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Carbon sequestration and storage in Norwegian Arctic coastal wetlands: Impacts of climate change

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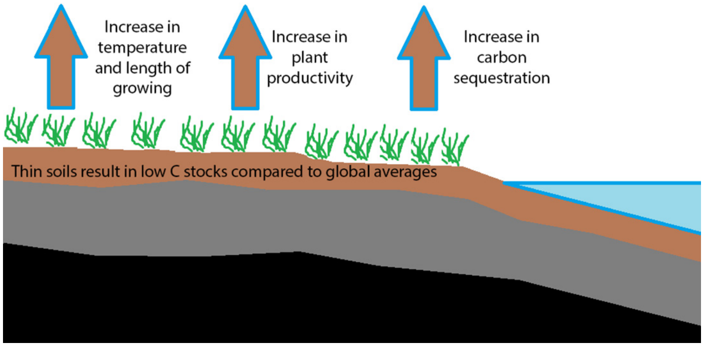
HIGHLIGHTS

- Arctic coastal wetlands store less carbon than global averages due to thin soils.
- Carbon sequestration rates are similar to those of temperate salt marshes.
- Extension of the growing season has resulted in increased carbon sequestration.

GRAPHICAL ABSTRACT



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ABSTRACT

Coastal wetlands contain some of the largest stores of pedologic and biotic carbon pools, and climate change is likely to influence the ability of these ecosystems to sequester carbon. Recent studies have attempted to provide data on carbon sequestration in both temperate and tropical coastal wetlands. Alteration of Arctic wetland carbon sequestration rates is also likely where coastal forcing mechanisms interact directly with these coastal systems. At present there are no data available to provide a detailed understanding of present day and historical carbon sequestration rates within Arctic coastal wetlands.

In order to address this knowledge gap, rates of carbon sequestration were assessed within five Arctic coastal wetland sites in Norway. This was undertaken using radiometric dating techniques (^{210}Pb and ^{137}Cs) to establish a geochronology for recent wetland development, and soil carbon stocks were estimated from cores.

Average carbon sequestration rates were varied, both between sites and over time, ranging between 19 and 603 g C m^2 y^{-1}, and these were correlated with increases in the length of the growing season. Stocks ranged between 3.67 and 13.79 Mg C ha^{-1}, which is very low compared with global average estimations for similar coastal systems, e.g. 250 Mg C ha^{-1} for temperate salt marshes, 280 Mg C ha^{-1} for mangroves, and 140 Mg C ha^{-1} for seagrasses. This is most likely due to isostatic uplift and sediment accretion historically outpacing sea level rise, which results in wetland progradation and thus a continuous formation of new marsh with thin organic soil horizons. However, with increasing rates of sea level rise it is uncertain whether this trend is set to continue or be reversed.

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1. Introduction

There is a general consensus that over the last century global climate has undergone change including increases in temperature and sea level rise (Rahmstorf, 2010), largely as a result of the 40% increase in atmospheric carbon since 1750 (IPCC, 2013). There are five major pools of global carbon: oceanic, geologic, pedologic (soil), atmospheric and biotic. Each of these carbon pools is interconnected and the oceanic, pedologic, and biotic pools can be considered as important buffers to climate change, with the oceanic pool being the most stable (Powlson et al., 2011).

Chmura et al. (2003) suggested that vegetated coastal ecosystems (salt marshes, mangroves and seagrasses) contain the largest stores of pedologic and biotic carbon (termed as blue carbon). Thus, vegetated coastal ecosystems provide an important ecosystem service by removing carbon from the atmosphere, although the majority of studies assessing global carbon budgets have focussed on forests and grasslands.

A range of studies state that climate change is likely to influence the ability of wetlands to sequester carbon (DeLaune and White, 2012; Bianchi et al., 2013; Doughty et al., 2016; Osland et al., 2016; Ward et al., 2016c; Mafi-Gholami et al., 2018; Saintilan et al., 2019), particularly in high latitudes due to changes in the length of the growing season (Chmura et al., 2003).

The effects of climate change on coastal wetlands are more complex than on interior wetlands due to the greater amount of influencing factors such as increased storminess, alterations to precipitation regimes, sea level rise, and in very high latitudes, changes in the concentration and duration of land-fast sea ice (Ward et al., 2016a; Ward et al., 2016b; Lima et al., 2020). These factors are often combined with other global change impacts including population growth, land use-land cover change, and environmental pollution, which can impact sedimentary and geochemical characteristics as well as the geomorphology of coastal systems (Ward et al., 2014; Celis-Hernandez, 2020; Bardos et al., 2020; Veettil et al., 2020).

Recent studies have attempted to provide data on carbon sequestration in both temperate and tropical coastal wetlands (Li et al., 2010; Kirwan and Mudd, 2012; Pendleton et al., 2012; Smoak et al., 2013; Duarte et al., 2013; Lovelock and Duarte, 2019). However, there has been no attempt to assess carbon sequestration or stocks within Arctic coastal wetlands, despite the extent of the Arctic Ocean coastline (45,389 km) (Symon et al., 2005), equivalent to the Atlantic coastline of the Americas. Furthermore, climate change has already disproportionately impacted the Arctic region (IPCC, 2013) with changes including significant reductions of summer and land-fast sea ice cover (Ding et al., 2017). Symon et al. (2005) suggest that this is likely to result in an alteration in coastal processes and more dynamic coastal environments.

Temperature increases and resultant extensions to the growing season are also likely to increase net primary productivity (Symon et al., 2005), with resultant changes in rates of carbon sequestration, particularly in ecosystems at the interface of marine and terrestrial systems. Significant alteration to Arctic wetland carbon sequestration is also likely where coastal forcing mechanisms interact directly with these coastal systems. At present, there are no data available to provide a detailed understanding of present day and historical carbon sequestration rates within Arctic coastal wetlands. Such data are essential for making any assessment of carbon storage within these ecosystems and of future trends in response to the continued warming of the Arctic region.

