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USAR
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An innovative method applicable to saltmarsh habitat restoration using dredged sediment was tested. Biodegradable wooden sluice boxes were placed in eroded "pits" or pools in the damaged saltmarsh and dredged sediment was pumped to fill these pits up to the level suitable for saltmarsh flora colonisation. The sluice boxes were used to carefully control volumes and dewatering of dredged material to maximise the resultant fill level. Sediment was left to settle during periods of high tide and water was prevented from entering and mixing the deposited sludge. During low tide, the supernatant was drained off, enabling more material to be deposited. This technique helped develop a layer of substrate for pioneer halophytes to colonise, without loss of material through natural entrainment and deposition back into source sites. Increases in colonisation, consolidation, shear strength and bulk density of the newly placed sediment proved the suitability of this technique for habitat restoration.

INTRODUCTION

Saltmarsh can be defined as an intertidal area which is flooded and drained by salt water during tidal cycles, supporting a diverse range of halophytic flora and micro, meso, and macro fauna. Saltmarsh habitats are known as 'Cinderella' ecosystems, seemingly inactive and unimportant. However, these environments are crucial and provide a number of vital ecosystem services, such as flood protection and carbon sequestration.

Some studies by Möller et al. [1–3] found wave energy attenuation averaged 2.1 %/m, averaging 92% dissipation over 310m of saltmarsh and have shown incident wave energy reduced by an average of 82% over a pioneer saltmarsh on the North Norfolk coast. In comparison to only 29% energy reduction over a comparable width of fronting sandflat. Demonstrating the importance of saltmarsh in absorbing erosive wave energy.

Further, Mcleod et al. [4] found that saltmarsh habitats sequester carbon at a rate ~55x greater than tropical rainforests, locking up to 87.2 ± 9.6Tg C y -1.

This is especially significant; saltmarsh occupies only a small fraction (0.3%) of the total land surface on Earth [5]. Further, human coastal development and associated coastal squeeze has reduced the size and number of mature saltmarsh habitats since the 19th century [6].

To combat this decline, various programmes have been developed to restore and conserve this unique habitat. However, saltmarsh geomorphological properties, such as soil cohesiveness and shear strength are unique and location specific [7]. This has led to many failures of saltmarsh restoration and regeneration projects. For example, the Isles Dernieres, LA, USA, transgressive barrier which failed to develop saltmarsh flora. This was found to be caused by the use of non-site specific sediment with inappropriate geomorphological properties to initiate saltmarsh colonisation [8].

Thus, it is our aim to determine whether using site specific sediment alongside new technological advances can successfully restore and regenerate lost saltmarsh habitat. These new technological advances refer to the use of sluice boxes to control sediment volume flux, without loss of material through natural weathering processes.

This study was carried out as part of the Interreg 2seas Using Sediment As a Resource (USAR) project aimed to re-use waste sediment to drive the wider ambition of a circular economy in Europe. Whilst also improving navigation and coastal defences with nature-based solutions (NBS).

The dredging campaign included mechanically and hydraulically removing 53,000m3 of sediment from the navigational channels. Sediment was mechanically deposited or pumped to re-use sites throughout the harbour, identified using historical 'RAF' aerial images dating back to 1947. This resulted in the restoration of 3 ha of intertidal mudflat and saltmarsh using advances in restorative techniques, namely the use of 'local' sediment and sluice boxes to compartmentalise and control the filling level and maximise the amount of available volume.

This nature inclusive design was aimed at providing a NBS to combat continued coastal erosion and a provide flexible defence to predicted sea level rise.

This paper reports on the results of successful saltmarsh flora colonisation of previously damaged pits within the habitat, across four winter dredging campaigns and habitat restoration works from 2016-2020.

LOCATION

Brightlingsea is located in the Tendring district of Essex on the banks of Brightlingsea Creek, a tributary of the River Colne.

The local saltmarsh habitat, specifically along the St. Osyth Saltings, is well established and has been dated, via peat seams, to 4,280 ± 45 years old [9]. Consequently, it supports a diverse range of biodiversity and is protected under national and international designations. Including Ramsar, Site of Special Scientific Interest (SSSI), Special Area of Conservation (SAC), Special Protection Area (SPA) and Marine Conservation Zone (MCZ). However, the St. Osyth saltmarsh has been subject to excessive erosion and 'cliffing', caused by coastal squeeze.

A significant cause of this are the St. Osyth Borrow Pits (SOP). These were dug in response to the 1953 storm and flooding, to construct an earthen sea defence embankment to protect the village of St. Osyth. The pits created zones of structural weakness within the pre-existing saltmarsh, resulting in erosion and entrainment of fine-grained silt and clay into the main channel. This has resulted in the siltation of economically important cargo routes, reducing income to the harbour and the wider community.

To combat both the increased channel siltation and loss of saltmarsh habitat, the SOP, alongside 4 compartments along Cindery island west, were identified as key sink locations to deposit dredged material under the USAR aims of recycling waste to promote nature inclusive design and coastal protection.

MATERIAL AND METHOD

These suitable restoration sites were determined using historical imagery analysis of RAF photographs dating back to 1947. Analysis focused on areas with historic saltmarsh retreat (Figure 1).

