2023-08-23

Sediment sorting within a relatively wave-exposed and sandy subtidal seagrass (Zostera marina) meadow

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Testing the Ability of Seagrass to Alter Sediment Characteristics

MSc Applied Marine Science

Dissertation

by

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Journal Format: Marine Geology

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Abstract

Seagrasses are well known for the ecosystem services they provide. Besides offering a habitat for myriad species; they reduce wave energy, trap fine sediments, and reduce sediment resuspension resulting in a lessening of the impact that wave dynamics have on coastal areas. They also have a greater capacity to capture and store atmospheric carbon than tropical rainforests, yet seagrass populations globally are swiftly declining. In this paper we test the sediment trapping paradigm of common eelgrass (*Zostera marina*) through investigation of the fine sediment fractions and inorganic carbon content of sediments taken from seagrass patches around the Isles of Scilly, UK. Sediments collected from vegetated sites within a large seagrass meadow were found to be over 100 microns smaller than those taken from unvegetated sites outside the meadow and 80 microns smaller than unvegetated sites within the seagrass meadow. In contrast, patchier sections of the meadow were less effective in reducing wave energy showing a lesser reduction in grain sizes and in particularly sparse regions the vegetated grains were larger than unvegetated grains confirming the sediment trapping paradigm. Inorganic content was found to be up to 50% higher for vegetated sediments within the seagrass meadow. Analysis of the topography, supplemented by the grain size analysis, revealed that seagrass patches raise the height of the seabed by up to 30 cm.

Keywords: Seagrass, Sediments, Laboratory Experiments, SE England

Highlights:

- Grain sizes are significantly lower in vegetated areas
- Carbonates in higher percentages in vegetated areas
- Seagrass patches represent topographic highs

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1. Introduction

Seagrasses play an integral part in coastal ecosystems, acting as safe havens and a food source for a multitude of aquatic species (Beck et al., 2001; Short et al., 2007), but they also provide ecosystem services to humans through their role in carbon sequestration and coastal dynamics. Seagrasses reduce wave energy (Fonseca and Cahalan, 1992; Peterson et al*.,* 2004), trap sediment (Gacia et al*.,* 1999, 2003; Hendricks et al., 2008) and prevent sediment resuspension (Ward et al., 1984; Terrados and Duarte, 2000). Along with mangrove forests and tidal marshes seagrass meadows act as an oceanic carbon sink by sequestering carbon from the atmosphere. Together these environments are known as 'Blue Carbon' habitats (Mcleod, et al., 2011; Green et al., 2018). Quantifying the contribution of seagrass meadows to coastal protection, particularly when considered in conjunction with their capacity to store carbon, should be investigated.

Seagrass provides coastal protection in various ways. The roots and rhizomes of seagrass anchor it to the seabed, whilst the exposed canopies reduce wave current speeds through the movement of their fronds. This attenuates the waves, resulting in the settling of sediments and nutrients as well as reducing sediment resuspension (Ward et al*.,* 1984; Gacia et al., 1999; Verduin and Backhaus, 2000; Paul et al., 2012) - the system of rhizomes and roots below-ground also does this to a certain extent (Hemminga and Duarte, 2000). Hydrodynamic parameters such as wave height and period, water depth and plant submergence ratio have all been shown to be relevant in the extent of wave dampening by seagrasses (Mendez and Losada, 2004, Stratigaki et al., 2011). Peterson et al*.* (2004) studied how seagrasses effect hydrodynamics through a mixture of modelling and field measurements. Their field data showed greater flow reductions in 10 out of 13 cases inside the canopies of the 5 seagrass beds studied. Greater flow reduction was correlated with greater vegetation density. Verduin and Backhaus (2000) obtained a series of high-resolution three-dimensional velocity measurements within, above, and adjacent to seagrass meadows of the species *Amphibolis antarctica* at different heights above the seabed. Their observations indicated an overall damping effect on water flow within the meadow. Specifically, a reduction in energy from 500 cm s^{-1} to 10 cm s^{-1} was measured. Reduced flows are common within a seagrass canopy due to the deflection of the current over the canopy and a loss of momentum within (Gambi et al., 1990; Koch and Gust, 1999; Verduin and Backhaus, 2000; Peterson et al., 2004). As a result, water speeds within the canopy can be 2 to >10 times slower than outside the bed (Ackerman, 1986; Gambi et al., 1990).

Changes in hydrodynamics around and within a seagrass canopy have varying effects on sediment transport. As wave energy within the canopy is reduced finer sediments can more easily settle. Water velocity decreases with distance into a seagrass canopy and with vertical distance below the canopy surface (Fonesca and Fisher, 1986; Gambi et al., 1990). Not only does this effect sedimentation but it also may reduce the diffusion boundary layer thickness around the blades of the seagrass allowing greater primary production and photosynthesis (Koch, 1994). Ward et al*.* (1984) showed that suspended particulate material (SPM) concentrations were greater in unvegetated regions compared to vegetated, an observation they attributed to vegetation attenuating wave energy, enhancing sediment deposition. They also found that during spring tides or storm surges, where water levels were elevated, the vegetation was less effective at attenuating the wave energy leading to increased SPM concentrations throughout the seagrass bed. This concurs with the general understanding that wave attenuation is highest when seagrasses occupy a large portion of the water column (Ward et al., 1984; Fonseca and Cahalan, 1992).

Greater sediment deposition leads to greater influx of organic and inorganic materials to the seagrass within the meadow (Ricart et al., 2015). Where sediments settle over seagrass beds there is a change in sediment surface elevation; specifically, an increase is observed (Ondiviela et al*.,* 2014). As the surface elevation increases, the waves that pass over the seagrass bed are further attenuated, reducing the impact they have on the land and beaches. Potouroglou et al*.* (2017) studied this phenomenon and concluded that seagrass had a “highly significant, positive impact on surface elevation”. According to Ondiviela et al*.* (2014), *Posidonia oceanica* may be the best species suited to coastal protection due to it being a highly abundant European species with the longest and widest leaves, the highest number of leaves per shoot, and the highest above-ground biomass. Although bigger species may be better for sediment deposition, small seagrasses such as *Halophila decipiens* and *Zostera novazelandica* can still alter the sediments they colonize (Fonseca, 1989; Heiss et al., 2000). Wilkie et al*.* (2012) studied the particle trapping and retention capabilities of *Zostera noltii*, a species of seagrass with the lowest above-ground biomasses. They found that large particles (150-250 µm) were retained more effectively within high density patches of this species compared to bare sand, but smaller particles (<63 µm) were found to be in similar concentrations within vs outside. Van Katwijk et al*.* (2010) investigated the differences in sediment modification between seagrass beds of varying sediment composition. Their results indicated that at wave-exposed sandy sites dense vegetation caused muddification (increase in fine sediments and organic content) of the sediment. Sparse vegetation was found to have no effect, as one would expect. However, they also found that in relatively sheltered areas with muddy sediments, dense vegetation had no effect on sediment composition, and in sparse vegetation sandification (decrease in fine sediments and organic content) occurred.

One can surmise that effectiveness of seagrasses in coastal protection depends on several criteria. Previous research indicates that the presence of seagrass does alter wave energy dynamics and the sedimentation deposition process, but the degree to which this happens depends on numerous factors. As seagrass’ capacity to attenuate waves relies on the movement of their fronds; differences in stiffness, density, leaf length and morphology will alter their effectiveness (Gacia et al., 2003; Orth et al*.,* 2006; Lavery et al., 2013), as well as the composition of the sediment where the seagrass is located, the shallowness and depth of the seagrass bed, and the density of the vegetation present. According to the literature, in each case, seagrasses were found to have some effect, albeit sometimes insignificantly, on wave dynamics and sediment deposition with the extent of such being highly variable.

In a period of changing climate and rising sea levels, and more frequent and violent storm events, coastal protection is more important than it has ever been. Coastal defences all come with their own drawbacks. Hard engineering defences such as groynes and barriers do well at protecting specific points on a coast, but often inhibit the natural sediment transport pathways depleting other areas of sediment leaving them further exposed (Ruiz-Martínez et al., 2015). Soft defence schemes such as beach nourishment have become more popular in recent years (Stive et al. 2013; Ruiz-Martínez et al., 2015) but this results in the repeated disturbance of natural beach communities and their ecosystems and long term may permanently change the benthic community (Bishop et al., 2006). Global distributions of seagrasses have been declining by 1.5% annually since records began in the late 1800’s (Waycott et al., 2009) and 65% of seagrass systems worldwide are thought to be degraded (Pendleton et al., 2012). Over the last two centuries the UK has lost >90% of its seagrass meadows, down to only 85 km^2, through a combination of pollution, dredging, bottom trawling, and coastal development. It is estimated that half of this loss occurred in just the last three decades (Green et al., 2021). Destruction and degradation of seagrasses leads to a loss of the many ecosystem services they provide, therefore seagrasses capacity to engineer its environment can be viewed as an argument for conservation and restoration efforts.

This paper aims to add to the growing evidence that seagrasses are a fundamental component of the global ecosystem by studying the impact of seagrass meadows on sediment characteristics, achieved through measuring the sediment grain sizes taken from within and outside of an eelgrass (*Zostera marina*) meadow located at the Isles of Scilly. Our hypothesis is as such; the presence of seagrass alters the characteristics of sediments found within a seagrass meadow, such that finer grains should be found in higher quantities within vegetated areas. In order to test said hypothesis, a range of sediment samples collected from the Isles of Scilly underwent grain size determination and carbonate analysis. Due to the relative densities of carbonate grains and quartz grains, and the non-uniform shapes of carbonate grains, carbonate could be more easily transported thus behaving like a fine quartz grain that only settles in reduced flows, and hence be found in greater abundance within seagrass meadows.

