

1 **Coring and Compaction: Best Practice in Blue Carbon Stock and** 2 **Burial Estimations**

3 Craig Smeaton^{1*}, Natasha L.M. Barlow² and William E.N. Austin^{1,3}

4
5 ¹ School of Geography & Sustainable Development, University of St Andrews, St Andrews,
6 KY16 9AL, UK

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

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

9
10 **Corresponding Author:** Craig Smeaton (cs244@st-andrews.ac.uk)

11 **Abstract**

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

23 **Highlights**

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

29

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

31

32

33

34

35

36

37

38

39

40

41

42

43

44 **1. Introduction**

45 Carbon (C) buried and stored in coastal ecosystems (saltmarsh, seagrass and mangroves) is
46 known as blue carbon (Nellemann et al., 2009). In the last decade blue carbon habitats have
47 risen in prominence and are increasingly recognised as potentially valuable nature-based
48 solutions to help reduce atmospheric CO₂ and mitigate climate change (Duarte et al., 2013,
49 Mcleod et al., 2011, Pendelton et al., 2012, Rogers et al., 2019). Underpinning this
50 understanding is a wealth of research largely focused on calculating both the quantity of
51 organic carbon (OC) stored and the rate at which this OC is buried in coastal ecosystems. The
52 foundation of these estimates is the collection and measurement of soil samples, normally
53 through sediment coring. Across the body of published blue carbon research different coring
54 approaches are adopted, generally falling into two categories: (i) palaeo-environmental
55 methods which often employ Russian and gouge corers (Frew, 2014; Glew et al., 2002), and
56 (ii) low cost, often disposable hammer/impact/piston techniques, where plastic piping is
57 hammered into the soil (e.g. Howard et al., 2014).

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

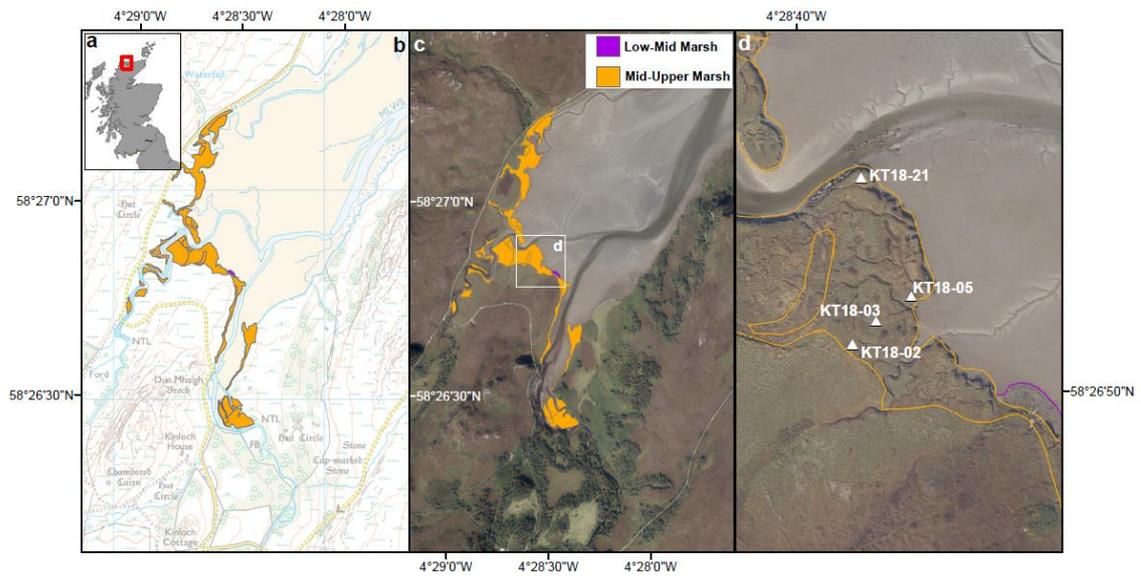
67 Gouge coring is minimally invasive and causes little disturbance to the soil; it largely avoids
68 compacting the soil, where soil compaction is more widely recognised as a significant problem
69 in achieving successful paleo-environmental reconstructions (Brain, 2016, Brain et al., 2017,
70 Edwards, 2006). Within blue carbon research, a number of studies acknowledge that hammer
71 coring causes compaction (Ewers Lewis et al., 2019, Kelleway et al., 2016a, b) but this
72 recognition is not universal. Where compaction is recognized during the coring procedure, a
73 simple linear correction, where the length of the soil core is divided by the sampling depth is
74 often applied (Ewers Lewis et al., 2019, Kelleway et al., 2016a, b). Compaction of the soils
75 increases the bulk density, decreases the porosity and dewateres the soil (Archer and Smith,
76 1972, Håkansson and Lipiec, 2000). Additionally, the loss of water may potentially flush
77 soluble and porewater OC from the soil, all of which will have a bearing on the OC stock and
78 burial estimates; it is therefore unlikely that simple linear corrections address this complexity.

