Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Social and Educational Sciences
Department of Geography

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Assessing the influence of relative sea level rise on carbon storage and sedimentation dynamics in an arctic salt marsh

Master's thesis in Geography
Supervisor: Chantel Nixon
Co-supervisor: Max Holthuis
May 2024

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Abstract

Based on future projections, the highest projected RSLR, which follows RCP8.5, might reach ~6 mm/yr by 2100 (Simpson et al., 2015). Norway are still experiencing uplift due to GIA, however in coastal areas the rate of uplift are lower since these areas had less ice covering the area, which again causes the RSLR to have a greater impact on these areas in Norway (*Framtidig havnivå langs Norskekysten*, 2024). This thesis aims to fill in gaps in knowledge on arctic salt marshes. The primary aim of the thesis is to look at what processes drives shifts in organic matter within arctic salt marsh sediments, and how these changes affect the resilience of salt marshes due to RSLR, and to determine how the RSLR will impact the carbon storage and sedimentation rates of a small arctic salt marsh near Kongsfjorden, Norway.

Cores collected from the Kongsfjorden salt marsh are analysed for δ13C, C/N, grain size, total organic carbon (TOC), and loss on ignition (LOI) to interpret sediment accumulation and organic matter deposition over time. The sediment cores illustrate changes, but it does not reflect the RSLR we are experiencing now. However, it does indicate that the salt marsh has been through a similar transition that we are experiencing now with RSLR in the past. With RSLR it is expected that we get an increase in the accumulation of organic matter. The sedimentation and CAR rates indicate a low rate of accumulation but does not take into account other factors that might influence the accumulation of organic matter. In the cores, we can clearly see high values of organic matter in the uppermost part of the cores, which indicate good conditions for organic matter accumulation, sequestration, and preservation. Alongside with the $\delta^{13}C$, C/N, TOC, LOI, and grain size the cores seems to have withstand changes in the environmental conditions, caused by either RSL, storm surges, changes in the tidal regime and sea-ice push, making them hold value as resilience to environmental changes. The current sedimentation rates observed are insufficient to keep pace with the current RSLR, however with RSLR we will also experience an increase in the sedimentation rate. The marsh shows dynamic responses to past sea level changes through increased sedimentation and organic matter accumulation, which are crucial for the stability of the marsh system. These findings highlight the importance of mitigating climate change and managing coastal ecosystems to protect these valuable habitats.

Sammendrag på norsk

Basert på fremtidige prognoser, kan den høyeste prosjekterte havnivåstigningen, som er RCP8.5, nå ~6 mm/år innen 2100 (Simpson et al., 2015). Norge opplever fortsatt landheving på grunn av glasial isostasi, men i kystområdene er landhevingen lavere siden disse områdene hadde mindre isdekke, noe som igjen gjør at havnivåstigningen har større innvirkning på disse områdene i Norge (*Framtidig havnivå langs Norskekysten*, 2024). Denne oppgaven har som mål å fylle kunnskapshull om arktiske saltmyrer. Det primære målet med oppgaven er å se på hvilke prosesser som driver endringer i organisk materiale i sedimentene i arktiske saltmyrer, og hvordan disse endringene påvirker saltmyrene sin motstandsdyktighet på grunn av havnivåstigningen, samtidig som å se på hvordan havnivåstigningen vil påvirke karbonlagringen og sedimentasjonsrater i en liten arktisk saltmyr nær Kongsfjorden, Norge.

Kjerner samlet fra Kongsfjorden saltmyr er analysert for δ13C, C/N, kornstørrelse, totalt organisk karbon (TOC), og glødetapsanalyse (LOI) for å se på sediment akkumuleringen og avsetningen av organisk materiale over tid. Sedimentkjernene illustrerer endringer, men de reflekterer ikke den havnivåstigningen vi opplever nå. Imidlertid indikerer de at saltmyren har gjennomgått en lignende forandring tidligere som den vi opplever med havnivåstigning nå. Med havnivåstigning forventes det en økning i akkumulering av organisk materiale. Sedimentasjons- og karbonakkumuleringsratene indikerer en lav akkumulerings rate, men tar ikke hensyn til andre faktorer som kan påvirke akkumuleringen av organisk materiale. I kjernene kan vi tydelig se høye verdier av organisk materiale i den øverste delen av kjernene, noe som indikerer gode forhold for akkumulering, sekvestrering og bevaring av organisk materiale. Sammen med δ13C, C/N, TOC, LOI, og kornstørrelse ser kjernene ut til å ha motstått endringer i miljø, forårsaket av enten havnivå, stormflo, endringer i tidevannsregimet og havis, noe som gjør dem verdifulle som motstandsdyktige kystøkosystem mot klimaendringer. De nåværende sedimentasjonsratene som er observert, er utilstrekkelige til å holde tritt med den nåværende havnivåstigningen, men med havnivåstigning vil vi også oppleve en økning i sedimentasjonsraten. Saltmyren viser dynamiske endringer på tidligere havnivåendringer gjennom økt sedimentasjon og akkumulering av organisk materiale, som er avgjørende for stabiliteten til saltmyr systemet. Disse funnene understreker viktigheten av å begrense klimaendringene og forvalte kystøkosystemer for å beskytte disse verdifulle habitatene.

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1 Introduction

Arctic coastal wetlands are of great importance when it comes to their potential to sequester and store carbon. The carbon that gets sequestered in vegetated coastal wetlands (e.g. salt marshes, mangroves) is termed "blue carbon". Atmospheric CO_2 gets taken up by coastal wetlands because they have the ability to vertically accrete sediments (a great proportion of which are organic) in step with relative sea level (RSL) rise. This natural process allows salt marshes to keep up with RSL rise (McTigue et al., 2019). Salt marshes also serve critical habitats for fish, birds and invertebrates, and function as protective barriers during storms.

By 2100, climate change will certainly have impacted coastal wetlands around the world, but there are many uncertainties as to how much of an impact it will have (Holden, 2017; Ward, 2020a). With global warming the RSL is expected to rise in most coastal regions on Earth; tide gauge data from the Norwegian coast tell us that the RSL is already rising in a few places, including parts of the south, west, and northern Norway, in spite of ongoing uplift of the landmass (i.e. glasioisostatic adjustment (GIA) related to the last ice age). RCP (Representative Concentration Pathways) are emission scenarios used to project greenhouse gas concentrations caused by climate change (Simpson et al., 2015). Which RCP the world will follow is unknown and dependent on human decisions; the complicated response of the cryosphere to CO_2 emissions is also difficult to predict, no matter which RCP is followed. With climate change increased storminess, changes in precipitation, and changes of land-fast sea ice can also be expected (Ward, 2020a), both which have important implications for Norway's salt marshes.

RSL rise and increased storminess on coastal salt marshes will lead to the landward migration of coastal wetlands. However, in areas where infrastructure (e.g. houses, roads) create a hard barrier, this will result in loss of important habitats and drowning of salt marshes, known as "coastal squeeze" (Hansen & Reiss, 2015). The ability of salt marshes to be able to keep up with the RSL rise is also dependent on sedimentation rates, carbon storage, and space to migrate inland (Yang et al., 2023). Anthropogenically 'protected' (hardened) coasts can also lead to sediment starvation, which will make it more difficult for salt marshes to accrete upwards and keep up with rising RSL.

The Norwegian coast experience different rates of vertical uplift related to last glacial maximum ice sheet loading and timing of deglaciation. Finnmark is among one of a few places in Norway expected to experience some of the biggest effects of RSL rise due to slow rates of vertical uplift (*Framtidig havnivå langs Norskekysten*, 2024). To get a better picture of the processes behind sediment accretion in a modern, arctic salt marsh in Finnmark and its history of carbon storage and accretion a small salt marsh was selected for study in Berlevåg municipality (Figure 1). Vertical land motion (uplift) in the region of the study site are currently 2.3 mm/year (Kartverket, 2024), having slowed since the last deglaciation that occurred around 15 ka BP (Simpson et al., 2015), and as more meltwater is added to the world's oceans due to melting of ice sheets and glaciers on Greenland and Antarctica, RSL rise will accelerate, impacting local coastal ecosystems here, including salt marshes (Romundset et al., 2017; Ward, 2020b). With ongoing global warming the winter sea ice in Finnmark may become thinner and the periods during which fjords and lakes are frozen will be shorter than today; a phenomenon already observed in other parts of the Arctic (Hanssen-Bauer et al., 2017). Less sea ice will influence sediment supply and erosion in the coastal zone, meaning less attenuation of wave energy.

Little research has been conducted on arctic salt marshes to date (Ward, 2020a; Woodroffe & Long, 2009), but temperate salt marshes are well studied (Ruiz-Fernández et al., 2018) and known to be extremely important ecosystems when it comes to carbon storage, floodwater attenuation, coastal protection, and fish nurseries. The physical and biological characteristics of sediments, especially and microfossils, from temperate salt marshes have been used to reconstruct past RSL change in many parts of the worlds where there is a temperate climate (i.e. not arctic and not tropical). While a few Holocene RSL curves have been reconstructed for various locations in Finnmark (e.g. Romundset et al., 2011), they are based on isolation basin data and geomorphology of raised beach ridges, however, an RSL curve has not been reconstructed in the Berlevåg municipality yet. Filling in gaps in knowledge of past RSL change and its impact on coastal environments, including the arctic salt marsh at Berlevåg, is essential, as salt marshes are important when it comes to mitigating climate change and preserving biodiversity.

1.1 Thesis aim, focus and research question

This thesis seeks to improve projections of the resilience of coastal wetlands to expected RSL rise in northern Norway, and to increase knowledge of arctic salt marshes in general. The focus of this thesis is therefore to document carbon storage and past sedimentation rates in a salt marsh near Kongsfjorden, Berlevåg municipality, where RSL has recently switched from falling to rising.

The specific research questions this thesis seeks to address are therefore as follows:

1. What processes drive shifts in organic matter sources and environmental conditions within arctic salt marsh sediments, and how do these changes affect the resilience and adaptive capacity of salt marsh ecosystems to future sea-level rise (SLR) scenarios?
2. How will RSLR impact carbon storage and the sedimentation rates for a small arctic salt marsh near Kongsfjorden, Norway?

To answer these research questions, four cores were extracted from a salt marsh near Kongsfjorden (Figure 1). This work is part of a Norwegian Research Council Fripro project called QUANTSEA (Quantifying past and future sea-level rise in Norway), which aims to reconstruct periods of RSL rise in the past, understand the physical processes that caused RSL rise and contribute to improved data and models predicting future RSL rise (*Quantifying Past and Future Sea Level Changes in Norway - Prosjektbanken*, n.d.).

Total Organic Carbon (TOC), $\delta^{13}C$, C/N, loss on ignition (LOI) and grain size analysis will be analysed for the cores, which will provide information about organic carbon and minerogenic sediments are currently stored in the salt marsh at Kongsfjorden today. Radiocarbon dates from the base of two cores will also be used to calculate sedimentation and carbon capture rates over the past couple of hundred years (based on basal ages of the cores) The radiocarbon dating is not part of this thesis, but has been obtained by master's student Simon Solheim Holme (Department of Geography, NTNU), who is developing age models for the same cores from Kongsfjorden. Relative sea-level projections for the year 2100 from Kartverket (2024) will also be used to determine how the salt marsh at Kongsfjorden might expand as well as the potential for future carbon storage.

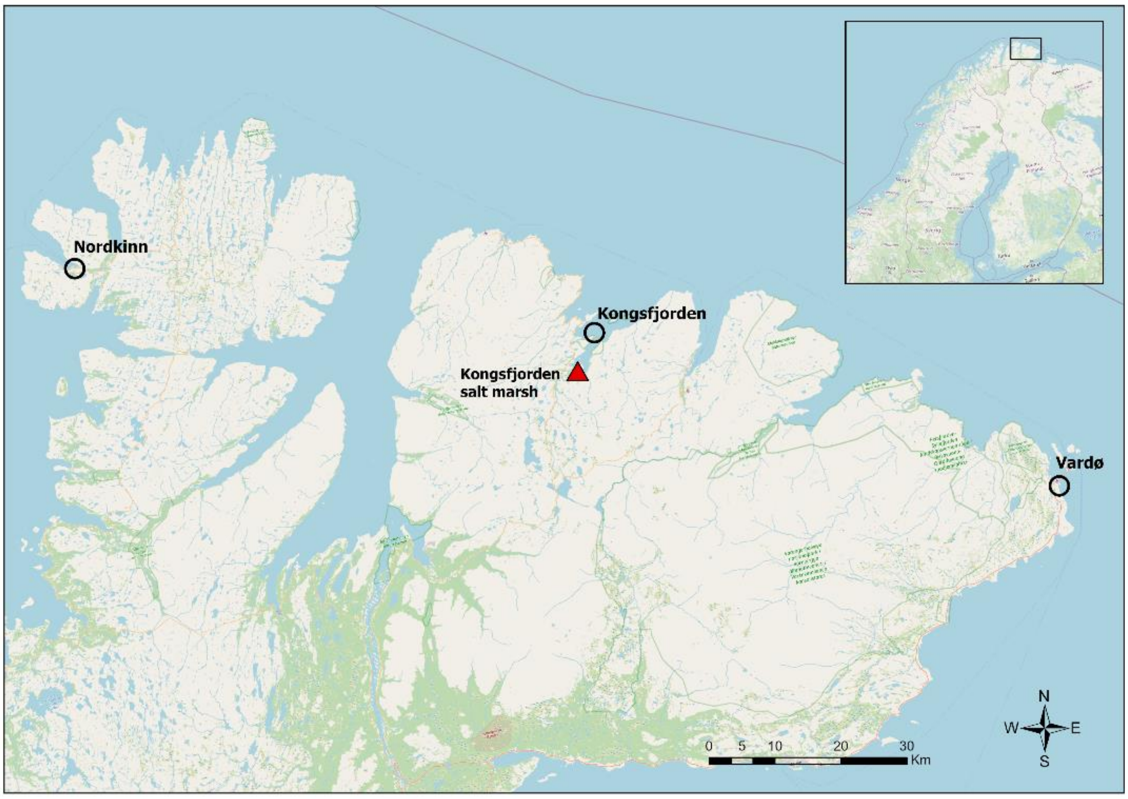


Figure 1: Overview photo of the study area, Kongsfjorden in Berlevåg municipality, northeastern Norway. Nordkinn, where the closest Holocene RSL curve has been reconstructed and the nearest tide gauge in Vardø are also shown on the map.

1.1 Thesis structure

This thesis has 6 chapters. Chapter 1 presents the background and introduction to the study area. Chapter 2 introduces the main theoretical concepts applied in this thesis. Chapter 3 describes the methodology, including all field and lab methods applied. In chapter 4 the results of the different analyses are presented, and chapter 5 is a discussion of the results. In chapter 6 the main conclusions of the thesis are presented as well as recommendations for future work.

2 Theory and background

2.1 Sea level

Mean sea level (MSL) represents the average of sea level measurements from a tide gauge, for example, for a given place over a fixed time period.

Global mean sea level (GMSL) refers to mean sea level averaged over time and over all the world's oceans. In contrast, changes in local sea level are the net result of changes in both local sea-surface height (corresponding to the volume of water in the ocean at that time, gravity etc.) and local land-level changes related to tectonics and glacioisostatic adjustment (GIA; discussed later in this section). There are several drivers of GMSL change, including, changes in ocean mass and density and changes in atmospheric pressure, winds, currents, and gravity. These different drivers have more or less importance depending on where you are in the world, resulting in regional differences (Simpson et al., 2015). Information on the different drivers of sea-level change and reconstructions of past sea level and climate provide useful information about the possible extent of future changes (Benn & David, 2010; Holden, 2017). During the last deglaciation, an enormous amount of meltwater was added to the world's oceans causing GMSL to rise 125-130 m (*Ice Sheets and Sea Level in Earth's Past | Learn Science at Scitable*, n.d.). According to recent projections, GMSL is expected to rise from 26-45 to 55-82 cm by 2100, depending on the different RCP scenarios, (Holden, 2017), which will place the world's salt marshes and low-lying coasts under enormous pressure.

2.1.1 Relative Sea level

Relative sea level (RSL) describes the direction and magnitude of sea level change relative to the land surface (Benn & David, 2010; Simpson et al., 2015). Relative sea level rise (RSLR) can result in a transgression (the inland displacement of the shoreline), while RSL fall can result in a regression (the seaward displacement of the shoreline), depending on other factors, such as sediment supply. During periods of RSL change marine, estuarine, freshwater and terrestrial sediments sequences can be deposited and preserved in on- and offshore basins, including salt marshes, and from the order of their sequence, a detailed history of past changes in RSL can be constructed (Benn & David, 2010; J.J. Lowe & M.J.C. Walker, 2014). For example, a sediment core showing marine sediments at its base, overlain by brackish, then sediments deposited in a freshwater/terrestrial environment, indicates a period of falling RSL. Different dating methods, for example, radiocarbon dating, can then be used to determine the age of the sediments and construct a timeline for past changes in RSL (Holden, 2017).

2.1.2 Tides

Tides cause a rise and fall in coastal water levels twice in a day. The difference between mean low tide (MLT) and mean high tide (MHT) in reference to the water level is known as the tidal range. This tidal range varies around the world, and we divide the tidal ranges to distinguish between micro- (<2 m), meso- (2-4 m) and macro-tidal (> 4 m) ranges. For the study area presented in this thesis the tidal range agrees with the mesotidal range (Holden, 2017). The tidal range also varies in time due to the interaction between the tidal forces of the sun and moon. Tidal currents are associated with the rise and fall in tides, and the bathymetry of the basin, and the strength of these tidal currents increases with the tidal range. Tides play an important role in the sedimentation and accumulation of organic material in salt marshes. The high tides bring in water rich in sediments, leading to faster sedimentation rates. Tidal flooding also introduces organic material from the ocean and the tide helps distribute and preserve this material on the marsh surface (Holden, 2017). Additionally dead organic matter, such as macroalgae and seagrass wash up during MHT and are commonly known as wrack. The accumulation of this also contributes to organic content of the sediments being deposited in salt marshes (Poore & Gallagher, 2013).

2.1.3 Vertical land motion

When we discuss sea level changes along the coastline, we must take into account VLM. There are several natural and anthropogenic processes which can cause vertical movements in coastal areas. For example, erosion, tectonic processes, mass loading and unloading effects, sediment deposition, and changes in the water density. In Norway GIA is thought to be the dominating driver to VLM (Benn & David, 2010; Simpson et al., 2015; Wöppelmann & Marcos, 2016). Glacioisostatic adjustment is the vertical motion of the Earth's crust and upper mantle (lithosphere) related to loading and unloading during glacial-interglacial cycles. For example, during glaciation, large ice sheets depressed the lithosphere vertically downwards (loading); during deglaciation (unloading), the lithosphere rebounded and caused a vertically upward motion. VLM in Norway is the uplift of the lithosphere after the Fennoscandian Ice sheet melted away, beginning in most coastal areas around 15,000 years before present (yBP). Land masses that were glaciated by large ice sheets during the last glacial maximum (LGM) (e.g. Canada, Scandinavia) are in many places, still adjusting to the last deglaciation. Through time, erosion and deposition caused by these large ice sheets has resulted in local sea level changes (Benn & David, 2010; Simpson et al., 2015). As the ice retreated, soil started to form, and peat accumulated in terrestrial and coastal wetlands, and this process contributed to the formation of ecosystems that continue as long-term carbon storage today (Holden, 2017).

2.1.4 Expected RSL change in Finnmark

Climate change is one of the most important drivers affecting the RSL in the future. With increasing temperatures, the oceans have become warmer (and will continue to do so), and ice on land will melt, both of which will contribute to the volumetric expansion of the ocean, or eustatic sea level rise. In addition, small and local changes such as ocean current changes, changes in air pressure, wind, ground water and the water level in lakes will contribute to RSLR. With different rates of ongoing uplift (positive VLM) RSLR across Norway's shorelines will vary, depending on the balance of eustatic changes and local rates of VLM (*Framtidig havnivå langs Norskekysten*, 2024).

Based on models and predictions about the future sea level, it is most likely that most of Norway will experience RSLR by the end of this century. However, there will be regional differences, because of the variations in VLM all over Norway. RSLR will have the greatest impact along the coast of Norway because this is where the ice was thinner during the LGM, and this includes Finnmark (Figure 2).

The projections produced by Karteverkt (the Mapping Authority of Norway; (*Søkeresultat*, 2024)) are based on different emissions scenarios by 2100: RCP2.6 (low emission), RCP4.5 (reduced emission) and RCP8.5 (high emission). Projections for future RSL consider different regional factors including ocean density, the distribution of water mass and changes in circulation, total mass changes in the ocean and related changes in the gravity field caused by the melting or formation of land ice, and uplift with related changes in the gravity field (*Framtidig havnivå langs Norskekysten*, 2024; Simpson et al., 2015).

For Berlevåg municipality the RSL projections for 2100 are between -8 to 49 cm for RCP2.6, between -2 to 59 cm for RCP4.5 and between 11-86 cm for RCP8.5, and the mean value is 21 cm for RCP2.6, 29 cm for RCP4.5, and 48 cm for RCP8.5 (Kartverket, 2024).

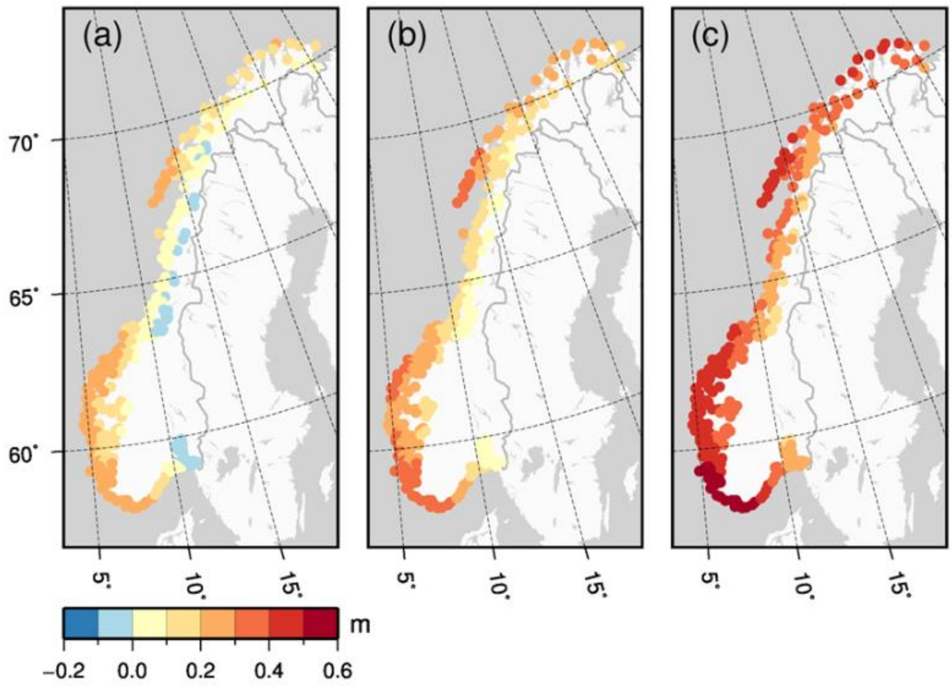


*Figure 2: RSL change along the coast of Norway for the period 2081-2100 for the three emission scenarios a) RCP2.6 b) RCP4.5 and c) RCP8.5 (*Framtidig havnivå langs Norskekysten*, 2024).*

2.1.5 Storm surges

Climate change has already made its impact in the Arctic with reduction of sea-ice in coastal environments, melting of coastal and offshore permafrost, rising RSL, and will certainly affect other processes relating to coastal dynamics (Ward, 2020a). With less sea ice there is more open water, and more frequent storms may expose salt marshes to erosion and flooding, however, vegetation can attenuate waves and currents, thereby mitigating erosion (Martini et al., 2019). Storms can also be an important source of sediment for marsh aggradation as sediment supply often increases during storms (Leonardi et al., 2018).

Seasonal, shore-fast sea ice can move sediments both on and offshore and serve to protect or erode shorelines (Walker, 2005), however, if there is too much sea-ice push during spring break-up for example, it is unlikely that a salt marsh would be able to establish itself in such an environment. Nonetheless, if sea ice conditions change with future climate change, this may negatively impact previously established salt marshes.

Storm surge events occur when low air pressure causes the sea surface to rise; strong winds can also push water up against the coast if blowing onshore; possibly to levels significantly higher than at the highest astronomical tide (HAT). A number of studies state that with climate change, increased storminess will be a influencing factor on coastal wetlands (Leonardi et al., 2018; Ward, 2020a). The intensity of a storm on a particular coast is dependent on three factors. The first factor is air pressure. With storm surge events, low pressure will follow and hence raise the water level. A second factor is the onshore wind. If the wind is directed towards the shore, it would contribute to the increase in water level. The last factor is the topography of the coast. The impact that storm surges bring is dependent on the characteristic of the coast. For the area which this thesis investigates the topography is characterized by a low-gradient, soft-sediment setting, and therefore more vulnerable to flooding and erosion during storm surges (Holden, 2017; Simpson et al., 2015).

2.2 Salt marshes

Salt marshes are complex systems and are part of coastal wetlands that form during intertidal inundations. Salt marshes are common all along the coast of northern-Norway, and form in low-energy estuarine settings where the accumulation of sediments is high (Alm, 1993; Kelletat & Scheffers, 2005; Miller et al., 2022). During MHT, sediments are transported by currents over the tidal mudflat and deposited in the upper intertidal zone as the tide retreats. Since salt marshes forms along the coast on tidal flats where they are protected from the sea, they often border terrestrial, freshwater, and marine environments. The frequency of marsh flooding depends on the elevation of the mudflat and the height of the incoming tide (the tidal range). With the input of sediments, the mudflat will accrete upwards which will cause the frequency of flooding to decrease. Salt-tolerant plant species will colonise the tidal-flat if wave energy is low enough (Borgersen et al., 2020; Holden, 2017; Kelletat & Scheffers, 2005) and these species will, once established, attenuate wave energy and trap more sediment (Leonardi et al., 2018).

There are two different type of salt marsh ontogenies within coastal ecosystems. Both of which increase the salt marsh area. Regressive salt marshes migrate into the basin (seaward), often as a response to RSL fall or to an increase in sediment supply or a combination of both. Salt marsh regression is controlled by the bathymetry of the shore and nearshore, sediment supply, and by RSL change. Transgressive salt marshes migrate landwards with RSLR. Salt marsh transgression is controlled by the rate of RSLR and the accretion or sedimentation rate. Transgressions cause increasing salinity of the soil and groundwater, which leads to the degradation of forests and the intrusion of salt marshes. The landward migration of salt marshes during a transgression may also be aided by storms that bring in saltwater during flooding contributing to tree mortality and organic matter degradation (Holden, 2017; Miller et al., 2022).

For the case of Arctic salt marshes, sea ice is an additional factor that can both protect and erode salt marshes. When the ice covers the fjord during the winter months, sediments, rocks, and vegetation get frozen in the ice. Depending on the tidal range, wind strength, and direction, erosion and on/offshore transport may occur during sea ice break-up in spring (Coulombier et al., 2012).

Finally, salt marshes are important ecosystems when it comes to the mitigation of climate change. This is because salt marshes have a great capacity for accumulation and storage of large amounts of organic blue carbon over timescales of centuries to millennia compared to other coastal ecosystems. Salt marshes also have a great capacity for absorption of water and can therefore, reduce and slow down the effects of coastal flooding (Borgersen et al., 2020; Miller et al., 2022; Yang et al., 2023).

2.2.1 Accretion processes

Sedimentation and therefore accretion of the salt marsh surface takes place when the wave energy or tidal currents are high enough to “stir up” the mud that sits on the outer mudflats and transport it inland, where it gets trapped by salt marsh vegetation and deposited onto the marsh surface (Boorman et al., 1998). Arctic salt marshes typically have processes that can generate and transport a large amount of coarse sediment sizes and other debris, for example sea ice, which differentiates them from temperate salt marshes (Martini et al., 2019). In the lower areas of the salt marsh, there are greater inputs of minerogenic material than at higher elevations, for example, during storm surges, spring tides and sea-ice push. At higher elevations minerogenic inputs are fewer due to less frequent flooding and organic matter making up a greater proportion of the soil accumulating there (Plater et al., 2015; Smith, 2003). During storms, lateral erosion of salt marshes may also occur (i.e. erosion in some areas and accumulation in others) (Schuerch et al., 2013).

