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The surface sediment carbon content of a north norfolk saltmarsh

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Abstract

Carbon sequestration is an important aspect of mitigating climate change and its detrimental environmental and economic effects. Vegetative ecosystems such as rainforests are often praised for their ability to sequester carbon through photosynthesis, however more efficient systems for sequestering carbon such as saltmarshes are often overlooked. Carbon storage was investigated in the developing salt marsh habitats of Holkham Bay, part of the Holkham National Nature Reserve in Norfolk, England between 31/07/2017 and 03/08/2017. This was done to assess the quantity of carbon that may be lost to rising sea levels associated with climate change and be released as CO2, which contributes to the greenhouse effect. Qualitative analyses of vegetation type and sediment texture were carried out using quadrat sampling ($n = 70$) and sediment cores ($n = 35$). Quantitative analysis of sediment carbon stock was carried out through loss on ignition. Carbon stock of the salt marsh was graphically represented using GIS mapping and an attempt was made to estimate the total carbon stock of the top 10 cm of the saltmarsh sediments. Measured values of carbon stocks at Holkham were compared with predicted values of carbon stock obtained using the Salt Marsh Carbon Stock Predictor tool. Significant differences in carbon stock between clay and sandy sediments were observed ($p < 0.001$), whilst vegetation communities showed no statistically significant difference in relation to carbon stock ($p > 0.05$). Estimates of carbon stock across the marsh (0.43 Km2) stand at 454-444 tonnes of carbon. Measured values of carbon stock were on average 14.18 Tonnes per Hectare lower than those predicted and are potentially due to marsh immaturity. Frequent anthropogenic disturbance at Holkham may be causing a reduction in carbon accumulation by the marsh vegetation. This study shows that substantial quantities of carbon could be lost from Holkham saltmarshes and indicates that larger marshes on the North Norfolk coastline may be substantially larger sinks of carbon, thus requiring continued protection and monitoring.

Introduction

A saltmarsh is an intertidal habitat that provides a range of ecosystem services. They can be regarded as the temperate version of the tropical mangrove forests and are often found on low energy or protected shorelines, being common around estuaries (Barbier *et al*., 2011). Saltmarshes are formed when a geographical obstacle, such as a land spit, causes water movement to slow, allowing for greater levels of sediment deposition (Allen and Pye 1992). Once the saltmarsh begins to form, the zonation of halophytic plants which accrete sediment over time leads to further marsh development (Silvestri *et al*., 2005).

One of the primary impacts of global climate change is that of rising sea levels. Increased temperatures lead to an acceleration of the melting of polar ice sheets and a subsequent increase in sea level (Overpeck *et al*., 2006). With sea levels predicted to rise by 65±12 cm by 2100 (Nerem *et al*., 2018). With the rising sea levels, the salt marsh may become permanently submerged to a point where the vegetation dies and as such, the sequestering of carbon from the atmosphere will cease (Craft *et al*., 2009). Carbon release as CO2 from these habitats is of growing concern to those studying climate change due to the impact of rising CO2 levels on the greenhouse effect (Pendleton *et al*., 2012).

The benefits saltmarshes provide to society are both direct and indirect, being both economic and for our well-being as a species. They provide protection from storm surges to coastal towns and cities (Koch *et al*., 2009, Barbier *et al*., 2011) and act as nursery grounds for juvenile fish (Beck *et al.,* 2001). Saltmarshes are often areas of special scientific interest (SSI's) due in part to their affiliation with migratory birds (Hughes 2004). They offer protection from coastal erosion and storm surges (King and Lester, 1995 and Möller *et al*., 2014). Saltmarshes are attractions for tourists which generate income for the local area (Barbier *et al*., 2011). Notably, they sequester substantial amounts of carbon from the atmosphere (Mcleod *et al*., 2011, Livesley and Andrusiak 2012) According to an evaluation by Beaumont *et al*., (2014) the economic value of saltmarsh carbon sequestration is between 34.56 – 118.26 £/ha/yr, making them a valuable resource in financial terms.