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

84 **2. Study Site**

85 The Kyle of Tongue saltmarsh is one of the most northerly marshes found on the UK mainland
86 (Fig.1). The marsh is situated at the head of the Kyle of Tongue (an infilled fjord), and as such
87 is categorised as a loch-head marsh; a classification unique to Scotland in a UK context
88 (Haynes, 2016). The marsh occupies an area of 9.31 ha with the majority of that being high-
89 mid marsh (9.08 ha) with only 0.23 ha considered low marsh (Fig.1) as characterised by
90 vegetation communities and elevation (Haynes, 2016). The vegetation coverage of the marsh

91 is dominated by *Carex flacca*, *Filipendulo-Iridetum pseudacori*, *Puccinellia-turf furoid* and
92 stunted forms of *Phragmites australis*. As with the loch-head marsh type, this vegetation
93 community is only found on the marshes of western and northern Scotland (Adam, 1978, Burd,
94 1989, Haynes, 2016).



95
96 **Figure.1** Location map detailing (a) the site in context of Scotland and (b) Ordnance Survey Map
97 detailing the location of the saltmarsh in relation to the Kyle of Tongue with the high (orange) and low
98 marsh (purple) highlighted (Haynes, 2016). (c) A regional overview. (d) Sampling locations across the
99 marsh environments (© Crown copyright and database rights [2019] Ordnance Survey (100025252).

100 3. Methods

101 3.1 Coring

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

107 The gouge cores were collected using a 1m fixed length core barrel with a 3 cm diameter. The
108 corer was manually pushed into the soil to the point of refusal, rotated and removed. Before
109 removal, the degree of compaction was assessed by measuring the soil surface within the core
110 tube relative to the height of the outer marsh surface; the difference between the measurements
111 was used to calculate compaction (Kelleway et al., 2016b). On site, the core face was cleaned
112 with a sharp knife, photographed and the soil profile described using the Tröels-Smith, (1955)
113 classification scheme for unconsolidated sediments. Once described, fixed volume (4 cm³)
114 samples were collected every 10 cm along the length of the core. The location and elevation of
115 the core was recorded using DGPS.

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

127

128 **3.2 Laboratory Analysis**

129 **3.2.1 Physical Properties**

130 The hammer cores were cut lengthways and split into working and archive sections; the soils
131 were described using the Tröels-Smith (1955) classification scheme. The distance between the

132 core top within the liner was compared to the ground level marked on the linear in the field
 133 allowing the total compaction of the core to be determined and assure no additional compaction
 134 or expansion has taken place post collection. Fixed volumetric samples (4 cm³) were extracted
 135 at 10 cm intervals throughout the length of the core using a fixed volume sampler (syringe).
 136 Sub-samples from both the gouge and hammer cores were weighed before and after drying at
 137 50°C for 48 hrs. This data allowed wet bulk density (WBD), dry bulk density (DBD), porosity
 138 and water content to be calculated following the standard methodologies (Athy, 1930, Appleby
 139 and Oldfield, 1978, Dadey et al., 1992):

$$140 \quad \text{Wet Bulk Density (g cm}^{-3}\text{)} = \frac{\text{Wet Mass (g)}}{\text{Wet Sample Volume (cm}^3\text{)}} \quad (1)$$

$$141 \quad \text{Dry Bulk Density (g cm}^{-3}\text{)} = \frac{\text{Dry Mass (g)}}{\text{Wet Sample Volume (cm}^3\text{)}} \quad (2)$$

$$142 \quad \text{Water Content (\%)} = \frac{\text{Wet Mass (g)} - \text{Dry Mass (g)}}{\text{Wet Mass (g)}} \times 100 \quad (3)$$

$$143 \quad \text{Porosity (\%)} = \frac{\text{Mass of Water in the Soil (g)}}{\text{Mass of Water in the Soil (g)} + \left(\frac{\text{Dry Mass (g)}}{\text{Dry Bulk Density (g cm}^{-3}\text{)}} \right)} \quad (4)$$

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

146 **3.2.2 Elemental Analysis**

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

3.2.3 Assessing OC stocks and burial rates

155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179

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 m² 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 where 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 m² of saltmarsh soil. Using the data collected from the cores the mass of soil and the OC stock for the soil underlying the 1 m² was estimated. These estimates were made following the standard methodology:

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

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

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

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.

