Geomorphology 456 (2024) 109191

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.journals.elsevier.com/geomorphology

# Spatial and temporal variation in long-term sediment accumulation in a back-barrier salt marsh

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ARTICLE INFO

*Keywords:*
Chronosequence
Elevation
Intertidal flats
Sediment accretion
Sea-level rise
Tidal creeks
Wadden Sea

ABSTRACT

In situ persistence of salt marshes in the face of sea-level rise relies on their ability to maintain substrate elevation through sufficient vertical accretion of sediment. However, sedimentation rates in salt marshes vary spatially and temporally, which complicates the assessment of their ability to keep up with sea-level rise. Here, we explore the spatial and temporal variation in sediment accumulation in a single back-barrier salt marsh site. Using one-time in situ measurements at the landscape scale, we obtained synoptic information of elevation and sediment thickness over the entire salt marsh in a chronosequence over centuries. Repeated measurements along short elevation transects (0.3–0.9 m +MHT) revealed decadal changes, complementing the broader marsh data with detailed information on elevation, thickness of the marsh deposits and accumulation rates. Thickness of the deposits was largely related to the elevation gradient: the sediment layer was thinner at the higher marsh (near the dunes and far away from the intertidal flats), and thicker at the lower marsh (near the intertidal flats). Moreover, the thickness of the layer increased with salt marsh age along the chronosequence, and age accounted for 72 % of variability in sediment accumulation. The rate of sediment accumulation was higher than the local rate of sea-level rise in the younger marsh, whereas it was equal to the rate of sea-level rise in the older marsh. In the older salt marsh, sediment accumulation was lower, possibly due to autocompaction in the thicker, older layers. Both at the landscape scale and along short elevation transects within individual drainage basins, sediment accumulation decreased with distance to sediment supply routes. However, their relative importance depended on the scale of observation. Distance to creeks accounted for 17 % of the variability in sediment accumulation at the landscape scale, compared to 4 % at the smaller scale. Similarly, the influence of distance to intertidal flats varied from 1 % at the landscape scale to 13 % at the smaller scale. Our main findings indicate that lower-elevation older marshes and higher-elevation younger marshes far away from sediment sources are at risk of not keeping pace with the local rate of sea-level rise and are potentially vulnerable to increased flooding.

## 1. Introduction

Salt-marsh sediments can have two modes of origin, allochtonous and autochtonous (Dijkema, 1987). In European back-barrier salt marshes, supply of the fine-grained sediments is allochtonous (De Groot et al., 2011b). Here, sedimentation is regulated by flooding (inundation), which depends on the elevation of the salt marsh, as well as on tidal regime and (storm-induced) waves (Ma et al., 2018). In contrast, autochthonous sediment is composed of organic material derived from salt-marsh vegetation (De Groot et al., 2011b). The supplementary source of such organic material, the so-called below-ground production, is small for North-west European salt marshes (French and Spencer, 1993; De Groot et al., 2011a). Soil carbon content is only c. 5–10 % in a Dutch salt marsh (Elschot et al., 2015). French (1993) estimated the contribution of organic material to be on the order of 0.02 cm/yr for a British salt marsh.

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https://doi.org/10.1016/j.geomorph.2024.109191
Received 5 September 2023; Received in revised form 6 April 2024; Accepted 7 April 2024
Available online 11 April 2024

Rates of accretion and surface-elevation change (SEC), often expressed per time unit as accretion rate (cm/yr) and rate of SEC (cm/yr), play crucial roles in the long-term development of salt marshes (Nolte et al., 2013a), and determine their capacity to persist under sea-level rise (SLR) (Fagherazzi et al., 2020). Following Cahoon et al. (1995), accretion is defined as the combined product of mineral sedimentation and organic production minus erosion and is typically considered at a yearly timescale (medium-term). Marsh surface-elevation change (SEC) is the net balance of accretion, erosion and subsidence (i.e., changes in soil volume due to shrinkage or compaction of deeper sediment layers). Over time, the sediment undergoes (auto) compaction (Cahoon et al., 1995; Bartholdy et al., 2010b), dewatering and oxidation, leading to a reduction of the initial thickness of the deposits, and is considered at a yearly to decadal timescale (medium to long-term) (Nolte et al., 2013a). Salt marshes can reach an elevation of just below Highest Astronomical Tide when there is sufficient supply of sediment, with a balance between sediment input during extreme high waters and local SLR (French, 1993; De Groot et al., 2011a; De Groot et al., 2011b; Fagherazzi et al., 2012). Thus, vertical salt-marsh growth depends on the changing balance between tidal regime, wind-wave climate, sediment supply, relative sea level, sediment compaction and subsidence, and vegetation (Allen, 2000).

