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Development of the reed bed in Matsalu wetland, Estonia: responses to neotectonic land uplift, sea level changes and human influences

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Abstract. We studied reed bed development in Matsalu wetland and the Kasari River delta, Estonia, since the late 18th century using historical schemes, topographical maps and aerial photographs. Our aim was to understand the mechanisms controlling reed distribution in Matsalu wetland, the largest coastal wetland of the eastern Baltic Sea occupying an area of about 25 km^2. Natural development of the reed bed in Matsalu Bay and the Kasari delta is mainly controlled by shoreline displacement due to post-glacial neotectonic land uplift. The dredging of the Kasari delta in the 1920s–1930s caused a rapid seaward migration of reed bed communities due to the dispersal of fragmented rhizomes on the shallow sea bottom and along the canal banks reaching Matsalu Bay, while the landward parts of the former wetland were occupied by meadow communities. The expansion of the reed bed started in between the 1951s and 1970s and a maximum extent of 27 km^2 was gained by the late 1970s at the peak of eutrophication. In the last decades the reed bed development has been influenced by sea level rise and increased intensity of cyclonic activity in the Baltic Sea, which has caused the deterioration of the reed bed that was weakened by eutrophication due to nutrient inflow from agricultural landscapes mainly in the 1960s–1980s.

Key words: *Phragmites*, land uplift, sea level, storminess, dredging, eutrophication.

INTRODUCTION

Coastal wetlands lie on the transition between aquatic and terrestrial environments and provide an important habitat for various species of plant, fish and wildlife occupying these unique ecological niches. Such wetlands are threatened and unstable habitat types throughout the world (Perillo et al. 2009). The size of coastal wetlands has changed dramatically over the past two centuries, mainly as a consequence of human activities, both due to direct management of coastal areas as well as indirect influences of global climatic change.

Common reed, *Phragmites australis*, is one of the most widely distributed plant species on the Earth. It is a typical dominant plant species in different wetland habitats, both in fresh-to-brackish-water and saline-water environments. The distribution of common reed in coastal zones is controlled by the water level (water depth) (Coops et al. 1996; Vretare et al. 2001; Deegan et al. 2007), tidal elevation (Squires & Van der Valk 1992), wave action (Coops et al. 1994), salinity of water and soil (Burdick et al. 2001) and redox conditions of the substrate (Weisner 1996; Van der Putten 1997; Sanchez et al. 1998).

Reed belts in land–water ecotones of central, eastern and southern Europe have deteriorated significantly in the last decades. This is known as the reed die-back syndrome (Armstrong et al. 1996). Eutrophication is generally regarded as a major factor in determining reed decline (Čížková et al. 1996), though the changes in water depth, temperature, reduced genetic variation and their interactions may also contribute to reed die-back (Van der Putten 1997). In contrast, in North America the reed has grown extensively over the past 20 years on the Atlantic coast (Tiner 1993) and *Phragmites* has become dominant in many coastal wetlands, which has resulted in monocultural environments that reduce both species diversity and wildlife habitat (Rice et al. 2000). Reed decline or invasion in those areas is apparently due to a complex interaction of causes, which makes it difficult to understand the environmental factors and/or physiological mechanisms involved.

In this contribution we study the reed bed development in Matsalu wetland in the eastern Baltic Sea. Matsalu wetland, including the reed bed and meadows of the Kasari River delta, is the largest coastal wetland of the eastern Baltic Sea where reed communities occupy today about 25 km^2. The reed bed serves as a major nesting place for a large variety of birds and as a most significant resting area on the Eastern Atlantic bird migration route. Contrary to the rest of Europe, the area of reed bed communities in Matsalu wetland has widened in the last 100 years from about 10 km^2 in the early 20th century to about 20 km^2 by the end of the 1930s and a maximum of around 27 km^2 in early 1980. The reed expansion in Matsalu wetland has probably resulted from a complex interplay between natural processes, such as the shoreline advance due to neotectonic land uplift, and human activities, both indirect and direct influences from wetland dredging and eutrophication. In the last decades, however, the enlargement of the reed beds has stopped and they show signs of deterioration (Meriste et al. 2012).

Our goal is to understand the processes controlling the reed bed development in the Matsalu wetland area. For this purpose we (1) provide a reconstruction of reed bed migration and invasion in Matsalu wetland using historical maps and contemporary aerophotographic data and (2) analyse reed bed development in the context of neotectonic land uplift, seal level changes and human influences.

MATERIAL AND METHODS

Study area

Matsalu wetland lies in the West Estonian lowland (grid: 58°42′30″–58°48′41″N/23°43′27″–23°58′38″E) in the eastern Baltic Sea. The wetland encompasses the easternmost end of Matsalu Bay and the Kasari River delta (Fig. 1). Matsalu Bay is a narrow (maximum width 6.5 km, surface area 67 km^2) shallow bay, 15 km long and with an average water depth of 1.5 m. The bathymetry of the bay is smooth and the water depth decreases gradually from 4 m at the westernmost entrance to the bay to less than less than 1 m in its eastern part (Fig. 1). The shallow eastern part of the bay contains numerous islets. The bay and the wetland are located in a shallow east–west oriented depression cut into bedrock composed of Palaeozoic carbonate rocks. The depression is filled with Late Glacial varved clays, which form most of the low-lying plain of the wetland.

Water chemistry in the bay is determined by the mixing of water from the Kasari River and Baltic Sea (specifically the Väinameri, a shallow sea area between western Estonian islands and the mainland). Salinity is usually 4–6‰ at the entrance to the bay, 1–4‰ in its central part and only 0.5–2‰ in its easternmost part. Ice formation starts typically at the end of November and ice usually melts in April. The shallowest parts of the bay (<0.7 m) may freeze to the bottom during cold winters. The water temperature reaches 25–26 °C in midsummer (Vetemaa et al. 2006). The currents in Matsalu Bay are weak and are created both by wind and streaming water from the Kasari River. The contemporary bottom sediments in Matsalu Bay are mostly sand, silt and clayey mud, whose thickness does not exceed 2 m.

The brackish-to-fresh water in the eastern part of the bay is due to the freshwater inflow from the Kasari River. The river enters the bay at its eastern and south-eastern end, forming the largest deltaic plain in the northern Baltic Sea (Mardiste & Kaasik 1985). The catchment of the Kasari River is about 3210 km^2 and the average annual inflow is approximately 950 million m^3 (Järvekülg 2001). The annual freshwater inflow from the Kasari River exceeds the amount of water in the bay itself by about 10–11 times. The estimated annual sediment load is about 6000 t and the most part of the carried sediment settles in the area of the Kasari River delta during the flooding periods (Järvekülg 2001). The delta plain is very low (<1.5 m above sea level, the relief gradient along the delta plain 0.2–0.25 m km^{-1}), with the average decline at the lower course of the river about 0.15 m km^{-1}. This allows extensive periodic floods in spring during the snow melting period and/or due to prolonged and heavy rainfall usually in autumn, but occasionally also in summer. The flooding of the wetland can be initiated also by strong and prolonged south-westerly winds, which cause the sea level rise and sea/river water invasion to flooded plains. The inundated area of meadows is approximately 40 km^2 (Kont et al. 2008).

