

# 1 **Vegetation interactions with geotechnical properties and erodibility of salt marsh sediments**

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3

## 4 **Abstract:**

5 Salt marshes provide diverse ecosystem services including coastal protection, habitat provision and  
6 carbon sequestration. The loss of salt marshes is a global scale phenomenon, of great socio-economic  
7 concern due to the substantial benefits that they provide. However, the causes of spatial variability in  
8 marsh loss rates are inadequately understood for the purposes of predicting future ecosystem  
9 distributions and functions under global environmental change. This study investigated the  
10 relationship between the presence of different saltmarsh plants and the mechanical properties of the  
11 underlying substrate that relate to its vulnerability to erosion. Relationships between three halophytes  
12 (*Puccinellia spp.*, *Spartina spp.* and *Salicornia spp.*) and sediment stability were assessed and  
13 compared to unvegetated substrates using *in-situ* and laboratory tests of substrate geotechnical  
14 properties and sediment characteristics. Sampling was conducted at two UK sites with contrasting  
15 sedimentology, one sand-dominated and one clay-rich. Sediment samples, collected simultaneously  
16 with measurements of shear strength, were analysed for moisture content, particle size and organic,  
17 carbonate and mineral compositions. These data were then used to explore the contribution of plant  
18 type, alongside the sedimentological parameters, to measured shear strength.

19 Shear strength of the sediment varied between and, to a lesser extent, within sites, with the four cover  
20 types having a similar effect on shear strength within sites relative to each other. Sediments covered  
21 by *Puccinellia spp* exhibit the highest shear strength, while bare sediments exhibit the lowest. The  
22 effect of vegetation type on shear strength was greater in the coarser sediments of Warton Sands.  
23 Surface cover type made a significant contribution to exploratory statistical models developed for the  
24 prediction of sediment shear strength. The findings support existing recognition that vegetation can  
25 enhance sediment shear strengths but extend the insight to reveal differences in this effect that show  
26 generality between sedimentological settings. Further, the combination of methods provides insight  
27 into the fundamental mechanics by which various measures of sediment stability may be affected by  
28 different surface cover types. Cohesion appears to be a more appropriate descriptor of sediment  
29 erodibility than shear strength or friction angle and is most greatly enhanced by the presence of a fine,  
30 fibrous root system such as that of *Puccinellia*. A more detailed understanding of the multi-scale  
31 mechanisms by which plants confer strength to substrates is needed to better anticipate their impact  
32 on sediment erodibility, and therefore salt marsh vulnerability.

## 33 **Introduction:**

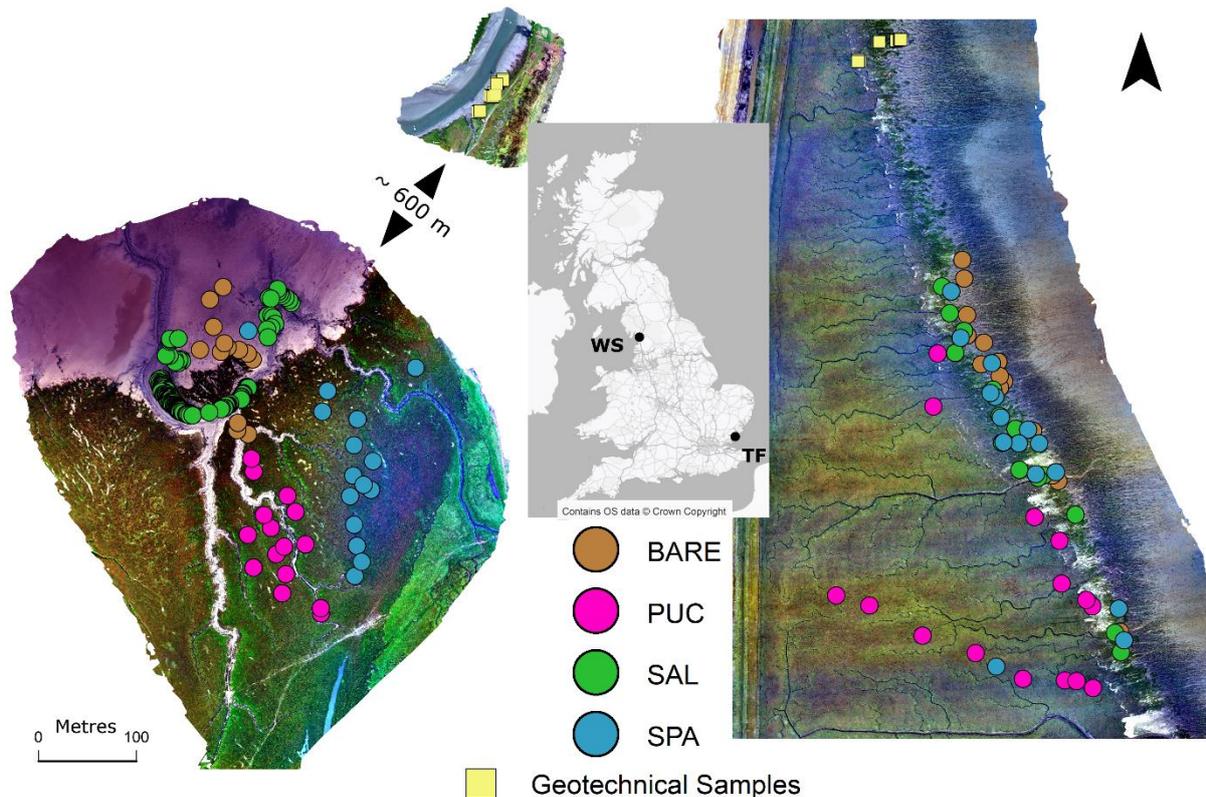
34 Salt marshes are highly valuable coastal biogeomorphic systems with global distributions on both  
35 temperate (McOwen et al., 2017) and tropical (Friess et al., 2012) coasts. They provide functions  
36 which include coastal protection (Fagherazzi, 2014, Möller et al., 2014) and carbon sequestration  
37 (Chmura, 2013) The long-term persistence of these landforms and their associated biota is of  
38 paramount importance in the context of global environmental change, yet they are commonly  
39 thought to be highly vulnerable to factors such as sea level rise and increased wave exposure  
40 (Crosby et al., 2016; Leonardi et al., 2016). An important, but still poorly understood, factor in  
41 determining marsh persistence, particularly in terms of lateral erosion processes occurring at their  
42 seaward margins, is the stability of the sediments in response to hydrodynamic forcing. This is widely  
43 recognised as fundamental for the prediction of morphological change (Brooks et al., 2021). The  
44 geotechnical attributes of a substrate (the parameters describing the ways in which it deforms and

45 fails when force is applied) are important for understanding its response to hydrodynamic forcing.  
46 These attributes are, however, difficult to measure and observe across the large areas required to  
47 capture the spatial heterogeneity in factors controlling marsh margin erosion rates. There is also  
48 increasing recognition that salt marsh vegetation plays an important role in determining substrate  
49 stability (Bernik et al., 2018; Chen et al., 2019; Ford et al., 2016), with the influence of vegetation  
50 being stronger in coarser sediments (De Battisti et al., 2019; Lo et al., 2017a). Grazing or mowing  
51 regimes that favour the establishment of plants with high root density have been shown to reduce  
52 the erodibility of marsh sediment under flume conditions (Marin-Diaz et al., 2021) Wang et al. (2017)  
53 also found belowground biomass and vegetation species to affect sediment erodibility in a flume  
54 context. Many of these studies use flumes or cohesive strength meters to observe the erosion  
55 resulting from particular flows of water. These observations, however, don't elucidate the processes  
56 by which the vegetation confers strength to the substrate and don't furnish estimates of shear  
57 strength and are thus difficult to incorporate into numerical simulation frameworks. This study  
58 therefore applies a range of geotechnical measurement approaches to different vegetation species  
59 and sediment types to provide mechanistic insight to the ways in which different plant species  
60 modify the properties of sediments. This study investigates whether different species of saltmarsh  
61 plant, exhibiting different growth forms and root structures (Chirol et al., 2021a), produce different  
62 controls on substrate geotechnical properties and sediment erodibility. If this were to be the case,  
63 then relatively simple vegetation survey methods, such as mapping from aerial or satellite imagery,  
64 might be used to characterise a component of the spatial variability in substrate properties. Such an  
65 approach would support numerical simulation, and site-based predictions, of system vulnerability to  
66 hydrodynamic/meteorological forcing. In this study, laboratory and field geotechnical measurements  
67 are applied to substrates from two types of substrate, each vegetated by three different species.  
68 Comparisons are also made to the attributes of unvegetated surfaces. In order to explore the  
69 mechanisms by which these differences may relate to the stability of larger landform units,  
70 differences in geotechnical response by surface cover type are explored, and interpreted in the  
71 context of the differing three-dimensional root network structures of the species involved (Chirol et  
72 al., 2021a). The way in which spatio-temporal vegetation distributions may affect site-scale erosion  
73 trajectories is illustrated through a conceptual model that could form the basis for numerical  
74 simulation in future work.