Blue carbon is the carbon stock (C-stock) of coastal habitats, specifically mangrove forests, seagrass beds and saltmarshes (Lavery *et al*., 2013). The present study investigates blue carbon in saltmarshes at Holkham Bay, Norfolk, which is an SSI. Previous research by Sousa *et al*., (2017) found C-stocks from sediments of *Atriplex portulacoides* in Portugal were at a value of 104,102 tonnes (T), with the plant biomass containing 13,118 T. Total C-stocks of the marsh were estimated at 252,052 T. According to Sousa *et al*., (2017), salt marshes accumulate carbon at a rate of ≈245 ± 26 gC m^{-2} y^{-1} globally. Saltmarshes around the world have been lost to anthropogenic influence such as reclamation projects (Gedan and Bertness, 2009). Combined with the effects of sea level rise, many saltmarshes are under significant threat of being lost.

According to those working within Holkham National Nature Reserve, there was no monitoring underway regarding the C-stocks of the marsh at the time of data collection. This study aims to find out how much carbon is stored in the top 10 cm of sediments in the saltmarsh at Holkham, to implement graphical mapping techniques as a method of representing C-stocks across the marsh and to provide evidence of why saltmarshes across North Norfolk such as at Holkham and Stiffkey should continue to be protected by government in order to prevent a loss of marsh area to rising sea levels. This work will aim to test the influences of vegetation type and sediment texture on the marshes C-stocks. Both one tailed hypotheses for this study are that vegetation type will have a significant effect on C-stocks and that sediment texture will have a significant effect on C-stocks. Hence the null hypotheses that neither vegetation type nor sediment texture will have a significant effect on C-stocks.

Methods

Survey area

The saltmarsh is characterised as being a back-barrier marsh due to being situated behind a barrier island. Formed of mainly pioneer and middle marsh, it has been classed as being in the early stages of development (Natural England, 2015). The marsh is predominantly covered by *Atriplex portulacoides, Limmonium binervosum, Puccinellia maritima, Salicornia europaea* and *Sueda vera*, characterised by the National Vegetation Classification system as SM14, SM21, SM13, SM8 and SM9 respectively. In situ observations reveal that much of the pioneer marsh is being heavily damaged by anthropogenic influences of trampling by pedestrians, horses and motor vehicles, thereby causing erosion of the pioneer marsh.

Data aquisition

Data collection in the field was adapted from Skov *et al*., (2016). A total of 70 random 75 x 75 cm quadrat samples were taken by means of a random number table throughout the marsh, in addition to 35 10 cm deep sediment cores (Figure 1). Initially 35 quadrats were used solely for random sampling of vegetation and sediment texture across the salt marsh. Organisms were identified and enumerated according to percentage cover. The dominant species in each quadrat was recorded and each quadrat was categorised according to the National Vegetation Classification system (NVC), which is a method of classifying vegetative communities based on the flora present within an area. At each sample site, soil texture was defined as either 'sandy' or 'clay' according to a simplification of the roll test (Skov *et al*., 2016), a qualitative assessment of soil composition. Soils classed as clay include loamy, silty and organic rich soils. Sediment cores were taken in conjunction with 35 quadrat samples and frozen at -12^{o}C pending loss on ignition analyses in the lab.

Laboratory analyses

Initial estimates of C-stock were carried out using the Salt Marsh Carbon Stock Predictor (SMCSP) produced by Skov *et al*., (2016) to calculate C-stocks in the sediment based on the vegetation present and soil texture across the salt marsh (Type 4 prediction). This method was only applicable to areas of *A. portulacoides* and *P. maritima* (NVC communities SM14 and SM13, respectively) as no data were available to produce estimates of carbon stock in areas characterised by the other three dominant species: *L. binervosum S. europaea* and *S. vera* and (NVC communities SM21, SM8 and SM9, respectively). Predicted values were compared to actual values obtained from loss on ignition.

