Coring and Compaction: Best Practice in Blue Carbon Stock and Burial Estimations

Craig Smeaton[1*], Natasha L.M. Barlow[2] and William E.N. Austin[1,3]

[1] School of Geography & Sustainable Development, University of St Andrews, St Andrews, KY16 9AL, UK

[2] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

[3] Scottish Association for Marine Science, Scottish Marine Institute, Oban, PA37 1QA, UK

Corresponding Author: Craig Smeaton (cs244@st-andrews.ac.uk)

Abstract

A comparison of gouge and hammer coring techniques in intertidal wetland soils highlights a significant effect of soil compaction of up to 28% associated with the widely applied hammer coring method employed in Blue Carbon research. Hammer coring reduces the thickness of the soil profile and increases the dry bulk density, which results in an overestimation of the soil OC stock of up to 22%. In saltmarshes with multiple different soil units, we show that hammer coring is unsuitable for the calculation of OC stocks and should be avoided in favour of Russian or gouge cores. Compaction changes both soil dry bulk density and porosity and we show that resultant radiometric chronologies are compromised, almost doubling mass accumulation rates. While we show that the OC (%) content of these sediments is largely unchanged by coring method, the implication for OC burial rates are profound because of the significant effect of hammer coring on soil mass accumulation rates.

Highlights

- Hammer coring causes soil compaction of up to 28% in saltmarsh soils.
- Hammer coring is unsuitable for the calculation of OC stocks in saltmarsh soils.
- Compaction due to hammer coring almost doubles calculated mass accumulation rates.
- Hammer coring artificially elevates calculated OC burial rates.

Keywords: Sediment**,** Coring; Compaction, Carbon; Intertidal; Saltmarsh;

1. Introduction

Carbon (C) buried and stored in costal ecosystems (saltmarsh, seagrass and mangroves) is known as blue carbon (Nellemann et al., 2009). In the last decade blue carbon habitats have risen in prominence and are increasingly recognised as potentially valuable nature-based solutions to help reduce atmospheric CO_2 and mitigate climate change (Duarte et al., 2013, Mcleod et al., 2011, Pendelton et al., 2012, Rogers et al., 2019). Underpinning this understanding is a wealth of research largely focused on calculating both the quantity of organic carbon (OC) stored and the rate at which this OC is buried in coastal ecosystems. The foundation of these estimates is the collection and measurement of soil samples, normally through sediment coring. Across the body of published blue carbon research different coring approaches are adopted, generally falling into two categories: (**i**) palaeo-environmental methods which often employ Russian and gouge corers (Frew, 2014; Glew et al., 2002), and (**ii**) low cost, often disposable hammer/impact/piston techniques, where plastic piping is hammered into the soil (e.g. Howard et al., 2014).

Russian and gouge corers have long histories of use across a variety of applications including peatland research, sea-level reconstructions, as well as blue carbon research (van Ardenne et al, 2018, Wollenberg et al., 2018). The low-cost hammer approach is almost exclusively used for blue carbon research, but generally not used in palaeo-environmental research. Initially, the hammer coring technique was used to sample seagrass soils; these soils are often submerged and sandy in nature making them difficult to core using other sampling methods (Macreadie et al., 2015, Serrano et al., 2018). However, in recent years the use of this approach has also been gaining popularity in saltmarsh and mangrove ecosystems (Kelleway et al., 2016a, Macreadie et al., 2013, Unger et al., 2016).

Gouge coring is minimally invasive and causes little disturbance to the soil; it largely avoids compacting the soil, where soil compaction is more widely recognised as a significant problem in achieving successful paleo-environmental reconstructions (Brain, 2016, Brain et al., 2017, Edwards, 2006). Within blue carbon research, a number of studies acknowledge that hammer coring causes compaction (Ewers Lewis et al., 2019, Kelleway et al., 2016a, b) but this recognition is not universal. Where compaction is recognized during the coring procedure, a simple linear correction, where the length of the soil core is divided by the sampling depth is often applied (Ewers Lewis et al., 2019, Kelleway et al., 2016a, b). Compaction of the soils increases the bulk density, decreases the porosity and dewaters the soil (Archer and Smith, 1972, Håkansson and Lipiec, 2000). Additionally, the loss of water may potentially flush soluble and porewater OC from the soil, all of which will have a bearing on the OC stock and burial estimates; it is therefore unlikely that simple linear corrections address this complexity.

The widespread use of these different coring methods in saltmarshes raise questions about their direct impact on any subsequent calculation of OC stock and burial rate. In this study, we explore two of the most commonly employed coring techniques (gouge and hammer) to determine how each method influences the recovered soil (i.e. physical properties, compaction) and how, in turn, this alters the OC stock and burial estimates in a temperate saltmarsh.

2. Study Site

The Kyle of Tongue saltmarsh is one of the most northerly marshes found on the UK mainland (Fig.1). The marsh is situated at the head of the Kyle of Tongue (an infilled fjord), and as such is categorised as a loch-head marsh; a classification unique to Scotland in a UK context (Haynes, 2016). The marsh occupies an area of 9.31 ha with the majority of that being high-mid marsh (9.08 ha) with only 0.23 ha considered low marsh (Fig.1) as characterised by vegetation communities and elevation (Haynes, 2016). The vegetation coverage of the marsh is dominated by *Carex flacca, Filipendulo-Iridetum pseudacori, Puccinellia-turf fucoid* and stunted forms of *Phragmites australis*. As with the loch-head marsh type, this vegetation community is only found on the marshes of western and northern Scotland (Adam, 1978, Burd, 1989, Haynes, 2016).