Rates of sediment accretion in salt marshes are susceptible to climate change and changes in RSL. With climate change, changes in the frequency of rainfall and vegetation will have a huge impact on the sediment supply. The rate of sediment accretion can be measured and is calculated by dividing the thickness of the sedimentary sequence being studied by its age (the latter of which is determined by dating the sediments that underly the salt marsh being studied). Accumulation rates vary depending on the specific location. In the North Sea and nearby areas (Europe) the accretion rate range from approximately -2.99 mm/yr to 12 mm/yr (Crosby et al., 2016).

The understanding of the processes that drives the elevation of coastal wetlands, such as sediment accretion, will let us predict their productivity and stability, which is important when it comes to understanding how future RSLR will impact these coastal ecosystems (Morris et al., 2002). With the RSLR in the future as a consequence of ongoing climate change, the sediment accretion rate in coastal salt marshes needs to be significantly higher than RSLR for the marsh to be able to survive (Leonardi et al., 2018).

2.2.1.1 Organic carbon

Salt marshes are ecosystems that can help attenuate global warming (Borgersen et al., 2020). This is because salt marshes have a great capacity for accumulating and storing large amounts of organic carbon referred as "blue carbon" over timescales of centuries to millennia compared to other coastal ecosystems. They therefore play an important role in the global carbon bonding, which otherwise would be left as atmospheric carbon, worsening global warming (McLeod et al., 2011). The carbon that is stored in salt marshes is a result of conditions which allow for fast accumulation and preservation of organic carbon in sediments (Miller et al., 2022).

The carbon accumulation rates in salt marshes are affected by several factors including salinity, sediment supply, and variability in the hydroperiod (McLeod et al., 2011). Carbon sequestration in Norway has been estimated based on carbon burial rates from other countries that are thought to have the same nature type as Norway. As such, for salt marshes in Norway the carbon burial rate has been estimated to be 100 g C m^{-2} yr^{-1} (Figure 3) based on estimates from Great Britain (Kyrkjeeide et al., 2020).

	Relative estimates			Totals for Norway			
	Standing stock / g C m^{-2}		Burial / g C m^{-2} yr^{-1}	Area / km^2	Standing stock / Gg C		Burial / Gg C yr^{-1}
Ecosystem	Biomass	Sediment			Biomass	Sediment	
Kelp forests[a]	450	0	30	8000	3600	0	240
Intertidal algae[a]	225	0	20	180	40	0	4
Seagrass meadows[b]	80	4900	20	93	7	460	2
Saltmarshes[c]	500	20,000	100	100	50	2000	10
Intertidal mudflats[d]	20	2000	16	1000	20	2000	16
Freshwater lakes[e]	3	50,000	5	18,000	50	900,000	90

[a] **All figures from Gundersen et al. (2011)**

[b] **Stock from Röhr et al. (2018) for Skagerrak; burial from Röhr et al. (2016) for Limfjorden; area from Gundersen et al. (2018a)**

[c] **Sediment and burial from Chmura et al. (2003) for Great Britain**

[d] **Burial from Alonso et al. (2012)**

[e] **Biomass from Cyr and Peters (1996); sediment stock is a rough extrapolation based on sedimentation since the last glaciation, compatible with estimates from North America (Alin & Johnson 2007, Munroe & Brencher 2019); burial from Algesten et al. (2003) for Sweden; area from Norwegian Water Resources and Energy Directorate (2018) for all Norwegian lakes $\geq$ 0.0025 km^2**

Figure 3: Estimates of carbon sequestration in Norway based on carbon burial rates from Great Britain (Kyrkjeeide et al., 2020).

The main source of organic matter in salt marshes is the death of *in situ* salt marsh vegetation, which increase in density landwards (Coulombier et al., 2012), but marine organic matter is also delivered to the marsh surface during the high tide. The sequestration of carbon in wetlands is dependent on the carbon input and output in the ecosystem. During tidal flooding, sediments are trapped on the marsh surface by the vegetation, and at the same time there is a steady intake of organic material (root fragments, seeds, leaves, and branches) which also contribute to sedimentation (Holden, 2017). During high tide, the carbon storage will therefore be high, while when the tide is low, the carbon storage will be low due to less organic material being deposited (Kyrkjeeide et al., 2020).

Sediment deposition and decomposition affect the rate of accumulation and preservation of organic carbon in salt marshes (Khan et al., 2015; Kyrkjeeide et al., 2020). There are two main processes when it comes to the accumulation and preservation of organic carbon, which are surface processes and post-depositional processes (Figure 4). The surface processes include tidal movement and the relocation of the plant material, physical breakdowns, decomposers, and microbial degradation. Post-depositional processes include bioturbation, diagenesis, microbial degradation, and degradation of decomposers. The major sources of organic matter come from autochthonous vascular plant material (litter and root ingrowth) which are produced within the ecosystem, and allochthonous organic matter brought in from outside of the ecosystem by tidal fluctuations (Khan et al., 2015).

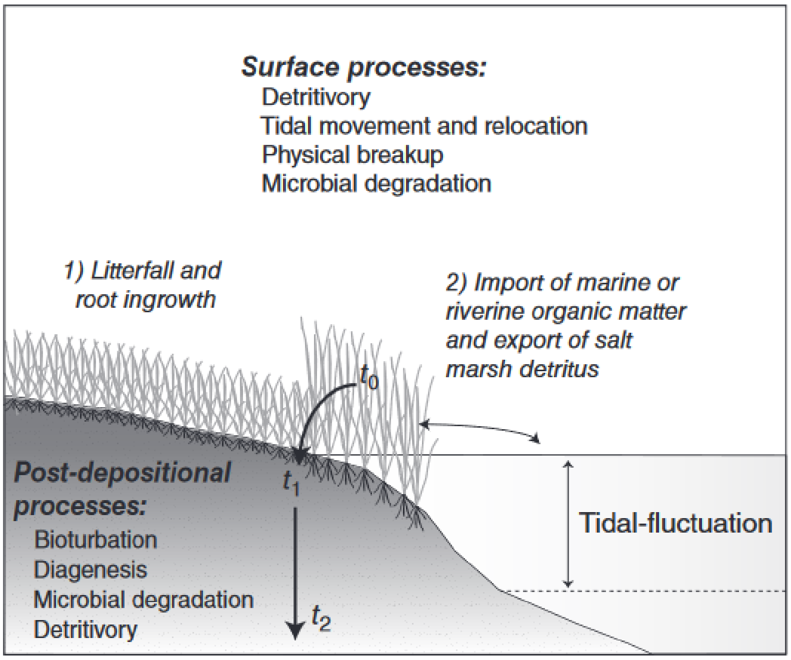


Figure 4: Sources of organic matter and processes affecting the accumulation and preservation of organic matter in salt marshes (Khan et al., 2015).

2.2.2 Zonation

Salt marshes have very distinct zones of vegetation, with the most salt-tolerant species occupying the lower elevations inside the tidal frame, and the least salt-tolerant species living close to HAT.

Different types of vegetation have different elevation ranges where they thrive based on their ecological niche, and this has a connection with the geomorphology and tidal range of the marsh (Yang et al., 2023). Salt marsh environments have been divided into three zones based on these different vegetation elevation ranges. The *subtidal zone* is submerged all the time, the *intertidal zone* is subaerial during low tide and fully submerged during high tide. The *supratidal zone* occurs above the highest regular tidal inundation (Vis et al., 2015), becoming flooded during HAT and storms, for example, and is therefore considered a terrestrial environment. These salt marsh vegetation zones also respond to changes in RSL. With RSLR, not only will the salt marsh aggrade vertically upward and inland, but the pattern of vegetation zonation will also migrate upland (Morris et al., 2002).

Transportation of the sediments are dependent on the velocity of the incoming water. Where we have low velocity, the size of the sediments will be finer, while larger sediment sizes indicate higher water velocities since larger sediment sizes require more power to be transported and smaller sediments require less. Dead and decaying vegetation is another important component of salt marsh sediments (Boorman et al., 1998), which can be used to characterize the different zones of the salt marsh being studied. Lower elevation environments in salt marshes tend to have more coarse-grained sediments, which should be moderately to well sorted. The higher elevation zones of salt marshes on the other hand, tend to consist of more fine grained sediments that are poorly to very poorly sorted. In addition to normal tidal movements, storm surges and spring tides will cause the particle size distribution to vary across the salt marsh surface in relation to how long and how often flooding occurs. (Borgersen et al., 2020; Rahman & Plater, 2014).

2.2.3 Vegetation in salt marshes

Salt marshes are usually flat, vegetated habitats, forming extensive grass "lawns." The species composition of the vegetation that forms salt marshes varies based on different environmental factors including: the duration of immersion, frequency of immersion, water saturation and salinity. Between the lower and upper parts of the salt marsh a shift in vegetation can occur, meaning that there are species that can tolerate both low marsh and high marsh environments. One important species in this transition zone between low and high marsh is the *Juncus Geradii* (Borgersen et al., 2020). Species that are both common and extensive in salt marshes in Norway are *Ligusticum scothicum*, *Juncus Geradii*, and *Carex salina* (probably a hybrid of the two species*)*, all of which can tolerate regular tidal flooding (Alm, 1993; *Artsdatabanken*, n.d.).

In Finnmark, the low salt marsh environment consists of lawns of *Puccinellia phryganodes*. *Carex* is a common genus of sedge with many species documented in arctic salt marshes of northern Norway, including *C subspathacea*, *C glareosa* and *C salina.* In freshwater sites in Finnmark, *Eleocharis uniglumis* may form wet meadows (Adam, 2002; Alm, 1993). *Triglochin maritima* is also a species which has been documented in the high marsh zones of Finnmark salt marshes (Dítě et al., 2019).

2.2.4 Distribution of salt marshes in Norway

Salt marshes are common along the entire coast of Norway where regular tidal flooding occurs, and wave energy is low. Salt marshes are predominately found at the heads of fjords and in sheltered bays and are non-existent in steep-walled fjords and the outer, high-energy strandflat coasts due to the lack in calm conditions needed for their formation (Adam, 2002; Ward, 2020a)

The extent and distribution of salt marshes in Norway has not been well documented, in part due to the fact that there is not a well-defined word in Norwegian for the term 'salt marsh'. However, if we include other nature types (e.g. seagrass meadows) as salt marsh areas, there are a total of 754 mapped nature types which probably belong under the definition salt marsh (Borgersen et al., 2020; Kyrkjeeide et al., 2020; NBFN, 2023). Regions like Jæren, Lista, parts of Finnmark, and some areas of Lofoten have protected and calm environments needed for salt marsh development (Borgersen et al., 2020; Ward, 2020b).

2.2.5 Climate change and other anthropogenic impacts to salt marshes

2.2.5.1 RSL

Higher temperatures can lead to carbon sinks becoming carbon sources, and on the other hand higher temperatures together with stable water levels could also increase the growth of moss and hence increase the sequestration of carbon (Kyrkjeeide et al., 2020).

Changes that come with climate change and RSLR will likely affect individual species. Coastal species that rely on salt marshes can experience changes such as shrinking of habitat or altering of environmental conditions. Species are adapted to specific zones within the salt marsh and with RSLR the marsh system could encounter changes which will cause the marsh to move landward, making the species forced to migrate to higher elevations (Schuerch et al., 2018).

RSLR also contributes to an increase in coastal erosion. As the sea level rises, there will be an increase in the frequency and intensity of tidal fluctuations, leading to an increase in erosion along the edges of the marsh (Kirwan & Megonigal, 2013).

2.2.5.2 Tidal fluctuations/Storms

With climate change an increase in the intensity and frequency of flooding caused by both the tidal fluctuations and storms will affect salt marshes (Schuerch et al., 2013). During severe storms, the water level will likely rise beyond what is expected in terms of tide. The impact of storm surge events is dependent on the topography of the coast. Low-gradient, funnel-shaped coastal morphology are more susceptible to extreme surges than straight coastlines (Holden, 2017). The vegetation of the salt marsh system also plays a role when it comes to the velocity of the wave. Vegetation characteristics like density, stiffness and coverage plays a major role when it comes to the hydrodynamic conditions such as the depth of the water, the height of the wave and the wave duration (Leonardi et al., 2018). During storms we also get an increase in the transport of sediments to the salt marsh which can cause the elevation of the marsh to grow and hence enhance its productivity (Hansen & Reiss, 2015).

Salt marshes are protected by the vegetation cover which protects the underlying sediments. If the vegetation gets exposed to forces causing it to weaken this would lead to local erosion which then can expand to bigger areas. In arctic areas, winter ice is one physical factor which can cause damage to the salt marsh vegetation by the deposition of big blocks on the mudflat. Deposition of dead organic matter (wrack) brought in during storms or tides can also cause the vegetation to weaken or die off. Grazing by geese and other animals may cause loss in vegetation, which could take several years to regrow, making the salt marsh vulnerable to erosion during this period. Erosion may also take place at the seaward margin by the action of waves. Erosion may not contribute to large changes within salt marshes, but once the area is affected further erosion may occur having the potential to reach a larger area (Adam, 2002).

Storm surges can affect the vertical and horizontal dynamics of a salt marsh system right after a storm period, but it can also affect the system with long term causes affecting erosion, deposition and sediment input and output. Storm surge events are proven to not having the most catastrophically impact on salt marshes. The reason for this is because the root system of the salt marsh vegetation goes deeper than in other coastal wetlands. The impact of storm surges varies on the magnitude of the storm and the properties of the salt marsh. The different impacts that storm surges bring are presented down below (Figure 5). **Deformation** is a subsurface process that is a consequence of storm surge events, which can lead to changes in the elevation of the salt marsh or deformation changes induced by groundwater flow and soil compaction. These events could also cause water flux shrinkage or swell (Leonardi et al., 2018). When the vegetation cover gets deteriorated by currents and waves, this can lead to an enhance in the lateral **erosion** of the marsh banks. Because of this shear stress, tidal flats can deepen which again will increase the wave energy and promote lateral erosion. This lateral erosion is wave-induced and is one of the main reasons for deterioration (Leonardi et al., 2018). Salt marshes are protected from erosion due to the plant cover above the sediments, but where we have intertidal basins, this could contribute to the expansion of these. Winter ice can also contribute to erosion of the salt marsh in Arctic regions. Sea ice brings big rocks and pebbles through sedimentation, affecting the salt marshes by depositing these blocks on top of the marsh or the vegetation, which then possibly will cause the formation of a new marsh. During equinoctial tides debris of tree gets carried during storm events and gets deposited on the marsh (Adam, 2002). When storms occur, **deposition** of a large amount of sediment may occur as a secondary effect/factor as well as other deposits that get washed up and forms wrack zones. Deposition can also originate from sources within the ecosystem. During storms, small incisions in the ecosystem will appear. This can be ponds which are easily created by already present **incisions** on the surface. These are formed by strong winds, which erodes the sediments further down the terrain. These ponds can eventually get connected to the tidal channels if they grow big enough (Leonardi et al., 2018).

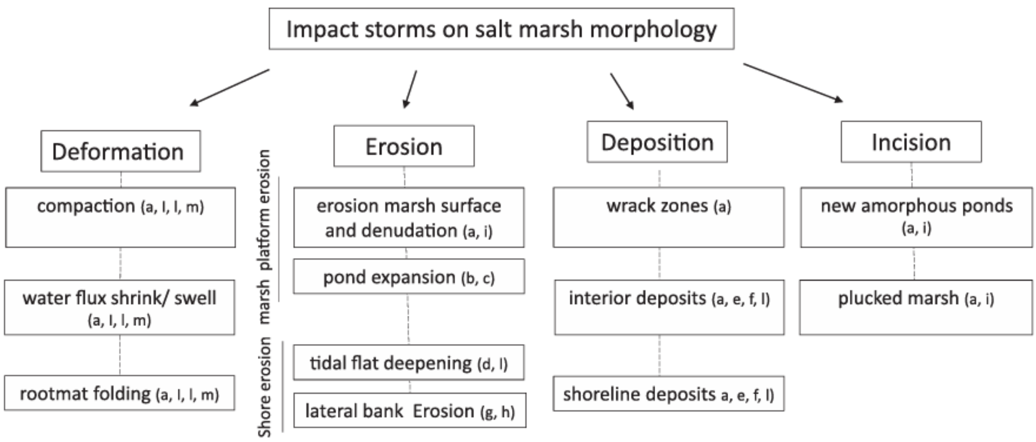


Figure 5: Impacts on salt marsh morphology by storms. (Leonardi et al., 2018).

In 2011 the storm Berit was one of the most powerful storms to hit Norway, and it also affected the coast of Finnmark. The storm made its impact on coastal communities with severe flooding and erosion. At Vardø, the water level rose to 217 cm (NN2000), and broke the previous record by 17 cm (Pedersen, 2011; *Søkeresultat*, 2024). This suddenly rise in water level highlights the vulnerability of coastal areas to extreme storms. Studying such events are crucial to develop better models for the future, preparing us to handle future storms better.

2.2.5.4 Sediment dynamics

There are different processes which control the sediment dynamics in coastal environments. Hydrodynamic processes can alter the marsh sediment dynamics (e.g. waves, currents, tides, wind) and these weathering processes plays a significant role when it comes to the movement of sediments. The input of sediment to the salt marsh system can occur both from within the ecosystem as well as being imported from outside the ecosystem. In salt marshes, biological, biophysical, and biochemical processes are also of importance. The morphology of the coastal landforms can change by the occurrence of erosion and deposition brought by the transport of sediments. The sediment (clay, silt, sand, and gravel) that gets transported also gets deposited as the coastal ecosystem evolves over time. (Adam, 2002; Holden, 2017).

2.2.5.5 Anthropogenic influences

In addition to being modified by processes caused by nature, we also have other factors affecting salt marshes. And these are caused directly and indirectly by human activity. In the northern part of Europe, humans have used salt marshes for centuries. They have been subjected to land use changes (e.g. agriculture, grazing, communities) for centuries and these factors can change sedimentation, carbon storage, and bring invasive species into the salt marsh (Adam, 2002; Hansen & Reiss, 2015).

2.2.6 Salt marsh resilience

The ability of salt marshes to keep up with the rising RSL is a consequence of climate change that is a matter of a great debate (Kirwan & Megonigal, 2013). Resilience in this thesis is described as the ability of coastal ecosystems to react in response to RSLR. Salt marshes are naturally ecological buffers that provide morphological protection in the presence of sand and gravel beaches, and coastal dunes.

Kirwan et al., (Kirwan & Megonigal, 2013) has focused his work on how sediment deposition, plant growth, and erosion interact to influence the resilience of salt marshes. They state that the accumulation of sediments is crucial for maintaining marsh elevation. They conclude that a reduced sediment supply can be a significant obstacle, affecting these ecosystems ability to keep up with sea-level rise. This makes the most important factor which determines the resilience is the sediment budget. If we have a positive sediment budget, which means that if more sediment enters the ecosystem it could contribute to the advancement of the salt marsh. While if we have a negative sediment budget, which indicates more sediments leaving the ecosystem than enters it, it will cause the coast to erode and the salt marsh to retreat in relation to RSL change. The accumulation rate of sediments will therefore be able to either keep up with RSLR or be subject to loss of salt marsh (Holden, 2017).

2.3 Analytical concepts

2.3.1 Loss on ignition

In salt marshes the highest zones (i.e. the high marsh) tend to be underlain by sediments with a higher proportion of organic matter than that of the low marsh, where more inorganic sediments are deposited. As such, the salt marsh zone into which subsurface sediments were originally deposited can be roughly interpreted by their organic matter content (Plater et al., 2015). Shifts in the proportion of minerogenic vs organogenic sediment can thus potentially provide some indication of changes in RSL and possibly also sea (for the latter, more minerogenic layers have been shown to indicate periods with increased ice extent, vs. organic-rich layers indicating periods with reduced ice coverage (Smith, 2003).

To be able to recognize paleoenvironmental changes through time, application of the loss on ignition (LOI) method applied to sediments underlying salt marshes allows for the identification of increasing or decreasing trends in the amount of organic matter that was deposited in and on the surface of a salt marsh through time (Plater et al., 2015).

Fluctuations in organic matter content also allow changes in decomposition, ecosystem production and carbon sequestration to be determined (Plater et al., 2015; Santisteban et al., 2004).

The standard LOI method is described as the inorganic material that remains after having been dried and ignited at a specific temperature and for a specific amount of time (Heiri et al., 2001). Although LOI is widely used, often in sea level studies, it is applied inconsistently; that is, a wide range of temperatures and different exposure times are used, mostly because the different types of sediments have varying amounts of organic matter (Heiri et al., 2001; Plater et al., 2015). The LOI method includes samples first being dried at 105°C to remove moisture (Wang et al., 2011), followed by weighing of the dried samples and then combustion at 530-550°C to determine the organic matter content (hence, the loss on ignition). Some researchers will add an additional combustion at 950°C to determine the carbonate content (Wang et al., 2011). Most of the organic matter will get ashed at temperatures between 200-350°C, while dewatering of clays does not occur until higher temperatures are reached. Organic matter such as peat, shows a loss in mass at temperatures ranging from 300-600°C. The temperature and duration of combustion should therefore depend on the nature of the materials and the purpose of the research. For example, if clay-rich samples are combusted at too high temperatures for too long, the organic carbon content may be overestimated due to clay dewatering (Plater et al., 2015; Wang et al., 2011).

The standard loss on ignition analysis follows that of Heiri et al. (2001).

1) The sample is dried at 105°C in a drying oven in a pre-weighted crucible (for about 12-24 hours). After cooling, the sample and the crucible are weighed, giving the dry weight of the sample.
2) The sample is then burned at 550°C for 4 hours. After being cooled down, the sample is weighed again. The amount of organic carbon in the original sample is represented by the difference in the weight of the dry sample and the combusted sample, expressed as percent (of the original, dry sample) lost after ignition.
3) If carbonates are being ashed as well, the sample returns to the muffle furnace at 950°C for 2 hours. The weight loss between 550-950°C can be converted to percent of sample that comprised of calcium carbonate.

Weight loss in sediments can be calculated by looking at the difference between the dry weight at 105°C, and the dry weight of the minerogenic sample that remains after ignition at 550°C (Heiri et al., 2001). The LOI percentage can therefore be calculated as follows:

$$\mathbf{LOI\ \% = \frac{mass_{105^oC} - mass_{550^oC} * 100}{mass_{105^oC}}}$$

The percentage of organic matter in the sediment sample is calculated by using the formula above, where the weight of the sample following burning at 550ºC is subtracted from that of the sample after drying at 105ºC. This is then divided by the weight of the dried sample and multiplied by 100.

Between 900-1000ºC, carbon dioxide develops from carbonate, and leaves oxide (Heiri et al., 2001). The calculation for the 950ºC step is the same as for 550ºC. But to calculate the difference from 550-1000ºC we use this calculation:

$$\textbf{LOI (organic matter + carbonate)} = \frac{mass_{105^oC} - mass_{950^oC} * 100}{mass_{105^oC}}$$

Salt marshes are typically composed of a mixture of organic and inorganic material, including clay, silt, fine sand, decomposed plant debris, and peat. Unlike marine and lake sediments, salt marsh sediments require lower temperatures (Figure 6; wetland), because they are much richer in organic matter compared to other environments (Plater et al., 2015; Wang et al., 2011).

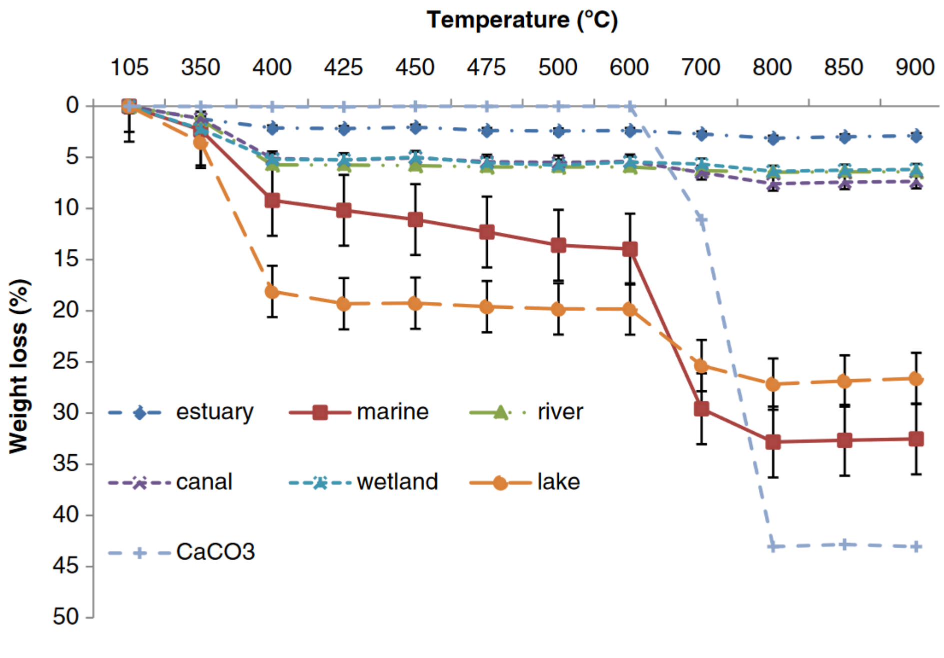


Figure 6: Weight loss (%) that changes in connection to different temperatures and different sedimentary environments (Wang et al., 2011).

The results of LOI analysis provides us with information on how organic-rich the sediment is, which tells us something about the environmental conditions in which it was originally deposited. High organic matter content indicates good conditions for plant growth, while low organic matter content indicates conditions that are less suitable for plant growth. LOI has also been examined in relation to elevation in microtidal salt marshes, high LOI values of ~60% indicate the upper marsh zone and lower values of 25-40% indicate the low marsh zone (Plater et al., 2015).

2.3.2 Stable isotopes of carbon ($\delta^{13}C$), C/N and TOC

Changes in the stable carbon isotope $\delta^{13}C$ and the relationship of total organic carbon to total nitrogen (C/N and TOC, TN) can be used as proxies for paleoenvironmental change, including RSL change (Mackie et al., 2007). $\delta^{13}C$ and C/N can be applied together to distinguish which depositional environment the sediments originated from (anthropogenic, terrestrial, or marine) and they can therefore distinguish between C_3 and C_4 vegetation and freshwater, brackish and marine organic matter. In the Arctic, the application of this method is more limited than other parts of the world. This is because the C_4 vegetation is very rare or has only recently been introduced to the region. C_4 plants are adapted to conditions such as high temperature, high light intensity and low moisture and therefore tend to occur in warmer climates. C_3 plants, on the other hand are more adapted to conditions such as colder seasons where the growth period is under conditions of lower temperatures with high moisture availability. C_4 plants do not appear in northern Europe, and there are several reasons for this (e.g. soil nutrient preferences, photosynthetic pathway) but overall it is that they thrive under different conditions than C_3 plants (Collins & Jones, 1986).

These proxies are used to study past sea level and paleoenvironmental change because different modern intertidal depositional environments (e.g. low marsh, high marsh, tidal flat and freshwater environments) have distinct bulk sediment and plant $\delta^{13}C$ and C/N values which occur at specific elevation ranges relative to the tidal frame (Khan et al., 2015; Pastene et al., 2019). Studies of $\delta^{13}C$ values of organic matter in cores representing nearshore sedimentary sequences (Holocene to modern in age), in the North Atlantic (Lofoten, Scotland etc.) have shown values ranging from -22‰ to -16‰, which can indicate a marine source for organic matter (Balascio et al., 2011; Khan et al., 2015; Mackie et al., 2007). In some cases, these interpretations have been tested against RSL reconstructions using microfossil data (e.g. diatoms) from co-located cores (Khan et al., 2015; Mackie et al., 2007). C/N values used together with $\delta^{13}C$ values can further help distinguish between marine and freshwater algae (Figure 7); for example, when $\delta^{13}C$ values are -22‰ to -20‰ and C/N values are 10 or less, this may indicate that a large proportion of organic matter in the sample comes from marine algae (seagrasses and macroalgae often have C/N values between 15 and 50; (Khan et al., 2015); when $\delta^{13}C$ values are -30‰ to -25‰ this may indicate that the organic matter comes from freshwater algae; if C/N values are greater than 20, it is more likely that the algae has a terrestrial source (Mackie et al., 2007).