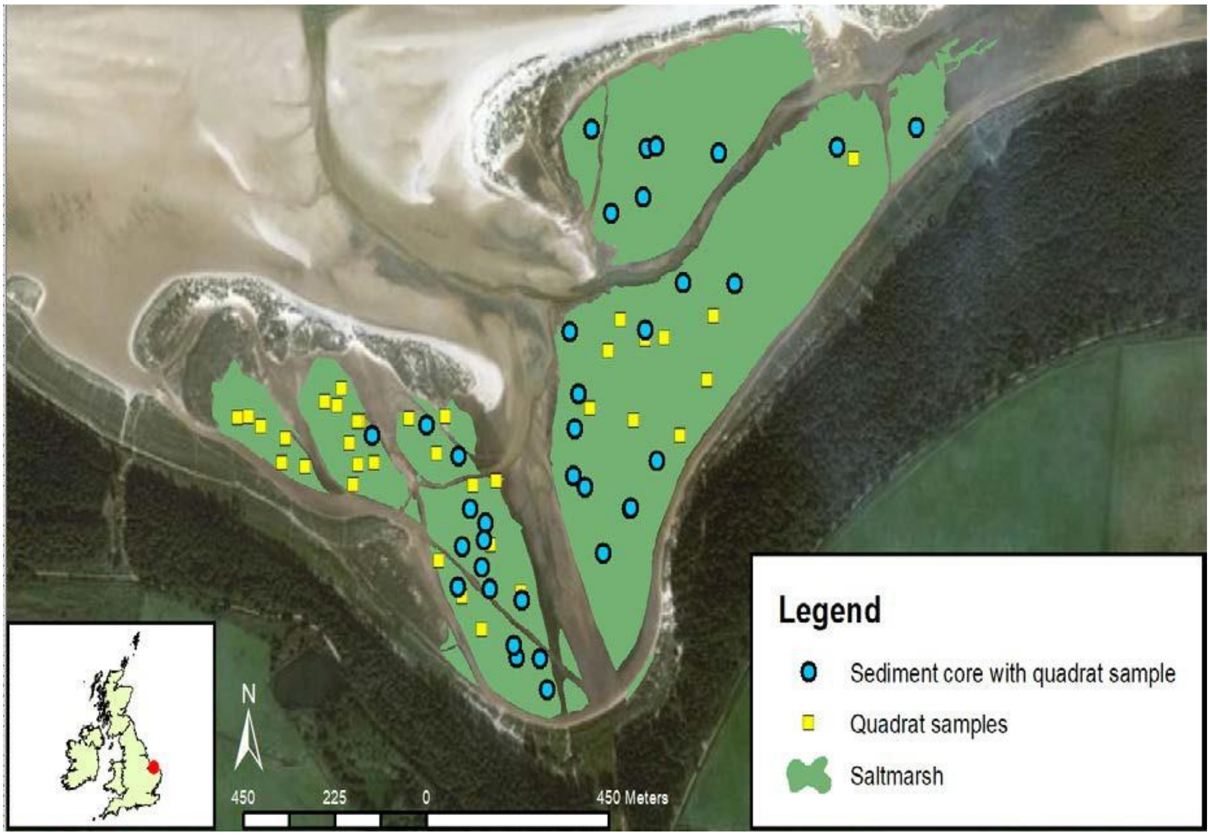

Figure 1: Locations of quadrat samples and sediment cores across the saltmarsh at Holkham bay. Map created using Arc GIS version 10.6 using world imagery basemap, sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS user community.

Loss on ignition was carried out in triplicate to ensure concurrent results and allow for the calculation of average values of C-stock for each sediment type and NVC community. Samples were dried in an oven at 60 ^oC for 24 hours to remove any moisture from the sediment before being ground with a mortar and pestle to homogenise the sample. Samples were then weighed using an electronic balance accurate to 0.01 g. Samples were heated to ~ 500 ^oC for 6 hours to remove any carbon from the soil. Samples were re-weighed; carbon content was calculated via the following formula:

Percentage carbon content was converted into a mass per area format by dividing the original sample weight by 100 before multiplying it by the % carbon content. This value was then multiplied by the area of the core to produce C-stock values of grams per metre squared (g/m2) and being scaled up to t/Ha.

Values for carbon content observed from loss on ignition were used to create predicted values of carbon content for the initial 35 quadrat samples. This was done by calculating mean values for each NVC community and its respective sediment category (e.g. SM14: Clay and SM14: Sandy) and applying them to quadrat samples that had the corresponding NVC and sediment classification.