The Kasari River has two channels at river reaches, both of which are artificial, excavated in 1927–1938. The lower course of the river is a delta with large fields of flooded meadows (up to 40 km^2) and reeds (25–30 km^2). Flooded meadows (dominated by *Carex* species) are used extensively for hay-making. The areas too wet for mowing are covered with reeds. The dominant species is *Phragmites australis*, but also *Schoenoplectus lacustris*, *S. tabernaemontanii*, *Typha angustifolia*, *Bolboschoenus maritimus*, etc. are found.

Phragmites australis appears to be dominant in 80%, *S. lacustris* in 6%, *S. tabernaemontanii* in 2.6% and *T. angustifolia* in 7.4% of the territory of reed bed communities. Stands, where two or three out of the four mentioned species are codominants, comprise 3.6% of the reed bed communities, while *Scirpus maritimus* L., *Glyceria maxima* or *Acorus calamus* L. grow only on 0.5% of the area (Ksenofontova 1989). The dense reed bed alters with open water to average water depth of ~0.3 m. In deeper water (up to ~1 m) small sporadically spaced *Phragmites* and *Schoenoplectus* clumps are found (Fig. 1).

During the Last Glacial Maximum the Matsalu Bay area was covered by the Scandinavian Glacier. As a result it is experiencing post-glacial glacioisostatic uplift with the current rate of 2–3 mm yr^{-1} (Vallner et al. 1988). The continuous uplift has resulted in a gradual change in relative sea level and the retreat of the sea and coastal habitats towards the west over the last 10 000 years.

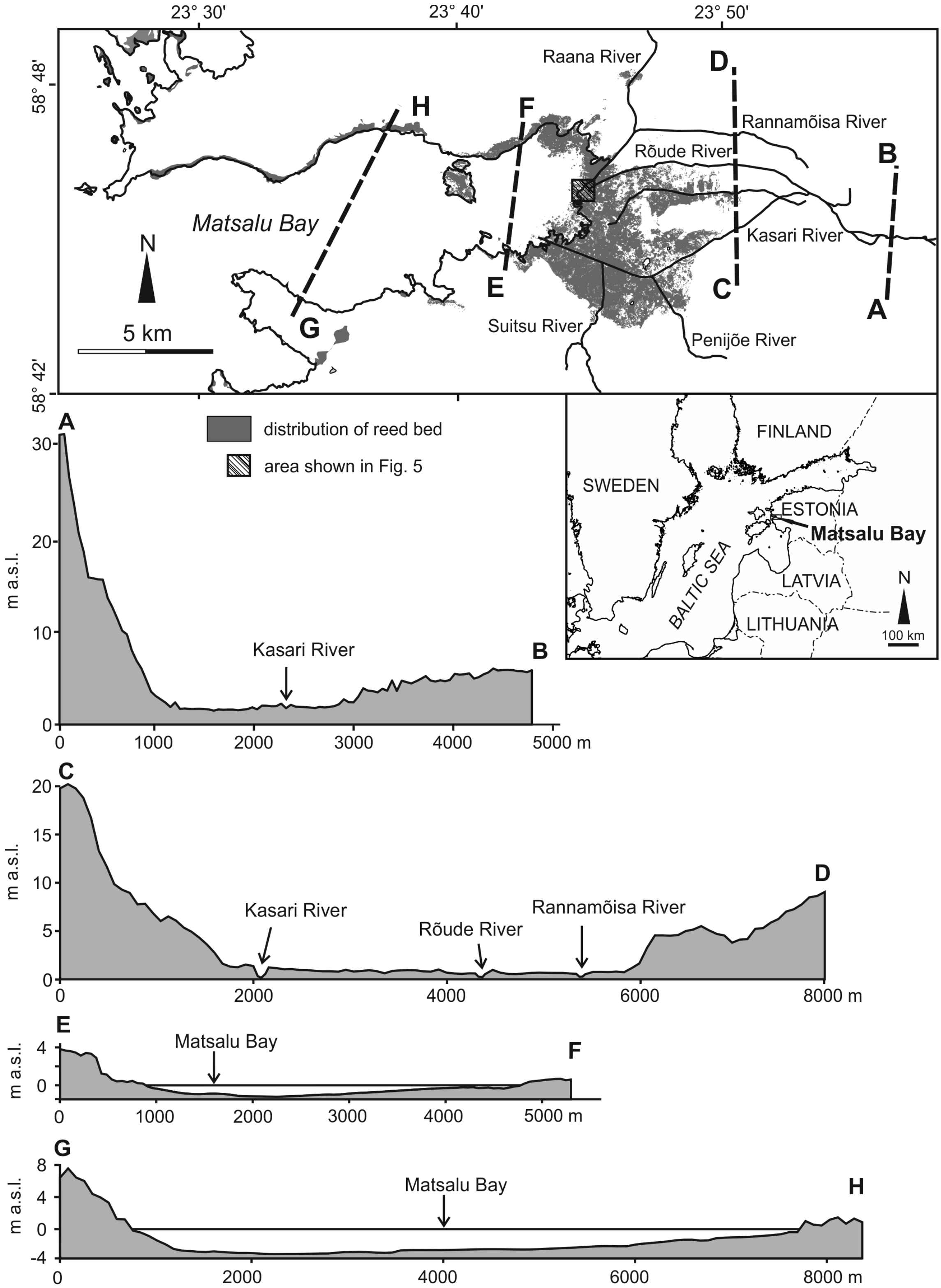

Fig. 1. Schematic map of Matsalu wetland with topographic and bathymetric cross sections of Matsalu Bay and the Kasari River delta. The distribution of the reed bed in Matsalu wetland is shown as in 2005.

The Matsalu wetland area is under protection as part of the Matsalu National Park. The reserve was founded in 1957 mainly to protect nesting, moulting and migratory birds. In 1976 Matsalu was included in the list of wetlands of international importance under the Ramsar convention.

Methods

The distribution and changes in reed bed vegetation were determined by interpretation of historical schemes and topographical maps, and aerial photographs of 1951, 1978, 1995, 2005 and 2008.

The pre-dredging development of the wetland was complemented with historical schemes and written data from the 18th and 19th centuries. The historical maps were originally not aligned to a coordinate system and a series of at least four Ground Control Points (GCP) were used to 'warp' the maps to the modern coordinate system. Fixed objects, i.e. churches and crossroads were used for GCPs and the scanned images were coordinated and registered to the Estonian coordinate system (L–EST 1992).

The reconstruction of the wetland system before the dredging in the 1920s–1930s is based on the topographic map of the Russian Empire of 1903 on a scale of 1 : 42 000 and the topographic survey of the dredging project (Vellner 1928a, 1928b). The distribution of the reed and the morphology of the delta complex immediately after the dredging were reconstructed from the topographic maps on scales of 1 : 50 000 and 1 : 200 000 of the year 1938. Old topographic maps were pre-coordinated into the Estonian coordinate system and are available at the Estonian Land Board website (www.maaamet.ee).