To ensure the SOP were secure and ready to receive the dredged material, 9 bespoke sluice boxes were installed, allowing for the controlled release of tidal waters. This facilitated the release and skimming of 'clean' surface water once the fine-grained sediment settled out of suspension (Figure 2).

It should be noted that all reuse sites are intertidal environments which caused complex and at time hazardous working conditions.

Brushwood fascines (Figure 3) were constructed adjacent to restoration compartments on Cindery West, to slow the flow of erosive wave energy and encourage deposition of sediment. This resulted in the vertical accretion of sediment providing a suitable substrate for saltmarsh development. The brushwood also provided compartmentalized areas suitable for placement of dredged material.

These compartmentalised techniques are emerging technologies in restorative processes and allow control of sediment and water flows, increasing potential for successful consolidation and eventual colonisation, rather than leaving the sediment to distribute under fully natural cycles, which can result in lower biological uptake.

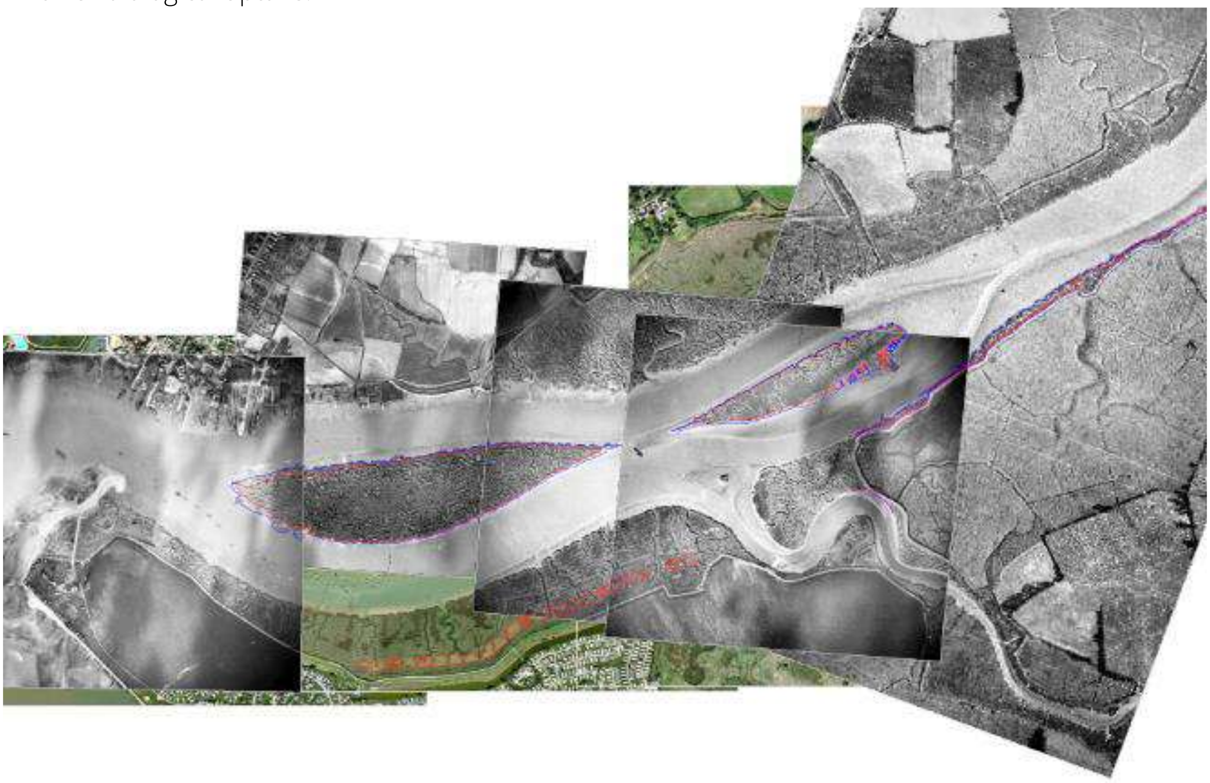

Figure 1. An overview of current and historic saltmarsh extent within Brightlingsea Creek, A) SOP, B) Cindery Island West

Figure 2. Sluice boxes installed at the SOP. Note the filtering of clean surface water

Figure 3. Brushwood fascine compartments prior to filling, as used at Cindery Island West

The dredging campaign started in the winter of 2016 and carried through to 2020. Four types of dredging were implemented across this period, including plough dredging, water injection, excavator (grab) and cutter suction. The latter two methods were used for habitat restoration.

RESULTS AND DISCUSSION

Year 1

Monitoring took place after the first period of dredging (Oct'2016-Mar'2017), looking at several environmental parameters. The most relevant to this report include sediment consolidation and pioneer halophyte succession. Using a Pilcon 33mm Hand Vane tester to assess mechanical strength and cohesiveness of deposited dredged sediment, consolidation measures can be assessed. This was done according to BS1377 standard.