C-stock was then plotted using Arc GIS and its ArcMap programme (Version 10.5.1) onto a geographical map of the salt marsh. C-stock was represented using proportional points, large points on the map represent greater quantities of carbon stored at that point. Each point has been assigned a range of values for carbon content (t/Ha). A second map was produced whereby the saltmarsh was divided into subsections, the mean C-stock for each subsection was calculated from the C-stock values obtained from within that subsection. Sections of the marsh were colour coded according to the mean values of C-stock calculated. This was done to provide a visual representation of C-stocks for the entire saltmarsh.

Statistical analyses

Data for C-stocks, NVC communities and sediment categories were imported into R Studio (Version 1.0.153). Mean values, standard deviation and standard error were calculated to represent values for carbon content in each NVC community per sediment category. These data were represented using a bar plot featuring error bars indicating standard deviation.

To test the assumptions required for analysis of variance (ANOVA) between sediment category and C-stocks and between NVC community and C-stocks, a Shapiro-Wilks normality test was applied followed by a Levenes test to investigate homogeneity of variances. Due to not meeting these assumptions, non-parametric testing using a Mann-Whitney U test was performed.

Results

Predictions of stored carbon in SM13 and SM14

Predictions of stored carbon in SM13 and SM14 in another study calculated the average value for C- stock as 29.5 tonnes per Hectare (t/Ha) (Skov *et al.,* 2016). Values obtained from analyses at Holkham differed significantly. Mean values for stored carbon across SM13 and SM14 in Holkham were calculated to be 15.323 t/Ha. Tables 1 and 2 compare these values for each subcategory.

Table 1: C-stock values predicted by the SMCSP for NVC communities SM13 and SM14 in both sandy and clay soils.

Predicted values (type 4 predictions)		
NVC	**Soil texture**	**C-stock (t/Ha)**
SM13	Sandy	26 (± 3.3)
	Clay	40 (± 3.3)
SM14	Sandy	19 (± 3.7)
	Clay	33 (± 3.7)
Mean SM13 and SM14	Sandy	22.5 (± 3.5)
	Clay	36.5 (± 3.5)

Table 2: Mean measured values of C-stock for Holkham marshes. Mean C-stocks for all categories combined were 14.177 t/Ha lower than those predicted by the SMCSP in table 1.

Mean measured values at Holkham Bay		
NVC	**Soil texture**	**C-stock (t/Ha)**
SM13	Sandy	11.007
	Clay	20.398
SM14	Sandy	8.805
	Clay	21.081
Mean SM13 and SM14	Sandy	9.906
	Clay	20.74

Loss on Ignition Analysis

The influence of sediment type (sandy or clay) had a significant effect on C-stocks. Shapiro- Wilk testing found data to be normally distributed (W = 0.76594, p = 4.688e-06). Levenes testing revealed the variances not to be homogenous. A Mann-Whitney U test revealed sediment types to be a significant factor in determining C-stocks (p = 7.261e-06). Clay sediments had greater quantities of stored carbon than sandy sediments ($\bar{x}$ = 20.6 ± 9.8 t/Ha clay [n = 56] and $\bar{x}$ = 9.8 ± 3.4 t/Ha sandy [n=14]).

