1 Limited vegetation development on a created salt marsh associated with over-

2 consolidated sediments and lack of topographic heterogeneity.

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Abstract

Restored salt marshes frequently lack the full range of plant communities present on reference marshes, with upper marsh species under represented. This often results from sites being too low in the tidal frame and/or poorly drained with anoxic sediments. A managed coastal realignment scheme at Abbotts Hall, Essex, UK, has oxic sediments at elevations at which upper marsh communities would be expected. But seven years after flooding, it continued to be dominated by pioneer communities, with substantial proportions of bare ground, so other factors must hinder vegetation development at these elevations. These poorly vegetated areas had high sediment shear strength, low water and organic carbon content and very flat topography, characteristics which occur frequently on upper parts of created marshes. Experimental work is required to assess which, if any, of these is responsible for the ecological differences, although other studies have shown that topographic uniformity is associated with reduced plant β-diversity, lower usage by fish and means that the created marsh has very different visual appearance to a natural marsh. On the upper intertidal sediment deposition rates are low and erosive forces too weak to generate microtopographic variation, even where creeks have been excavated. So without active management intervention, these conditions will persist indefinitely.

Introduction

Salt marshes are being created in increasing quantities worldwide to replace those destroyed by coastal erosion, land reclamation and coastal development (French 2006; Wolters et al. 2005; Zedler 2001). If created marshes are intended to compensate for areas destroyed by coastal development they should, as far as possible, match the ecological characteristics of natural marshes. In Europe such "compensatory measures ... should ... address, in comparable proportions, the habitats and species negatively affected [and] provide functions comparable to those... of the existing site" (European Commission 2008), and in the USA there is a requirement that marsh creation should result in no net loss of wetland area and function (Zedler 2004). In the UK, the majority of replacement salt marshes are created through the process of managed coastal realignment, where sea defences are relocated landward and the old seaward wall is breached to allow tidal inundation (French 2006). The areas to which tidal flooding is restored were often salt marshes before being embanked for use as agricultural land. Salt marshes develop naturally on sheltered sediment at the appropriate tidal elevation. If restored sites are at similar elevations to natural marshes, it might be expected that vegetation would develop on restored sites that is very similar to that on natural marshes (Burd 1995; French 2006; Parker et al. 2006). However, plant community development often fails to replicate the vegetation found on nearby natural reference marshes (Garbutt and Wolters 2008; Mossman et al. 2012b; Thom et al. 2002). Invertebrate communities can also be slow to develop, particularly higher in the tidal frame (Atkinson et al. 2001; Mazik et al. 2010). So most created salt marshes provide an imperfect substitute for natural marshes (Mossman et al. 2012a).

If we are to increase the likelihood of created marshes developing ecological characteristics that are similar to nearby reference marshes, we need to understand the environmental and ecological processes that lie behind this divergence. Some aspects of this problem are already well characterised. Shrinkage and compaction of soils after reclamation has led to areas being low in the tidal frame when reflooded (Crooks et al. 2002; Pethick 2002). At the managed realignment site at Tollesbury in Essex, south-east England, for example, much of the site was too low for marsh development (Garbutt et al. 2006). In addition, at tidal

66 elevations corresponding to low and mid-marsh, the soils on re-flooded areas are often

67 more anoxic than those at the same elevations on reference marshes, and this can still be

68 true on sites flooded accidentally many decades ago (Mossman et al. 2012a). The anoxia

69 results from poor drainage, at least in some cases due to the development of impervious

70 layers or 'aquacludes' (Blackwell et al. 2004; Crooks et al. 1998, 2002). Anoxic or suboxic

71 soils limit plant colonisation, favouring pioneer species that are tolerant of reducing soils

72 and limiting the abundance of others (Davy et al. 2011; Mossman et al. 2012b). However,

73 sections of a number of restored sites at elevations high in the tidal frame remain

74 significantly less vegetated than those at equivalent elevations on natural reference

75 marshes, despite having sediments that are well oxygenated (Mossman et al. 2012a). The

76 reasons for this are unclear. One possible explanation is that hypersaline conditions may

77 develop in summer, as occurs on unvegetated areas of natural marshes (Bertness 1991;

78 Bertness et a. 1992). Most created marshes lack the creeks that occur on natural marshes,

79 and this may also contribute to the ecological differences. On a natural marsh, Morzaria-

80 Luna et al. (2004) found that plant species richness was slightly higher in areas close to

81 creeks, and these areas also had higher topographic heterogeneity. Topographic variation is

82 also associated with increased use of natural marshes by fish (Able et al. 2003). However, an

83 experimental assessment at Friendship Marsh in the Tijuana Estuary showed that while

84 creek excavation did generate topographic heterogeneity by "jump starting" the

85 development of the drainage network (Wallace et al. 2005), the effect of this on plant

86 survival was only modest (O'Brien and Zedler 2006) and although one fish species showed

87 higher abundance where creeks were excavated, a second species occurred at lower

88 abundance (Larkin et al. 2008).

89

90 In 2004, two years after restoration of tidal inundation to a managed realignment at

91 Abbotts Hall in Essex, UK, vegetation colonisation was extensive, with only 30% bare ground

92 (Mossman 2007). Much of the re-flooded area was at elevations at which upper marsh

93 communities usually occur, and sediments were oxic throughout much of the site. In

94 addition, creeks had been excavated on part of the site. Seven years after restoration (in

95 2009), we carried out intensive sampling to assess vegetation development on a site where

96 the most common impediments to vegetation development, such as anoxic sediment and

97 unsuitable elevation, were absent. We expected that the rapid pace of vegetation

98 colonisation would have continued. However, development of typical high marsh

99 communities dominate by perennial species had not taken place. Here we quantify the

100 environmental characteristics at the site to try to understand what may be responsible for

101 this.

102

Methods

The study area

105 Abbotts Hall is situated on the north bank of the Blackwater Estuary in Essex, south east

106 England (Fig. 1) (51° 47' 8" N, 0° 50' 43" E). The was been reclaimed in the 18th Century and

107 used as grazing marsh, then was levelled and converted for arable use between 1943 and

108 1970 (Essex Wildlife Trust 2003). In 1996, tidal flow was restored to the area shown in Fig 1

109 via a culvert (Nottage and Robertson 2005). As part of the 1996 scheme, a network of

110 artificial creeks was excavated in an attempt to recreate natural marsh drainage conditions

111 and sediment deposition (Dixon et al. 1998). The amount of seawater reaching the site was

112 lower than expected (ABP 1998) and vegetation development was very poor (Diack 1998),

113 so in 2002, a larger area (49 ha) of intertidal habitat was created by breaching the sea wall in

114 five places, including sections lying outside of the area shown in Fig. 1. The creeks excavated

115 in 1996 were 1-3 m wide and deep, with a total length of 2.2 km, and are clearly visible on

116 Fig. 1. Spoil from these excavations was left in situ in a pile adjacent to the excavated creeks

117 (an example is visible at right hand side of Fig. 2b). The tops of these piles were just above

118 the level of the highest tides. An area of natural reference marsh (approximately 70 ha)

119 occurs adjacent to the managed realignment site. Extensive vegetation colonisation had

120 occurred on the managed realignment two years after the sea wall was breached and

121 sediments then were relatively well oxygenated (Mossman 2007), and five years after

122 breaching the vegetation was described as "similar to the adjacent ancient saltmarsh" based

123 on data from a single transect (Hughes et al. 2009).