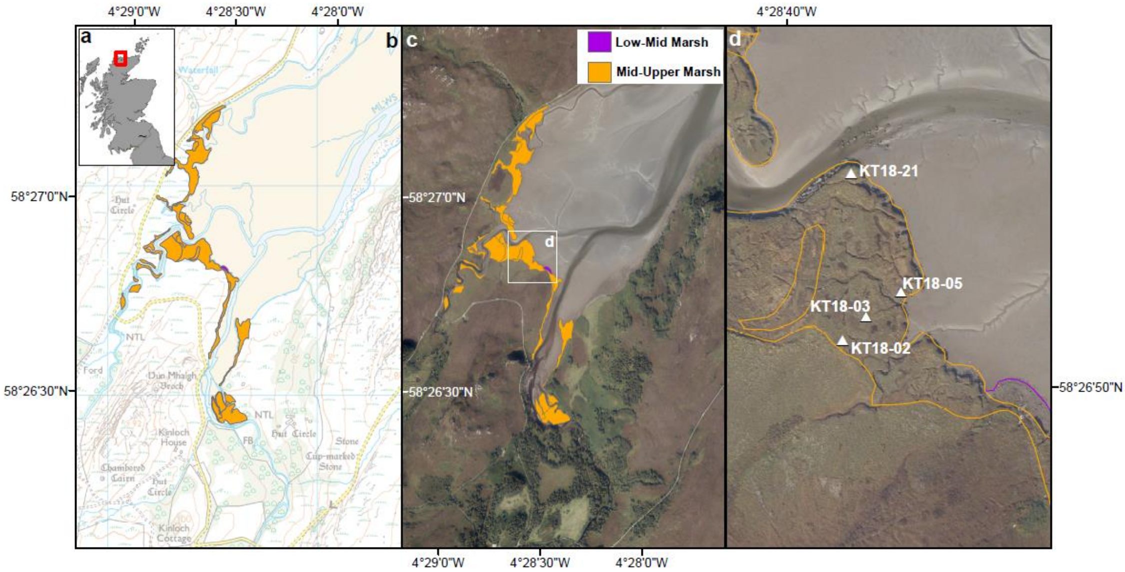

Figure.1 Location map detailing (**a**) the site in context of Scotland and (**b**) Ordnance Survey Map detailing the location of the saltmarsh in relation to the Kyle of Tongue with the high (**orange**) and low marsh (**purple**) highlighted (Haynes, 2016). (**c**) A regional overview. (**d**) Sampling locations across the marsh environments (© Crown copyright and database rights [2019] Ordnance Survey (100025252).

3. Methods

3.1 Coring

Dual coring (gouge and hammer) was undertaken at four sites on the Kyle of Tongue saltmarsh in November 2018. Three of the core sites were situated along a transect perpendicular to the shoreline, while a fourth site was located on a protruding raised platform to the west of the saltmarsh (Fig.1d). Gouge and hammer cores were collected at each site; the gouge cores were collected first to ensure minimal disturbance of the soils prior to collection of the hammer cores.

The gouge cores were collected using a 1m fixed length core barrel with a 3 cm diameter. The corer was manually pushed into the soil to the point of refusal, rotated and removed. Before removal, the degree of compaction was assessed by measuring the soil surface within the core tube relative to the height of the outer marsh surface; the difference between the measurements was used to calculate compaction (Kelleway et al., 2016b). On site, the core face was cleaned with a sharp knife, photographed and the soil profile described using the Tröels-Smith, (1955) classification scheme for unconsolidated sediments. Once described, fixed volume (4 cm^3) samples were collected every 10 cm along the length of the core. The location and elevation of the core was recorded using DGPS.

Adjacent hammer cores were collected 25 cm from the gouge core locations; each new location was recorded with DGPS. The core tube consisted of 150 cm lengths of polyvinyl chloride (PVC) piping with a 6.16 cm inner-diameter and a wall thickness of 0.24 cm. The PVC pipe was enhanced with a sharpened bevelled edge to allow more efficient cutting of root material during the insertion of the core tube into the soil. Core tubes were manually hammered into the soil to a depth of 100 cm below the external soil surface. The top of the core was sealed to create a vacuum and the core was pulled out of the soil using a tractor jack. Total compaction was measured in the field by comparing the external and internal elevation of the marsh surface recorded from outside and inside the core tube. The top end of the core was plugged with foam, while both ends were capped and sealed with tape to prevent disturbance during transport. Cores were stored at 4°C in a cold room at the University of St Andrews until processing.

3.2 Laboratory Analysis

3.2.1 Physical Properties

The hammer cores were cut lengthways and split into working and archive sections; the soils were described using the Tröels-Smith (1955) classification scheme. The distance between the core top within the liner was compared to the ground level marked on the linear in the field allowing the total compaction of the core to be determined and assure no additional compaction or expansion has taken place post collection. Fixed volumetric samples (4 cm^3) were extracted at 10 cm intervals throughout the length of the core using a fixed volume sampler (syringe).

Sub-samples from both the gouge and hammer cores were weighed before and after drying at 50°C for 48 hrs. This data allowed wet bulk density (WBD), dry bulk density (DBD), porosity and water content to be calculated following the standard methodologies (Athy, 1930, Appleby and Oldfield, 1978, Dadey et al., 1992):

$$Wet\ Bulk\ Density\ (g\ cm^{-3}) = \frac{Wet\ Mass\ (g)}{Wet\ Sample\ Volume\ (cm^3)} \quad (1)$$

$$Dry\ Bulk\ Density\ (g\ cm^{-3}) = \frac{Dry\ Mass\ (g)}{Wet\ Sample\ Volume\ (cm^3)} \quad (2)$$

$$Water\ Content\ (\%) = \frac{Wet\ Mass\ (g) - Dry\ Mass(g)}{Wet\ Mass\ (g)} \times 100 \quad (3)$$

$$Porosity\ (\%) = \frac{Mass\ of\ Water\ in\ the\ Soil\ (g)}{Mass\ of\ Water\ in\ the\ Soil\ (g) + \left(\frac{Dry\ Mass\ (g)}{Dry\ Bulk\ Density\ (g\ cm^{-3})}\right)} \quad (4)$$

The degree of compaction of the soils collected by hammer coring was determined by comparing the thickness of discrete soil horizons observed in the adjacent gouge cores.