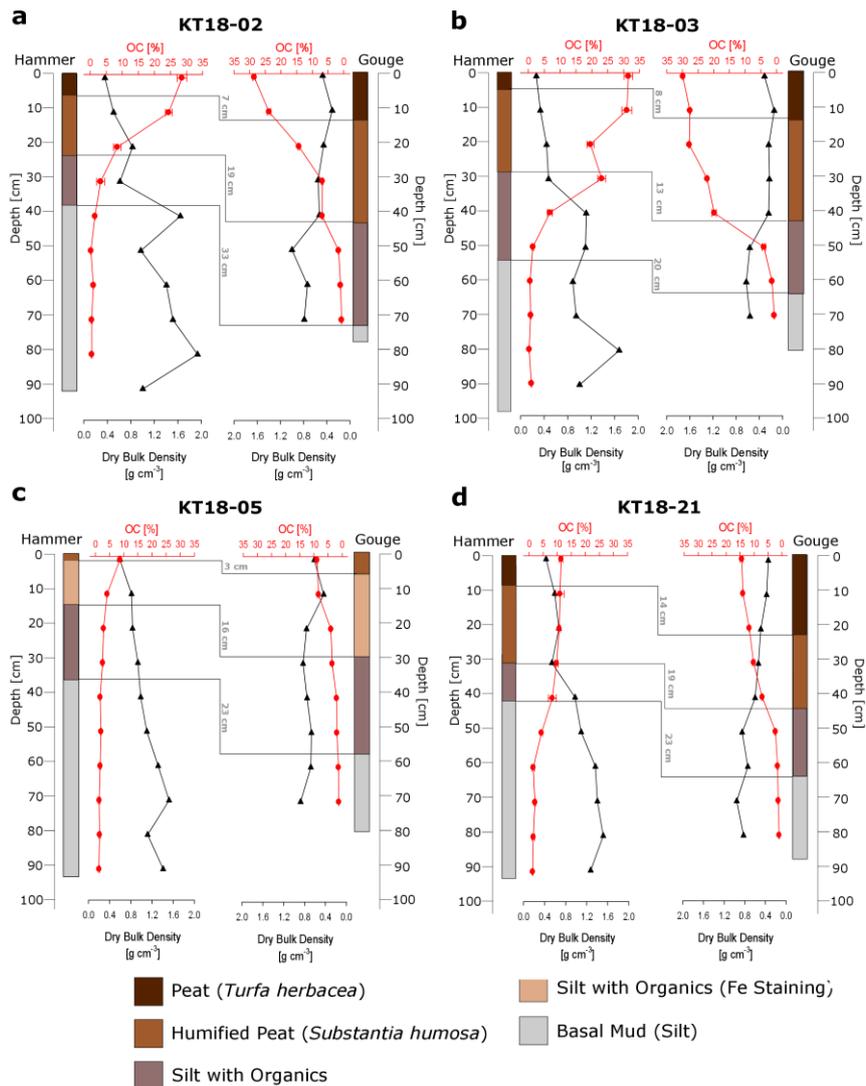
Sedimentation and mass accumulation rates of saltmarsh soils are commonly calculated using radiometric age control (²¹⁰Pb and ¹³⁷Cs) (Krishnaswamy et al., 1971, Appleby and Oldfield, 1978). Dry bulk density and porosity are key to these calculations. In order to test the effect of soil compaction on 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 diameter gouge corer from the same location as core KT-18-03. The new DBD and

180 porosity data from the gouge and hammer cores collected at site KT-18-03 were used, together
181 with the original radiometric age control data, to recalculate the most common age-depth
182 methods: simple linear interpolation, the constant rate of supply (CRS) model (Appleby and
183 Oldfield, 1978) and the constant initial concentration (CIC) model (Robbins and Edgington
184 1975).

185 **4. Results and Interpretation**

186 **4.1 Saltmarsh Soil Profiles**

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



199

200 **Figure 2.** Comparison of the effects of the coring method on the soil profiles, OC content and
 201 dry bulk density across the four sites. The grey lines represent the difference in cumulative
 202 depth (cm) of the soil horizons in each core as described by the Tröels-Smith classification
 203 scheme (1955). The thickness of the different soil units can be found in the supplementary table
 204 2.