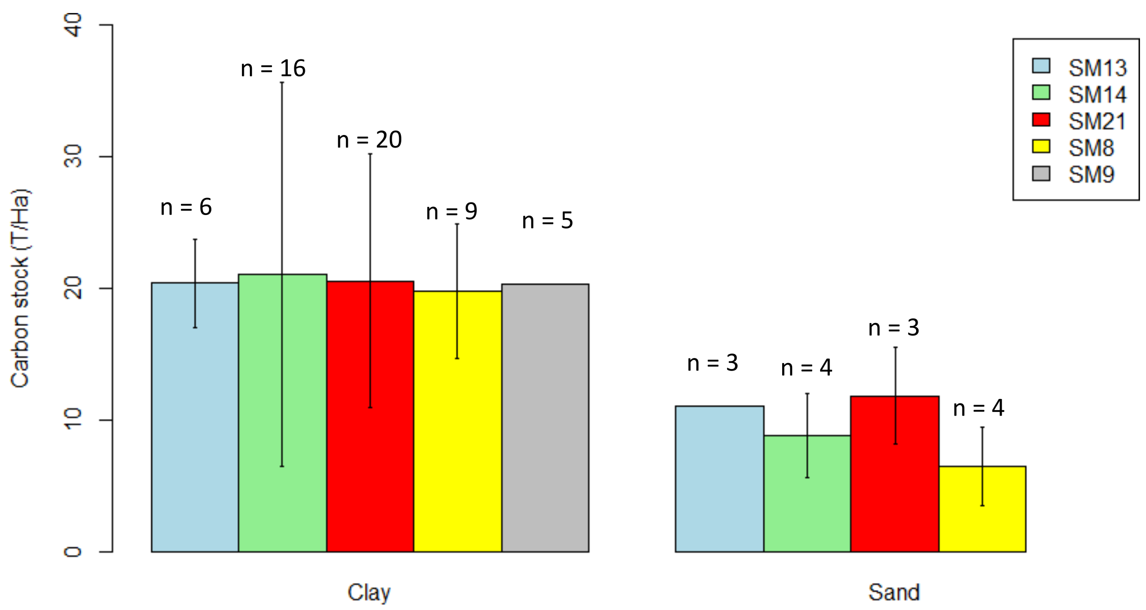

Figure 2: Mean C-stock values for each NVC community in samples where sediment texture was defined as Clay (Left) and as Sandy (Right). Error bars representing standard deviation. SM14 in Clay soils showed the greatest level of variation, ranging between 5.9 and 72.1 t/Ha. Data for SM9 in Sandy sediments were not available and is not plotted.

Mean values for C-stock per NVC type in each sediment category were plotted onto a bar graph (Figure 2). SM13 showed highest values for average C-stock ($\bar{x}$ = 18.52 ± 6.33 t/Ha) whilst SM8 was the lowest ($\bar{x}$ = 15.98 ± 8.89 t/Ha).

Total carbon content of Holkham saltmarsh.

The total C-stock of the marsh was calculated in two different ways. The first method was calculating the average C-stock of the entire marsh and multiplying it by the total marsh area. This method gave a total C-stock value for the top 10 cm of sediment of 454 Tonnes of carbon. The second method was to divide the marsh into sections that were geographically separated and calculate the average C-stock for each section, before multiplying this value by the area of that section. This method gave a total value of 444 Tonnes of carbon across the top 10cm of the vegetated marsh area. The most common range of values for C-stock was 20.1 – 35 t/Ha (Fig. 3).