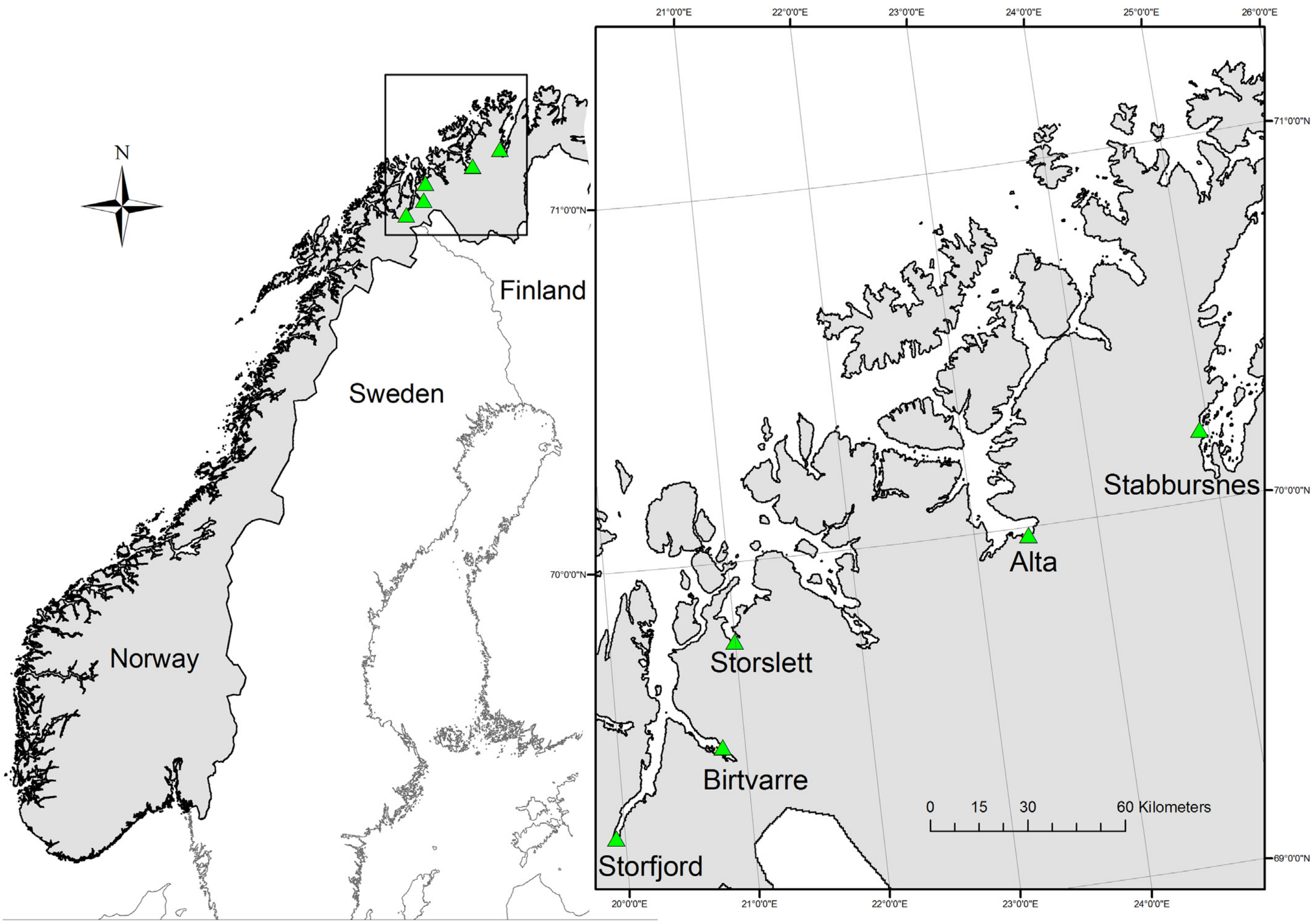

Fig. 1. Five study sites within Norway: Storfjord, Birtvarre, Storslett, Alta and Stabbursnes.

In order to address this knowledge gap, this study assessed rates of carbon sequestration within Arctic coastal wetlands and identified drivers of changes in rates over the last 150 years using radiometric dating techniques (^{210}Pb and ^{137}Cs) to establish a geochronology for recent wetland development.

2. Study area

The study sites are located along the Arctic coast of Norway between Tromsø (69.6492° N, 18.9553° E) and Stabbursnes (70.1613° N, 24.9537° E) (Fig. 1, Table 1). In the last ten years average annual precipitation was 551 mm, predominantly falling between July and January (Table 1). Over the same period, average summer temperatures were 10.1 °C with a short growing season of ~120 days (where temperatures are >5 °C) and average winter temperatures were − 3.5 °C (Table 1). Plant productivity is quite high within these coastal ecosystems (Dijkema, 1990), and Arctic coastal wetlands provide an important habitat for hundreds of thousands migratory geese, ducks and charadriiformes (Henningsson and Alerstam, 2005). The plant communities are substantially influenced by cattle, reindeer and goose grazing and typically consist of *Puccinellia phryganodes*, *Puccinellia retroflexa borealis*, *Cochlearia officinalis*, *Carex subspathacea*, *Festuca rubra*, *Carex glareosa*, *Carex mackenziei*, and *Juncus gerardii* (Martini et al., 2019).

The Arctic mainland of Norway has an uplifting coastline with a rate of ~1 mm yr^{-1} (Eronen et al., 2001), similar to rates occurring in Scotland and south Estonia where it has been suggested that recent sea level rise is now outpacing combined coastal wetland sediment accretion and uplift (Teasdale et al., 2011; Ward et al., 2014). Arctic coastal wetlands in Norway are typically located at the head of deep fjords with small estuaries which drain from the surrounding mountain catchments and glaciers. The size of the wetlands is dependent on available sediment deposition and inheritance, which provides a shallow platform to the typically deep and steep coastline within the fjords (Martini et al., 2019).

The bedrock surrounding the fjords consists of Precambrian-Silurian crystalline rocks (Levell, 1980) with Mesozoic sedimentary rocks within the coastal areas (Roberts et al., 1997) overlain by between 50 and 200 m of Quaternary sediments dependent on location within the fjord channels. Coastal sediments are of periglacial/ glacial origin (e.g., glacial moraines, glacio-fluvial deposits, fluvial deposits, sea-fjord deposits and thick marine deposits) (NGU, 2017). Fjords are typically between 150 and 280 m deep although within the Porsanger and Alta depth is substantially less (~15 m at the head of the fjords), which results in extensive intertidal mudflat and salt marsh coverage. The banks of the fjords form the boundary between the sedimentary and crystalline rocks (NGU, 2017). The Norwegian Current and the Coastal Current are the dominant marine currents in the region, bringing warm water flowing to the northeast. The Coastal Current has the strongest influence on the hydrodynamics of the fjords in Finnmark (Wassmann et al., 1996). Sea surface temperatures within the fjords fluctuate between 5 and 11 °C throughout the year (Eilertsen and Skarðhamar, 2006). The five study sites were selected to take into account the variability in Norwegian Arctic coastal wetlands consisting of the two largest coastal wetlands in the region (Alta within Altafjord and Stabbursnes within Porsangerfjord) and smaller fjordhead coastal wetlands, similar to those of Scotland, that are typical of the region (Birtvarre, Storfjord and Storslett) (Fig. 2). The Alta coastal wetland is adjacent to Altaelva, one of the largest rivers in the region, providing a substantial supply of sediments to the site (Fig. 2a). Stabbursnes is located at the mouth of the small, steep mountain fed Stabburselva (Fig. 2b). Birtvarre is located at the head of Kå fjord, and the coastal wetland is located at the mouth of Kåfjordelva (Fig. 2c). Storfjord is located at the head of Lyngen fjord and the coastal wetland is at the mouth of Signaldaelva (Fig. 2d). Storfjord is located at the head of Reisa fjord and the coastal wetland is at the mouth of Reisaelva, this site is the least sheltered from the open ocean (Fig. 2e).

Table 1
Coordinates for all study sites together with average length of growing season, average annual temperatures, and average annual precipitation. Meteorological data for each site run from: Alta 1873-present, Stabbursnes 1957 to present, Birtvarre 1954 to present, Storfjord 1954 to present, and Storlsett 1958 to present.

Site name	Latitude (DD)	Longitude (DD)	Average annual temperature (°C)	Average annual precipitation (mm)	Length of the growing season (days)
Alta	69.9783	23.4315	2.5	431	118
Stabbursnes	70.1942	24.9275	1.8	403	110
Birtvarre	69.4959	20.8204	3.6	1006	130
Storfjord	69.2713	19.9266	2.9	401	125
Storslett	69.7819	20.9953	2.5	782	119

3. Material and methods

3.1. Field data collection

Two soil cores (75 mm diameter, depth to refusal) were collected using a stainless-steel Russian corer, within each of the five coastal wetlands (Stabbursnes, Storslett, Birtvarre, Alta, and Storfjord, a total of ten cores) following a walkover survey to visually determine the heterogeneity (which was limited) of the soil profile within each site. Refusal, was at all times a thick (>1 m depth), minerogenic glacio-fluvial cobble/ boulder layer with a very low organic matter content. Cores were selected from the low and high marsh ecological zones within each site, with the low marsh typically inundated at each high tide and the high marsh inundated only during spring high tides. The high marsh typically consisted of *Carex subspathacea* mixed with *Puccinellia phryganodes* (Storfjord, Alta, Birtvarre), *Carex subspathacea* mixed with *Festuca rubra* (Storslett), and *Carex subspathacea* mixed with *Juncus gerardii* (Stabbursnes). The low marsh was dominated by *Juncus gerardii*.

Each core was inserted into the soil ensuring minimal compaction (<5% as per Ward et al., 2014). These samples were sealed in the field, removed intact and frozen within 4 h of collection for transport to the laboratory for analysis.

3.2. Granulometry and organic matter analysis

Cores were extracted in the laboratory allowing the outer section of the core to defrost enabling extraction from core barrels with no compaction, which was tested by measuring the core both before and immediately after extraction. Cores were then meticulously cleaned and each core was sliced into 0.5 cm depth increment sub-samples and dried at 40 °C until constant weight (to ensure minimal loss of lead isotopes). Total organic matter was estimated using the loss on ignition (LOI) method combusting samples at 450 °C for 12 h (Bisutti et al., 2004; Lima et al., 2020). The LOI method can have problems with losses of structural water in clays (at temperatures >500 °C) and $CaCO_3$ in carbonate soils (at temperatures of 800 °C or higher) or incomplete combustion of organic components (typically <400 °C). However, this is unlikely to have influenced results for soil organic carbon (%C_{org}) at these sites due to the very low clay and carbonate content and the temperature of combustion.