3.2.2 Elemental Analysis

Elemental analysis (EA) was used to quantify the OC content of the saltmarsh soils. The oven dried samples were milled to a powder, and a 10 mg sub-sample was placed in a silver capsule. The soils within the silver capsules were treated with HCl through acid fumigation to remove carbonate (Harris et al., 2001) and, after drying (24 hrs at 50°C), the samples were analysed using an Elementar EL Vario following the methodology of Verardo et al. (1990). Analytical precision was estimated from repeat analyses (*n=18*) of standard reference material B2178 (Medium Organic Content Standard; Elemental Microanalysis, UK); the analytical precision for the OC measurements was ± 0.09 %.

3.2.3 Assessing OC stocks and burial rates

To test the potential impacts of compaction associated with hammer coring on soil mass and OC stock estimations; we undertook a simple test, where we calculated both soil mass (kg) and OC stock (kg) for an area of 1 m^2 using the thickness (m) of the different soil horizons associated with each coring method. The saltmarsh soil mass and OC stocks were calculated down to the depth were the basal silts are introduced in the stratigraphy (Fig.2) as these represent the switch from saltmarsh to intertidal mudflat habitat which is currently not considered a blue carbon environment (Nellemann, et al., 2009). The test assumed that each core was representative of the surrounding 1 m^2 of saltmarsh soil. Using the data collected from the cores the mass of soil and the OC stock for the soil underlying the 1 m^2 was estimated. These estimates were made following the standard methodology:

$$Soil\ Volume\ (m^3) = Area\ (m^2) \times Soil\ Unit\ Thickness\ (m) \quad (5)$$

$$Soil\ Mass\ (kg) = Soil\ Volume\ (m^3) \times Dry\ Bulk\ Density\ (kg\ m^{-3}) \quad (6)$$

$$OC\ Stock\ (kg) = Soil\ Mass\ (kg) \times OC\ Content\ (\%) \quad (7)$$

This approach was used with the stratigraphic data collected from both the hammer and gouge cores, enabling the soil mass and OC stock estimates to be compared in order to assess any effect of coring-related compaction on the soils.

Sedimentation and mass accumulation rates of saltmarsh soils are commonly calculated using radiometric age control (^{210}Pb and ^{137}Cs) (Krishnaswamy et al., 1971, Appleby and Oldfield, 1978). Dry bulk density and porosity are key to these calculations. In order to test the effect of soil compaction on calculated sedimentation and mass accumulation rates, we have used a previously published (Barlow et al., 2014) radiometric age model from a core collected using a wide dimeter gouge corer from the same location as core KT-18-03. The new DBD and porosity data from the gouge and hammer cores collected at site KT-18-03 were used, together with the original radiometric age control data, to recalculate the most common age-depth methods: simple linear interpolation, the constant rate of supply (CRS) model (Appleby and Oldfield, 1978) and the constant initial concentration (CIC) model (Robbins and Edgington 1975).

4. Results and Interpretation

4.1 Saltmarsh Soil Profiles

The soil profiles of the Kyle of Tongue saltmarsh have four main units, with a fibrous peat (*Turfa herbacea*) surficial layer overlying humified peat (*Substantia humosa*) and organic rich silt, which sits upon a basal layer of marine mud (Fig.2), (and further summarised in Barlow et al, 2014). Core KT18-05, the more seaward core of the main transect, however, differs from the others in that it lacks the surficial fibrous peat layer and has a thin layer of humified peat capping the underlying silts. In places, iron (Fe) staining is observed in the silt layer, indicating the presence of Fe oxides, most likely a consequence of increased oxygen penetration into the soil layer (Luther III et al., 1992, Kostka, and Luther III, 1994) at this site. The soil units themselves differ significantly in thickness between coring sites, with the fibrous peat ranging from 4-9 cm, the humified peat ranging from 120-310 cm and the organic rich silts ranging from 70-350 cm (Fig.2). The hammer core generally penetrated further into the basal silty mud than the gouge core.