124

125 We studied three areas of marsh. These were an area where no creeks had been excavated

126 ('non engineered site', area A in Figs. 1 and 2), one that included an excavated creek

127 ('engineered site', area B in Figs. 1 and 2) and one on an area of natural reference marsh

128 ('reference site', area C in Figs. 1 and 2). On both parts of the restored site, the landward

129   part of the marsh consists of a relatively well vegetated and rather flat surface. This is visible

130   as darker areas on Fig. 1 and these can also be seen in Fig. 2a and b. It is located at

131   approximately 2.25 to 2.5m ODN (see also Fig. 6), an elevation at which species-rich

132   marshes dominated by *Puccinellia maritima* and *Atriplex portulacoides* normally occur in

133   this region (Mossman 2007). Seawards of this is an area of mudflat with pioneer vegetation,

134   visible as the lighter coloured parts of the site in Fig. 1. As we wanted to focus on factors

135   influencing the vegetation on the upper parts of restored marshes, the areas sampled were

136   located approximately mid-way between the landward sea wall and the areas of mudflat

137   and pioneer communities. To allow comparison with the restored sites, the reference site

138   was located in an area where the main marsh surface was at an elevation of around 2.25m

139   ODN, but as the reference marsh is quite heavily dissected by creeks, some sampling points

140   are located lower in the tidal frame (c.f. Fig. 6).

141

142   Many restored marshes appear to be topographically more uniform than reference marshes

143   and this could be a cause of ecological differences (Grant and Mossman, *pers. obs.,* and

144   compare figure 2c with figures 2a and b). To allow us to quantify spatial heterogeneity of

145   elevation on small and intermediate scales, at each of the sites we used systematic sampling

146   of a grid rather than using random or transect sampling. A square 6 by 6 grid at 10 m

147   spacing was laid out in a 50 x 50m section of each area, with 36 sampling points at the

148   intersections of the grid lines. Eight of these points were randomly selected and additional

149   sampling points were located at 1 m and 2 m N, S, E and W from the focal point; giving an

150   additional 64 sampling points. The same eight positions were used in each site to give

151   consistency in sampling spatial patterns. This sampling design resulted in a total of 100

152   sampling points at each of the three sites. As noted above, all three areas were at relatively

153   high tidal elevations and the area covered by the sampling grid had vegetation that was

154   visually similar to the whole of that section of the site.

155

156   In August 2009, the elevation, vegetation and soil characteristics were assessed at each of

157   the sampling points. The vegetation was assessed by estimating the percentage cover in a

158   0.25 m^2 quadrat (centralised over each sampling point) of all plant species and bare ground,

159   to the nearest 5%, assigning an abundance of 1% to species present at < 5% area. Plant

160   species observed within each sampling grid but that did not fall into any quadrats were also

161   noted. Plant species nomenclature followed Stace (2001).

162

163   At each sampling location, elevation of the marsh surface relative to Ordnance Datum

164   Newlyn (ODN - the UK national topographic datum, based on mean sea level at a site in

165   south west England) was measured at the centre of each sampling point using a differential

166   GPS (Topcon, Newbury, UK), with an accuracy of <2 cm and precision of <1.5 cm. The levels

167   of mean high water neap (MHWN) and mean high water spring (MHWS) tides, measured on-

168   site, were respectively 1.83 and 2.99 m ODN (Mossman et al. 2012c). Substrate redox

169   potential was measured at low tide with a single reading from the centre of the sampling

170   unit, taken after 90 seconds of equilibration at 4 cm below the marsh surface using a BDH

171   Gelplas combination redox electrode with an Ag/AgCl reference. Values are expressed

172   relative to a standard hydrogen electrode (Eh) by adding 204 mV. Redox potential was not

173   taken at two locations on the engineered site because the substrate was too hard for the

174   probe to be inserted. Soil shear strength was measured using a hand-held shear vane with a

175   precision of <1 kPa. Where the readings exceeded the maximum of the scale (>100 kPa), a

176   value of 120 kPa was used in the statistical calculations. Approximately 40 g of soil from the

177   surface 5 cm was taken from the centre of each of the 36 main grid sample points at each of

178   the three sites, placed a sealed bag and stored at 4 °C within 48 h. Approximately 5 g of

179   these un-sieved sediment samples were analyzed in the laboratory for gravimetric soil water

180   content (after drying for 24 hours at 80°C) and organic matter (percentage loss on ignition

181   after 20 h at 390 °C) in accordance with standard methods (Miller 1982). Two replicates of

182   gravimetric water content and loss on ignition were made for each sample and the mean

183   used in statistical analyses. We did not measure sediment nutrient concentrations as these

184   are unlikely to be limiting as the site had previously been used for intensive arable farming

185   and our previous work has found relationships between sediment nutrient concentrations

186   and vegetation on created marshes to be weak or absent (Davy et al. 2011).

187

188   Initial data analysis and fitting of LOESS regressions (locally weighted non-linear regressions,

189   using an Epenechnikov kernel) to relationships between elevation and individual plant

190   abundances and environmental variables, were carried out using SPSS version 16 (SPSS Inc,

191   Chicago, Ill.). In order to examine, and test the significance of, differences in vegetation

192 communities between sites, multidimensional scaling (MDS) and one-way analysis of

193 similarity (ANOSIM, which tests whether similarities between groups are smaller than

194 expected by chance using permutation tests) were carried out on a matrix of Bray-Curtis

195 similarities of vegetation data after square root transforming abundances. SIMPER

196 (Similarity Percentage) analysis is a method for assessing which taxa are primarily

197 responsible for an observed difference between groups of samples and was used to identify

198 the species responsible for the differences in vegetation communities between the three

199 sies. MDS, ANOSIM and SIMPER were carried in PRIMER v6 (Plymouth Routines In

200 Multivariate Ecological Research, Primer-E, Plymouth; Clarke and Gorley 2006).

201 Heterogeneity of site elevations was quantified using R (R Development Core Team 2008),

202 writing our own code to calculate horizontal distances and elevation differences between all

203 pairs of sampling points at each site and using the *stats* package to fit LOESS regressions.