2. Field Site Overview

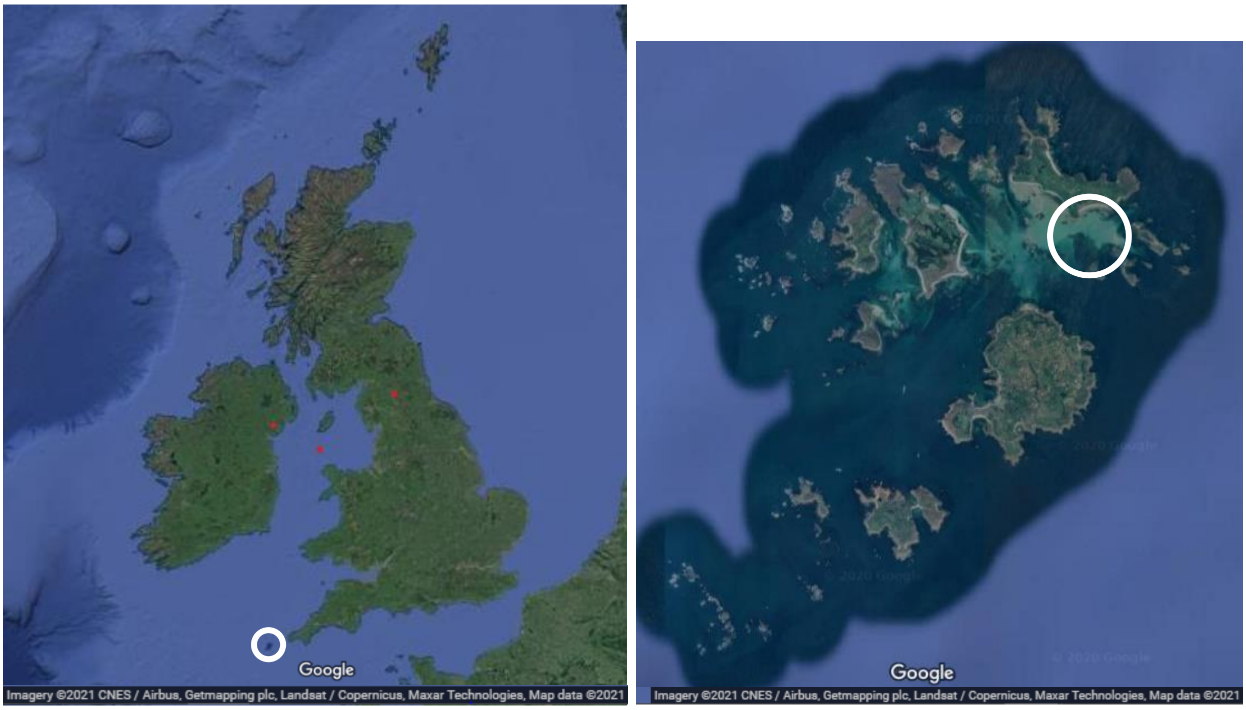


Figure 1: Location of study site. (Left) Location of the Isles of Scilly in relation to the rest of the UK; and (Right) Field site location within the Isles of Scilly. White circles indicate site.

Field work was carried out at the Isles of Scilly with attention focused on a small patch of seagrass off Par Beach and a large seagrass meadow north of Great Ganinick (shown in figure 1 and 3). Par beach is situated within Higher Town Bay, which itself is located on the southern edge of St. Martin's. The seagrass beds studied are in the sub-tidal zone, with tides ranging from 0.5 m to 6.0 m. These strong tidal streams flow across the bay and the beds are also exposed to the prevailing south-westerly winds. The sea floor comprises medium sands which, given the strong tidal streams, are liable to erosion. This sediment movement and erosion is prevented in some places, however, by the eelgrass rhizomes that help bind the sand and promote accretion.

Figure 2 displays topographic data for both locations. In both images heightened areas of blue represent the presence of seagrass (as denoted) such that the top of the heightened patches represents the top of the seagrass canopy and gaps represent patches of bare sand. The central line that runs through the patches represents the seabed.

A few factors contribute to the relatively unperturbed nature of the seagrass meadows and patches found here. In this sub-tidal environment, there are no large grazing species typical to inter-tidal seagrass regions such as geese (Zipperle et al., 2010) or marine grazers typical of tropical seagrass habitats (Fourqurean et al*.,* 2010). Despite there being some damage due to mooring boats, the small population size combined with little industrial or agricultural impact leads to relatively clean water (Munro & Nunny 1998) that, in combination with a lack of grazers, has allowed eelgrass to grow as a natural monoculture.

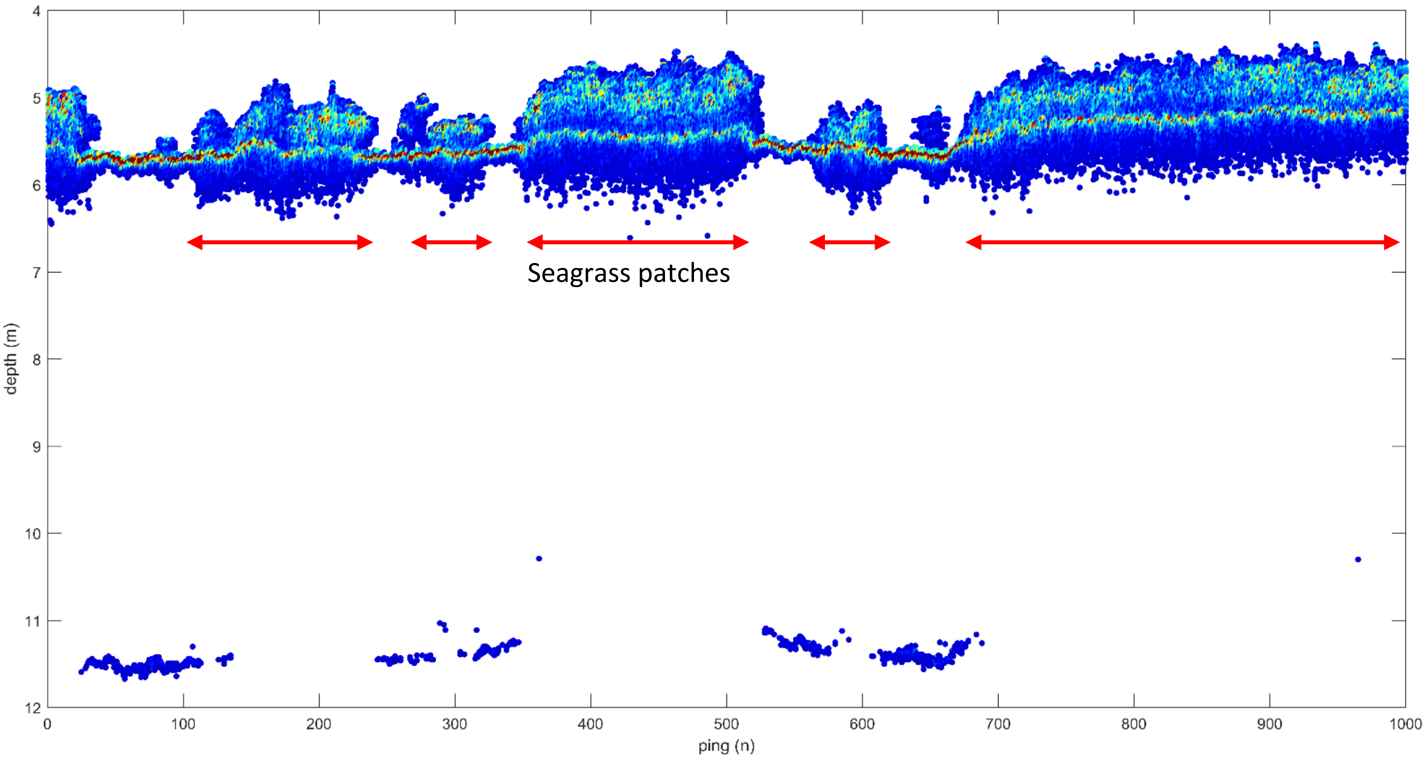
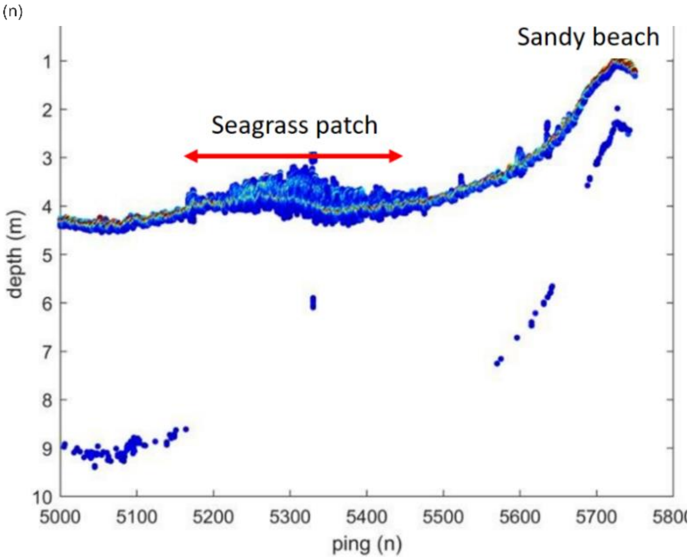


Figure 2: Echosounder Plots. (Above) Plot of processed single-beam data taken using an echosounder for a line across the Great Ganinick seagrass meadow. (Right) Plot of raw single-beam data for the Par Beach seagrass patch. X-axis represents time travelled by the boat.



3. Materials and Methods

3.1 Field Methods

Prior to sample collection, the study area was extensively mapped from the air and sea surface using autonomous vehicles. This not only provided highly detailed maps of the seagrass meadows but also provided information on the abundance and length of seagrass fronds. These were also measured by hand; fronds had an average length of 44 cm, average width of 0.75 cm, and on average had 1.1 shoots per plant. An extensive array of self-logging wave and current sensors were also deployed around the larger seagrass meadow to directly assess the wave and current filtering capacity of seagrass. The pressure sensors were deployed for a 2-month period. Following mapping, sediment samples were collected from a boat from over 60 predetermined positions using GPS as displayed in figure 3. Within the larger seagrass meadow, smaller patches (1-2 meter in diameter) of bare sand were often present. If within 5 meters of a seagrass sample location a bare patch was present, two samples were taken: one from the seagrass and one from the bare sand patch. A series of samples were also collected along a single transect line from the smaller patch near Par Beach including samples from the beach and dune. The samples were bagged on the boat, decanted to remove large organic material such as roots and leaves as well as the finest materials, and then stored for a few weeks. Following this they were washed with a 64-micron sieve to remove any salts, and any large root or plant material was removed. Finally, samples were dried in an oven overnight and bagged in preparation for analysis.