Initially, the data shows the shear strength of recently dredged material is lower than adjacent (A&B on Figure 4) natural intertidal mud. This is likely due to disturbance by the dredging process, reducing cohesiveness and mechanical strength of flocculated mud. However, location 4 did show shear strength was higher than surrounding mud, possibly due to location specific presence of detrital carbonate, which aids increases in compaction [10] or presence of compacted mud such as London clay, dredged from deeper layers in the channel.

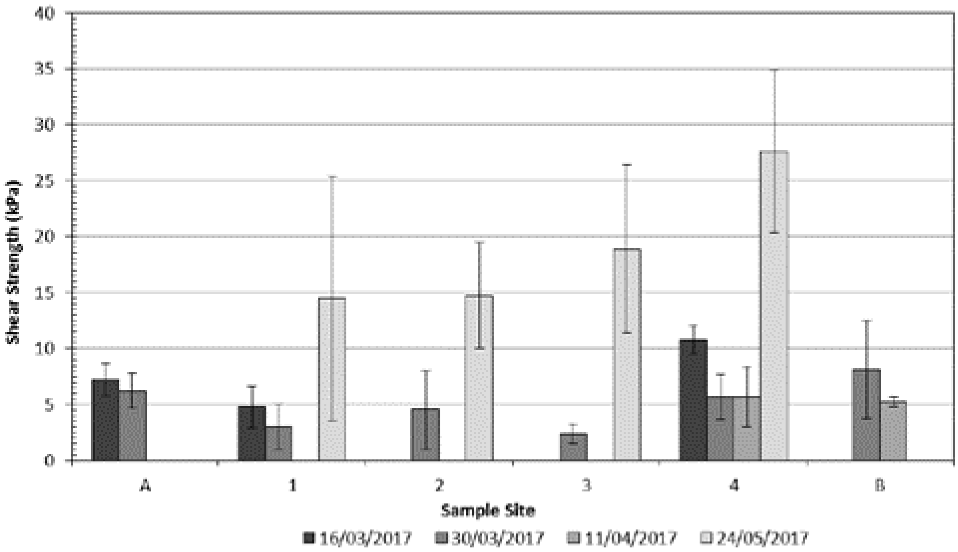

Figure 4. Shear strength measurements within each restoration compartment on Cindery island West. Note increasing shear strength (consolidation) over time

The data show a proportionate relationship between time and mechanical shear strength, with consolidation increasing with time, as expected (Figure 4). Further, consolidation within compartments 2 and 4 is higher than baseline measurements at reference stations (A&B).

It is likely that this recent and pronounced increase in shear strength is partly due to the macroalgal colonisation observed onsite, facilitating the binding and stabilisation of the sediment. This is supported by visual observations of macroalgal biofilm colonisation on newly deposited dredged sediment, in May 2017 (Figure 5). That is indicating the start of pioneer seral succession. This is also explained by the intertidal nature of the sites, with regular draining leading to consolidation over time. Despite the apparent increase in sediment cohesiveness, there is large variability in the data due to small spatial scale variabilities on site. This makes it unfeasible to quantify the impact of the works accurately after 1 year.

Year 2

Following ~4months, the shear strength of sediment within the restoration compartments was equal to that of surrounding mudflat (Figure 6).

This is likely due to dewatering of the sediment during periods of low water when the sediment was exposed, facilitating water loss through drainage, evaporation, settlement, and material consolidation. A significant increase in shear strength of the reference stations has been observed and mirrored to an extent by that of the restoration compartments. However, whilst shear strength within the reference sites subsequently decreased, shear strength within the restoration compartments has remained high. This is considered to represent geological succession of the sediment towards a substrate more common with lower saltmarsh, as a result of continued dewatering due to the increased elevation.

Figure 5. Visual evidence of Macroalgal colonisation on newly placed material- Cindery Island west

