Recent rates of sedimentation on irregularly flooded Boreal Baltic coastal wetlands: responses to recent changes in sea level

Raymond D. Ward[a], Phillip A. Teasdale[a], Niall G. Burnside[a], Christopher B. Joyce[a] and Kalev Sepp[b]

[a] Aquatic Research Centre, School of Environment & Technology, University of Brighton, Lewes Road, Brighton, BN2 4GJ, UK.

[b] Department of Landscape Management, Estonian University of Life Sciences, Fr.R. Kreutzwaldi 1, 51014, Tartu, Estonia.

Corresponding author email: R.D.Ward@brighton.ac.uk , telephone: 0044 (0)1273642393

Abstract

Boreal Baltic coastal wetlands differ markedly from temperate salt marshes by their generally low maximum elevation (between 0 and 1 m above m.s.l.), low seaward gradients and the irregular nature of flooding that is characteristic of the NE Baltic Sea coastal region. As a result of these factors these wetlands have been considered to be threatened by future sea level rise. This study presents results for two Boreal Baltic coastal wetland sites in Estonia using ^{210}Pb and ^{137}Cs radiometric dating to investigate the sedimentary development of these coastal systems. Recent coastal evolution has been largely driven by continuing glacio-isostatic adjustment (GIA), with maximum rates of 2.8 mm yr^{-1} around the NW Estonian coast and the inherited geomorphological setting of generally flat-lying coastal topography, resulting in coastal emergence. Broad agreement exists between calculated rates of sedimentation identified within the core sequences. Average rates of sedimentation using the ^{210}Pb$_{excess}$ CF:CS (or 'simple') model range between 0.2-1.3 mm yr^{-1}.

These rates are corroborated using ^{137}Cs, which also suggests an increase in sedimentation rates during recent decades approaching maximum values for current land uplift. Additionally, the $^{210}Pb_{excess}$ CRS model reveals periods of sedimentation greatly in excess of these values in response to coastal flooding from known storm activity. This study indicates that changes in sea level caused by variations in atmospheric pressure and storm surges can contribute a significant sedimentary component, which coupled with GIA processes has driven coastal wetland development/ emergence and the historical progradation of these wetland systems. The recent acceleration in the rate of global sea-level rise may subtly alter this relationship. However current rates of GIA and sedimentation will continue to maintain the progradation of Boreal Baltic coastal wetlands in the coming decades.

Keywords: Baltic coastal wetlands, ^{210}Pb, ^{137}Cs, sedimentation, storm surges, sea level rise

1. Introduction

Extensive ecologically diverse Boreal coastal wetlands characterize significant areas of the Baltic coastline (Fig. 1). They are unique to the Baltic Sea region being found in Estonia, Sweden, Finland and to a lesser extent parts of the Latvian coastline (EU Habitats Directive, 1992; Ward, 2012). Boreal Baltic coastal wetlands differ markedly from more temperate saltmarshes by their generally low maximum elevation relative to mean sea level, low seaward gradients and the irregular nature of flooding that is characteristic of the NE Baltic Sea coastal region. As a result of these factors, Boreal Baltic coastal wetlands are characterised by a discrete internal micro-topography that exerts a major control upon the unique ecological zonation that has afforded them protection under the EU RAMSAR convention (Ward, 2012).

The recent evolution of these coastal systems is a complex product of the interplay between regional antecedent glacial erosion, late Holocene sea-level history, continuing glacio-isostatic uplift (GIA) resulting in coastal emergence and the inherited geomorphological setting of generally flat-lying coastal topography.

Rates of crustal uplift display subtle variation along the Estonian coastline with estimated values of < 0.5 mm yr^{-1} in the south-west of the country rising to 2.8 mm yr^{-1} in the northwest around the major near-shore islands of Saaremaa, Hiiumaa, Muhu and Vormsi (Fig. 1), (Eronen et al., 2001).

Fig. 1 here

Flooding of Baltic coastal wetlands is irregular, and is not driven by tidal inundation as tidal amplitudes in the Baltic Sea are negligible at < 0.02 m (Suursaar et al., 2001b). In this region, coastal flooding occurs sporadically in response to the movement of atmospheric pressure systems and fluctuating meteorological conditions across the North Atlantic and Fennoscandia (Suursaar and Sööäär, 2007). When low pressure systems bring about storm surges, rapid changes in sea level can occur that are significantly above the expected range of -0.37 m to + 0.63 m derived from average yearly atmospheric pressure variations for the Baltic region (ranging from between 950-1050 mb, Swedish Meteorological and Hydrological Institute, 2013). Any rise in water levels is exacerbated by the funnelling effect within embayed areas and inlets, where the largest expanses of coastal wetland occur

(Kotta et al., 2008). On occasions, flooding can extend inland for significant distances (~ 2 km) due to the low-lying topography and land gradients.

Mean sea level within the NE Baltic Sea region is primarily controlled by global sea-level change and differential Fennoscandian GIA (Suursaar et al., 2007). These authors have estimated recent rates of relative sea-level rise from three tide gauges along the Estonian coast and provide values of 1.5 - 1.7 mm yr^{-1} at Tallinn, 1.7 - 2.1 mm yr^{-1} from Narva-Jõesuu and 2.3 - 2.7 mm yr^{-1} from the gauge at Pärnu in the south-west of the country. These data suggest a quasi-equilibrium relationship between regional relative sea-level rise in the north and central western coastline, which corresponds well with the estimated 20th Century global estimate of 1.7 mm ± 0.5 mm yr^{-1} (Church and White, 2006). Further to the south around Pärnu Bay (Fig. 1), the situation is somewhat different suggesting greater dominance of relative sea-level rise. However, Suursaar et al., (2007) stress that the data from the Pärnu tide gauge record are significantly influenced by positive winter trends due to increased storminess and greater intensity of strong westerly winds highlighted by the NAO-index (Orviku et al., 2003; Suursaar et al., 2006a; 2006b).

Recent satellite altimetry data suggest a late 20th Century/ early 21st Century acceleration in the rate of global sea-level rise with current estimations of ~ 3.3 mm ± 0.3 mm yr^{-1} (Cabanes et al., 2001; Holgate and Woodworth, 2004; Church and White, 2006). Hence, the interplay between crustal emergence, sea-level rise and flooding periodicity may be changing around the Estonian coastline with sea-level rise perhaps becoming more dominant. A similar scenario has been highlighted in a recent study of late Holocene coastal wetland development in western Scotland (Teasdale et al., 2011), where more subtle rates of residual GIA (< 0.5 - 1.0 mm yr-1) now appear to be outpaced by modern rates of regional sea-level rise (Johansson et al., 2004; Rennie and Hansom, 2011).

Other mechanisms may also exert an influence upon sea-level fluctuations around the Estonian coast. During winter months, the presence of sea-ice affects the inundation capacity of meteorologically driven changes in sea level but these can still occur through 'ice-push' processes when wind direction is favourable and during winter periods when the coast is 'ice-free'. A recent study by Jaagus (2006) has highlighted significant reductions in the period of sea-ice cover in recent decades, particularly along the western shoreline of Estonia in conjunction with an identified regional trend of intensified autumn and winter storminess which has initiated infrequent but significant erosion and morphological adjustment of some areas of the Estonian shoreline (Orviku et al., 2003; Suursaar et al., 2003; Rivis, 2004; Kont et al., 2007; Orviku, 2009; Suursaar and Kullas, 2009). Notable amongst recent severe storms was the event in January 2005, named 'Gudrun', which caused significant erosion and morphological adjustment of low cliff deposits around the western Estonian coastline (Tõnisson et al., 2008). Maximum recorded sea level inundation of + 2.75 m above mean sea level occurred within the Gulf of Riga around the city of Parnu, central west Estonian coast during the Gudrun event (Suursaar et al., 2006a; Fig. 1).

Despite on-going emergence of the Estonian coastline, considered by some authors to be the dominant factor controlling the recent development of Boreal Baltic coastal wetlands (Kont et al., 2007), these low-lying environments are now considered by some authors to be at risk of increased coastal flooding in response to recent significant changes in regional wind regime and winter NAO index (Ekman, 1998; Keevallik and Rajasalu, 2001; Kont et al., 2003; Kont et al., 2008; Suursaar et al., 2007; Suursaar and Sooäär, 2007) and current estimated rates of early 21st Century global sea-level rise (Kont et al., 2008). However, these studies do not consider the recent sedimentary response of the Estonian coastal wetlands, and as such, little is currently known about relationships between rates of sedimentation, response to irregular flooding periodicity, recent relative sea level and climate change within the eastern Baltic Sea.

Here, we present the findings of recent work undertaken on two Boreal Baltic coastal wetlands in Estonia using the ^{210}Pb and ^{137}Cs radiometric dating methods to investigate the recent sedimentary development of these unique and ecologically important systems. The findings are discussed in light of historical fluctuations in sea level driven by storm surges and/or atmospheric pressure change and a regional outlook of the effects of climate change on Baltic coastal wetlands is presented.

2. Regional setting

In NW Estonia, Boreal Baltic coastal wetlands are particularly prevalent within the shallow enclosed embayments on the mainland and around coastlines of the near-shore islands of Saaremaa, Hiiumaa, Muhu and Vormsi (Fig. 1), where they represent the most commonly occurring morpho-ecological features of the low-gradient coastal plain.