The spatial relationship and changes in Matsalu wetland in the last sixty years were determined by the interpretation of aerial photographs. Aerial photographs were taken in early May to late June. For 1951, 1978 and 1995 black-and-white aerial photographs and for 2005 and 2008 colour images by the Estonian Centre of Forest Protection and Silviculture and the Estonian Land Board were available. Aerial photographs for 1995, 2005 and 2008 were already in coordinated digital format. Scanned photographs for 1951 and 1978 were coordinated and registered to the Estonian coordinate (L–EST 1992) system using at least four GCPs per image.

The modern topography of the area was interpreted using the Light Detection and Ranging (LIDAR) survey of Matsalu wetland of year 2001 with an average point density of 16 points per hectare. The LIDAR database was combined with unpublished bathymetry data of Matsalu Bay and an elevation model of Matsalu wetland was created using MapInfo 8.5®.

Colours and symbols as well as written commentaries on historical topographic maps were used to interpret the distribution of the reed bed and vegetation classes. On aerial photographs the classification of wetland vegetation types (distribution of the dominant wetland species *Phragmites australis*, *Schoenoplectus* sp. and *Typha angustifolia*) was performed using the supervised clustering method in the IDRISI Andes code. Training areas were selected and the interpretation of reed bed distribution was controlled against the vegetation mapping transects crossing the reed bed on land and in the Matsalu Bay area in years 2002–2008. On transects the boundaries between dominant species areas were determined and stored using GPS and compared to the distribution of vegetation classes recognized on aerial photographs. However, the results of the clustering on aerial photographs of different years were not comparable to each other because the photographs were taken at the beginning of the vegetation period (late April–early July) when the plant cover was still developing. Therefore, only the distribution of the reed bed (*sensu lato*) as the area covered by *P. australis*, *Schoenoplectus* and *Typha* was classified and measured.

The water chemistry data (NO_3^-, PO_4^{3-}, SO_4^{2-} and Cl^-) for the Kasari River were obtained from the Estonian Meteorological and Hydrological Institute for years 1946–1991 (Kaarel Kaisel, unpublished database) and from the Estonian Environmental Research Centre for 1992–2009. The data represent the long-term monitoring of the water quality at the Kasari gauge (Fig. 1). There is a gap in measurements in 1968–1976 when the sampling programme was not running. Analysis of the water samples at an affiliate laboratory of the Estonian Environmental Research Centre was carried out using standardized methods. The methodology of sample analysis before 1970 was not available. The yearly average sea level data for the Port of Virtsu gauge were obtained from the Estonian Environment Agency.

RESULTS AND DISCUSSION

Pre-dredging development

Although in details largely inaccurate, the first comprehensive non-instrumental map of Matsalu wetland and the Kasari River delta was published in 1798 by Count v. Mellin (Fig. 2A). The map shows the river delta entering Matsalu Bay through numerous braided streams about 5 km east from the present-day shoreline. The Saastna Peninsula at the southern shore of the bay entrance is shown as an island, which became merged with the mainland only by the 19th century. On the map by Fr. Schmidt of 1871, which is notably more accurate but yet not connected to the triangulation network, the

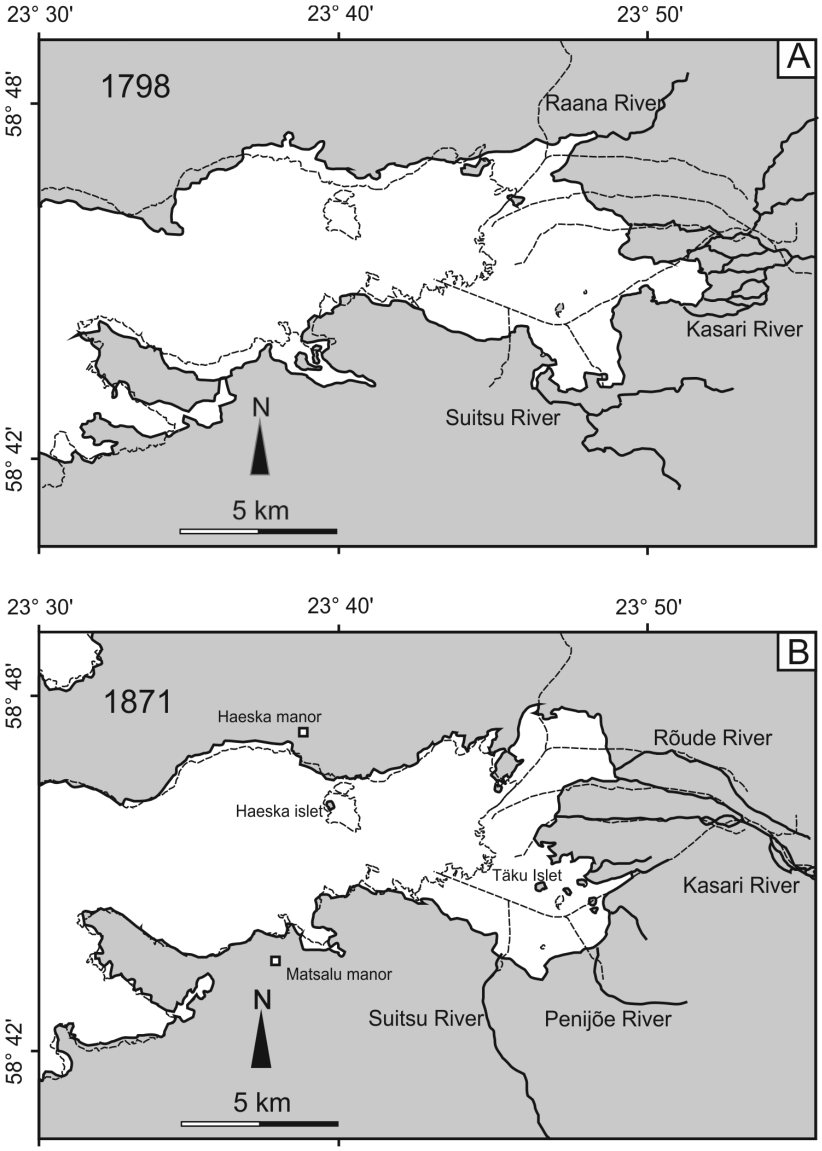

Fig. 2. Simplified historical schemes of Matsalu wetland and the Kasari River delta from (**A**) the 1798 map compiled by Count v. Mellin and (**B**) the 1871 map compiled by Fr. Schmidt. The dashed line shows the position of the modern coastline and rivers/channels.

shoreline and the delta complex show an advancement for a few kilometres compared to the map of 1798 with the most remarkable displacement of the Kasari delta along the central axis of the bay, which resulted in the formation of two smaller closed bays at both sides of the delta (Fig. 2B). The first written remarks on Matsalu wetland originate also from the 1870s when the area, and particularly the distribution of the reed bed communities and a large variety of birds were described by an ornithologist Valerian Carl Michael Russow and local nobleman Gernet (Kumari 1973). According to their description, the reed bed communities were distributed only between the lower courses of the Rannamõisa, Kloostri and Penijõe rivers, whereas the rest part of the bay between Haeska and Matsalu manors and the area surrounding Haeska and Täku islets was open water. Based on their estimate, the total area of the reed bed at that time was about 10 km^2 (Fig. 2A, B; Kumari 1973; Mägi 2003).