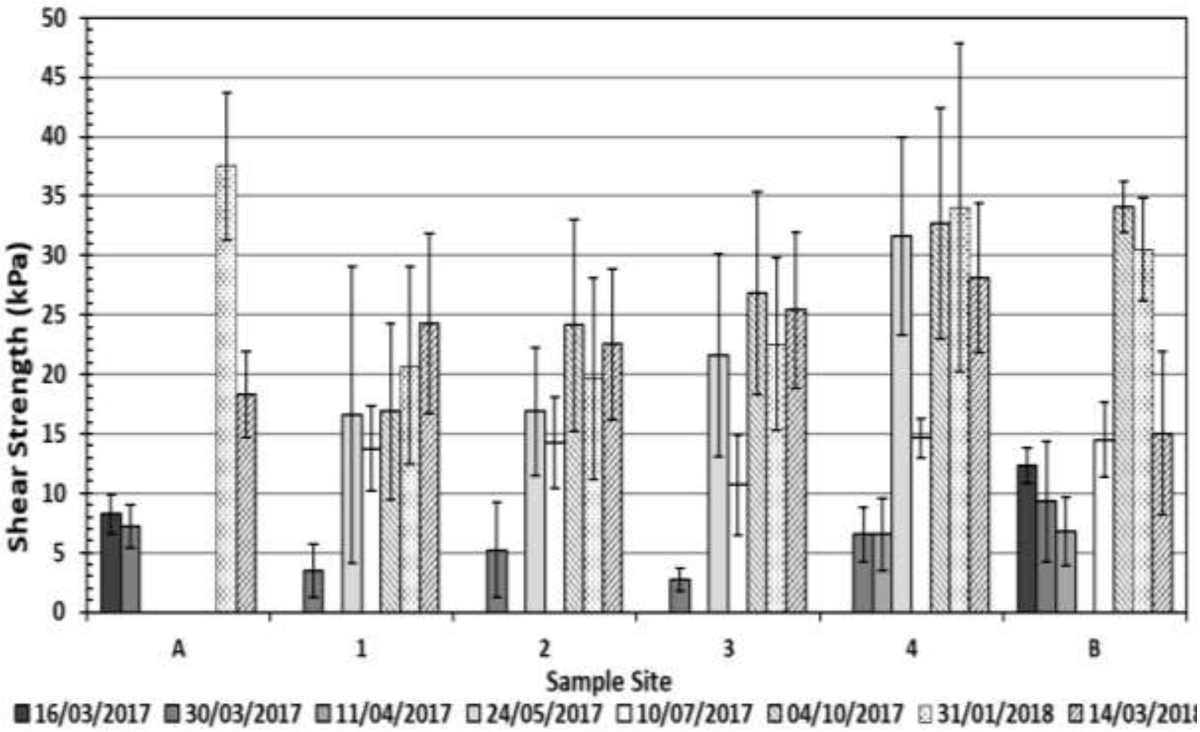

Figure 6. Shear strength of dredged material after year 2 monitoring. Note continued consolidation over time

Furthermore, visual observations of pioneer saltmarsh flora colonisation, supports above observed increased shear strength and consolidation. This is likely the result of increased organic compounds and fibres, which have been shown to significantly increase soil shear strength through presence of aromatic cyclic alkenes [11].

Years 3 and 4

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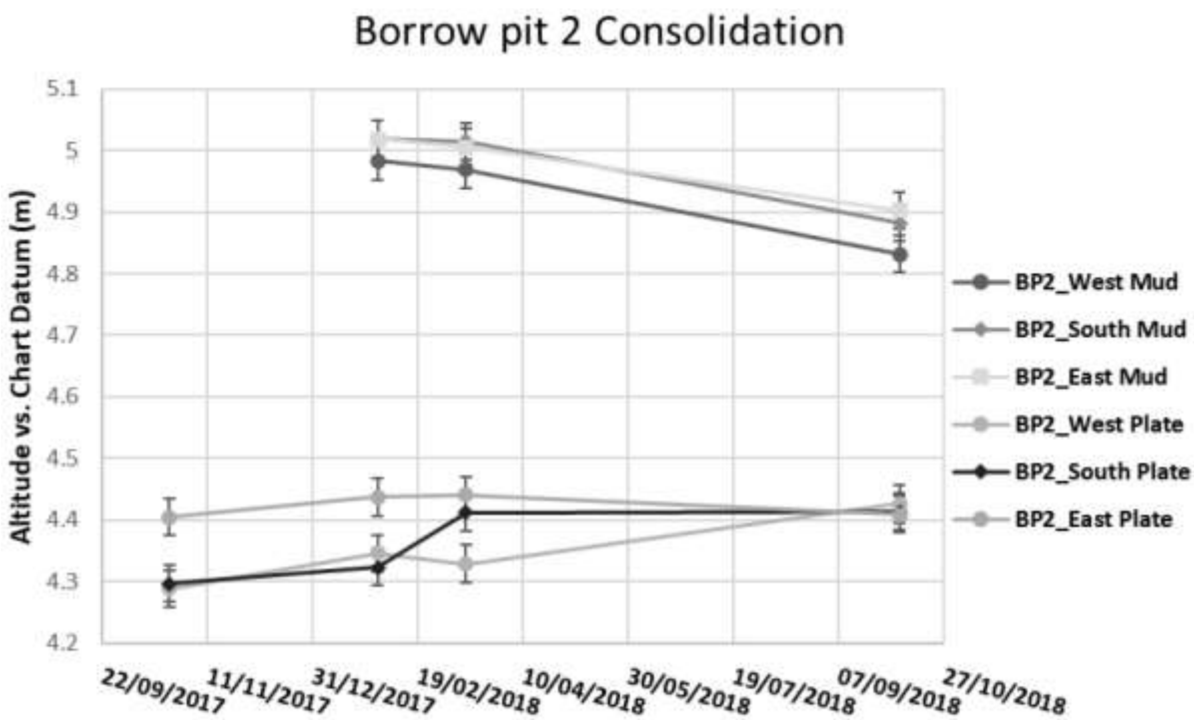
No dredging works took place during year 3, hence no monitoring was performed. However, drone monitoring, aerial elevation models and GPS readings were taken-recording consolidation of newly placed sediment (Figure 7).