204

Results

Vegetation data

207 A total of 16 plant species were found, although two of these, *Picris echioides* and an

208 unidentified moss, were essentially non-maritime species that occurred only on the highest

209 part of the engineered site, i.e. on creek berms above the high-tide level. Multidimensional

210 scaling showed that the plant communities on both the engineered and non-engineered

211 parts of the created marsh remain markedly different from those on the reference marsh

212 (Fig. 3). None of the samples from either part of the created marsh plot in the area at the

213 top and centre of Fig. 3 where the bulk of the reference samples are located, although the

214 engineered part of the site showed greater similarity to the reference marsh than the non-

215 engineered part. In addition, a small number of reference samples, mostly from the low

216 marsh, *are* similar to samples from the created marsh. ANOSIM confirms that pairwise

217 differences between the three sites are significant (P < 0.001 in all cases). There are a

218 number of species contributing to these differences, and the mean abundances of the

219 commonest species are presented in Fig. 4. The abundance of individual species changed

220 with elevation, as well as showing differences between sites, so we have used LOESS

221 regressions to visualise these patterns in more detail and demonstrate that the differences

222 between the sites are not simply due to differences in elevation (Fig. 5). On the reference

marsh there was 100% vegetation cover in most quadrats at elevations greater than 2.1 m

ODN, but vegetation cover remained incomplete at elevations above this on both parts of

the created marsh, with about 30% bare ground at 2.25 m ODN on the engineered site, and

about 60% on the non-engineered part (Fig. 5a). Two species, *Puccinellia maritima* and

Atriplex portulacoides were common between 2 m and 2.6 m ODN on the reference marsh,

with *Puccinellia* dominating between 2.3 and 2.5 m ODN, and abundance of *Atriplex* peaking

at around 2.2m ODN. At elevations below 2 m ODN, *Salicornia europaea* was the

commonest species, although *Atriplex* and *Puccinellia* were present in a small number of

quadrats. *Atriplex* and *Puccinellia* were present at much lower abundance, and occurred at

higher elevations, on the engineered site and were rather rare on the non-engineered site

(Fig. 5d, e). SIMPER analysis indicates that the abundance of these two species and the

occurrence of bare ground made the largest contribution to the differences between sites.

The annuals *Salicornia europaea* and *Suaeda maritima* were more common on the

realignment site, with the latter particularly abundant on the non-engineered part, peaking

at about 80% cover at 2.5 m ODN (Fig. 5b, c).

Other species were present at much lower abundance, so data are not presented

graphically. The grass *Elytrigia atherica* occurred at high abundance (> 60% cover) in some

quadrats, almost entirely those between 2.5 and 2.75 m ODN, but was absent from the

majority of quadrats. It occurred at a cover of > 50% in more quadrats (15) on the non-

engineered site than on the engineered or reference sites (5 and 8, respectively), which was

significantly different from a uniform distribution (χ^2= 6.2, d.f. = 2, P = 0.04). However, 28%

of sampling points on the non-engineered site were between 2.5 and 2.75 m ODN, as

compared with only 6 and 7% for the engineered and reference sites, and if we calculate

expected values based on these proportions, the difference was not significant (χ^2 = 3.6, d.f.

= 2, P = 0.17). Four characteristic mid to upper marsh species (*Sarcocornia perennis*;

Triglochin maritima; *Plantago maritima* and *Limonium vulgare*) were present on the

reference marsh but absent from both parts of the realignment site, and *Aster tripolium* was

more than ten times more abundant on the reference site. *Agrostis stolonifera* and *Spartina*

anglica occurred only on the engineered site. One-way Anova showed that, apart from

Plantago ($F_{2,287}$ = 2.8, N.S.) and *E. atherica* ($F_{2,287}$ = 3.5, P = 0.03), all the above differences in

mean abundance between sites were significant at P < 0.001.

255

Environmental characteristics

There were also substantial differences between the sites in their environmental characteristics, displayed visually for elevation in Fig. 6 and using LOESS regressions against elevation for the other parameters in Fig. 7. On the non-engineered area, most of the sampling points fell within a restricted elevation range, with only a few samples close to a former drainage ditch lying below 2m ODN. Sampling points on the engineered area covered a much larger elevation range because creeks were excavated to about 1.25m ODN, and the spoil from this excavation was left as a berm, with a crest that was well above 3 m ODN. On the reference site, the highest sampling points are at similar elevations to the highest parts of the non-engineered site, but the whole marsh is dissected by creeks, so there were many more low lying sampling points.

The sites differed in mean elevation, redox, shear strength, water and organic content (Table 1; $P < 0.001$ in all cases, Anova). The non-engineered parts of the realignment site had the *highest* mean elevation, as the absence of any creeks results in no sampling points on this site being below 1.94 m ODN (Fig. 6). The mean redox potentials at all elevations in all sites were above 0 mV (Fig. 7a). The non-engineered site also had a markedly higher mean redox potential, because this declined steadily with elevation and almost all sampling points below 2 m ODN were on the other two sites. Nevertheless, the redox potential on the non-engineered site was somewhat higher than at similar elevations on the other two sites (Fig. 7a). Sediment shear strength was high throughout the non-engineered site, with most quadrats having shear strengths greater than 80 kPa (Fig. 7b). By contrast, shear strengths on the reference marsh were lower than 40 kPa in sampling points below 2.3 m ODN. They increased on the higher marsh, but very few sampling points exceeded 80 kPa. On the engineered site, shear strengths were higher than those on the non-engineered site above 2.3 m ODN, declining to very low values at the lowest elevations. Sediment water content at 2 m ODN on all sites was in the region of 50%, but declined steadily with increasing elevation on both the engineered and non-engineered realignment sites (Fig. 7d). By contrast, water content increased on the upper parts of the reference marsh, where sediment organic content was also markedly higher than on the realignment sites (Fig. 7c, d).

288 **Environmental heterogeneity**

289 The data on elevation heterogeneity confirmed the visual impression given by the

290 photographs in Fig. 2. On the reference marsh, locations that are 1 m apart horizontally

291 typically differed by 15 cm in elevation, rising to about 30 cm for locations 8 m apart (Fig. 8),

292 reflecting the dissection of the site by an extensive system of creeks (Fig. 2c). By contrast,

293 locations up to 10 m apart on both parts of the realignment site were likely to differ in

294 elevation by only 10 cm, reflecting the flat surface topography visible in Figs. 2a and b. The

295 three sites only showed similar patterns of heterogeneity in elevation at horizontal scales

296 greater than 40 m.

297

298 # Discussion

299 Seven years after full restoration of tidal influence, the vegetation at the restored salt marsh

300 at Abbotts Hall continues to be dominated by the two annual species, *Salicornia* and

301 *Suaeda*, with substantial areas of bare ground. There is rather little colonisation by

302 perennial species normally characteristic of mid and upper marshes, despite much of the

303 site being at appropriate elevations. The failure of vegetation communities to develop on

304 restored or created sites within similar timeframes has been noted previously (e.g. Havens

305 et al. 2002; Mossman et al. 2012a; Wolters et al. 2005). At some restored sites, the delay in

306 colonisation by mid and upper marsh species has been attributed to relatively low tidal

307 elevations and poorly oxygenated sediments, which are more suitable for inundation-

308 tolerant, pioneer species, such as *Salicornia* (Crooks et al. 2002; Davy et al. 2011; Mossman

309 et al. 2012b). This is not the case for much of the Abbotts Hall site, which is at elevations

310 suitable for mid and high marsh communities, and has oxic sediments. It is not clear why

311 these communities have not rapidly developed following the restoration of tidal flow.