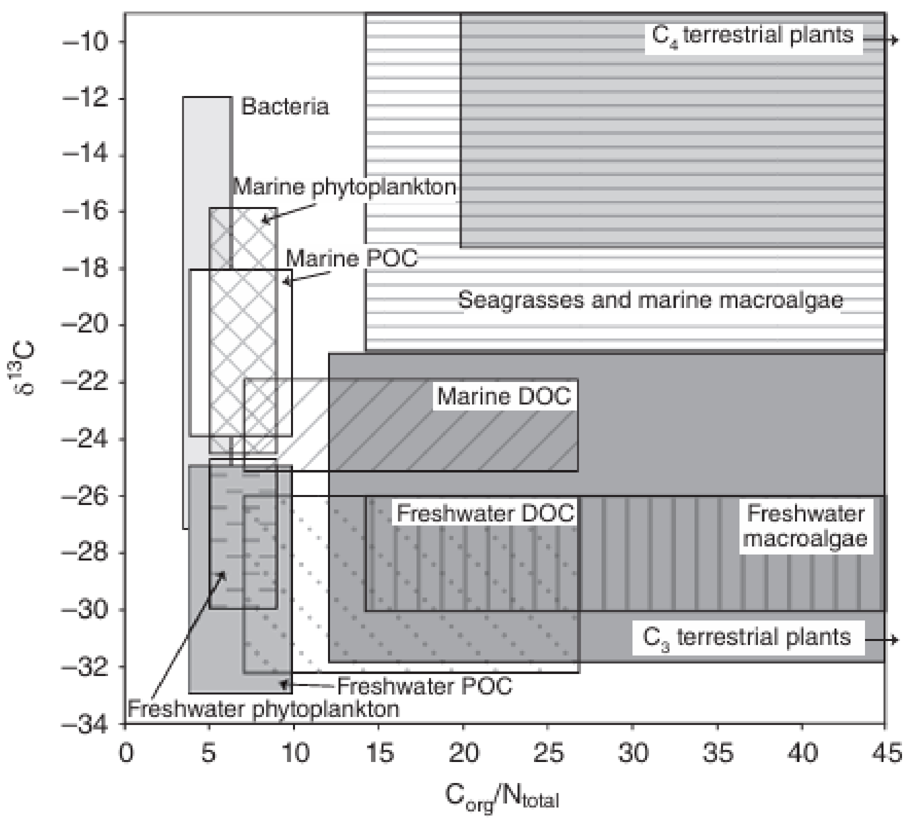


Figure 7: δ13C and C/N values used to distinguish between the different organic matter sources in intertidal wetlands (Khan et al., 2015).

Analysing stable carbon isotope $\delta^{13}C$ and C/N requires the collection of plant and sediment samples, both above and below ground. Plant samples should be dried or frozen immediately up until the analysis, to avoid any changes in the isotopic composition of the sample. Sediment samples and cores should be stored at low temperatures (~4ºC) in a dark room to limit microbial activity and cancel photooxidation of the organic components (Khan et al., 2015).

When it comes to errors and disadvantages of this method most of the errors lay in the preparation of the sample. When getting the samples ready it is important to have enough material to get accurate instrumental reading; and this lies on ~500 µg C. Generally, it is assumed that carbon compromise ~40 % of plant material, so it is therefore necessary to have at least 1.25 mg plant sample before the pretreatment. With sediments, the amount of sample will be based on the amount of organic matter content that is within the sample. The colour of the sediments could be a rough indicator for this, to determine the nature of the soil. Black or dark brown colour represents high organic matter content, and light brown colours contains relatively less organic matter content. Inorganic carbon has an isotopic composition which varies a lot from the sources of the organic material, with values close to 0±4‰. It is therefore important and necessary to remove these carbonates from the sample before the analysis takes place, And it is also important that the samples are as homogenized as possible, since the analyses will be more correct if the samples burn uniformly during ignition (Holden, 2017; Khan et al., 2015).

The method requires the samples to be pretreated before the analysis. First the samples are placed in centrifuge tubes and 3 M HCl are added slowly (if samples have high carbonate content, they will produce a lot of foam) and the sample is run in a centrifuge at approx. 2500 rpm for 10 minutes. Then 3 M HCl are added to the samples again and the sample is loosened by shaking it. The sample is then left in the tube for 24 hours. Then the sample gets centrifuged at approx. 2500 rpm for 10 minutes and the acid is once again removed from the sample. Then the samples are washed with demi-water until the samples are neutral. This follows the same procedure as with the HCl, which include the sample being centrifuged at approx. 2500 rpm for 10 minutes and then the acid is removed. It is important that the in between each addition of demi water, the samples are shaken to loosen the sample from the bottom. This is done for about 2-3 runs depending on the acid content of your samples. The samples are then dried in an oven at 50ºC for as long as it takes for the samples to get completely dry. The samples are thereafter homogenized using an agate mortar (Gates et al., 2020; Khan et al., 2015). The precision is typically < 0.3‰ for δ13C (*δ13C, δ15N or δ34S in Bulk Solid Materials*, n.d.).

2.3.3 Grain size analysis

Grain size is a useful property of sediment to study that gives information about the source, origin, deposition and environment of sediments (Blott & Pye, 2001; Holden, 2017; Switzer & Pile, 2015). The grain size of materials can be used together with other analyses to determine the palaeoenvironment of sediments, which again can then be used to document changes in things like RSL, climate, sea ice etc. (Switzer & Pile, 2015). The sorting of the sediments in a sample is also a useful measure of the palaeoenvironment.

There are three major grain size classifications (Figure 8). These are: gravel, which have grain sizes greater than 2 mm; sand, which is less than 2 mm but greater than 63 µm; and mud, includes grain sizes less than 63 µm. This classification follows the Udden-Wentworth grain size classification where these three major classes can be divided further into smaller classes (e.g. very fine sand, fine sand, medium sand, coarse sand, and very coarse sand) (Holden, 2017).

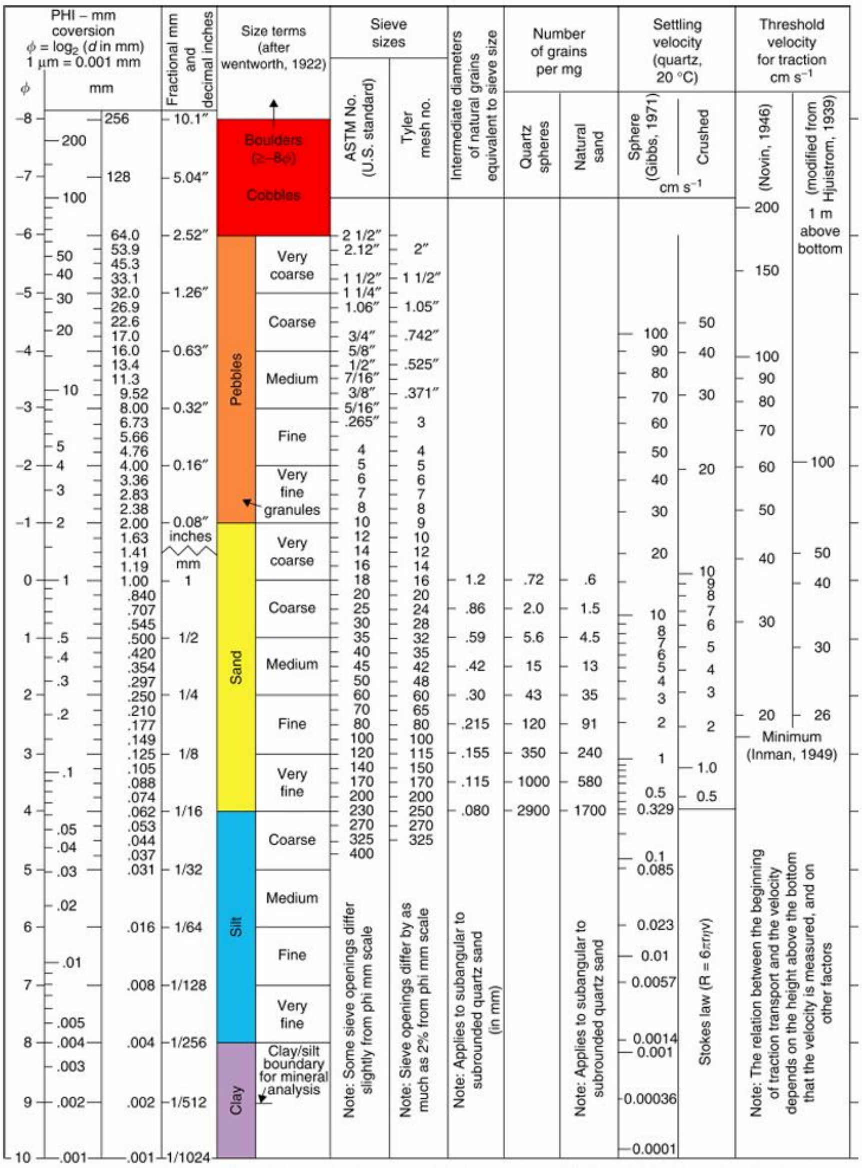


Figure 8: The Udden-Wentworth grain size classification which shows the relation between ϕ, mm and size classifications (Switzer, 2013).

To prepare samples for grain size analysis, there are many different techniques that can be used. These methods include sieving, the pipette method and laser diffraction analysis (LDA). Sieving is a method that is used for sand and gravel size materials, and the pipette method is a method for measuring mud. The LDA method works in a way where a laser is directed against a cell, and it gets diffracted by the grains that pass through the ray. The instrument then measures the sample characteristics and transforms it into a particle-size distribution. A variety of machines can be used to conduct this method (e.g. a Malvern Mastersizer 2000). Previous research shows that LDA is a precise technique in the analysis of the particle-size characteristics of sediments and soils. (Switzer & Pile, 2015).

2.4 Study area

The arctic salt marsh that is the focus of this study will be henceforth referred to as Kongsfjorden, due to its proximity to a small village by the same name. The Kongsfjorden field site is located in Berlevåg municipality, northwestern Varangerhalvøya, Finnmark, Norway (Figure 1).

The study area is located in a low-relief part of the fjord where both fluvial and coastal sediments are deposited and preserved. Sediments are transported and deposited to the salt marsh system from tides, waves, and slope wash. In winter, sea ice forms in this part of the fjord and the land is frozen. In spring, depending on winds, sea-ice transports sediments to the marsh system as well. The areas serves as an important habitat for animals, especially migrating birds.

2.4.2 Glacial and deglacial history of the region

The glacial and deglacial history of the study area at Kongsfjorden is important to include because it provides us insight into the nature of the underlying sediments and geomorphology, as well as expected VLM related to most recent glacial/deglacial cycle, which impacts things like RSL history and projections for the future and susceptibility to erosion.

All of Varangerhalvøya was glaciated during the last glacial maximum by the Fennoscandian Ice Sheet (Romundset et al., 2011). Deglaciation began around 15,000 yBP (Romundset et al., 2017). Marine limit, defined here as the highest elevation of the sea since the last glacial maximum, is around 60 m a.s.l (Sanjaume & Tolgensbakk, 2009).

Romundset et al. (2017) have radiocarbon dated basal sediments from a lake inside an end moraine and cosmogenically dated boulders from the surface of the moraine (near Kongsfjord), concluding that the deglaciation occurred between 16,000-14,000 yBP here. The formation of the Kongsfjorden moraine occurred at the front of a grounded fjord glacier, which was locally confined to the valley in which the study area and Kongsfjorden are located. The present surface of the end moraine is engraved with raised beaches that reach the elevation of local marine limit (53.5 m and 59 m a.s.l.). Present day rates of VLM (uplift) are approximately 2.3 mm/yr at Kongsfjorden (Kartverket, 2024).

2.4.1 Post-glacial RSL change

Studies on raised beaches and beach morphology (Marthinussen, 1945) have been used to map Tapes and Younger Dryas isobases in Finnmark around Varanger peninsula. However, more recent detailed work on RSL change in this region has been undertaken to the east and west (Romundset et al., 2011) of the study area. The Holocene RSL history is therefore better-known west towards Nordkinn, and east towards the Russian border than for the study area. The Holocene RSL curve for Nordkinn (Figure 9) by Romundset et al. (2011) is the closets estimate for that of the study area. The Nordkinn curve is based on radiocarbon dated deposits from isolation basins and indicates that RSL fell about 12 m between approximately 10,500-9,500 yBP. This was followed by a small transgression (1-2 m) between ca. 9,500-5000 yBP. After 5000 yBP, RSL fell another 12 m to MSL. The Holocene RSL history of the Nordkinn area is similar to that of surrounding areas to the west and south (Rolvsøya and Sørøya). The transgression that occurred at around 9,500-5000 yBP is commonly known as the Tapes transgression, where great amounts of meltwater from North America caused RSL to rise in many coastal areas of Norway (Romundset et al., 2011, 2017).

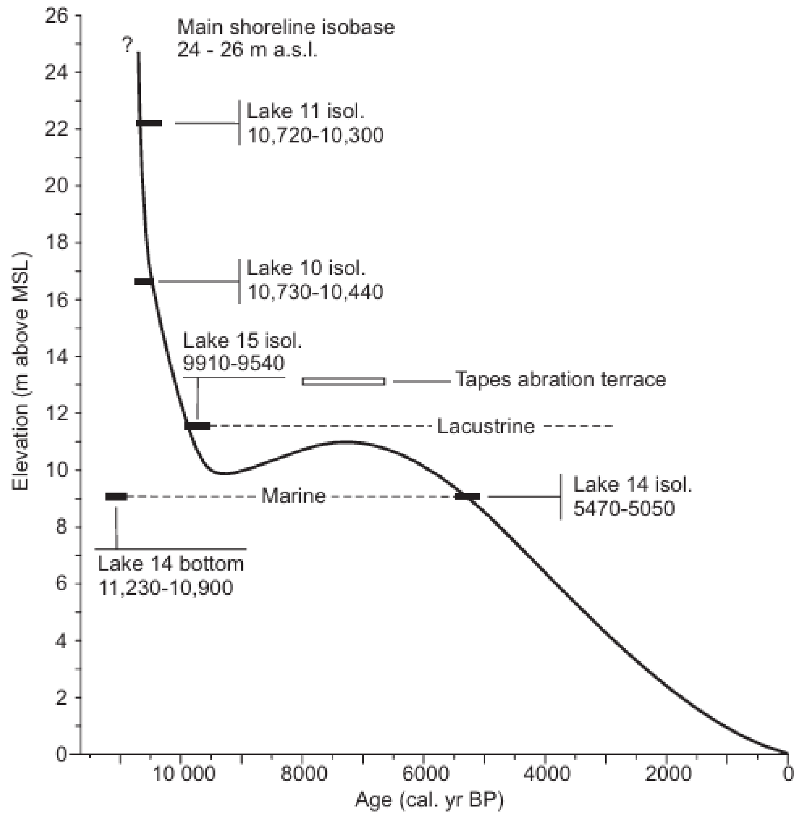


Figure 9: Holocene relative sea level curve for Nordkinn based on radiocarbon dated deposits from isolation basins (Romundset et al., 2011).

Tide gauge measurements gives us the most accurate recent RSL change data, (Benn & David, 2010). The rate of RSLR reported in the study area is based on changes in mean water level relative to the tide gauge at Vardø. The current RSL rate is 1.2 ± 1.0 mm/ yr, while accounting for GIA the geocentric rate is 3.9 ± 1.3 mm/yr (Simpson et al., 2024).

2.4.4 Surficial geology

Finnmark experiences average summer temperatures of 10.1ºC with a growing season of approximately 120 days. Winter temperatures drop to an average of 3.5ºC (Ward, 2020b).

The low-lying coastal landscape surrounding Kongsfjord salt marsh is characterized by raised beach ridges, freshwater wetlands, moraines, and bedrock ridges (Figure 10) (Romundset et al., 2011; *Søkeresultat*, 2024). The surficial geology underlying the study area includes fluvial, raised marine, modern coastal, glacial, and glaciomarine sediments as well as weathering bedrock. A prominent end moraine restrics flow from the Barents Sea and outer Kongsfjorden into the inner fjord, called Strømmen. This end moraine indicates that a lobate fjord glacier was present and may have possibly drained from the "plateau inland."

(Romundset et al., 2017). The narrow opening in the moraine creates strong currents in and out of Strømmen.

Due to limited wave energy, we get the deposition of finer particles such as minerogenic sediment. The Norwegian and North Atlantic ocean currents are the two main currents bringing warm water to the Arctic region, making the climate mild and wet (Romundset et al., 2011). Although there are numerous ponds and lakes surrounding the study area, none of them appear to be hydrologically connected to the salt marsh. Based on this it is likely that any material deposited in the supratidal zone originates from sediments located upslope from the marsh or originates in situ. In the intertidal zone sediments and organic matter are delivered to the marsh surface from the tidal currents and sea ice cover during the winter (Sharma et al., 2019).

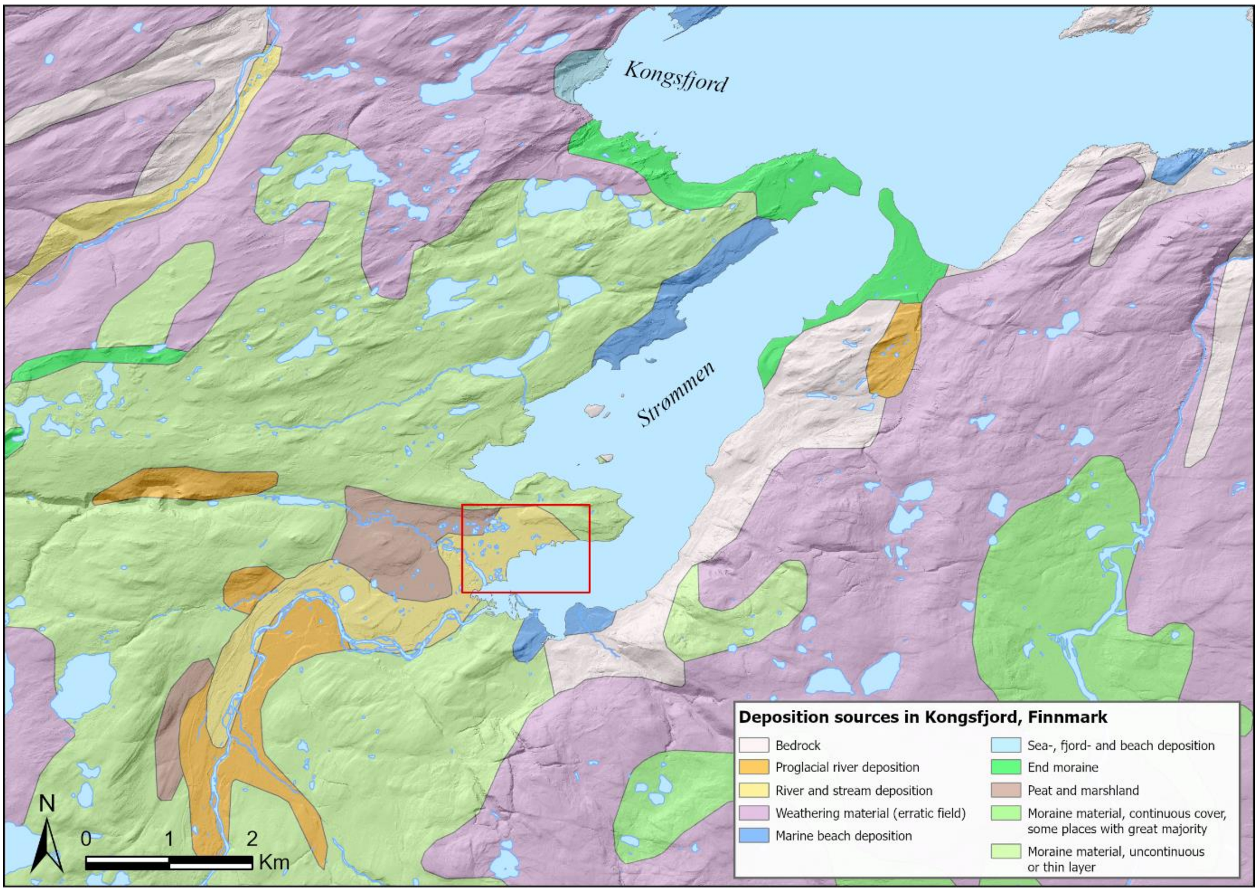


*Figure 10: Quaternary map of the study area. Data from NGU (*Løsmasser*, n.d.).*

2.4.3 Kongsfjorden salt marsh

The salt marsh (Figure 11 & 12) is located deep within the fjord arm Strømmen, which is connected to the outer fjord via a ~260 m long inlet that bisects an end moraine (*Løsmasser*, n.d.). This narrow inlet through the moraine helps create a low-energy environment, well separated from the open coastline, and has possibly contributed to the growth of the salt marsh at Kongsfjorden. This works as a barrier that dampens the wave energy and may reduce the tidal range, which, at Kongsfjord, is 233 cm between MHT and MLT (*Søkeresultat*, 2024). Although fetch is limited, coastal currents are strong due to this narrow passage, and during winter, sea ice forms over the inner parts of Strømmen.

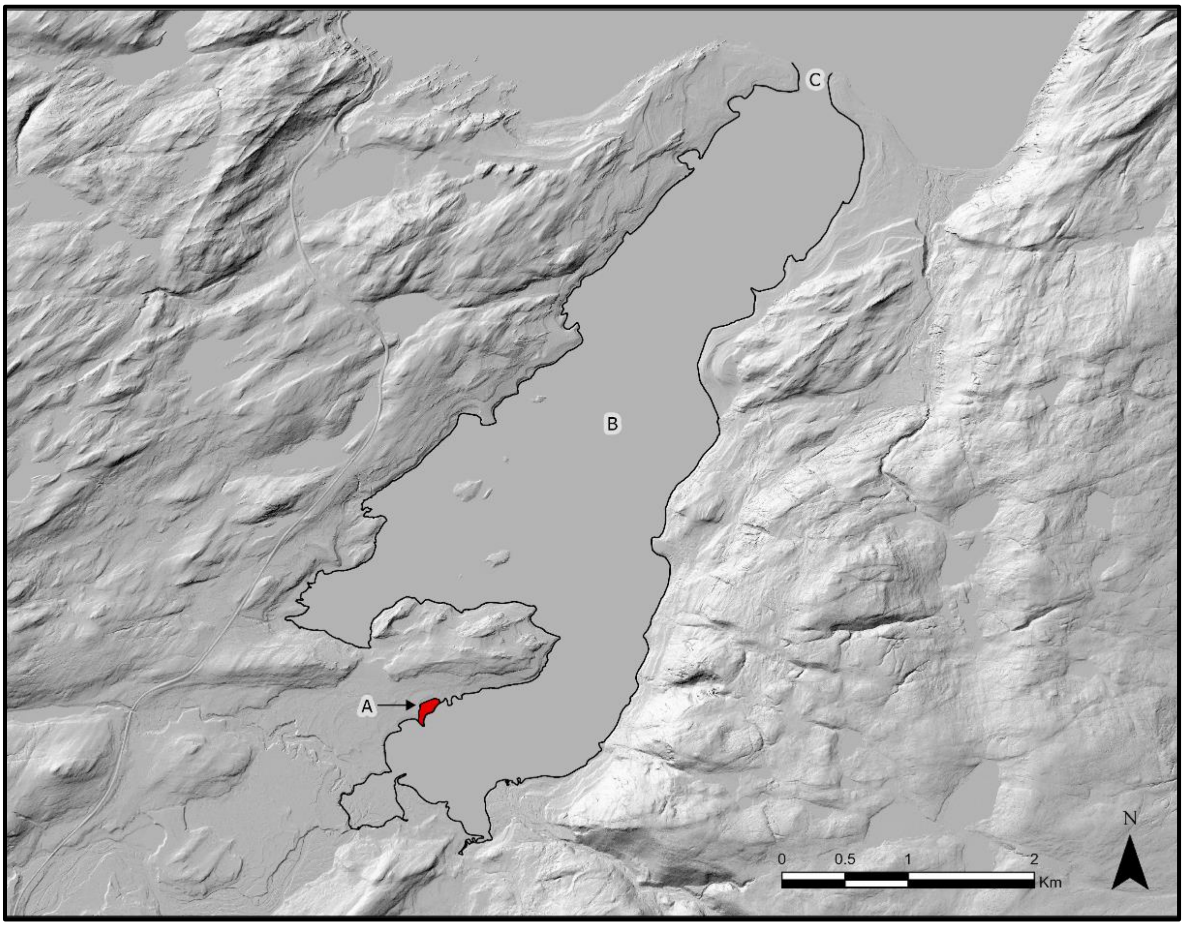


Figure 11 Hillshade over the Strømmen fjord with A) Salt marsh study site B) Strømmen, and C) the narrow inlet separating the inner fjord from the more open coastline of Kongsfjord and the Barent Sea.

The entire salt marsh system is protected by a boulder barricade near and parallel to the shoreline. Immediately below the salt marsh there are two small intertidal basins behind and between the boulder barricades. Moving further inland, the intertidal basins transition into a low marsh zone which is characterized by *Pucciniella phryganodes*. The high marsh is characterized by *Carex* species. The highest salt marsh system consists of raised beaches overgrown by terrestrial vegetation with small freshwater wetlands occupying the swales.

Figure 12: Overview of the salt marsh in Kongsfjorden, circled in red.

By using a DEM together with the vertical datum NN2000 as reference level from Kartverket we can get tidal measurements for the study area (Figure 13). MSL which is calculated by looking at the average between 1996 and 2014. MHT is +70 cm. HAT is at +140 cm. MLT (mean low tide) is -112 cm, and LAT (lowest astronomical tide) is -194 cm (*Søkeresultat*, 2024). The salt marsh is flooded at high tide and subaerially exposed at low tide.

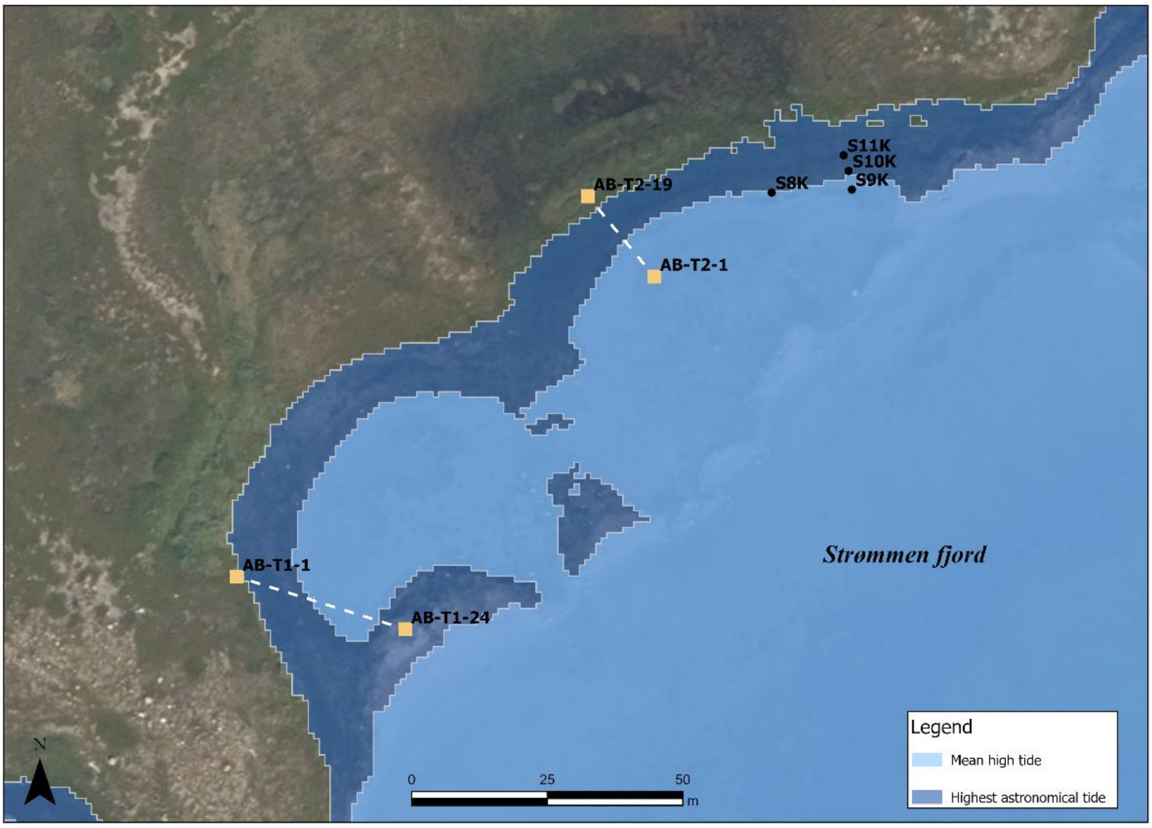


Figure 13: Map showing the mean high tide (MHT) and the highest astronomical tide (HAT) at Kongsfjorden study area. The location of the sediment cores (S8K, S9K, S10K, and S11K) are also included as well as the vegetation transects AB-T1 and AB-T2.