Soil organic carbon was estimated from soil organic matter using the equation specifically recommended for blue carbon accounting (Howard et al., 2014):

$$\%C_{org} = 0.47 \times \%LOI + 0.0008 \times (\%LOI)^2 \qquad (1)$$

Soil organic carbon values were used to calculate carbon density using the equation:

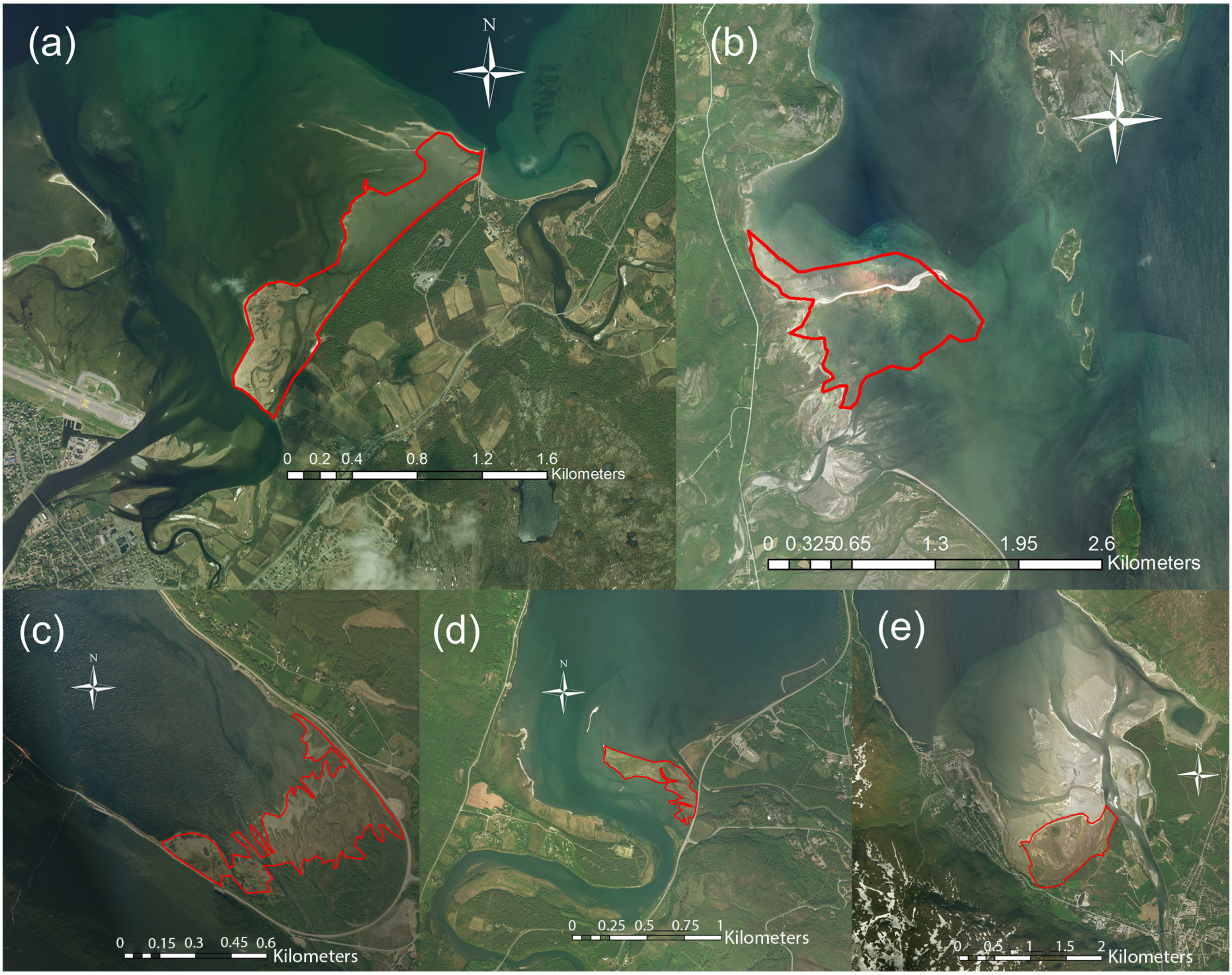

Fig. 2. Location of the study sites, showing the proximity to fluvial sources, constaints to migration (e.g.roads and other infrastructure) as well as the area of the site (a: Alta; b: Stabbursnes c: Birtvarre d: Storfjord; e: Storslett).

$$\text{Soil carbon density} = \text{dry bulk density} \times (\%C_{org}/100) \quad (2)$$

Dry bulk density was estimated using the equation from Dadey et al. (1992):

$$\text{Dry bulk density} = (1-\phi)P_s \quad (3)$$

where ϕ = porosity, and P_s = grain specific gravity (in this case 2.5 g/cm^3, Dadey et al., 1992).

Sediment particle size analysis was conducted on samples with organics removed in a Malvern Mastersizer 2000 (Laser PSA). 10 ml of sodium hexametaphosphate was added to each sample and this was mixed in a vortex mixer for 5 min. Following this samples underwent 30 s of ultra-sonication prior to particle size analysis. Texture was categorised using the Wentworth (1922) classification derived from three analytical runs to provide an average (standard error < 1%).

3.3. ^{210}Pb and ^{137}Cs dating carbon sequestration rates

In order to estimate rates of carbon sequestration, a core profile geochronology was established. Over short time periods (decades to 150 years), ^{210}Pb dating is a well-established methodology that uses the half-life of this radionuclide (22.6 years) to date specific horizons within the soil profile (Wise, 1980; Cundy and Croudace, 1996; Plater and Appleby, 2004; Ward et al., 2014). The geochronology was calculated using the Constant Rate of Supply (CRS) model (Appleby and Oldfield, 1992). The CRS model provides a detailed geochronology using inventories to calculate date of deposition for each depth within the soil profile which can be used to identify the variation in carbon sequestration rates over time. For dating purposes, the supported component was assessed via direct measurement of the daughter radionuclide ^{214}Pb, in conjunction with the estimation of constant ^{210}Pb activity at depth. In this study ^{214}Pb closely approximated ^{210}Pb at the lowest depths of the core, thus indicating that the measurement of ^{214}Pb is a robust proxy for supported ^{210}Pb (Brown et al., 2019).

^{137}Cs in soils is predominantly derived from global inputs from the detonation of nuclear weapons prior to the Partial Test Ban Treaty in 1963 (Ritchie and McHenry, 1990) and in Europe from the Chernobyl nuclear reactor accident in 1986 (Anspaugh et al., 1988), which strongly impacted on northern and eastern European nations including Norway.

^{210}Pb and ^{137}Cs down core activity profiles were obtained at a depth resolution of 0.5 cm and determined using a Canberra ultra-low background high purity germanium well-type gamma spectrometer. Background emission subtractions are undertaken on a fortnightly basis