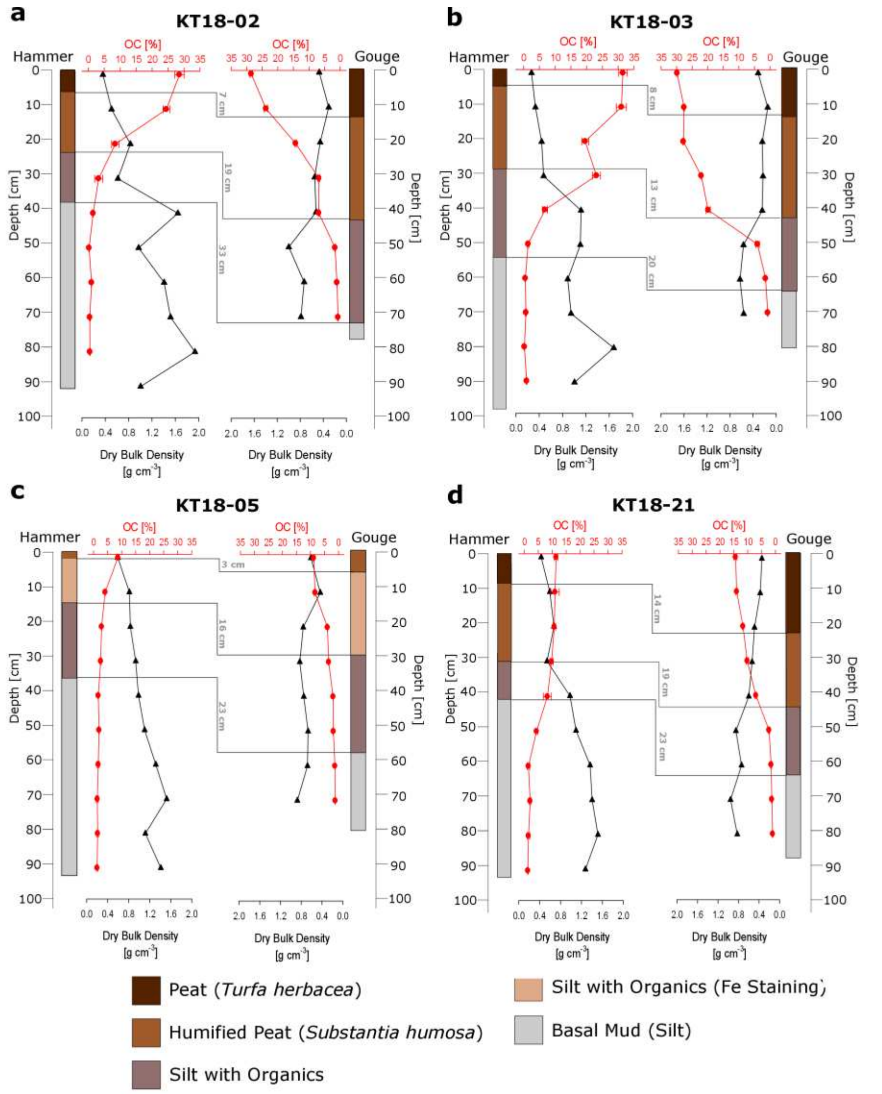

Figure 2. Comparison of the effects of the coring method on the soil profiles, OC content and dry bulk density across the four sites. The grey lines represent the difference in cumulative depth (cm) of the soil horizons in each core as described by the Tröels-Smith classification scheme (1955). The thickness of the different soil units can be found in the supplementary table 2.

4.2 Compaction

By comparing the soil profiles obtained from the hammer cores (both in the field and the laboratory) to those recorded from the gouge cores, where compaction observed in the field was minimal (< 2 %), it is estimated that the soils from the hammer cores were compacted by between 22.9% and 27.8% (Fig.3). The laboratory-based compaction calculations compare favourably to the field-measurements, confirming that the field-based estimates of total depth compaction are robust (Fig.3). KT18-02 and 03 are the only cores where the field measurements are exceeded by the laboratory-based estimates of compaction. This is potentially due to the stretching (a piston effect) of certain soil horizons during extraction. For example, it was observed upon extraction of core KT18-03 that the degree of overall compaction had reduced from the *in situ* measurements in the field. Indeed, when the soil profile is examined in greater detail, the equivalent silt unit in the hammer core is thicker than that in the adjacent gouge core, further suggesting that stretching of the soil profile has taken place whilst extracting the material from the ground (Fig.3).

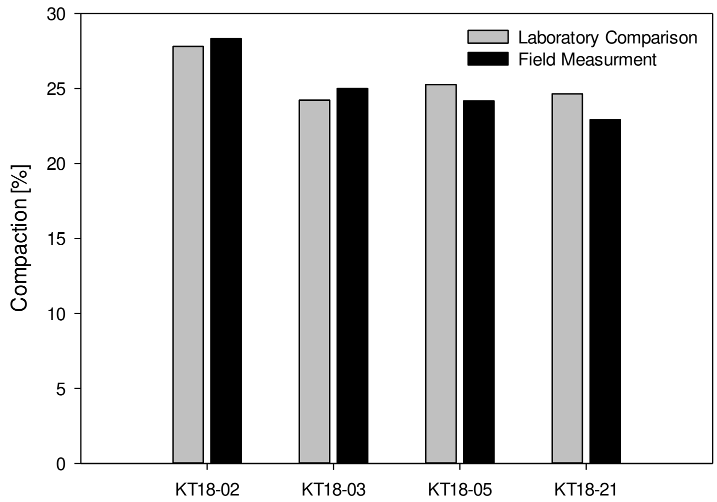

Figure 3. Comparison of field- and laboratory-based measurements of total soil compaction (%) in the four hammer cores.

These measurements are useful to quantify the total amount of compaction which has occurred during the coring process, but they don't provide the required insight into the degree of compaction of the individual soil units. However, by comparing the adjacent soil profiles recovered from the two coring techniques, the level of compaction for each of the soil units can be calculated (Table 1).