312

313 Initially, Abbotts Hall was rapidly colonised by *Salicornia* and *Suaeda*, and after two years

314 the mean percentage of bare ground was only 35% (Mossman 2007). But in 2009, seven

315 years following tidal restoration, both the engineered and non-engineered parts of the

316 restored site still had very different vegetation from the adjacent reference marsh. A

317 substantial proportion of bare ground remained and the two annual species, *Salicornia* and

318   *Suaeda* were also still abundant. Vegetation on the engineered part of the site was more

319   similar to the reference marsh as a result of colonisation of the upper elevations by

320   *Puccinellia* and *Atriplex*. However, the abundance of *Salicornia* and bare ground remained

321   higher than on the reference marsh. This lack of colonisation by higher marsh species is

322   despite the area being slightly *higher* in the tidal frame than the reference site, and having

323   sediments that are slightly better oxygenated at any given elevation than those on the other

324   two areas. So whilst suitable elevations in the tidal frame and moderately oxic sediments

325   are necessary conditions for development of mid-marsh communities, they do not

326   guarantee success. In the UK, most managed realignment sites are relatively low in the tidal

327   frame, but we have observed similar failure of vegetation development on higher sections

328   of some other restored marshes (Mossman et al. 2012a). What might be responsible for this

329   failure?

330

331   Perhaps there has simply not been sufficient time for the vegetation to fully develop. It is

332   true that succession can be relatively slow, but on natural marshes the rate of succession

333   from mudflat to pioneer communities to the colonisation by later successional mid and

334   upper marsh species is usually constrained by rates of sediment deposition (Boorman 2003).

335   In locations where natural marsh development has been initiated by a change in the local

336   hydrodynamic or sedimentary environment rather than by gradual sediment deposition,

337   succession takes place rapidly. Species-rich vegetation, including high marsh perennials such

338   as *Armeria maritima; Juncus maritimus* and *Triglochin maritima*, developed in 17 years on

339   an area of previously bare sand in North Wales (Packham and Liddle 1970). In the

340   Netherlands, Olff et al. (1997) found that ten years after initial colonisation, vegetation was

341   dominated by *Spergularia maritima, Suaeda maritima, Limonium vulgare* and *Puccinellia*

342   *maritima*. Natural recolonisation is also rapid when turf is stripped from existing salt

343   marshes; *Puccinellia maritima* recolonises within a year, even at elevations above its normal

344   range, and re-establishment of full vegetation cover is complete after 3-5 years (Cadwalladr

345   and Morley 1974; Gray and Scott 1977a, b). In contrast to these examples, restored sites

346   flooded accidentally more than a century ago still show marked differences in vegetation

347   communities (Mossman et al. 2012a). Are the "missing" species those that disperse only

348   slowly to created marshes? Some perennial species are rare on created marshes of all ages,

349   even many decades after restoration (Mossman et al. 2012a). Colonisation by some

350   perennials, such as *Limonium vulgare* , *Plantago maritima* and *Triglochin maritima*, may be

351   slowed by low seed viability and long reproductive cycles (Boorman 1967; Hutchings &

352   Russell 1989; Davy & Bishop 1991). But the two species that make the greatest contribution

353   to the difference between the created and reference marshes at Abbotts Hall are *Atriplex*

354   *portulacoides* and *Puccinellia maritima*. Both of these have rapidly colonised other managed

355   realignment sites and are often dominant on older accidentally restored sites (Mossman

356   2007).

357

358   What other environmental factors might be responsible? Sediments on the created marsh

359   have higher shear strength, and lower water and organic matter contents than the

360   reference marsh. So water availability will be low and it will be difficult for plant roots to

361   penetrate the soil. Establishing which, if any, of these possible factors are responsible will

362   require field experimentation. Addition of organic matter to soils on Friendship Marsh in the

363   Tijuana Estuary increased plant survival rates (O'Brien and Zedler, 2006), although it is not

364   possible to judge the relative importance of the effects of increased organic matter, nutrient

365   content and decreased bulk density. We have not measured soil nutrient concentrations,

366   because these are unlikely to be limiting at a site previously used for intensive arable

367   farming before flooding. At another site, plant species distributions showed weak or non-

368   significant relationships with soil nutrients were measured (Davy et al. 2011).

369

370   The reference marsh shows considerable topographic heterogeneity, even on horizontal

371   scales of a few metres. This is typical of natural marshes, and develops, at least in part,

372   during the early stages of plant colonisation of mudflats and results in heterogeneity of

373   sediment redox (Stribling et al. 2006, 2007). This in turn produces heterogeneity of plant

374   communities (Morzaria-Luna et al. 2004; Varty and Zedler 2008). By contrast, the restored

375   marsh surface lacks topographic heterogeneity, as a result of levelling for arable farming.

376   This is true of many managed realignment sites, and means that their visual appearance is

377   rather different to that of natural marshes, in ways that are obvious even to people without

378   detailed knowledge of their ecology (c.f. Fig. 2). As well as being responsible for a lack of

379   ecological heterogeneity, the lack of topographic variation may help to create conditions

380   that are hostile to plant colonisation. When the restored marsh has been flooded by a high

381   spring tide, water will drain away much more slowly than from a marsh with a more

382   heterogeneous surface and natural, or artificial, creeks. Many managed realignment sites

383   that were previously used for arable farming have substantial areas of shallow standing

384   water after high spring tides (pers. obs.). If hot, dry weather follows a period of spring tides,

385   evaporation of this standing water will produce high surface salinities, inhibiting

386   germination and growth, even of halophytes. A similar process was responsible for the slow

387   recolonisation of large open areas created by ice scour observed on New England marshes

388   (Bertness et al. 1993; Shumway and Bertness 1992, 1994), where initial plant colonisation

389   provides shading, reduces evaporation and salt stress and facilitates the colonisation of

390   other plants (Bertness 1991).

391

392   If topographic uniformity does contribute to the failure of later successional plants to

393   colonise, then the restored marsh could become more similar to reference sites over time if

394   sediment erosion and/or deposition generate more natural topography. This can occur

395   when the restored sites are at low elevations as patchy vegetation colonisation may also

396   increase topographic heterogeneity (Stribling et al. 2007). But rates of sediment supply are

397   low on the high marsh, so more varied microtopography cannot develop as a result of

398   differential deposition. Erosion could generate heterogeneity on higher sites if sediments

399   are relatively soft. But at Abbotts Hall, high sediment shear strengths will inhibit erosion and

400   high in the tidal frame flooding is less frequent and water velocities, and therefore erosive

401   forces, are lower (Atkinson et al. 2001; Wallace et al. 2005). This may be why excavation of

402   creeks alone has limited impacts on the upper marsh topography (Wallace et al. 2005) and

403   on plant survival there (O'Brien and Zedler, 2006).