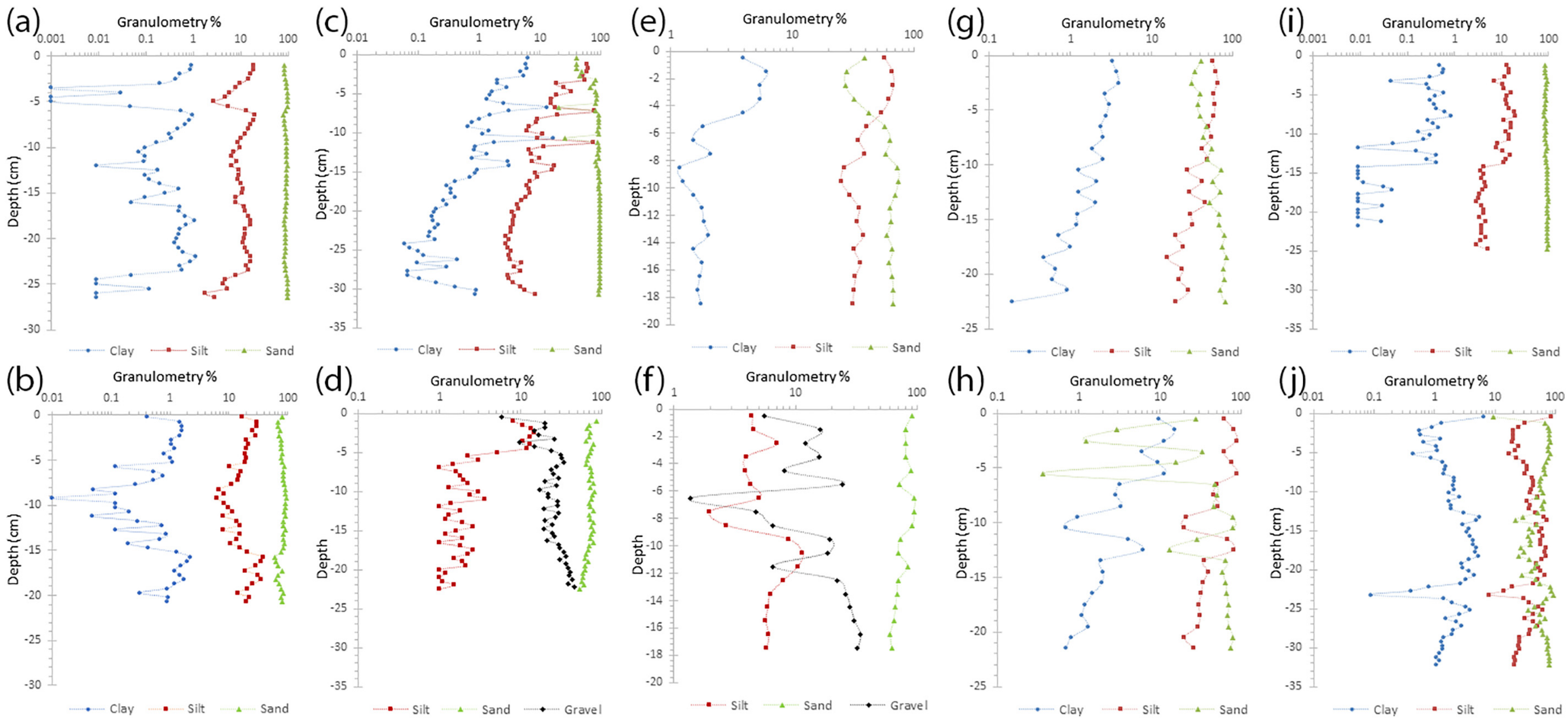

Fig. 3. Stratigraphy of the core sequences showing percentage of clay, silt, sand and gravel using the Wentworth (1922) classification for all sites (a: Alta low marsh; b: Alta high marsh; c: Stabbursnes low marsh; d: Stabbursnes high marsh; e: Birtvarre low marsh; f: Birtvarre high marsh; g: Storfjord low marsh; h: Storfjord high marsh; i: Storslett low marsh; and j: Storslett high marsh).

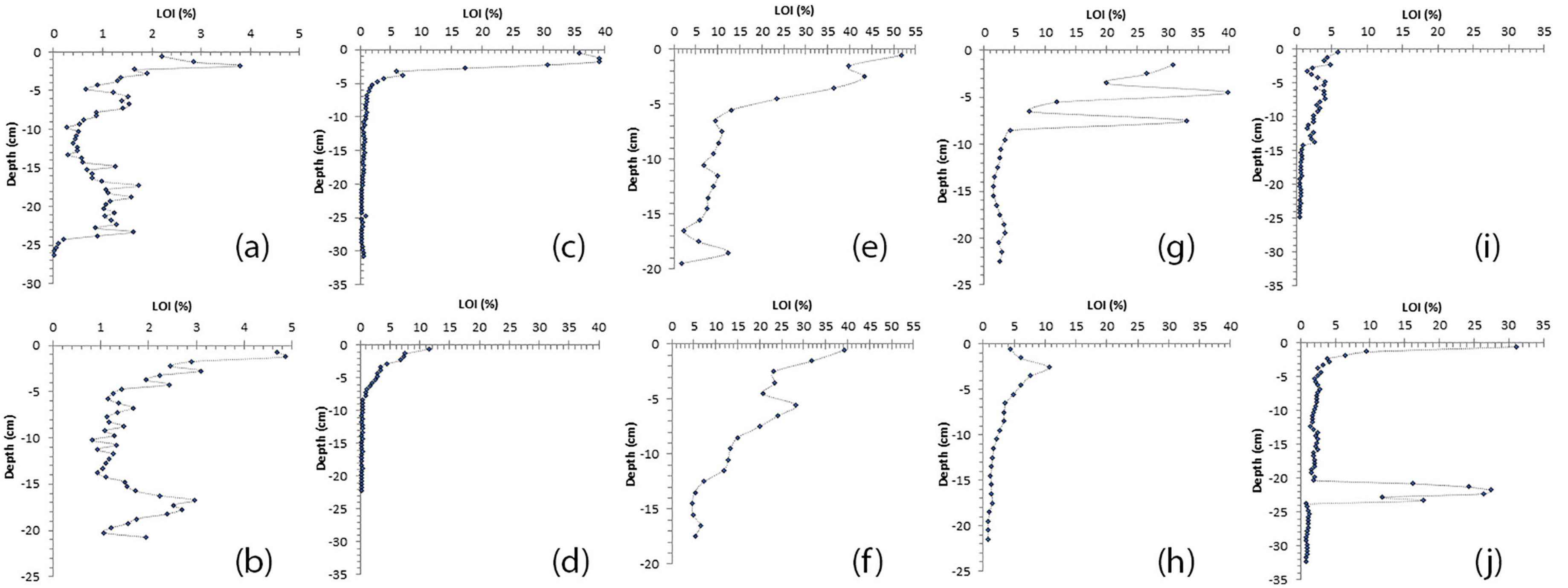

Fig. 4. Stratigraphy of the organic matter derived from loss on ignition (LOI) for all sites (a: Alta low marsh; b: Alta high marsh; c: Stabbursnes low marsh; d: Stabbursnes high marsh; e: Birtvarre low marsh; f: Birtvarre high marsh; g: Storfjord low marsh; h: Storfjord high marsh; i: Storslett low marsh; and j: Storslett high marsh).

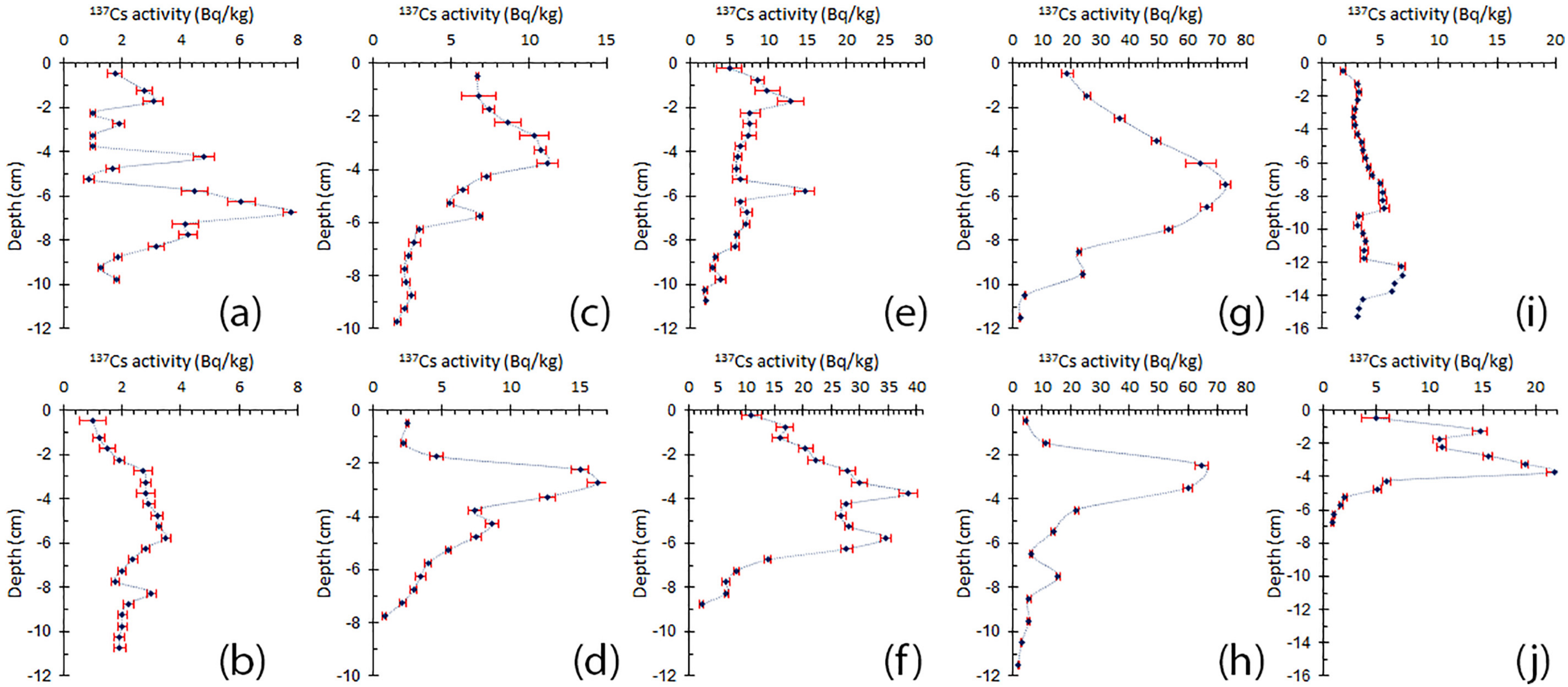

Fig. 5. ^{137}Cs activity profiles for all cores at all sites (a: Alta low marsh; b: Alta high marsh; c: Stabbursnes low marsh; d: Stabbursnes high marsh; e: Birtvarre low marsh; f: Birtvarre high marsh; g: Storfjord low marsh; h: Storfjord high marsh; i: Storslett low marsh; and j: Storslett high marsh).