Figure 8 shows consolidation rate over 1 year, across two pits, showing location (South, East, and West) of mud placement with respect to marker plates. These marker plates were placed into the pits before filling, using GPS measurements to mark their elevation as well as elevation of surrounding mud.
Following filling, the newly placed mud shows a significant altitude decrease with respect to chart datum (m) and base plate markers, indicating significant consolidation of between 10 and 18cm. In pit 2, the observed changes in the base plate elevation were attributed to the baseplate becoming slightly angled towards the centre of the pits. The measured part of the plate was that closer to the edge of the pit, hence appearing to slightly grow in elevation. It is likely that this angle change was caused by the centre of the pits subsoil being compressed by the additional sediment weight above.

Figure 7. GPS measurement of base plate elevation



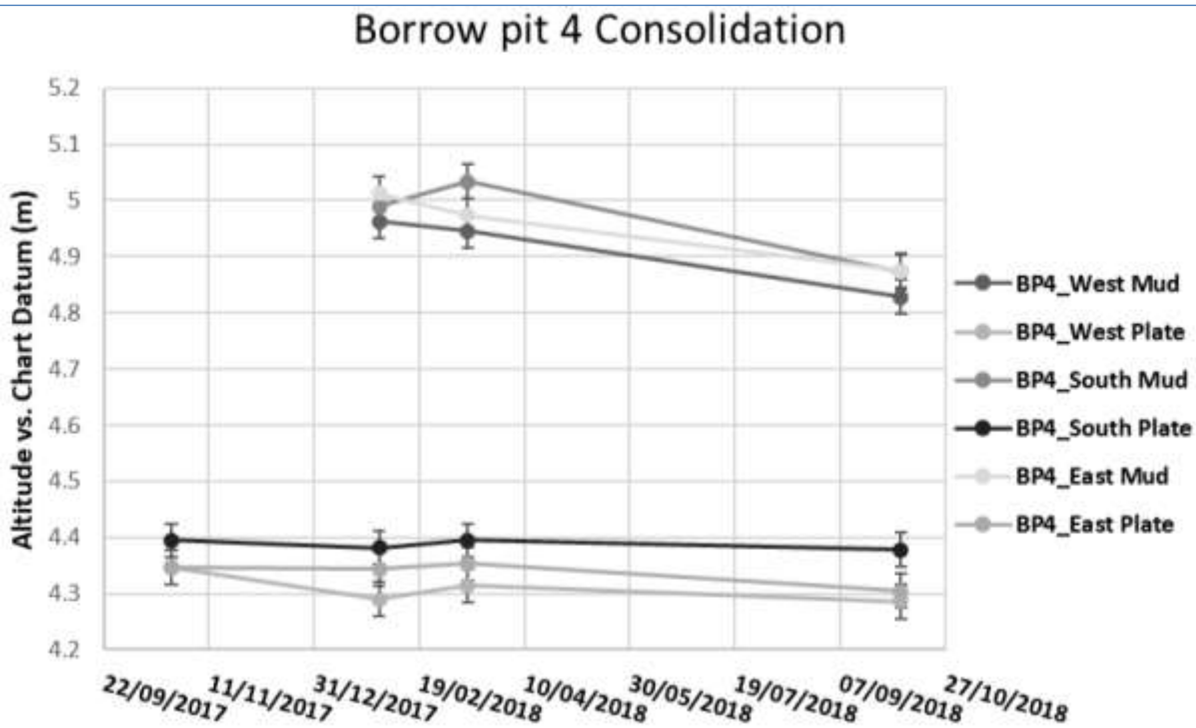


Figure 8. Consolidation of newly placed dredged sediment (Pits 2 &4) in comparison to mud plate and base substratum level

In addition to the data in Figure 8 shown above, further evidence of increasing rates of consolidation and strength can be demonstrated in Figure 9. Dry bulk density (g cm-3) clearly increases with time, across both pits 2 and 4, from 0.65 to 0.88 g cm-3 for pit 2 and 0.70-0.87 for pit 4 g cm-3. This indicates increases in vertical compression, accretion, and consolidation, alongside the influence of complex aromatic organic compounds from observed pioneer floral succession (see Figure 10).