The vegetation found in Baltic coastal wetlands is comprised of a mosaic of seven predominant plant communities (Burnside et al., 2007; Ward et al., 2013). These plant communities have been found to be located at distinct elevations within the Boreal Baltic wetlands (Ward et al., 2010; Fig. 2) and the open swards are maintained by low intensity grazing without which these wetlands would revert to reed and scrub dominated wetlands (Berg et al., 2011).

Fig. 2 here

Two sites were selected for the purposes of this study, located at Tahu Bay (Estonian: Tahu laht) (Silma Nature Reserve) and at Matsalu Bay (Estonian: Matsalu laht) (Matsalu National Park) (Fig. 1). Both sites are low-lying with maximum heights of the fringing scrub woodland plant zone not exceeding 1.2 m above mean sea level (m.s.l.) as measured at Kronstadt using the BK77 ellipsoid. A recent study by Suursaar et al. (2007), investigating hydro-dynamical modelling of Estonian coastal waters driven by fluctuations in wind climate, has identified the shallow embayment coasts of Tahu and Matsalu bays as being among the most sensitive areas to meteorological (wind driven) coastal flooding (Fig. 1). The Tahu study site comprises an area of 104 ha on the north-west side of Tahu Bay (50 km^2) (Figs. 1, 3). The bay receives moderate freshwater input from the Taebla River which drains a catchment of some 107 km^2 (Kotta et al., 2008).

Fig. 3 here

The site at Matsalu comprises 190 ha of coastal wetland in the Matsalu National Park situated within Matsalu Bay (Figs. 1, 4). Matsalu Bay covers an area of 65 km^2 and receives significant freshwater input from the Kasari River which drains a large catchment of western Estonia of some 3214 km^2 (Kotta et al., 2008).

Fig. 4 here

Greatest inundation occurs when the two sites are exposed to storm winds emanating from the west and southwest (Kont et al., 2007). During periods of high water much of the wetland area is inundated by brackish water (~ 5 ppt) from the Baltic Sea resulting in sediment accretion where overland flow occurs. Sea level in the region is typically at its lowest in spring and early summer when easterly winds prevail (EMHI, 2011). During the winter months sea-ice covers the coastal zone in most years and during winter the wetlands are also covered by snow for a minimum of two months.

Rates of residual GIA are highest in N W Estonia. Subtle differences in rates of crustal uplift between the site locations are apparent, with 2.3 mm yr^{-1} at Matsalu Bay and 2.8 mm yr^{-1} at the Tahu site within Haapsalu Bay, (Eronen et al., 2001) (Fig. 1).

3. Material and methods

Core sites were selected on the basis of ecological zonation, and hence elevation above m.s.l. Elevation data were recorded using a real time kinematic differential GPS (Leica GPS1200 Surveying System, accuracy < 0.02 m). All data were recorded using the Estonian National Grid 1997 system and elevation relative to the Baltic Height System (BK77; Яковлев, 1989) as measured at Kronstadt 59°59’43” N, 29°46’00”. The core sites encompassed zones of the Estonian wetlands that experience both more regular (Lower Shore, LS) and comparatively irregular flooding (Tall Grass, TG) (Berg et al., 2011). At the Tahu and Matsalu sites one core was taken from the LS zone with the second core taken from the TG environment.

Two shallow (< 30 cm) sediment cores were extracted from each site using 75 mm diameter plastic tubing driven into the sediment substrate. For one sample this proved to be ineffective due to increased stiffness of the underlying sediment. In this case an intact sample was obtained by digging a shallow trench and manually cutting a monolith section which was retained using 75 mm diameter plastic guttering.

At Tahu the core removed from the LS community was within 30 m of the shoreline and at an elevation of 0.07 m above m.s.l. The TG core was removed from the nearest TG patch to the coast which at this site was located some 250 m directly inland and at an elevation of 0.70 m above m.s.l. (Fig. 3).

At the Matsalu coastal wetland site the core removed from the LS community was also within 30 m of the shoreline at an elevation of 0.04 m above m.s.l. with the TG core site situated 20 m directly inland of the LS core at an elevation of 0.69 m above m.s.l. (Fig. 4). The elevation for each sediment core was recorded in metres using a dGPS with a mean vertical accuracy of 0.02 m.

Core barrels were subsequently frozen and then extruded by allowing the outer core surface (in contact with the core barrel) to thaw, thus enabling the core section to be pushed from the barrels without introducing any sediment compaction. This process was assessed by measuring the length of the core section before and immediately after the extraction procedure. This revealed that no undue compaction of the sediment matrix had occurred.

Under laboratory conditions the cores were cleaned, logged and sliced at 1 cm intervals followed by oven-drying of the sub-samples at 40° C prior to analysis. Dried samples for gamma spectrometry were then prepared by gently disaggregating the material using a pestle and mortar. Approximately 3 - 5 g of dried sediment was carefully weighed into cylindrical plastic vials for determination of $^{210}Pb_{total}$, ^{137}Cs and ^{214}Pb down-core activities.

Prior to particle size analysis organic material was removed by loss on ignition (LOI). Core sub-samples previously dried at 40°C were combusted in a muffle furnace at 360ºC for 24 hours (Schulte, 1995). Using the LOI method to estimate soil organic matter can be influenced by loss of clay bonded water at high temperatures (Sun et al., 2009). However, this is unlikely to have significantly affected the results in this study due to the very low percentages of clay in the samples (typically ~1 %). Following LOI, particle size analysis was carried out on non-ground samples using a Malvern Mastersizer 2000 laser particle size analyser, with particle size grading undertaken in accordance with the Wentworth (1922) size classification scheme. 10 ml of sodium hexametaphosphate (calgon) was added to the samples prior to particle size analysis and samples were stirred for 5 minutes in order to deflocculate the clay particles. A small (~ 1 – 1.5 g) sub-sample was analysed with the final data for each size classification (clay, silt and sand), representing an average of three separate analytical runs (standard error < 1 %).

3.1 ^{210}Pb dating

Using measured activity profiles of ^{210}Pb (half-life (t½) = 22.26 years) is a widely established method for the dating of recent coastal sediment sequences (Wise, 1980; Thompson et al., 2001; Teasdale et al., 2011). In previous studies of temperate tidally flooded mature ('high') marsh environments, the upper sections of sampled cores commonly used for dating purposes have been shown to be generally oxic (Cundy and Croudace, 1996; Thompson et al., 2001; Teasdale et al., 2011). Within such settings, the semi-diurnal nature of flooding periodicity acts to limit inundation frequency of the upper intertidal zoneover the monthly tidal cycle, promoting the development of oxic conditions which act to enhance immobility of

^{210}Pb. Similar or lesser inundation frequency occurs in both the LS and TG zones where soils are also predominantly oxic; from visual observation of these short cores there is no discernible redox boundary.

The ^{210}Pb method is based upon the measurement of ^{210}Pb 'excess' activity incorporated into the accumulating sediment from atmospheric fallout. Total measured ^{210}Pb within sediment sequences is the sum of this 'excess' activity and the 'supported' activity derived from the in-situ decay of ^{210}Pb present within the sediment matrix. For dating purposes, the supported component is commonly assessed via direct measurement of ^{226}Ra activity, that of daughter radionuclides ^{214}Bi and/or ^{214}Pb, in conjunction with estimation of constant ^{210}Pb activity at depth. In this study ^{214}Pb was utilised as it closely approximated ^{210}Pb at the lowest depths of the core, thus indicating that for these sites measurement of ^{214}Pb is a robust proxy for supported ^{210}Pb.

3.2 ^{210}Pb dating models

Sedimentation rates for the 4 cores were calculated using the Constant Flux: Constant Sedimentation (CF:CS) (or 'Simple' model) and the Constant Rate of Supply (CRS) model, as outlined in Appleby and Oldfield (1992) and Appleby (2001). The CF:CS model provides an average estimation of the rate of sedimentation over the entire depth of the core sampled. These were determined from the fit of the least squares regression of the natural log of $^{210}Pb_{excess}$ (unsupported) activity plotted against depth.

The CRS model uses inventories to calculate specific ages at any depth (x) where the total inventory within the core is determined from the sum of $^{210}Pb_{excess}$ x Dry

Bulk Density x thickness of the core slice (Thompson et al., 2001). Dry bulk density for individual depth samples was estimated by the calculation:

$$P_d = (1 - \varphi)\, P_s$$

where P_d = bulk density, ϕ = porosity, and P_s = grain specific gravity (in this case 2.5 g/cm^3) (Dadey et al., 1992). Implicit within this model is that the major source of ^{210}Pb is derived from direct atmospheric input with ^{210}Pb activity being inversely proportional to mass flux of sediment (Appleby and Oldfield, 1992).

3.3 ^{137}Cs dating

Significant global atmospheric inputs of ^{137}Cs occurred in 1963 prior to the signing of the weapons test ban treaty (Ritchie and McHenry 1990) and further atmospherically derived ^{137}Cs, in particular to northern Europe, occurred as a result of the Chernobyl nuclear power reactor accident on the 26th of April 1986. This resulted in the deposition of ^{137}Cs and other radioisotopes throughout many European countries (Anspaugh et al., 1988) and the Baltic Sea region received significant quantities of fallout radio-caesium in the days following the accident (Povinec et al., 2003). Measured ^{137}Cs activity maxima within undisturbed sediment sequences therefore provide useful geochemically independent marker horizons for the assessment of sediment accumulation rates. Discharges from other sources are not considered to contribute to significant ^{137}Cs inventories within the north-east Baltic Sea region (HELCOM, 2003).