		Mean Dry Bulk Density (g cm^{-3})		**Mean Water Content (%)**		**Porosity (%)**		**Compaction (%)**
Site	**Soil Unit**	**Gouge**	**Hammer**	**Gouge**	**Hammer**	**Gouge**	**Hammer**	**Hammer**
KT18-02	Peat	0.39	0.36	70.09	25.14	51.69	45.67	53.85
	Humified Peat	0.45	0.67	58.90	36.11	53.94	41.68	21.4
	Silt with Organics	0.70	0.62	45.25	42.01	45.93	36.96	25
KT18-03	Peat	0.23	0.27	81.36	23.86	46.09	44.46	63.64
	Humified Peat	0.24	0.39	71.83	30.76	46.89	38.01	20.51
	Silt with Organics	0.40	0.90	58.76	49.94	46.13	39.51	-19.23
KT18-05	Humified Peat	0.61	0.59	58.42	42.78	44.24	33.28	50
	Silt with Organics (Fe)	0.60	0.81	43.22	54.73	40.23	34.05	53.85
	Silt with Organics	0.79	0.88	36.63	60.92	36.11	33.75	28.13
KT18-21	Peat	0.36	0.43	67.55	35.65	43.67	40.58	60.87
	Humified Peat	0.54	0.60	57.33	42.56	44.82	41.68	21.21
	Silt with Organics	1.02	0.98	36.82	61.05	38.49	37.13	61.11

Table 1. Comparison of the dry bulk density (g cm^{-3}) and water content (%) of the saltmarsh soils across the four coring sites, using the two coring methods. Additionally, the degree of compaction (%) for each soil unit calculated by comparing the thickness of each soil unit (Fig.2) from the gouge and hammer cores (negative compaction values are indicative of stretching).

The surficial layers of fibrous and humified peat experience the greatest compaction (Table 1). In core KT18-05, we observe above average compaction of the silt layer (Table 1), most likely due to the thin overlying peat layers (Fig.2). The compaction of the soil profiles significantly dewatered the upper peat units, which in turn increases soil DBD (Table 1). It was hypothesised that dewatering of the soils would flush the soluble OC from the compacted sediment and, in turn, evacuate porewater dissolved organic carbon (DOC) and reduce the measured OC content. However, a comparison of the down core OC content of the sediments obtained by both coring methods (Fig.2) indicates only minimal differences between OC content. These differences in OC are well within the range of natural variability and we therefore conclude that coring compaction in itself does not directly impact the relative (%) OC content of saltmarsh soils.

4.3 Consequences for OC stock and burial estimations

The alteration (generally reduction) in the thickness of the individual soil units, combined with increases in DBD associated with the hammer coring technique, are likely to alter soil mass and OC stock estimates. However, the reduction in soil thickness and increase in DBD may act to offset one another, while still resulting in accurate estimates of soil mass and OC stock. Saltmarsh soil mass and OC stock estimates differ between the hammer and gouge cores for all sites (Table 2). The hammer cores KT18-02, 05 and 21 all overestimate the normalized soil mass by between 3.9 - 37 % in comparison to the gouge core estimates. The resulting OC stocks derived from these cores are also overestimated by between 14.8 to 22%. KT18-03 differs from the other sites in that the hammer core estimates are slightly lower than the gouge equivalents for both the soil mass and OC stock (Table 2). This difference is potentially a consequence of the material stretching when the core was removed from the ground (Fig.2), resulting in a soil profile similar to that observed in the gouge core.

		Soil Mass (kg)		OC Stock (kg)	
Site	**Soil Unit**	**Gouge**	**Hammer**	**Gouge**	**Hammer**
KT18-02	Peat	21.6	41.3	6.2	10.8
	Humified Peat	120.3	117.1	19.8	16.7
	Silt with Organics	237.1	235.0	5.7	9.6
	Total	**379**	**393.4**	**31.6**	**37.1**
	Difference (H-G)	**+14.4 kg (3.9 %)**		**+5.5 kg (14.8 %)**	
KT18-03	Peat	10.7	25.6	3.37	7.4
	Humified Peat	129.5	124.7	32.74	31.1
	Silt with Organics	233.4	163.1	24.34	19.5
	Total	**373.6**	**313.1**	**60.46**	**57.9**
	Difference (H-G)	**-60.5 kg (16.1%)**		**-2.56 kg (4.2 %)**	
KT18-05	Humified Peat	23.7	56.1	2.06	5.0
	Silt with Organics	437.5	447.8	15.47	17.5
	Total	**461.3**	**503.9**	**17.53**	**22.5**
	Difference (H-G)	**+42.6 kg (8.5%)**		**+5.0 kg (22.1 %)**	
KT18-21	Peat	38.6	92.8	4.4	13.7
	Humified Peat	156.8	187.3	17.1	18.1
	Silt with Organics	72.7	143.2	6.0	2.78
	Total	**268.12**	**423.2**	**27.5**	**34.0**
	Difference (H-G)	**+155.2 kg (36.7 %)**		**+6.5 kg (19.2 %)**	

Table 2. Soil mass and OC stock estimates for 1 m^2 of saltmarsh using the thickness of each unit measured from each of the cores.

While the differences between the gouge and hammer core-derived OC stocks may seem relatively small (-2.56 to 6.51 kg) it is worth highlighting that these estimates are for an area 1 m^2. When these estimates are scaled up to the total area of the Kyle of Tongue saltmarsh (9.31 ha), itself a relatively small saltmarsh by UK standards, the OC stock calculation could result in an underestimation of 238 tonnes OC all the way to an overestimation of 606 tonnes OC, if the hammer coring method was employed in deriving those soil OC stocks.

Furthermore, as bulk density and porosity are essential components required for the successful radiometric age-calculation of soil profiles (Appleby and Oldfield, 1978, Appleby, 2002) these coring-related compaction changes will directly impact the calculation of OC burial rates. By inputting the DBD and porosity value calculated for the gouge and hammer core from site KT-

18-03 into the Barlow et al. (2014) radiometric age model, the effect of compaction can be assessed. The outputs from the age model (Fig.4) show that the age profile and mass accumulation rate calculated from the gouge core does differ from that of Barlow et al. (2014) but this difference is minor. The age models (CRS, CIC and simple linear) developed for the hammer core significantly diverge from both that of Barlow et al. (2014) and that calculated for the gouge core. Furthermore, the increase in DBD significantly increases the mass accumulation rate to almost double that of the gouge core; this artificially increased mass accumulation rate will therefore propagate into significantly increased OC burial rate estimates in hammer cores.