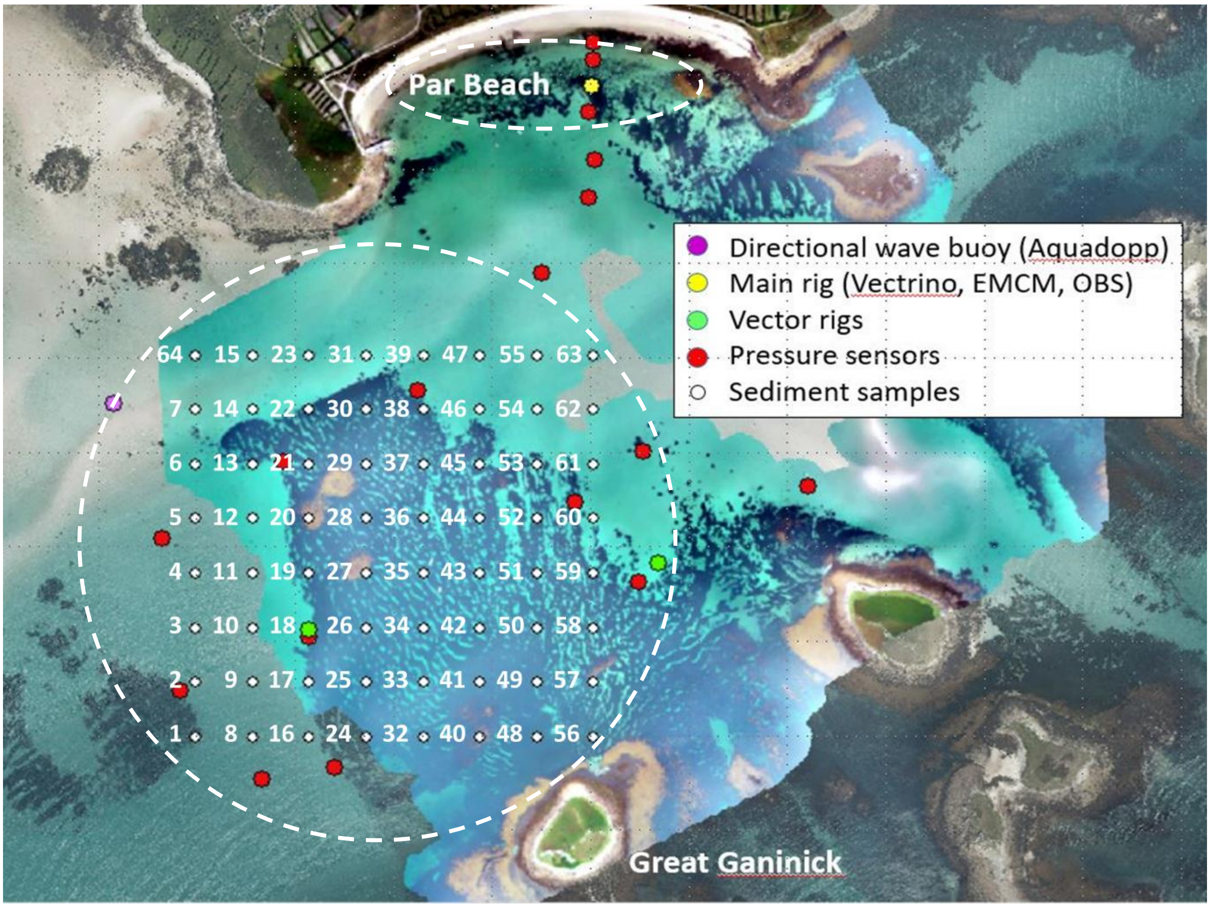


Figure 3: Field Site Map. White circles indicate study sites. Sampling was carried out on the seagrass patch south of the beach at Higher Town Bay and the seagrass meadow north of Great Ganinick. Locations of directional wave buoys, the main rig, vector rigs, pressure sensors, and sediment sample points are displayed. The sample numbers for the large seagrass meadow are also displayed.

3.2 Laboratory Methods

Each of the 115 samples collected were divided into 2 equal parts using a Riffle Box sample splitter and re-bagged. One half of each sample was to be used in grain size analysis and the other for inorganic carbon content analysis as well as acting as backup sample.

Each sample in turn was separated using a 1-micron sieve into sediments of sizes <1mm (fines) and >1mm (course). Each sub-sample was weighed immediately after sieving using a 2-point balance connected to a computer. The finer sediment fraction for each sample was mixed well – stirred for at least 30 seconds with a spatula to ensure the sample was thoroughly mixed – and 3 sub-samples of a few grams each were taken and put into test vials for laser diffraction analysis. The test vials were placed in a sample rack as each sub-sample was collected. The remaining fine sediment and coarse sediment sub-samples were then bagged separately and put back with the original sample. Prior to analysis on the laser sizer, each sample vial was filled to approximately two thirds of the way to the top with deionised water. The samples were then analysed over the weekend and, after a quick quality check of the results, were discarded.

Ceramic crucibles were weighed on a 4-point balance. A representative portion from the non-sieved 'backup' sediment was taken for each sample and placed into the corresponding crucible for carbonate analysis. This was achieved through measuring the loss on ignition. The first step was to ensure all the samples were thoroughly dried, done by leaving them overnight in an oven at 105 ^{o}C. The crucibles were then reweighed and placed into a furnace set to heat up to 550 ^{o}C for 4 hours to burn off any remaining organic carbon in the sample. The crucibles were removed and reweighed and put into the furnace again, this time with it set to 950 ^{o}C for 4 hours to remove inorganic carbonates. The crucibles were weighed a final time and stored in a desiccator until the data could be checked, and then discarded. If samples could not be analysed on consecutive days, i.e., if the first step was done on a Friday and had to be left over the weekend, then they were also stored in the desiccator. The 2-burn process allows one to calculate the changes in weight between steps which can then be equated to the organic/ inorganic carbon content of each sample. As most of the organic material had been removed prior to analysis, the organic carbon content determined through this process is not representative of the true sample and thus these results were omitted.

The already sieved fine grain samples were also used in grain-size analysis using a sediment settling tube. The settling tube at Plymouth University has a length of 2.5 m and a diameter of 25 cm. A balance is installed above the tube with a catch tray suspended from it at 2.2 m (the height of the water column) below the water surface using fishing lines. The cumulative weight on the tray is recorded by the balance at a resolution of 1 mg and logged on a computer at 5 Hz. 5 to 15 grams of sediment was slightly hydrated to achieve a "sand-castle" like consistency, and then spread out evenly on a sediment delivery device. Any excess water was removed with tissue paper to prevent the sediment from dropping from the delivery device. The device was then gently placed on the surface of the water at the top of the settling tube, being careful not to disturb the wires that connect the balance to the catch plate at the bottom, and the balance was set to start recording. Once the rate of weight change on the display had significantly reduced, such that the reading remained constant for a few seconds, the balance was stopped and tared, and the next sample could then be dropped. Following each set of 10 drops the catch plate was unhooked and tipped vertically to allow the sediment to fall off and left for at least 5 mins to allow the balance to settle before continuing. Once approximately half of the samples had been dropped the sediment that had collected at the bottom of the settle tube was removed by allowing some of the water to flow out. The settle tube was then filled back up to the same water level and, after 5 minutes, analysis continued.

3.3 Analytical Methods

3.3.1 Loss on Ignition

As previously mentioned in section 3.1, most organic material was removed from the sediment samples prior to analysis. The amount of inorganic carbon in each sample was calculated as a percentage of the weight remaining following the organic burn off at 550 °C. This was achieved through a simple calculation of weight change between the post-organic and post-inorganic runs after subtracting the tare weight of each crucible. As CO_2 is lost through this process but it is the inorganic carbon – the carbonate content – that is important, the answer is multiplied by a factor of 1.3636 (Ratio of CO_3^- to CO_2 = 60/44 g mol^{-1} = 1.3636)

3.3.2 Settle Tube

Data captured by the computer connected to the balance for the settle tube was recorded as a series of text files. These were copied into a unified Excel spreadsheet with each sample occupying its own column and any negative weight readings were zeroed. The aim here was to find the median fall velocity. To find this for each sample, the max weight recorded for each was halved. This weight represents the point where half of the sediment particles have already settled, and the other half are still suspended. Using the simple equation $speed = \frac{distance}{time}$, where d=2.2 m and knowing the frequency of the recordings being 5 Hz, a settle velocity was assigned to each incrementing weight measurement for each sample.

The median settle velocities were then converted into a median diameter to allow comparison of the two grain function analyses (Settle tube vs Laser sizer). This was achieved using a 7th order polynomial (equation 2) derived from the equation by Ferguson and Church (2004) that expresses settling velocity as a function of sediment size (equation 1), where *w* is settle rate in m s^{-1}, D is diameter in m, *R* = submerged specific gravity (1.65 for quartz in water), *g* = acceleration due to gravity (9.8 m s^{-2}), ν = kinematic viscosity of the fluid (1.0 x 10^{-6} kg m^{-1} s^{-1} for water at 20°C, C_1 = 20 and C_2 = 1.1:

$$w = \frac{RgD^2}{C_1\nu + \left(0.75C_2RgD^3\right)^{0.5}} \qquad \textbf{(Eq. 1)}$$

$$D = A + Bw + Cw^2 + Dw^3 + Ew^4 + Fw^5 + Gw^6 + Hw^7 \qquad \textbf{(Eq. 2)}$$

Where: A = 0.03561856014511 B = 0.10163559543580 C = -0.01749790005660
D = 0.00362080863528 E = -0.00038504423114 F = 0.00002410565667
G = -0.00000079928527 H = 0.00000001082329

The first sample had a median settle velocity of 0.021 m/s, which after converting to the correct units and plugging into the equation gives a median grain size of 197.3 microns.

3.3.3 Laser Sizer

For each of the three subsamples per sample that underwent laser diffraction five measurements were taken resulting in a total of fifteen readings per sediment sample and, using Excel, any outliers were removed (Figure A.1 in appendix). Once all outliers had been removed, to supplement the grain size data from the laser diffractor, the sieving data collected previously was incorporated. The collective data was then further processed using Gradistat (S.J., Blott and K., Pye, 2001), a grain size distribution and statistics package within Excel. The resulting data was a comprehensive analysis of the grain size for each sediment sample, including mean and median diameter, sorting, and skewness for a variety of method of moments (arithmetic, geometric, logarithmic) including Folk and Ward methods, as well as a classification of the type of sediment. The most applicable method of moment; geometric (S.J., Blott and K., Pye, 2001) was chosen for the next step of data analysis.