3 Methods

3.1 Field work

Field work was conducted by Max Holthuis and Chantel Nixon between 9.06.2022 to 13.06.2022 in Inner Kongsfjord on the north coast of Varangerhalvøya, Finmark (Figure 1).

A salt marsh was identified in the study area and four shovel cores were extracted along a transect extending coast-perpendicular from the low marsh to the upper limits of the saltmarsh (Figure 12). The zones were identified based on surface vegetation. Based on pictures and observations in the field, plant species, particularly the *Carex* species and *Pucciniella phryganodes*, which grows in salt marshes in northern-Norway (Alm, 1993), were used to confirm that the area was indeed a salt marsh. *Puccinellia phryganodes*, dominates the lowest zone of the salt marsh and *Carex* species are normally found higher up in the marsh. Along the same transects modern vegetation samples were gathered to compare the surface samples with the findings from the sediment cores to improve the accuracy and reliability of predictive models (see below)

Once the core placements were chosen, four blocks of sediments were extracted, with approximate dimensions of 30 cm x 30 cm x 20-30 cm and labelled S8K, S9K, S10K, and S11K. The depth of the blocks was based on depth of refusal, which in this location was a coarse gravel-sand layer, often only 20 cm or less below the surface. After the salt marsh cores were extracted, they were wrapped in plastic and transported to NTNU in Trondheim, where they were placed in a fridge and kept at 4-5ºC until they could be subsampled for further analyses.

3.2 Lab work

3.2.1 Logging the samples

Core stratigraphy of all four cores were sketched at NTNU in autumn 2023. The top few millimetres of the surface of the shovel core were carefully scraped off to reveal the stratigraphy of the sediments, which is important since during storage, oxidation can occur and potentially discolour the sediments. Growth of bacteria on the core surface may also occur, which can affect different analyses (Khan et al., 2015). Once cleaning of the core surface was complete, pictures were taken and core stratigraphy sketched, with visible changes in colour, texture and the condition of any organic matter noted.

3.2.2 Loss on ignition

Cores S9K and S11K were sampled for loss on ignition in the Physical Geography Lab at NTNU, Trondheim, Norway. The sample resolution was every 1 cm, resulting in 13 samples from S9K (0-13 cm) and 17 samples from S11K (0-17 cm). The size of the samples varied a bit since there were some large roots and gravel particles in the cores. Further down the cores grain size increased, resulting in samples with variable weights ranging from ~1 to 3.5 g (wet weight). After weighing the samples, they were placed in a fridge at 4ºC until the analyses.

For the analysis, each sample was placed in pre-weighted crucibles and weighed again before they were dried for 48 hours in a drying oven that held 60ºC. This temperature deviates from the recommended temperature (105ºC; (Heiri et al., 2001)), but it was not possible for the oven at NTNUs Physical Geography Lab to reach this temperature. They were therefore dried for longer than 24 hours. After drying they were weighted again before they were placed in an Nabertherm Controller R7 muffle furnace which held 480ºC. The samples were burned for 4 hours, and ten samples were placed in the furnace at the same time given that I had 30 samples, which meant that I would have three runs. After the first ignition at 480ºC they were cooled down before they were weighed again at room temperature. Thereafter they were placed in the muffle furnace again and the temperature was set to 1000ºC. The samples were then ignited for 2 hours, and then cooled down and weighed one last time.

To calculate the LOI, the formula from Heiri et al. (2001) was used and replaced with temperatures used in this thesis.

$$\textbf{LOI 480°C \%} = \frac{\text{mass}_{60°C} - \text{mass}_{480°C}}{\text{mass}_{60°C}} * 100$$

To determine the difference from the samples ignited at 480ºC and 1000ºC, we followed this calculation to determine the LOI at 1000ºC and thereafter the difference in percentage from 480ºC to 1000ºC:

$$\textbf{LOI 1000°C \%} = \frac{\text{mass}_{60°C} - \text{mass}_{1000°C}}{\text{mass}_{60°C}} * 100$$

$$\textbf{\% Increase} = (\%1000°C) - (\%480°C)$$

For this study we used LOI temperatures and exposure times close to those proposed by Heiri et al. (2001), but for the first heating, a temperature of 60ºC was chosen because the drying oven could not reach a temperature of 105ºC, and therefore the exposure time got longer. For the first ignition, samples were ignited at 480ºC for 4 hours. For the second ignition, samples were ignited at 1000ºC for 2 hours. The chosen temperatures minimize the risk of overestimating the organic matter content due to the dewatering of clay. The temperatures are therefore effective for determining the organic matter without burning off clay minerals. As for the combustion at 1000ºC, it ensures that all of the organic matter is combusted, and it also allows us to look at the carbonate content in the sediments, which occur at higher temperatures.

3.2.3 TOC, C/N and $\delta^{13}C$

Samples taken for TOC (total organic carbon), C/N and $\delta^{13}C$ were sampled in the same way as for loss on ignition. The size of the samples varied ~1-3 g, but only about 1 mg is needed for this type of analysis (Lamb et al., 2007). The analyses were carried out with 23 samples from S8K (0-23 cm), 13 samples from S9K (0-13 cm), 17 samples from S10K (0-17 cm) and 17 samples from S11K (0-17 cm). The 70 samples in total were placed in 15 ml centrifuge tubes and kept at 4ºC until later analyses.

Processing for TOC, TN, C/N and $\delta^{13}C$ analysis was conducted at a lab at the Trondheim Biological Station. Here, 3 M HCl was first added to the samples to remove any calcium carbonate (from, for example, broken shells or foraminifera). The samples were shaken and left to sit for 5 minutes. After 5 minutes, the samples were centrifuged at 2500 rpm for 10 minutes and the acid decanted from the vials. 3 M HCl was once again added to the sample, shaken, and left to sit under a fume hood for 17.5 hour. The samples were then centrifuged for 10 minutes at 2500 rpm, the acid decanted and then rinsed with demi-water to remove the acid. The samples were then placed in a drying oven at 50 degrees for four days. All of the samples were then pulverized with a mortar and pestle until the sample was homogenized and there were no coarse grains or root fragments left.

Sixteen samples of vegetation from the saltmarsh at Kongsfjorden were also analysed for TOC, C/N and $\delta^{13}C$ for comparison of the modern salt marsh environment to downcore environments preserved in the organic matter of the subsurface peat. The same preparations for the sediment samples were applied to the vegetation samples, but without the acid rinsing. The samples were dried in a drying oven at 50ºC for 24 hours. The samples were then pulverized with a mortar until the grain size was homogenized.

All the 86 samples (sediments/peat and plants) were thereafter transported to FARLAB at University of Bergen (UiB) for further analyses. At Bergen, the dried samples were weighed by using a microscale (Mettler Toledo MX5) and placed in tin capsules before they were released into an autosampler (Thermo Scientific Delta V+ connected to a Flash 1120 Elemental Analyzer and a Flash HT) for bulk stable carbon isotope ratio ($\delta^{13}C$) analysis.

Replicates were taken for about 20 per cent of the samples to analyse for quality control. To measure the precision of the isotope results, pooled standard deviation was applied to the results from the 86 samples and the replicate samples. The calculation was performed in Excel. Pooled standard deviation is a weighted average of the standard deviation when you have different amount of sample weights (Gabbert et al., 2022, p. 226). Pooled standard deviation is frequently used in different areas when it comes to statistics, but it is also common to use in lab-based sciences, where they can indicate the precision of an analysis (Tim, 2016).

To calculate the pooled variance of my samples, the following equation was used (Tim, 2016):

$$s_{pooled} = \sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2+\ldots+(n_k-1)s_k^2}{n_1+n_2+\ldots+n_k-k}}$$

Figure 14: Formula on how to calculate the pooled standard deviation (Tim, 2016).

The analytical precision for the replicate samples was ±0.35 ‰ for $\delta^{13}C$, C/N and TOC.

The sedimentation rate was calculated by taking the depth of where the radiocarbon dating was taken (at the basal contact between the salt marsh peat and the underlying sand and gravel) in the core and dividing it by the calibrated radiocarbon date. This calculation suggest a linear rate of sediment accumulation. To calculate the carbon accumulation over that period of time, the TOC (%) for the entire core (S8K and S10K) was multiplied by the depth interval and then divided by the total time span.

3.2.4 Grain size analysis

The remaining sediments following ashing in the muffle furnace (LOI analysis) from S9K and S11K were used for grain size analysis. Each sample was placed in a plastic container and transported to EARTHLAB at the University of Bergen for grain size analysis. Samples were gently ground with a mortar and pestle and placed in an ultrasonic bath before being analysed in a laser diffraction particle size analyser (Malvern Mastersizer 3000). Five analytical runs were done on each sample to provide an average. The GRADISTAT program was used to analyse the data received from the Malvern Mastersizer at EARTHLAB.

To interpret the grain size data it was been plotted on both regular scatter diagrams and bivariate scattergrams to show the summary statistics (mean grain size, sorting, skewness, and kurtosis) of PSD. (Switzer, 2013). In this case, inclusive mean (ϕ) grain size and mean (σ_I) sorting, were plotted from samples taken from core S9K and S11K.

3.2.5 Radiocarbon dating (^{14}C)

Samples for radiocarbon dating were taken by master's student Simon Solheim Holme, who is developing age models for cores S8K and S10K from the same study area. Samples were taken from the base of the peat and top of the gravelly sand, in core S8K, between 22-23 cm and in core S10K, between 12,5-13,5 cm (with 0 cm being the surface of the marsh). As much material was sampled from these horizons as was needed to reach minimum sample weights for radiocarbon analysis. Peat from both cores (i.e. between 22-23 cm in S8K and 12,5-13,5 cm in S10K) was analysed under a dissection microscope and seeds (from the same species as much as possible) were picked for radiocarbon dating, with the assumption that of all the organic matter in peat, seeds are the most likely to be *in situ* (as opposed to, for example roots, which can grow a long way downwards or leaf litter, which may be wind-blown or water-transported onto the marsh surface). The seeds from S10K and S8K was then sent to NTNU Universitetmuseum for radiocarbon dating. Radiocarbon dates were calibrated using IntCal20 (Reimer et al., 2020).

3.3 Statistical analysis

Maps were created with ArcGIS Pro version 3.1.4 (ESRI), grain size and pooled standard deviation statistics were conducted in Microsoft Excel version 2403 Build 16.0.17425.20176 (Microsoft Corporation), and Grapher 11 version 11.3.717 (Golden Software) was used to create graphs used to describe the results.

4 Results

Results from the surface vegetation and sediment survey and isotope analyses are presented first, in section 4.1 below. This is followed by descriptions of stratigraphy and isotope analyses for each of the four cores from this study (S8K, S9K, S10K, and S11K; 4.2). For cores S9K and S11K, results of LOI and grain size analyses are also presented. All numbers presented as a percentage in this chapter have been rounded up or down to the closest integer number. Figure 15 shows the sample sites and the different zones.

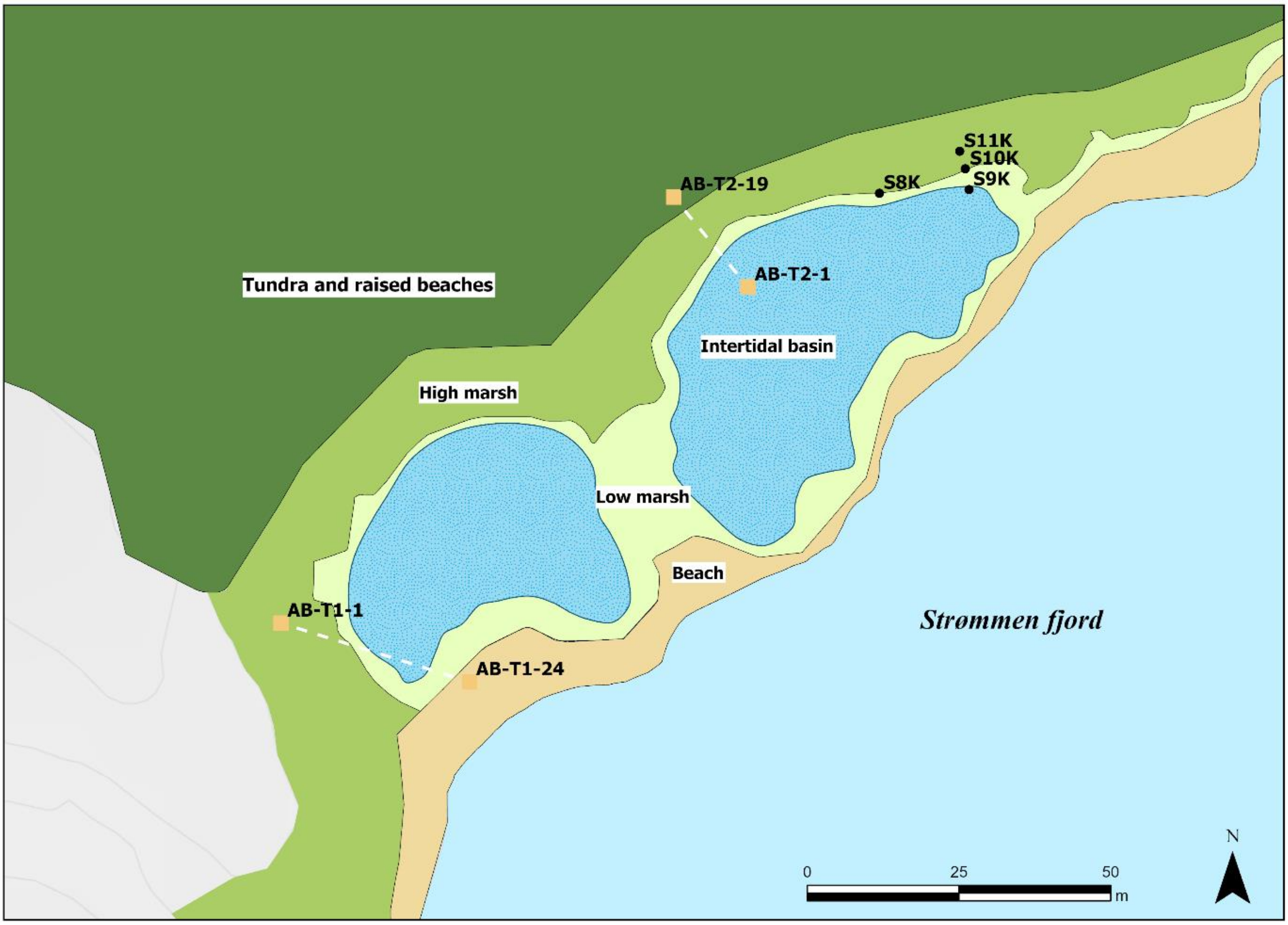


Figure 15: The salt marsh showing the locations of the cores as well as the surface sediment and vegetation transects (AB-T1 and AB-T2). High marsh, low marsh, beach, and tundra zones are based on unpublished data from M. Holthuis (2023). Department of Geography, NTNU.

Table 1: Elevation (m) of all the cores at Kongsfjorden.

CORE NAME	Coordinate Reference system	NORTHING	EASTING	ELEVATION (m)
S8K	UTM Zone 35N	7841282.63	583889.422	0.631053
S9K	UTM Zone 35N	7841280.3	583903.983	0.417706
S10K	UTM Zone 35N	7841283.78	583904.088	0.757006
S11K	UTM Zone 35N	7841286.77	583903.712	0.844838

4.1 Modern Vegetation Survey and Vegetation Samples

Four vegetation zones (intertidal basin, low saltmarsh, high saltmarsh, and tundra/terrestrial wetland) were differentiated based on surface vegetation observations at the study site at Kongsfjorden and mapped with GPS in the field (Figure 16).

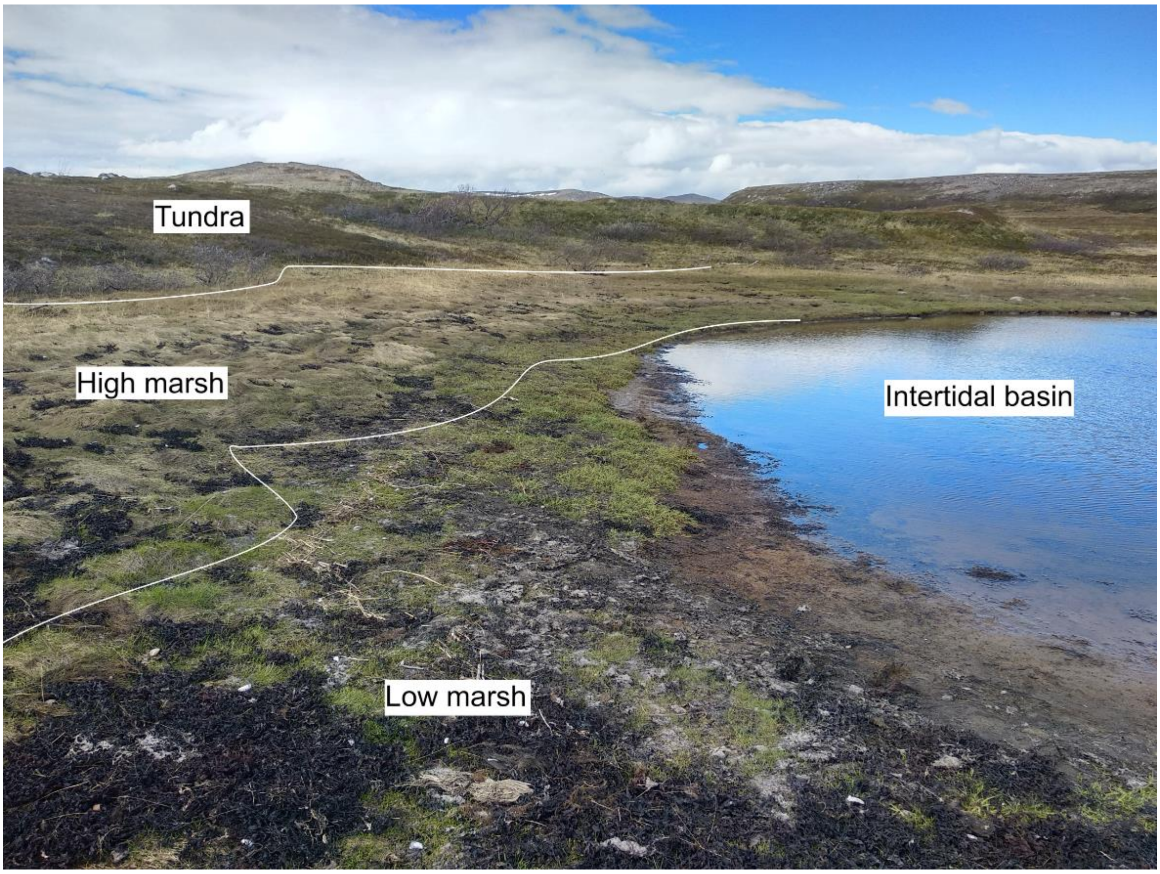


Figure 16: The different vegetation zones. The white line illustrates the transition from the intertidal basin and low marsh to the high marsh and then from high marsh to tundra/raised beach ridge moving right to left on the photo (i.e. seaward to inland).

There are two intertidal basins that connect during the highest tide. The two basins lie in the upper intertidal zone and are submerged during MHT, but separated otherwise, by a cobble-gravel-boulder barricade and some less well-defined beach ridges (Figure 17). During the spring high tide, the boulder barricades are just barely submerged (Figure 18).

Figure 17: Cobble-gravel-boulder barricade separating one of the intertidal basins from the open tidal flat during low tide.

Figure 18: The flooded low marsh and intertidal pond at Kongsfjord during high spring tide, looking east. Dark patches are marine algae. Vegetation here is mainly graminoids. The white line indicates where the cobble/boulder barricade lies.

The salt marsh is characterized by low-growing, salt-tolerant vegetation. From low marsh to high marsh a mix of species were observed such as *Pucciniella phryganodes*, *Comarum palustre* and *Ligusticum scoticum*. The uppermost reaches of the high marsh and the tundra border are dominated by *Empetrum Nigrum* and *Salix* species. On the seaward side of this border, *Rhodiola Rosea, Comarum Palustre, Ligusticum scoticum* were observed.

Transect AB-T1

At AB-T1-1 (point on the modern vegetation transect; Figure 19), which begins at the margin of the high marsh, the dominant vegetation includes heather, crowberry (*Empetrum nigrum*), and Salix spp. Between points AB-T1-2 and AB-T1-7 dry, yellow graminoids dominated. *Ligusticum scoticum*, *Comarum palustre* and some mosses were also observed between sample points AB-T1-2 and AB-T1-7 with *L.scoticum* mostly present at the wrack lines. At points AB-T1-8 and AB-T1-9 similar plants were observed, but the graminoids are shorter and green. At the next zone between AB-T1-10 and AB-T1-14 washed up algae was observed, as well as short green graminoids. In the transition to the intertidal basin, which includes transect sample points AB-T1-15 to AB-T1-17, algae, kelp, drifting seaweed, and grassy sea moss were noted. In the transition back out of the pond towards the boulder barricade (points AB-T1-18 to AB-T1-20; Figure 19), short green graminoids were observed. At point AB-T1-21 the vegetation consists of a mix between greener and shorter graminoids and yellow and longer graminoids. At points AB-T1-22 and AB-T1-23 the samples are taken on the little ridge close to the sea, where there is a poorly vegetated sandy area. The lowest zone (AB-T1-24) consists of tall, yellow graminoids and even taller dune grasses (*Leymus arenarius*). Here there is also a very sandy substrate before the zone transitions to the coarser beach.

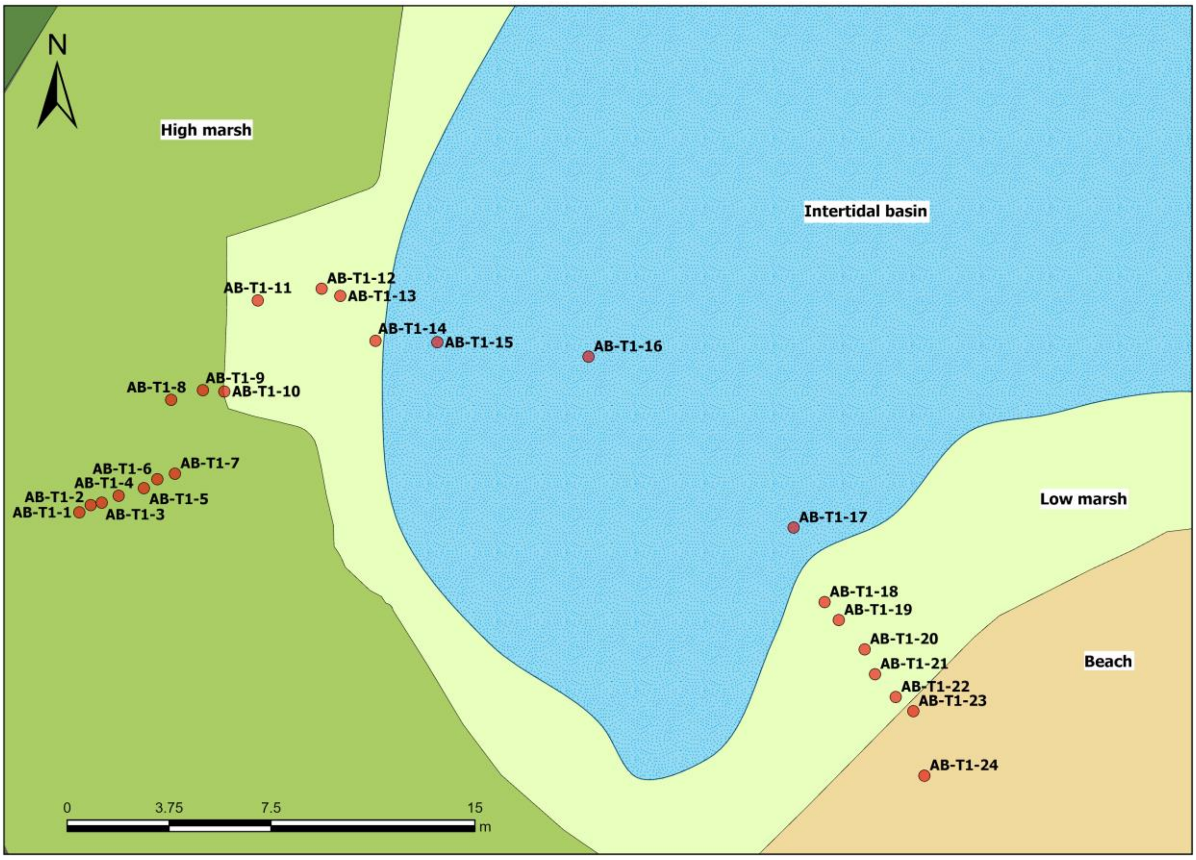


Figure 19: The AB-T1 vegetation transect within the different zones of the marsh.

Transect AB-T2

Along the AB-T2 transect (Figure 20) plant samples were collected from the intertidal basin (AB-T2-1 to AB-T2-2). In the transition from the intertidal basin to the low marsh (AB-T2-3 to AB-T2-7) vegetation samples included short, green graminoids. In the high marsh (AB-T2-8 to AB-T2-19) the vegetation consisted of longer and more yellow graminoids, which became greener landwards, before becoming yellow again (most yellow at AB-T2-18). In this zone vegetation present included *Carex*, and *Comarum palustre*. At AB-T2-16 there is a change in the appearance of the graminoids, where they become more green. Dried seaweed was also observed here, stranded during high tide or a storm. AB-T2-17 was co-located with the highest wrack line and *Comarum palustre* was noted. At point AB-T2-18, *Salix* species dominated. The last vegetation sample (AB-T2-19) was taken in the terrestrial tundra zone with *Empetrum nigrum* dominating, together with some unidentified plants.

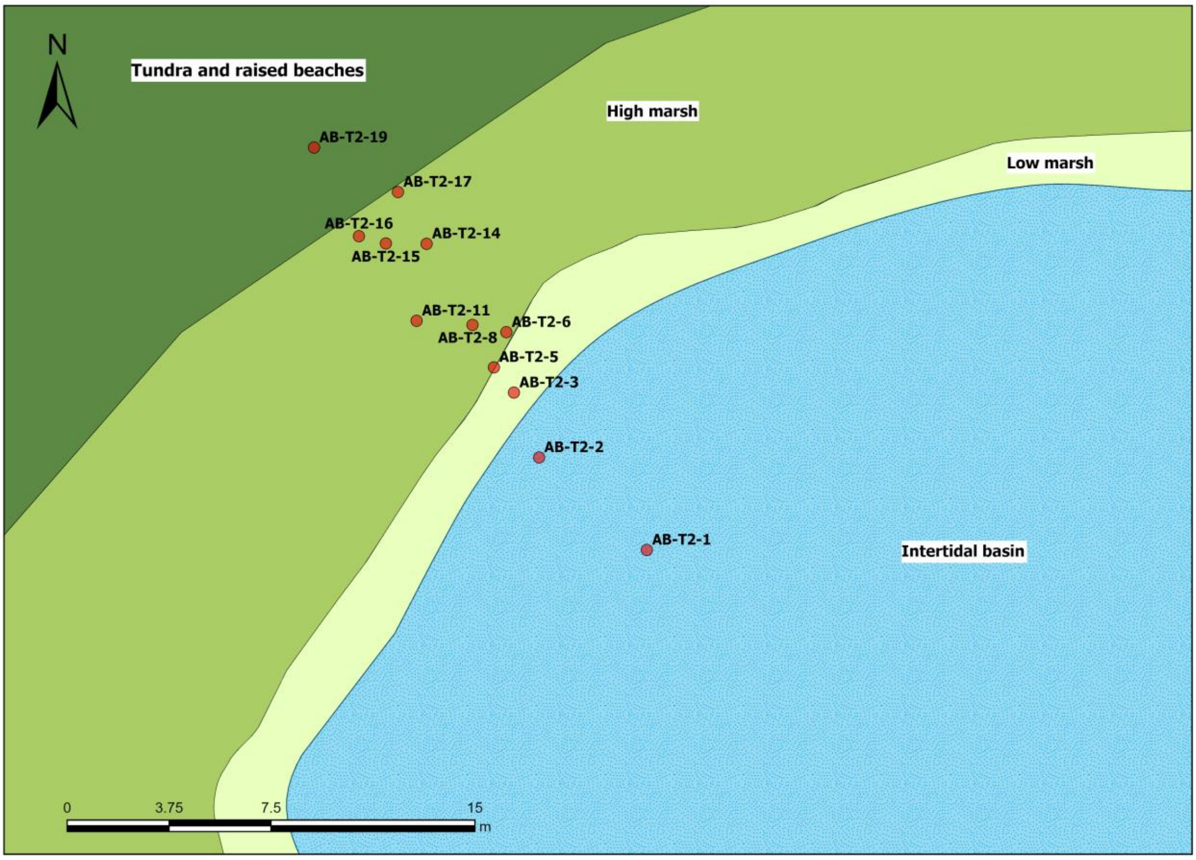


Figure 20: The AB-T2 vegetation sample transect within the different zones of the marsh.