The first large-scale instrumental survey of the area was completed by the end of the 19th century and the map was published in 1903 (Fig. 3A). The configuration of the delta and the shallow bay is similar to that on the map of 1871. However, the entrance area of the small

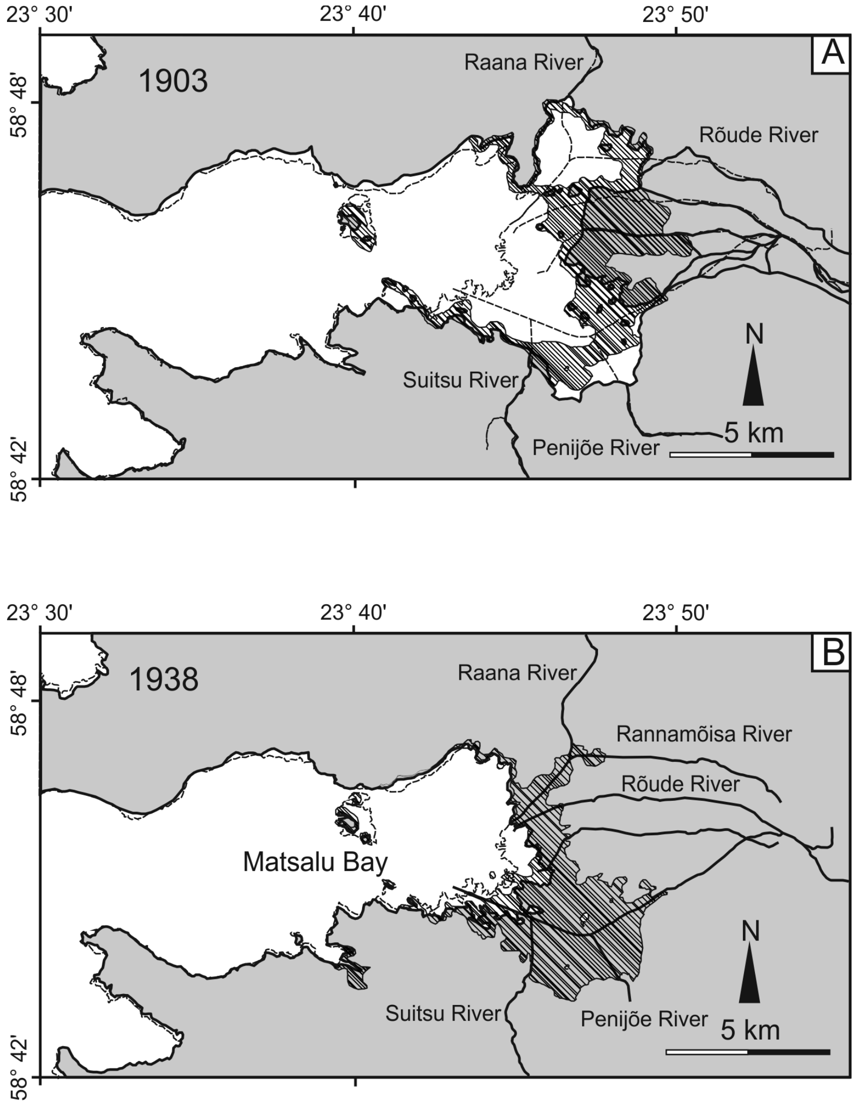

Fig. 3. Simplified maps of Matsalu wetland and the Kasari River delta from (**A**) the 1903 map of the Russian Empire on a scale of 1 : 42 000 and (**B**) topographic maps on a scale of 1 : 50 000 of 1936–1939. The dashed line shows the position of the modern coastline and the shaded areas show the distribution of the reed bed.

closed bay north of the delta has been reduced and, according to the symbols indicating the vegetation on the map, was isolated from the rest of the bay by a reed bed belt. The area of the reed bed as shown on this map is about 19 km^2. Kupffer (1911), however, estimated the area covered by the reed bed to be about 15 km^2, while according to Härms (1926), the reed bed coverage in Matsalu wetland was about 16 km^2. Härms (1926) was also the first to notice the gradual decrease in the bay area due to the westward expansion of the reed culms and the reed colonization in the closed bays, particularly in the northeastern part of Matsalu Bay.

Before the dredging the Kasari River flowed into Matsalu Bay through several branches named as the Raana, Rõude, Aru and Kloostri rivers (Fig. 3A). The branching occurred about 5 km before the entrance to the bay and the branches flowed in natural shallow riverbeds that were linked to each other by a network of smaller strings. The natural river system could not drain enough water flow during the melting of snow and heavy rain periods, causing extensive (~40 km^2 in area) flooding lasting for several weeks, which interfered and spoiled the management of hay-rich meadows. For that reason the drainage of the floodplains was undertaken in 1926–1938 (Veering 1983).

The dredging operation completely reshaped the hydrological system of the wetland as instead of natural rivers 3.5–3.7 m deep and 20 m wide canals were dredged

(Vellner 1928a, 1928b). In most cases the dredged channels did not follow the original river system, especially in the delta area and in the eastern part of the bay. The channels were dredged 1.5–8 km from the coastline into the open sea to ensure the proper drainage of inflowing river water (Viikman 1931).

Dredging effects

The dredging caused immediate and significant changes both in wetland functioning and in the distribution of wetland communities. First of all, the length of the flooding period decreased from an annual average of 247 days in 1924–1929 to 189 days per annum in 1939–1943 and to only 107 days in 1955–1959 (Truus & Sassian 1999). The distribution of the reed bed experienced the most rapid changes in a semiclosed open water area in the northwestern part of the bay, which became occupied by dense reed already by the end of the 1930s (Fig. 3B) and was replaced by (wet) meadow communities during the 1950s. The area of the reed bed reached 20 km^2 according to the topographic survey of 1936–1938.

During the next decades reed distribution advanced fast westwards, specifically along the southern and northern coasts of the bay and along the shores of the dredged channels. As interpreted from aerophotographs of 1951, the reed bed area was ~21 km^2, and it achieved its maximum of about 27 km^2 by the end of the 1970s (Kseneofontova 1989; Fig. 4). The intervention of the reed towards open sea was, however, accompanied by gradual retreat of the reed beds at the mainland side, mainly by the introduction of the meadow species among which *Carex disticha* and *C. elata* were dominant.

In the first decades after the dredging, until the end of the 1970s, the reed migration strategy was characterized by a rapid formation of numerous small reed culms emerging far from the boundary of dense reed, specifically along the dredged channels and in shallow parts of Matsalu Bay. The latter became isolated from the main part of the bay by channels like in the area between the Kasari and Penijõe rivers in the southeastern corner of the former Matsalu Bay (Fig. 1), while the reed bed disappeared in flooded meadows and wetlands at the mainland side of the Kasari delta drained by dredging. In the 1970s–1980s, however, the advance of the reed bed at the sea side of the delta stopped and in most areas the number of new stands emerging form the massive reed belt has considerably reduced. Instead, the contiguous expansion and integration into a massive clonal reed belt are observed (Figs 4, 5), while the estimated total area of the reed bed has shown a slightly decreasing trend over the last 25 years (Fig. 4).