#### 75 [Study locations:](#)

76 Sites were selected from contrasting biosedimentary regimes representative of the approximate end-  
77 member conditions for the range of sediments observed within salt marsh systems in the UK. Warton  
78 Sands (WS), in Northwest England, sits within the wider Morecambe Bay system. It is macro-tidal  
79 environment with a mean spring tidal range of 8.49m at Heysham, 13 km from the site (National Tidal  
80 and Sea Level Facility, 2021). The WS sediments are coarse with a high proportion of sand. Tillingham  
81 Farm (TF) is an open-coast marsh located on the macro-tidal Dengie Peninsula, Essex, in the Southeast  
82 of England. Mean spring tidal range at Sheerness, 30 km from the site, is 5.21m (National Tidal and  
83 Sea Level Facility, 2021) and the sediments are finer, containing a higher proportion of clay and silt  
84 than WS (see results for sedimentological descriptions). Vegetation communities show differences at  
85 the scale of each site, but both locations contain monospecific areas of the three halophytes  
86 investigated in this study, allowing a comparison to be drawn at the patch scale. Figure 1 shows the  
87 study locations and sampling distributions.

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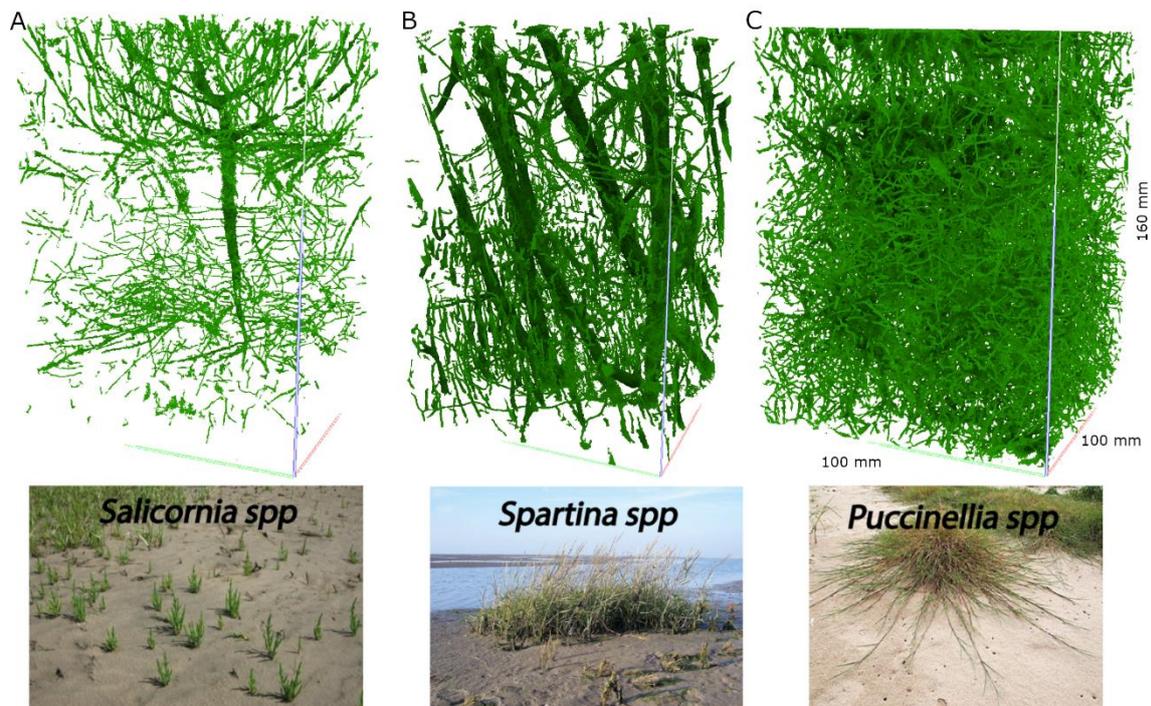


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90 Figure 1 - Study locations at Warton Sands (WS, left) and Tillingham Farm (TF, right) showing sampling locations (circles) for  
 91 shear vane and associated sedimentology for the four cover types investigated, and geotechnical laboratory sample  
 92 locations (squares). UAV orthomosaics by B Evans, left to right: 22/09/2019, 18/01/2019, 08/08/2019.

93 **Methods:**

94 Two sampling campaigns were conducted, one in Winter 2018-2019 and one in Summer 2019; in the  
 95 winter campaign undisturbed cores were extracted for laboratory testing by shear box, tor vane and  
 96 triaxial tests (square symbols, Figure 1 - Study locations at Warton Sands (WS, left) and Tillingham  
 97 Farm (TF, right) showing sampling locations (circles) for shear vane and associated sedimentology for  
 98 the four cover types investigated, and geotechnical laboratory sample locations (squares). UAV  
 99 orthomosaics by B Evans, left to right: 22/09/2019, 18/01/2019, 08/08/2019. Figure 1). In the  
 100 summer campaign, *in-situ* shear vane measurements were taken alongside sediment sampling and  
 101 ground survey to characterise vegetation distributions (circles, Figure 1). Three plant species were  
 102 investigated. These were *Puccinellia spp.* (PUC), *Spartina spp.* (SPA), and *Salicornia spp.* (SAL).  
 103 Unvegetated sediments, lacking vascular plant cover, were sampled as a control (BARE) to provide  
 104 four surface cover types at each site. The plant species were selected because they have contrasting  
 105 root morphologies. *Salicornia* has a sparse tap root structure, *Spartina* has a denser, thicker tap root,  
 106 while *Puccinellia* has a dense network of fine, fibrous roots. These differences are discussed further  
 107 in (Chirol et al., 2021a), where they are hypothesised to influence sediment characteristics in  
 108 contrasting ways. Photographs of each species and representations of the undisturbed root 3-  
 109 dimensional network maps derived from micro-CT scans of cores are presented in Figure 2 to  
 110 illustrate the morphological contrasts.



111

112 *Figure 2 - photographs (bottom) and undisturbed root network segmentations (top) for the three species investigated,*  
 113 *Salicornia (A), Spartina (B) and Puccinellia (C). Adapted from Chirolet al.(2021a), figures 2 and 3.*

114 The winter campaign was conducted on 12<sup>th</sup>-13<sup>th</sup> January at TF and 18<sup>th</sup>-19<sup>th</sup> January at WS. The  
 115 summer campaign was conducted at TF on 8<sup>th</sup>-9<sup>th</sup> August and WS on the 21<sup>st</sup>-22<sup>nd</sup> September. We  
 116 assume that the effects of the root networks on geotechnical properties follows the same relative  
 117 relationship in winter and summer, even if the magnitude of any effect may vary, since the root  
 118 networks of all species investigated persist inter-annually despite seasonal dieback of above-ground  
 119 elements. Our analysis takes into account that antecedent conditions may have resulted in  
 120 differences in moisture between sites (see below).

121 In Winter, undisturbed cores of 150 mm diameter and 150 mm depth were extracted for shear box  
 122 analysis following the careful procedure described in Chirolet et al. (2021b). The same procedure was  
 123 used to extract 100 mm diameter, 200 mm long cores for triaxial testing (BS1377: Part 8:1990  
 124 Method 7). Three replicate cores were extracted from monospecific patches of each plant type (PUC,  
 125 SPA, SAL) and unvegetated sediment (BARE). Cores were packaged in insulated, padded containers  
 126 and returned to the laboratory where they were cold stored at 5°C while awaiting analysis. Samples  
 127 were analysed sequentially, such that storage periods for some were substantially longer than for  
 128 others as a consequence of the time required for analysing each sample. This may affect the results  
 129 obtained to some extent (Tolhurst et al., 2000).