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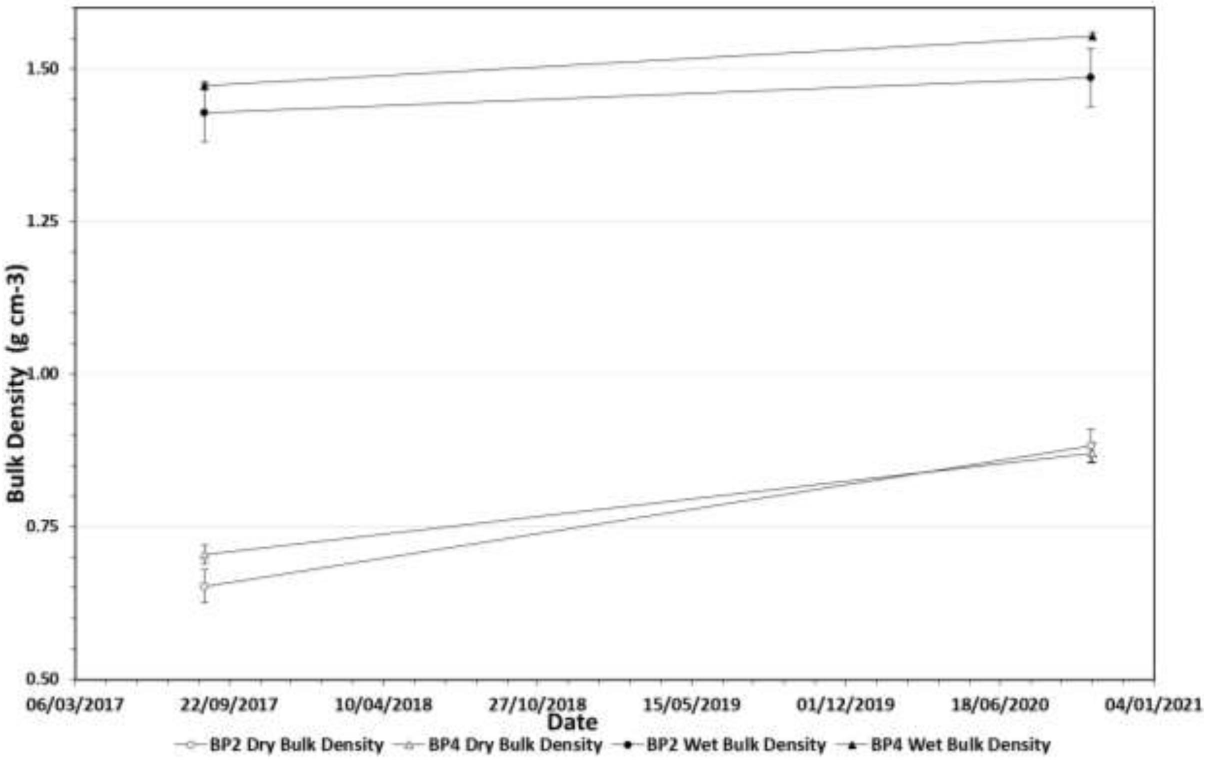

Figure 9. Dry and Wet Bulk density (g cm3) (pits 2 and 4) over time. Note increase in dry bulk density in both pits, indicating an increase in consolidation of newly placed dredged material

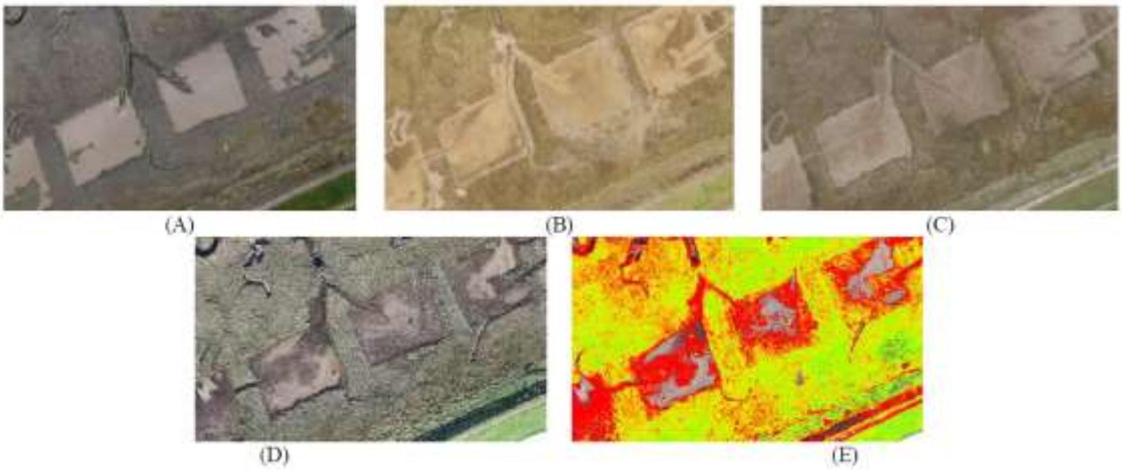

Figure 10. A) Before works, May 2017. B) After filling, Mar, 2018. C) After works and one season of consolidation, Oct 2018. D) After another season of consolidation and colonisation, Oct 2020). E) GNDVI in Oct 2020

Wet bulk density is fairly consistent for both pits, increasing gently from 1.43 to 1.49 for pit 2 and 1.47-1.55 g cm-3 for pit 4. Analogous to dry bulk density, the increase observed represents a slight decrease in porosity, likely caused by soil dewatering as a result of increasing consolidation rates. These values correspond well with other wet bulk density values, measured on newly deposited dredged material. Widdows et al. [12] found wet bulk density values between 1.37-1.41 g cm-3 across a saltmarsh restoration site, using dredged material at Titchmarsh, Essex. This site was found to have accelerated rates of consolidation, correlating well with the findings in this study.