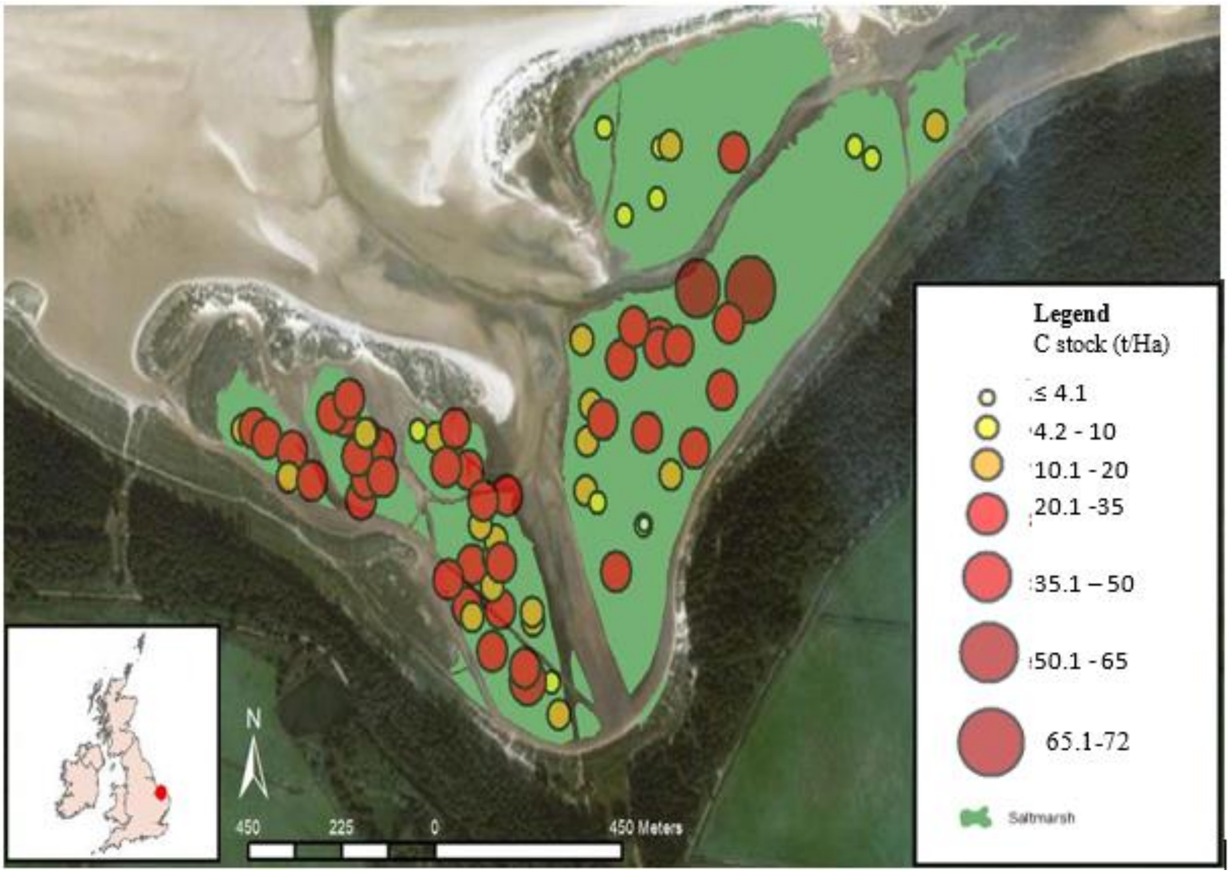

Figure 3: C-stocks of Holkham saltmarsh represented using proportional symbols. Larger symbols relate to larger quantities of stored carbon (t/Ha). Modal range of C-stock = 20.1–35 t/Ha. Mean C-stock across the marsh = 18.7 ± 9.7 t/Ha. Map created using Arc GIS version 10.6 using world imagery basemap, sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS user community.

The largest values for C-stock are found in the eastern side of the marsh (65.1-72 t/Ha), this area of marsh showed variation in C-stocks. Western areas of marsh appeared to have more consistent C-stocks, predominantly within the ranges of 20.1-35 t/Ha (Figure 3). The largest concentration of carbon (~255 tonnes) is found in the eastern side of the marsh in area H (Figure 4).