130 In summer, measurements and samples were taken within fifteen 1m<sup>2</sup> quadrats for each plant type  
 131 where the vegetation cover was monospecific or very heavily dominated by the relevant (visual  
 132 estimate of 95-100% cover). The exception was SAL at Warton, where no patches larger than 1m<sup>2</sup>  
 133 were found. Shear vane tests were therefore conducted immediately adjacent to the relatively  
 134 sparsely distributed individuals.

135 **Shear box tests:**

136 Following  $\mu$ CT scanning, the shear strength of a subset of the cores was tested using a Wykeham  
 137 Farrance Model No. 25402 shear box apparatus at the British Geological Survey, Keyworth, UK.

138 Shear box testing is time-consuming so it was not possible to test all surface cover/sediment type  
139 combinations for which samples were acquired. WS BARE and TF BARE were tested to isolate the  
140 differences in shear strength arising from the differing sediment types of the sites without  
141 vegetation influences. TF PUC and TF SPA were also tested as these have substantially different root  
142 network morphologies (Chiril, et al., 2021a) which might be expected to influence substrate shear  
143 characteristics. Cores were removed from their plastic cases and sub-sampled by the same careful  
144 trimming method as used for field collection. Three 60mm by 60mm by 20mm shear box samples  
145 were extracted at different depths along the vertical axis of each core. These three sub-samples  
146 were then tested using the standard shear box procedure to BS1377 (BSI, 1990, pp48). A normal  
147 (vertical) stress was applied to each subsample (20, 40 or 80 kPa) and the sample sheared  
148 horizontally while the imposed stress and resulting strain were monitored. Estimates of cohesion (c)  
149 and friction angle ( $\phi$ ) were calculated by fitting a least-squares regression line through the peak  
150 stress values of the three resulting stress-strain curves. Thus, the shearing of three sub-samples  
151 constitutes a single shear box test. Cohesion is represented by the intercept of the regression line  
152 while friction angle is the inverse tan of the slope coefficient. Strain rates were maintained at 0.05  
153 mm min<sup>-1</sup>, low enough to allow pore pressures to equalise during deformation, based on initial  
154 consolidation characteristics. The shear box test was, therefore, considered to be a 'drained' test. As  
155 a result of COVID-19 restrictions, it was not possible to complete all planned shear box tests and only  
156 two replicates were achieved for WS BARE and TF BARE compared to three replicates for TF PUC and  
157 TF SPA. Much of the existing literature, however, does not attempt any replication of shear box tests  
158 in order to infer geotechnical attributes (e.g. Ali & Osman, 2008; Mouazen, 2002; Wang et al., 2013;  
159 Zhou et al., 2019).

160 Figure 3 shows vertical photographs of the 60 mm square shear box cutting shoe that was used with  
161 sediments from the four surface cover types tested. Contrasting granulometry, pore and root  
162 structures are clearly visible.



163

164 *Figure 3 – Vertical photographs of Shear box samples from four surface cover types. Top left TF BARE,*  
165 *top right TF PUC, bottom left TF SPA, bottom right WS BARE. Samples are 60x60 mm and are sheared*  
166 *along the plane depicted.*

167

168 [Torvane shear testing \(laboratory\):](#)

169 During sub-sampling for the shear box tests, the cores were trimmed to a 110mm square column. A  
170 Gilson HM504-A torvane was used at two depths (centred at 50 and 100mm) on each side of this  
171 column to provide eight measurements per core which were then averaged. Further trimming was  
172 then conducted for the shear box tests. The torvane is a spring-loaded torque meter with short  
173 vanes on a circular disc. Vanes are inserted into the soil by about 5mm until the disc sits flush with  
174 the sediment surface. The handle is twisted until the sediment shears and the vanes spin. The  
175 maximum torque thus applied is read from a dial and converted to shear strength by applying a  
176 calibration factor (Jafari et al., 2019).

177 **Triaxial tests:**

178 Triaxial tests were conducted on undisturbed cores of 102mm diameter and approximately 200mm  
179 height using a GDS Labs triaxial tester to the BS1377 Part 8 (1990) standard. Tests were made on one  
180 sample from each site/surface cover type combination, resulting in eight tests being conducted.  
181 Constraining pressures of 5, 10 and 20 kPa were used to assess behaviour of these sediments under  
182 realistic ranges of hydrostatic forcing. For example, 5 kPa is equivalent to the loading from a 0.51 m  
183 column of pure water, while 20 kPa equates to 2.0 m. Thus we simulated approximate  
184 hydrostatic/hydrodynamic loadings that may be experienced by NW European marsh sediments  
185 under both normal and storm surge conditions. Wet bulk density was calculated for each sample  
186 prior to testing.

187 **Shear vane (field):**

188 Sediment shear strength was measured in the field using two H-60 vane testers. These are spring-  
189 loaded torque meters akin to the torvane except that their vanes are radial and protrude from a  
190 shaft, allowing for measurement within the sediment rather than at its surface. Vanes were inserted  
191 to a depth of 7.5 cm in order to engage with the active root layer of the vegetation. Shear strength  
192 was measured at 15 monospecific 1 m by 1 m quadrats per surface cover type (Figure 1) with ten  
193 randomly located measurements per quadrat. In the case of WS SAL, shear vane measurements  
194 were conducted immediately adjacent to 150 individual plants. The shear vane data have been  
195 previously described (Chiról et al., 2021a) but this study relates these observations to sedimentology  
196 directly associated with the shear vane sampling locations rather than proximal sediment cores.

197 **Sedimentology:**

198 Sediment samples were taken within the top 7.5cm depth at each quadrat. In the case of WS SAL,  
199 sediment samples were taken at every tenth sampling point at which the shear vane was used.  
200 samples subsampled to provide three replicates for laser particle size analysis using a Malvern  
201 Mastersizer and providing a particle size distribution (PSD), and for composition by loss-on-ignition.  
202 Loss-on-ignition was conducted at incrementally increasing temperatures of 105°C, 400°C, 480°C and  
203 950°C, with samples being heated for six hours per temperature before weighing. These furnished  
204 estimates of percentage composition of water, carbohydrates, total organics and calcium carbonate  
205 respectively.

206 **Statistical analyses:**

207 Differences in sediment shear strength and characteristics between sites and surface cover types  
208 were tested in Matlab software using the Kruskal-Wallis test followed by multiple-comparison  
209 compensation (Dunn-Sidak). To avoid inflated type 1 error rates related to pseudoreplication in the  
210 case of the shear vane and torvane, the mean of measurements from each quadrat or core  
211 respectively was used to represent that replicate in the Kruskal-Wallis tests. Since sample sizes were  
212 small and it was not possible to test for homoscedasticity between treatments, we formulated our  
213 Kruskal-Wallis tests in terms of stochastic dominance rather than differences in medians, whereby  
214 the existence of stochastic dominance implies that samples drawn from one treatment are likely to  
215 be higher than samples drawn from a contrasting treatment. Correlations between measurements  
216 acquired by different tests were used to explore how the data provided by different methods relate  
217 to each other. Exploratory modelling to investigate how different parameters affect shear strength,  
218 as measured by the shear vane, was conducted in R (R Core Team, 2013) using boosted regression  
219 trees (BRTs) and the 'gbm' package (Elith et al., 2008). The sedimentological parameters of median  
220 grain size (d50), proportion below 63µm (Below63), Kurtosis of PSD, Skewness of PSD, percentage  
221 total organics (Organics), percentage water (Moisture), and percentage Calcium Carbonate (CaCO<sub>3</sub>)  
222 alongside surface cover type (CoverType) were used as predictors for shear strength (dependent

223 variable). Given that antecedent conditions, rather than vegetation or sediment factors, are likely to  
 224 account for differences in moisture between sites, the analysis reported here focussed on within-site  
 225 controls. The boosting process introduces a degree of stochasticity to model results. Elith et al.  
 226 (2008) argue that this effect is subtle and unlikely to affect model interpretation so results from a  
 227 single training of the model are reported here. Elith et al. (2008) recommend that models should be  
 228 fitted using between  $10^3$  and  $10^4$  trees to optimise generality and control overfitting. This is  
 229 achieved by tuning the hyperparameters of tree complexity (controlling the number of branches  
 230 within each tree) and the learning rate (which controls the contribution of each tree to the ensemble  
 231 result). A tree complexity of 6 and a learning rate of 0.001 were used, typically producing models  
 232 based on between 2000 and 4000 trees. All predictors were provided to the algorithm to develop  
 233 benchmark models. The 'gbm.simplify' function was then used to drop uninformative predictors and  
 234 select a parsimonious final model that optimised performance (Miller, 2002). For exploratory  
 235 purposes, the model performance was evaluated based on the training correlation and using 10-fold  
 236 cross-validation.