404

405   It is likely that the high sediment shear strength results from deflocculation of clay minerals

406   in the low salinity conditions during aerial exposure, leading to loss of soil structure. This in

407   turn results in over-compaction when flooded by sea water, a process that has led to the

408   widespread development of over-consolidated sediments in the Holocene estuarine

409   deposits of South-East England (Crooks 1998; Crooks et al. 2002). These consolidated layers

410   can impede drainage in freshly deposited sediment and contribute to the development of

411   anoxic conditions at low lying sites (Crooks et al. 2002), and over-compaction of sediments

412   also seems to have hindered the ecological development of the Seal Sands managed

413   realignment (Evans et al. 1998). Once a marsh has been flooded, large scale sediment

414 treatment to break up over-consolidated sediment is extremely challenging. As noted

415 above, excavation of creeks seems to be of limited value on high marsh sites, and it may be

416 necessary to carry out more aggressive surface treatment to prevent over-consolidated

417 layers forming. This might involve deep ploughing or even the mixing of soil and seawater

418 into a slurry before flooding. Experimental evaluation of the options is required, but if over-

419 consolidated sediments can be avoided, this will result in a created marsh surface that is

420 more likely to undergo small scale erosion and deposition to generate topographic

421 heterogeneity. This will certainly create a marsh with a more "natural" appearance and one

422 that may also be less hostile for plant colonisation and provide microsites suitable for the

423 growth of different species (Varty and Zedler 2008).

424

425 **Acknowledgements**

428

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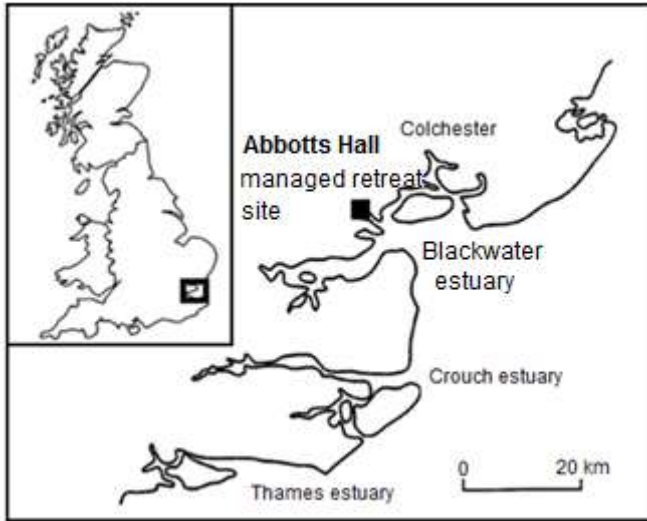
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560 Fig. 1. Location of study site within the UK and location of three sampling areas; A = Non-
561 engineered part of the restored salt marsh; B = Engineered part of the restored salt marsh; C
562 = Reference salt marsh. Aerial photography from Google maps (© Google, 2009)
563
564

a

b

c

565
566 Fig. 2. Photographs showing characteristics of each site. Taken 22/08/09. A) non-engineered
567 part of the restored salt marsh; b) engineered part of the restored salt marsh, with
568 embankment of spoil from excavating creek to right; c) reference site
569

2D Stress: 0.11
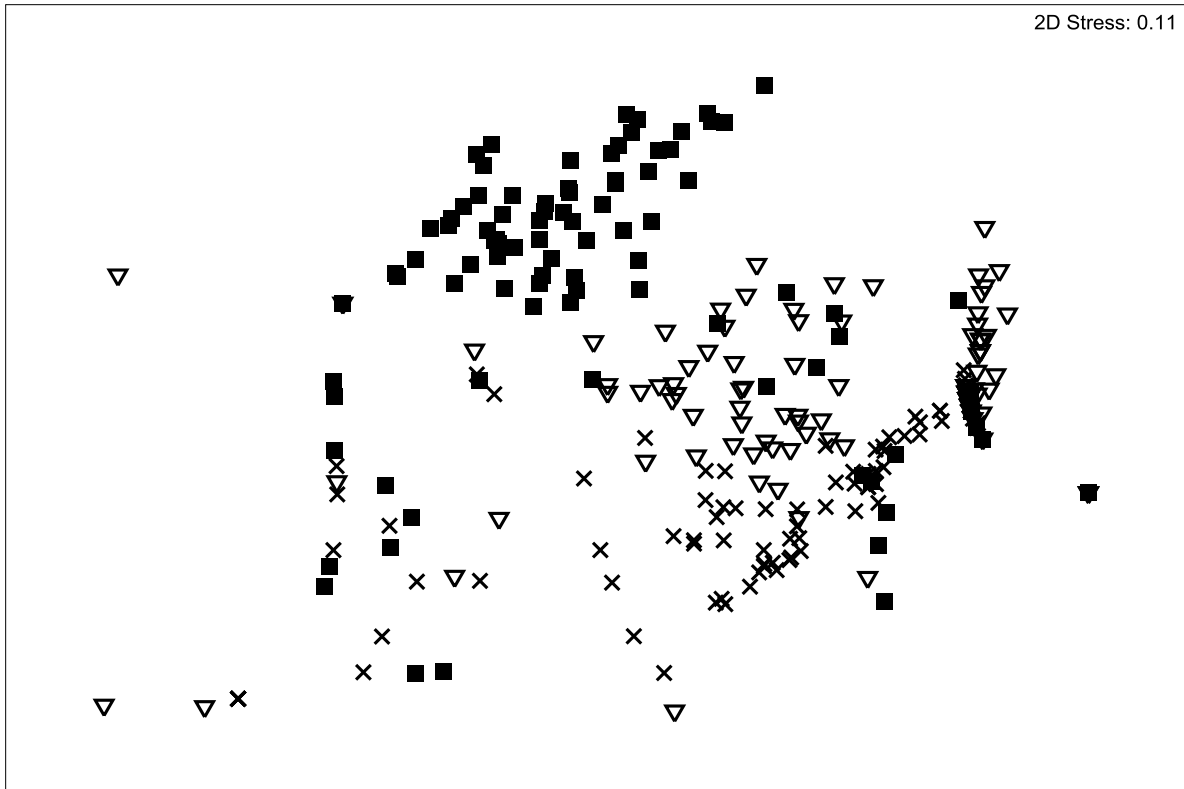
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571 Fig. 3. MDS plot of vegetation data at Abbotts Hall realignment site and adjacent reference
572 marsh. ■ indicates reference site, ∇ engineered part of the restored saltmarsh; × non-
573 engineered part of the restored saltmarsh
574