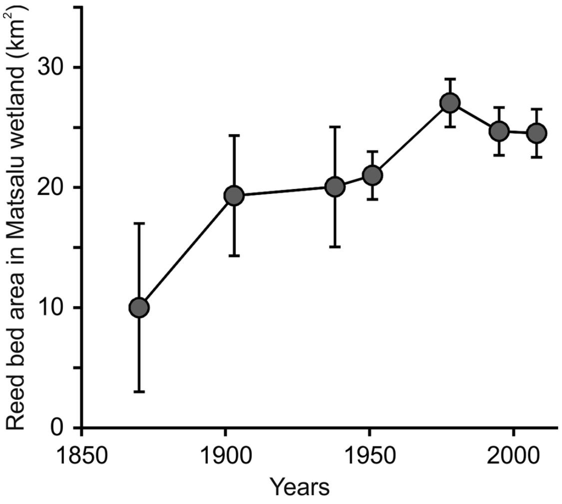

Fig. 4. Changes in the total area of the reed bed in Matsalu wetland in years 1870–2005. The whiskers show an estimated error for different data sets.

Factors controlling changes in reed bed distribution

Compared to the beginning of the 20th century, the front of the massive reed bed in Matsalu wetland had advanced by the end of the century on average 2.5 km (in places up to 5–6 km) to the west. However, our results suggest that the most significant advance of the reed bed from the position it occupied in the early 20th century to the present outer limits occurred in about 40 years, in the 1930s–1970s, which gives an average displacement rate of nearly 50 m per year. Importantly, the expansion of the total area covered by reed bed communities in the same period was rather subdued compared to changes in the reed bed position relative to the shoreline. It is evident that, instead, the large area occupied by hydrophilic reed bed species shifted westwards, while the inner (eastern) parts of the former wetland with improved/better soil drainage conditions were occupied by meadow communities.

The distribution of the reed bed in Matsalu wetland is largely controlled by the water depth tolerance of the reed in open water and suitable hydrological conditions on dry land (e.g. Hocking 1989; Weisner & Strand 1996). More than 75% of the reed bed within the wetland is found in an elevation zone between 0.3 m water depth and 0.7 m above sea level (Fig. 1). The 0.3 depth isobaths denote the front of dense intergrown stands in the bay, whereas separate patches of *P. australis* are found in up to 0.8 m water depth. *Schoenoplectus* (<10% of the reed bed area), however, can occupy a maximum of 1.2 m depth where it is the only reed bed species.

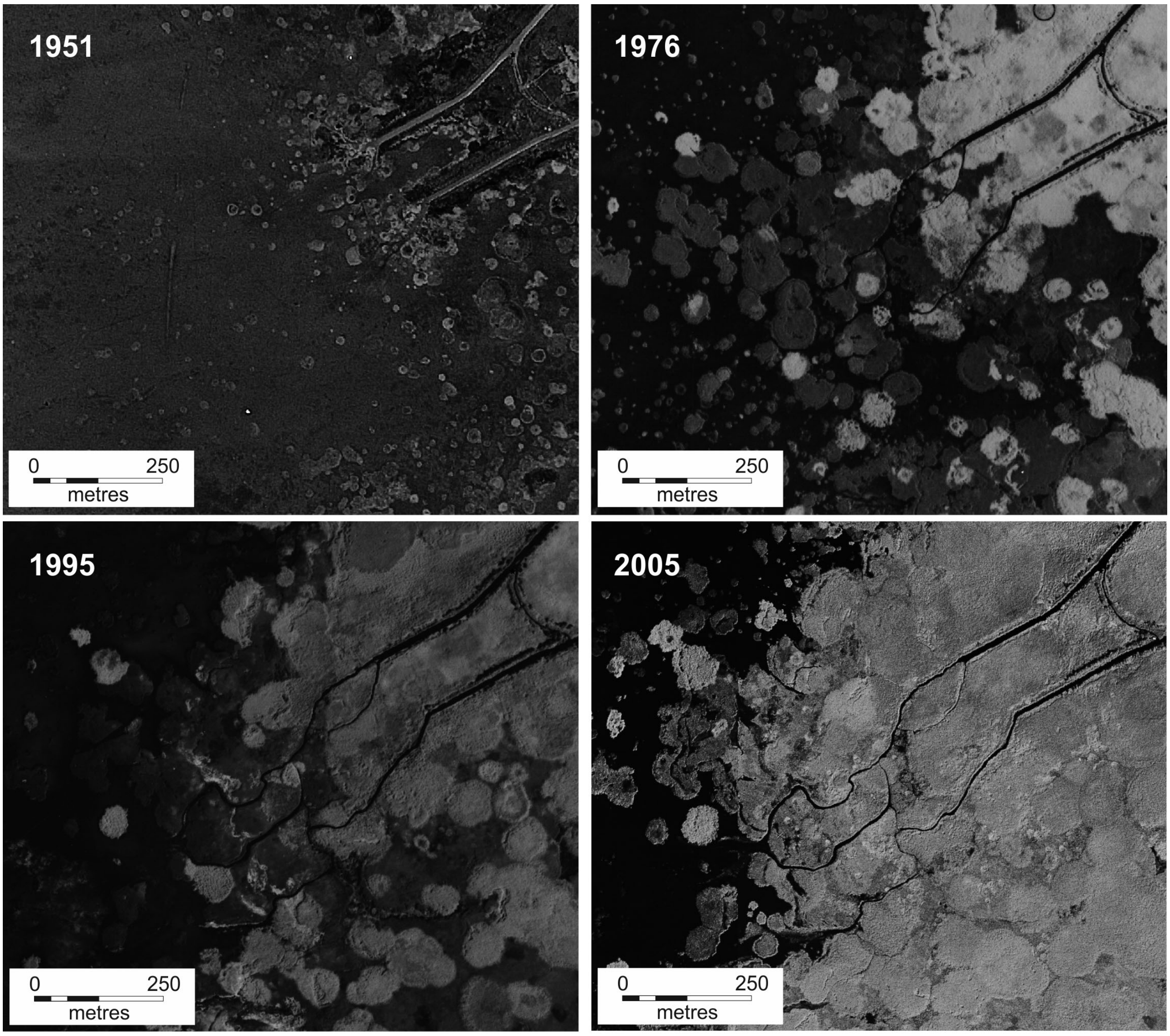

Fig. 5. Aerial photographs of the reed bed distribution at the Raana–Rannamõisa river mouths from years 1951, 1976, 1995 and 2005 of the area shown in Fig. 1.

This well-defined depth-elevation control suggests that the change in the mean sea level in the Baltic Sea, and particularly in Matsalu Bay, is one of the factors controlling the reed bed distribution in Matsalu wetland. In the northern Baltic Sea, including northwestern Estonia, neotectonic crustal movements are characterized by nearly linear relative glacio-isostatic uplift with a rate of 2–2.5 mm yr^{-1} in northwestern Estonia (Vallner et al. 1988; Johannsson et al. 2004).