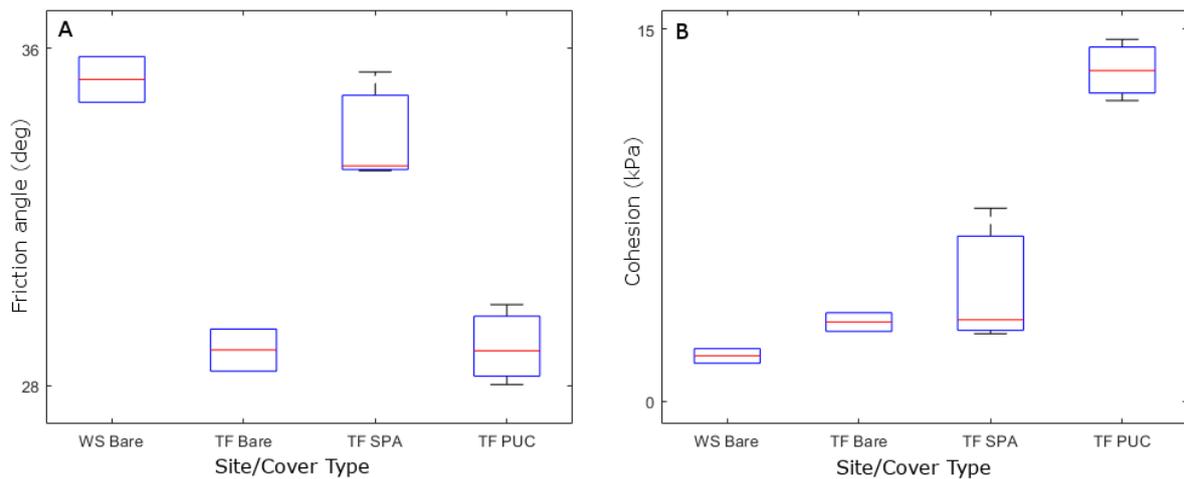
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238 **Results:**

239 **Shear box**

240 The shear box test produced estimates of cohesion and friction angle (Figure 4). A Kruskal-Wallis test  
 241 for stochastic dominance between cover types returned p-values of 0.066 for friction angle and  
 242 0.054 for cohesion. Subsequent multiple comparison analysis showed stochastic dominance in terms  
 243 of cohesion for WS BARE being lower than TF PUC.

244



245

246 *Figure 4 - Boxplots of friction angle (A) and cohesion (B) derived from shear box tests. WS BARE and TF BARE n=2, TF SPA*  
 247 *and TF PUC n=3*

248 Peak shear strength at 20 kPa normal stress correlated strongly with moisture content of the sample  
 249 prior to testing, with a Pearson's R of 0.73, while at 40 kPa and 80 kPa this correlation was weak  
 250 (R=0.18 and 0.08 respectively, n=10). Friction angle and cohesion were negatively correlated (R = -  
 251 0.66, n=10).

252

253 **Torvane:**

254 Torvane measurements taken while preparing shear box samples produced mean shear strength  
255 measurements for TF BARE of 12.27 kPa, TF PUC of 13.77 kPa, TF SPA of 13.24 kPa and WS BARE of  
256 8.91 kPa. Populations were analysed for stochastic dominance of shear strengths between surface  
257 cover types using a Kruskal-Wallis test followed by multiple comparison. WS BARE shear strength  
258 was significantly lower than all three TF cover types ( $p < 0.01$ ). No significant differences were found  
259 between the TF cover types themselves ( $p > 0.59$  in all cases).

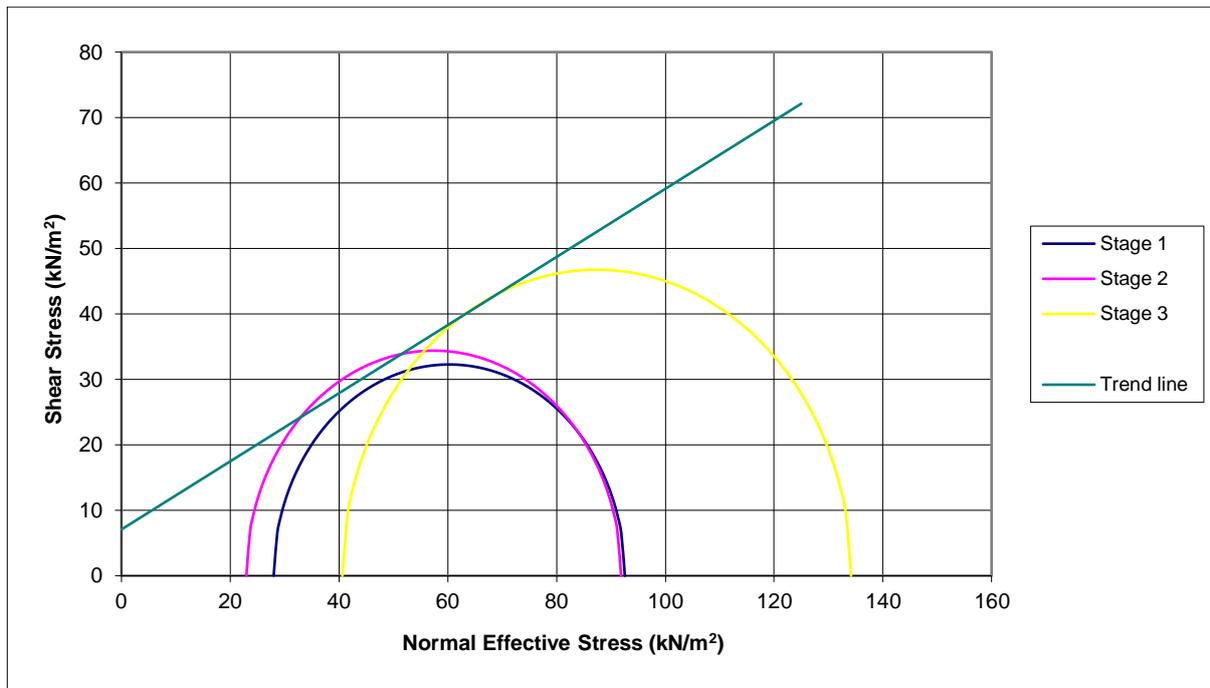
260 Torvane shear strengths correlated moderately with shear box peak shear strengths at 20 kPa  
261 normal stress, but not at 40 kPa or 80 kPa with Pearson's R of 0.58, 0.09 and 0.10 respectively.  
262 Moderate positive correlation was found between torvane shear strength and shear box cohesion ( $R$   
263 = 0.50) while a moderate negative correlation was found for friction angle ( $R = -0.44$ ). There was a  
264 moderate positive correlation between torvane shear strength and moisture ( $R=0.47$ ), driven largely  
265 by inter-site differences in moisture content.

266

267 **Triaxial tests:**

268 The narrow range of confining pressures that were adopted to test behaviour under realistic  
269 hydrostatic/dynamic pressures for surface sediments at the two sites resulted in significant overlap  
270 between Mohr circles calculated at each test stage. As a consequence, it was not possible to fit  
271 robust trendlines through these circles and six of the eight tests returned negative, or null, estimates  
272 of cohesion. Negative values of cohesion are not physically meaningful so cannot be interpreted. The  
273 tests that returned positive cohesion estimates were WS PUC and WS SPA, returning cohesion  
274 estimates of 7.08 kPa and 3.16 kPa and friction angles of 27.49° and 31.3° respectively. These values  
275 are broadly comparable to those acquired from the shear box tests, although WS PUC and WS SAL  
276 were not assessed in the shear box. Figure 5 shows the resulting Mohr circles and trend line  
277 for the WS PUC test. As is evident, a large amount of overlap still occurs in this sample. Some of this  
278 overlap arises from the fact that the equipment used was unable to maintain the effective stress to  
279 the required degree of precision. Some overlap may arise from incomplete consolidation which is  
280 typically negligible when testing across a wider range of effective stresses.