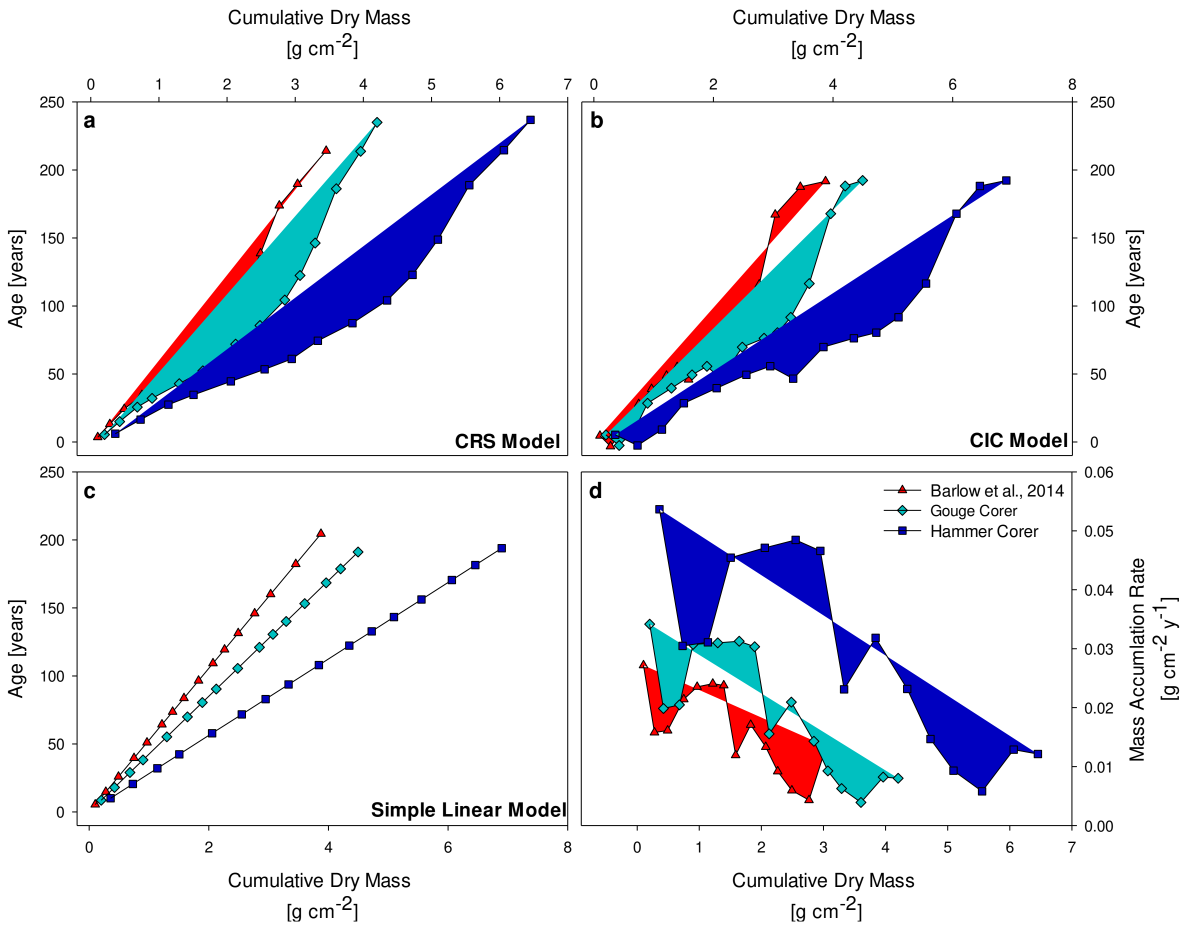

Figure 4. The effect of compaction on radiometric dating (based on original data from the Kyle of Tongue reported by Barlow et al., 2014) of cores collected from site KT-18-03 using

different calculation approaches (**a**) constant rate of supply (CRS) model (Appleby and Oldfield, 1978). (**b**) Constant initial concentration (CIC) model (Robbins and Edgington 1975). (**c**) Simple linear model (**d**) Mass sedimentation rates calculated from the CRS model.

5. Discussion

The comparison of the two coring techniques clearly highlights that hammer coring can cause significant compaction and alter the physical properties of collected saltmarsh soils (Fig.2). While soil compaction using the hammer coring method has previously been observed in saltmarshes (Callaway et al., 2012, Ewers Lewis et al., 2019, Kelleway et al., 2016a, b, Unger et al., 2016), the consequences of compaction are rarely discussed in light of their impact on OC stock and burial estimates.

OC stock estimates are calculated using the thickness of a soil unit and DBD, yet both these properties are shown to have been altered during hammer coring (Fig.2). By comparing the soil profiles collected in the gouge compared to the hammer cores, we observe that hammer coring has a significant impact, by both reducing the thickness of each soil unit and increasing the DBD, which generally leads to an overestimation of the saltmarsh soil OC stock (Table 2). Yet the degree of this uncertainty in OC stock is highly variable because each unit within the soil profile compresses by different amounts (Table 1). This highlights that the linear corrections used to compensate for coring-related compaction (Ewers Lewis et al., 2019, Kelleway et al., 2016a, b) would be unsuitable to deal with the stratigraphic complexity of the soils examined here. In saltmarshes with complex soil profiles (i.e. multiple different soil units), we have shown that hammer coring is unsuitable for the calculation of OC stocks and should be avoided. Callaway et al., (2012) suggested that where compaction was >3 cm in cores of 50 cm length, that those cores should not be used for OC stock calculations; we consider this to be a reasonable suggestion.