Colonisation

After 4 years of dredging a total of 3ha of saltmarsh was restored. Monitoring carried out after the last year clearly showed widespread colonisation across all restoration sites. With mature halophytic species, including Spartina spp. and Aster tripolium (Figure 10), all colonising virgin dredged sediment. These aerial drone images of a single location within the SOP, from 2017-2020, clearly show changes over time from consolidation followed by colonisation and succession of saltmarsh flora.
The colonisation of the restoration sites occurred at the lower, and thus faster, time scale of average pioneer colonisation, calculated as 1-5 years [13].
This is supported by effective accretion of sediment in Cindery West and SOP, calculated as 0.4m and 0.37m, respectively. This is significantly higher than average sediment accretion rates in natural saltmarsh habitats. Stumpf [14] found average sedimentation rate as 0.05m-y. Further, Armento and Woodell [15] found average rate of accretion as 0.06m-y in Long Island saltmarsh over a period of 100 years-demonstrating the success of this project in accelerating natural accretion and thus providing suitable substrate for saltmarsh colonisation. This additional head start is essential as the pits have been present in the saltmarsh since 1960s and the natural accretion rates were not sufficient to enable the saltmarsh to recover.
Further, the presence of adjacent mature saltmarsh has aided in the accelerated colonisation seen in Brightlingsea. The presence of mature root systems has prevented the newly placed material from escaping and has provided seeding opportunities once the sediment has consolidated.

GNDVI survey

The marsh was surveyed using an infrared camera to calculate GNDVI index showing the photosynthetic activity of the freshly vegetated parts of the pits and comparing them to the mature marsh. Due to lower density of the pioneering plants in the filled pits, the overall photosynthetic activity is lower than the adjacent mature marsh, however this is expected to equalise as more plants continue to colonise the sites.

Vegetation survey

The similarity of the vegetation within the compartments to the established saltmarsh vegetation was determined by undertaking surveys of alternate compartments and comparing the composition of the vegetation above and below each compartment and within the compartment itself using quadrat surveys. Safety prevented direct surveys of the vegetation within the compartments away from the edge, thus the vegetation was classified into three density classes with an estimate of the cover of each density class determined in the field. The total area of vegetation was determined from aerial photographs. The three density classes were sparse (1-10% vegetation cover), low (11-25% vegetation cover) or moderate (26-50% vegetation cover). The composition of each density class was determined from a sample of accessible areas.
The mean extent of vegetation was 67%, but with the range of cover between 4 and 99% (Figure 11), with the majority of the vegetation within the 'sparse' density class.
The established saltmarsh vegetation comprises a low marsh community of perennial species with a closed sward of mainly Suaeda maritima (Su) and Puccinellia maritima (Pu) with occasional Spartina anglica (Sp) Atriplex portulacoides (At), Salicornia europaea (Sa) and Aster tripolium (As). The extend of bare sediment is very low (<5%). There was no substantial difference in the vegetation of the established saltmarsh below and above each compartment.

Within the restoration compartments the vegetation comprised Suaeda maritima and Spartina anglica, with the proportion of both species being similar across the density classes (Figure 12). Aster tripolium was only present in the moderately dense swards.

Elsewhere, where vegetation has been monitored on sites with 'managed realignment', through breaching sea walls to allow saltmarsh to develop on farmland, the reported time for the vegetation to be similar in the species richness and abundance is between five and 14 years [16].

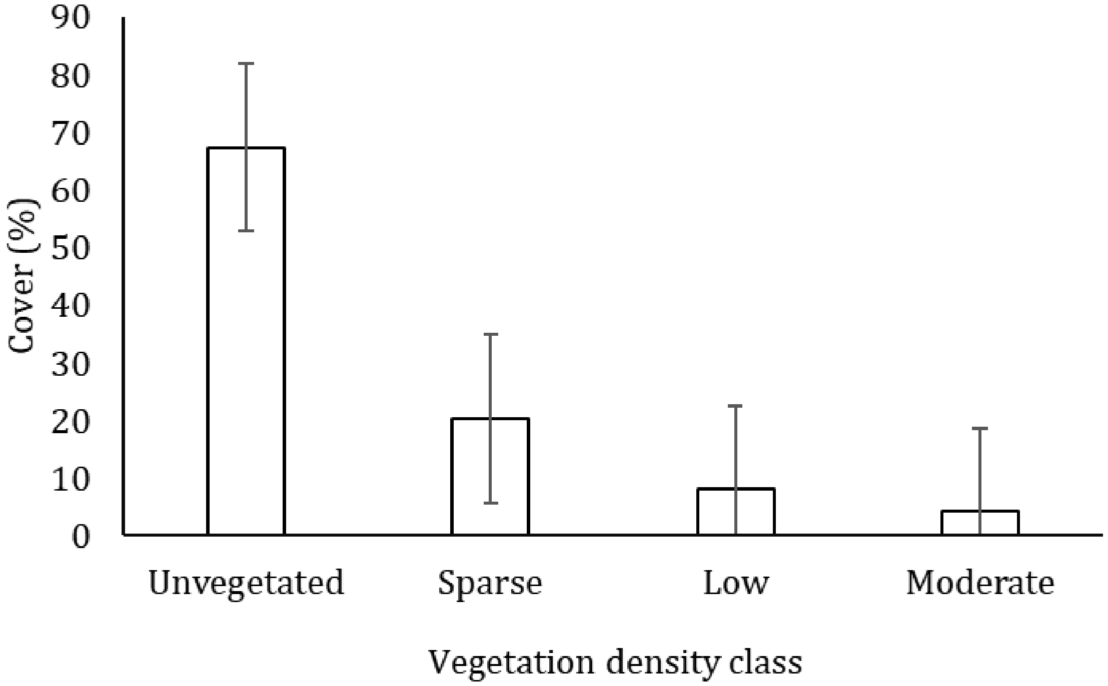

Figure 11. Extent of unvegetated sediment and vegetation density classes across the compartments (mean ±SE)