281



282

283 *Figure 5 - Mohr circles from triaxial shear test on WS PUC, with cohesion (y-intercept) of 7.08 kPa and*  
 284 *friction angle (arc-tangent of slope) of 27.49°, with substantial overlap between Stage 1 and Stage 2.*

285 Wet bulk densities for all combinations of site and cover type are shown in table XX

286 *Table 1 - wet bulk density for eight combinations of site and surface cover type derived from triaxial test samples*

Site/Cover Type combination	Wet bulk density (kg m <sup>-3</sup> )
TF_BARE	1590.79
TF_PUC	1422.68
TF_SAL	1520.04
TF_SPA	1272.32
WS_BARE	1905.44
WS_PUC	1877.99
WS_SAL	1851.73
WS_SPA	1731.29

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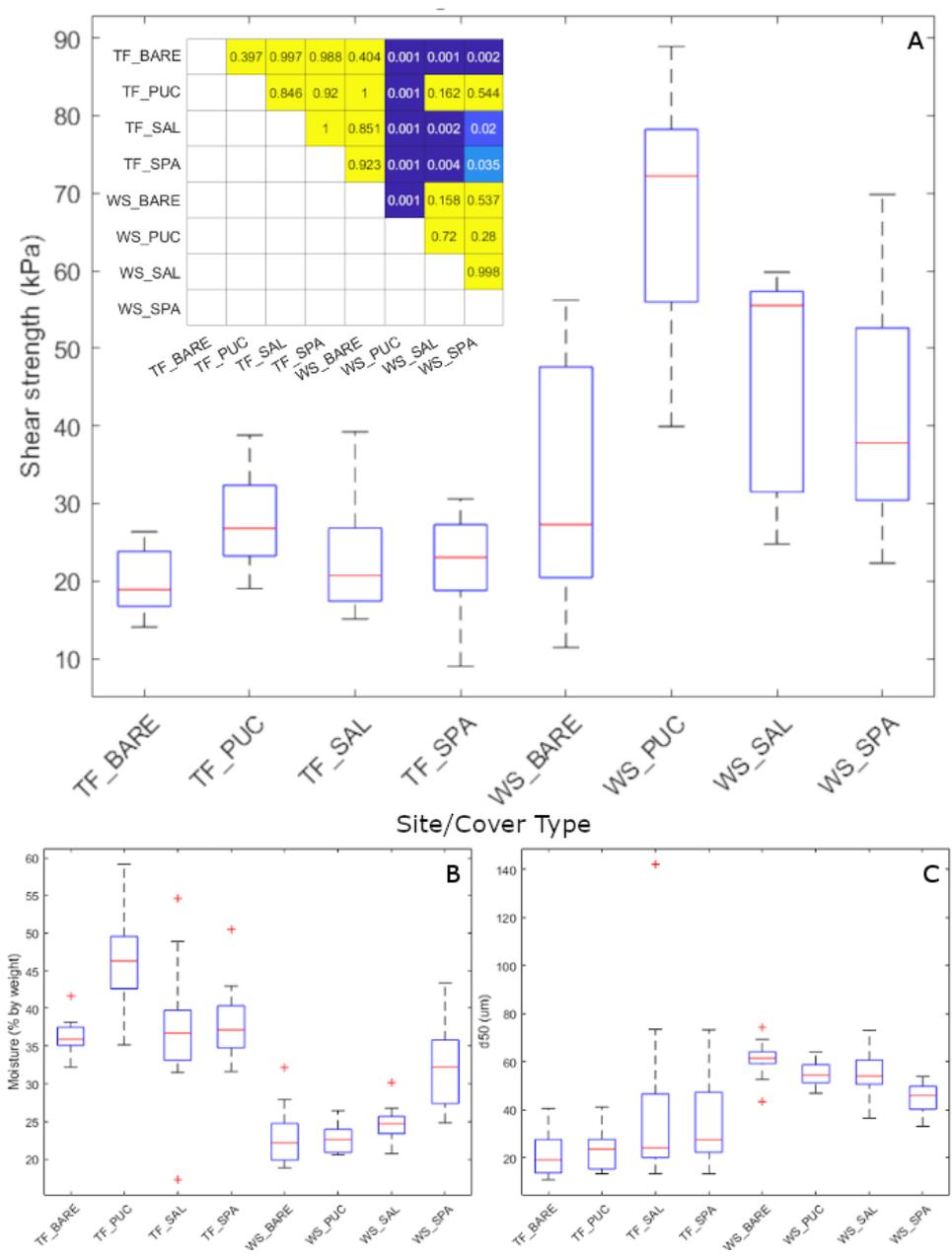
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290 **Variability in sediment parameters measured in the field**

291 Shear strength, measured in the field by the shear vane, showed differences between treatments  
 292 (Kruskal-Wallis  $p < 0.001$ ). post-hoc comparisons showed no differences between cover types within  
 293 sites, with the exception of WS PUC, which contrasted with WS BARE. Widespread differences were  
 294 observed between sites with the exception of TF PUC, which was not separable from WS SAL and WS  
 295 SPA. Within sites the pattern of PUC being strongest, SPA and SAL being very similar and BARE being  
 296 weakest is consistent between sites, even though the sample populations are not statistically  
 297 separable at the level of replication available. The moisture contents and median grain sizes of the  
 298 sediments showed similar inter-site differences, but not within-site variability between surface cover  
 299 types, (Figure 6, panels B and C). Kruskal-Wallis tests returned  $p$ -values  $< 0.001$  for both parameters,

300 suggesting that stochastic dominance exists between treatment groups. Subsequent multiple  
 301 comparisons showed widespread contrasts in both moisture and  $d_{50}$  between sites, but no  
 302 differences between plant surface cover types within sites, with the exception of separability  
 303 between WS SPA and both WS BARE and WS PUC (Table 2). WS SPA, having the finest and wettest  
 304 sediments found at WS, was not separable from the vegetated TF surface cover types in terms of  $d_{50}$ ,  
 305 nor was its moisture content separable from TF cover types with the exception of TF PUC, which was  
 306 the driest TF cover type.

307  
 308



309  
 310 *Figure 6 – Panel A - Shear strengths measured in the field using H-60 vane tester. Inset matrix shows*  
 311 *p-values of post-hoc multiple comparisons following Kruskal-Wallis test for differences between*  
 312 *means (blue = significantly different at  $p < 0.05$ ). Panel B – moisture contents. Panel C – median grain*  
 313 *size ( $d_{50}$ ).*

314

315 Variance in shear strength was greater for all cover types at WS than TF. This is in contrast to the  
316 variance in moisture content and  $d_{50}$ , which was typically smaller at WS than at TF, although WS SPA  
317 exhibited greater variance than the other WS cover types, and WS BARE showed greater variance  
318 than its TF counterpart. The relatively high variance in moisture for WS SPA did not appear to  
319 translate into greater variance in shear strength for this cover type than for the other WS  
320 treatments. This may imply that the variability in shear strength at WS is primarily responsive to  
321 factors other than the moisture or  $d_{50}$  measured here.