Sedimentation rates in salt marshes vary spatially and temporally, which can complicate the assessment of their ability to keep up with SLR. Spatial variation has been widely documented, especially between levee or creek edges and interior marsh areas. Salt marsh edges and creeks are key sediment supply routes, and accretion rates are generally higher near these features (Reed et al., 1999; Bartholdy et al., 2010a; several authors in Bakker et al., 2016; Van Dobben et al., 2022). More coarse-grained material is deposited in sites with high water velocity as close to creeks and intertidal flats; at some distance from sediment supply routes, only fine-grained material is deposited (De Groot et al., 2011b). The resuspension of sediment on an adjacent intertidal mudflat can contribute sediment allowing salt marshes to keep pace with sea-level rise (Ma et al., 2014). Sediment deposition increases within metres from the creek banks and rapidly declines with greater distance away from the creek (Leonard and Luther, 1995; Reed et al., 1999; Temmerman et al., 2003). During higher tides, enhanced flow velocities may increase resuspension within a creek and sediment supply to the marsh surface (Reed et al., 1999), but may also be a source of scouring and resuspension/erosion of sediment off the marsh platform itself.

Temporal variation in sedimentation rates has been studied across a range of time frames and measuring techniques, from short-term sedimentation during single or spring-neap tidal cycles (Reed, 1989; Leonard, 1997; Temmerman et al., 2003), up to medium- and long-term rates of decades or hundreds of years (French and Spencer, 1993; Kearney et al., 1994; Cahoon et al., 1995). For instance, an average surface-elevation change rate of 0.27 cm/yr was reported for sites in 12 back-barrier salt marshes in the international Wadden Sea, with data collected since 1992 in series ranging from four years up to 23 years, and varied between 0.04 and 0.37 cm/yr (several authors in Bakker et al., 2016; Esselink et al., 2017). These rates, estimated from Sedimentation Erosion Bars (SEB) and accounting for changes in SEC (Nolte et al., 2013a), represent an indirect measure of net sediment accumulation over decades. For mid- and long-term estimations of sediment accumulation, i.e. without deep subsidence, it is preferable to employ direct measurements of the thickness of salt-marsh deposits above a horizon with a known age. This can be accomplished through the implementation of marker plots, as described by Nolte et al. (2013a), or by using the base of the marsh deposits in case the age of this surface is known (De Groot et al., 2011a). The latter method offers an additional advantage as it allows for cost-effective measurements to be taken over a larger area compared to traditional marker horizon or SEC methods. Such long-term data suggest that accumulation over the past century caused a maximum elevational difference of 12 cm (i.e. sediment accumulation of 0.12 cm/yr) in back-barrier marshes of Schiermonnikoog, the Netherlands (Olff et al., 1997), and 0.27 cm/yr in Skallingen, Denmark (Bartholdy et al., 2010b). In the United Kingdom, salt marshes have been found to adapt to relative SLR rates below 0.7 cm/yr (Horton et al., 2018). Global measurements of marsh elevation change have found that marshes are building in elevation at rates of 0.3 cm/yr for high-elevation marshes, and 0.7 cm/yr for low-elevation marshes, which is similar to or exceeding the rate of historical SLR (Kirwan et al., 2016).