and energy and efficiency calibrations were made with a mixed gamma-emitting radionuclide standard, QCYK8163. The limits of detection vary with radionuclide, sample mass and count times, but these were 8 Bq kg^{-1} for ^{210}Pb, and 1 Bq kg^{-1} for 137Cs, for a 260,000 s count time, where required extended count times were conducted.

Carbon sequestration rates (C_{seq}, g C m^2 year^{-1}) were calculated using the rate of sediment accretion (cm yr^{-1}) derived from the ^{210}Pb CRS geochronology data multiplied by the density of soil carbon (g cm^{-3}) (Greiner et al., 2013):

$$\text{Cseq} = \text{Carbon density} \times \text{sediment accretion rates}. \tag{4}$$

3.4. Comparing carbon sequestration with environmental and meteorological variables

Glacial Isostatic Adjustment (GIA) calibrated sea level data collated from the Norwegian Mapping and Cadastre Authority archives (NGU, 2017) were obtained for the three nearest tide gauge stations to the study sites, which were Tromsø (52, 72 and 73 km from Storfjord, Birtvarre and Storslett respectively), Honningsvåg (78 km from Stabbursnes), and Hammerfest (74 km from Alta), with the closest allocated to the corresponding study site. Additionally, climate data were obtained from the Norwegian Meteorological Institute archives (MET Norway, 2019), including mean annual precipitation and length of the growing season (calculated as number of days per year where temperatures exceeded 5 °C, Ratas and Nilson, 1997). These data were available at a daily resolution from late 1800's (Alta), early 1950's (Stabbursnes, Storslett) and the early to mid-1960's for Birtvarre and Storfjord. Sea level, precipitation and growing season data were averaged for each period (inter-dated horizons up to a maximum of a decade) relating to the geochronologies derived from the ^{210}Pb dating for the soil profiles. These data, combined with d50 and sorting coefficients (Trask, 1932) for corresponding soil horizons, were compared with the dated carbon sequestration rate results using a Pearson's test for correlation (Lima et al., 2020) to evaluate the relationships between these environmental factors and carbon sequestration. All statistical analyses were performed in Minitab 19.

4. Results and interpretation

4.1. Sediment characterisation

Within both the low and high marsh cores from Alta, the soil predominantly consisted of sand, as was the case for the cores from the low marsh at Storfjord (Fig. 3a, b). The high marsh cores from Stabbursnes and Birtvarre were also predominantly sand (Fig. 3d, f), with substantial gravel fractions and no clay. The most recently deposited sediments were predominantly silt in the low marsh cores from Stabbursnes and Birtvarre (from the 1990s to present, Fig. 3c, e), a change from predominantly sand fractions in older soils. The same trend can be seen in the low and high marsh cores from Storfjord (1950s and 1940s respectively, Fig. 3g, h). Clay fractions were highest in the low marsh cores from Stabbursnes and Birtvarre and in the upper marsh cores from Storfjord and Storslett (between 1 and 10%, Fig. 3c, e, h, and j respectively).

Organic matter varied substantially both between sites and down the cores. At Alta organic matter did not exceed 5% (Fig. 4a,b) and was lowest at the very bottom of the lower shore core where it reached the low organic cobble bed. The Stabbursnes and Birtvarre cores showed the highest organic matter, which was evident in the walkover study. Values ranged from 12 to 54% in the upper layers (Fig. 4c,d,e,f), although variation was much lower in the dateable stratigraphy, particularly for Birtvarre. At Storfjord low marsh, there was substantial variation in the upper dateable stratigraphy (Fig. 4g), this was less pronounced in the upper marsh core (Fig. 4h). At Storslett low marsh the organic matter content was quite low (~4%) and varied within the upper dateable stratigraphy (Fig. 4i). In the Storslett high marsh core, organic matter was much higher, up to 31% in the upper stratigraphy (Fig. 4j), this decreased to 3–4%, with an exceptional band of highly organic material between 20 and 24 cm deep.

Table 2
Comparison between ^{210}Pb and ^{137}Cs dating for the 1963 and 1986 inputs for all cores. BMD = below ^{210}Pb measured dating. EAD = equivalent age depth compared to 1963 dates. LM and HM denotes low and high marsh respectively.

Site	^{210}Pb EAD 1963	^{210}Pb EAD 1986
Alta LM	1957	1983
Alta HM	1924	1946
Stabbursnes LM	1957	1984
Stabbursnes HM	1955	1991
Birtvarre LM	1966	1998
Birtvarre HM	1951	1976
Storfjord LM	1919	1973
Storfjord HM	BMD	1974
Storslett LM	BMD	1941
Storslett HM	1934	1987

4.2. ^{210}Pb and ^{137}Cs dating

^{137}Cs was found in all cores within the five study sites and there were two peaks identified within each core (Fig. 5). These were related to a deeper peak in ^{137}Cs activity derived from global atmospheric deposition as a result of above ground nuclear weapons testing reaching a peak in 1963 and a shallower profile peak related to the 1986 Chernobyl nuclear disaster. There is some evidence for post depositional migration of ^{137}Cs in all cores, highlighted by broadening of peaks, particularly in the Storfjord cores (Fig. 5g, h). ^{137}Cs was also evident at depths that predate the occurrence of this artificial radionuclide as well as in surface sediments, in spite of there being no recent records of addition (Table 2). Within the Alta low marsh core (Fig. 5a) there are additional peaks in ^{137}Cs activity, which is likely to be linked to reworking of older sediments and relocation in shallower horizons within the soil profile. There was a broad agreement between dating between ^{210}Pb and ^{137}Cs, although not within the Alta high marsh and Storslett low marsh cores (Table 2). There was also weak agreement between the ^{210}Pb and ^{137}Cs dates for the Storfjord low and high marsh and Storslett high marsh for 1963 (Table 2), most likely due to post depositional remobilisation of 137Cs.

Average carbon sequestration rates derived from ^{137}Cs were lowest at Alta, the site with highest fluvial inputs, in the low and high marsh over both recorded time periods, 1963 and 1986 (Table 3). The highest recorded rates of carbon sequestration were recorded for Storfjord low marsh at 1337 gC m^2 year^{-1} over the period 1963 to present and 1569 gC m^2 year^{-1} over the period 1986 to present.

The ^{210}Pb downcore profiles show evidence of exponential decay, to background, with initial concentrations of 100–350 Bq kg^{-1} (Fig. 6), with the exception of the Alta cores where initial concentrations were

Table 3
Average sequestration rates derived from ^{137}Cs dating. LM and HM denotes low and high marsh respectively.