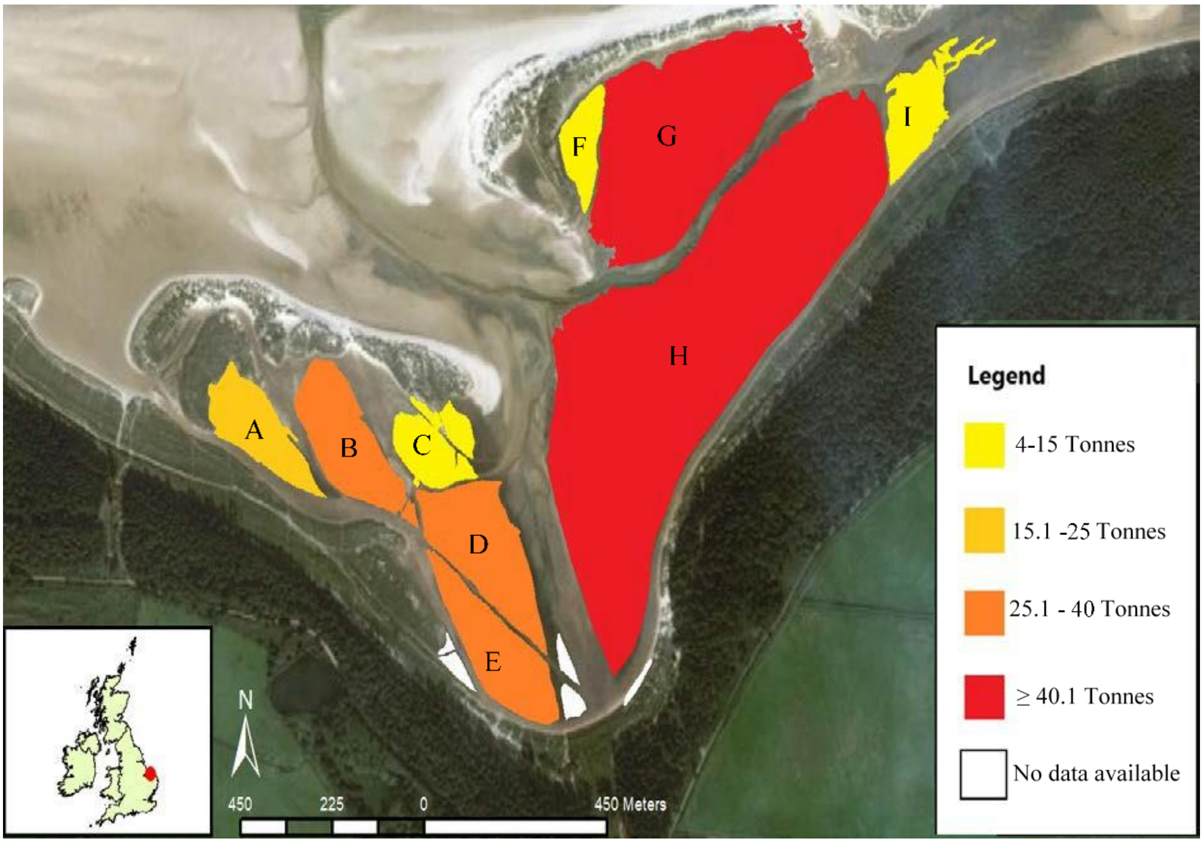

Figure 4: Data shown in figure 3 were extrapolated to produce an overview of total marsh C-stocks. Mean (t/Ha) ± SD and total C stock (Tonnes) values for C-stock in each section are as follows: A: $\bar{x}$ = 18.9 ± 3.88, Total = 19.08, B: $\bar{x}$ = 20.28 ± 3.79, Total = 28.74, C: $\bar{x}$ = 18.31 ± 5.42, Total = 14.99, D: $\bar{x}$ = 17.89 ± 3.69, Total = 30.73, E: $\bar{x}$ = 19.81 ± 8.86, Total = 27.24, F: $\bar{x}$ = 8.54, Total = 4.49, G: $\bar{x}$ = 11.70 ± 7.9, Total = 58.8, H: $\bar{x}$ = 20.5 ± 15.09, Total = 255.08, I: $\bar{x}$ = 14.7, Total = 12.99. Areas F and I contain one sample each and therefore no standard deviation is calculated for these areas. Map created using Arc GIS version 10.6 using world imagery basemap, sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS user community.

Discussion

Saltmarsh habitats can act as a substantial sink of carbon when compared to terrestrial habitats such as woodland (Mcleod *et al*., 2011). Differences in marsh characteristics such as vegetation and sediment composition can cause variation in carbon stocks across a marsh (Tables 1 and 2). An equilibrium between the vertical accretion of sediments by marsh vegetation and sea level rise (SLR) is needed for the survival of saltmarshes (Donnelly and Bertness 2001). An acceleration of SLR that exceeds the rate of marsh vertical accretion will lead to submergence of the marsh and therefore a loss of marsh area. Hence SLR is a growing threat to saltmarshes (Morris *et al*., 2002). Research by Kirwan *et al*., (2016) contradicts this point, stating that biophysical feedbacks such as the acceleration of vertical accretion rates is often ignored. Managed retreat strategies may help to improve the longevity of the marsh, as seen in Byers and Chmura, (2007). However, Holkham bay faces a steep incline upwards when moving inland close to the shoreward edge of the marsh which is followed immediately by woodland (Figure 1), making any inland movement of the marsh problematic. Current and future management strategies should focus primarily on creating pathways for the inland retreat of marshland to avoid significant losses of marsh area. Secondly, such strategies may use managed retreat methods to increase the sediment loading capacity of the marsh, and so assist in the vertical accretion of marsh sediments in order to maintain an equilibrium with sea level rise (Esteves and Williams, 2015).