Down-core activity profiles were determined by counting prepared sub-samples on a Canberra well-type ultra-low background HPGe gamma ray spectrometer at the University of Brighton. Spectra for ^{210}Pb and ^{137}Cs were accumulated using a 16k channel integrated multichannel analyzer and analysed using the Genie™ 2000 system. Energy and efficiency calibrations were carried out using a bentonite clay standard spiked with a mixed gamma-emitting radionuclide standard, QCYK8163, and checked against an IAEA marine sediment certified reference material (IAEA 135). Detection limits are dependent on radionuclide gamma energy, count time and sample mass, but were typically *ca.* 15 Bq/kg for ^{210}Pb, and 3 Bq/kg for ^{137}Cs, for a 150,000 second count time. ^{137}Cs and ^{210}Pb inventories were used to determine likely pathways of these radionuclides to the sediments although due to the spatial heterogeneity of atmospheric deposition of ^{137}Cs and paucity of accurate data it is not possible to use the inventory ratio of these two radionuclides to assess erosion occurrences (Plater and Appleby, 2004). Alternate 1 cm depth samples were run for an additional count time of 260,000 s in an attempt to measure ^{241}Am, which in previous studies has been found to be linked to pre-1963 weapons testing. However, ^{241}Am activities were below levels of detection in these samples.

4. Results and Interpretation

4.1 Character of the Estonian coastal wetland sediments

The shallow stratigraphy of the four cores is shown in Fig. 5. These are characterised by an upper dark-brown/black unit consisting of organic-rich silty sand which contains abundant rootlets and near-surface rhizome structures. This unit is of variable thickness within the two cores at each site, with greater total depths being recorded in those from the LS zones (maximum 16 cm at Tahu), with an upper maximum organic content of 53 wt% and 57 wt% situated at 4 cm and 2 cm depth for the Tahu and Matsalu LS cores, respectively. The relatively lower thicknesses of organic-rich material within the TG cores reflect the more infrequent flooding and low organic productivity of the coastal wetlands (Ward, 2012). Beneath this organic-rich unit the stratigraphy grades over ~3 - 5 cm into a blueish-grey/light-grey sand with some lenses of silty clay. Particle size analysis reveals that in all four cores the total clay content is very low, with values not exceeding 3.6 % and the sediment matrix is dominated by high sand content which in all cores is greater than 75 % and silt material ranging from 7.5 – 27 %, (Fig. 5). Coefficient of sorting was calculated using Trask's (1932) equation, where S_o is the sorting coefficient and D25 and D75 are the particle diameters for which 25% and 75%, respectively, of the sample is finer than.

$$S_o = \sqrt{\frac{D75}{D25}}$$

Mean coefficient of sorting values for the sediment cores were: Tahu LS 1.14 (SD 0.031), Tahu TG 1.14 (SD 0.032), Matsalu LS 1.14 (SD 0.018), and Matsalu TG 1.16 (SD 0.028). In a regression analysis there was found to be a significant relationship between coefficient of sorting and depth in all but the Tahu TG core (Tahu LS $p = 0.001$, $R^2 = 50.1\%$; Tahu TG $p = 0.326$, $R^2 = 3.0\%$; Matsalu LS $p = 0.040$, $R^2 = 26.8\%$; Matsalu TG $p = 0.014$, $R^2 = 24.4\%$). In the lower elevation plant community at both sites there was found to be an increase in the sorting coefficient toward the surface suggesting a decrease in the degree of sorting with time. However, in the Matsalu TG core there is a decrease in the sorting coefficient suggesting an increase in the degree of sorting with depth (as a proxy for time) although this relationship is not statistically significant.

Fig. 5 here

In a regression analysis there was no significant relationship between depth and D90 values for the higher elevation plant communities, nor a high standard deviation for D90 values in all cores. However, there was a significant increase in D90 values in the lower elevation plant communities at both sites, although a considerably stronger relationship at Tahu (Tahu LS p = 0.000, R^2 = 75.4%; Matsalu LS p = 0.010, R^2 = 41.9%).

In a regression analysis to assess the relationship between D10 and depth there was found to be no significant relationship at Tahu nor in the lower elevation plant community core at Matsalu (Matsalu LS p = 0.100; Tahu LS p = 0.198; Tahu TG p = 0.153). However, there was a weak significant relationship between D10 values and depth in the Matsalu TG core (Matsalu TG p = 0.006, R^2 = 26.2%) in which D10 values increase in more recently deposited sediments.

The relative proportions of clay, silt and sand material through the core sections indicate that there has been no large-scale variation in the proportions of these different sediment materials over time. The shallow sedimentary succession observed within the Estonian core sequences represents the current juxtaposition of recently uplifted coastal plain embayments containing former sub-marine silty sands and limited clays material laid down by the Late Littorina Sea (Puurmann & Ratas, 1998), which have been colonized by brackish wetland species following recent coastal emergence.

4.2 ^{210}Pb dating

At the Tahu site, measured $^{210}Pb_{total}$ down-core activity profiles exhibit a near exponential decline in activity with depth to depths of 18 cm and 5 cm in the LS and TG cores respectively (Fig. 6).

The only exception to this occurs within the LS core where a significant near-surface reduction in ^{210}Pb activity occurs at 2 - 3 cm depth, possibly resulting from the in-wash of older sediment affecting the LS core. Between 12 - 18 cm depth for the LS core and 3-5 cm for the TG core ^{210}Pb total activity approximates the supported component (Fig. 6). Mean activity for ^{214}Pb in the Tahu LS core was 24 Bq/kg, which was comparable to the average of the readings of ^{210}Pb total activity at the bottom of the core (22 Bq/kg). Hence, supported activity was estimated to be 24 Bq/kg for the Tahu LS core. Using the same approach, supported ^{210}Pb activity for the TG core was determined at 19 Bq/kg.

Fig. 6 here

Similarly, within the two cores from Matsalu, measured $^{210}Pb_{total}$ down-core activity profiles also show near exponential declines in activity with depth, although some fluctuations in near-surface activity are apparent in the LS core at the uppermost 5-6 cm and may be due to the influence of recent erosional processes affecting the LS zone at this site. Variation in near-surface activity is less apparent within the TG core at Matsalu. Mean values of 26 Bq/kg and 22 Bq/kg were estimated for the LS and TG cores, respectively.

Average rates of sedimentation for the four cores using the CF:CS or 'simple model' (Appleby, 2001) are shown in Table 1. These reveal generally low rates of sedimentation within the TG cores with calculated average values of < 0.5 and 1.0 mm yr^{-1} for the Tahu and Matsalu sites respectively. Higher values are recorded for the LS cores from each site with average rates of 1.3 mm yr^{-1} in the Tahu core and a similar value of 1.0 mm yr^{-1} from the LS core at Matsalu.

Table 1 here

The variation in average CF:CS model-derived sedimentation values is partially reflected within the $^{210}Pb_{excess}$ CRS model derived age/depth profiles (Fig. 7) although these models reveal subtle differences in the recent sediment response of the different plant communities.

In the TG core from Tahu, a maximum reliable $^{210}Pb_{excess}$ date of 1899 (± 9 years) AD is reached at a shallow depth of 3 - 4 cm, reflecting the low rates of recent sediment accretion defined by the average values. No significant changes in sediment accretion are recorded within this core over the period 1899 – 2010 AD, although an overall subtle increasing trend over time from values of 0.1 mm yr in 1899 AD to < 0.5 mm yr^{-1} within the surface sediments is discernible (Fig. 7).

In the LS core a maximum $^{210}Pb_{excess}$ date of 1903 (± 17years) AD occurs at a depth of 17 - 18 cm. Steeper gradients in the CRS-derived age/depth model occurring within the dated periods of 1920-1935 AD and 1990-2000 AD reflect periods of increased sedimentation rates with values of up to 5 mm yr^{-1} recorded around 1925 AD.

Fig. 7 here

At Matsalu, the TG and LS cores record maximum $^{210}Pb_{excess}$ ages of 1886 (± 12 years) AD and 1899 (± 14 years) AD and at depths of 11 - 12 cm and 12 - 13 cm respectively (Fig. 7). Unlike the TG core from Tahu, the TG core at Matsalu records an early period of relatively increased rates of sedimentation around 1910 AD with values of 2.4 mm yr^{-1}. This corresponds quite well with the similar time-scale of increased sedimentation in the LS core from Tahu. Throughout the rest of the core profile, a subtle increase is evident up to the near-surface sediments where the modern rate declines to 0.9 mm yr^{-1}. The LS core at Matsalu shows little evidence for the periods of increased sedimentation rates that can be seen in the other cores. However, subtle increases in sedimentation can be identified between the period 1970-1989 AD and a more rapid increase in the near-surface sediments deposited between 2007 and 2010 AD.

4.3 ^{137}Cs impulse dating

Measured ^{137}Cs down-core activity profiles are shown in Fig. 8. In the LS cores from both sites a distinct peak in measured ^{137}Cs activity is evident at a depth of 6 - 7 cm, confluent with measured activity levels associated with the 1986 Chernobyl accident (Povinec et al., 2003; Anderson et al., 2011).

Within the Tahu LS core some broadening of this peak is evident, likely to be due to post-depositional migration and perhaps low retention of ^{137}Cs in the clay deficient sediments, although this is not apparent in the LS core from the Matsalu site where the 1986 Chernobyl activity marker horizon is quite well defined.

