	1.901	0.602
T11	Fine Silt	Poorly Sorted	7.01	7.74	1.768	0.675
T12	Medium Silt	Poorly Sorted	6.72	9.46	1.865	1.151
T13	Medium Silt	Poorly Sorted	6.91	8.33	1.636	0.581
T14	Fine Silt	Poorly Sorted	7.02	7.68	1.931	0.614
T15	Medium Silt	Poorly Sorted	7	7.84	1.902	0.629
T16	Medium Silt	Poorly Sorted	6.19	13.7	1.990	1.224
T17	Fine Silt	Poorly Sorted	7.02	7.71	1.922	0.661
T18	Coarse Silt	Poorly Sorted	5.5	22.1	1.896	1.589
T19	Medium Silt	Poorly Sorted	6.22	13.38	1.994	1.115
Creek	Medium Silt	Very Poorly Sorted	6.6	10.34	2.053	0.849
T20	Medium Silt	Poorly Sorted	6.94	8.12	1.847	0.585
T21	Medium Silt	Poorly Sorted	6.57	10.53	1.913	0.733
T22	Fine Silt	Very Poorly Sorted	7.06	7.48	1.971	0.564
T23	Medium Silt	Poorly Sorted	6.79	9.04	1.937	0.657
T24	Medium Silt	Poorly Sorted	6.35	12.22	1.755	0.794
T25	Medium Silt	Poorly Sorted	6.71	9.53	1.921	0.796
T26	Medium Silt	Poorly Sorted	6.91	8.34	1.907	0.711
T27	Medium Silt	Very Poorly Sorted	6.97	7.97	1.953	0.558
T28	Coarse Silt	Poorly Sorted	5.72	19.04	1.954	1.424
T29	Medium Silt	Poorly Sorted	6.72	9.51	1.938	0.742
T30	Medium Silt	Very Poorly Sorted	6.89	8.44	2.068	0.575
T31	Coarse Silt	Poorly Sorted	5.75	18.6	2.000	1.356
T32	Coarse Silt	Very Poorly Sorted	5.86	17.25	2.156	1.206
T33	Medium Silt	Very Poorly Sorted	6.72	9.48	1.963	0.518
S1	Medium Silt	Poorly Sorted	6.39	11.9	1.830	0.610
S2	Medium Silt	Poorly Sorted	6.69	9.69	1.624	0.673
S3	Fine Silt	Poorly Sorted	7.24	6.59	1.904	0.470

S4	Medium Silt	Poorly Sorted	6.58	10.43	1.941	0.803
S5	Medium Silt	Very Poorly Sorted	6.4	11.83	2.145	0.808
S6	Coarse Silt	Poorly Sorted	5.38	23.99	1.962	1.275
S7	Fine Silt	Very Poorly Sorted	7.01	7.75	1.971	0.580
S8	Medium Silt	Very Poorly Sorted	6.37	12.11	2.071	0.785
S9	Medium Silt	Poorly Sorted	6.64	10.05	1.936	0.762
S10	Medium Silt	Poorly Sorted	6.35	12.28	1.940	1.142
S11	Medium Silt	Poorly Sorted	6.6	10.31	1.740	0.928
S12	Medium Silt	Poorly Sorted	6.97	7.96	1.705	0.888
Saltpan	Fine Silt	Poorly Sorted	7.31	6.28	1.910	0.506

Table 8: Grain size data produced via gradistat on sediment information.

Sample ID	Sample type:	Textural group:	Sediment name:
T1	Bimodal, Poorly Sorted	Sandy Mud	Very Fine Sandy Very Coarse Silt
T2	Polymodal, Poorly Sorted	Mud	Coarse Silt
T3	Unimodal, Poorly Sorted	Mud	Coarse Silt
T4	Polymodal, Poorly Sorted	Mud	Medium Silt
T5	Trimodal, Poorly Sorted	Mud	Medium Silt
T6	Polymodal, Poorly Sorted	Mud	Medium Silt
T7	Unimodal, Poorly Sorted	Mud	Fine Silt
T8	Unimodal, Poorly Sorted	Mud	Medium Silt
T9	Unimodal, Poorly Sorted	Mud	Coarse Silt
T10	Bimodal, Poorly Sorted	Mud	Coarse Silt
T11	Unimodal, Poorly Sorted	Mud	Medium Silt
T12	Unimodal, Poorly Sorted	Mud	Medium Silt
T13	Polymodal, Poorly Sorted	Mud	Medium Silt
T14	Bimodal, Poorly Sorted	Mud	Coarse Silt
T15	Bimodal, Poorly Sorted	Mud	Medium Silt
T16	Unimodal, Poorly Sorted	Mud	Coarse Silt
T17	Trimodal, Poorly Sorted	Mud	Coarse Silt
T18	Trimodal, Poorly Sorted	Sandy Mud	Very Fine Sandy Very Coarse Silt
T19	Unimodal, Poorly Sorted	Mud	Coarse Silt
Creek	Unimodal, Very Poorly Sorted	Mud	Very Coarse Silt
T20	Polymodal, Poorly Sorted	Mud	Medium Silt
T21	Unimodal, Poorly Sorted	Mud	Coarse Silt
T22	Bimodal, Very Poorly Sorted	Mud	Medium Silt
T23	Bimodal, Poorly Sorted	Mud	Coarse Silt

T24	Polymodal, Poorly Sorted	Mud	Coarse Silt
T25	Polymodal, Poorly Sorted	Mud	Coarse Silt
T26	Bimodal, Poorly Sorted	Mud	Medium Silt
T27	Trimodal, Very Poorly Sorted	Mud	Coarse Silt
T28	Unimodal, Poorly Sorted	Mud	Very Coarse Silt
T29	Trimodal, Poorly Sorted	Mud	Coarse Silt
T30	Bimodal, Very Poorly Sorted	Mud	Very Coarse Silt
T31	Unimodal, Poorly Sorted	Sandy Mud	Very Fine Sandy Very Coarse Silt
T32	Bimodal, Very Poorly Sorted	Sandy Mud	Very Fine Sandy Very Coarse Silt
T33	Polymodal, Very Poorly Sorted	Mud	Very Coarse Silt
S1	Polymodal, Poorly Sorted	Mud	Medium Silt
S2	Polymodal, Poorly Sorted	Mud	Coarse Silt
S3	Trimodal, Poorly Sorted	Mud	Fine Silt
S4	Trimodal, Poorly Sorted	Mud	Coarse Silt
S5	Trimodal, Very Poorly Sorted	Mud	Very Coarse Silt
S6	Unimodal, Poorly Sorted	Sandy Mud	Very Fine Sandy Very Coarse Silt
S7	Trimodal, Very Poorly Sorted	Mud	Coarse Silt
S8	Unimodal, Very Poorly Sorted	Mud	Very Coarse Silt
S9	Bimodal, Poorly Sorted	Mud	Coarse Silt
S10	Trimodal, Poorly Sorted	Mud	Coarse Silt
S11	Unimodal, Poorly Sorted	Mud	Medium Silt
S12	Unimodal, Poorly Sorted	Mud	Medium Silt

Saltpan	Trimodal, Poorly Sorted	Mud	Medium Silt