322 *Table 2 - Results of Kruskal-Wallis and multiple comparison for differences between moisture and  $d_{50}$*   
323 *across eight sample conditions.  $n=15$  per condition. Significant ( $p < 0.05$ ) differences denoted by 'M'*  
324 *for moisture (upper right) and 'D' for  $d_{50}$  (lower left)*

	TF BARE	TF PUC	TF SAL	TF SPA	WS BARE	WS PUC	WS SAL	WS SPA
TF BARE					M	M	M	
TF PUC					M	M	M	M
TF SAL					M	M	M	
TF SPA					M	M	M	
WS BARE	D	D	D	D				M
WS PUC	D	D	D	D				M
WS SAL	D	D		D				
WS SPA	D							

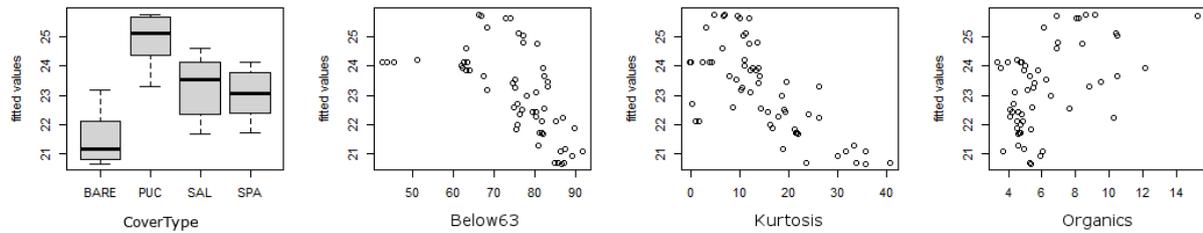
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326 **Exploratory multivariate modelling:**

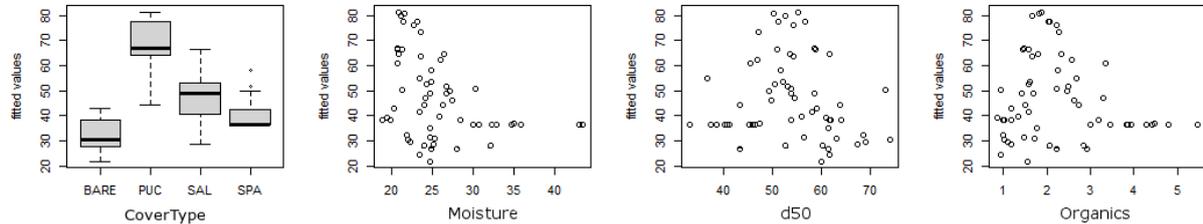
327 At both TF and WS sites, when using the full predictor set, surface cover type contributed most to  
328 model fit. The full model at TF produced a training correlation of 0.48 and a cross-validation (CV)  
329 correlation of 0.22. Surface cover type contributed 21% to the fit, ahead of the other parameters. At  
330 WS, training and CV correlation were considerably higher at 0.90 and 0.69 respectively, with surface  
331 cover type contributing 34% to the fit.

332 In the simplified model CoverType, Kurtosis, Below63, and Organics were selected as predictors for  
333 the shear strength at TF. Training correlation was 0.48 and CV correlation was 0.28. CoverType and  
334 Below63 both contributed 28% to the fit, followed by Kurtosis and Organics, both at 22%. At WS,  
335 training correlation was 0.90 and CV correlation was 0.74. CoverType contributed most to the fit at  
336 39%, followed by Moisture (27%),  $d_{50}$  (20%) and Organics (14%). Fitted values for both models are  
337 shown in Figure 7. The improved CV correlations compared to the full models indicate better  
338 generality.

TF



WS



339

340 *Figure 7 - Fitted values (kPa) for BRT models predicting shear strength at TF (top) and WS (bottom).*  
 341 *Note the contrasting range of shear strength values between sites (vertical axes).*

342 As described previously, the range and variance of the shear strength values obtained were much  
 343 higher for WS than TF, probably accounting, in part, for the relatively poor training and CV  
 344 correlations at TF. At both sites, the surface cover type exerted a primary influence on the model,  
 345 and the relative influences of the different covers were similar at both sites. BARE produces the  
 346 lowest shear strengths, while PUC produces the highest, with SAL and SPA resulting in intermediate  
 347 shear strengths, with those associated with SAL being somewhat higher. The percentage organic  
 348 content of the sediments was selected at both sites, although it was the least informative predictor.  
 349 Parameter ranges varied considerably, making direct comparison challenging. Relationships between  
 350 shear strength and the percentage of the sediment below 63 $\mu$ m and the kurtosis of the particle size  
 351 distribution (TF) were moderately well-defined negative associations, while the relationships at WS  
 352 with moisture and median grain size were less clear. The low training and CV correlations at TF  
 353 means that other factors (not observed here) account for most of the variance in shear strength.  
 354 Nevertheless, the coherent patterning of relative effects of cover types when compared to WS, and  
 355 the relatively well-defined structure within the Below63 and Kurtosis relationships to shear strength  
 356 at TF, provide added confidence that these factors are correctly identified by the model as important  
 357 predictors.

358

359 **Discussion**

360 In broad terms the data presented here support the findings of previous studies assessing the effect  
 361 of vegetation on salt marsh erodibility in that vegetation is shown to positively affect a number of  
 362 parameters often thought to be related to an increase in the stability of marsh sediments (e.g. De  
 363 Battisti et al., 2019; Chen et al., 2019; Ford et al., 2016; Lo et al., 2017; Marin-Diaz et al., 2021; H.  
 364 Wang et al., 2017). In contrast to many of these studies which have measured sediment erodibility  
 365 using hydrodynamic exposure, this study measured sediment geotechnical properties including  
 366 shear strength, cohesion and friction angle directly using a variety of methods. Nevertheless, some  
 367 commonality in findings emerges, principally that vegetation and sedimentology combine to control  
 368 shear strength and erodibility of sediment. It is clear, however, that establishing a general function  
 369 to translate between geotechnical attributes and erodibility remains challenging. For example, the  
 370 sandier WS sediments studied here produce higher shear strengths and friction angles than their TF

371 counterparts yet are more erodible. The between-site contrast is probably driven by WS having  
372 coarser sediments and lower sodium absorption ratio than TF (Chiról et al., 2021a; Grabowski et al.,  
373 2011). Meanwhile, within-site increases in shear strength that are observed in vegetated compared  
374 to bare sediments can be expected, from the existing literature, to translate into reduced erodibility.  
375 Therefore, depending on context, either a positive or negative relationship between shear strength  
376 and erodibility is possible, and the sign of this relationship will depend on the mechanism by which  
377 shear strength is increased. The torvane measurements, by contrast, showed the bare WS sediment  
378 to have significantly lower shear strength than the three TF cover types, including bare ground. This  
379 suggests that the shear vane and the tor vane measure different components of the sediment  
380 strength, with the relationships found between the torvane measurements and the shear box  
381 cohesion and friction angle estimates suggesting that the torvane is more sensitive to sediment  
382 cohesion, while the shear vane measurement is probably more responsive to friction angle. By  
383 employing multiple methods, each measuring sediment properties in slightly different ways, a  
384 nuanced understanding of mechanisms by which vegetation affects sediment stability both directly  
385 and indirectly is established. For example, sediment cohesion, or the emulation thereof by root  
386 systems, emerges as the geotechnical attribute that appears most directly to relate to erodibility, as  
387 would be measured by hydrodynamic exposure and subsequent observation of erosion. The field  
388 shear vane data provide an indication that vegetation cover enhances shear strength. This emerges  
389 from the contrasts between, for example WS PUC and WS BARE. The lack of contrast between TF  
390 PUC and WS SAL/SPA where one exists between these WS cover types and the other TF cover types  
391 also suggests that *Puccinellia*, in particular, increases shear vane measurements. There is a  
392 consistent relative pattern of shear strengths by cover type at each site, with bare ground being  
393 lowest and *Puccinellia* being highest. While these within-site differences are not statistically  
394 significant given the power of the non-parametric tests that were appropriate to this dataset, this  
395 consistency offers some indication that the differences in shear strength between cover types are  
396 not random. The magnitude of any 'vegetation effect' appears to be larger in the coarser sediments  
397 of WS, where *Puccinellia* emerges as statistically different from bare ground. This aligns with the  
398 findings of, for example, De Battisti et al (2019). These observations do not, however, necessarily  
399 imply that vegetation cover directly causes any differences in shear strength.

400 It has been argued that edaphic factors, rather than biotic ones, are the primary control of species  
401 zonation within a saltmarsh (Adam, 1990). Notwithstanding that intra-specific variability in tolerance  
402 or adaptation to these factors also exists, subsequent research has tended to confirm this assertion,  
403 finding relationships between vegetation growth and substrate properties such as salinity (Snow &  
404 Vince, 1984). Effects on inter-specific competition caused by waterlogging and sedimentology have  
405 been observed (Huckle et al., 2000) while Cui et al.(2011) identified spatially variable relationships  
406 between plant communities and edaphic factors such as bulk density, pH, salinity and moisture  
407 content along a topographic gradient. De Battisti et al. (2019) find that *Spartina* root densities are  
408 partially controlled by soil redox potential. Moffett and Gorelick (2016) also document spatial  
409 associations between plant species type and soil geochemistry, although Chiról et al. (2021a) find no  
410 intra-site variability in sodium absorption ratio related to species cover at the sites studied here.  
411 Vegetation has been shown to exert reciprocal controls on soil properties such as drainage, organic  
412 content and geochemistry, thus altering edaphic conditions (Caçador et al., 2000; Gebrehiwet et al.,  
413 2008; Koretsky et al., 2008). More recently these studies have been extended to assess the role of  
414 hydrodynamic exposure in determining survivorship of different species (Schoutens et al., 2021),  
415 introducing an additional dimension of abiotic complexity. Thus, the distribution of vegetation within  
416 the intertidal zone is closely coupled to many substrate parameters that are likely to influence shear  
417 strength and erodibility.