Sites	Average sequestration rates (gC m^2 year^{-1})	
	1963	1986
Alta LM	17	13
Alta HM	46	22
Stabbursnes LM	450	593
Stabbursnes HM	326	340
Birtvarre LM	56	63
Birtvarre HM	973	1277
Storfjord LM	1337	1569
Storfjord HM	540	372
Storslett LM	374	389
Storslett HM	378	856

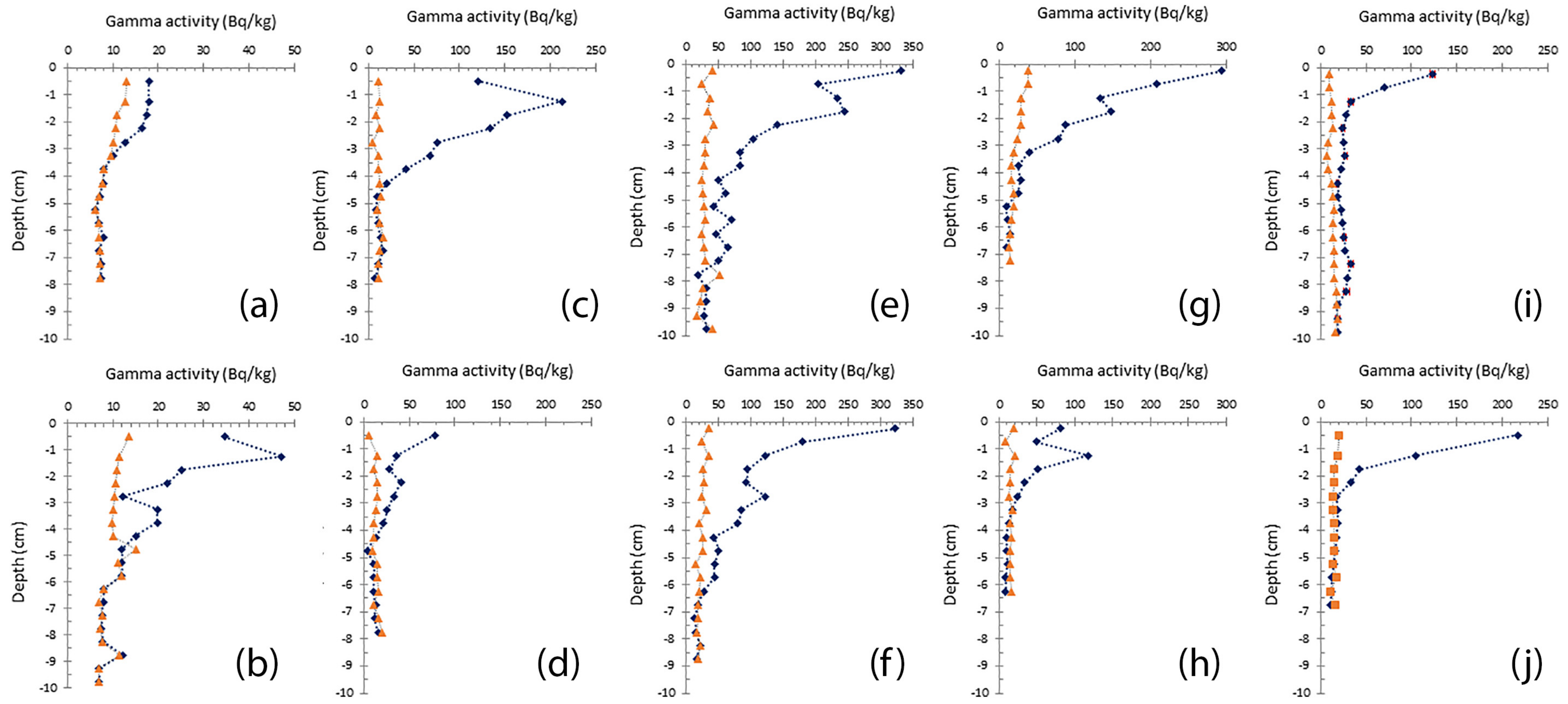

Fig. 6. ^{210}Pb activity profiles (circles) for all cores with ^{214}Pb activity shown (triangles) as a proxy for ^{226}Ra and ^{210}Pb$_{\text{supported}}$ (a: Alta low marsh; b: Alta high marsh; c: Stabbursnes low marsh; d: Stabbursnes high marsh; e: Birtvarre low marsh; f: Birtvarre high marsh; g: Storfjord low marsh; h: Storfjord high marsh; i: Storslett low marsh; and j: Storslett high marsh).

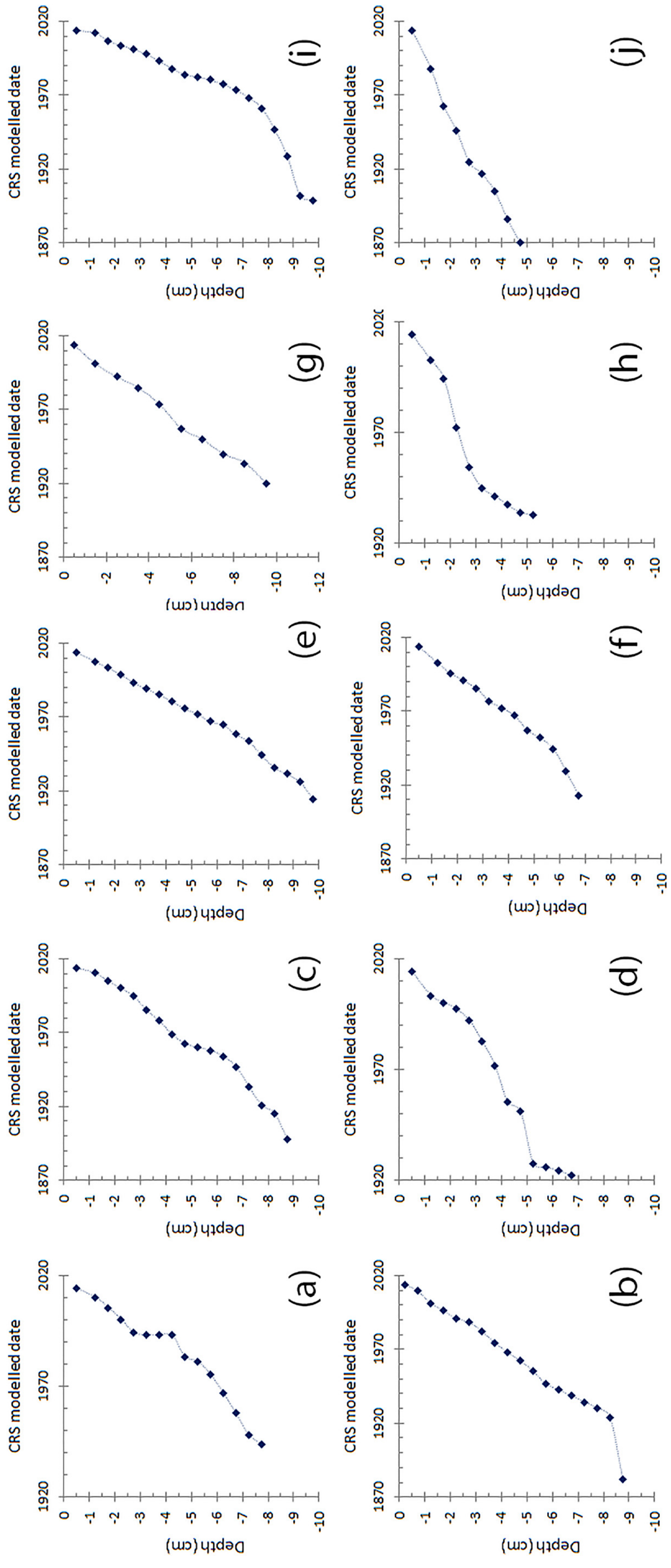

Fig. 7. ^{210}Pb$_{excess}$ CRS model age/depth profiles for all cores (a: Alta low marsh; b: Alta high marsh; c: Stabbursnes low marsh; d: Stabbursnes high marsh; e: Birtvarre low marsh; f: Birtvarre high marsh; g: Storfjord low marsh; h: Storfjord high marsh; i: Storslett low marsh; and j: Storslett high marsh).

substantially lower (18–48 Bq kg^{-1} Fig. 6a, b for low and high marsh respectively). Background concentrations of ^{210}Pb were 6–36 Bq kg^{-1}, and these were estimated using ^{214}Pb which is in secular equilibrium.

Soil horizons dated using the CRS method provided the oldest dateable sediments between 1870 and 1930, which is within the accepted limits of dating for this method (100–150 years) (Fig. 7). The maximum depth that was able to be dated was within the Storfjord low marsh core (10.75 cm) (Fig. 7g) representing a date of 1909 and the shallowest was in the Storslett high marsh core at 4.75 cm representing a date of 1870 (Fig. 7j). It should be noted that the ^{210}Pb and ^{137}Cs dating may be compromised in the Alta low marsh core as a result of erosion of surface sediments, considering the CRS model assumptions.