Total carbon stocks across Holkham saltmarsh vary between sub-sections of the marsh as seen in Figure 4. Sousa *et al*., (2017) report marsh area in Portugal to be ~4400 Ha and total C-stock to be 252,053 T in the top 25 cm of marsh sediments. Converting this to t/Ha gives a value of ~57 t/Ha. This value is approximately three times that of values obtained at Holkham in the top 10 cm of sediment. However, the depth of sediment cores taken by Sousa *et al*., (2017) was 15 cm greater than those taken at Holkham. Despite the largest concentrations of carbon being found in the top 10 cm of soil, sediment core depth must be considered when comparing C-stocks with the current literature.

Clay soils tend to have larger C-stocks than coarser sediment (Fig. 2). Kelleway *et al*., (2016) reported that sediment particle size was a principal factor when predicting the quantity of stored carbon. Particle size analysis of Holkham saltmarsh sediments may provide new insights into the distribution of C-stocks across the marsh if used in conjunction with loss on ignition. National vegetation classification communities at Holkham were not a significant factor in explaining C-stocks across the marsh. This may be explained by the maturity of the marsh. Holkham bay saltmarshes are still in development, therefore biomass and rates of carbon accumulation by vegetation may be much lower than that of a more developed or larger marsh where biomass is greater. This may also assist in explaining why the measured values of C-stock at Holkham for SM13 and SM14 were lower than those predicted (Tables 1 and 2).

It is also possible that frequent anthropogenic disturbance could have caused a loss of C-stock in the marsh and so have led to lower values of C-stock than those predicted. Holkham is heavily trampled by pedestrians, cars and horses. Persico *et al*., (2017) investigated the effects of disturbance caused by wild hogs (*Sus scrofa*) on South-Eastern US saltmarsh. It was suggested that disturbance by hogs would cause patches of saltmarsh to change from carbon sinks to carbon sources over time. This could lead to a reduction in the capacity of vegetation to accumulate carbon in addition to a loss of previously stored carbon in sediments due to soil respiration following disturbance. It is therefore plausible that trampling by humans, horses and motor vehicles might cause similar damage to the saltmarsh vegetation at Holkham. It would therefore be useful for future studies to investigate temporal variations in marsh biomass production in trampled and non-trampled areas of the marsh.

This work highlights the importance of Holkham bay as a carbon sink and suggests that other marshes within Holkham National Nature reserve such as Warham are likely to be much larger sinks of carbon due to their greater size. However, Holkham Bay marsh is a small area of marsh and must be considered carefully before drawing more general conclusions as to the capacity of other marshes to store carbon. Failure to do so could potentially lead to gross underestimates of C-stock. Chew and Gallagher, (2018) report that allochthonous and recalcitrant organic carbon (black carbon) contribute to overestimations of blue carbon stocks. It is further argued that as black carbon is not readily oxidised, it should be excluded when calculating the level of mitigation of CO2 emissions (i.e. C-stocks). Further investigation is required to account for the ratio of black carbon within marsh sediments to provide a more comprehensive account of carbon stock. An idealised method for future research should consider the following when assessing saltmarshes as carbon sinks: Biomass and type of vegetation, proportions of black carbon, local geomorphology, local rates and future predictions of SLR, temporal analyses of vertical sediment accretion rates (Kulawardhana et al., 2015), sediment particle size, and sediment bulk density

Conclusion

This study shows that saltmarshes in Holkham bay are significantly affected by sediment texture (determined largely by sediment particle size), and that NVC communities in this case do not have a significant effect on C-stocks. C-stocks of saltmarshes can be effectively mapped using the methods outlined in this study when attempting to visualise spatial variations of stored carbon. This study demonstrates the effectiveness of using geographical mapping of C- stocks. Such maps can be used to assess key areas of marsh that require monitoring and protection due to their significance as a C-stock.

Estimates of C-stock across Holkham saltmarsh show that marshes in early development can store substantial quantities of carbon in the top 10 cm of sediment alone and therefore indicates that C-stocks in larger, more developed local marshes will be even higher. This value of C-stock will be even greater when accounting for above ground biomass and the C-stock of sediments below 10 cm depth. Hence it is strongly recommended that efforts to mitigate marsh loss from sea level rise be of great importance to governing bodies when designing and implementing protection plans for the coastline.

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