Fig. 8 here

Two peaks with lower measured activity levels of 50 and 75 Bq/kg^{-1} for the Tahu and Matsalu LS cores respectively are evident at a depth of 9 - 10 cm. These are confluent with measured activity levels and depths associated with atmospheric weapons testing recorded in temperate salt marsh sediments from other north European locations (Cundy and Croudace 1996; Thompson et al., 2001; Anderson et al., 2011). In the shallower TG cores, the only discernible measured peak in ^{137}Cs activity occurs at a depth of 2 - 3 cm within the Tahu TG core. Here, the activity of

131 Bq/kg^{-1} is associated with deposition of ^{137}Cs derived from the Chernobyl accident. ^{137}Cs activities in the TG core from the Matsalu site are inconsistent with those measured in the other three cores. Here, measured activity levels are lower throughout the core profile with highest values of 47.4 Bq/kg^{-1} located in the surface sediments. This suggests that there has either been recent erosion resulting in removal of the 1986 Chernobyl marker horizon and/or significant relocation of ^{137}Cs due to post-depositional mobility. In this core ^{137}Cs is present in the lowest reaches, indicating measured activity within age/depth horizons that greatly exceed the maximum age of introduction of this artificial radioisotope to the environment (> 65 years). The ages of the sediments at these core depths are confirmed by the calculated age and low average rate of sedimentation derived from the $^{210}Pb_{excess}$ CF:CS model (Table 1). This suggests post-depositional mobility of ^{137}Cs down the Matsalu TG core. Therefore, it was not possible to date this core using ^{137}Cs with any certainty. Rates of sediment accretion using the Chernobyl and Weapons Testing ^{137}Cs marker horizons from the LS and Tahu TG core are shown in Table 2.

Table 2 here

The highest ^{137}Cs and ^{210}Pb inventories were found in the Tahu LS core, followed by the Matsalu LS and TG cores with similar inventories for both radio nuclides (Table 3). However, the Tahu TG core had considerably lower inventories than all the other cores almost half that of the Matsalu cores. There was however little variation between the inventory ratio values of all cores (Table 3).

Table 3 here

5. Discussion

5.1 ^{210}Pb and ^{137}Cs dating

Previous studies have shown that higher proportions of soil organic matter increase post-depositional mobility of ^{137}Cs (Ritchie and McHenry, 1990; Rosen et al., 2009). The data from this study show that the soils for both the LS and TG communities in both the Tahu and Matsalu sites are predominantly composed of sand with a lesser proportion of silt and a very small (c. 1%) clay fraction (Fig. 5). Modelling studies by Borretzen and Salbu (2002) have suggested that following introduction of ^{137}Cs to sediments a proportion of the ^{137}Cs remains mobile whilst a lesser proportion becomes adsorbed relatively quickly in clay rich soils. This, together with the low clay content, may therefore have exerted some influence on ^{137}Cs retention in these sediments. Other mechanisms responsible for ^{137}Cs mobility may include reversible ion-fixation (Evans et al., 1983), vertical redistribution such as that seen within the pore waters of lake sediments (Comans et al., 1989) likely to be driven by Fe and Mn oxyhydroxide cycling (Benoit and Hemmond, 1990). In conjunction with the irregular nature of flooding, inundation of the Estonian coastal wetlands also takes place via horizontal percolation of water between plant communities with discrete differences in elevation relative to mean sea level. This process is known to cause ‘pooling’ within the micro-topographical depressions that occur throughout these wetland environments (Ward, 2012). Horizontal percolation does not appear to have significantly influenced the down-core ^{137}Cs activity profiles within three of the cores. However, within the Matsalu TG core the proximity of the core site to the adjacent and more regularly flooded LS plant community, as opposed to the position of the Tahu TG core, may have resulted in greater horizontal pore water pressures during inundation events. Greater horizontal pore water pressures increase horizontal pore water advection of ^{137}Cs (Harvey et al., 1995) along with vertical relocation of ^{137}Cs to depths that pre-date the occurrence of caesium in coastal wetland sediments (Thompson et al., 2001; Teasdale et al., 2011). The Matsalu TG core was taken from a section of the TG community within 20 m of the sea (Fig. 4). The Tahu TG core however, was removed from a section of the wetland with 250 m of the LS and US plant community between it and the sea (Fig. 3). Ward (2012) has shown that micro-topography affects the hydrology of these wetlands and inundation occurs by both overland flow and percolation. However, with respect to accretion, percolation does not supply sediment to the wetland. Therefore, whilst the plant community patches where the Tahu and Matsalu TG cores were located were likely to have similar water-table levels, the frequencies and depths of inundation and the amount of sediment deposited on the Tahu TG core site area was likely to have been appreciably lower.

Total inventory values of both ^{137}Cs and ^{210}Pb from the cores at Tahu and Matsalu suggest that while atmospheric deposition is one source pathway for these radionuclides within all cores, the greater inventory values for both radionuclides in the Tahu LS core and the Matsalu LS and TG cores (Table 3) suggests that there is also a ^{137}Cs and ^{210}Pb input from allochthonous sediment sources in these cores, although not within the Tahu TG core. The similar $^{137}Cs/^{210}Pb$ inventory ratios recorded within all cores suggests that the proportions of influx are similar from both marine-derived and atmospheric radionuclide supply routes. Whilst there is some additional input of both radionuclides from allochthonous sources, the broad agreement in mean sediment accretion rates derived from the CF:CS and CRS methods suggests that this has not compromised these dating tools.

At Matsalu, inundation of the TG core site by overland flow may explain the higher rates of sedimentation recorded at this point. Within the Tahu TG core, calculated rates of sedimentation suggest a quasi-equilibrium relationship between ongoing GIA, and recent sea-level rise. However, within both the LS cores current rates of sedimentation coupled with GIA appear to be outpacing recent sea level rise. This scenario may change given recent evidence which strongly suggests a late 20th/ early 21st Century acceleration in the rate of global sea-level rise (Church and White, 2006).

The near-exponential decline in measured down-core $^{210}Pb_{excess}$ activity within the Tahu and Matsalu cores indicates a relatively constant supply of atmospherically derived ^{210}Pb to the surface of these Boreal Baltic coastal wetland sites, implicit in the assumptions inherent within the CF:CS and CRS dating models (Appleby and Oldfield, 1992).

However, the Matsalu TG core exhibited much lower activity in the surface layers in comparison to the other three cores. From this, it appears that there has been a removal of the surface layer of the soil. This may also explain the lack of distinct peaks in ^{137}Cs activity down the core profile that could be attributed to the Chernobyl and pre-1963 weapons testing signatures. Andersen et al. (2000) found similar results due to the reworking of sediments and erosion for both ^{137}Cs and ^{210}Pb in the Humber estuary, NE England. An increase in sedimentation, and a related decrease in clay content, could also potentially explain the distribution of ^{137}Cs in the Matsalu TG core, although not the low levels of ^{210}Pb. The results of this study show a significant increase in the D10 particle size with time in the Matsalu TG core although not the other cores. This could potentially be a factor that has influenced the location of ^{137}Cs within the core as a result of a decrease in the relative proportion of the fine fraction to which ^{137}Cs can readily adsorb.

The ^{137}Cs down-core profiles from both the Tahu cores and the Matsalu LS core exhibited similar activity levels and a similar trend down the profile, with two distinct peaks visible. The upper and larger peak represents deposition derived from the 1986 Chernobyl disaster, and the lower peak found at a greater depth corresponds to the pre-1963 above-ground Weapons Test signature. In the LS cores the overall shape of the ^{137}Cs activity depth profile is similar to those reported by Callaway et al. (1996) from salt marsh sediments on the Polish coast in the southern Baltic Sea. These cores show some evidence, (i.e. the broadening of the ^{137}Cs peaks) for post-depositional mobility, however, this has not compromised the use of these marker horizons for dating purposes.

^{137}Cs dating is in good broad agreement with rates of sediment accretion derived from both the CF:CS and CRS methods for ^{210}Pb and provide a geochemically independent comparison with the ^{210}Pb methods (Teasdale et al., 2011). Soil organic matter and particle size have an effect on the location of radionuclides in the core profile particularly in areas with fluctuating water tables and can result in mobility of elements in solution through the core pore waters. Several studies have shown that ^{137}Cs is selectively fixed to clay minerals and is less mobile in clay rich soils (Walling and He, 1993; Cundy and Croudace, 1996; Rosen et al., 2009).

5.2 Sedimentary records of storm events

During the last century documented storms have impacted the NW Estonian coastline and in more recent decades the frequency of these inundation events is known to have increased (Jaagus et al., 2008). This is reflected by an increase over time in the D90 fraction for the lower elevation plant communities at both sites presented in this study. The results of this study also show that there has been a significant increase in the sorting coefficient in the LS community cores at both sites over time. This suggests that there has been an increase in the frequency of inundation by low energy waves. The significant decrease in the sorting coefficient over time in the Matsalu TG core suggests an increase in deposition from high energy waves. Due to the greater elevation above sea level as a result of continuing GIA, the Matsalu TG core area is likely to be inundated only by storm surges rather than the more frequent and lower energy rises in local sea level caused by changes in atmospheric pressure.

$^{210}Pb_{excess}$ CRS modelled sedimentation rates from the Tahu and Matsalu cores reveal a variable record of sedimentation in response to storm inundation events.