Land uplift is a predictable and continuous natural change gradually altering boundary conditions of the localized ecology. It can be described as an environmental forcing factor, which operates on a long time scale. Indeed, considering the flat and low-lying topography of the wetland with an average topographic gradient of 0.25–0.5 m km^{-1} along the long axis of Matsalu Bay, we could expect the shoreline displacement caused by the relative glacio-isostatic component to be in the range of 5–10 m per year. This would be comparable with the reed bed expansion rate in the pre-dredging period and probably in the 1970s–1980s.

Sedimentation is another factor that potentially can control the water depth and therefore reed bed distribution in the bay. However, modern sedimentation rate in Matsalu Bay is rather low (Lutt & Kask 1978; Lutt 1985). Lutt (1980) estimated that a maximum of about 2 m of recent marine sand-silt sediments have accumulated in the somewhat deeper western part of the bay since the

Boreal period (ca 9000 BP) of the Holocene. In the shallow (water depths <1 m) eastern part of the bay the thickness of recent clayey silt and fine sand sheets above Late Glacial varved clay reaches only a few to a maximum of a couple of tens of centimetres (Lutt 1985). The lack of sediment and its slow accumulation rate can be explained by the shallow bathymetry that is generally above the wave base and the gentle relief of the bay surroundings causing the deficit of sediment loadings.

Sediment supply into the bay is mostly controlled by the Kasari River. However, the suspended load of the river is quite low (8 g m^{-3}), totalling ca 7600 t of sediment per year (Eipre & Pärn 1982). About 45% of the total inflow in the Kasari River falls into the spring flooding period when the maximum flow rate is 500–750 m^3 s^{-1}, whereas the average annual rate is 23–28 m^3 s^{-1} (Mardiste & Kaasik 1985). Most part of the sediment during the flooding period is deposited in an about 20–30 m wide zone along the river channels. Levee sediments right next to the channels in an up to 5 m wide zone are typically up to 20 cm thick sandy silt sediments. Further away towards the floodplain they become rapidly replaced by fine-grained silt and mud which thins out to a few centimetres (Mats Meriste unpublished data 2002–2013). Although some water flows over the floodplain directly to the reed bed, most of the material settles out near the river channels and the sediment load carried by the river is not capable of accommodating large bay areas. There is no significant organic-rich mud (gyttja) sedimentation in the eastern part of the bay or at the delta front. However, Ksenofontova (1989) estimated biomass production in the Matsalu reed bed (including rizosphere) to be in the order of 2000–3000 kg ha^{-1}. It mostly decomposes in the autumn period, but part of it is accumulated as reed–sedge peat within the reed bed. The thickness of reed–sedge peat and partly decomposed reed litter varies typically between 20 and 30 cm and contributes significantly to the sediment pile once the dense reed bed has been established.

The shoreline displacement and accompanying intervention of the reed caused by glacio-isostatic uplift and sedimentation in the bay are nearly an order of magnitude less than the observed displacement rate during the post-dredging period of 'explosive' migration and subsequent expansion of reed in Matsalu wetland. This suggests that the rapid invasion of the reed bed is connected and coincident with the major disturbance of the wetland ecosystem caused by extensive dredging in 1928–1938.

Mal & Narine (2004) have shown that the clonal growth of the main reed species *P. australis* is the major means of its population growth and spread, whereas in submerged conditions *P. australis* is not able to spread by seedlings (e.g. Weisner & Ekstam 1993; Weisner et al. 1993) and the expansion takes place by horizontal growth of rhizomes. Typically the rate of horizontal expansion of reed in tolerable water depths is generally less than 1 m yr^{-1} in temperate climate regions (Weisner 1987), but can be locally as high as ~4 m yr^{-1} (Clevering & van der Toorn 2000). Nevertheless, the invasion can be significantly enhanced by the dispersal of rhizome fragments (Bart & Hartman 2002). These viable segments, containing at least one axillary bud, are efficiently distributed by water currents and machinery and successful establishment of reed rhizome segments is highly favoured by their placement on bare wetland soils (Ailstock et al. 2001).

The dredging of Matsalu wetland in 1926–1938 cut through the existing reed bed, causing the fragmentation and subsequent redeposition of rhizomes along the dredged channels and on the shallow sea bottom all over the eastern part of Matsalu Bay. The new stands emerged most successfully along the channels, which was probably constrained by the effective rhizome re-burial and the most favourable water depth conditions, and well-drained soils on the channel banks that were originally raised above the average seal level.

In this sense the channels served as corridors that facilitated the dispersal of reed at the landscape scale and its subsequent invasion into the ecosystem that the channel intersected (e.g. Maheu-Giroux & de Blois 2007). A similar, either naturally or anthropogenically forced, rapid establishment of new reed clones has been reported along the coastal regions of North America in association with hurricanes or large storms (Chambers et al. 2003) and the construction of (rail)roads, ditches and dykes (Keller 2000; Ailstock et al. 2001; Maheu-Giroux & de Blois 2007). On the mainland side of the delta, however, the hydromorphic soils were more efficiently drained as a consequence of the dredging and the reed bed communities were replaced by meadow species, whose establishment was even more facilitated by increased mowing of flood plains.

The post-establishment spread and growth of reed in the Kasari delta after the dredging seems to be affected by a combined effect of mean sea-level variation coupled with storminess (wave-climate), and eutrophication. Meriste et al. (2012) showed that the average annual advance of the reed bed front in Matsalu Bay was in the range of ~1.5 m yr^{-1} in 1951–1976. This is 3–6 times less than would be potentially expected from the rate of the shoreline displacement due to land uplift, but agrees with the rate of reed expansion (~1 m yr^{-1}) reported in temperate climate regions (Weisner 1987; Weisner & Ekstam 1993). This indicates that reed bed invasion is somewhat lagged behind land uplift.

On the other hand, since the late 1980s, the main reed bed growth has proceeded by clonal integration of the existing patches rather than the establishment of new forerunners. Meriste et al. (2012) interpreted the change in the growth strategy of the reed bed as resulting from the gradual increase in high sea level events and overall storminess due to increase in the intensity of westerly and southwesterly cyclonic activity (Johannsson et al. 2003; Orviku et al. 2003; Suursaar et al. 2006; Kont et al. 2008; Jaagus & Suursaar 2013) that can raise the sea level in Matsalu Bay up to 2 m above its average summer level.

Annual mean wave height rose rapidly by 1–2% from the 1960s until 1997 in the Baltic Sea (Zaitseva-Pärnaste et al. 2009). This is an important factor controlling the average sea level in semi-closed bays such as Matsalu Bay. The increased storminess has major influence on Matsalu Bay where the topographic gradient is low (0.2–0.5 m km^{-1}). Kont et al. (2003) estimated that a 1 m sea level rise would inundate over 76 km^2 in the Matsalu area, including the entire reed bed and most of the flooded meadows. Moreover, the rate of global sea level rise, estimated at 1.9 ± 0.4 mm yr^{-1} since 1961, is accelerating (Church & White 2011), meaning that the relative land uplift rate in Matsalu Bay estimated by Vallner et al. (1988) at 2–3 mm yr^{-1} is decreasing. Long-term sea level rise is confirmed by tidal gauge measurements, showing that the isostatically controlled declining trend of mean sea level in Finland and northern Estonia, which was evident up to the early 1980s, has changed to a nearly stable trend (Johannsson et al. 2003, 2004; Suursaar & Kullas 2006; Suursaar et al. 2006). Moreover, Jaagus & Suursaar (2013) show that the local sea level rise at the Estonian coast accelerated in 1950–2011 and without the influence of land uplift it was slightly higher (2.2–3.2 mm yr^{-1}) than the global mean (1.9 mm yr^{-1}) during this period.