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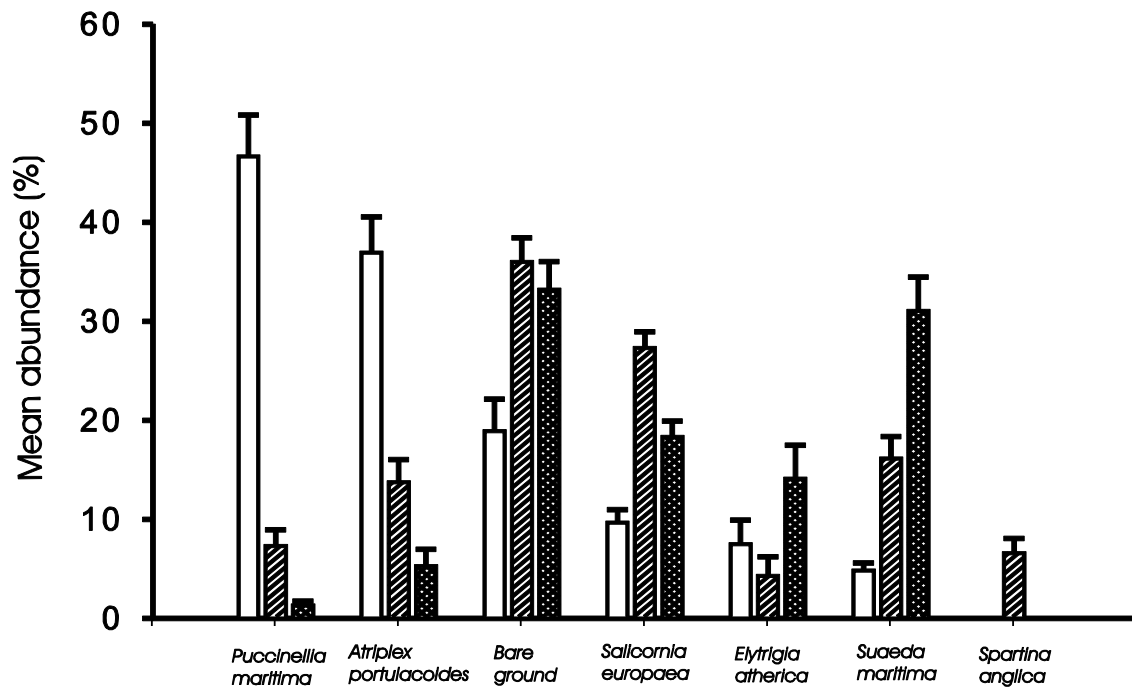
Fig. 4. Mean abundance of six commonest species and bare ground on the reference salt marsh
(open bars) and engineered (diagonal) and non-engineered (cross-hatched) parts of the restored salt
marsh. All species with mean abundance > 5% in at least one of the three areas are plotted. Error bar
is 1 standard error. Differences between sites are significant (P<0.001) for all species.

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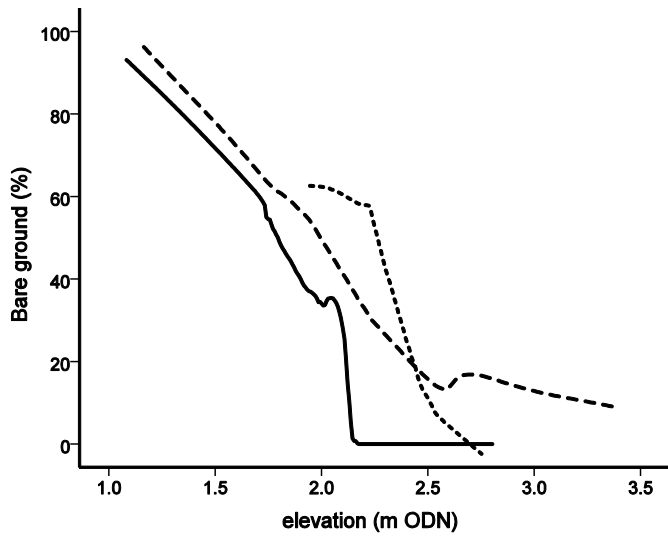
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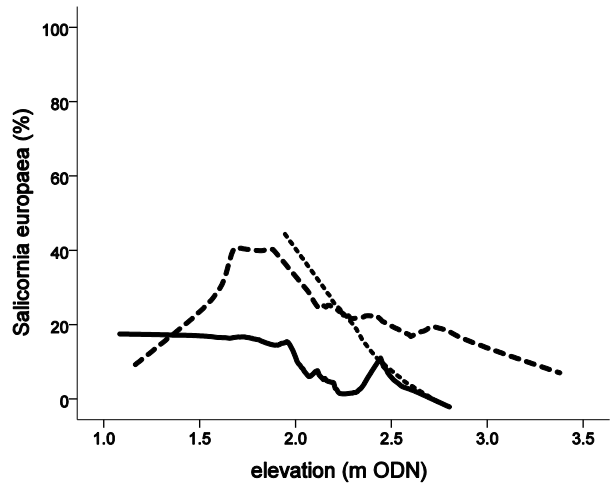
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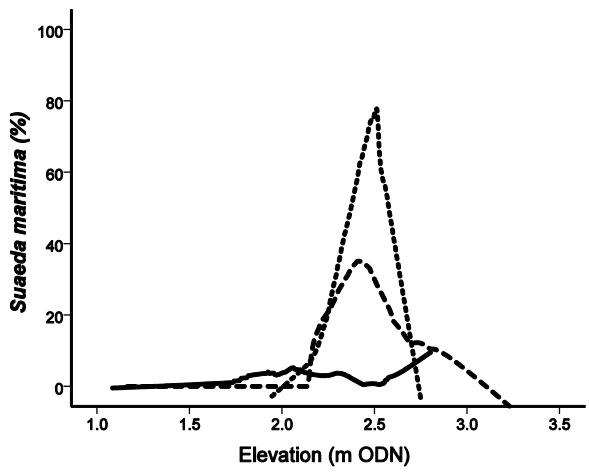
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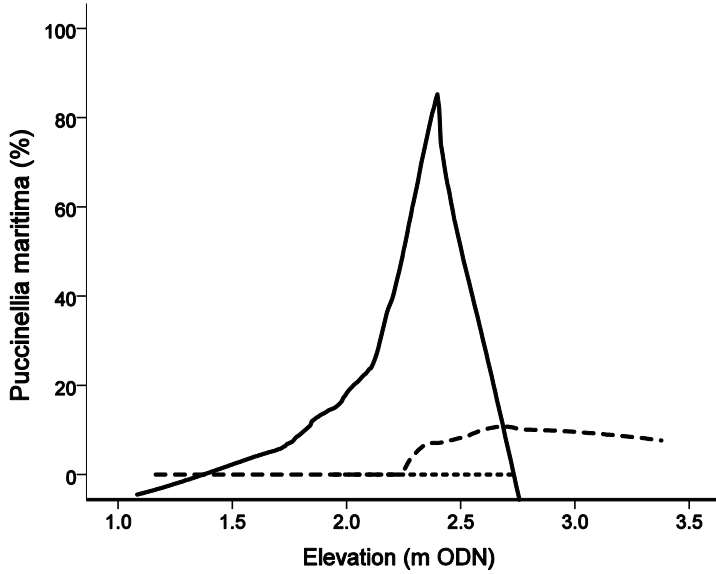