The low rates of sediment accretion recorded in the Tahu TG core (Fig. 7) suggests that inundation events are rare at this elevation and distance from the shore, although the increase in accretion rates may indicate that there has been more frequent inundation since the 1960s in response to a rise in relative sea level and an increase in storminess within Estonian coastal waters (Keevallik and Rajasalu, 2001; Suursaar et al., 2007). In contrast, the Tahu LS community has undergone more significant fluctuations in rates of sediment accumulation which have varied through time from 1 – 5 mm yr^{-1} (Fig. 7). Increased sediment accretion in the period extending from the early to mid-1920s and again in the early 1930s are associated with two extended periods of high average sea levels in west Estonia, according to the Pärnu tidal gauge (Suursaar *et al.*, 2007), which is also evident at the base of Matsalu TG core. However, there is little evidence of further storm signatures from this time up to the 1990s, which may be the result of site orientation relative to storm track direction and seasonality (e.g. presence of sea ice). Following this a more recent period of enhanced sedimentation is apparent in the mid-1990s which is likely to be associated with a period of increased storminess in 1992 - 1993 (Kont et al., 2007; Orviku et al., 2009).

Sedimentation rates from the Matsalu LS core reveal an increase in sediment accretion during the mid-1970s. This coincides with a known increase in the number of storm days in 1975-1976, recorded in both the Vilsandi and Pärnu tide gauges (Kont et al., 2007; Suursaar et al., 2007). Similar to the Tahu LS core, the Matsalu LS core also records a period of enhanced sedimentation in the early to mid-1990s associated with increased maximum sea level recorded at both the Vilsandi and Pärnu tide gauges located in north and north-west Estonia respectively (Fig. 1) and highlighted by Suursaar and Sööäär (2007).

The Matsalu LS core records one further increase in sediment accretion after 2004. This is likely to be associated with a severe winter storm in 2005 “Gudrun” (Orviku et al., 2009) that deposited significant quantities of material in Matsalu Bay (Lotman pers. comm. 2010). The historical trend of Boreal Baltic coastal wetland development has been one of progradation of coastal wetlands into adjacent water bodies driven in part by GIA and sediment accretion (Ward, 2012). This study has shown that past rates of sedimentation have fluctuated in response to changes in local sea level, driven by both atmospheric pressure and storm surges in the Baltic Sea. Additionally, there has been an overall increase in the rate of sediment accretion since the 1960s likely to be associated with recent climate change in the Baltic and perhaps the late 20th Century acceleration in the rise of global sea level and a decrease in sea ice (and subsequent increase in sediment deposition due to storm surges). The influence of coastal forcing mechanisms does not appear to threaten the future development of ecologically important Boreal Baltic coastal wetlands in Estonia which look set to follow historical trends of progradation due to the combination of present day rates of GIA and sedimentation.

6. Conclusions

Baltic coastal wetlands are characterised by predominately sand and silt material with little clay present although the organic above and below-ground component also contributes a significant proportion of the sediment matrix.

The near-exponential decline in measured $^{210}Pb_{excess}$ activity results in good agreement between the CF:CS and CRS model age-depth estimations. Independent dating control is provided using the ^{137}Cs marker horizons, where distinct peaks in measured activity associated with the pre-1963 Weapons Test signature and deposition derived from the 1986 Chernobyl accident are evident. Despite some evidence for post-depositional migration in the Matsalu TG core and broadening of peaks in ^{137}Cs activity, these marker horizons do not appear to have been significantly compromised for dating purposes.

This study has provided the first evaluation of sediment accretion rates in Boreal Baltic coastal wetlands revealing that subtle differences in rates of sediment accretion have occurred between the Matsalu and Tahu sites, and between the LS and TG communities. This work has shown that changes in sea level caused by variations in atmospheric pressure and storm surges can contribute a significant sedimentary component, which coupled with GIA processes, has driven coastal wetland development resulting in the historical progradation of these wetlands. The recent acceleration in the rate of global sea level rise may subtly alter this relationship, however we conclude that current rates of GIA and sedimentation will result in continued progradation of Boreal Baltic coastal wetlands in Estonia.

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Figure captions

Figure 1: Location of Boreal Baltic coastal wetland study sites with isobases of current glacio-isostatic adjustment (GIA) in Estonia, (grey dashed lines), (redrawn from Eronen et al., 2001). Also shown are the locations of tide-gauge stations (grey triangles).

Figure 2: Ecological zonation of Boreal Baltic coastal wetland sites in Estonia (after Ward, 2012). CS = Clubrush Swamp; RS = Reed swamp; LS = Low Shore; US = Upper Shore; TG = Tall Grass, OP = Open Pioneer; SW = Scrub Woodland.

Figure 3: Location of core sites for the Low Shore (LS) and Tall Grass (TG) (highlighted by black stars) within Tahu Bay, Estonia. Plant communities are shown by shading, community abbreviations are explained in figure 2 and detailed descriptions can be found in Burnside et al. (2007). Maximum inundation due to yearly average atmospheric pressure variation is shown by the cross-hatching. Maximum recorded inundation in these wetlands, as a result of the 2005 storm Gudrun, is denoted by diagonal hatching.

Figure 4: Location of core sites for the Low Shore (LS) and Tall Grass (TG) cores (highlighted by black stars) within Matsalu Bay, Estonia. Plant communities are shown by shading, community abbreviations are explained in figure 2 and detailed descriptions can be found in Burnside et al. (2007). Maximum inundation due to yearly average atmospheric pressure variation is shown by the cross-hatching. Maximum recorded inundation in these wetlands, as a result of the 2005 storm Gudrun, is denoted by diagonal hatching.

Figure 5: Stratigraphy of the core sequences from the Low Shore (LS) and Tall Grass (TG) plant communities at the Tahu and Matsalu study sites, (a and b = Tahu LS and TG cores; c and d = Matsalu LS and TG cores).

Figure 6: $^{210}Pb_{excess}$ activity/depth profiles for the four cores with ^{214}Pb activity shown (white squares) as a proxy for ^{226}Ra and $^{210}Pb_{supported}$. Also shown are the graphical plots of the natural logarithm of $^{210}Pb_{excess}$ plotted against depth used for the CF:CS or 'simple model' estimations of average sedimentation over the entire age/depth period. (a and b = Tahu LS and TG sites; c and d = Matsalu LS and TG sites).

Figure 7: $^{210}Pb_{excess}$ CRS model age/depth profiles for the four cores. Error for age estimations are based upon the value of $^{210}Pb_{excess}$ ± 0.002 Bq/kg^{-1}, (where not visible, age error bars are smaller than the marker option used). Also shown are calculated rates of sedimentation for the four sites plotted against $^{210}Pb_{excess}$ CRS modelled age, (a and b = Tahu LS and TG sites; c and d = Matsalu LS and TG sites).

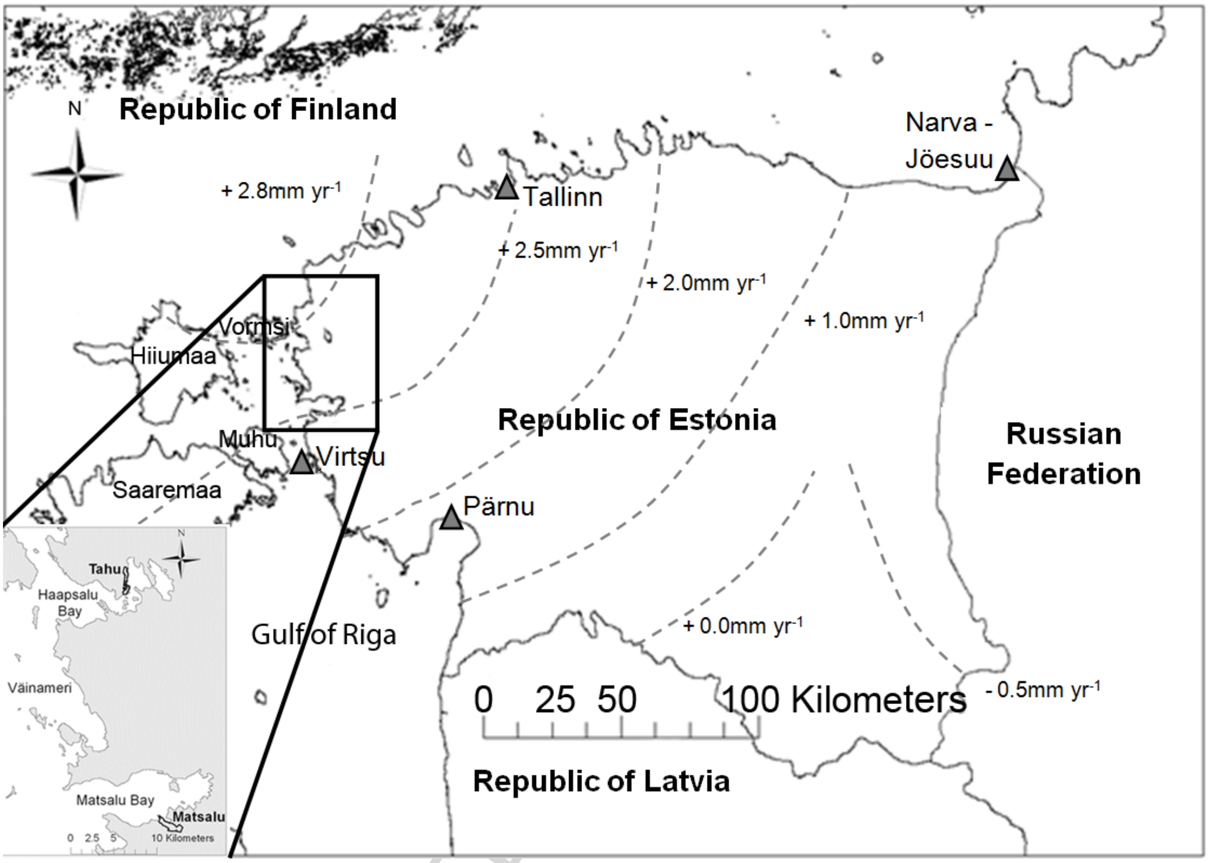
Figure 8: Measured ^{137}Cs activity/depth profiles for the Tahu and Matsalu cores, (a and b = Tahu LS and TG sites; c and d = Matsalu LS and TG sites). Where not visible, error bars in measured activity are smaller than the marker option used.