4.2 Surface Sediment and Vegetation C/N, $\delta^{13}C$ and TOC

The surface and vegetation survey follows a transect from the low marsh up to the terrestrial environment at the study site and is divided into different units based on plant composition. Samples were taken along transect AB-T2 and one sample was taken from AB-T1 (AB-T1-24) to represent all zones in the salt marsh (Table 2).

The sample from the beach (AB-T1-24) has a $\delta^{13}C$ value of -28‰ and a C/N ratio of 28. The TOC value from this sample is 33. At point AB-T2-1 which are taken from the intertidal basin the $\delta^{13}C$ value is -18‰, C/N is 19 and the TOC is 27%. At AB-T2-2 the $\delta^{13}C$ value is -17‰ and the C/N is 33, and the TOC is 28%. For point AB-T2-3 which indicates the transition from the intertidal basin to the low marsh, the $\delta^{13}C$ value is -29‰, the C/N is 22 and the TOC is 35%. At AB-T2-5 which indicates the low marsh, the $\delta^{13}C$ value is -26‰, the C/N is 27, and the TOC is 28%. At point AB-T2-6 the $\delta^{13}C$ is -26‰, C/N is 22 and TOC is 25%. For AB-T2-8 which lies in the high marsh zone, the $\delta^{13}C$ value is -28‰, C/N is 30, and TOC is 39%. For AB-T2-11 the $\delta^{13}C$ values is -29‰, C/N is 28, and TOC is 45%. At point AB-T2-14 the $\delta^{13}C$ values is -28‰, C/N is 32, and TOC is 46%. At AB-T2-16 the $\delta^{13}C$ values is -25‰, C/N is 23, and TOC is 42%. For AB-T2-17 the $\delta^{13}C$ value is -17‰, C/N is 31, and TOC is 36%. At AB-T2-19 which marks the beginning of the tundra, the $\delta^{13}C$ value is -29‰, C/N is 47, and TOC is 54%.

Table 2: Vegetation samples

SAMPLE NAME	NORTHING	EASTING	ELEVATION (m)	C/N	$\delta^{13}C$	TOC (%)
AB-T1-24	7841217.18	7841217.18	0.876	28	-28‰	33%
AB-T2-1	7841271.76	583865.23	0.025037	19	-18‰	27%
AB-T2-2	7841275.86	583862.02	0.165801	33	-17‰	28%
AB-T2-3	7841278.37	583861.60	0.381544	22	-29‰	35%
AB-T2-5	7841279.43	583861.05	0.557806	27	-26‰	28%
AB-T2-6	7841280.60	583861.75	0.601248	22	-26‰	25%
AB-T2-8	7841281.11	583860.59	0.73984	30	-28‰	39%
AB-T2-11	7841281.66	583858.61	0.874698	28	-29‰	45%
AB-T2-14	7841284.36	583859.53	0.993413	32	-28‰	46%
AB-T2-16	7841285.12	583857.15	1.139853	23	-25‰	42%
AB-T2-17	7841286.43	583858.88	1.223712	31	-17‰	36%
AB-T2-19	7841288.63	583856.17	1.491853	47	-29‰	54%

Surface samples were taken from the AB-T2 transect (Table 3). At AB-T2-1 the $\delta^{13}C$ value is -15‰, C/N is 11, and TOC is at 0%. For AB-T2-15 the $\delta^{13}C$ value is -28‰, C/N is 17, and

TOC is 41%. At AB-T2-17 the $\delta^{13}C$ is -27‰, C/N is 18, and TOC is 42%. For AB-T2-19 the $\delta^{13}C$ value is -30‰, C/N is 27, and TOC is 49%.

Table 3: Surface sediment samples.

SAMPLE NAME	NORTHING	EASTING	ELEVATION (m)	C/N	$\delta^{13}C$	TOC (%)
AB-T2-1	7841271.76	583865.23	0.025037	11	-15‰	0%
AB-T2-15	7841284.66	583858.06	1.081798	17	-28‰	41%
AB-T2-17	7841286.43	583858.88	1.223712	18	-27‰	42%
AB-T2-19	7841288.63	583856.17	1.491853	27	-30‰	49%

4.3 Cores

In all four cores from the study site, S8K, S9K, S10K, and S11K (Figure 15) the stratigraphy includes organic-rich sediments overlying coarser gravelly sand. The longest core (S8K) was 23 cm and the shortest, 13 cm (S9K). The uppermost organic-rich unit present in all four cores is characterized by abundant whole organic matter (roots, seeds, etc.), particulate organic matter, fine-grained minerogenic sediments, and occasional gravel clasts and sand. The elevation for each core is presented in Table 4.1. Radiocarbon dates from near the contact between the organic-rich sediment and the gravelly-sand in cores S8K and S10K are presented in section 4.7.

4.3.1 Core S8K

Stratigraphy

Core S8K is 23 cm long and is described based on a visual assessment of colour, texture, and structures (Figure 21). The S8K core was taken in the low marsh vegetation zone with at an elevation of 0.63 m.

From the bottom of the core between 20-23 cm the sediments have a mixture of coarse sand, silt, some unsorted gravel, and organic matter present with a dark brown colour.

From 20 to 7 cm the sediments are differentiated by a transition from a dark brown to light-brown organic-rich sediment moving up core. There are small root fragments which are visible throughout the entire unit. Sand and some small gravel particles are also scattered throughout the unit.

Between 7 to 0 cm the sediments are characterized by organic-rich, dark brown sediments with abundant, whole fragments of organic matter (roots). Sediments appear to be fine-grained (sand and silt).

Figure 21 Sediment core S8K (0-23 cm).

TOC, C/N and $\delta^{13}C$

In sediment core S8K, the $\delta^{13}C$ and C/N values (Figure 22) show, for the most part, parallel trends, while TOC negatively covaries with $\delta^{13}C$ (and also with C/N except in the upper 5 cm of S8K). Between 23 and 21 cm $\delta^{13}C$ and C/N values decrease from -16‰ to -27‰ and from 26 to 18, respectively, while TOC (%) increases from 3.5 to 9. From 20 to 8 cm, $\delta^{13}C$ increases, decreases, then increases again between -30‰ to -18‰, while C/N varies back and forth in a similar way between approximately 17 and 26. In the same interval TOC (%) again shows the opposite trend, decreasing from 11 to 4, then fluctuating around 4-6%, increasing to approximately 8%, then decreasing to about 5% at 8cm downcore. From 7 cm to the top of the core, $\delta^{13}C$ decreases in value (-21‰ to -26‰; although there is a slight increase in the upper cm), while C/N decreases to 14, then increases in the upper few cm to 22. TOC (%) shows an overall increasing trend from 6 to 14% in the upper 7 cm of S8K.

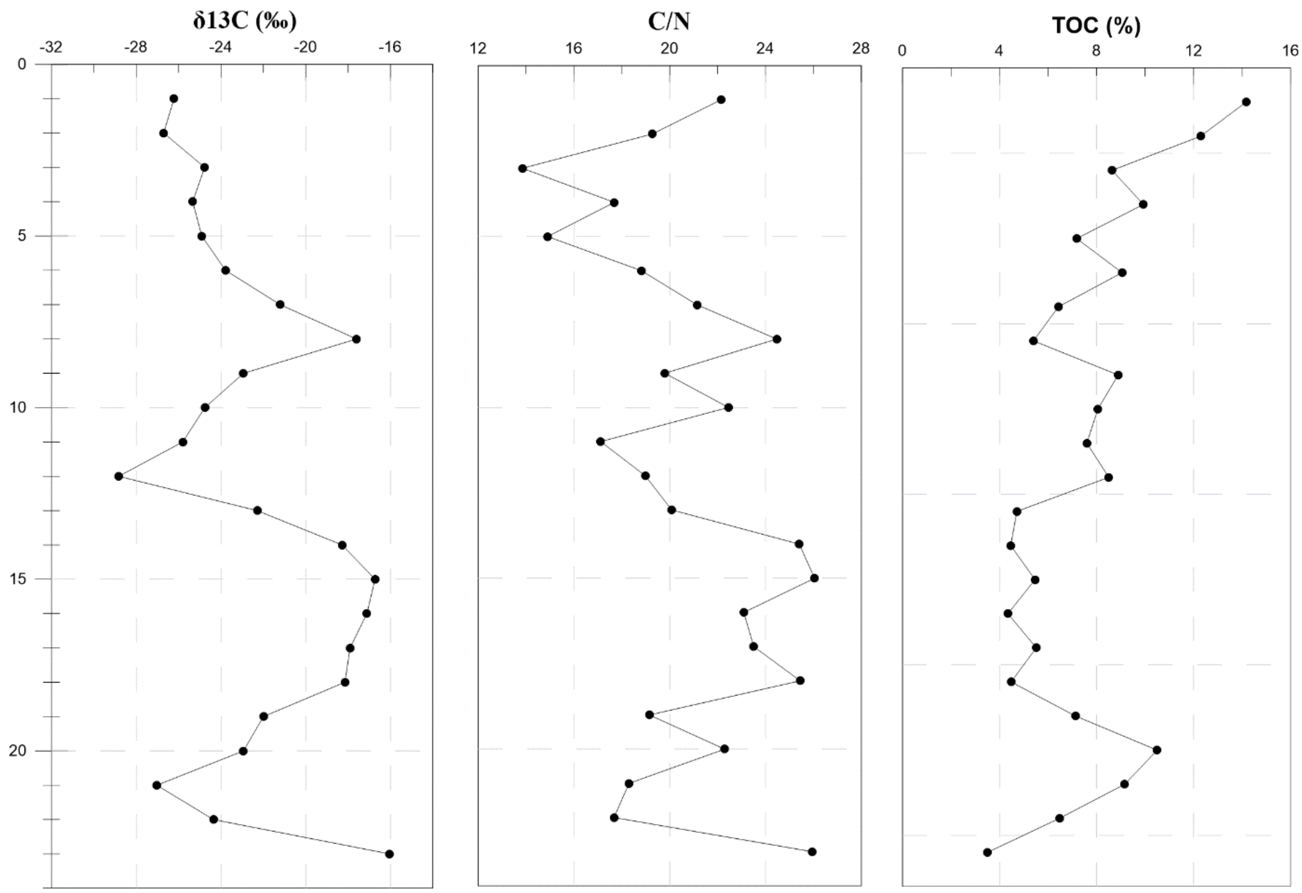


Figure 22: $\delta^{13}C$, C/N and TOC values for S8K.

4.3.2 Core S9K

Stratigraphy

S9K is a 13 cm long core (Figure 23) which has 12 cm with roots that stretch further down then the actual core. The S9K core was taken from near the edge of the intertidal basin in the low marsh vegetation zone at an elevation of 0.41 m. This core is described based on visual inspection of colour, structures, and texture.

From the bottom of S9K (i.e. the lowest depth) between 13 and 11 cm the sediments have abundant root fragments and are a greyish brown colour. There is one angular gravel clast at 12 cm that is approximately 2 cm in diameter.

From 11 to 4 cm there is a sudden colour change to a lighter brown and there are whole fragments of organic matter present. There appears to be coarse and unsorted sand present. Two fragments of angular gravel, both 2 cm in diameter, were observed between 3-5 cm depth.

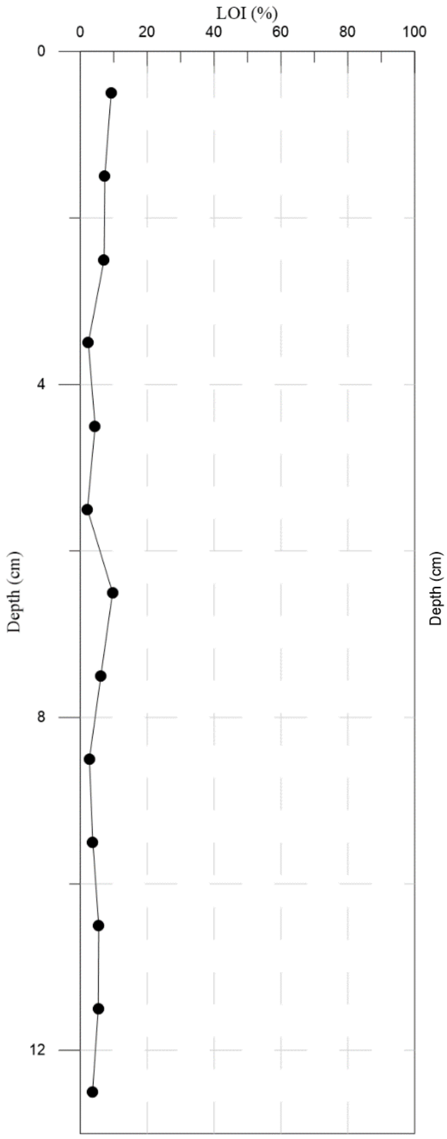
The uppermost sediments from 3-0 cm are an almost black to- dark brown in colour and have some visible root fragments but appears to consist mostly of unsorted coarse sand.

Figure 23: Sediment core S9K (0-13 cm).

Loss on ignition

The result of the LOI for S9K is presented in figure 24 Percent organic content above the gravelly-sand unit is low, consistently less than 10%. Within this range, there is a decreasing trend between the top of the core and about 4 cm depth, followed by an increase in organic content at 7 cm core depth. Further down core it decreases at about 9 cm depth and then increases at 10-12 cm depth before decreasing again towards the base of the core.

The results obtained from the two-hour ignition at 1000ºC show almost no detectable reduction in weight (Figure 25).



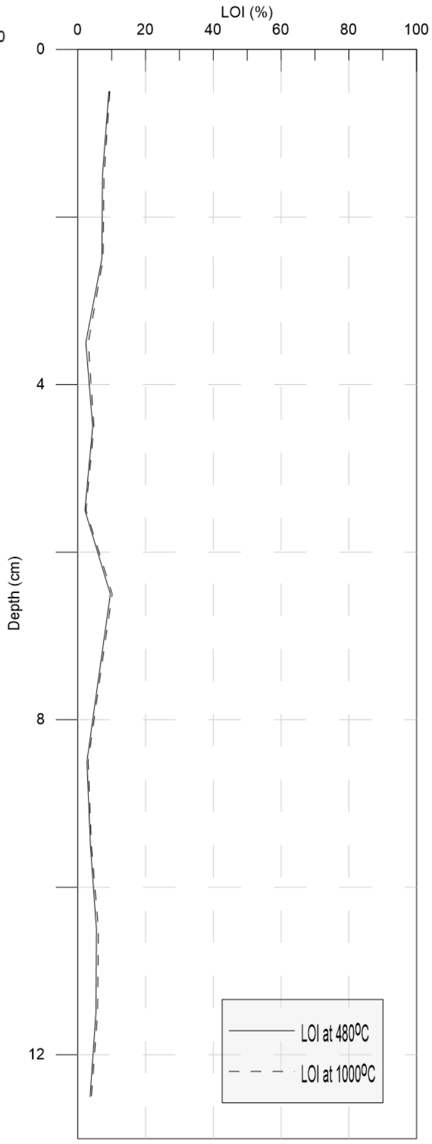


Figure 24: LOI for S9K.

Figure 25: LOI difference between 480ºC and 1000ºC for S9K.

TOC, C/N and $\delta^{13}C$

Between the base of S9K (Figure 26) and 11 cm, $\delta^{13}C$ and C/N values decrease from -8‰ to -20‰ and from 73 to 27, respectively. TOC (%) increases from 2 to 4%. From 10 to 4 cm, $\delta^{13}C$ fluctuates between -14‰ and -17‰, and C/N between 40 and 31, while TOC (%) increases to 6% then decreases to 3%. From 3 cm and to the top of the core, $\delta^{13}C$ decreases from -16‰ to -25‰, C/N decreases from 25 to 15, and TOC (%) increases from 2 to 4%.

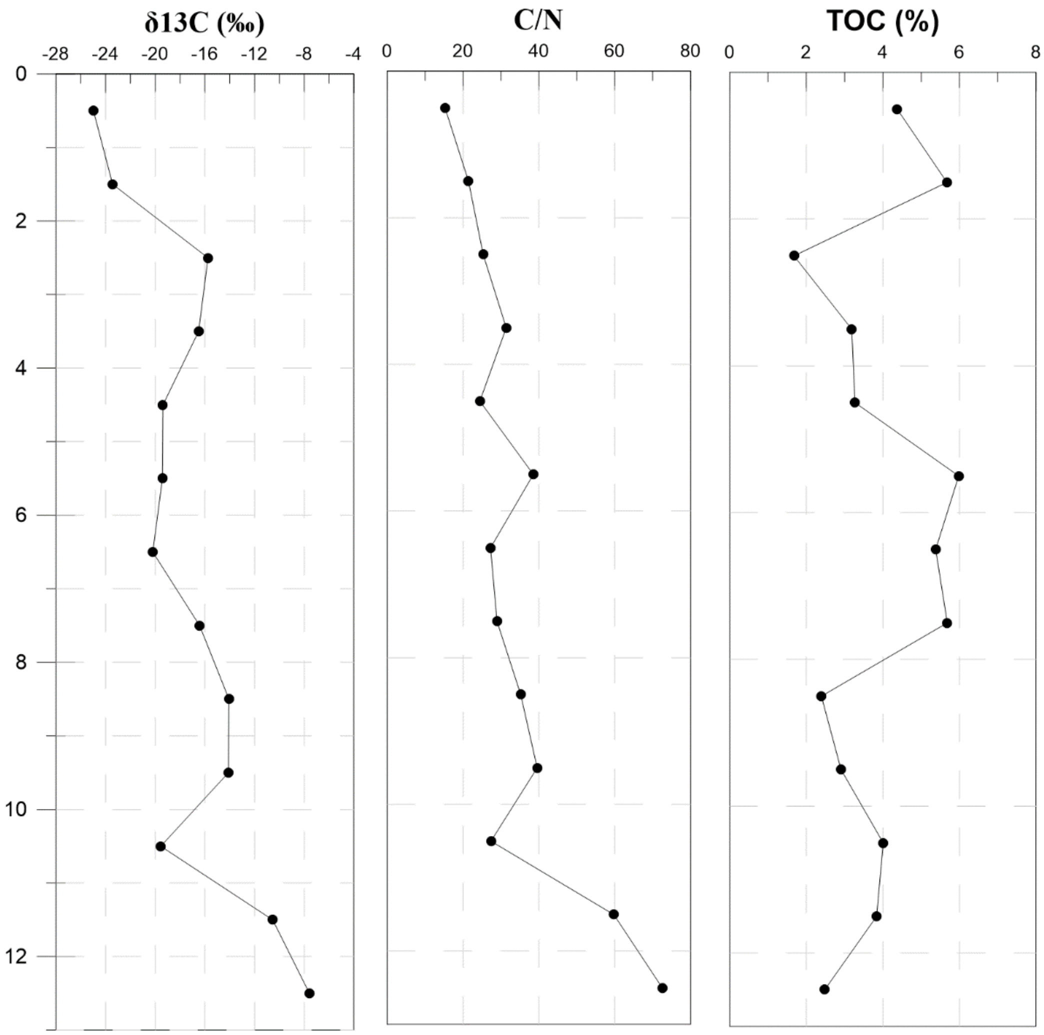


Figure 26: $\delta^{13}C$, C/N and TOC (%) values for S9K.

Grain size analysis

In S9K, the minerogenic sediment component consists of moderately well-sorted sand, which becomes slightly coarser, then finer moving down core (Figure 27). Minerogenic sediments at the base of the core, between ca 11 and 13 cm, consist of coarse silt (40-50 microns).

Between 4 and 10 cm, sediments are predominantly sand, finding downwards to coarse silt (~40-400 microns). The top of the core (0-3 cm) also consists primarily of medium sand (~350-400 microns).

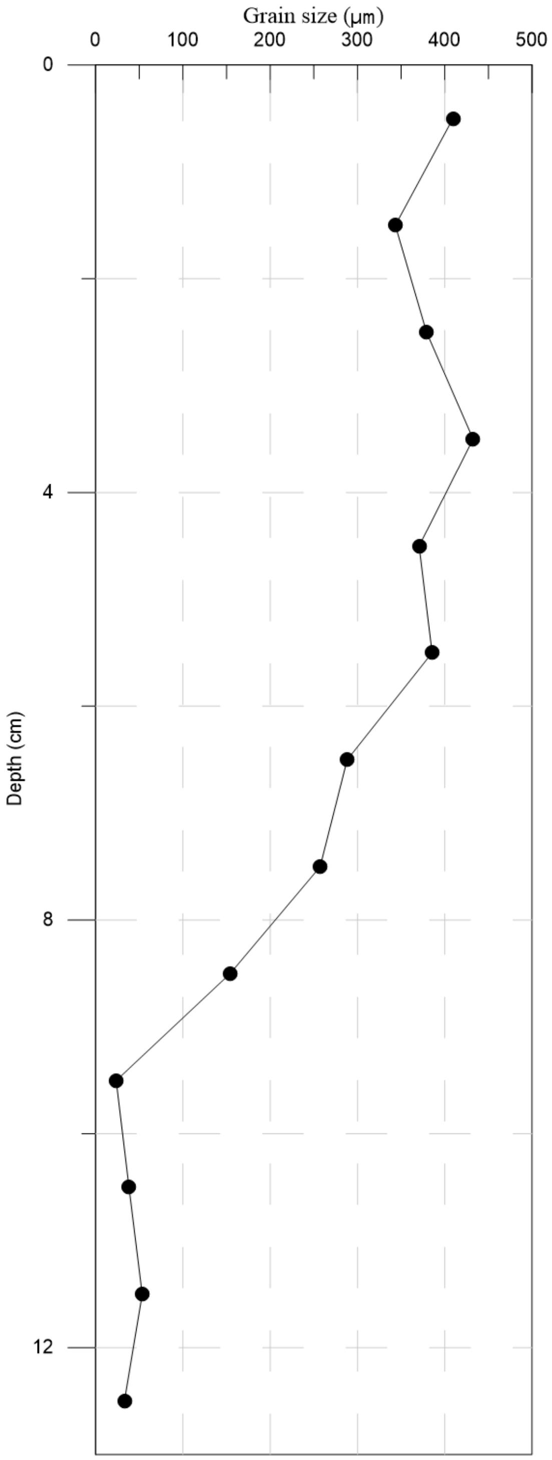


Figure 27: Grain size for S9K.

4.3.3 Core S10K

Stratigraphy

S10K is a 17 cm core (Figure 28) and was taken from the high marsh at an elevation of 0.75 m. This core is described based on visual visible changes in colour, structures, and texture.

Between 17 and 14 cm (i.e. the bottom of the core) sediments appear to consist of whole and particulate organic matter as well as coarse sand and some small pieces of gravel.

From 13 to 6 cm the sediments are light brown in colour with root fragments throughout (some black root fragments). This section also appears to contain some sand and gravel that is, finer in size than that below.

At 4.5-5.5 cm depth there is a fine, 1-2 cm layer of lighter brown gravel, sand, and organic matter. Otherwise, the interval from 6 cm to the top of the core can be described as dark brown with many organic fragments, including roots. Grains of fine sand also appear towards the top.

Figure 28: Sediment core S10K (0-17 cm).

TOC, C/N and δ13C

Between 17 and 14 cm in core S10K (Figure 29), $\delta^{13}C$ and C/N values decreases from -5‰ to -17‰ and from 54 to 22, respectively. TOC (%) values range from 3 to 2%. Between 13 and 6 cm, $\delta^{13}C$ fluctuates from -10‰ to -11‰ with low values of -18‰ in between, while C/N ranges from 35 to 27 and TOC (%) is steady at 3%. From 5 cm and to the top of the core, $\delta^{13}C$ values decrease from -5‰ to -24‰ and C/N values from 48 to 16. TOC (%) increases from 2 to 17%.

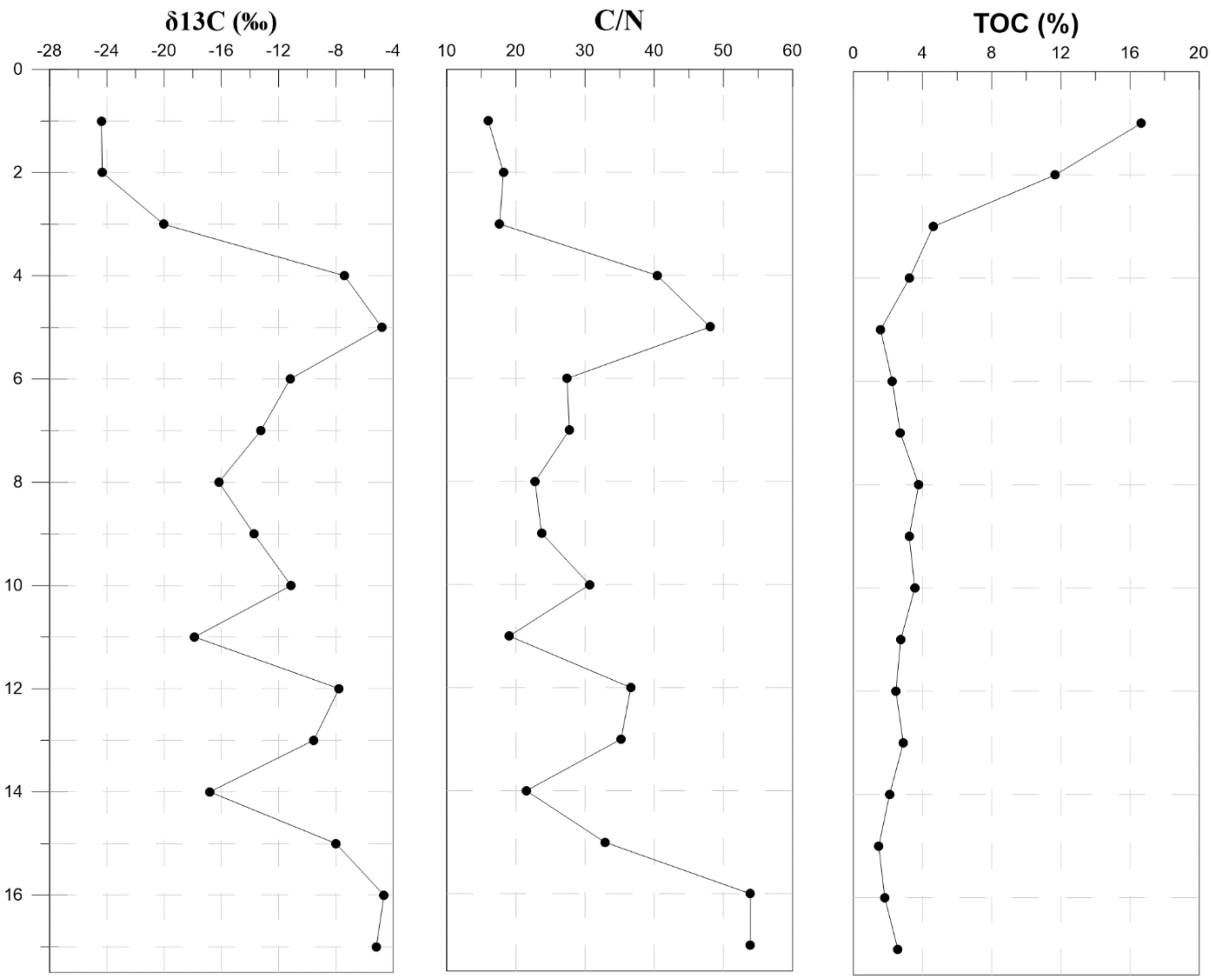


Figure 29: δ^{13}C, C/N and TOC values for S10K.

4.3.4 Core S11K

Stratigraphy

S11K is 17 cm in length (Figure 30). This core was taken from the high marsh at an elevation of 0.84 m. The core is described based on visual inspection of colour, texture, and structures.

At the bottom of the core, between 17 and 15 cm, sediments consist of light to medium brown sand. Some pieces of gravel are also present alongside root fragments.

From 14 to 13 cm sediments are dark brown and appear to be more compact than at the base of the core. There appears to be diffuse sand present throughout this interval. Small root fragments are also visible. In the lower part of the layer against the border to the bottom of the layer, there is one piece of angular gravel, 0.5 cm in diameter, at 14,5 cm depth.