Changes in sea level trends are even more evident in the eastern–central Baltics. Relative isostatic land uplift in the Port of Virtsu, located about 20 km south of Matsalu Bay, is estimated to be 1.8 mm yr^{-1} (Vallner et al. 1988). Suursaar et al. (2006) show that this would correspond to 95 mm of land uplift in the Virtsu station during 1950–2002, while annual mean sea level changed only –8 mm during the same period. Analysis of sea level data collected at the Port of Virtsu during 1947–2011 (Fig. 6) suggests that the actual water level rise was 96 mm. This agrees with long-term mean sea level variations in Finland, which have been on average 5 cm higher than the historical linear trend would suggest (Johannsson et al. 2004).

Another important variable controlling the trends in reed growth in Matsalu wetland is eutrophication that is generally regarded as a major factor in determining reed decline (die-back syndrome) in Europe (Brix 1999). The shallow Matsalu Bay and Kasari River delta are strongly influenced by input of nutrients from the agricultural areas in the Kasari River catchment. Such areas were increasing from the 1950s, when intensive agriculture was established in the Kasari River catchment, until the late 1980s, when the estimated annual nutrient load reached about 2000–2400 t N_{tot} and 70–100 t P_{tot} (Porgassaar 1993; Fig. 7). The dissolved orthophosphate concentration, measured at the Kasari River gauge since the 1950s (Fig. 7), shows that maximum loadings were achieved by the late 1970s and early 1980s and a slow decrease occurred in the last decade to levels comparable to those of the 1950s. The concentration of nitrate, however, was highest in the late 1950s and has decreased gradually over the last 50 years. Interestingly, the Cl^- and SO_4^{2-} concentrations in the Kasari River water show the same tendency as dissolved orthophosphate – the maximum concentration of both ionic species was achieved by the 1970s and the loadings started to decrease

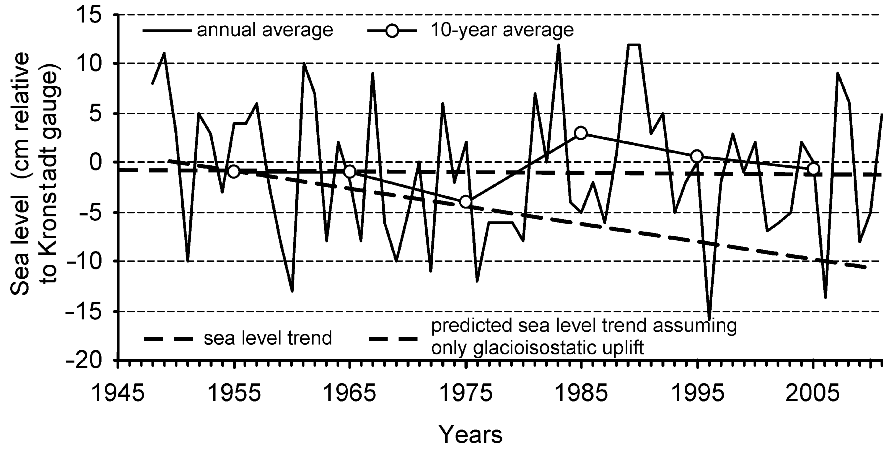

Fig. 6. Changes in mean sea level at the Port of Virtsu (ca 20 km south of Matsalu Bay) during 1947–2010.

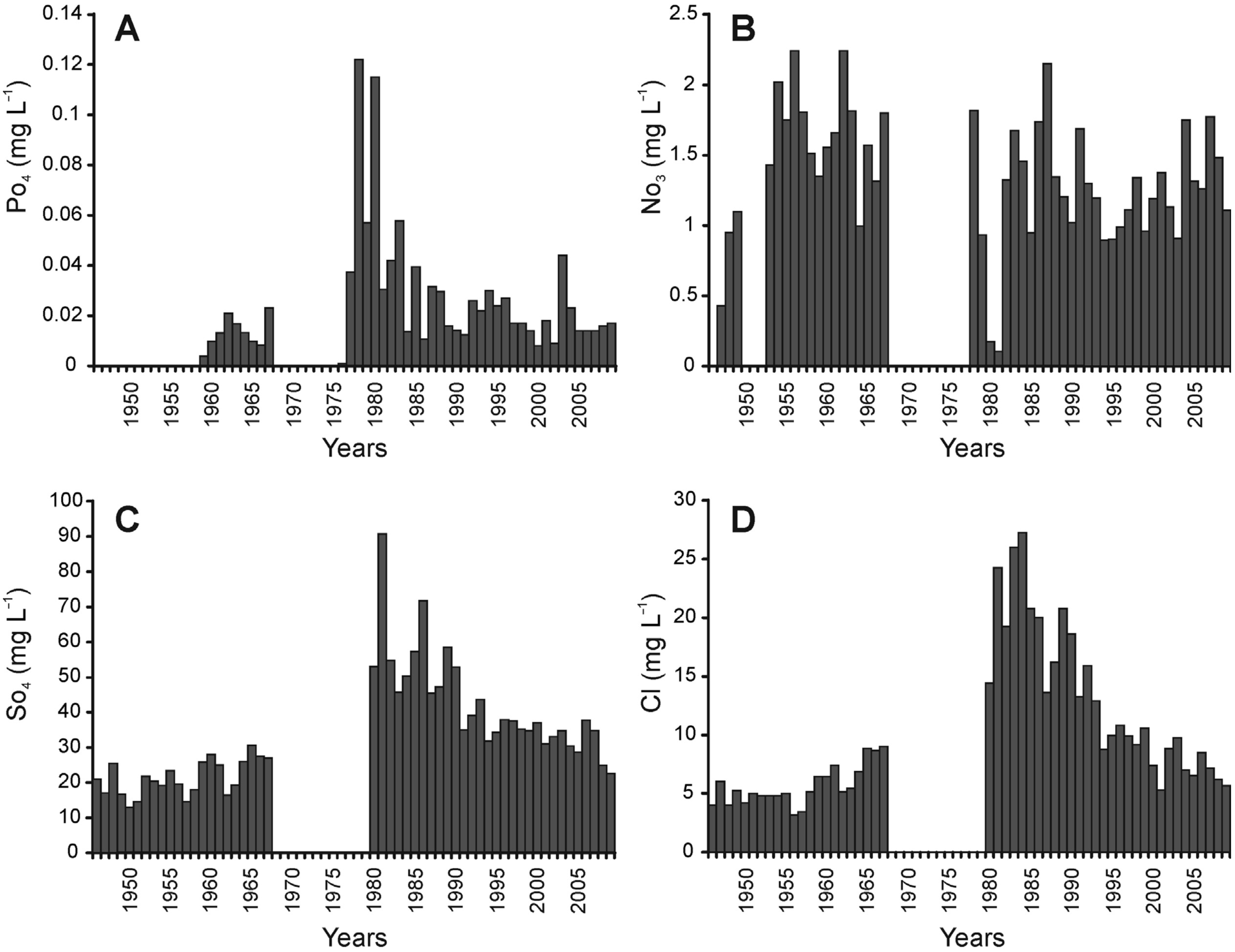

Fig. 7. Dynamics of dissolved orthophosphate (**A**), nitrate (**B**), sulphate (**C**) and chlorine (**D**) at the Kasari River gauge in 1946–2009.