3.4 Statistical Methods

The following sets of data were conglomerated into a unified excel spreadsheet; Inorganic carbon %; Coarse grain %; Median settle velocity; Median grain size calculated from settle velocity; Median grain size from laser sizer; Mean grain size; Sorting; Skewness; and Sample type. Relationships between these different parameters were investigated statistically using various methods of plotting and analysis. Firstly, a correlation matrix was created to highlight what relationships between the data sets were present. Data approached a normal distribution and differences between vegetated and unvegetated sediments were tested using a two-tailed t-test and Analysis of Variance. The student t-test was carried out on 3 parameters – mean grain size; inorganic carbon %; and median settle velocity – comparing bare sand and seagrass sediments from the large seagrass meadow (samples 1 – 64) to assess the statistical significance of the results. The ANOVA test was also carried out for clarification of the t-test results. Each of these statistical tools were carried out using Excel.

4. Results

A summary of results for mean grain size, inorganic carbon content and settle velocity, as well as sorting and skewness, for each of the sample sets are displayed in table 1.

	GREAT GANINICK (MEADOW)			PAR BEACH (PATCH)		
	Bare Sand Outside	Bare Sand Inside	Seagrass Inside	Bare Sand	Seagrass	Beach and Dune
MEAN SEDIMENT SIZE (µm)						
MIN	207.18	203.27	208.85	291.38	260.80	462.46
MAX	590.87	626.14	654.44	712.69	396.10	1083.94
MEAN	378.82	358.16	278.85	451.52	301.95	757.40
CARBONATE CONTENT (%)						
MIN	2.25	11.20	10.41	3.23	8.02	0.91
MAX	25.60	20.43	20.44	11.17	12.14	1.44
MEAN	10.99	15.45	15.20	8.45	10.15	1.16
SETTLE VELOCITY (m/s)						
MIN	0.0174	0.0182	0.0156	0.0263	0.0268	0.0710
MAX	0.0775	0.0531	0.0588	0.0468	0.0334	0.1196
MEAN	0.0392	0.0328	0.0270	0.0348	0.0289	0.0982
SORTING						
MIN	1.478718	1.632294	1.649844	1.941501	1.612128	1.341602
MAX	2.270062	2.416356	2.463460	2.271113	2.149940	1.727985
MEAN	1.719797	1.957717	1.856211	2.120331	1.781601	1.608267
SKEWNESS						
MIN	-0.878466	-1.025496	-1.054600	-1.110140	0.102649	-4.219379
MAX	0.607817	0.847073	0.664146	0.567721	0.453193	-0.046834
MEAN	0.141103	0.194019	0.269710	-0.067790	0.235231	-1.638190

Table 1: Summary of Results. Results are split by geographic location and divided into the different sample subsets for each area.

Significant differences were found between sediments taken from patches of seagrass and those taken from bare sand patches in terms of sediment grain size, the inorganic carbon content and settle velocity. The densest areas of the seagrass meadow north of Great Ganinick showed an increase of the fine sediment fractions and inorganic matter in vegetated areas compared to the unvegetated areas, as well as lower mean grain sizes. The same was found to be true of the bare sand patches within the seagrass meadow compared to outside, to a lesser extent. The Folk and Ward description for all sediment samples ranged from poorly sorted medium sand to moderately well sorted fine sand, with the occasional coarse sand classification. These coarser grains were grouped primarily around the northern edge of the seagrass meadow.

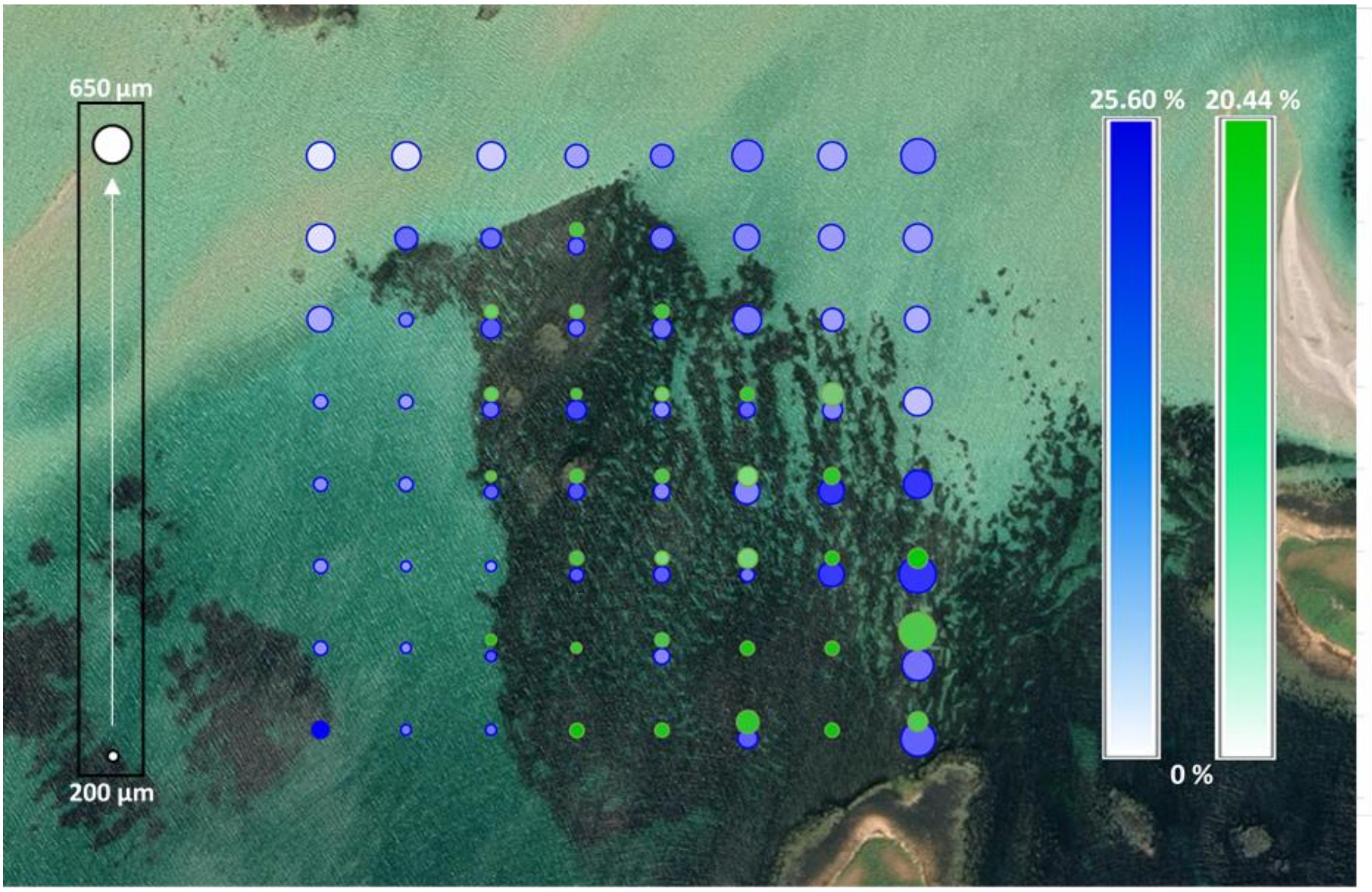


Figure 4: Mean Grain Size and Inorganic Carbon Map. Size of the points represent the relative mean sizes of the sediment grains found and the darkness of the colour of each point represents the inorganic carbon %.

Figure 4 shows the relative mean grain sizes and inorganic carbon content of the sediments taken from the seagrass meadow north of Great Ganinick. For unvegetated sediments, the smallest grains are located beyond the south-west edge of the meadow and the largest around the northern and eastern boundaries including bare sand samples taken from within the meadow at the most eastern sample points. The vegetated sediments follow a similar pattern; they are smallest on the western, more densely vegetated, side of the meadow and generally increase in size towards the east. Grain size as a function of distance from meadow edge was investigated but due to difficulty defining the edge this data was omitted. For inorganic carbon content, the highest percentages were found in the densest part of the meadow (i.e., the lower-mid/ lower-right areas of the meadow).

Grain sizes were found to be normally distributed for all sample types across both locations with slight positive skewness (Figure 5). For the Great Ganinick seagrass meadow seagrass sediments make up the majority of the finest fractions with the bell curve shifted left of the two bare sand curves. For the Par beach sediments similar distributions are observed but to a much lesser extent. Here, the distribution of fractions is similar, the difference being seagrass sediments having much higher percentages of the same fractions as the bare sand sediments. The noticeable difference is the distribution of beach and dune sediments which represents much larger grain sizes.