418 It is likely, therefore, that the differences in shear strength that we observe reflect the combined  
419 influence of these parameters alongside any mechanical modifications to the soil matrix arising from  
420 the plant elements themselves. This raises the question of what the relative contributions of these  
421 processes are to the substrate shear strength and, potentially more importantly, to sediment  
422 erodibility. Analogues in other vegetated soil systems (e.g. O’loughlin & Ziemer, 1982) and the  
423 emerging literature in the context of salt marshes (e.g. Chen et al., 2019; Ford et al., 2016; Gillen et  
424 al., 2020), as well as the findings we present here, all provide evidence that vegetation does make a  
425 significant contribution to soil shear strength through direct, mechanical means, but our results also  
426 suggest potential indirect interactions with erosion processes. Thus, block failure resulting from low  
427 bulk shear strength may increase the surface area of exposed sediment (Allen, 1989). Blocks, once  
428 fallen to occupy lower surface elevations are also exposed to higher magnitude/frequency of  
429 wave/tide forcing and thus greater likelihood of grain-by-grain erosion.

430 Our exploratory modelling using BRTs consistently selected the surface cover type on saltmarsh  
431 substrates as being an important predictor of substrate shear strength. At WS, the contribution of  
432 cover type was the dominant factor in a model that accounts for most of the variance in shear  
433 strength across the site. At TF, model performance was poorer but cover type was the joint most  
434 important predictor, alongside the percentage of sediment below 63  $\mu\text{m}$  in size. The relative  
435 patterns of the magnitude of influence of different surface cover types are consistent between sites.  
436 This reinforces the conclusion that *Puccinellia* increases sediment shear strength most, while  
437 unvegetated substrates tend to have the lowest shear strengths. This observation is further borne  
438 out by the torvane measurements conducted in the laboratory, which suggest the same sequence of  
439 relative shear strength effects within TF. The good performance of the BRT model at WS, where  
440 training correlation was 0.90, and its strong dependence on cover type (38%), suggests that  
441 vegetation presence and composition has a greater influence on shear strength in sandier sediments  
442 than it does in clay-rich environments. Furthermore, it suggests that, at least for sandier  
443 environments, the mapping of vegetation distributions could provide insight to a significant  
444 component of the spatial variability in substrate shear strengths. The strong vegetation influence in  
445 sandy systems, also identified as suppressing erosion rates measured in the field (Lo et al., 2017),  
446 potentially arises because the root networks are able to reinforce the coarser sediment matrix in  
447 ways that bind the sediments together to mitigate the lack of cohesion in such substrates. This may  
448 be facilitated for different species in different ways through mechanical or geochemical  
449 modification of the substrates, or through the introduction of root exudates and their effects on the  
450 rhizosphere (e.g. Wang et al., 2016). Where clay content is higher, however, any such effect may be  
451 less significant because cohesion is higher anyway. Observations of intra-specific differences in root  
452 morphology between the two sedimentologies investigated here were observed at the same sites by  
453 Chiról et al. (2021a); they attribute these to the relative ease of root penetration, and thus more  
454 extensive network formation, in the sandier WS sediments compared to those of the TF site. A  
455 similar phenomenon of more extensive root networks being observed in sandier sediments was also  
456 discussed by De Battisti et al (2019) although alternative causes of differences in network  
457 morphology and plant allometry have also been proposed, such as salinity (De Battisti et al., 2020) or  
458 wave exposure (Cao et al., 2020), which may be independent of site sedimentology. Structural  
459 differences in root network attributes may therefore account for some of the observed contrast in  
460 cover type effect on geotechnical properties between sites (Figure 4, Figure 6).

461 The fact that percentage organic content was selected by the BRT models at both sites, albeit as the  
462 least informative predictor, is instructive. This finding suggests that vegetation effects over longer  
463 timescales are also important. Broadly speaking, higher organic matter contents were associated  
464 with higher shear strengths at a within-site scale (Figure 7). Autochthonous organic matter

465 accumulation arises from the primary productivity of the vegetation cover and its subsequent  
466 decomposition. Sediment organic matter content therefore reflects, in part, the vegetation history  
467 of the location, notwithstanding that organic material may be imported or exported (Alongi, 2020;  
468 Ganju et al., 2019). As such, a relatively small component of sediment shear strength at both sites  
469 appears to be dependent on longer-term vegetation attributes which may or may not be reflected in  
470 the present-day species distributions. The magnitude of this effect and the timescales over which it  
471 develops and operates are a topic for further study.

472 The laboratory-based geotechnical tests allowed for the further exploration as to how vegetation  
473 alters sediment shear strength. The shear box data only showed a significant difference for the  
474 cohesion values of WS BARE and TF PUC, with the higher cohesion in TF PUC probably being related  
475 to a combination of sedimentological differences (higher clay content) and the effect of the  
476 *Puccinellia* root system. The pattern of relative parameter values was, however, consistent with  
477 other measurements, such as the shear vane, and can be explained by existing mechanistic  
478 understandings. It is possible, therefore, that the results may hint at findings that may become  
479 significant with additional data. Whilst it is not possible to draw robust statistical inferences from  
480 this dataset, the pattern of differences between cover types does suggest that vegetation presence  
481 and species may alter the properties of the underlying sediments. The position of WS BARE as having  
482 the highest friction angle and lowest cohesion was consistent with what would be expected based  
483 on the sedimentology of the two sites. TF BARE and TF PUC both have low friction angles, while that  
484 for TF SPA is almost the same as WS BARE, despite the sediment matrix being composed of much  
485 finer particles. It would appear that the *Spartina* root system (De Battisti et al., 2019) may interact  
486 with the sediments in a way that emulates a coarser particle size distribution and therefore a higher  
487 friction angle where bulk failure processes are concerned. In contrast, the TF BARE and TF SPA  
488 cohesion values were very similar, while that for TF PUC was much higher. The *Spartina* root system  
489 therefore does not appear to have much effect on the bulk sediment behaviour related to cohesive  
490 strength, while *Puccinellia* may act to increase apparent cohesion.

491 It is important to note that these geotechnical tests are typically conducted and interpreted in the  
492 context of sediments that do not contain plant elements. The friction angle therefore usually refers  
493 to the angle through which a grain of sediment must be raised in order to lift the material free of the  
494 matrix and allow shear to take place. Thus, cohesion typically refers to the strength of the sediment  
495 at no normal load, a function of the electrostatic forces between particles. Plant root networks have  
496 long been considered to contribute primarily to the cohesion component in the context of hillslope  
497 processes (e.g. O'loughlin & Ziemer, 1982), although our observations here suggest that *Spartina*  
498 roots may result in elevated friction angles while having minimal influence on cohesion (Figure 4). It  
499 is unlikely that the differences that were observed in these test parameters in the presence of plant  
500 root networks arise from the same differences in physical processes and forces that could be  
501 inferred for 'pure' sediments. If the inter-particle interactions controlling the measured friction angle  
502 and cohesion values are similar between samples from a given site, then the mechanical root  
503 network effect is acting to *emulate* a modification of these parameters. Future work focusing on  
504 understanding the physics of this emulation would be a valuable contribution towards characterising  
505 biosedimentary system behaviours. The results observed in this study make intuitive sense when  
506 considering the behaviour of the differing root morphologies in the context of planar shear, as  
507 imposed by the shear box apparatus. The large, vertical tap-root system of *Spartina* (visible as round  
508 features representing root cross-sections viewed from above in Figure 3) is relatively rigid and  
509 unlikely to be sheared or bent within the shear box test. To allow strain within the matrix  
510 surrounding them, the strong vertical root segments would need to be rotated towards the  
511 horizontal plane during shearing, displacing sediment while doing so. By contrast, small, fibrous

512 *Puccinellia* roots, however, are likely to merely bend along the shear plane until they come into  
513 tension; their tensile strength thereafter may account for the apparently elevated cohesion  
514 measurements. It is therefore hypothesised that different plant species may modify the bulk  
515 responses of sediments to shear forces in ways that appear as altered friction angles or cohesion  
516 values. The physics of the distribution of forces within the sediment, however, will be different to  
517 those normally inferred from measured friction angles / cohesion. In terms of predicting the  
518 response to erosive forces in a field situation, this distinction may become important, and the  
519 importance of the root-induced geotechnical differences will vary depending on the mode of failure  
520 being considered. For example, the *Puccinellia* root system may increase resistance to the formation  
521 of tension cracks and toppling failures, while the vertical *Spartina* roots may provide more resistance  
522 to rotational slumping. Again, further research is required if the function of these root systems in  
523 controlling various modes of erosion is to be understood.