in the late 1980s and early 1990s. Although in Estonia the post-Soviet re-organization in industry and consequent decrease in the atmospheric SO_4^{2-} deposition have been interpreted as a reason for changes in sulphate concentration changes in streams (Treier et al. 2004), we suggest that sulphate and chlorine contents can be interpreted as proxies for the use of fertilizers and runoff from agricultural landscapes. Common fertilizers used in Estonian agriculture in the Soviet time were ammonium-sulphate, K-salts (K_2SO_4-sulphate, KCl) and superphosphate ($CaSO_4$–$Ca(H_2PO_4)_2$). The excess of nutrients and most of Cl^- and SO_4^{2-}, which are not used for biomass production, are consequently leached out form the soil.

The use of mineral fertilizers on arable lands in Estonia increased from about 5 kg N ha^{-1} and 7 kg P ha^{-1} in 1950–1955 to a maximum of about 95–100 kg N ha^{-1} and 22–25 kg P ha^{-1} in 1980–1990 (Astover et al. 2006). Already in 1990–1995 the use of mineral fertilizers was drastically lower – 40 kg N ha^{-1} and 7 kg P ha^{-1}, which resulted in a decrease in N and P loadings in Estonian river catchments (Iital et al. 2005, 2010). However, the decrease in N and P loadings was caused not only by lesser use of organic and inorganic fertilizers, but also by a drop in livestock numbers, reduction of the area of agricultural land, increased proportions of abandoned land at the expense of cultivated areas and better farm management practices.

The positive balance of nutrients in the 1970s–1980s caused severe eutrophication of large lakes in Estonia (Nõges et al. 2005) and could have significantly promoted the reed bed expansion in Matsalu wetland until the early 1980s. Ksenofontova (1989) noticed that by the mid-1980s the abundance and biomass of submerged and floating-leaved plants occupying open water areas between reed stands extending into Matsalu Bay increased significantly, the height and culm thickness of *P. australis* increased and bent shoots were more frequent, suggesting the eutrophic level of the environment. However, eutrophication is considered also as a major factor in determining reed decline, and the reed weakening by eutrophication is further forced by increased accumulation and decomposition of organic matter under anoxic conditions releasing fatal phytotoxins (Armstrong et al. 1996; Čížková et al. 1996). The resulting weaker culms are susceptible to mechanical damage by waves, impact of floating objects and ice-rafting. This effect is the most prominent on exposed shore segments and/or capes where the reed bed in Matsalu Bay is retreating today. Furthermore, Clevering (1998) shows that deep waters and litter-rich soils create unfavourable conditions for *P. australis*, which suggests a combined negative impact of rising sea level and eutrophication on the current status of the reed bed in Matsalu wetland. Also, although nutrient loadings into Matsalu wetland have significantly decreased over the past two decades, reeds may show a delayed response to changes in environmental conditions (Ostendorp 1989; Gigante et al. 2011) causing reed decline for a prolonged period.

CONCLUSIONS

The development of the reed bed in Matsalu Bay and the Kasari River delta is controlled by the interaction of natural processes and human intervention. The shoreline advancement due to neotectonic land uplift was a dominant factor determining the reed bed distribution until the 1920s–1930s. The dredging of the distributary rivers of the Kasari delta in the 1920s–1930s caused a rapid seaward colonization of the reed bed along the dredged channels by the dispersal and reburial of fragmented rhizomes at the channel banks and on the shallow sea bottom of Matsalu Bay. The expansion of the total area covered by reed bed communities in the same period was negligible and the former wetland areas in the mainland portion of the reed bed were replaced by meadow communities. In the 1930s–1970s a large field of the reed bed developed mostly in the bay area between dredged canals, at an accelerated rate due to inflow of nutrients from agricultural landscapes the use of which was intensified from the early 1950s until the 1980s. However, the seaward expansion of the reed bed in Matsalu Bay and the Kasari River delta has stopped since the late 1980s and instead the total area of the reed bed has decreased. This is interpreted as a result of combined effects of dropped inflow of nutrients, eutrophication causing the weakening of the reed bed, and a global sea level rise and increased intensity of cyclonic activity in the area over the last few decades that create unsuitable conditions for reed bed growth.

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Matsalu märgala roostike areng neotektoonilise maakerke, veetaseme muutuste ja inimmõju tingimustes

Mats Meriste ja Kalle Kirsimäe

Matsalu lahte suubuva Kasari jõe suudmealale on moodustunud ulatuslik deltasüsteem, mille lauge reljeefiga deltatasandikud on tuntud unikaalsete taimekoosluste, linnu- ja loomarikkuse poolest. Viimase paarisaja aasta jooksul on Matsalu märgala looduslikud ja poollooduslikud keskkonnad läbi teinud ulatuslikke muutusi, mida kontrollivateks faktoriteks on: a) neotektooniline maakerge, b) Läänemere keskmise veetaseme ja tormilisuse varieerumine ning c) otsene ja kaudne inimmõju, mille teguriteks on Kasari delta kanaliseerimine 20. sajandi algul ning eelmise sajandi teisel poolel intensiivistunud toitainete sissekanne ja eutrofeerumine. Kuni 20. sajandi esimeste kümnenditeni kontrollis roostike levikut ja aeglast läänesuunalist liikumist suhteline neotektooniline maakerge. Kasari deltaharude kanaliseerimisega 20. sajandi 20.–30. aastatel kaasnes märgalakoosluste kiire läänesuunaline (s.o avalahele) migreerumine, mille põhjustas süvendamisega väljakaevatud ja fragmenteeritud pilliroo risoomide laialikandumine ning juurdumine madalas avalahes ja piki kaevatud kanalite vallide servaalasid. Kanalite rajamine ei põhjustanud koheselt roostiku kogupindala märgatavat suurenemist, kuid alates 1950. aastatest toimus roostike kiire laienemine, mis saavutas maksimaalse ulatuse 1970. aastate lõpuks. Selle põhjuseks oli intensiivistunud maakasutusega kaasnenud toitainete sissevool, mis saavutas maksimumi 1970.–1980. aastateks. Viimase 20 aasta vältel on roostike levikupilt püsinud põhijoontes muutumatuna ja avatud rannikulõikudel on täheldatav roostiku servaala taandumine, mille tõenäoliseks põhjuseks on toitainete sissevoolu vähenemine ning Läänemere keskmise veetaseme tõus, mis Lääne-Eestis kompenseerib neotektoonilist maapinnatõusu, ja samuti kasvanud tormilisus, mis pärsib kasvutingimusi roostike servaaladel.