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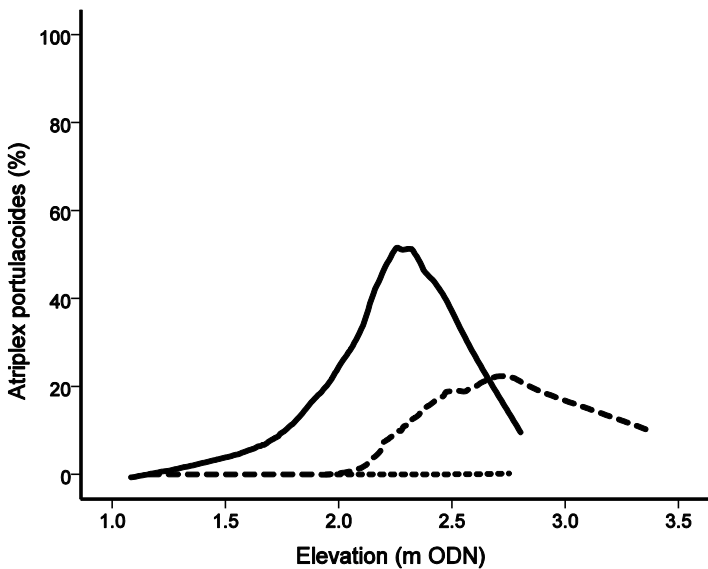
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594   Fig. 5. LOESS regressions showing relationship between percentage cover of individual plant
595   species and elevation at Abbotts Hall restored and reference salt marshes. a) bare ground ,
596   b) *Salicornia europaea* ; c) *Suaeda maritima* d) *Puccinellia maritima* e) *Atriplex*
597   *portulacoides.* Solid line – reference site; dashed line engineered part of the restored site;
598   dotted line – non-engineered part of the restored site
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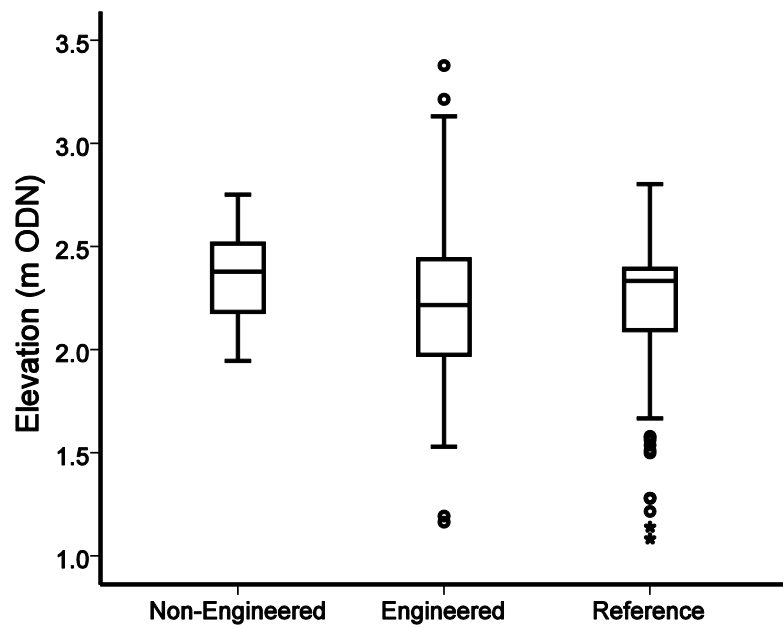
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602 Fig. 6. Range of elevations occurring at the engineered and non-engineered part of the