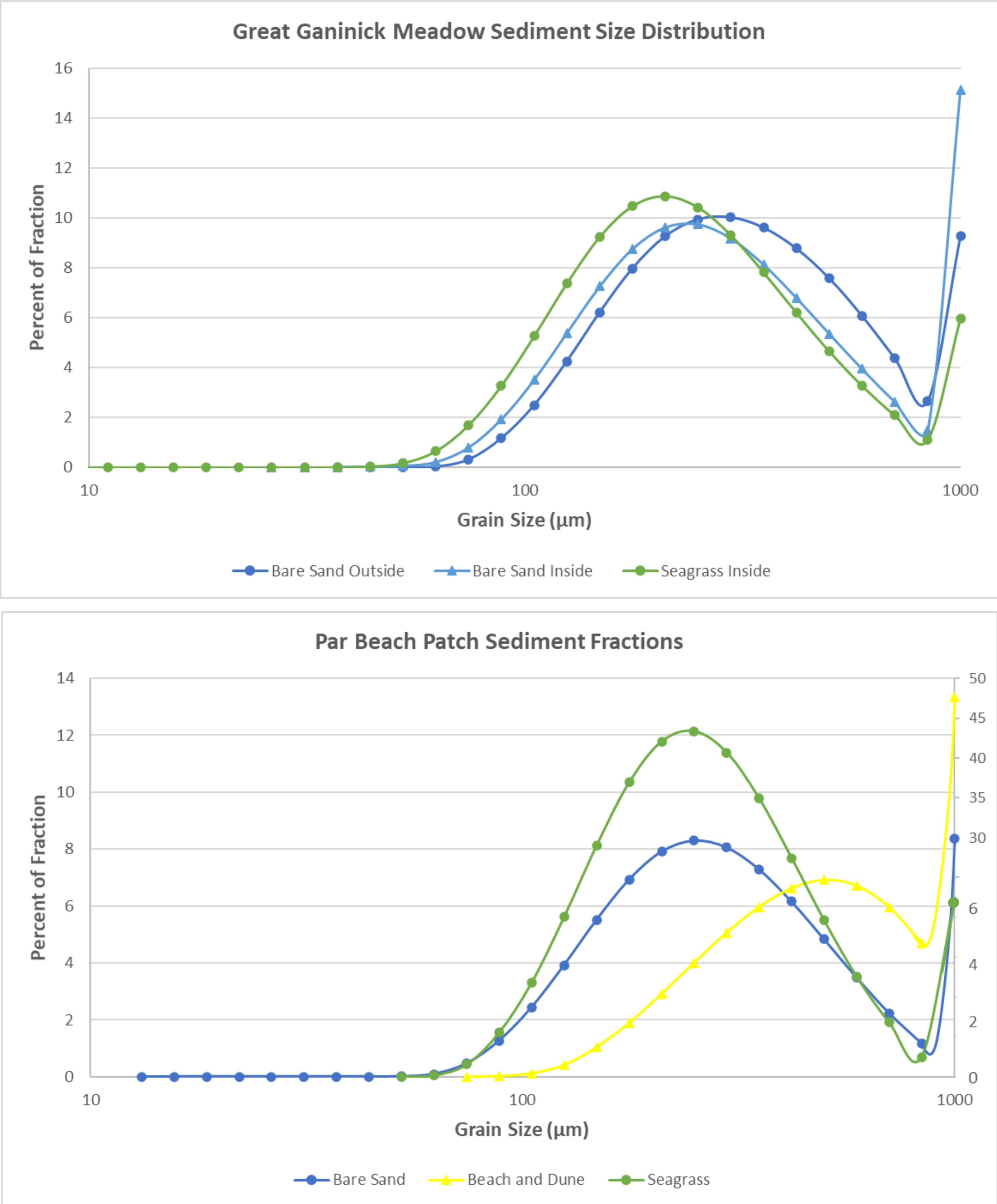


Figure 5: Sediment Grain Size Distribution. Average percentages of different grain sizes for the seagrass meadow north of Great Ganinick (top) and the dune line from Par Beach (bottom). This table incorporates data from the laser sizer (everything below 1000 microns) and the sieving data (1000 microns and above).

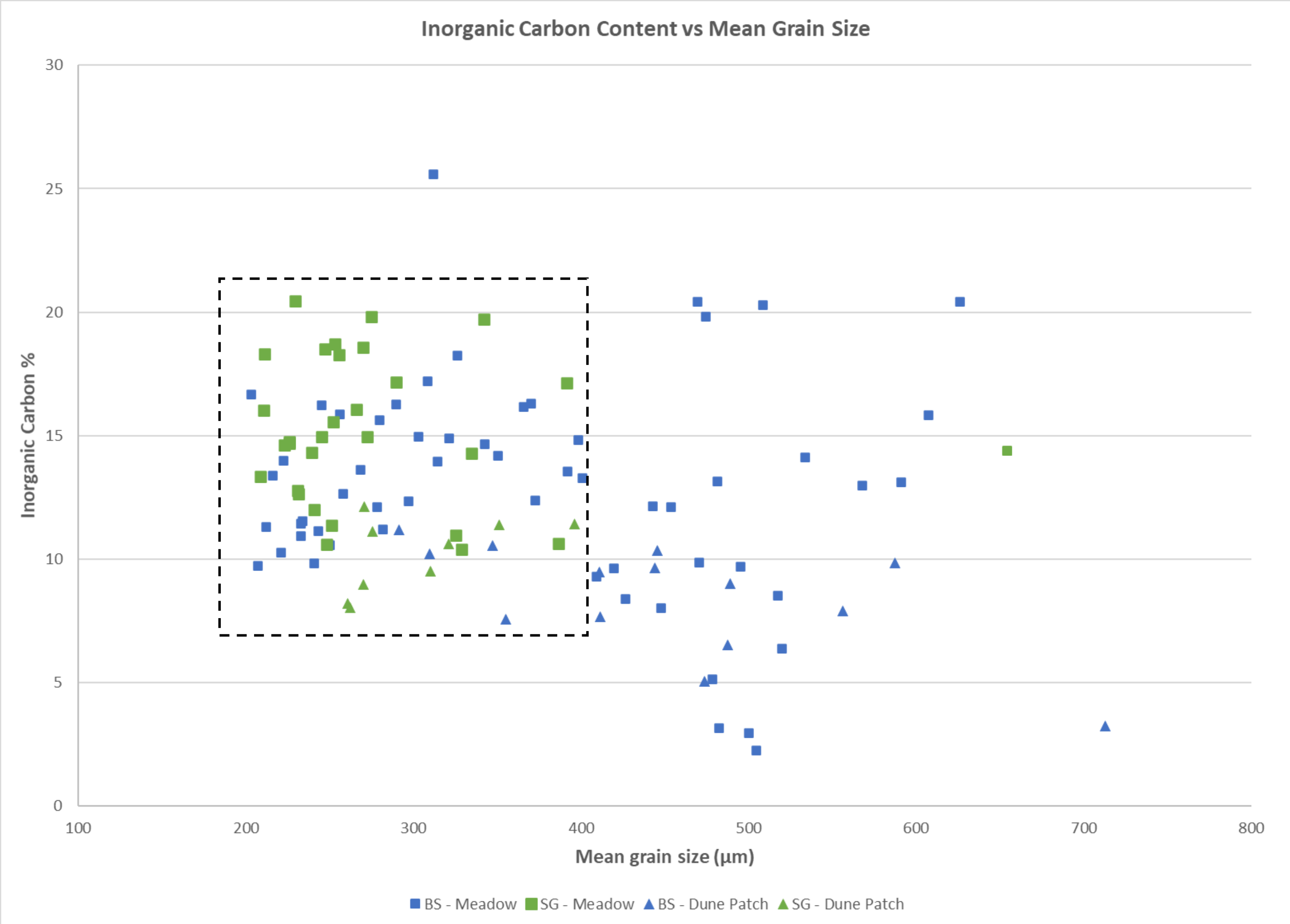


Figure 6.1: Scatter Plot of Inorganic Carbon Content versus Mean Grain Size. Samples from both locations are represented. Note the grouping of seagrass sediments highlighted by the dashed box.

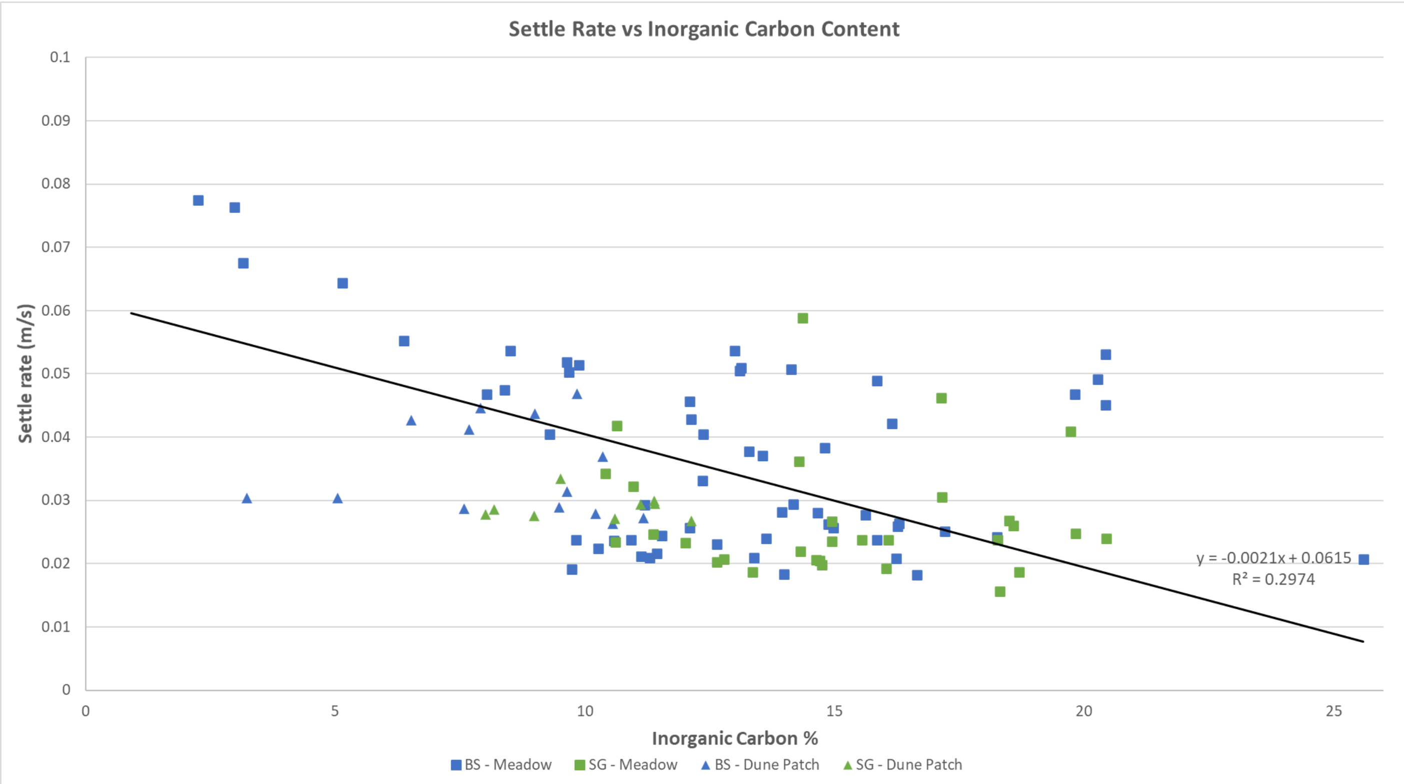


Figure 6.2: Settle Rate versus Inorganic Carbon Content. Seagrass sediments are closely grouped as denoted by the dashed box.