Table captions

Table 1: Average rates of sedimentation for the Tahu and Matsalu cores determined from the $^{210}Pb_{excess}$ Constant Flux: Constant Sedimentation (CF:CS) or 'simple' model.

Table 2: Rates of sedimentation in the Tahu LS and TG cores and the Matsalu LS core using the measured ^{137}Cs activity marker horizons from pre-1963 weapons testing and the 1986 Chernobyl accident. Lower and upper estimations are obtained using the maximum and minimum possible depth for each peak in ^{137}Cs activity.

Table 3: ^{137}Cs, ^{210}Pb inventories (Bq/cm^{-2}) and $^{137}Cs/^{210}Pb$ inventory ratios for the Tahu and Matsalu LS and TG cores.



Republic of Finland
N
+ 2.8mm yr-1
Tallinn
Narva - Jõesuu
+ 2.5mm yr-1
+ 2.0mm yr-1
+ 1.0mm yr-1
Vormsi
Hiiumaa
Republic of Estonia
Russian Federation
Muhu
Virtsu
Saaremaa
Pärnu
Tahu
Haapsalu Bay
Väinameri
Matsalu Bay
Matsalu
0 2.5 5 10 Kilometers
Gulf of Riga
+ 0.0mm yr-1
- 0.5mm yr-1
0 25 50 100 Kilometers
Republic of Latvia

Figure 1

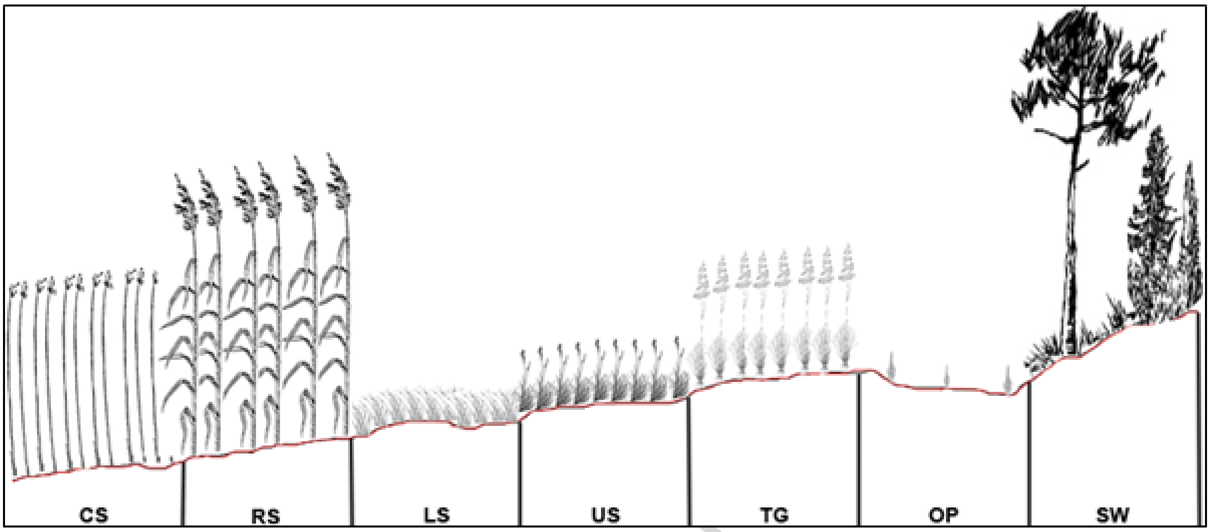
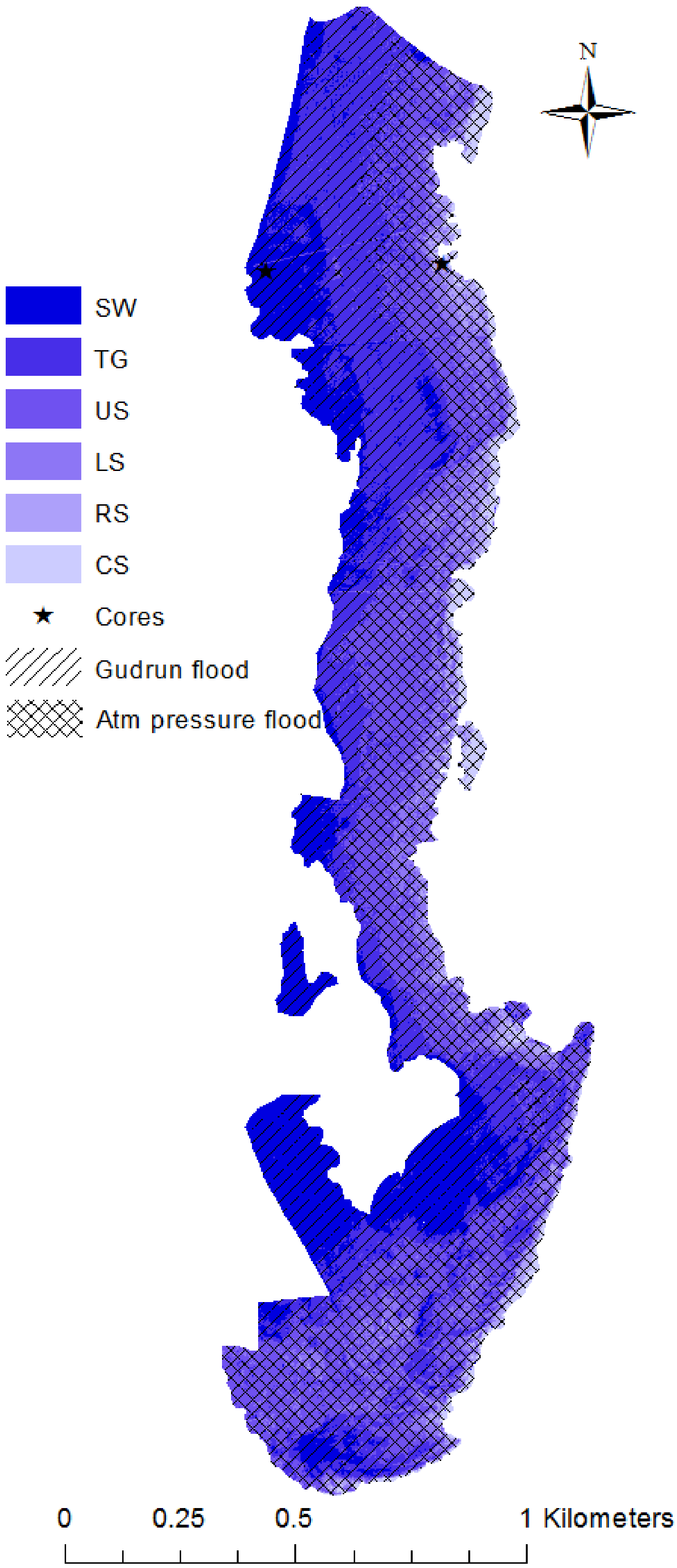


Figure 2



N
SW
TG
US
LS
RS
CS
Cores
Gudrun flood
Atm pressure flood
0
0.25
0.5
1 Kilometers