603 Abbotts Hall restored salt marsh and at the adjacent reference marsh
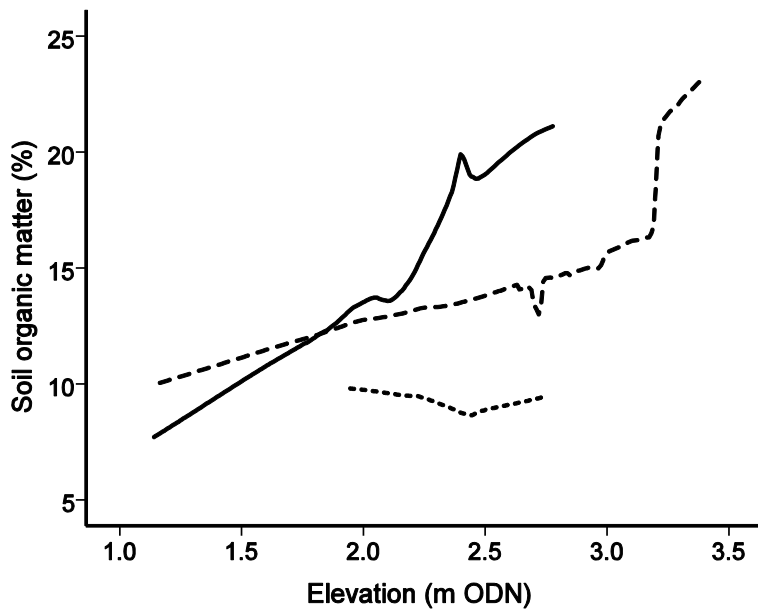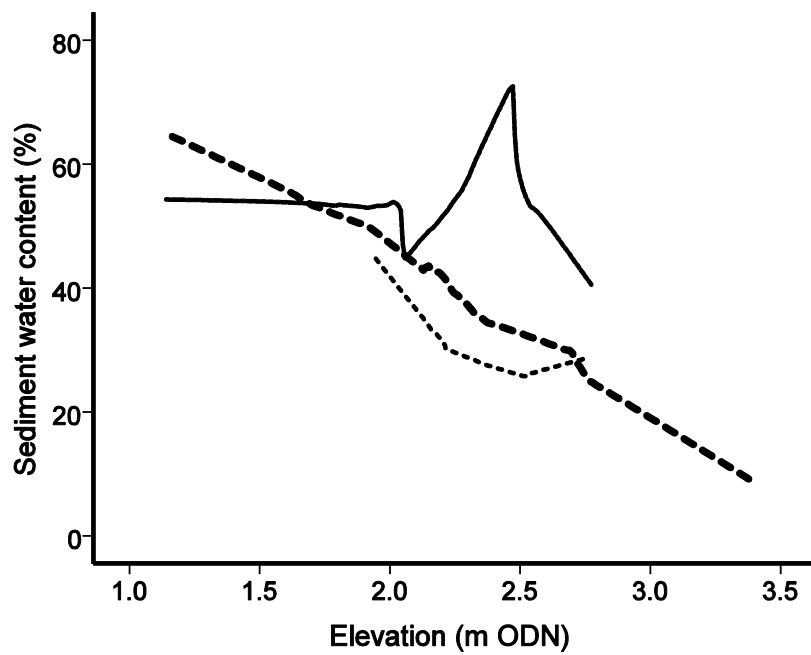
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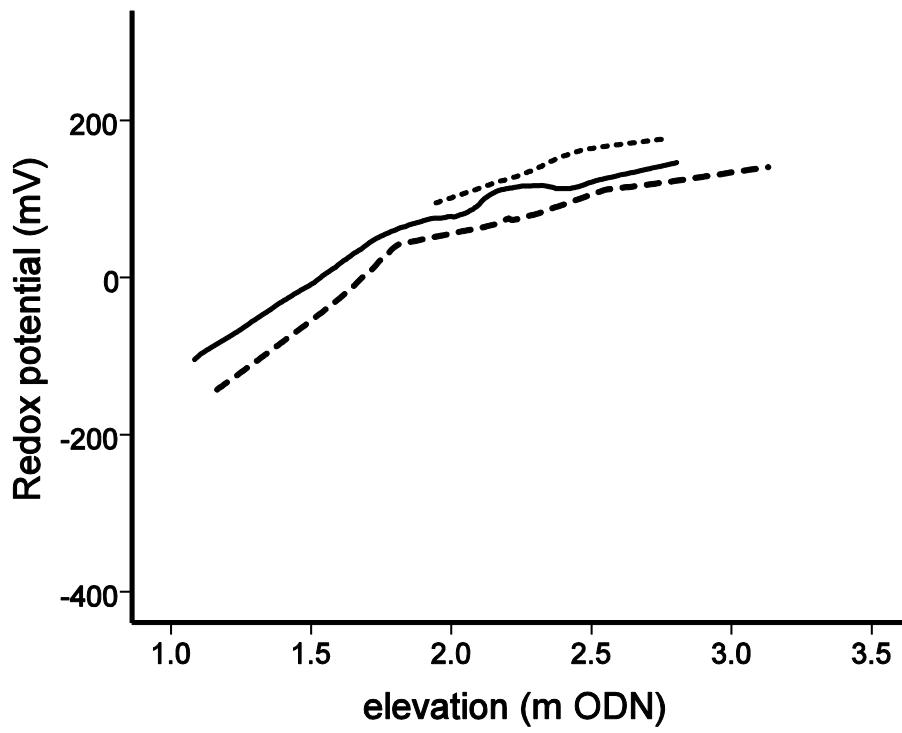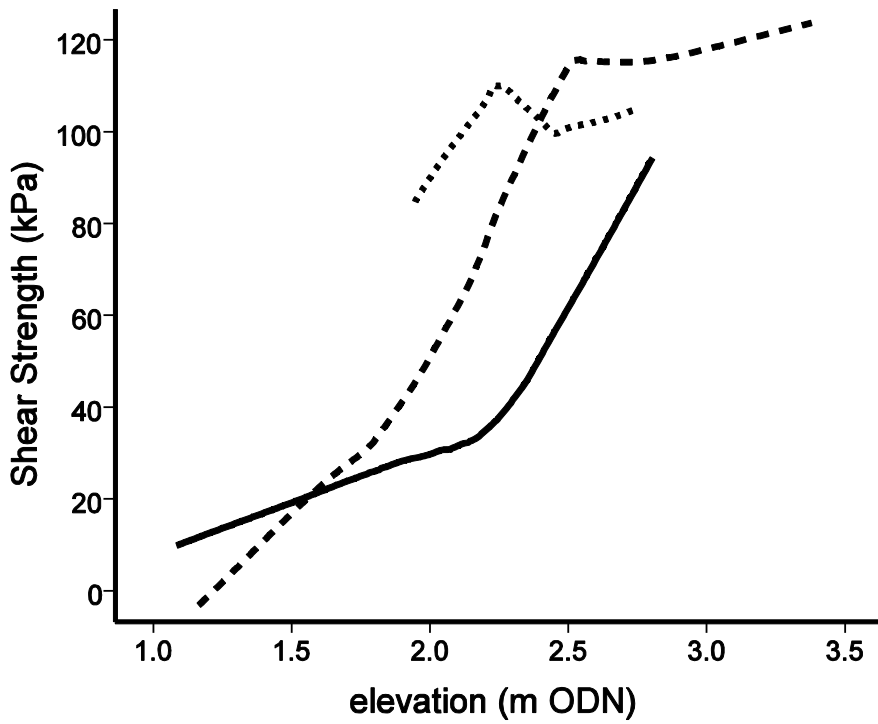
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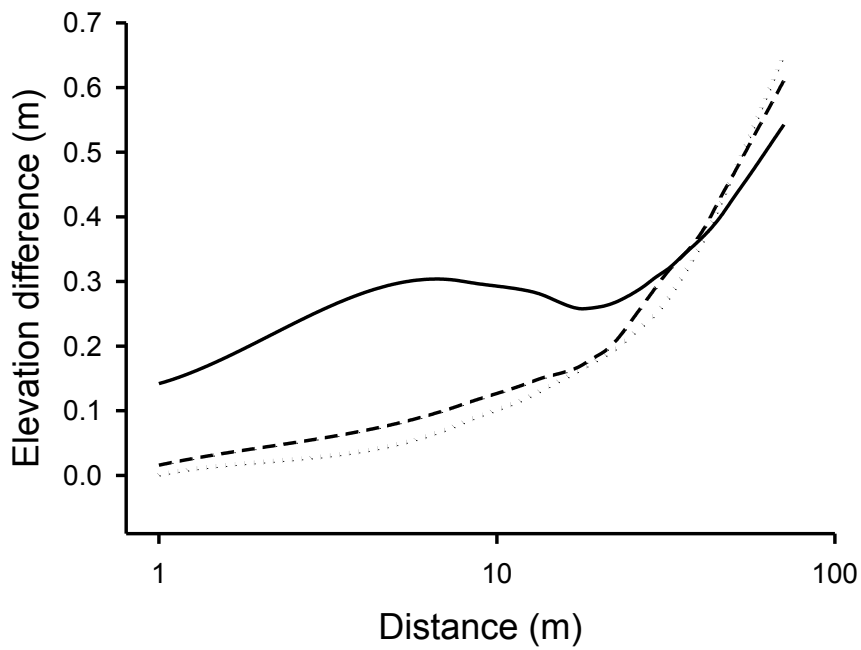

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615   Fig. 7. LOESS regressions showing relationships with elevation of a) redox; b) shear strength;

616   c) soil organic matter and d) water content. Details as Fig. 5.

617

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619
620 Fig. 8. Spatial scales of topographic heterogeneity on the three sites at Abbotts Hall, quantified using
621 the relationship of elevation difference between pairs of sampling points to the horizontal distance
622 between them. Lines are LOESS regressions fitted to all pairwise differences between sampling
623 points. Dotted line shows relationship for the non-engineered part of the restored salt marsh,
624 dashed line for the engineered part of the realignment site and solid line for the adjacent reference
625 salt marsh.
626