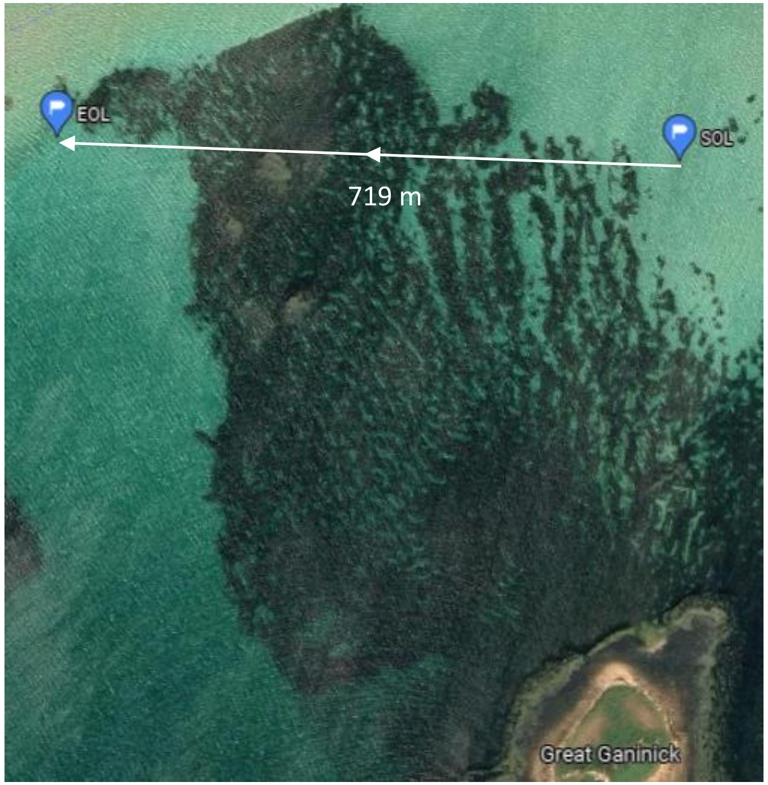
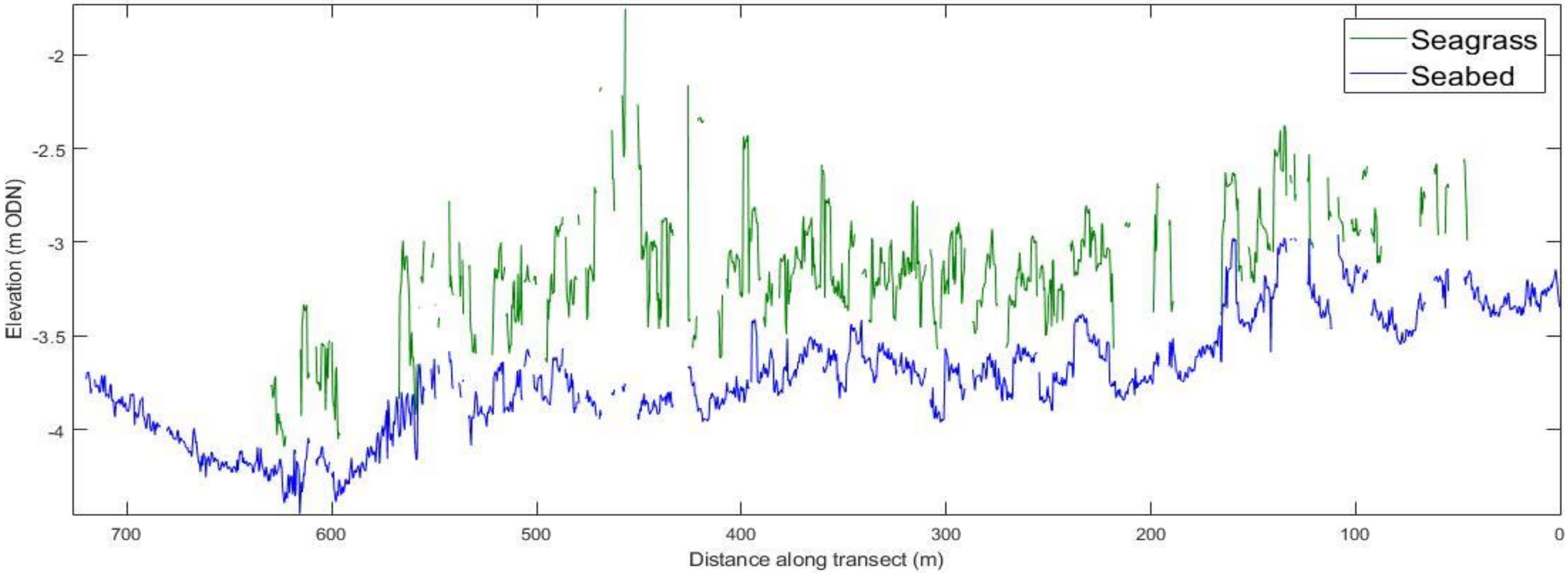


Figure 7: Topographic data for Great Ganinick Seagrass Meadow. (Right) Satellite image of the seagrass meadow including the transect line and direction in which topographic data was retrieved. (Below) Processed topographic data that displays the height of the seabed where seagrass is both present and absent. Note the relationship between presence of seagrass and increased bed elevation.



Inorganic carbon content was plotted against mean grain size and settle velocity as shown in figures 6.1 and 6.2. In the former, grouping of the seagrass sediments is evident (denoted on graph) with all but a single outlier being situated between 200 and 400 microns. The spread for unvegetated sediments is much greater for both locations. Inorganic carbon content was found to have a negative correlation with settle velocity (as shown in the correlation matrix - Table 2). This is visualised in figure 6.2 where settle rate is observed to decrease as inorganic carbon content increases, with a coefficient of determination of ~30 %. Grouping of the seagrass sediments is again evident around a settle rate of 0.02 – 0.04 m/s. The observed trend can be explained by the morphology of the inorganic materials; they have non-uniform shapes (i.e., shell material) that increase drag whilst settling.

Figure 7 represents the topographic data from the transect line shown in the satellite image. The total distance of the line is approximately 720 m. There is a significant difference evident in the height of the seabed where seagrass is located compared to where it is absent, up to 30 cm in some areas.

The data collected was applied to a correlation matrix as displayed in Table 2.

	Mean	*% Inorganic Carbon*	*Median Settle Rate*	*% Coarse*	*SORTING*	*SKEWNESS*
Mean	1.00					
% Inorganic Carbon	-0.45	1.00				
Median Settle Rate	0.88	-0.55	1.00			
% Coarse	0.84	-0.24	0.59	1.00		
SORTING	0.17	0.35	-0.12	0.46	1.00	
SKEWNESS	-0.88	0.39	-0.82	-0.78	-0.01	1.00

-1 **1**

Table 2: Correlation Matrix. Table displaying correlations between data sets. Colour scale represents strength of the correlation with 1 representing a strong positive correlation and -1 a strong negative correlation.

The strongest positive correlations exist between mean grain size and settle rate, and proportion of coarse material. Medium positive correlations are present between settle rate and coarseness as well as sorting and coarseness. Strong negative trends were found between skewness and mean grain size, settle rate, and coarseness. Medium negative correlations were found between inorganic carbon content and mean grain size and similarly with settle rate.

Figure 8 represents the results of the student t-test on various parameters. Figure 8.1 displays the statistical analysis of mean grain size, inorganic carbon content, and settle rate for the sediments taken from the Great Ganinick seagrass meadow. Highly significant statistical differences in mean grain size, inorganic carbon content, and settle velocity were found for vegetated areas compared to unvegetated areas ($p < 0.05$), with the greatest confidence in the sediments found at seagrass patches within the meadow compared to bare sand sediments outside of the meadow. The results indicate that the sediment representing the bare patches in the seagrass meadow is the same material as the bare sand outside the meadow. This means that the sediments found at seagrass patches, which represent positive relief features, are deposited on top of the original material, which in turn leads to increased surface elevation (as shown in figure 7). Similar results are seen for the Par Beach seagrass patch as shown in figure 8.2. The similar trends observed between sites are confirmed in figure 8.3; a comparison of the combined vegetated and unvegetated sediments for both sites which shows no statistically significant difference between the two sites in terms of grain size and settle velocity, but a statistically significant difference in inorganic material is present.

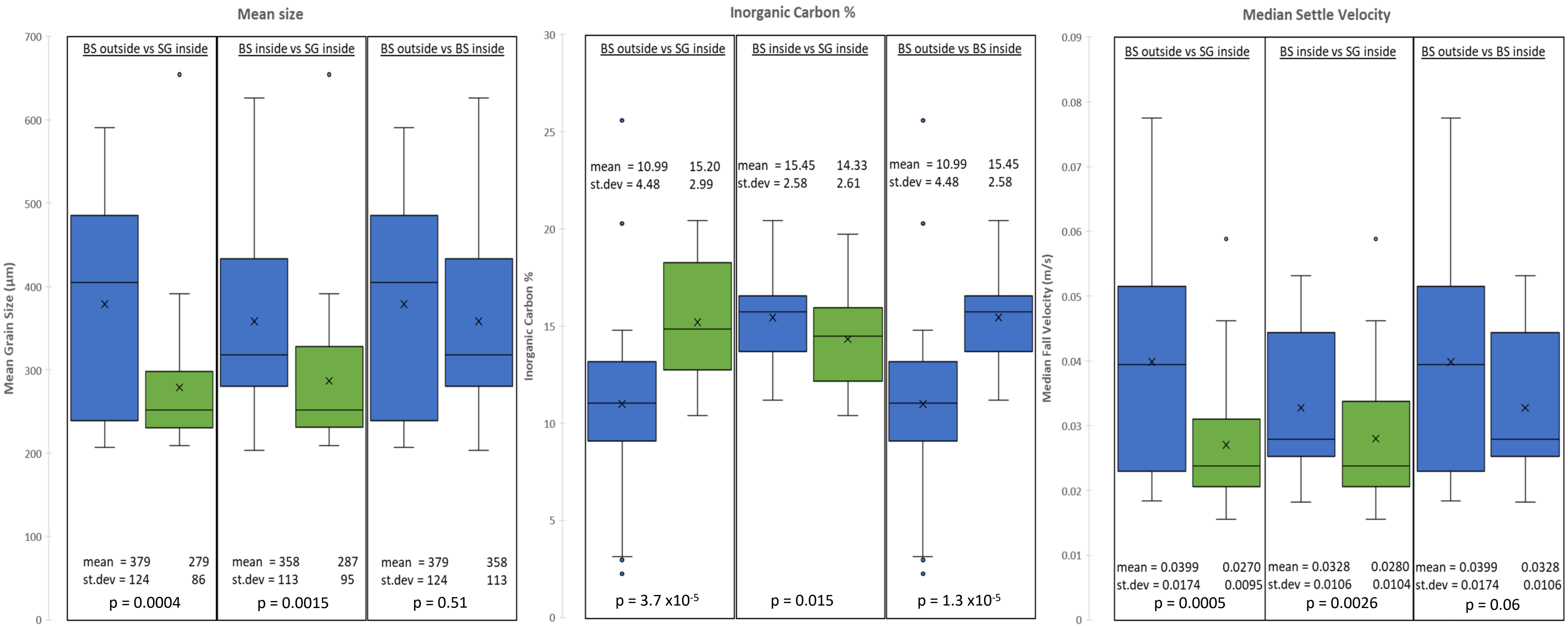


Figure 8.1: Boxplots of Seagrass Meadow Statistics. (Left) Plot of mean grain size distribution including statistical significance and outliers. (Middle) Plot of inorganic carbon content. (Right) Plot of settle rate. Within each parameter, from left to right; Bare sand outside the meadow vs seagrass inside; bare sand and seagrass pairs within the meadow; Bare sand outside the meadow vs bare sand inside. The line through each box represents the median value, and X is the mean value which is displayed along with the standard deviation. P values represent the statistical significance of the data according to the student t-test where traditionally if $p < 0.05$ the null hypothesis can be disregarded. Bare sand samples are in blue and seagrass sediments are in green.