Between 12 and 4 cm the sediments in S11K are light brown, which becomes darker, further up. Some sand and gravel are present towards the base of this interval, including an angular gravel clast, 0.5 cm in diameter. Root fragments are visible throughout.

The upper part of the core (3-0 cm) is characterized by dark brown, organic-rich sediment. Large roots are visible throughout the layer.

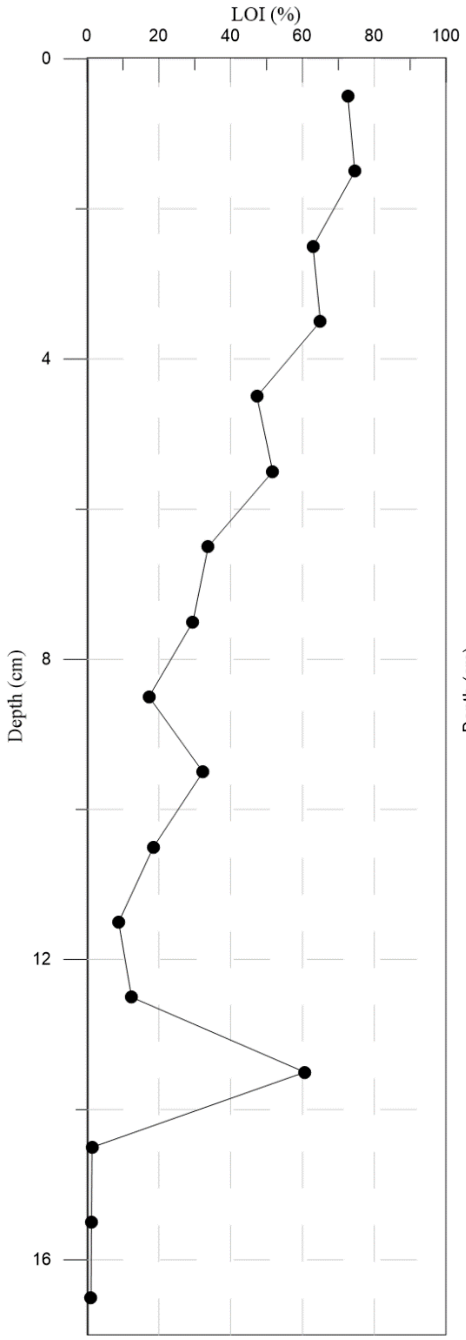
Figure 30: Sediment core S11K (0-17 cm).

Loss on ignition

Figure 31 presents results of the LOI analysis at 480ºC and 1000ºC for S11K.

Percent organic content in S11K at 480ºC ignition ranges from almost 0% to over 70% and shows a clear, decreasing trend down-core except for a large spike at 14 cm down core.

For the two hour ignition at 1000ºC, it was little change in the weight loss (%), compared to the ignition at 480º (Figure 32). It was almost no detectable reduction in weight.



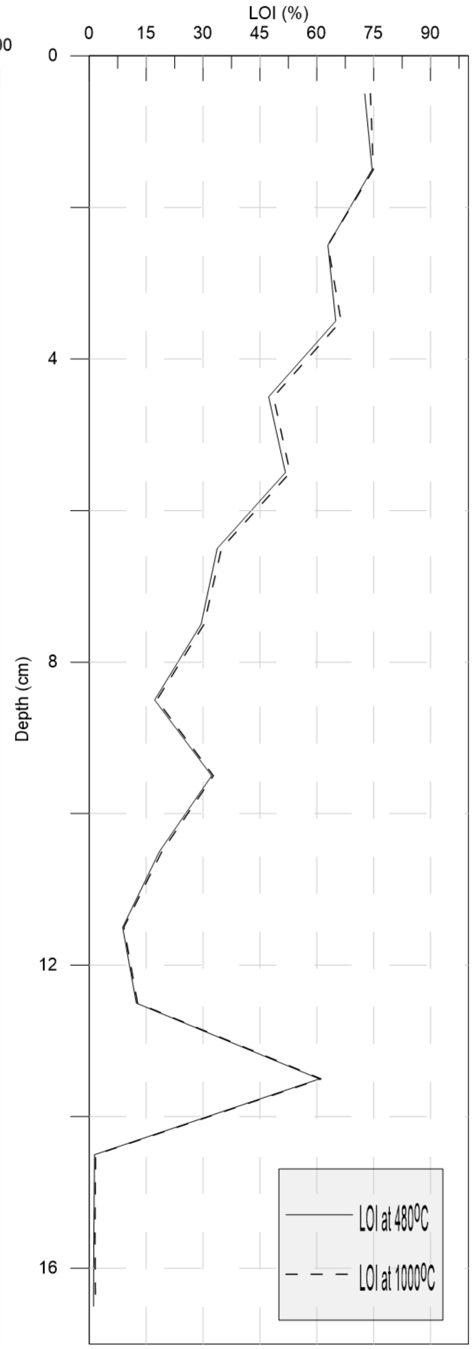


Figure 31: LOI for S11K.

Figure 32: LOI between 480ºC and 1000 ºC for S11K.

TOC, C/N and δ13C

For core S11K (Figure 33), $\delta^{13}C$ and C/N values between 17 and 15 cm hover around -5‰ to -6‰ and C/N increases from 40 to 43, with a TOC (%) value of 1%. From 14 to 13 cm, $\delta^{13}C$ decreases from -18‰ to -27‰ and C/N from 20 to 17, with TOC (%) from 2 to 33%. From 12 to 4 cm hovers around $\delta^{13}C$ values from -21‰ to -27‰ and C/N values from 16 to 14 and TOC (%) from 3 to 31%. The upper 3 cm of S11K have $\delta^{13}C$ values ranging from -24‰ to -28‰, C/N values from 14 to 19, and TOC (%) values from 32 to 37%.

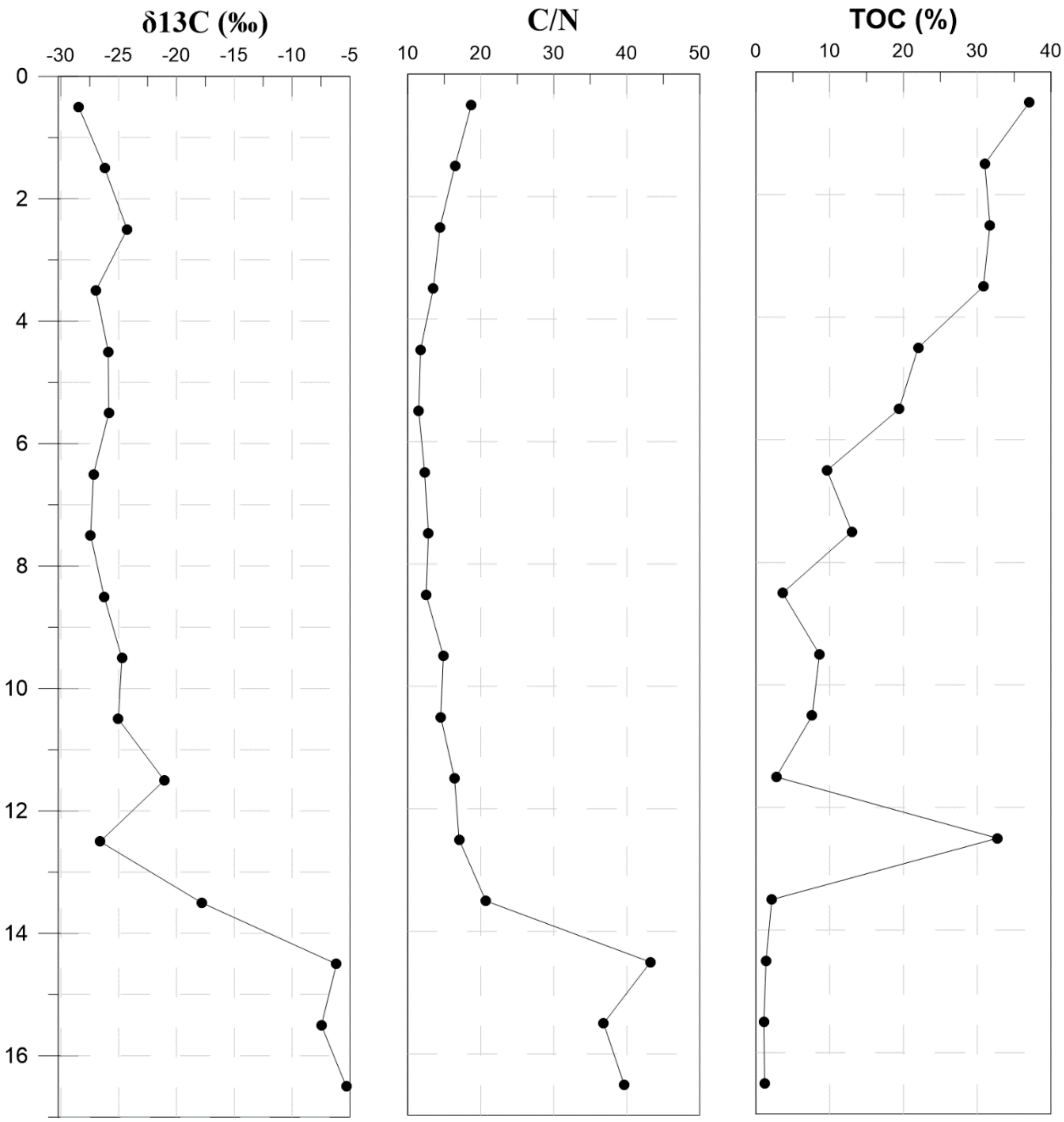


Figure 33: δ13C, C/N and TOC values for S11K.

Grain size analysis

In S11K, grain size fines upwards overall (Figure 34). The sediments at the bottom of the core (17 to 15 cm) consist of coarse sand (800 microns), with some gravel pieces. From 14 to 13 cm the sediments shift towards a sandy mud (600-100 microns). Between 12 to 4 cm the sediments also consist of fine sand to coarse silt (200-50 microns), with occasional gravel fragments. At the top of the core the sediments consist of very fine sand, silt and clay (100-10 microns).

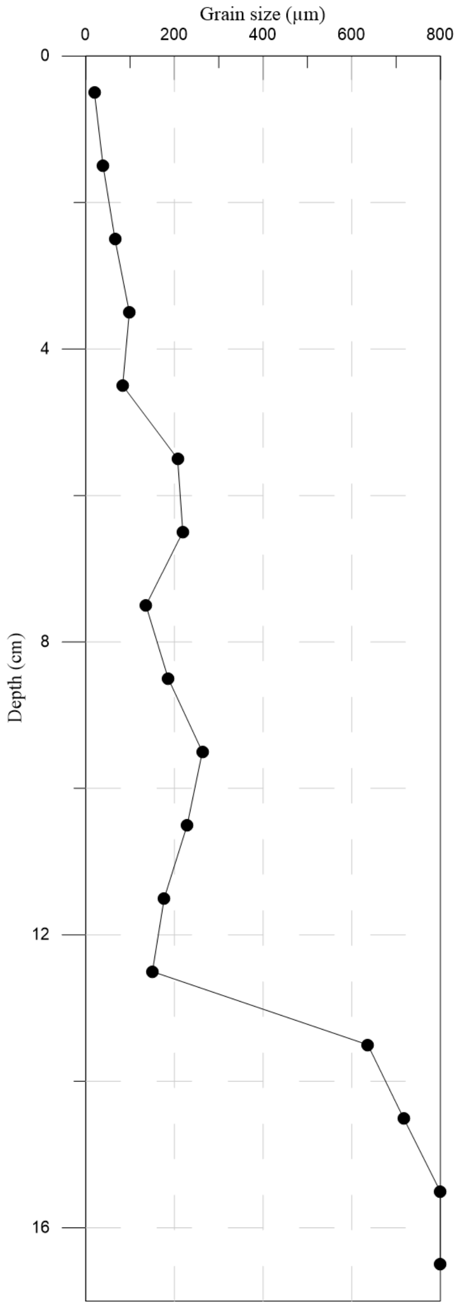


Figure 34: Grain size for S11K

4.4 Radiocarbon dating and sedimentation rates

Below in table 4 are the radiocarbon dated samples of organic matter extracted from Kongsfjorden sediment cores S8K and S10K. The calibrated dates are presented in years AD. Sedimentation and carbon accumulation rates are also presented in the same table.

Table 4: Radiocarbon dates and carbon accumulation rates for cores S8K and S10K, determined by ^{14}C.

Core	Depth (cm)	Weight	Dated material	Uncalibrated age BP	Calibrated age (2 sigma)	Sedimentation rate	CAR (g $C*m^{-2}*year^{-1}$)
S8K	22-23 cm	7 mg dry weight 1.527g wet weight	Plant remains (seeds) & Alkali residue	286±17 BP	1522 to 1656 AD	Min: 0.46 mm/yr Max: 0.63 mm/yr	3.0×10^{-3} m/yr
S10K	12,5-13,5 cm	10 mg dry weight 6.660 g wet weight	Plant remains (seeds) & Alkali residue	80±13 BP	1697 to 1912 AD	Min: 0.41 mm/yr Max: 1.23 mm/yr	4.37×10^{-4} m/yr

5 Analyses and discussion

In order to understand past environmental change and potential impacts of global warming on a small coastal area near Kongsfjord, Finnmark, this study has documented different sources of sediments (organic and minerogenic) over the past several hundred years in an Arctic salt marsh. Such proxies, including grain size, stable isotopes of carbon and nitrogen, have been used in previous research to document energy and RSL change, and sources of organic matter deposited on the marsh surface (e.g. Faust & Knies, 2019; Lamb et al., 2006). In the following sections the results of our analyses are discussed for each core and all together to understand how the Kongsfjorden salt marsh has responded to recent changes in RSL and its role as a sink for blue carbon.

5.1 Elemental proxy

S8K

The analysis of sediment core S8K reveals variations in the characteristics and compositions in organic matter through different depths (Figure 35), which provides insight in the deposition processes within this environment. The C/N and $\delta^{13}C$ values are plotted together based on Lamb et al., (2006) figure which shows the different organic matter inputs to coastal environments.

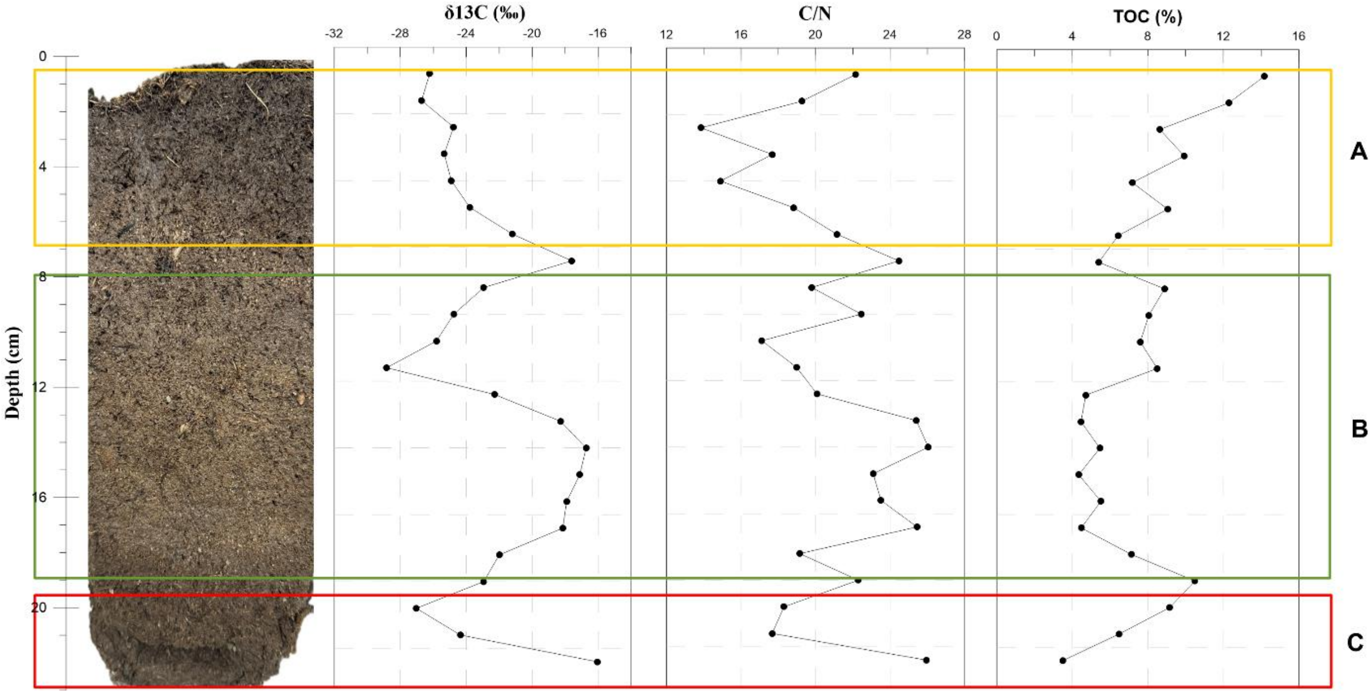


Figure 35: $\delta^{13}C$, C/N and TOC values for S8K, divided into units based on their correlation.

Unit C shows $\delta^{13}C$ values that are quite variable $\delta^{13}C$ suggesting that the organic matter originate from freshwater and marine sources (Figure 36), as well as values within the C_4 plant range. Since we do not have C_4 plants in Norway, this value could rather indicate the presence of seagrasses or algae (Khan et al., 2015). The high C/N ratio suggest that the organic matter input are from freshwater and marine DOC. Together with low TOC this indicates that the organic matter accumulation was not that high, and it was a significant decomposition of organic matter. Moving up the core towards unit B the values stabilizes more and fluctuates around a mean. The low $\delta^{13}C$ values together with the C/N indicates that the organic matter source originate from both marine and freshwater DOC, but also here some values are within the C_4 range. The TOC also fluctuates, but shows an overall decrease in this unit, indicating that the accumulation of organic matter was low. Towards the top of the core (unit A) there is a decrease in both $\delta^{13}C$ and C/N, but with a slight increase in the upper cm. This suggest that the organic matter input originate from freshwater and marine DOC, as well as C_3 terrestrial plants. The TOC shows an overall increase towards the top indicating greater conditions for the accumulation of organic matter.

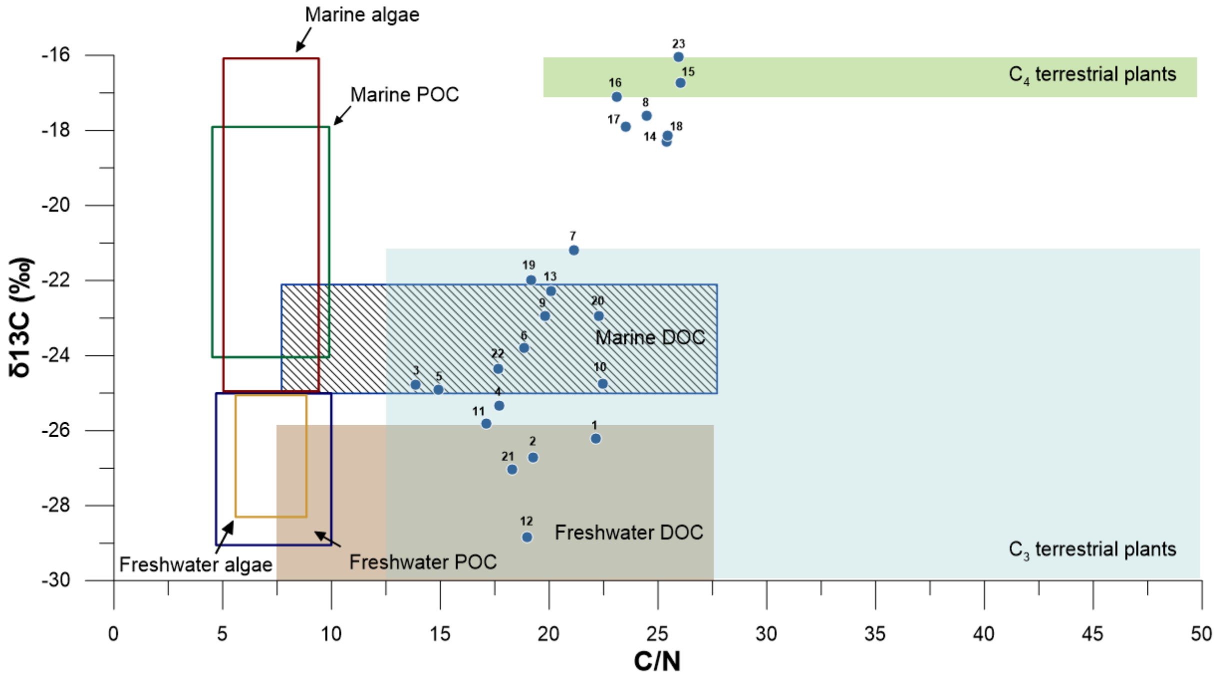


Figure 36: δ¹³C and C/N values for S8K.

Core S8K suggest a transition from a marine to a freshwater environment. This transition could indicate historical changes in both sea level and input of sediments, hence reflecting a retreating salt marsh or changes in the hydrological conditions.

S9K

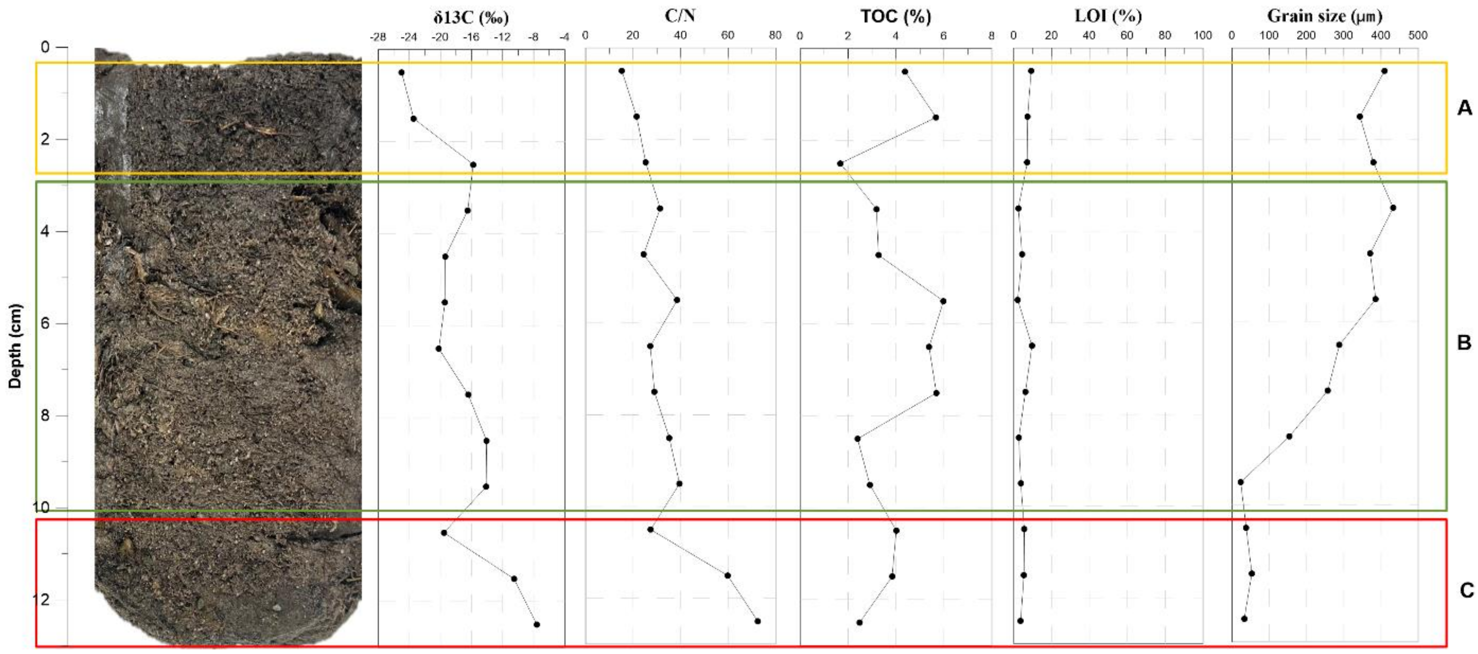


Figure 37: δ13C, C/N and TOC values for S9K, divided into units based on their correlation.

At the bottom of the core (unit C; Figure 37) $\delta^{13}C$ values are high, and based on Mackie et al., (2007) these values suggest that it is a marine environment. The $\delta^{13}C$ together with C/N (Figure 38) have values within the C_4 range, which then could indicate based on Khan et al., (2015) that there is presence of seagrasses and algae within the sediments. The very low TOC together with low LOI indicates significant decomposition. Together with the grain size below 100 µm, this suggest low-energy conditions, causing finer sediments to get deposited. Moving up core (unit B) are stable, and $\delta^{13}C$ values indicate a marine environment, and also here low $\delta^{13}C$ values together with high C/N are within the C_4 plant range. TOC together with LOI increases a bit before it decreases again towards the top of the unit. However, the grain size increases up to 450 µm, and this high-energy could come from either a storm surge event or sea-ice, which could have a great impact on sediment dynamics in Arctic coastal environments. At the top of the core $\delta^{13}C$ and C/N decreases. The $\delta^{13}C$ values suggest that we go from a marine to a brackish environment, with the source of organic matter coming from marine DOC. The TOC and LOI increases, and the grain size increases reflecting a high-energy environment.

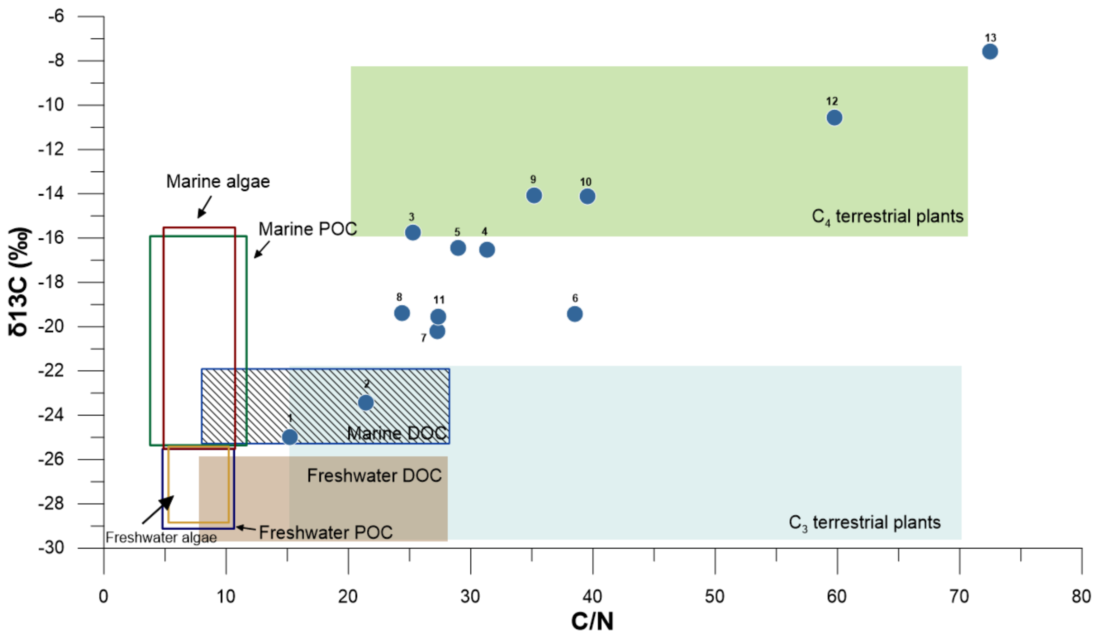


Figure 38: δ13C and C/N values for S9K.

The data suggest that we went from a marine to a brackish environment.