4.3. Carbon stocks and sequestration rates

Estimated average carbon sequestration rates were lowest from the low and high marsh plant communities at the Alta site (19 and 22 gC m^2 $year^{-1}$, Table 4). Low values were also recorded in the low marsh at the Birtvarre site. Trends in carbon sequestration rates between sites were similar to those recorded using the ^{137}Cs dating method. Values were also similar for all sites with the notable exception of the high marsh for Birtvarre and the low marsh for Storfjord, where values were substantially lower using the ^{210}Pb derived results (973–1277 gC m^2 $year^{-1}$ from ^{137}Cs compared with 603 gC m^2 $year^{-1}$ using ^{210}Pb results for Birtvarre high marsh, and 1337–1569 gC m^2 $year^{-1}$ from ^{137}Cs dating compared with 390 gC m^2 $year^{-1}$ using ^{210}Pb results for Storfjord low marsh).

The highest carbon sequestration rates were recorded for Storslett low marsh within the most recently formed soils (2117 gC m^2 $year^{-1}$, since 2010, Fig. 8i), and the lowest peak sequestration values were recorded in the low and high marsh at Alta (81 and 188 gC m^2 $year^{-1}$) recorded in the mid-1990s and since 2010 respectively (Fig. 8a, b). Peaks in carbon sequestration were noted in the most recently formed soils in the low marsh at Stabbursnes (Fig. 8c), the high marsh at Alta (Fig. 8b) and both the low and high marsh at Storslett (Fig. 8i, j).

In the walkover study, there was not found to be a substantial variation in the particle size nor organic matter throughout the sites. Carbon stocks were found to range between 3.67 and 13.79 MgC ha^{-1} derived from the cores collected. The upper marsh at Storslett had the highest values recorded, and the upper marsh at Alta had the lowest values (Table 5).

4.4. Comparison between environmental and meteorological variables and carbon sequestration rates over time

Results from the tests for correlation between GIA corrected sea level rise, length of the growing season, average annual precipitation, D50, and sorting coefficient showed that only length of the growing season was significantly correlated with carbon sequestration rates ($r = 0.815$, $p < .001$, Table 6), and the extension of the growing season results in increased carbon sequestration. Average annual precipitation was significantly correlated with D50 ($r = 0.651$, $p = .02$), although not with carbon sequestration rates (Table 6).

Table 4
Average sequestration rates derived from CRS ^{210}Pb dating. LM and HM denotes low and high marsh respectively.

Sites	Average sequestration rates (gC m^2 $year^{-1}$)		No. of years analysed (LM, HM)
	Low marsh	High marsh	
Alta	19	22	70, 133
Stabbursnes	260	321	100, 92
Birtvarre	49	603	100, 102
Storfjord	390	340	95, 77
Storslett	368	159	116, 144

5. Discussion

5.1. Radiometric dating

^{137}Cs was found at all sites and exhibited a typical profile for the region (Ward et al., 2014), with two primary peaks. The deeper peak related to the pre-1963 above ground nuclear weapons testing and a shallower peak related to the 1986 Chernobyl nuclear incident. There appears to have been some post depositional remobilisation of the ^{137}Cs due to its location at the surface, which post-dates recorded inputs, and deep in the sediment profile prior to the occurrence of this artificial radionuclide. ^{137}Cs activity within the soil profile is within the range of published values for the region of 4–80 Bq kg^{-1} (Callaway et al., 1997; Cundy and Croudace, 1996; Andersen et al., 2000; Povinec et al., 2003; Teasdale et al., 2011; Ward et al., 2014). There is also some evidence of broadening of the ^{137}Cs activity peaks in the sediment profile, particularly notable within the Storfjord low and high marsh cores (Fig. 5g, h). Previous studies have shown that in cores with high proportions of soil organic matter post depositional mobility of ^{137}Cs is enhanced (Ritchie and McHenry, 1990; Rosen et al., 2009; Ward et al., 2014), as is likely to be the case in these Arctic coastal wetland soils. Other studies have suggested that this is likely to be exacerbated in coarse grained soils where there are small fractions of fine sediments, particularly clay (Borretzen and Salbu, 2002; Teasdale et al., 2011). Borretzen and Salbu (2002) demonstrated that following deposition, there is rapid adsorption of ^{137}Cs to clay fractions. The low clay content of the soils in the studied Arctic coastal wetlands is likely, at least in part, to be the cause for the broadening of the ^{137}Cs peaks. There is also likely to be horizontal percolation of sea water through these coarse-grained soils during tidal or storm induced inundation, which increases pore water pressure and has been suggested as a mechanism for post depositional relocation of ^{137}Cs to surface sediments (Harvey et al., 1995; Thompson et al., 2001; Teasdale et al., 2011). However, similar results obtained using both the ^{210}Pb and ^{137}Cs dating methods suggest that these are reliable and provide a robust validation dataset (Ward et al., 2014).

All cores showed a near exponential decay of ^{210}Pb from the surface to background levels estimated using ^{214}Pb, indicating a constant supply of atmospherically derived ^{210}Pb, which is implicit in the assumptions for the CRS method (Appleby and Oldfield, 1992). The cores from both the Alta low and high marsh exhibit much lower ^{210}Pb activity than the other sites, 18 and 47 Bq kg^{-1}, which suggests that surface erosion is likely to have taken place, and there was visual evidence from the field that there had been erosion and recolonization of the plant community, particularly evident in the sparse vegetation of the low marsh compared to other sites. Similar ^{210}Pb profiles have been found in Loch Head salt marshes in Scotland (Teasdale et al., 2011) and Boreal Baltic coastal wetlands (Ward et al., 2014), in both cases attributed to removal of surface sediments curtailing the ^{210}Pb exponential decrease in activity profile.

5.2. Carbon sequestration rates and stocks in Arctic coastal wetlands

Mean carbon stocks across all 5 sites are 6.29 ± 3.35 MgC ha^{-1} taken from cores driven to refusal, which in this case was a thick (>1 m depth), minerogenic glacio-fluvial cobble/ boulder layer with very low organic matter content (<0.001%) rather than bedrock. This can be compared with global average values compiled by Duarte et al. (2013), of 162 MgC ha^{-1} for salt marshes, 255 MgC ha^{-1} for mangroves and 140 MgC ha^{-1} for seagrasses, which puts Arctic coastal wetlands at the very low end of the carbon stock values. This is most likely in part due to the very thin layer of organic marsh soil (from 9 cm in Birtvarre high marsh to 33 cm in Storslett high marsh), compared with coastal wetlands such as temperate and tropical salt marshes, mangroves and seagrasses, which typically have organic soils >1 m (Howard et al., 2014). Furthermore, the historical progradation of these marshes