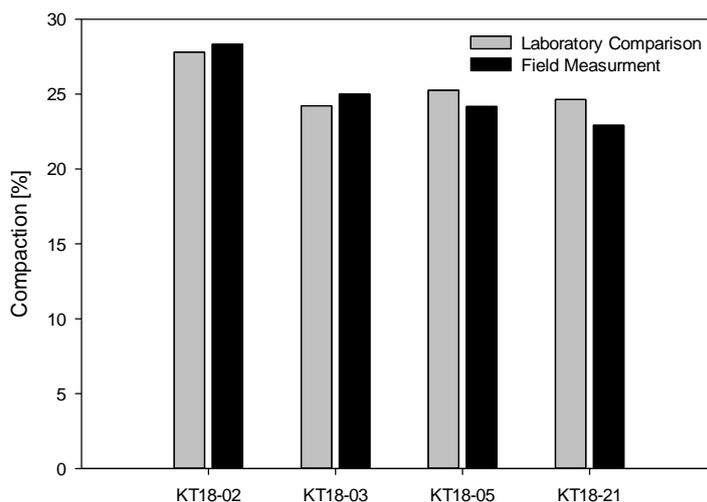
205

206

207

208 **4.2 Compaction**

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



222 **Figure 3.** Comparison of field- and laboratory-based measurements of total soil compaction
223 (%) in the four hammer cores.
224

225

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

Site	Soil Unit	Mean Dry Bulk Density (g cm ⁻³)		Mean Water Content (%)		Porosity (%)		Compaction (%)
		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

231

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

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

247 **4.3 Consequences for OC stock and burial estimations**

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

260

Site	Soil Unit	Soil Mass (kg)		OC Stock (kg)	
		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 %)	

262

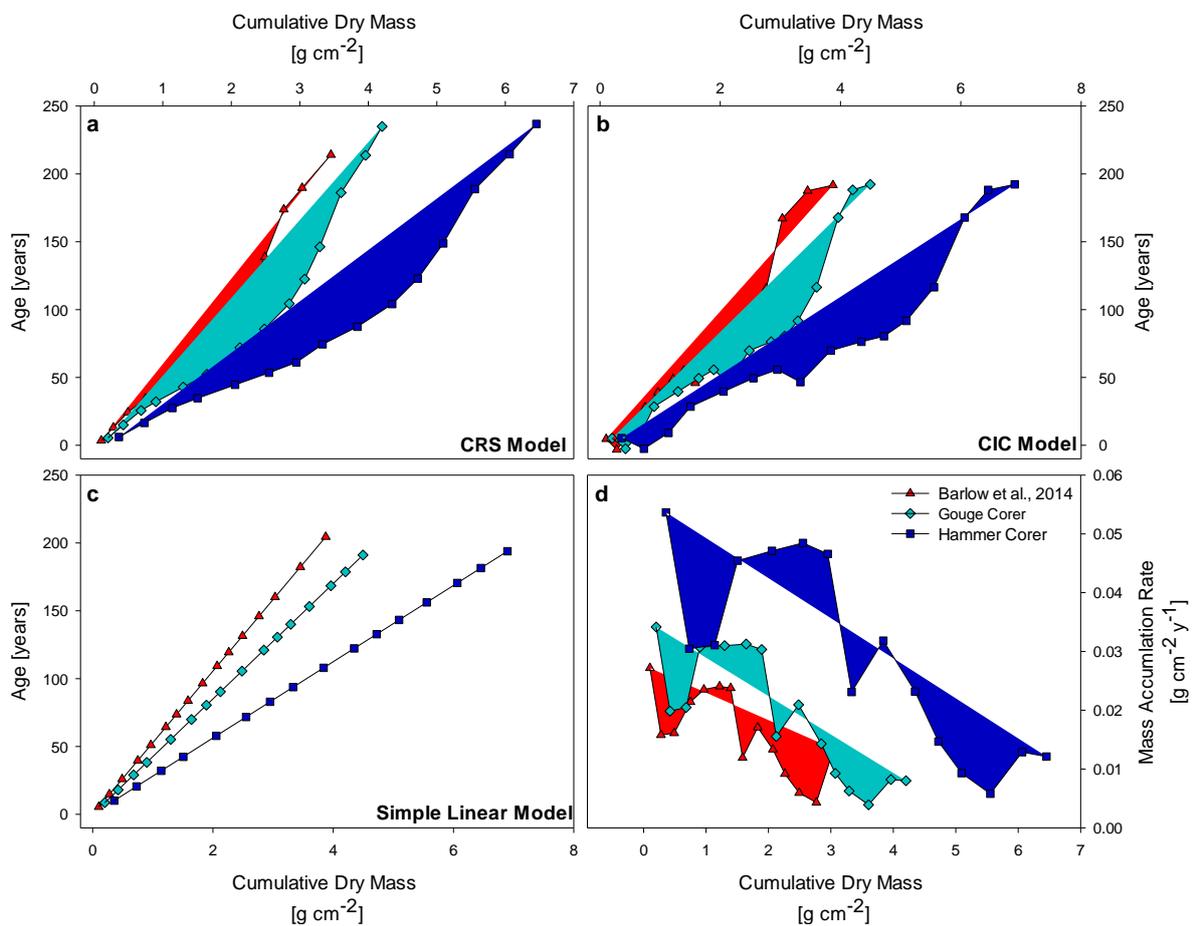
263 **Table 2.** Soil mass and OC stock estimates for 1 m² of saltmarsh using the thickness of each
264 unit measured from each of the cores.