The grain size in the low unit of the core (unit C) suggest lower conditions and deposition in sheltered areas. In the units further towards the top of the core, the grain size is coarser which indicates high energy conditions or input from sources that are nearby. The sorting of sediments is also a factor to consider. Where the sorting is well sorted means that it is further away from the input source. While if we have poorly sorted grains the sediments have been transported closer to the source. For S9K (Figure 39) we see that the sorting is moderately sorted in the uppermost layers 0-6 cm and poorly sorted for the bottom layers of the core 7-13 cm. This then suggests that the core has been involved in a shift, where at the formation of the salt marsh it was close to the source of sediment, while it is now further away from the source of input. Rahman and Plater (2014) has linked this "sorting" to processes such as elevation and flow velocity of tidal currents. They state that the mean grain size will decrease as the wave energy decreases. Based on this we can assume that at the bottom of the S9K core where the mean grain size is fine and poorly sorted the incoming wave velocity and tidal currents increased. Towards the upper part of the core, the mean grain size decreases and gets coarser and the grains are moderately to well sorted. This could also indicate a shift from a high marsh to a low marsh. According to Rahman and Plater (2014) the uppermost salt marshes are associated with fine grained which are poorly to very poorly sorted, while the lower salt marsh are associated with more coarse grained which are moderately to well sorted. In the case of this salt marsh, the upper part of the core which is the part that gets submerged frequently show both coarser grains and a better sorting than downcore. However, the bottom of the core according to this explanation of high marsh ecosystem, indicates that this salt marsh was a high marsh. Being higher up in elevation than today it did not get subjected to tidal currents and high wave velocity as often as it does today. With low energy the sediment accretion could be enhanced, and it will promote vertical accretion. With high-energy we can see an increase in erosion and reworking of the sediments, and this could therefore potentially compromise the elevation of the marsh and its resilience to RSLR.

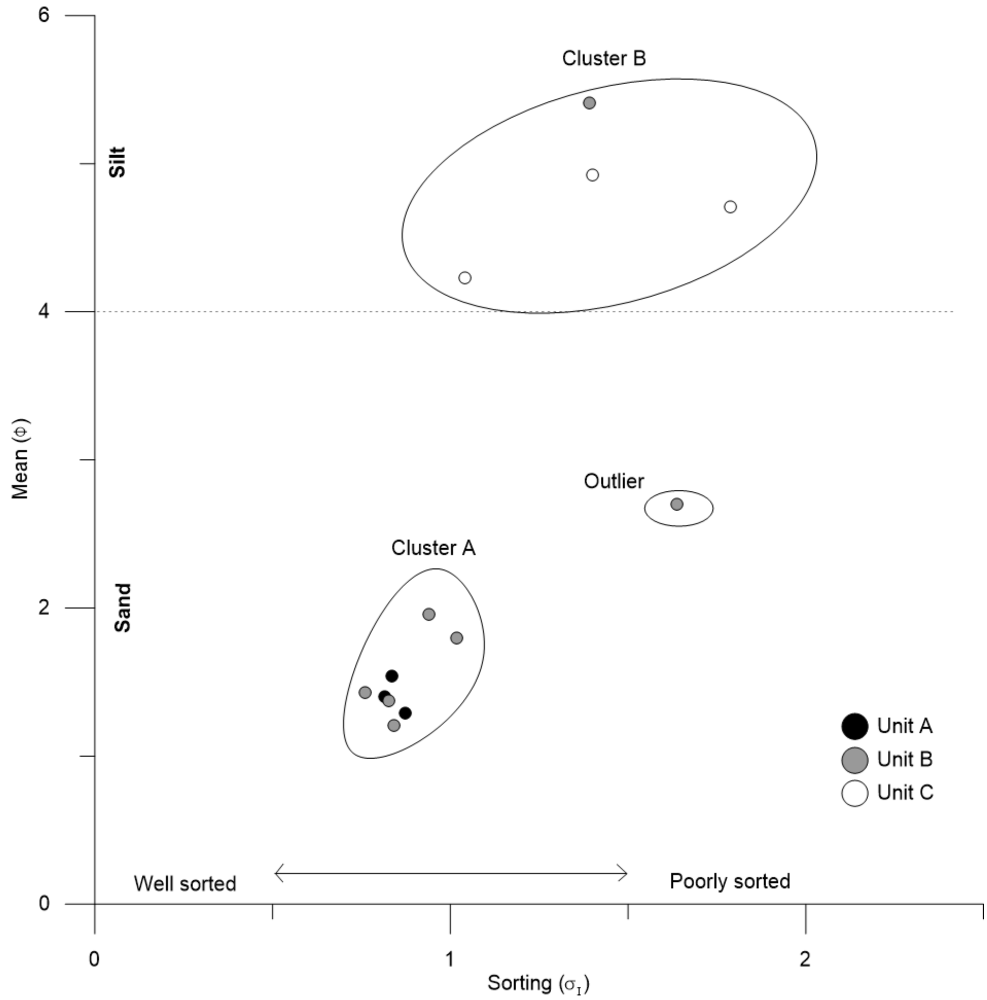


Figure 39: Bivariate plot of mean (ϕ) against sorting (σI) for all samples from S9K. Two clusters are observed. Cluster A is predominately sand and are well sorted. The single sample that does not have a cluster, consists of fine sand and are poorly sorted. Cluster B is associated with silt deposits.

S10K

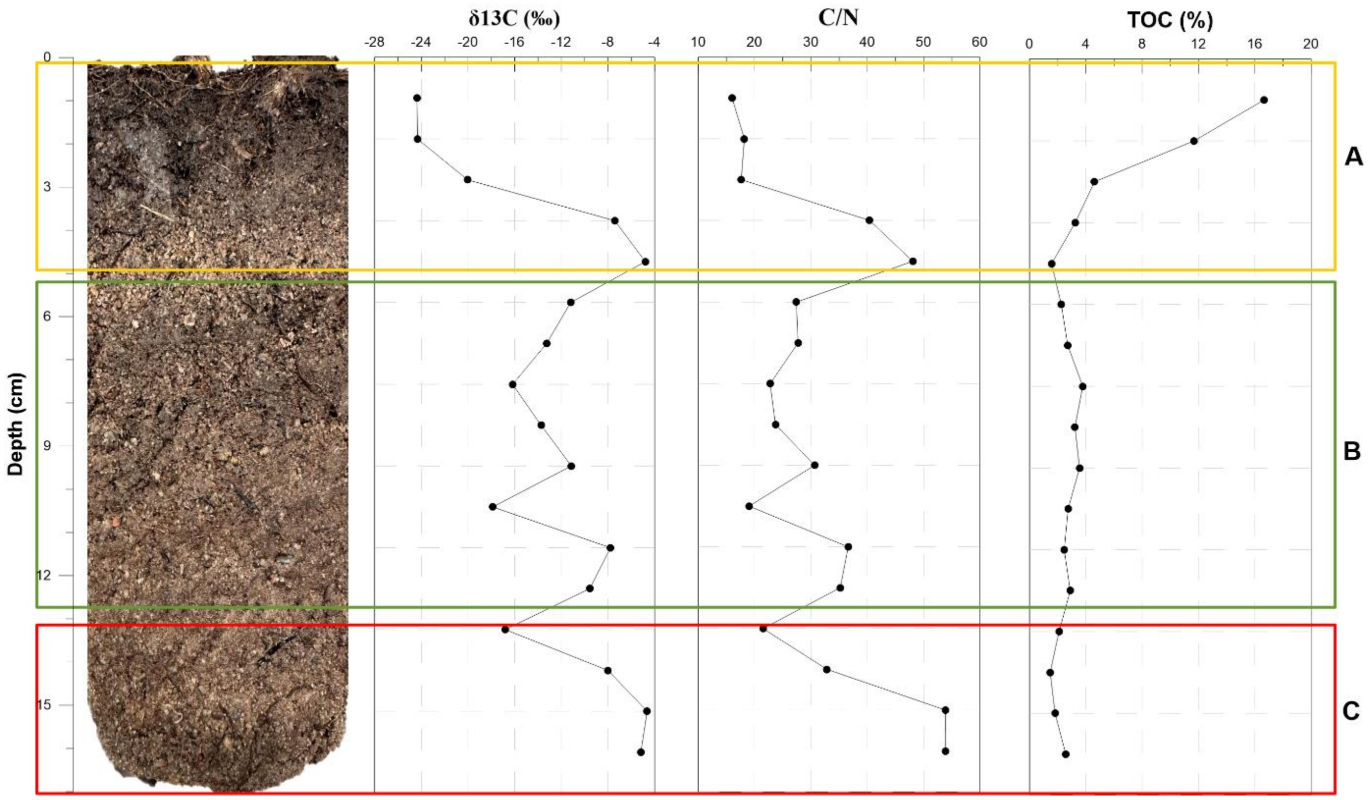


Figure 40: δ13C, C/N and TOC values for S10K, divided into units based on their correlation.

In core S10K unit C (Figure 40), the $\delta^{13}C$ values are high together with high C/N. This indicates a marine environment and the organic matter source falls within the C_4 plant range (Figure 41), which could indicate the presence of seagrasses and algae (Khan et al., 2015), as well as inputs from marine DOC. The TOC is very low, which suggest low accumulation, and a high decomposition rate. In unit B the $\delta^{13}C$ and C/N fluctuates, but the values are still indicative of a marine environment. The TOC also increases in this unit suggesting that the accumulation of sediments are higher. The source of organic matter also falls within the C_4 plants range suggesting input from seagrasses and algae. Towards the top of the core (unit A) the $\delta^{13}C$ values decreases indicating a shift from a marine to a brackish environment. The source of organic matter in the uppermost part of the core originate from C_3 vegetation, marine DOC and possibly seagrasses and algae sources. The TOC increases as well towards the top, and together with C/N this upper layer is a zone of high carbon sequestration, with high organic matter input.

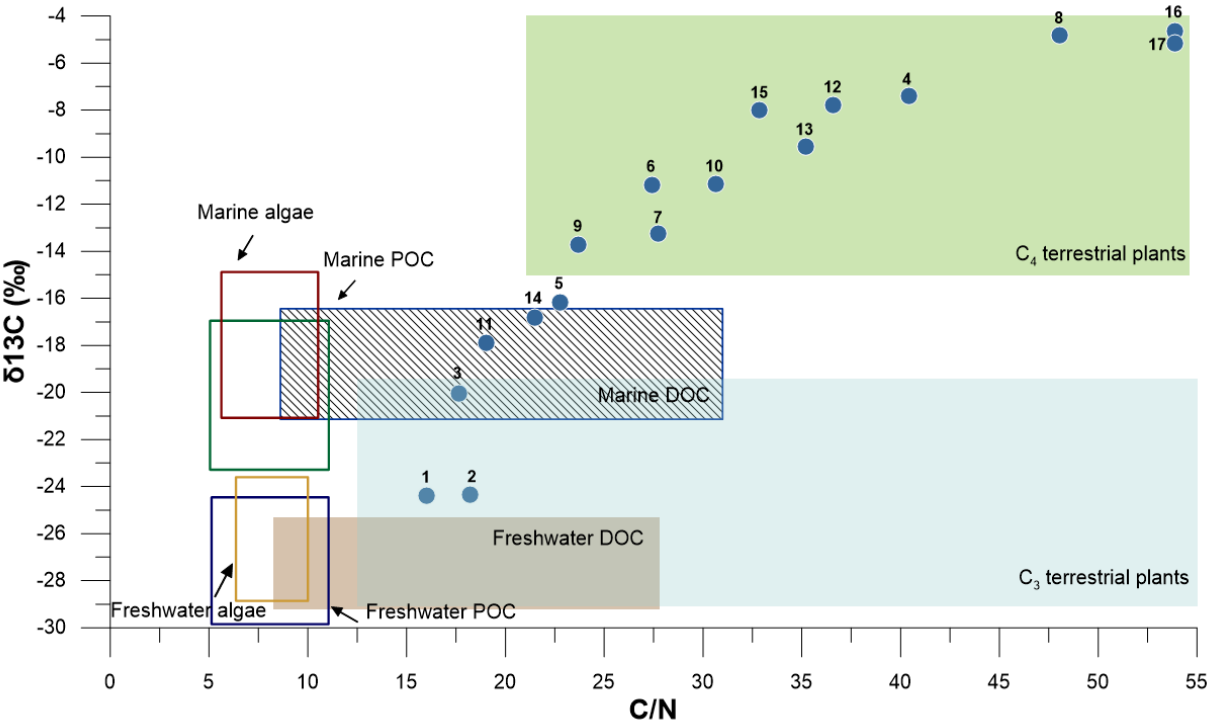


Figure 41: δ13C and C/N values for S10K.

S11K

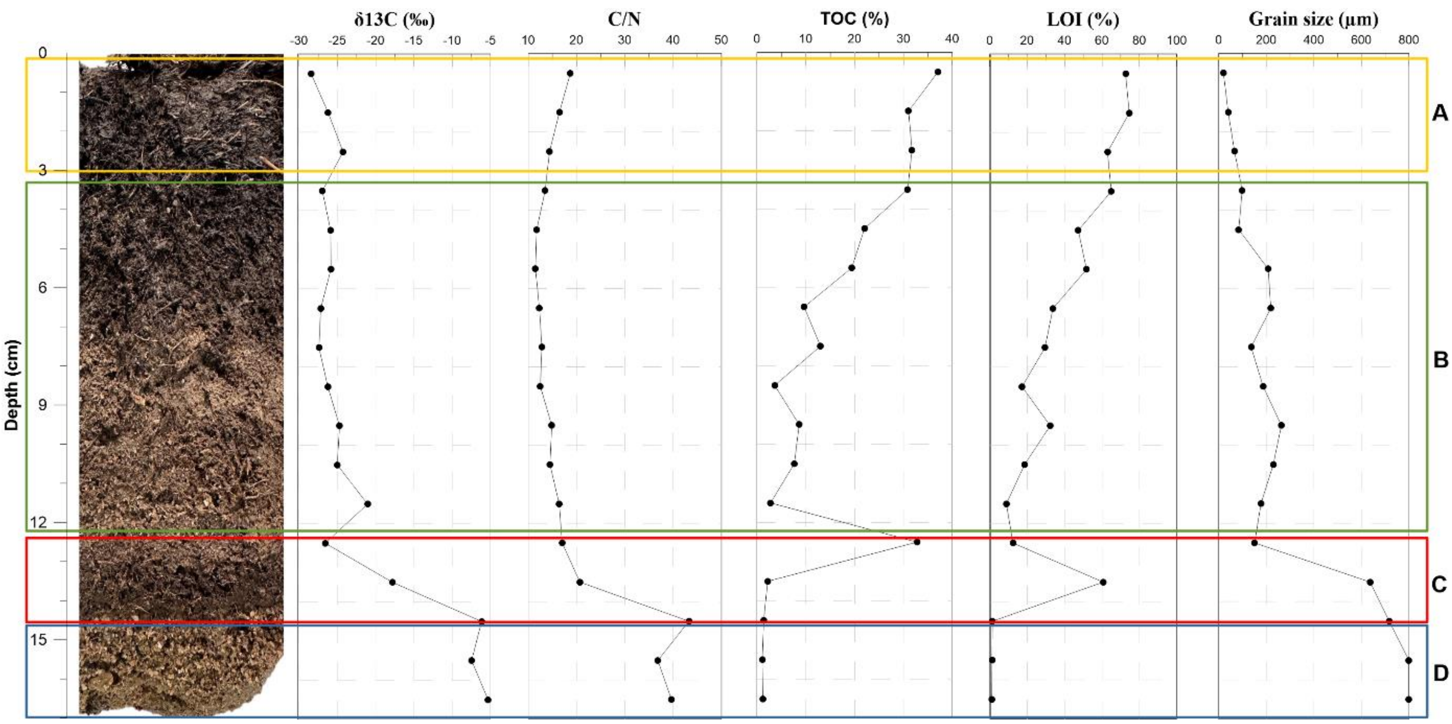


Figure 42: δ13C, C/N and TOC values for S11K, divided into units based on their correlation.

In S11K, unit D (Figure 42) the $\delta^{13}C$ values indicate a marine environment, together with the C/N (Figure 43) the source of organic matter falls within the C_4 terrestrial plant range, which since there are no C_4 plants in Norway, indicate the presence of seagrasses and algae (Khan et al., 2015). The TOC and LOI suggest that we had an environment with low accumulation and more decomposition of organic matter. The high value of grain size indicate a high-energy environment. In unit C we get a shift from marine to freshwater environment with the source of organic matter coming from freshwater DOC. In this unit TOC and LOI get a huge spike which indicates great conditions for the accumulation of organic matter. The grain size decreases which indicates a low-energy environment as well. In unit B the $\delta^{13}C$ and C/N values stay stable, and the source of organic matter originate from freshwater DOC, marine DOC and from C_3 terrestrial plants. The TOC and the LOI increases giving way for favourable conditions for the accumulation of organic matter. The grain size decreases which indicates a low-energy environment where finer sediments settles. At the top of the core (unit A) the $\delta^{13}C$ and C/N values indicates that the source of organic matter is derived from freshwater DOC and marine DOC. The TOC and LOI continues to increase, and the grain size gets finer. This is consistent with observations by Adam (2002) who observed that high accumulation of organic matter together with fine grain size are indicative of stable and productive salt marshes.

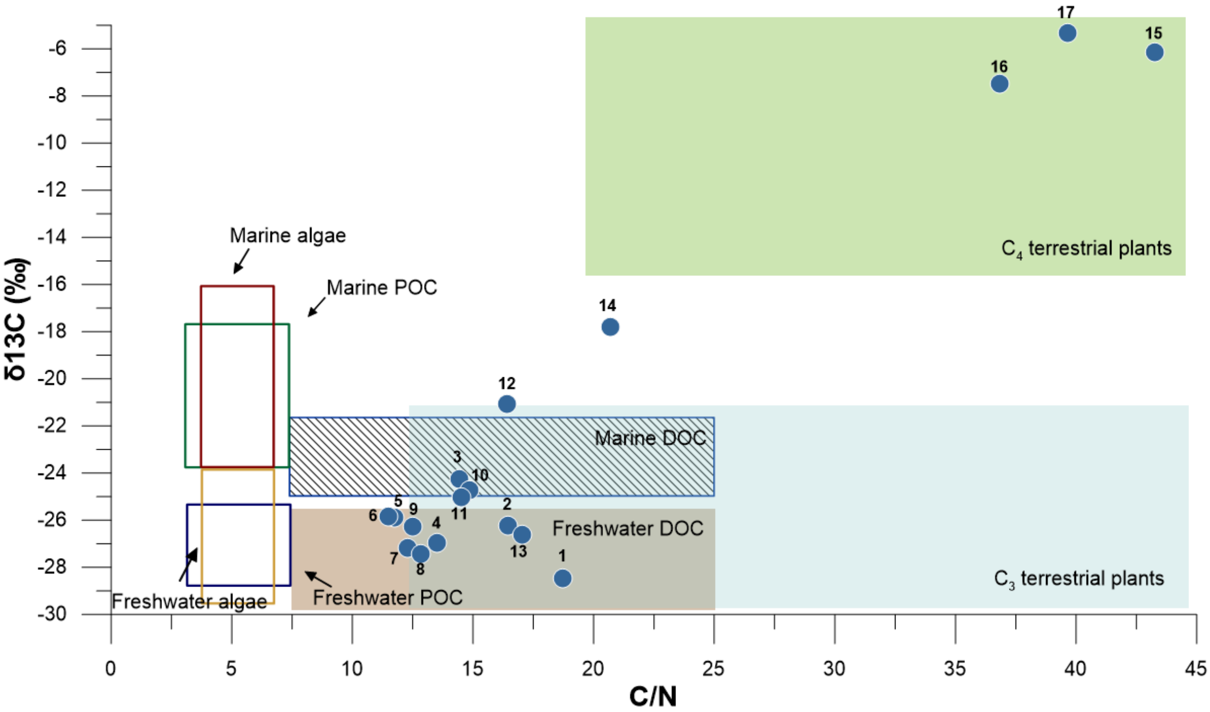


Figure 43: δ13C and C/N values for S11K.

The data indicates that we have had a transition from a marine environment to a freshwater environment.

The grain size distribution for S11K is divided into two clusters (Figure 44). Cluster A contains sediment samples from the bottom of the core, and they show a mean grain size that is coarse and well sorted. Cluster B contains sediment samples from the uppermost part of the core, and they are in between the fine sand to coarse silt and are moderately to poorly sorted. Thus, the bottom part of the core indicates a low salt marsh system where we see a shift from fast-tide to slow-tide, while the upper part of the core indicates a high marsh system. The grain size has varying values, with values being low right before the 14 cm mark, where it consists of coarser grain, suggesting a high-energy depositional environment. The sorting of grain size also gives us information about the history of the sediments. Griffiths explains in (Switzer, 2013) that the mean grain size and the mean sorting are controlled by hydraulically forces in different environments, meaning that where we have well-sorted sediments this has a connection with the mean grain size consisting of fine sand. In S11K we can see in the uppermost layers 0-11 cm that the grains are poorly sorted, and on 12 cm depth we get moderately sorted grain size, at 13 it is very poorly sorted and at 14 cm depth it is moderately well sorted. In the bottommost layer of the core 15-17 the sorting is moderately. These shifts indicate how far the sediment has travelled to be deposited. This indicates that at the first 0-11 cm the source of sediments got transported a little close to the deposition. At 12 cm depth the source was a little bit further away. At 13 cm depth the source of sediment was transported from a source nearby. At 14 cm depth the source was far away. While at the bottom of the core at 15-17 cm depth the source of sediment was transported from a far but closer than at 14 cm depth.

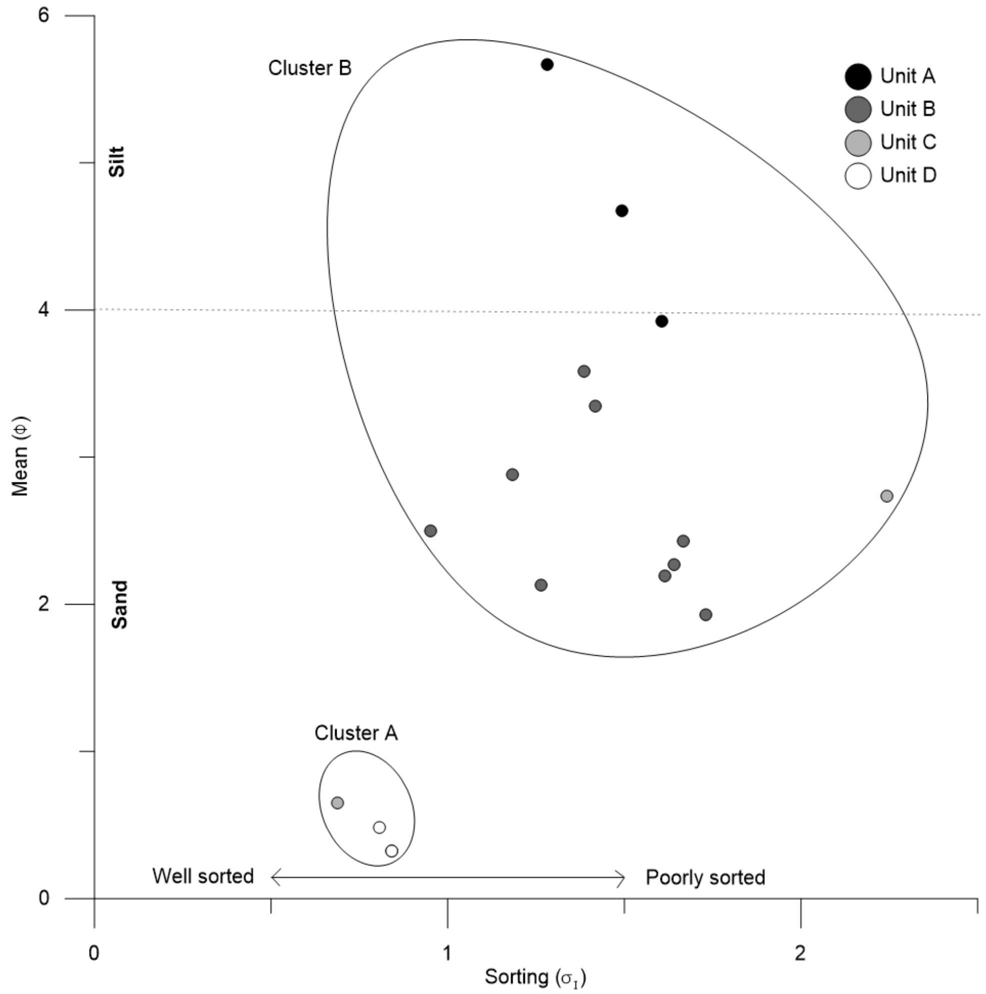


Figure 44: Bivariate plot of sorting (ϕ) against the mean (σI) for all samples at S11K. Two clusters are observed. Cluster A is predominately sand. Cluster B have more variability and consists of both sand and silt. Predominately fine sands to silts.

5.2 Surface and vegetation

Salt marshes are influenced by factors beyond sedimentation alone. Vegetation also plays a significant role in stabilizing sediments and promoting vertical accretion. The presence of tall grasses near the intertidal basins, which helps trap the sediments, contrasts with shorter grasses further inland, indicating areas more prone to erosion. This vegetation structure highlights the importance of biotic factors in enhancing sediment stability and accumulation.

The vegetation in Kongsfjorden salt marsh significantly contributes to its resilience against RSL rise. Tall grasses and sedges near the intertidal zones trap sediments effectively, reducing wave energy and promoting sediment deposition. Further inland, the shorter vegetation suggests less energy and potential for erosion, highlighting a gradient of stability across the marsh. The differences in vegetation types and their distribution also reflects the marsh's response to environmental changes. For example, as the organic matter input shifts from marine-influenced to terrestrial-influenced as seen in the sediment cores, it suggest a dynamic interaction between the source of organic matter and the sea level. This interaction is critical for maintain the marsh's role as blue carbon sink, as it supports continuous carbon sequestration.

Vegetation zones in the Kongsfjorden salt marsh was determined based on the surface vegetation from the transects AB-T1 and AB-T2. There seems to be a transition of shorter grass to longer grass in a landward direction, but however there are some patches of grass in between that does not follow this. There could be many reasons for this, included grazing of birds or species which grows patch-wise, but it will not be discussed further in this thesis since it is not of importance to interpret the energy of the environment.

Towards the seaside of the salt marsh, *Triglochin maritima* was identified in the field together with *Juncus Geradii* (Figure 45). Here the surrounding area consists of sandy patches with cobbles around. And this vegetation type is known to get subjected by briefly flooding making it appear in high marsh areas and its optimum growing environment is sandy and gravel soils (Dítě et al., 2019). However, the area in which this grow in the study areas is characterized by beach/low marsh. In relation to RSLR, species can migrate towards either lower or higher elevations. In this case, the species is recorded at a lower elevation suggesting that the vegetation has migrated with reference to RMSL (Yang et al., 2023). The vegetation seems to have responded to the trends in increasing RSL. However, there seems to be a different in the length of the grass between the two different transects. In transect AB-T2 the short grass is found at the lower elevations while the longer grass appears in the higher elevations. In the AB-T1 transect it is the opposite, the grass is tallest close to the shore, and it gets shorter the more landward, as can be seen in the case described above, which is from the AB-T1 transect. As mentioned above there could be several reasons for this, and there will also always be some variations when it comes to vegetation growth. The vegetation specie can also grow in patches causing this difference, so it is therefore difficult to rely on this alone to determine if the vegetation and elevation changes response to a rise in RSL. But the lower elevated areas are the ones that gets more often flooded and the salinity will therefore be higher in these areas. And this can lead to limits in the growth of vegetation (Dítě et al., 2019). But this can also be explained by the morphology and the tidal range of the area. Based on the map over the incoming tide (Figure 13) we can clearly see that the AB-T2 transect gets submerged during MHT because of an opening into the intertidal basins. And the boulders as well as the sandy dune patch work as a barricade for the AB-T1 transect that does not get impacted by this. The AB-T1 transect does not get impacted by this, only when the tide is at the HAT level which only reaches this height if there are storm event or other astronomical factors causing it to reach this level.

Figure 45: Triglochin maritima and Juncus Geradii with surrounding cobbles and low-growing vegetation.

The $\delta^{13}C$ values from the vegetation samples (Figure 46) indicate that the source originate from freshwater DOC, but predominantly from C_3 terrestrial plants.
The surface samples indicates a mix of sourced, some surface samples have $\delta^{13}C$ values around -28‰ to -30‰, and with high C/N ratios, pointing towards freshwater DOC. One of the surface samples (AB-T2-1) have a $\delta^{13}C$ value of -15‰, with a low C/N, suggesting a more marine influence.

The vegetation samples is influenced by high TOC values (mean ~37,81 %; Table 2), with the lowest values in the intertidal basin with values getting increasingly higher towards the tundra. This also applies to the surface samples, with a TOC of 0% in the intertidal basin, and a TOC of 49% in the tundra.