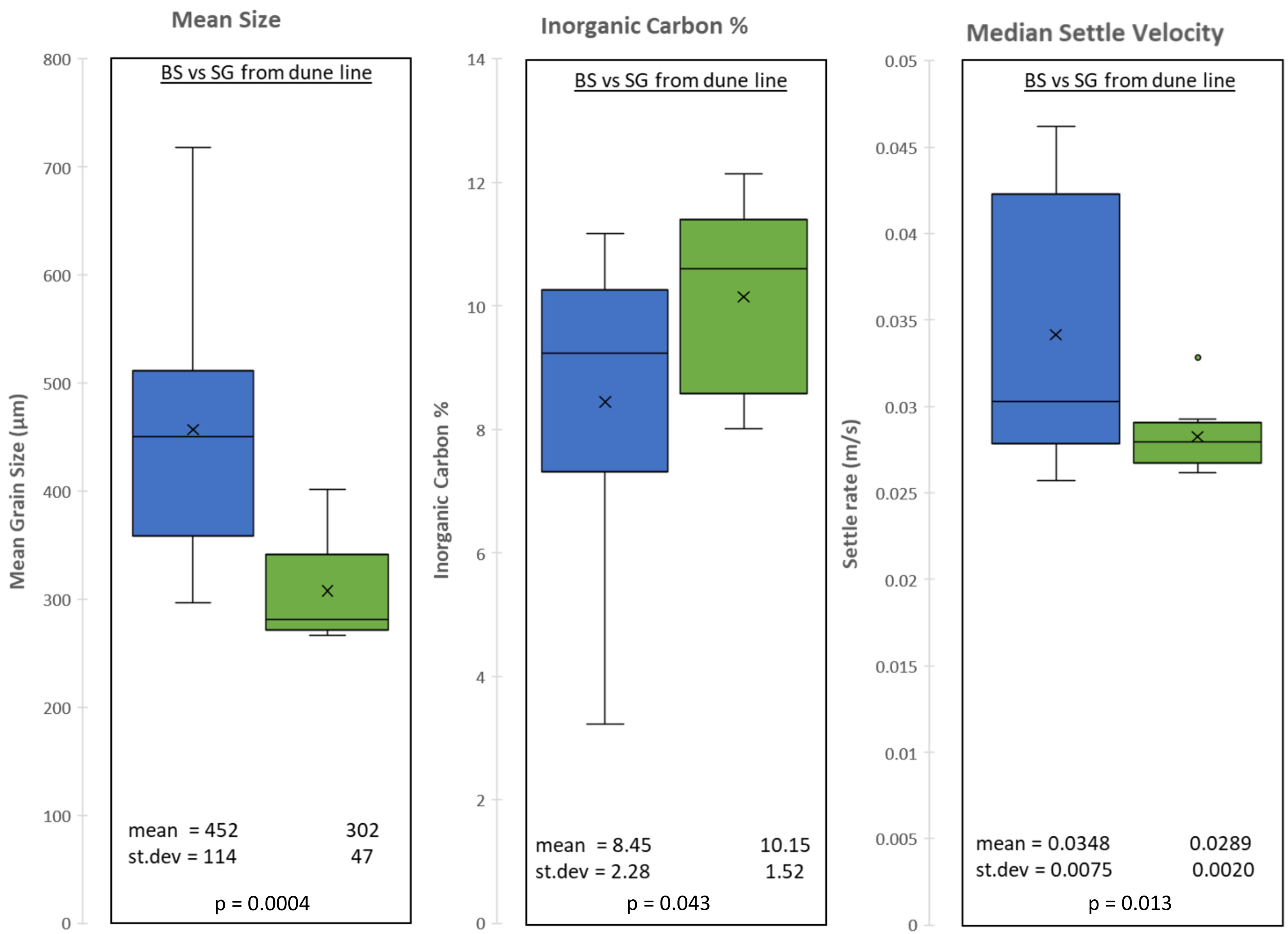


Figure 8.2: Boxplots of Par Beach Patch Statistics. (Left) Plot of mean grain size distribution including statistical significance and outliers. (Middle) Plot of inorganic carbon content. (Right) Plot of settle rate. The line through each box represents the median value, and X is the mean value which is displayed along with the standard deviation. P values represent the statistical significance of the data according to the student t-test where traditionally if $p < 0.05$ the null hypothesis can be disregarded. Bare sand samples are in blue and seagrass sediments are in green.

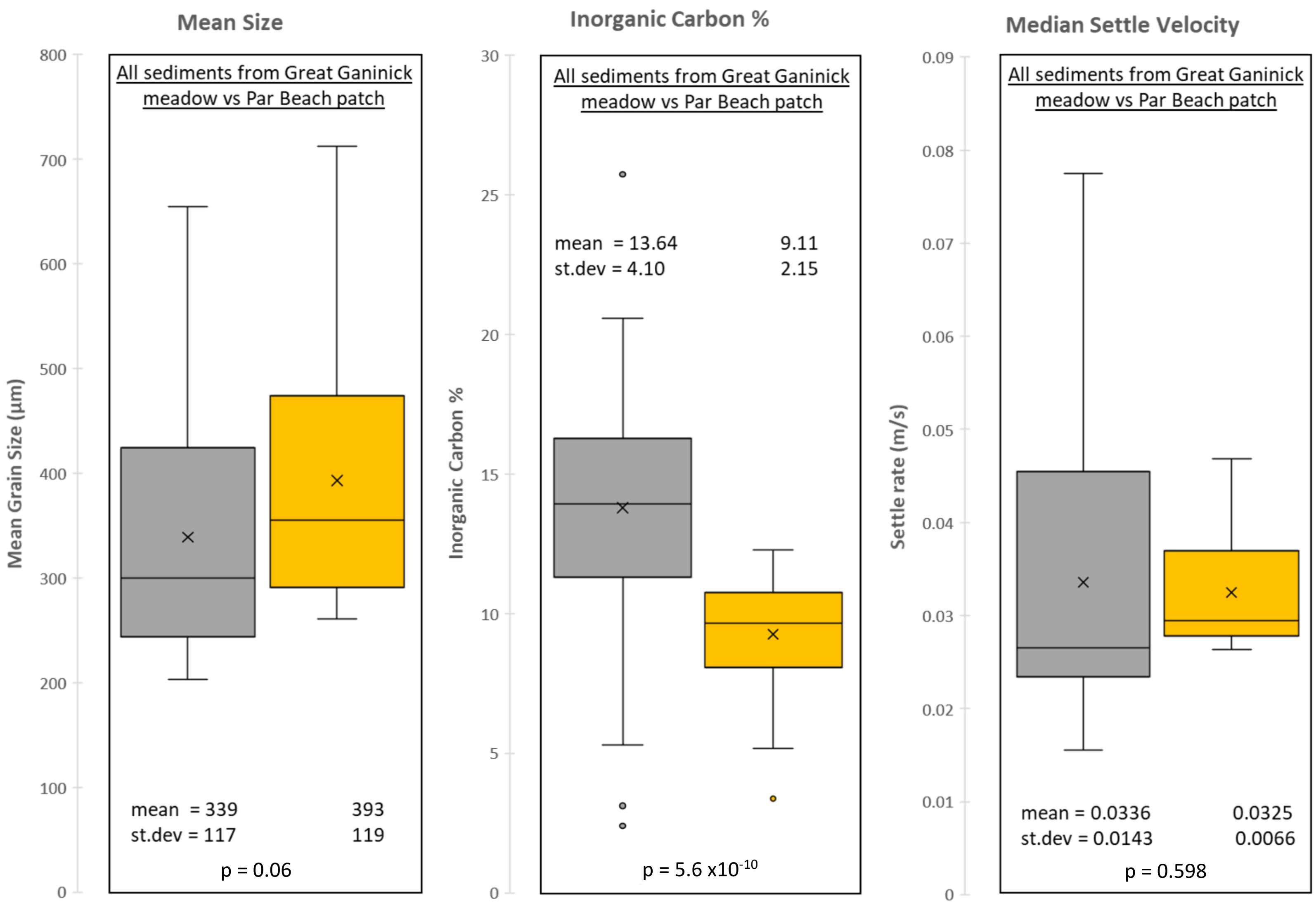


Figure 8.3: Boxplots of collective sediment comparisons for both sites. (Left) Plot of mean grain size distribution including statistical significance and outliers. (Middle) Plot of inorganic carbon content. (Right) Plot of settle rate. The line through each box represents the median value, and X is the mean value which is displayed along with the standard deviation. P values represent the statistical significance of the data according to the student t-test where traditionally if $p < 0.05$ the null hypothesis can be disregarded. Great Ganinick meadow sediments are in grey and Par Beach patch sediments are in orange.

5. Discussion

The present study confirms the previously stated hypothesis that, for sub-tidal environments, seagrasses do alter the characteristics of sediments such that they are finer and higher in inorganic carbon than those found at unvegetated sites.