OC burial rates for the recent past (last 150 years) are often calculated from chronologies produced from ^{210}Pb and ^{137}Cs radiometric dating of soils, while long-term burial rates are often estimated using radiocarbon (^{14}C). DBD and porosity are key components to the measurement and production of radiometric chronologies (Appleby and Oldfield, 1978, Appleby, 2002). As compaction changes both of these soil properties, the resultant radiometric chronologies will be compromised (Fig.4). Johannessen and Macdonald (2016), for example, have recently critically reviewed the misunderstanding and use of ^{210}Pb dating, arguing that this has resulted in significant overestimation of OC burial in seagrass soils. However, soil compaction during the coring process and resulting errors in the ^{210}Pb chronology were not considered by Johannessen and Macdonald, (2016) nor in the response by Arias-Ortiz et al., (2018). For the reason discussed, there are few studies which use hammer cores for dating in saltmarshes (Boyd et al., 2017, Unger et al., 2016) and as there is no way to correct for the alteration to any complex soil profile, OC burial rates derived from hammer cores should be treated with caution.

The advantages to hammer coring are its low cost, provision of large quantities of sample material and its application in settings and soils where other corers would struggle to recover sediments (i.e. submerged soils, sands). Indeed, this explains why the hammer coring method is so widely used for seagrass sampling, for example. However, in saltmarshes, other effective coring options are available and are therefore preferable.

6. Recommendations

By comparing gouge and hammer cores, we show that the hammer coring method is unsuitable for the reliable estimation of OC stocks and burial rates in saltmarsh soils. We acknowledge that in some environments and sediment types hammer coring is the only viable, practical option. In these circumstances, some simple steps can be taken to improve research outcomes: (**i**) report if compaction took place and the correction factor applied; (**ii**) provide a description of the soil profile; (**iii**) set a threshold (e.g >3cm for 50cm cores, Callaway et al., 2012) for compaction which, if exceeded, will preclude the cores being used for OC stock estimates; (**iv**) avoid the dating of bulk soil samples collected by hammer cores. While the above steps will not resolve all of the coring-related issues identified in this study, they will allow the calculation of OC stocks with an appropriate reporting of potential errors due to compaction. Where possible, we therefore strongly recommend the use of tried and tested coring methods, such as gouge and Russian corers, which provide a strong foundation to reliably estimate saltmarsh blue carbon stocks and burial rates.

Acknowledgments

This work was supported by the Natural Environment Research Council (grant NE/R010846/1) Carbon Storage in Intertidal Environments (C-SIDE) project. Further we would like to thank Luis Rees-Hughes (University of Leeds) for field assistance.

References

Adam, P. (1978). Geographical variation in British saltmarsh vegetation. The Journal of Ecology, 339-366.

Appleby, P. G. (2002). Chronostratigraphic techniques in recent sediments. In *Tracking environmental change using lake sediments* (pp. 171-203). Springer, Dordrecht.

Appleby, P. G., & Oldfield, F. (1978). The calculation of lead-210 dates assuming a constant rate of supply of unsupported 210Pb to the sediment. Catena, 5(1), 1-8.

Archer, J. R., & Smith, P. D. (1972). The relation between bulk density, available water capacity, and air capacity of soils. *Journal of Soil Science*, *23*(4), 475-480.

Arias-Ortiz, A., Masqué, P., Garcia-Orellana, J., Serrano, O., Mazarrasa, I., Marbà, N., ... & Duarte, C. M. (2018). Reviews and syntheses: 210Pb-derived sediment and carbon accumulation rates in vegetated coastal ecosystems–setting the record straight.

Athy, L. F. (1930). Density, porosity, and compaction of sedimentary rocks. *AAPG Bulletin*, *14*(1), 1-24.

Barlow N.L.M, Long A.J., Saher M.H., Gehrels W.R., Garnett M, Scaife R. 2014. Salt-marsh reconstructions of relative sea-level change in the North Atlantic during the last 2000 years. *Quaternary Science Reviews.* 99 1-16

Boyd, B. M., Sommerfield, C. K., & Elsey-Quirk, T. (2017). Hydrogeomorphic influences on salt marsh sediment accumulation and accretion in two estuaries of the US Mid-Atlantic coast. *Marine Geology*, *383*, 132-145.

Brain, M. J. (2016). Past, present and future perspectives of sediment compaction as a driver of relative sea level and coastal change. *Current Climate Change Reports*, *2*(3), 75-85

Brain, M. J., Kemp, A. C., Hawkes, A. D., Engelhart, S. E., Vane, C. H., Cahill, N., ... & Horton, B. P. (2017). Exploring mechanisms of compaction in salt-marsh sediments using Common Era relative sea-level reconstructions. *Quaternary Science Reviews*, *167*, 96-111.

Burd, F. (1989). *Saltmarsh survey of Great Britain: an inventory of British Saltmarshes* (No. 17).

Callaway, J. C., Borgnis, E. L., Turner, R. E., & Milan, C. S. (2012). Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. *Estuaries and Coasts*, *35*(5), 1163-1181.

Dadey, K. A., Janecek, T., & Klaus, A. (1992). Dry-bulk density: its use and determination. In *Proceedings of the Ocean Drilling Program, Scientific Results* (Vol. 126, pp. 551-554). College Station, TX, USA: National Science Foundation, & Joint Oceanographic Institutions Incorporated.