Two important temporal factors influencing sedimentation rates are the time interval covered by the measurements and the age of the marsh, defined as the years since initial vegetation colonization. The time interval is relevant because short-term accretion rates can be twice as high as the longer-term rates, even on the same core samples (Kearney et al., 1994), potentially overestimating the marsh's ability to keep pace with SLR. These higher accretion values can be explained by accelerating rates of SLR in recent decades, and by the autocompaction of sediment over longer time scales (Bartholdy et al., 2010b), resulting in a lower actual elevation change than estimated on shorter time frames. Furthermore, marsh accretion is time-dependent and influenced by marsh age. Although elevation primarily dictates the rate of SEC in marsh ecosystems, temporal dynamics can play a role. As the marsh grows vertically, the yearly accretion rates decrease due to the rising elevation (Steers, 1997), indicating that the rate of SEC at a specific location can change over time. Pethick (1981) further showed an asymptotic relation between marsh age and surface-elevation change. This indicates that older marshes may experience slower rates of elevation increase, a crucial factor in understanding long-term marsh resilience. However, if a marsh grows at the same rate as SLR and sediment supply remains constant, its annual accretion rate might not vary significantly despite elevation increases.

In this study, we aim to address a gap in the understanding of salt-marsh sedimentation by focusing on the interplay of spatial and temporal scales across marshes of different ages. We explore the dynamics of a salt marsh that expands over time in various directions, as opposed to a single, homogeneous direction. Our study provides an ideal setting to compare accretion rates across different time scales in a salt marsh characterized by gradients in both age and initial elevation. Our dataset covers two spatial scales: one at the landscape scale, where a grid of points covers almost the entire salt marsh (from the dune ridge to the intertidal flat), providing indirect insights into the spatial and temporal patterns of sediment accumulation. The second at smaller scales, where transects were repeatedly measured over time and space, enabling a more detailed examination of small-scale gradients with elevation differences of approximately 1 m (from a local small dune to the adjacent salt marsh). Our data collection efforts involved medium-term observations over several decades, capturing different stages of salt-marsh establishment over two centuries (i.e., a chronosequence). This approach, combining repeated medium-term observations (approximately every five years) with assessments of total accretion since initial vegetation colonization, allows us to explore the evolution of these salt marshes over both short (years) and long (centuries) timescales. Additionally, we aim to assess the influence of inundation, soil elevation, and sediment supply routes (such as the edge of the salt marsh and dissecting creeks) on the variation in sediment layer thickness and accumulation over the different spatial and temporal scales. The findings will be placed in the context of identifying which elevation best keeps pace with sea-level rise, while also considering the age of the salt marsh.

## 2. Methods

### 2.1. Study area

The study site is the back-barrier salt-marsh system of the island of Schiermonnikoog, one of the Dutch West Frisian barrier islands (53°30′N, 6°10′E) between the North Sea in the north and the Wadden Sea in the south (Fig. 1A). On barrier islands, salt marshes develop following several stages (see Olff et al., 1997 for a schematic view of the

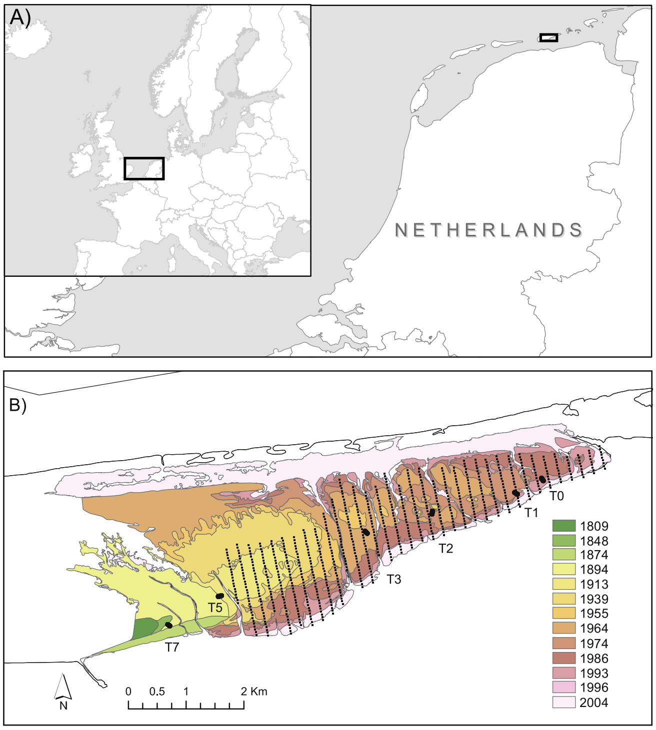


**Fig. 1.** A) The location of the study site, the salt marsh of Schiermonnikoog, in the Netherlands. Base map: © EuroGeographics for the administrative boundaries. B) The ages of the salt marsh on Schiermonnikoog (source: Jager, 2006) and layout of the field measurements in the large-scale grid and in the small-scale elevation transects. The regularly spaced dots indicate the large-scale grid of 820 measuring points. The short elevation transects appear as small clusters and are labelled from T0 to T7 (online version in colour).

