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

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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 the ^{210}Pb and ^{137}Cs radiometric dating methods 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 and 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.

1. Introduction

Extensive ecologically diverse Boreal coastal wetlands characterise 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 adjustment (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).

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., 2006b). 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 between 950 and 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,

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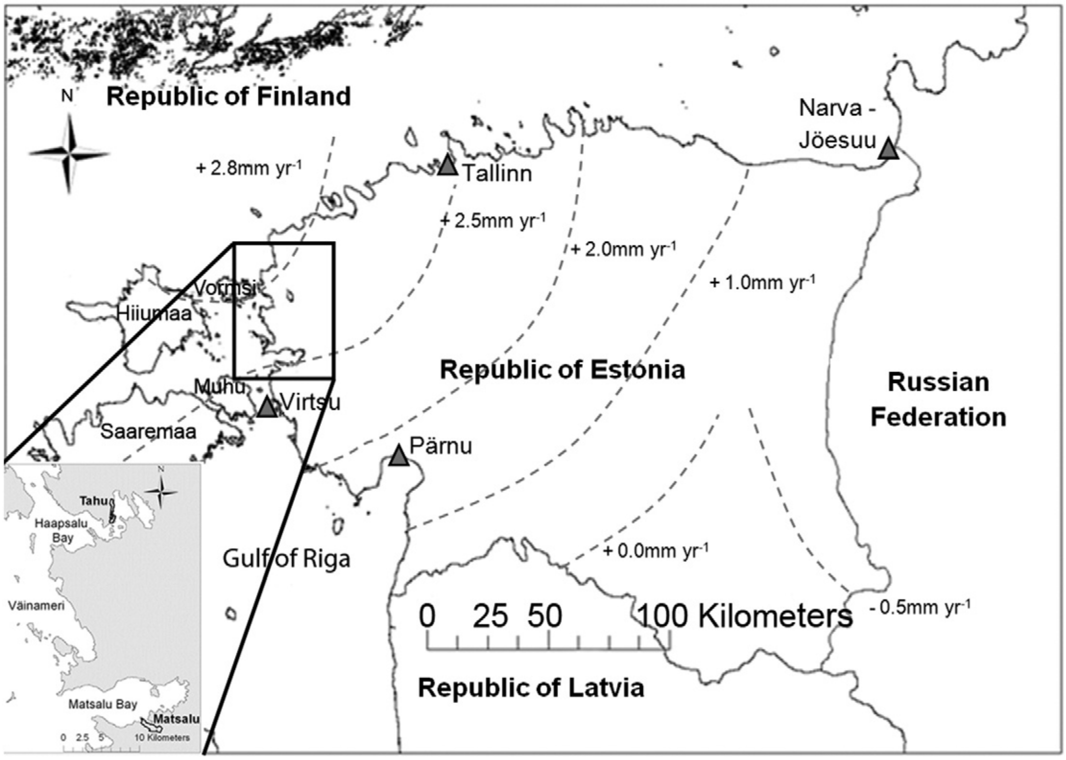

Fig. 1. Location of Boreal Baltic coastal wetland study sites with isobases of current glacio-isostatic adjustment (GIA) in Estonia, (grey dashed lines). Also shown are the locations of tide-gauge stations (grey triangles).
Redrawn from Eronen et al., 2001.

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 $\pm$ 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,b).

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 $\pm$ 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 et al., 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 Pärnu, 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; Suursaar and Sööäär, 2007; Suursaar et al., 2007; Kont et al., 2008) 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