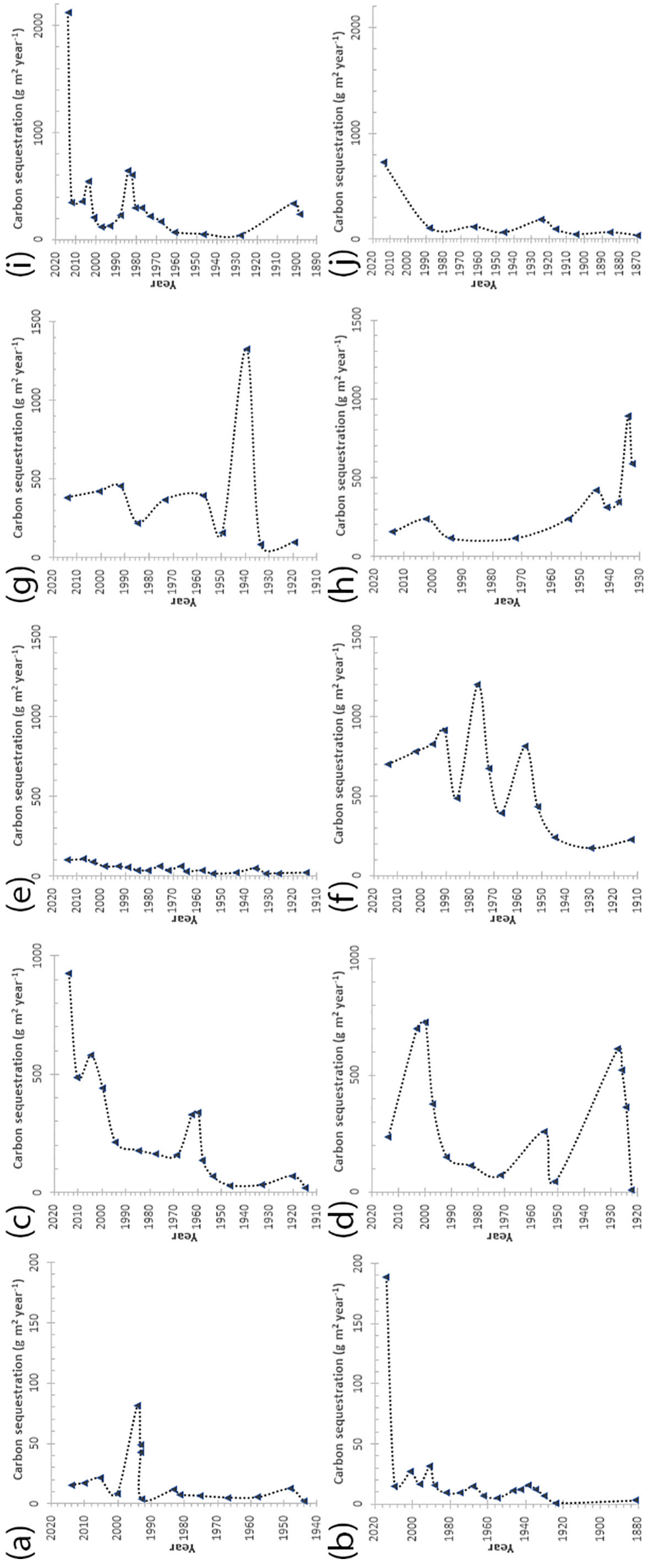

Fig. 8. Carbon sequestration rates over time estimated using the 210Pb CRS dating method for all cores at all sites (a: Alta low marsh; b: Alta high marsh; c: Stabbursnes low marsh; d: Stabbursnes high marsh; e: Birtvarre low marsh; f: Birtvarre high marsh; g: Storfjord low marsh; h: Storfjord high marsh; i: Storslett low marsh; and j: Storslett high marsh).

Table 5
Carbon stocks as calculated from the upper and low marsh for each site.

Site	MgC ha^{-1}	
	Low marsh	High marsh
Alta	3.74	3.67
Birtvarre	6.29	5.15
Storfjord	10.53	3.96
Storslett	6.31	13.79
Stabbursnes	5.68	3.82

(Martini et al., 2019) suggests that these are relatively young marshes, most likely formed in the last 200–300 years, based on the elevation, thickness of the marsh soils, and historical rates of accretion. Ward et al. (2014) found similar results from uplifting coastal wetlands in north Estonia, although unlike the Estonian example, the Arctic coastal wetlands in this study are unlikely to continue progradation due to high rates of sea level rise and low rates of sediment accretion, even accounting for GIA. There was some geomorphic evidence in Birtvarre, Storfjord and Storslett, of recent erosion of the fore marsh, this further suggests that progradation has at least partially ceased.

The highest carbon stocks were recorded for the Storfjord low (10.53 MgC ha^{-1}) and Storslett high marsh (13.79 MgC ha^{-1}) sites (Table 5), and the lowest carbon stocks were recorded for Alta low and high marsh (3.79 and 3.67 MgC ha^{-1}, Table 5). It is likely the low values for the Alta site are due to a substantial minerogenic input from fluvial sources due to its location at the mouth of the 3rd largest river in the region, the Altaelva river. It was also noted that there was a lower surface activity of ^{210}Pb in the low and high marsh at Alta than all other sites (Fig. 6), suggesting that there has been erosion of the surface sediments. Similar results, where erosion influences carbon stock values, have been found for other vegetated coastal environments including salt marshes in Scotland (Teasdale et al., 2011), Boreal Baltic coastal wetlands (Ward et al., 2014), and temperate seagrasses (Lima et al., 2020).

The high values for carbon stocks recorded for the Storfjord low marsh and the Storslett high marsh were a result of a combination of deeper organic soil profile and high carbon density. Both of these sites are likely to have the oldest wetlands, considering the rates of accretion and the depth of the organic soil horizon compared to the other sites (Figs. 4 and 8).

Average rates of carbon sequestration over the whole dated time period varied from 19 to 603 gC m^2 year^{-1}, comparable to global average rates of sequestration for salt marshes at 218 gC m^2 year^{-1} (Duarte et al., 2013). This further supports the suggestion that the reason Arctic coastal wetlands have low carbon stocks is due to their relatively young age as a result of GIA, through the continuous formation of new marsh from lower intertidal and sub tidal ecosystems, as has been found in other uplifting coastal wetlands (Teasdale et al., 2011; Ward et al., 2014).

The results of the analysis of environmental and meteorological factors influencing carbon sequestration, showed that the length of the growing season was found to have a significant influence, although there were no other significant correlations. Temperatures have been widely noted as rising higher, and more rapidly, in the Arctic than in any other global region (IPCC, 2013). These increases in temperature have been linked to extensions in the growing season, particularly in Eurasia (Park et al., 2016). It has been noted that in temperature limited systems, such as the Arctic, recent warming driven by climate change has resulted in greater plant productivity (Symon et al., 2005; Walker et al., 2012; Forkel et al., 2016; Ju and Masek, 2016; Park et al., 2016; Yu et al., 2017). This appears to be leading to increases in rates of carbon sequestration in Arctic coastal wetlands, although it is unclear if changes in carbon inputs are as a result of in-situ production or supplied by associated terrestrial or marine systems. In a study of in-situ carbon sequestration based on micrometeorological flux tower data, rates of removal of atmospheric CO$_2$ were high in a range of wetlands in the north American and European Arctic, with the highest rates being found in coastal wetlands (Coffer and Hestir, 2019). These researchers also found that the coastal wetland sites had increasing rates of in-situ carbon sequestration, whereas the inland wetland sites were exporting carbon. Similar results have been found for freshwater wetlands and heath in the Alaskan Arctic, where these ecosystems were also found to be recent exporters of carbon as a result of recent warming trends (Euskirchen et al., 2017).

Historical progradation of Arctic coastal wetlands has been suggested to be reversing as a result of decreases in rates of GIA, increases in sea level rise and low sediment accretion rates. This is likely to lead to an increase in the hydroperiod resulting in an increase in accommodation space, rather than the historical process whereby, new soils have been continually formed and older marsh soils eventually become terrestrial. In this scenario, this is likely to lead to an aging of marsh soils, and potentially as a result greater carbon stocks, particularly where there is greater organic matter input as a result of general warming trends as suggested by the results of this study.

6. Conclusions

The results of this study provide the first assessment of carbon stocks and sequestration rates for Arctic coastal wetlands and suggest that Norwegian Arctic coastal wetland ecosystems are responding to extensions in the growing season by increasing carbon stocks and rates of sequestration as a result of increased plant productivity; however, it is uncertain if this is in situ or from proximate terrestrial and/or marine systems.

Rates of carbon sequestration are similar to those reported for salt marshes from other global regions. While carbon stocks in the area appear to be increasing, they are still low compared with other climatic regions. This is mostly as a result of the young age of Arctic coastal wetlands due to historical GIA processes and resultant historical formation of new marsh from low intertidal sand/mudflats, and subsequent transformation of old marsh to other fully terrestrial plant communities. This historical progradation of Arctic coastal wetlands is likely to have been reversed, meaning that there is also likely to be a thickening of organic rich soils. Thus, it is clear that Arctic coastal wetlands provide an important ecosystem service through storing and sequestering carbon in their soils and that this ecosystem service is expected to be increased rather than diminished, unlike in other Arctic ecosystems.

Table 6
Matrix results from the Pearson's correlation tests comparing d50 (median sediment grain size), sorting coefficient, rates of sea level rise (GIA corrected), length of the growing season and mean annual precipitation. Results show Pearson's r, and p value ($n = 140$, $^* < 0.05$, $^{**} < 0.01$, and $^{***} < 0.001$).

Environmental variable	Sequestration rate	Sorting coefficient	d50	Growing season	Precipitation
Sequestration rate					
Sorting coefficient	0.092				
d50	−0.333	−0.076			
Growing season	0.815***	−0.050	−0.229		
Precipitation	0.455	−0.155	−0.651*	0.370	
Sea level rise	−0.344	−0.220	−0.320	0.053	0.083

CRediT authorship contribution statement

Raymond D. Ward: Funding acquisition, Investigation, Formal analysis, Writing - original draft.

Declaration of competing interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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