The results indicate that within a seagrass meadow, specifically where seagrass is located, there is an increase in finer grains compared to unvegetated regions ($p = 0.0004$) such that the mean grain size for vegetated areas is ~100 microns less than those found from bare sand (Figure 8.1). When comparing vegetated areas to unvegetated areas within the seagrass meadow (i.e., where sediments were collected in pairs) an increase in finer grains was still observed such that the mean grain size was ~70 microns less ($p = 0.0015$). Looking at the differences between the unvegetated regions within the seagrass meadow and the unvegetated areas outside the meadow highlights a possible slight increase in finer material within the seagrass meadow such that those found within were on average ~20 microns smaller than those outside, however this comes with a very low statistical significance where $p > 0.05$ ($p > 0.50$) so must be attributed to random chance. As stated previously in the section 4, this suggests that the finer material found at vegetated regions is being deposited on top of the coarser material, which itself results in an increase in the bed height. This is confirmed by the topographic data in figure 7 that shows an increase in bed height where seagrass is located, which is in line with previous studies (Ondiviela et al*.,* 2014; Potouroglou et al*.,* 2017) that found significant differences in the bed height for vegetated patches on an annual scale. Analysis of variance (Table A.1 in appendix) on mean grain size of the three categories; bare sand outside the meadow, bare sand inside the meadow, and seagrass inside the meadow resulted in a high probability of statistical significance ($p = 0.00132$).

An increase in the inorganic carbon content of the sediments found at vegetated sites compared to unvegetated sites was observed ($p = 0.000037$) with a ~50 % increase from 10.99 % to 15.20 % in the average inorganic carbon content, however, between vegetated and unvegetated areas within the meadow a slight decrease in inorganic carbon was measured with vegetated sediments containing 14.33 % and unvegetated sediments containing 15.45 % ($p = 0.015$). The t-test revealed a high statistical significance ($p = 0.000013$) in the increase of inorganic material found for bare sand patches inside the seagrass meadow compared to outside, such that bare sand inside the meadow contained ~50 % more inorganic material than outside (10.99 % outside vs. 15.45 % inside). This suggests that regardless of where the sediments within the meadow came from (bare sand or seagrass) they will contain more inorganic material than sediments located outside of the meadow. This aligns with previous findings by Gacia et al. (2003) who found that inorganic material concentrations in seagrass leaves increased with seagrass age and leaf size, and Ricart et al. (2015) who found that carbon stocks were approximately 20% higher inside a seagrass patch compared to bare sediments. Spatially, the highest percentages were found in the densest part of the meadow (i.e., the lower-mid/ lower-right areas of the meadow in figure 4).

The average median settle velocity for vegetated sediments at the seagrass meadow was shown to be ~25 % slower than that of the bare sand sediments with settle rates of 0.0270 m/s and 0.0399 m/s respectively ($p = 0.0005$). Similar yet less significant results were found for the two sediment types within the meadow. Bare sand sediments within the meadow had an average settle velocity of 0.0328 m/s compared to 0.0280 m/s for the seagrass sediments ($p = 0.026$). There was also an observed difference in the settle velocities between the bare sand sediments outside the meadow and inside the meadow such that those inside had a mean settle velocity of 0.0328 m/s compared to 0.0399 outside, however the t-test revealed a probability where $p > 0.05$ ($p = 0.06$) so this cannot be confirmed as a statistically significant result. These findings are in line with previous research by Van Katwijk et al. (2010) who found that, at wave-exposed sandy sites like that of those found at the Isles of Scilly, dense vegetation caused an increase in fine sediments and organic content and Peterson et al. (2004) who's research into the hydrodynamics involved with seagrass meadows concluded that greater canopy density resulted in greater flow reductions – thus allowing finer sediments to settle. The spatial trends observed in figure 4 can are also backed by Van Katwijk et al. (2010), such that not only are the finest grains located within the densest areas, but that sparsely vegetated areas led to a decrease in fine sediments and organic materials. For inorganic carbon content, the highest percentages were found in and around the densest areas of the meadow.

The results from the seagrass meadow sediments were consistent with the smaller seagrass patch located south of Par Beach (Figure 8.2) where the sediments found at the vegetated areas were on average 150 microns smaller than the bare sand sediments ($p = 0.0004$) and there was an approximately 25 % increase in inorganic material from 8.45 % to 10.15 % ($p = 0.043$). For settle velocity the findings were again similar to the other site with a settle velocity of 0.0289 m/s for the vegetated sediments and 0.0348 m/s for the unvegetated sediments ($p = 0.013$).

Comparing the overall sediments of the two survey sites together (figure 8.3) reveals no significant trends between locations in terms of mean grain size or settle rate ($p > 0.05$), meaning the two data sets support one another. However, there was a high statistical significance in the inorganic carbon content between the sediments of both sites. The seagrass meadow, including both vegetated and unvegetated sediments, had a mean inorganic carbon content of 13.64 % compared to 9.11 % for the seagrass patch ($p = 5.6 \times 10^{-10}$). This could be attributed to the increased size of the seagrass meadow relative to the seagrass patch: the sediment trapping ability of the meadow is greater given the bigger area, i.e., denser seagrass patches result in greater wave attenuation leading to more effective sediment deposition. To investigate this the seagrass sediments of the meadow and patch were compared using the student t-test, and despite the seagrass meadow having a mean grain size of 279 µm and the seagrass patch 302 µm, the probability of this finding being statistically significant was low ($p = 0.598$). This difference could then be attributed to accumulation of carbonates produced by epiphytes on the seagrass leaves as opposed to influx from outside (Frankovich and Zieman, 1994; Canals and Ballesteros, 1997).

6. Conclusion

At both locations significant differences in grain size of 100 microns and greater between the sizes of sediment grains was found in vegetated areas compared to unvegetated sites, including 20 – 50 % greater amounts of inorganic material critical for the ecosystem that exists within a seagrass meadow. The greatest differences were found between bare sand and vegetation in the densest parts of the meadow and in some cases, where the meadow was particularly patchy, the opposite was observed with grains being bigger than those outside the meadow.

Topographic data in conjunction with the sediment analysis reveals that seagrass patches do increase the height of the seabed where they are present such that, in places, the seabed was 30 cm higher than adjacent bare sand patches.

7. Acknowledgements

I would like to thank Richard Hartley for his assistance with the laboratory work and guidance in data processing, as well as my supervisor, Gerd Masselink, for his guidance and feedback throughout the project.

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9. Appendix

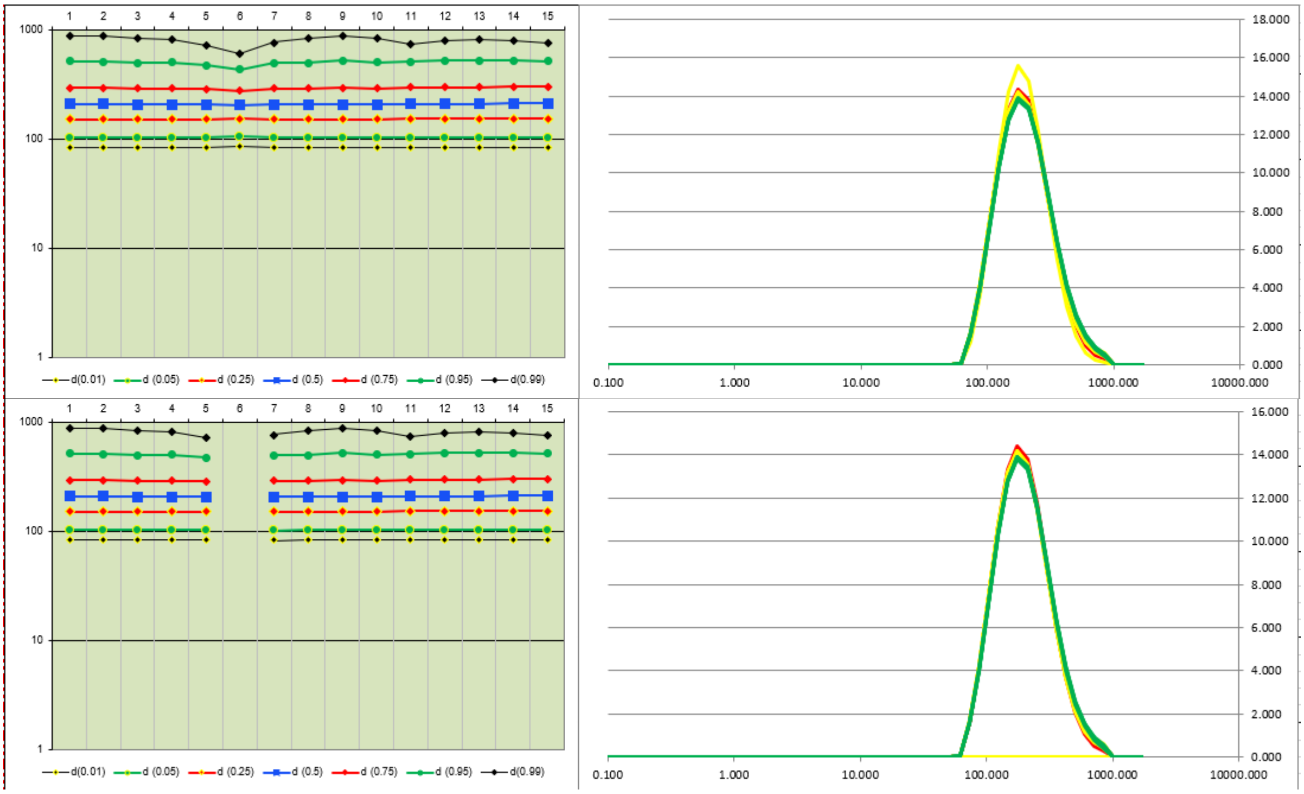

Figure A.1: Example of single outlier removal of laser diffraction data. (Top = before, Bottom = after)

SUMMARY

GROUPS	*Count*	*Sum*	*Average*	*Variance*		
BS OUT	34	12879.78	378.8171	15339.57		
BS IN	24	8595.954	358.1648	12701.56		
SG IN	30	8365.488	278.8496	7451.931		

ANOVA

SOURCE OF VARIATION	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
BETWEEN GROUPS	171259.6	2	85629.79	7.174872	0.00132	3.103839
WITHIN GROUPS	1014448	85	11934.68			
TOTAL	1185707	87				

Table A.1: Analysis of Variance on Great Ganinick Seagrass Meadow.