524 The triaxial test results showed that simulating realistic conditions with small overburdens is  
525 challenging, both in terms of the precision of the equipment deployed and the behaviours of the  
526 sediments being tested. A few studies exist, however, that have used triaxial tests to assess the  
527 contribution of root elements to sediment properties. For example, Patel and Singh (2020) found  
528 small increases in shear strength measured by triaxial test conferred to artificial mixtures of clayey  
529 and sandy sediments containing glass fibre reinforcement. Meng et al. (2020) also observed  
530 variability in shear strength related to the rooting geometry of Golden Vicary Privet (*Ligustrum spp.*)  
531 in a controlled planting experiment and found that the root network's effect was largely to enhance  
532 the sediment cohesion rather than friction angle. As noted previously in the context of the shear  
533 box, this is unlikely to represent a true increase in cohesion but rather soil-root interactions  
534 presenting a similar phenomenon within the context of the parameters measured by the test. It  
535 seems likely that triaxial testing could furnish valuable insights to the role of vegetation elements in  
536 determining salt marsh stability, but, given the nature of the sediments and conditions that need to  
537 be simulated, this may prove challenging. It is important to note that the different storage durations  
538 for each sample may contribute to the patterns observed in the laboratory geotechnical tests.

539 The bulk density measurements suggest that, irrespective of site sedimentology, unvegetated  
540 sediments have higher bulk densities than their vegetated counterparts. *Spartina* seems to be  
541 associated with the lowest bulk densities at both sites. All else being equal, higher bulk density tends  
542 to reduce erodibility (Watts et al., 2003; Winterwerp et al., 2012). The data presented here suggest  
543 that the presence of vegetation decouples the expected relationship between bulk density and  
544 sediment stability, in that vegetated sites with lower bulk densities than bare sites nevertheless  
545 consistently exhibit higher shear strength, friction angle and cohesion, irrespective of the method  
546 used to measure these attributes. The presence of vegetation therefore confers strength to the  
547 sediment greater than that which may be lost by the attendant reduction in bulk density. Within the  
548 vegetated cover types for each site, the relative pattern of bulk density tends to reflect the relative  
549 pattern of, for example, shear strength. This suggests that changes in bulk density may represent an  
550 indirect mechanism whereby vegetation type interacts with substrate geotechnical properties.

551 The findings of this study provide the basis for conceptual models of how various vegetation  
552 distributions, perhaps related to site topography, might result in spatio-temporal variations in  
553 vulnerability to erosion. This concept is here explored through the example of the erosional setting  
554 of the TF site. The saltmarsh – mudflat margin at TF is ramped, rather than cliffed, with a shore-  
555 normal ridge-runnel morphology superimposed on the general seaward slope. Erosion therefore  
556 manifests itself as the retreat of a relatively wide zone of elevation loss over a relatively shallow  
557 slope. Removal of material at the transition from marsh to mudflat may lead to lowered sediment

558 surface elevations, increased hydroperiod and a transition to a vegetation community dominated by  
559 pioneer species (Adam, 1990; Feagin et al., 2010; Moody et al., 2013). Given the erosional setting,  
560 the pioneer-dominated seaward fringe presumably represents the previous location of a higher  
561 marsh platform dominated by *Puccinellia* and *Atriplex*, as is still observed to landward. We show that  
562 the pioneer species are associated with lower shear strengths and cohesion than *Puccinellia*.  
563 Whether sediment shear strength or cohesion, as measured by the techniques described above is  
564 the best proxy for the substrate's ability to resist erosion remains, to some extent, an open question.  
565 If, however, higher shear strengths or increased cohesion imply reduced erodibility for a given  
566 hydrodynamic exposure, then the vulnerability of the seaward zone of the marsh may increase  
567 following a transition from mature to pioneer vegetation, supplying a positive feedback that  
568 accelerates retreat rates. Our study suggests that within-site variations in geotechnical properties  
569 likely result from a combination of factors, including vegetation species transitions and organic  
570 matter contents. Over time, changes in the saltmarsh community, including those enforced through  
571 direct (e.g., grazing) or indirect (e.g., sea level rise) interventions, may thus act to influence the rate  
572 at which marsh margins can erode. Conceptualising the linkage between marsh to tidal flat transition  
573 morphology, sedimentology, and vegetation in this way provides a potential mechanism by which  
574 margin morphology is linked to erosion rates, as suggested by other studies (Evans et al., 2019;  
575 Finotello et al., 2020; Tonelli et al., 2010). Further insights into these interactions are now needed,  
576 not least in light of evidence of the positive elevational response of saltmarsh surfaces under  
577 *Puccinellia* to enhanced CO<sub>2</sub> (Reef et al., 2016) and of low surficial erosion under *Puccinellia* in  
578 extreme storm surge conditions (Spencer et al., 2016). Emphasis must be placed on the  
579 understanding of interactions between vegetation, root morphology and soil geochemistry in future  
580 studies in order to address these specific species-level controls on saltmarsh landform evolution.

581

## 582 **Conclusions:**

583 Salt marsh vegetation distributions are responsive to edaphic and other factors relating to site  
584 topology while at the same time engineering these factors via biophysical feedbacks. Disentangling  
585 which factors dominate the spatial variability in substrate shear strength remains a challenging  
586 problem. Nevertheless, vegetation distributions and types show associations with variability of  
587 sediment geotechnical parameters within sites. To what extent vegetation is responsive to, or  
588 determinative of, that variability in properties may be of secondary importance for applied  
589 purposes. Different halophyte species also affect components of the shear strength, such as  
590 cohesion and friction angle, in different ways that appear to relate to root morphology. We  
591 therefore conclude that the mechanical deformation of root networks under shear, which involves  
592 different force vectors depending on root morphology, contributes substantially to the observed  
593 variability in shear strength. Vegetation mapping may therefore provide useful insight to the spatial  
594 variability of substrate geotechnical properties. The direct effects of root networks on cohesion and  
595 friction angle, however, are unlikely to reflect true modifications of these parameters as they would  
596 be interpreted in root-free sediments. The secondary effects of roots on soil structure and  
597 geochemistry probably affect its mechanical properties such as cohesion in a stricter sense and may  
598 be more important in terms of determining marsh substrate vulnerability to particulate scale erosion  
599 than those conferred mechanically. We argue that, while useful, shear strength alone is an  
600 inadequate descriptor of erodibility for the purposes of predicting rates of morphological change.  
601 Components of sediment strength such as cohesion emerge from this study as more closely  
602 representing the expected erodibility of sediments under hydrodynamic forcing. This aspect will be  
603 explored further in future work. A more nuanced conversation, one that is explicit about the time

604 and space scales of interest and addresses appropriate erosion processes, controls and measures of  
605 erodibility, is required in order to advance our understanding, and representation, of marsh  
606 erosional processes beyond simplistic assumptions about relationships between shear strength and  
607 morphological change. In order to better constrain the processes through which vegetation affects  
608 erodibility, and on what timescales, will require further detailed experimental investigation using  
609 multiple methods, controlling for multiple factors, and exposing sediments to realistic erosive forces.  
610 This, coupled with a body of literature on the effects of cumulative, longer-term hydrodynamic  
611 forcing, will facilitate the morphodynamic predictions required to support effective coastal  
612 management.

613

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