main development stages). In the first few stages, embryonic dunes are formed on bare beach surfaces, and later evolve into large dunes, mainly on the North Sea side (De Groot et al., 2017). The sand flat behind these dunes is subsequently only flooded at the side of the Wadden Sea, during high spring tides and storm surges, and no longer from the North Sea side (Olff et al., 1997). Mean tidal range is 2.28 m (Van Dobben et al., 2022). The reduced velocity and turbulence of the water results in sedimentation of silty sediment on top of the sandy base, which is influenced by silt-trapping vegetation. Inundation rates decrease to zero near the dunes, resulting in little sedimentation. The sandy base decreases in elevation towards the intertidal flats. Over time, this variation in elevation results in slow accumulation at the high marsh, experiencing less frequent inundations, and faster accumulation in the low marsh, which is inundated more frequently (Olff et al., 1997; De Groot et al., 2017). This silt layer changes shape due to the feedback between plant growth and sedimentation, as the edge between the salt marsh and the adjacent intertidal flat becomes increasingly steep and vulnerable to wave attack (Van de Koppel et al., 2005). Hence, the surface topography in the marsh at a coastal barrier island is initially determined by the antecedent topography of the sandy subsoil. The topography of the sandy subsoil was shaped by aeolian processes when it was still a beach, and has subsequently been ‘fossilized’ by the silt deposition (De Leeuw et al., 1993). Since the island of Schiermonnikoog migrates and extends eastwards (Isbary, 1936), a chronosequence is formed where the western part of the salt marsh is the oldest part and young stages of salt-marsh development can be found in the eastern part of the island (see Fig. 1B and Olff et al., 1997 for a reconstruction of salt-marsh development on the island). The construction of a sand-drift dike for coastal protection in 1958 stopped the natural dune dynamics and accelerated salt-marsh development (De Groot et al., 2017; Bakker et al., 2023).

European back-barrier salt marshes are mainly formed through mineral deposition, in contrast to many American marshes which are derived from accumulating organic material (Bakker et al., 2015). The back-barrier salt marshes along the Wadden Sea, which are the focus of this study, are indeed minerogenic. They are built of marsh sediments that consist of fine-grained mineral material (also referred to as mud, including particles <0.064 mm) in sites with low water velocity, and non-cohesive sediment (also referred to as sand, with particles from 0.064 mm to 2.0 mm) in sites with high water velocity, such as along creeks and the edge of the salt marsh near the intertidal flats. The flow-resistant surface vegetation both traps and binds tidally introduced mineral sediment (Olff et al., 1997), thus building up to a vegetated marsh platform. The marshes are part of a drainage basin or catchment area (Bakker et al., 2023). We assume that sedimentation is strongly dominant over vertical erosion in our marshes, based on sedimentation and erosion rates over the period 1935–2005 in the Wadden Sea basins (Elias et al., 2012; Wang et al., 2018).

### 2.2. Field measurement set-up

Field measurements of elevation and thickness of the salt-marsh deposits were conducted in two layouts, representing two spatial scales. Firstly, measurements were carried out at the landscape scale, from the foot of dunes to intertidal flats. A grid was established covering most of the salt marsh of Schiermonnikoog, with lines (1000–1600 m in length) running roughly north-south perpendicular to the salt marsh edge from young to old salt marsh, and 200 m apart. At each 50 m interval along these lines, a measurement point was located, resulting in about 820 points (Fig. 1B). Elevation was measured with respect to Dutch Ordnance Level (NAP), which represents ca. average sea level. Mean High Tide (MHT) is 1 m +NAP at the study site. MHT is important with respect to inundation, and hence sedimentation. For every 1 m × 1 m plot, at both the large and small scale, we measured elevation to the nearest mm with respect to NAP using an optical levelling instrument before 2005, and a Trimble Spectra Precision laser from 2005 onwards. Measurements were done in 2010. The entire area of this grid has never been grazed by cattle. Livestock grazing can reduce accretion rates by increasing soil compaction due to trampling, and by affecting vegetation structure and thereby lowering sediment deposition (Elschot et al., 2013; Nolte et al., 2013b).