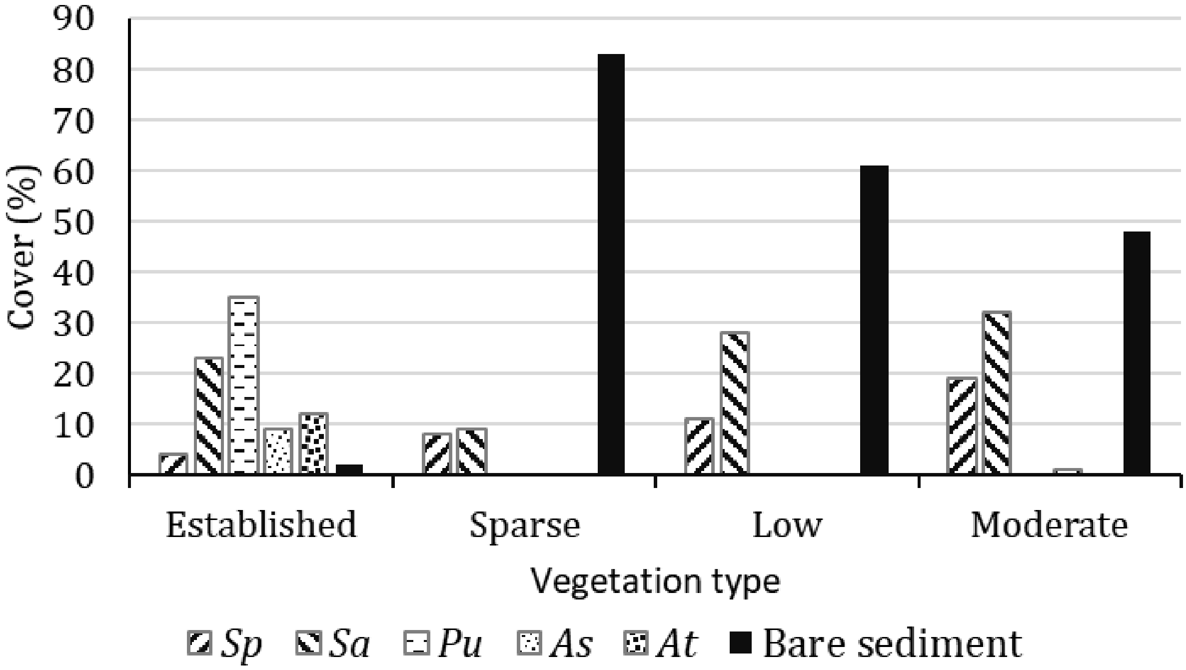

Figure 12. Composition of vegetation within the established saltmarsh and the vegetation density classes

The overall composition is consistent with the sequence of colonisation at these managed realignment sites, with the vegetation within the compartments being typical of an early successional stage. As succession progresses the vegetation is likely to become closer in composition to the established saltmarsh, in terms of species and abundance, although the overall extent of similarity is likely to be determined by physico-chemical characteristics of the compartments.

CONCLUSIONS

Following winter dredging campaigns across 4 years, 53,000m3 of local sediment was beneficially reused to regenerate and re-establish historic saltmarsh extents along two main restoration sites, determined from historical aerial imagery analysis.

The pumping of dredged sediment into the SOP and Cindery West resulted in initial consolidation and then pioneer biocolonisation of saltmarsh flora. Seral succession has developed over four years to produce well established saltmarsh extents. Providing increased vertical extent and vegetation cover for wave attenuation, and continued sediment deposition. Creating a sustainable, dynamic coastal defence measure.

The success of this project is further amplified by comparing results to the Isles Dernieres transgressive barrier, LA, USA. The use of local sediment, with site specific geomorphological properties, has been shown to successfully support the fast consolidation and colonisation rate within Brightlingsea. This was facilitated by using sluice box technology to control water and sediment volumes in the SOP and avoid natural loss of sediment. This enabled a much higher elevation to be achieved in the restoration pits, sufficient for pioneering saltmarsh species to colonise. It is expected that with some vegetation present, the natural accretion rates will now be more than erosion rates and the saltmarsh will be able to fully colonise the restoration sites in the years to come. This is a major improvement as previously, the sites remained as mudflat for over 50 years with no change in elevation through natural accretion, proving the saltmarsh was in this case unable to repair itself.

Further study is needed, particularly vegetative surveys over longer time frames, monitoring the progression dynamics, including time period and distribution, from pioneer saltmarsh through seral stages to mature upper saltmarsh.

This project demonstrates the feasibility of reusing local waste sediment in nature inclusive designs to develop solutions to societal problems such as climate change and sea level rise.

ACKNOWLEDGMENT

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