Figure 3

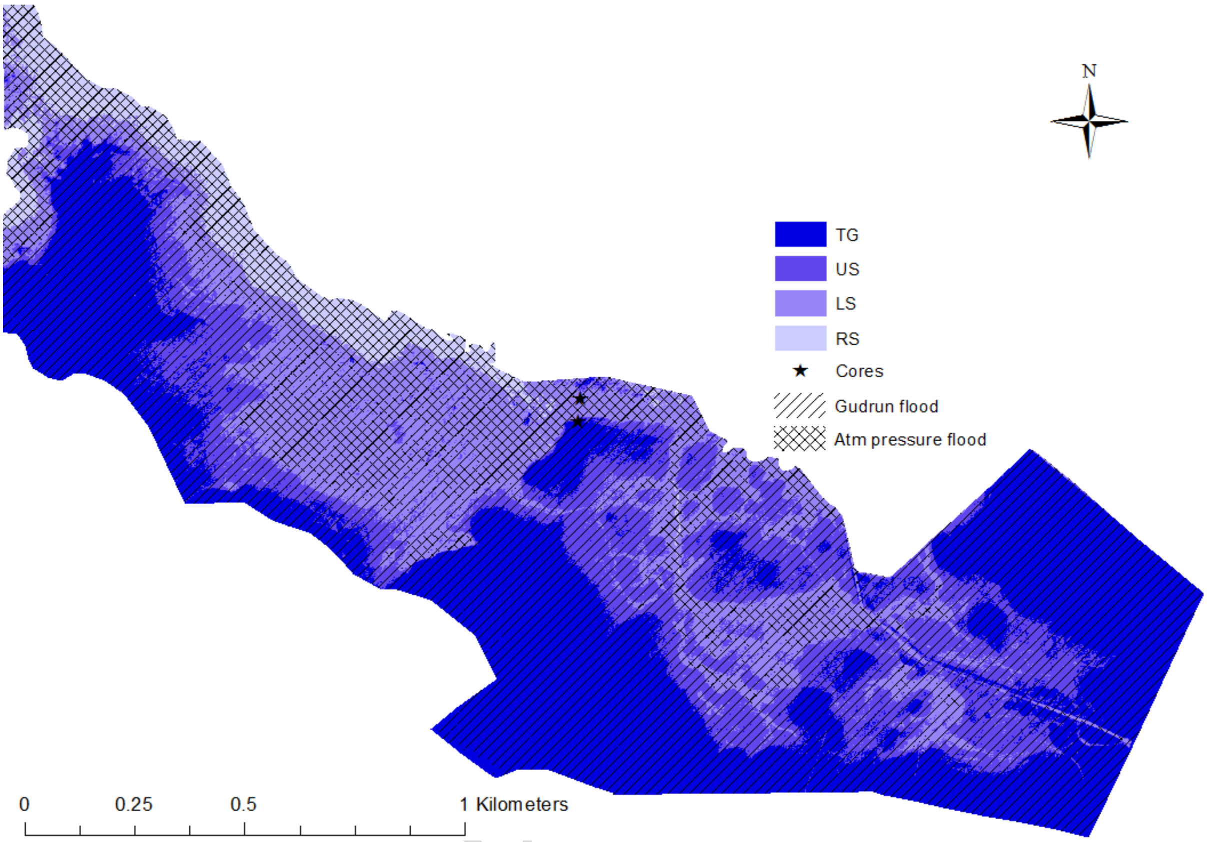

N
TG
US
LS
RS
Cores
Gudrun flood
Atm pressure flood
0
0.25
0.5
1 Kilometers

Figure 4

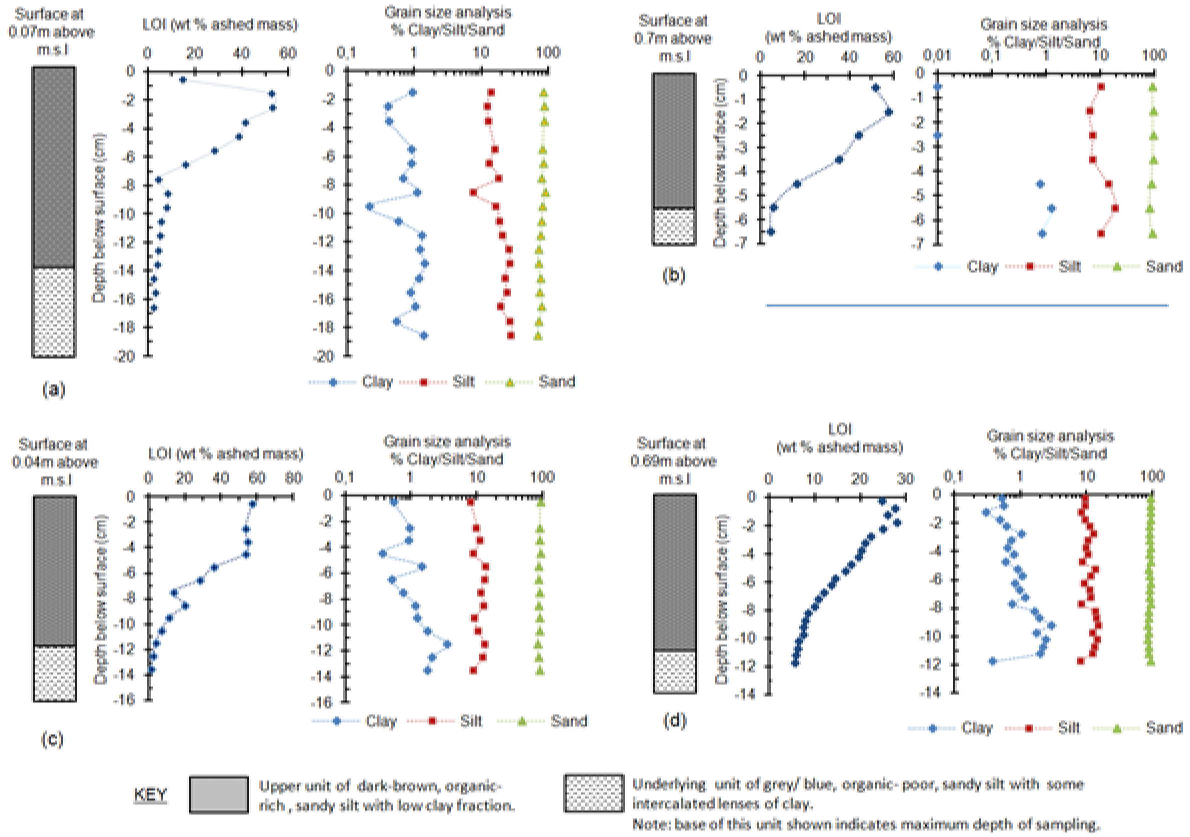
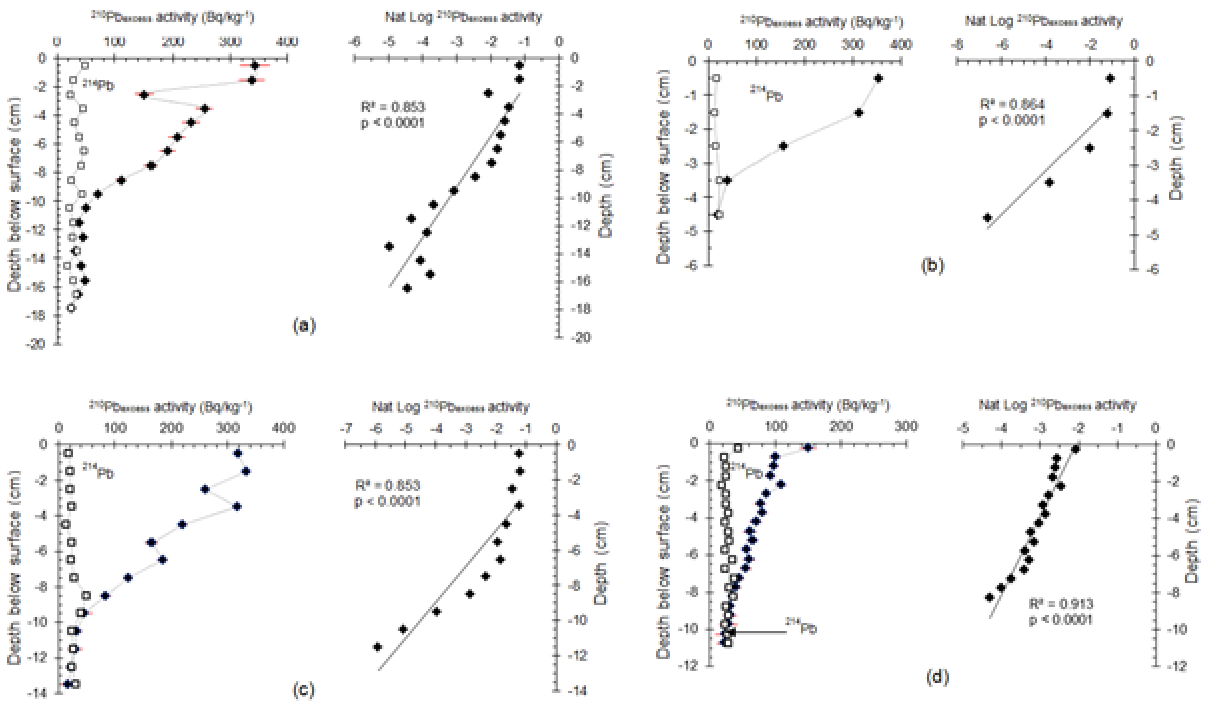
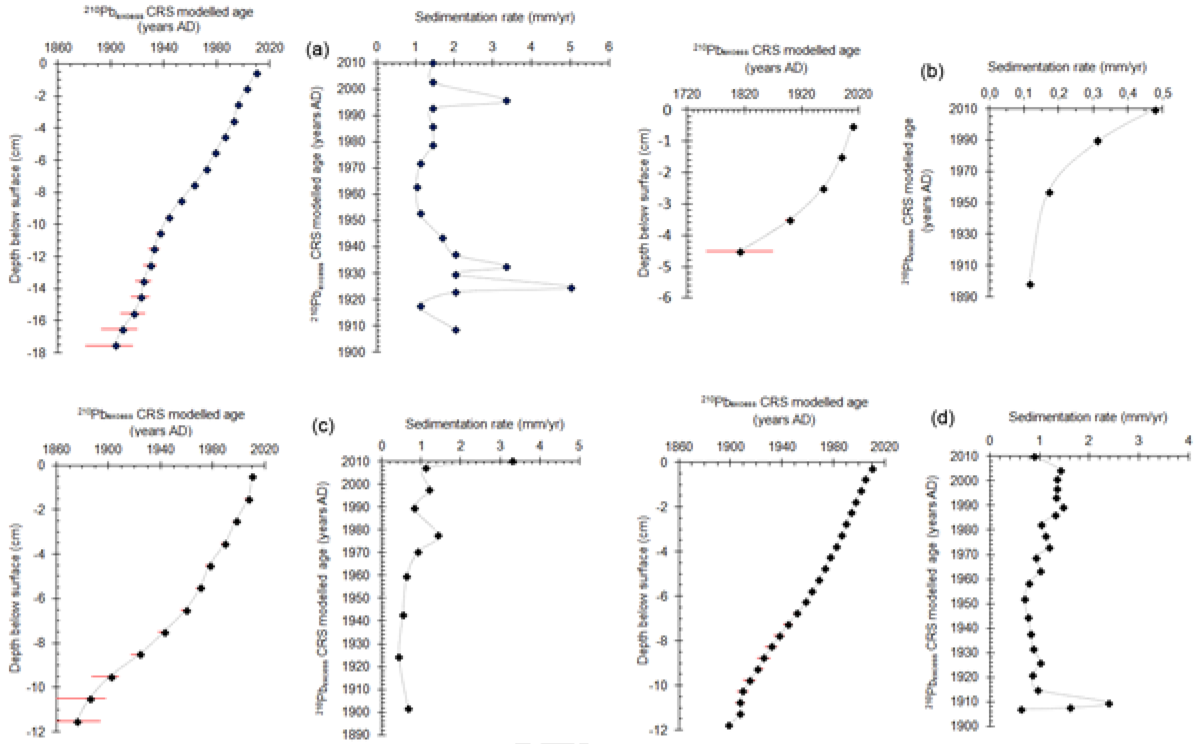