Secondly, small-scale transects consisted of six permanent transects (hereafter referred to as short transects) on the sub-catchment scale, which were established in the field in 1992 on the gradient between a low dune and adjacent salt marsh. Each transect consisted of a grid of 10 columns and a variable number of rows (50–68, depending on the local topography) of 1 m × 1 m plots located adjacent to each other in a grid, with the longest dimension of the grid extending along the slope of the elevation gradient (Olff et al., 1997). The division between high and low salt marsh is taken as 0.35 m +MHT, i.e. about 100 inundations per year

**Table 1**
Estimated inundation frequency along the elevation gradient within the salt marsh of Schiermonnikoog, based on recorded tidal data from 1997 to 2009. Elevation is expressed in m +NAP, m +MHT and as Standardized Water Level Index (SWLI). Mean High Water Spring is about 1.7 m +NAP.

| Elevation (m +NAP) | Elevation (m +MHT) | Standardized Water Level Index (SWLI) | Average inundation frequency (%) | Average inundation frequency (times/yr) |
|---|---|---|---|---|
| 1.1 | 0.1 | 83 | 47.1 | 260 |
| 1.2 | 0.2 | 86 | 32.3 | 178 |
| 1.3 | 0.3 | 89 | 21.1 | 117 |
| 1.4 | 0.4 | 92 | 14.1 | 78 |
| 1.5 | 0.5 | 95 | 9.4 | 52 |
| 1.6 | 0.6 | 98 | 6.3 | 35 |
| 1.7 | 0.7 | 101 | 4.3 | 24 |
| 1.8 | 0.8 | 104 | 3.1 | 17 |
| 1.9 | 0.9 | 107 | 1.3 | 7 |

(Table 1). The six short transects are used to represent sites at different stages of salt-marsh development, defined here as years since initial vegetation colonization. These transects are separated between 1 and 3 km, and spanning about 8 km from young to old salt marsh (Fig. 1B). Elevation was measured with the same method as in the large-scale grid. Measurements were done in 1992, 2001, 2005, 2007 and 2009. It should be noted that the age of a marsh does not directly correspond to its developmental stage because the rates of processes in each zone may differ. Nevertheless, the fact that all these salt-marsh zones are located within the same barrier island should help minimize these potential errors. In addition, the spatial age gradient of the marsh was combined with repeated observations of the same area, which should further help in reducing errors.

### 2.3. Top-layer thickness

In the centre of each plot for both the large-scale grid and the short transects, we took a soil sample with a narrow auger (1 cm diameter and 53 cm length), resulting in a total of 500 to 680 measurements per transect and 820 measurements for the large-scale grid. This is an effective method for taking a large number of soil cores, given the thickness of the salt-marsh deposits (hereafter called *top-layer thickness*) at this site. From the soil core samples (Fig. 2), we distinguished two strata: 1) the underlaying base layer consisting of sand from aeolian or tidal flat origin (may include some thin fine-grained laminae), and 2) a dark, organic top layer of mud consisting of salt-marsh deposits (may contain thin layers of sand, see De Groot et al., 2011a). In most cases the two strata were fairly easy to distinguish in the field. According to Olff et al. (1997), elevational variation has two components, the time-independent elevation of the sandy subsoil (base elevation) and the time-dependent thickness of the top layer. Surface elevation is thus correlated with age, but by using base elevation (surface elevation minus top-layer thickness), succession can be reconstructed for a given location, and the dependence of sediment accumulation and plant species composition on this independent variable can be studied (Olff et al., 1997).