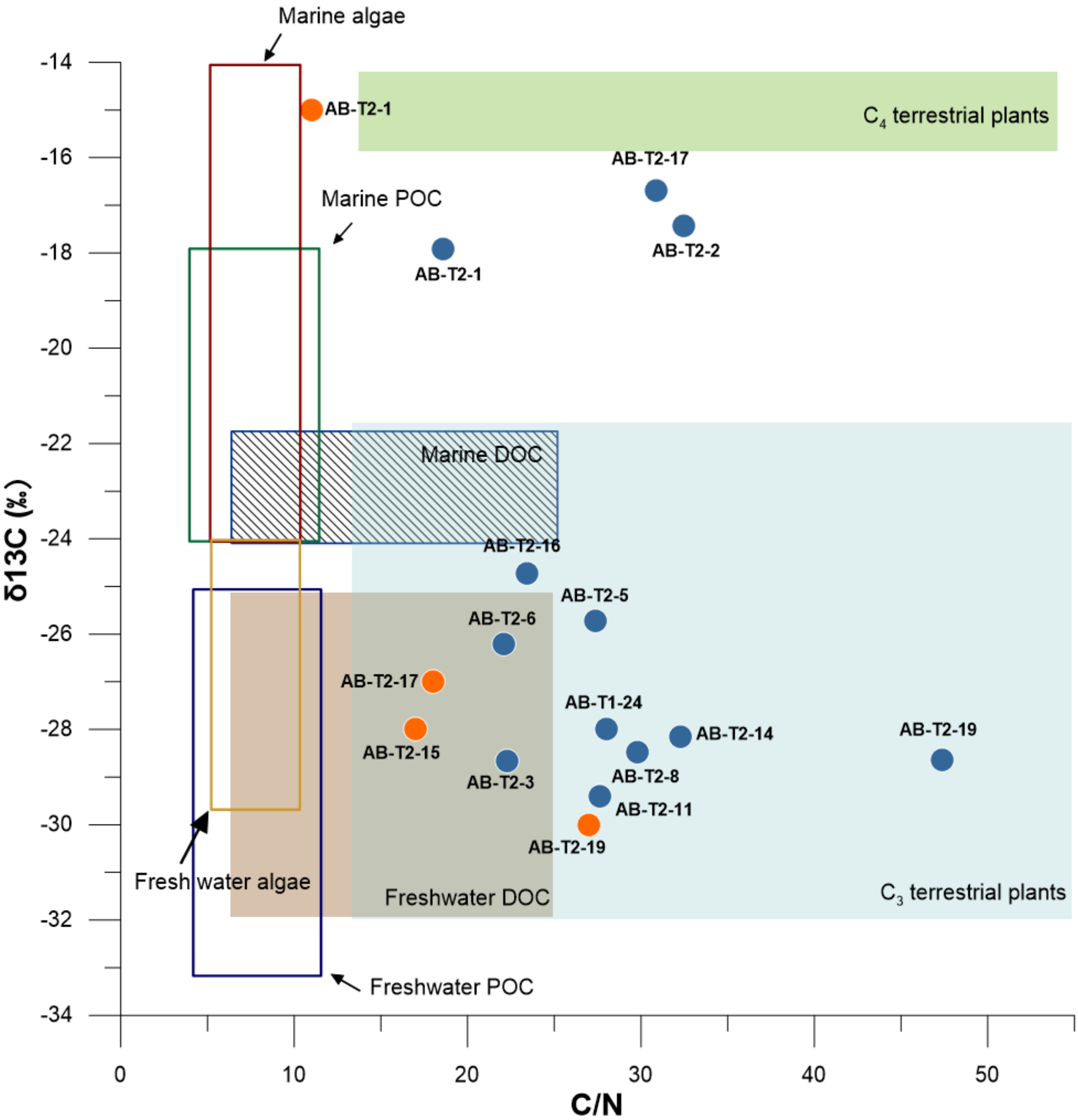


Figure 46: $\delta^{13}C$ and C/N values of vegetation samples (blue) and surface samples (orange).

5.3 Comparative analysis

Comparing the results from the four cores, together with the surface and vegetation samples we can make some assumptions about the evolution and resilience of the salt marsh. The variations in $\delta^{13}C$, C/N, TOC, LOI, and grain size across different depths in each core reflects changes in organic matter sources, depositional environments, and energy conditions over time.

The processes influencing shifts in organic matter sources within Arctic salt marsh sediments include variations in vegetation, sediment supply, and hydrological changes. The analysis of $\delta^{13}C$ and C/N ratios in the sediment cores indicates that terrestrial sources contribute significantly to organic matter accumulation. These inputs, together with vegetation such as tall grasses, enhance the marsh's resilience by stabilizing sediments and reducing wave energy impact, thus supporting sediment accumulation and vertical accretion which is necessary to cope with RSLR.

Changes in environmental conditions (e.g. increased storminess, SLR, changes in land-fast sea ice and changes in precipitation) will affect the carbon sequestration in salt marshes due to climate change (Ward, 2020a). Storm events can enhance sediment deposition, contributing to the marsh's elevation. However, increased marine inputs may lead to organic matter decomposition and reduced elevation, negatively impacting the marsh's resilience.

All cores show evidence of transitioning from marine to brackish and then to freshwater conditions. This indicates that the salt marsh has experienced significant environmental changes, which are likely driven by sea-level fluctuations or by hydrological changes. Overall, the $\delta^{13}C$ and C/N show a decreasing trend from the bottom of the cores to the top, which could be linked to falling RSL over time (the past hundred years) in this area, which we know has been happening until now according to the ongoing uplift and the reconstructed Holocene RSL curve for Nordkinn. The decreasing organic content and changing $\delta^{13}C$ values suggest that we experience periods of increased inundation. As sea level rises, the frequency and duration of flooding increases, which leads to a higher sediment deposition rate, as well as shifts in plant species due to changes in salinity and hydrology. Kirwan et al. (2016) examined how accelerated sea-level rise impacts the sustainability of salt marshes. The observed trends in sediment accretion and organic matter content in the cores support that these marshes are dynamically responding to rising sea levels through increased sedimentation and organic matter accumulation. We also know from the raised beaches and the glacial history of this region that the RSL was higher in the past before it fell to its modern position. The tide gauge data up here suggests that RSL "might" be rising now, but at very slow rates.

The grain size indicates varying energy conditions with coarser grains suggesting higher energy environment, possibly due to storm surges or tidal fluctuations. In contrast, finer grains reflect lower-energy conditions, which are ideal for the preservation of organic matter. Grain size distribution varied between core S9K and S11K, indicating different hydrodynamic forces in the salt marsh system. During spring break-up of sea ice in the fjord, ice can be pushed onshore by wind and cause the deposition of coarse-grained sediments from the tidal flat onto the marsh surface. This explains the observations of the random gravels and sand in the otherwise fine-grained, organic-rich soil in the cores. Sharp transitions in grain size could indicate storm events, which can enhance the deposition of mineral-rich sediments over organic-rich sediments, which again can alter the structure and composition of the sediment. Turner et al., (2007) studied the impact of hurricanes on marsh sedimentation, and found that storms can deposit sediments in the layers of the salt marsh. The presence of coarser layers within the cores suggests that there have been events that has contributed to sediment deposition and marsh accretion.

With RSLR low-lying coastal wetlands will experience a higher frequency and higher intensity of flooding, which will impact the sediment distribution. The decrease in wave energy will cause coarse sediments to settle in the intertidal zones, while fine sediments transported by the tides will get deposited in newly formed zones which will then experience flooding, and here we will get a sequence where the finer sediments cover the coarser sediments. Hence, mean grain size can therefore be linked and interpreted to accretion processes. If we have vertical accretion we will clearly be able to see a decrease in the mean grain size in an up-core trend (Rahman & Plater, 2014). In this, case it seems that the changes between grain size distribution in both core S9K and S11K the trend in mean grain size reflects a transition/shift through low and high salt marsh environments.

The LOI data from core S9K and S11K reveals a decrease in LOI values towards the seaward edge and an increase in LOI values landward indicating a clear difference and distinction between low marsh and high marsh environment, indicated by Shaw et al. in (Plater et al., 2015), who showed a correlation between elevation and distance in a microtidal salt marsh, where generally LOI values at ~60% indicate upper salt marsh and 25-40% indicate low salt marsh. High TOC and LOI values in the upper layers of the cores suggest that we have a high sediment accretion and organic matter deposition. Morris et al., (2002) highlighted the interaction between sediment supply and plant productivity in affecting the marsh accretion. The values in the cores therefore suggest periods of high productivity and sediment supply, which is crucial for marsh stability, and therefore these processes are essential when it comes to the marshes ability to keep up with sea-level rise.

Vegetation and surface samples from the AB-T2 transect together with AB-T1-24 support these findings. Taller grasses near the intertidal basins, which trap and stabilize sediments, transition to shorter grasses inland where wave energy diminishes, further promoting sediment deposition and marsh accretion. The $\delta^{13}C$ results from transect AB-T2 agrees with the different zonation's of salt marsh figure, with the intertidal basin being the most saline together with the high marsh, with the tundra being influenced by freshwater (Figure 46).

5.4 Future RSLR

To understand the impact RSLR will have on carbon storage and sedimentation rates in the arctic salt marsh near Kongsfjorden, it is important to consider environmental conditions, historical trends, and future projections.

Environmental conditions, which include topography, hydrology and the composition of vegetation plays an important role when it comes to the carbon storage and sediment accretion. Kongsfjorden salt marsh is characterized with gentle slopes, however the area is prone to wave action and erosion caused by storms, like the one in 2011 (Pedersen, 2011), which caused the water level to rise to 217 cm. It is also expected with RSLR that we will experience increased inundation and wave energy which also could lead to erosion and loss of marsh area. When it comes to RSLR there exists a upper limit that indicates the salt marsh systems ability to keep up with the changes and where it is unstable (increased erosion, loss in carbon stock) in the rate of RSLR (Miller et al., 2022; Morris et al., 2002).

But with RSLR we also need to consider that the tide will reach further and higher upshore, the same goes for storm surges. The current rate of RSLR is 3.9 ± 1.3 mm/yr (Simpson et al., 2024) considering GIA. Based on the different emission scenarios proposed by Kartverket (*Søkeresultat*, 2024) by 2100 we can make some assumptions as to how far inland the marsh can expand. The low emission scenario (RCP2.6) indicate a SLR of 21 cm by 2100. For the reduced emission (RCP4.5) we might get a SLR of 29 cm. And for the high emission (RCP8.5) we will get a rise of 48 cm. Based on the topography of the area (Figure 47) the salt marsh will be able to expand given the projection of 48 m of RSLR. The boulder barricade that sits on the edge of the marsh helps when it comes to the survival of the salt marsh keeping it from drowning.

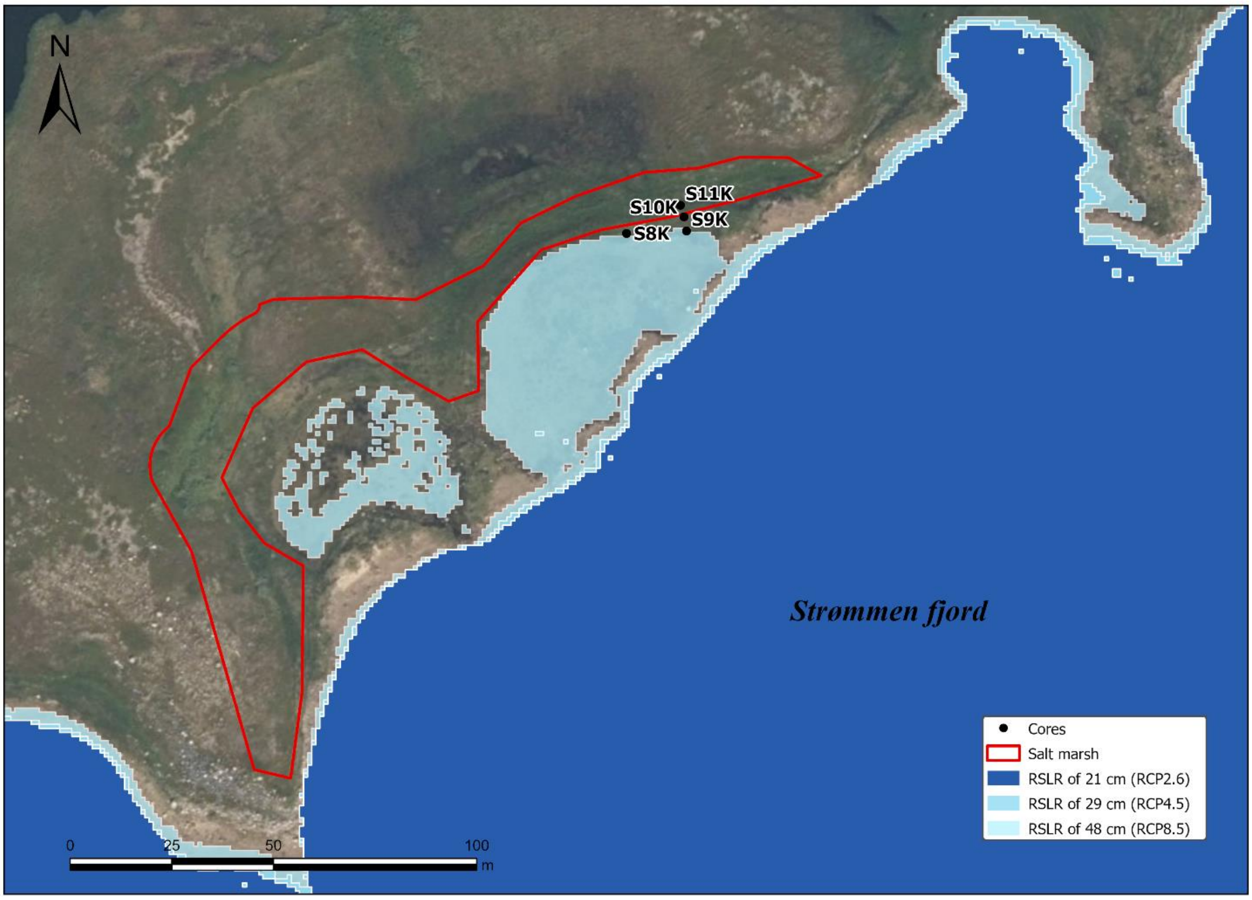


Figure 47: Kongsfjorden salt marsh area. The study area is marked by red, the cores as points, and the predicted loss as a result of RSLR projections by 2100 is illustrated by blue shading.

Kongsfjorden salt marsh serve as a significant carbon sink, which accumulates organic matter over time. However, RSLR can alter the carbon sequestration by changing the distribution of vegetation and hydrological systems. With changes in the hydrological systems, this could cause the tidal inundation zones to expand and may promote the growth of carbon-rich vegetation species that are adapted to saline conditions. Increased erosion and sediment loss caused by RSLR can lead to the mobilization of stored carbon (Chmura et al., 2003). Salt marshes serve as important ecosystems which are important when it comes to mitigating climate change. By analysing the LOI, we gain insight into the organic carbon content within the sediments, which is crucial for carbon sequestration in salt marshes. High LOI values, as seen in S11K, indicate high carbon storage, while lower LOI values suggest lower carbon storage.

Based on the radiocarbon dating, CAR, and the depth of refusal we can suggest that the salt marsh is fairly young (Miller et al., 2022). In Kongsfjorden salt marsh, the CAR is 3.0 x 10^{-3} m/yr at S8K and 4.37 x 10^{-4} m/yr at S10K based on a linear rate of accumulation. CAR values are high at S10K, located just above the low-high marsh border, while at S8K, CAR values are lower, and the core is also located just below the high-low marsh border. Carbon accumulation rates are normally higher closer to the land, and the rates will increase with RSLR. The trend of high carbon accumulation towards the higher elevations is likely due to different source of input across the marsh, with more organic rich sediments from terrestrial sources being available higher up in the marsh (Miller et al., 2022). At Kongsfjorden, the salt marsh has persisted and have been able to resist in relation to changes in the depositional conditions based on the different environmental changes in the core from the $\delta^{13}C$ and C/N. However, this does not necessarily indicate changes in RSLR. The amount of TOC in the cores indicates high levels of carbon in the uppermost layers, with only S11K having higher TOC values with increased depth. One of the major drivers of CAR is the vertical accretion, and there is a positive relationship between RSLR and CAR, with organic carbon values increasing with the depth (McTigue et al., 2019). Coastal wetlands with low energy promote the vertical accretion allowing the salt marsh to keep up with RSLR, thus maintaining a resilience to this change. The grain size data suggest that in S9K we have fine grain sizes down towards the bottom of the core, while in the uppermost layers of the core we have medium grain sizes. In S11K we have coarse sand towards the bottom of the core and finer grain sizes on the uppermost layers of the core. Together this indicates a low energy system, allowing the accumulation of organic matter to exceed.

Average sedimentation rates for Kongsfjorden using radiocarbon dating (Table 5) show a minimum rate of 0.46 mm/yr, and a maximum rate of 0.63 mm/yr for S8K. For S10K the minimum sedimentation rate is 0.41 mm/yr, and maximum 1.23 mm/yr. If the accumulation rates exceed the RSLR rates then the salt marsh will be able to survive and to expand into the salt marsh system (regression), but if the accumulation rates follow the rate of RSLR this will lead to a salt marsh that moves landward with the RSLR (transgression) (Miller et al., 2022). By comparing these sedimentation rates of S8K and S10K with the projected RSLR by 2100, we are able to see if the sediment accretion will keep up with the projected RSLR (Figure 48 & 49). Based on the figure, it seems like both the minimum and the maximum sedimentation rate will not be enough if we will experience the projected RSLR by 2100. However, with RSLR we will experience an increase in flooding which can bring both water and sediments to the salt marsh system which will promote plant growth and will also promote organic matter accumulation (Miller et al., 2022).

Table 5: Minimum and maximum average rates of sedimentation (mm/yr)for low and high marsh zones and projected RSLR at the study site.

Core	Sedimentation rate	RSLR by 2100 (RCP2.6)	RSLR by 2100 (RCP4.5)	RSLR by 2100 (RCP8.5)
S8K	Min: 0.46 mm/yr Max: 0.63 mm/yr	2.76 mm/yr	3.81 mm/yr	6.31 mm/yr
S10K	Min: 0.41 mm/yr Max: 1.23 mm/yr	2.76 mm/yr	3.81 mm/yr	6.31 mm/yr

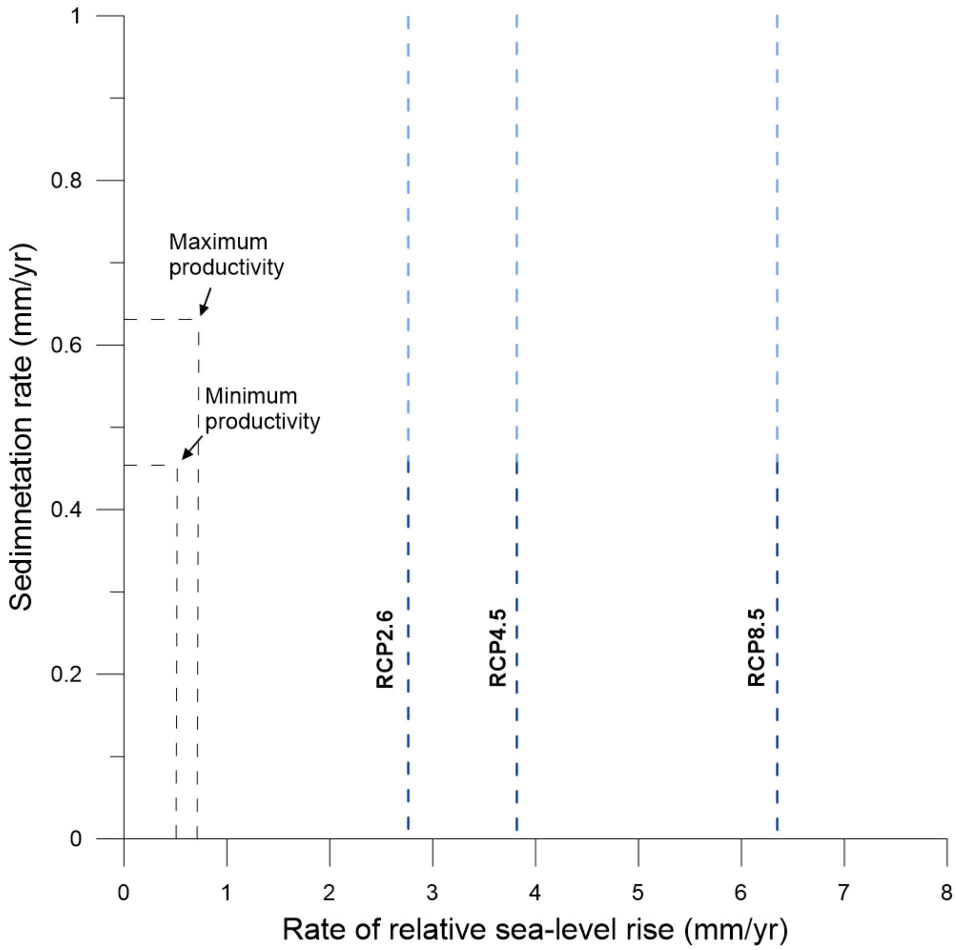


Figure 48: Projected rate of RSLR (mm/yr) based on RCP2.6, RCP 4.5 and RCP8.5, for core S8K.

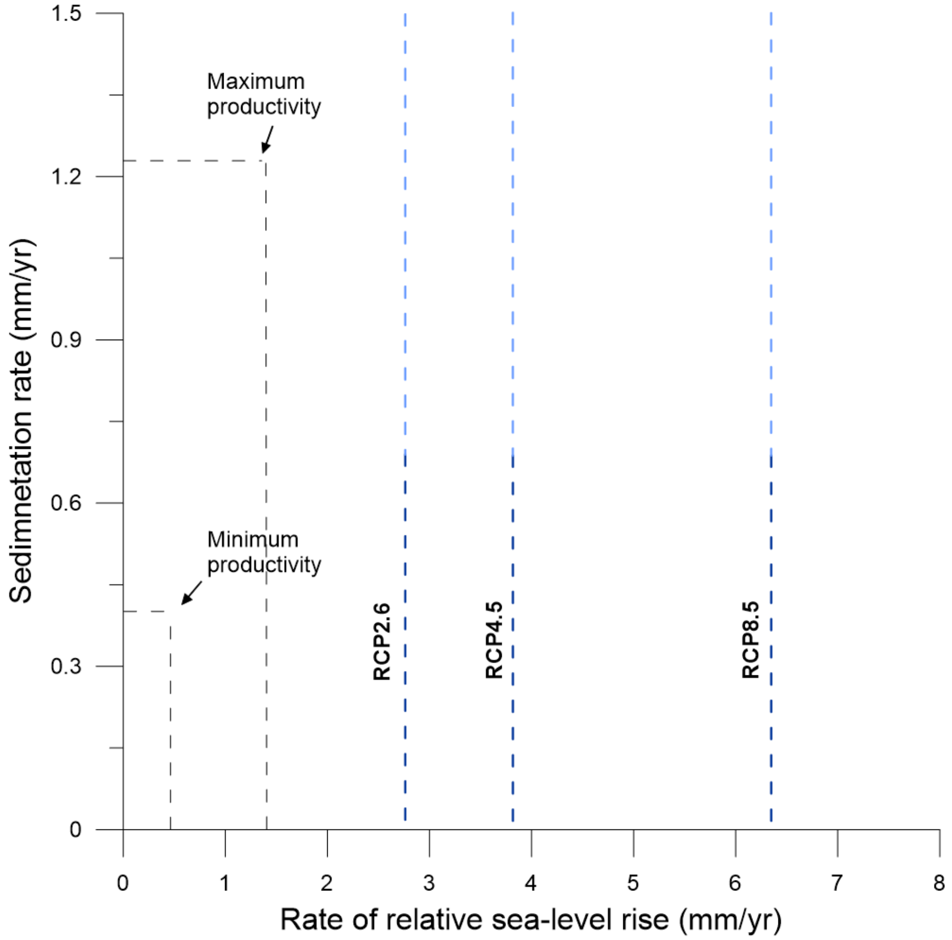


Figure 49: Projected rate of RSLR (mm/yr) based on RCP2.6, RCP4.5 and RCP8.5, for core S10K.

Sedimentation is not the only factor that drives responses to RSLR (Adam, 2002; Schuerch et al., 2018). Other factors such as sea-ice, are of great importance when it comes to the accretion of sediments. This, together with increased storminess, much like the rapid accumulation of sediments during the storm "Berit" (Pedersen, 2011) are factors to consider that may contribute to the resilience of the salt marsh.

The vegetation also plays a key role in the accretion of sediments. In the salt marsh at Kongsfjorden we have relatively tall grasses close to the intertidal basins that gets flattened as the tide comes in. Further inland the grass/sedges get shorter or maintain their height as they do not get flattened since the waves does not reach that far inland, but it could indicate a high energy system based on the AB-T1 transect. When we have tall grasses, it helps decrease the incoming energy which helps trap and stabilize the sediment. Morris et al., (2002) proposed an optimal elevation for plant growth, which is critical for maintaining marsh stability, and our sediment core data, with fluctuating organic content and grain size, likely reflect these elevation-dependent growth and sedimentation processes together with the vegetation. On the salt marsh transition from beach to low marsh we can clearly see a difference in the vegetation from a mix of short and longer graminoids to short graminoids based on the AB-T1 transect. In the AB-T2 transect we can see a difference in the vegetation in the transition from low marsh to high marsh where the vegetation gets longer/taller. The short grass indicates that we have an area that is subjected to a more intense energy which means it is more prone to erosion. While further inland the grass gets taller indicating a reduction in the wave energy which indicates that it contributes to the accumulation and deposition of sediments. Other studies support these findings, emphasizing the importance of sediment supply and vegetation in maintaining salt marsh elevation. Kirwan et al., (2016) found that accelerated SLR increases sediment deposition rates but also stresses plant communities, which are vital for organic matter accumulation and sediment stabilization. Schuerch et al., (2018) highlight that sufficient sediment supply is essential for marsh resilience, particularly under higher SLR scenarios. With this it is likely that the salt marsh will be able to withstand RSLR but will migrate inland.

In summary, the Kongsfjorden salt marsh has mechanisms to keep up with RSLR through an increase in sediment and organic matter accumulation. However, the resilience and adaptive capacity of arctic salt marshes, depend on a balance between sedimentation, organic matter inputs, and environmental changes driven by both local and global processes affecting the ecosystem.

6 Conclusion

Based on future projections, the highest projected RSLR, which follows RCP8.5, might reach ~6 mm/yr by 2100 (Simpson et al., 2015). Norway are still experiencing uplift due to GIA, however in coastal areas the rate of uplift are lower since these areas had less ice covering the area, which again causes the RSLR to have a greater impact on these areas in Norway (*Framtidig havnivå langs Norskekysten*, 2024).

A Holocene RSL curve west of the study area show that the RSL has been falling for the past ~7000 years (Romundset et al., 2011). Nonetheless, the tide gauge data from Vardø indicate that the RSL has started to rise in this region, and are already impacting these coastal ecosystems (*Framtidig havnivå langs Norskekysten*, 2024).

The sediment cores illustrate changes, but it does not reflect the RSLR we are experiencing now. However, it does indicate that the salt marsh has been through a similar transition that we are experiencing now with RSLR in the past. With RSLR it is expected that we get an increase in the accumulation of organic matter. The sedimentation and CAR rates indicate a low rate of accumulation, but this follows a linear accumulation, and does not take into account other factors that might influence the accumulation of organic matter. In the cores, we can clearly see high values of organic matter in the uppermost part of the cores, which indicate good conditions for organic matter accumulation, sequestration, and preservation. Alongside with the $\delta^{13}C$, C/N, TOC, LOI, and grain size the cores seems to have withstand changes in the environmental conditions, caused by RSL, storm surges, changes in the tidal regime and sea-ice push, making them hold value as resilience to environmental changes.

In conclusion, the resilience and adaptive capacity of Arctic salt marshes to RSLR are driven by the interaction between vegetation, sediment supply, and hydrological changes. While these ecosystems have mechanism to cope with wising sea levels through sediment accumulation and organic matter deposition, the current sedimentation rates are insufficient to match the projected RSLR, leading to landward migration or marsh loss. Therefore, enhancing sediment supply and allowing for landward migration are critical strategies to ensure long-term stability and functionality of these valuable habitats. This research contributes to the broader understanding of climate change impacts on coastal wetland and reinforces the importance of maintaining vegetative cover and sediment supply to ensure the long-term stability and resilience of salt marsh ecosystems.

There was recently published a new report on sea-level rise in Norway with new projections for 2100. These new numbers have not been included in this thesis, but it would be beneficial for future research to look into these new projections and see if the new projections would make a big difference in the resilience of the salt marsh at Kongsfjorden, including both uplift rates and RSLR.

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