Surface at 0.07m above m.s.l
LOI (wt % ashed mass)
Grain size analysis % Clay/Silt/Sand
Depth below surface (cm)
Clay
Silt
Sand
(a)
Surface at 0.7m above m.s.l
LOI (wt % ashed mass)
Grain size analysis % Clay/Silt/Sand
Depth below surface (cm)
Clay
Silt
Sand
(b)
Surface at 0.04m above m.s.l
LOI (wt % ashed mass)
Grain size analysis % Clay/Silt/Sand
Depth below surface (cm)
Clay
Silt
Sand
(c)
Surface at 0.69m above m.s.l
LOI (wt % ashed mass)
Grain size analysis % Clay/Silt/Sand
Depth below surface (cm)
Clay
Silt
Sand
(d)
KEY
Upper unit of dark-brown, organic-rich, sandy silt with low clay fraction.
Underlying unit of grey/ blue, organic- poor, sandy silt with some intercalated lenses of clay.
Note: base of this unit shown indicates maximum depth of sampling.

Figure 5



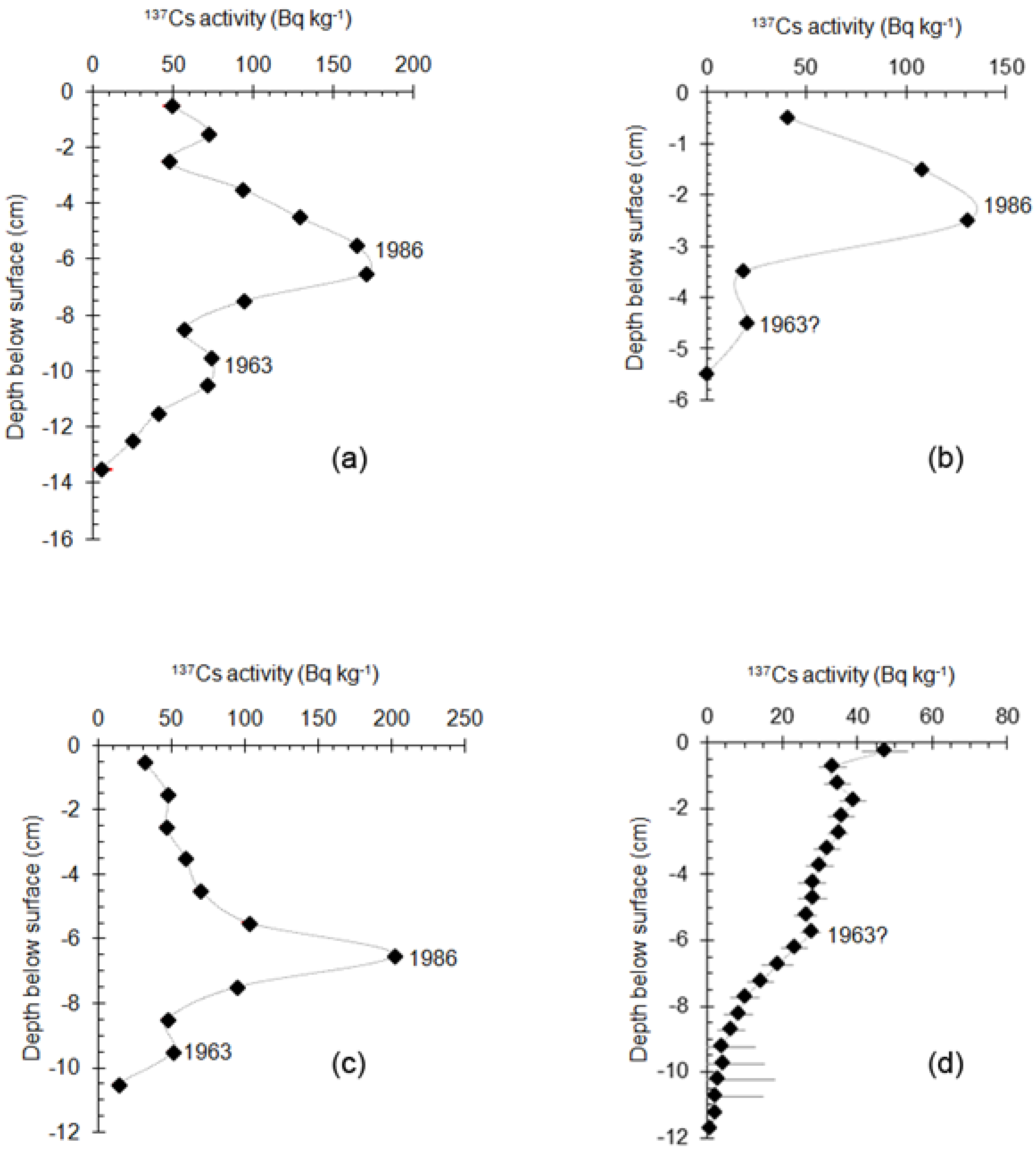
$^{210}Pb_{excess}$ activity (Bq/kg^{-1})
Nat Log $^{210}Pb_{excess}$ activity
Depth below surface (cm)
Depth (cm)
^{214}Pb
R² = 0.853
p < 0.0001
R² = 0.864
p < 0.0001
R² = 0.853
p < 0.0001
R² = 0.913
p < 0.0001
(a)
(b)
(c)
(d)

Figure 6



(a)
(b)
(c)
(d)
210Pb excess CRS modelled age (years AD)
Sedimentation rate (mm/yr)
Depth below surface (cm)
210Pb excess CRS modelled age (years AD)

Figure 7



^{137}Cs activity (Bq kg^{-1})
0
50
100
150
200
Depth below surface (cm)
0
-2
-4
-6
-8
-10
-12
-14
-16
1986
1963
(a)
^{137}Cs activity (Bq kg^{-1})
0
50
100
150
Depth below surface (cm)
0
-1
-2
-3
-4
-5
-6
1986
1963?
(b)
^{137}Cs activity (Bq kg^{-1})
0
50
100
150
200
250
Depth below surface (cm)
0
-2
-4
-6
-8
-10
-12
1986
1963
(c)
^{137}Cs activity (Bq kg^{-1})
0
20
40
60
80
Depth below surface (cm)
0
-2
-4
-6
-8
-10
-12
1963?
(d)

Figure 8

Table 1: Average rates of sedimentation for the Tahu and Matsalu cores determined from the $^{210}Pb_{excess}$ Constant Flux: Constant Sedimentation (CF:CS) or 'simple' model.

		Sediment Accretion Rates (mm yr^{-1})		
Site	Ecological zone	*Lower 95%*	*Average*	*Upper 95%*
Tahu	Low Shore (LS)	1.1	1.3	1.7
	Tall Grass (TG)	0.1	0.2	0.8
Matsalu	Low Shore (LS)	0.5	0.7	1.1
	Tall Grass (TG)	0.9	1.0	1.3

Table 2: Rates of sedimentation in the Tahu LS and TG cores and the Matsalu LS core using the measured ^{137}Cs activity marker horizons from pre-1963 weapons testing and the 1986 Chernobyl accident. Lower and upper estimations are obtained using the maximum and minimum possible depth for each peak in ^{137}Cs activity.

		Sediment Accretion Rates (mm yr^{-1})					
Site	Ecological zone	*Lower*	***1963***	*Upper*	*Lower*	***1986***	*Upper*
Tahu	Low Shore (LS)	1.2	1.4	1.5	2.3	2.7	2.9
	Tall Grass (TG)	0.3	0.5	0.6	0.6	1.0	1.3
Matsalu	Low Shore (LS)	1.8	2.0	2.5	2.3	2.7	3.1
	Tall Grass (TG)	(no definitive impulse activity peaks due to post-depositional remobilization)					

Table 3: ^{137}Cs, ^{210}Pb inventories (Bq/cm^{-2}) and $^{137}Cs/^{210}Pb$ inventory ratios for the Tahu and Matsalu LS and TG cores.

Core	^{210}Pb Inventory (Bq/cm^{-2})	^{137}Cs Inventory (Bq/cm^{-2})	$^{137}Cs/^{210}Pb$ Inventory ratio
Tahu LS	3.01	1.69	0.55
Tahu TG	0.97	0.38	0.39
Matsalu LS	1.99	0.8	0.4
Matsalu TG	1.94	0.98	0.51

Highlights:

- First evaluation of sediment accretion rates in Boreal Baltic coastal wetlands
- Recorded subtle differences in sedimentation between sites and plant communities
- Deposition largely driven by atmospheric pressure/storm surges (i.e. sea level)
- Predicted continued progradation of Baltic coastal wetlands in spite of global SLR