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. Nature Climate Change, 3(11), 961.

Edwards, R. J. (2006). Mid-to late-Holocene relative sea-level change in southwest Britain and the influence of sediment compaction. *The Holocene*, *16*(4), 575-587.

Ewers Lewis, C. J., Baldock, J. A., Hawke, B., Gadd, P. S., Zawadzki, A., Heijnis, H., ... & Macreadie, P. I. (2019). Impacts of land reclamation on tidal marsh 'blue carbon'stocks. *Science of The Total Environment*, *672*, 427-437.

Frew, C. (2012). Section 4.1.1: Coring Methods. In: Cook, S.J., Clarke, L.E. & Nield, J.M. (Eds.) Geomorphological Techniques (Online Edition). British Society for Geomorphology; London, UK. ISSN: 2047-0371.

Glew, J. R., Smol, J. P., & Last, W. M. (2002). Sediment core collection and extrusion. In *Tracking environmental change using lake sediments* (pp. 73-105). Springer, Dordrecht.

Håkansson, I., & Lipiec, J. (2000). A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil and Tillage Research, 53(2), 71-85.

Harris, D., Horwáth, W. R., & Van Kessel, C. (2001). Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis. *Soil Science Society of America Journal*, *65*(6), 1853-1856.

Haynes, T.A. (2016). Scottish saltmarsh survey national report. Scottish Natural Heritage Commissioned Report No. 786

Howard, J., Hoyt, S., Isensee, K., Telszewski, M., & Pidgeon, E. (2014). Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses.

Johannessen, S. C., & Macdonald, R. W. (2016). Geoengineering with seagrasses: is credit due where credit is given?. *Environmental Research Letters*, *11*(11), 113001.

Kelleway, J. J., Saintilan, N., Macreadie, P. I., & Ralph, P. J. (2016b). Sedimentary factors are key predictors of carbon storage in SE Australian saltmarshes. Ecosystems, 19(5), 865-880.

Kelleway, J. J., Saintilan, N., Macreadie, P. I., Skilbeck, C. G., Zawadzki, A., & Ralph, P. J. (2016a). Seventy years of continuous encroachment substantially increases 'blue carbon'capacity as mangroves replace intertidal salt marshes. Global change biology, 22(3), 1097-1109.

Krishnaswamy, S., Lal, D., Martin, J.M. and Meybeck, M., 1971. Geochronology of lake sediments. *Earth and Planetary Science Letters*, *11*(1-5), pp.407-414.

Kostka, J. E., & Luther III, G. W. (1994). Partitioning and speciation of solid phase iron in saltmarsh sediments. *Geochimica et Cosmochimica Acta*, *58*(7), 1701-1710.

Luther III, G. W., Kostka, J. E., Church, T. M., Sulzberger, B., & Stumm, W. (1992). Seasonal iron cycling in the salt-marsh sedimentary environment: the importance of ligand complexes with Fe (II) and Fe (III) in the dissolution of Fe (III) minerals and pyrite, respectively. *Marine chemistry*, *40*(1-2), 81-103.

Macreadie, P. I., Hughes, A. R., & Kimbro, D. L. (2013). Loss of 'blue carbon'from coastal salt marshes following habitat disturbance. *PloS one*, *8*(7), e69244.

Macreadie, P. I., Trevathan-Tackett, S. M., Skilbeck, C. G., Sanderman, J., Curlevski, N., Jacobsen, G., & Seymour, J. R. (2015). Losses and recovery of organic carbon from a seagrass ecosystem following disturbance. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1817), 20151537.

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., ... & Silliman, B. R. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Frontiers in Ecology and the Environment, 9(10), 552-560.

Nellemann, C., & Corcoran, E. (Eds.). (2009). *Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment*. UNEP/Earthprint.

Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S., ... & Megonigal, P. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PloS one*, *7*(9), e43542.

Robbins, J.A. and Edgington, D.N., 1975. Determination of recent sedimentation rates in Lake Michigan using Pb-210 and Cs-137. *Geochimica et Cosmochimica Acta*, *39*(3), pp.285-304.

Rogers, K., Kelleway, J. J., Saintilan, N., Megonigal, J. P., Adams, J. B., Holmquist, J. R., ... & Woodroffe, C. D. (2019). Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. *Nature*, *567*(7746), 91.

Serrano, O., Almahasheer, H., Duarte, C. M., & Irigoien, X. (2018). Carbon stocks and accumulation rates in Red Sea seagrass meadows. *Scientific reports*, *8*(1), 15037.

Tröels-Smith, J. (1955). Characterization of unconsolidated sediments: Dansk Geologiske Undersøgelse, ser.

Unger, V., Elsey-Quirk, T., Sommerfield, C., & Velinsky, D. (2016). Stability of organic carbon accumulating in Spartina alterniflora-dominated salt marshes of the Mid-Atlantic US. *Estuarine, Coastal and Shelf Science*, *182*, 179-189.

van Ardenne, L. B., Jolicouer, S., Bérubé, D., Burdick, D., & Chmura, G. L. (2018). The importance of geomorphic context for estimating the carbon stock of salt marshes. *Geoderma*, *330*, 264-275.

Verardo, D. J., Froelich, P. N., & McIntyre, A. (1990). Determination of organic carbon and nitrogen in marine sediments using the Carlo Erba NA-1500 Analyzer. Deep Sea Research Part A. Oceanographic Research Papers, 37(1), 157-165.

Wollenberg, J. T., Ollerhead, J., & Chmura, G. L. (2018). Rapid carbon accumulation following managed realignment on the Bay of Fundy. *PloS one*, *13*(3), e0193930.