265

266 While the differences between the gouge and hammer core-derived OC stocks may seem
267 relatively small (-2.56 to 6.51 kg) it is worth highlighting that these estimates are for an area 1
268 m². When these estimates are scaled up to the total area of the Kyle of Tongue saltmarsh (9.31
269 ha), itself a relatively small saltmarsh by UK standards, the OC stock calculation could result
270 in an underestimation of 238 tonnes OC all the way to an overestimation of 606 tonnes OC, if
271 the hammer coring method was employed in deriving those soil OC stocks.

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

276 18-03 into the Barlow et al. (2014) radiometric age model, the effect of compaction can be
 277 assessed. The outputs from the age model (Fig.4) show that the age profile and mass
 278 accumulation rate calculated from the gouge core does differ from that of Barlow et al. (2014)
 279 but this difference is minor. The age models (CRS, CIC and simple linear) developed for the
 280 hammer core significantly diverge from both that of Barlow et al. (2014) and that calculated
 281 for the gouge core. Furthermore, the increase in DBD significantly increases the mass
 282 accumulation rate to almost double that of the gouge core; this artificially increased mass
 283 accumulation rate will therefore propagate into significantly increased OC burial rate estimates
 284 in hammer cores.



285
 286
 287 **Figure 4.** The effect of compaction on radiometric dating (based on original data from the Kyle
 288 of Tongue reported by Barlow et al., 2014) of cores collected from site KT-18-03 using

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

292

293 **5. Discussion**

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

300

301 OC stock estimates are calculated using the thickness of a soil unit and DBD, yet both these
302 properties are shown to have been altered during hammer coring (Fig.2). By comparing the soil
303 profiles collected in the gouge compared to the hammer cores, we observe that hammer coring
304 has a significant impact, by both reducing the thickness of each soil unit and increasing the
305 DBD, which generally leads to an overestimation of the saltmarsh soil OC stock (Table 2). Yet
306 the degree of this uncertainty in OC stock is highly variable because each unit within the soil
307 profile compresses by different amounts (Table 1). This highlights that the linear corrections
308 used to compensate for coring-related compaction (Ewers Lewis et al., 2019, Kelleway et al.,
309 2016a, b) would be unsuitable to deal with the stratigraphic complexity of the soils examined
310 here. In saltmarshes with complex soil profiles (i.e. multiple different soil units), we have
311 shown that hammer coring is unsuitable for the calculation of OC stocks and should be avoided.
312 Callaway et al., (2012) suggested that where compaction was >3 cm in cores of 50 cm length,

313 that those cores should not be used for OC stock calculations; we consider this to be a
314 reasonable suggestion.

315

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

329

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

335

336

337

338 **6. Recommendations**

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

352

353 **Acknowledgments**

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

357

358 **References**

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

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

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

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

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

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

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

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

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

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

383 Burd, F. (1989). *Saltmarsh survey of Great Britain: an inventory of British Saltmarshes* (No.
384 17).

385 Callaway, J. C., Borgnis, E. L., Turner, R. E., & Milan, C. S. (2012). Carbon sequestration and
386 sediment accretion in San Francisco Bay tidal wetlands. *Estuaries and Coasts*, 35(5), 1163-
387 1181.

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

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

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

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

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

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

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

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

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

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

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

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

419 Kelleway, J. J., Saintilan, N., Macreadie, P. I., Skilbeck, C. G., Zawadzki, A., & Ralph, P. J.
420 (2016a). Seventy years of continuous encroachment substantially increases 'blue
421 carbon' capacity as mangroves replace intertidal salt marshes. *Global change biology*, 22(3),
422 1097-1109.

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

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

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

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

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

437 Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., ... & Silliman, B.
438 R. (2011). A blueprint for blue carbon: toward an improved understanding of the role of
439 vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and the Environment*,
440 9(10), 552-560.

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

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

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

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

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

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

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

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

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

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