Dating of the top layer was done by dating the contact surface between the two strata, using a map of the vegetated areas from aerial photographs, taken in 1927, 1952, 1969 and 1980, and a topographical map (1:50,000) surveyed in 1853 (Fig. 1B; De Leeuw et al., 1993; Olff et al., 1997; De Groot et al., 2011a). If the surface was bare of vegetation, we assumed it was intertidal flat or beach without dominant fine-grained deposits. As soon as vegetation had established, we defined it as salt marsh and assumed fine-grained sediment was potentially being deposited. Thus, all fine-grained sediment in our core that is overlying a base layer of sand must have been deposited after the vegetation has been established. The year of vegetation establishment was taken as the middle year between either maps or photographs showing the last year without vegetation and the first year with vegetation. The thickness of the top layer was estimated to the nearest 0.5–1 cm for every sample (De Groot et al., 2011a), and any interspersed sand layers were excluded in 1992 and 1997, and included in 2005 and 2009 for the short transects. This difference introduces only small errors, since the contribution of sand to the total top layer is small (De Groot et al., 2011a). The same procedure was followed in the large-scale grid in 2010, including the sand layers.

### 2.4. Total sediment volume

To calculate an estimate of total marsh sediment volume at the landscape scale, and in the three sections of different marsh age (Fig. 3), the large grid points of top-layer thickness were interpolated using kriging. An ordinary kriging interpolation was carried out in ArcMap version 10.7.1 using a Gaussian semivariogram model (further described in Section 2.8), to obtain a raster map of top-layer thickness with cell size of 13 m × 13 m. Afterwards, total sediment volume was calculated as the product of average thickness and surface area over the entire marsh area and in each section.

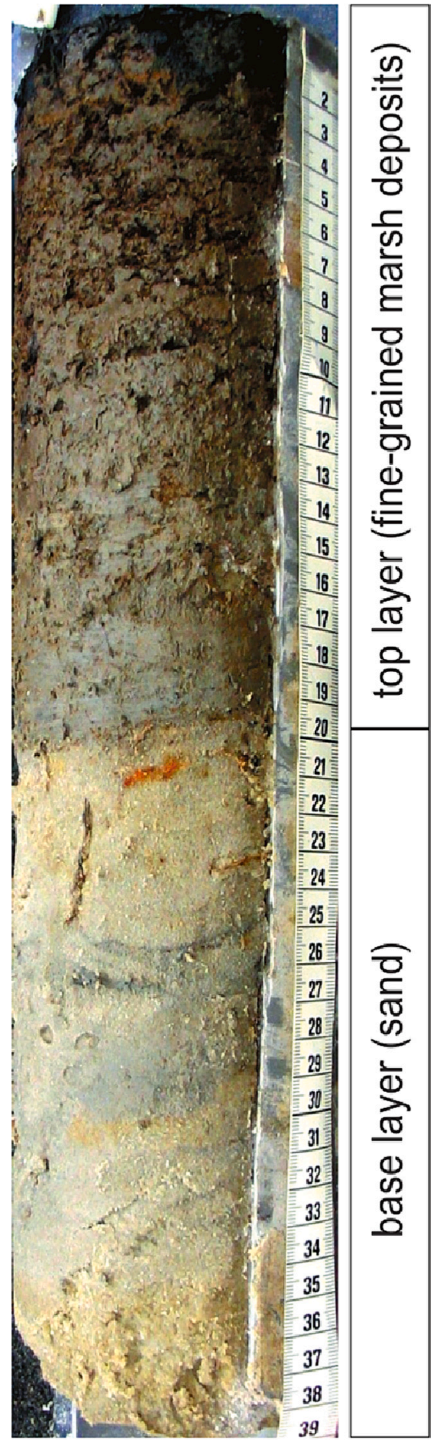


**Fig. 2.** Example of a salt marsh sediment core, showing a top layer of fine-grained, mostly mineral salt-marsh deposits (dark) on top of a base layer of sand (light). Scale is in cm. The core samples used in this study were narrower than the one shown here (taken from De Groot et al., 2011b).

### 2.5. Time

Sediment accumulation rates in the landscape-scale grid were calculated by relating each grid point to the age of initial vegetation establishment (Fig. 1B) using GIS software, and then dividing the

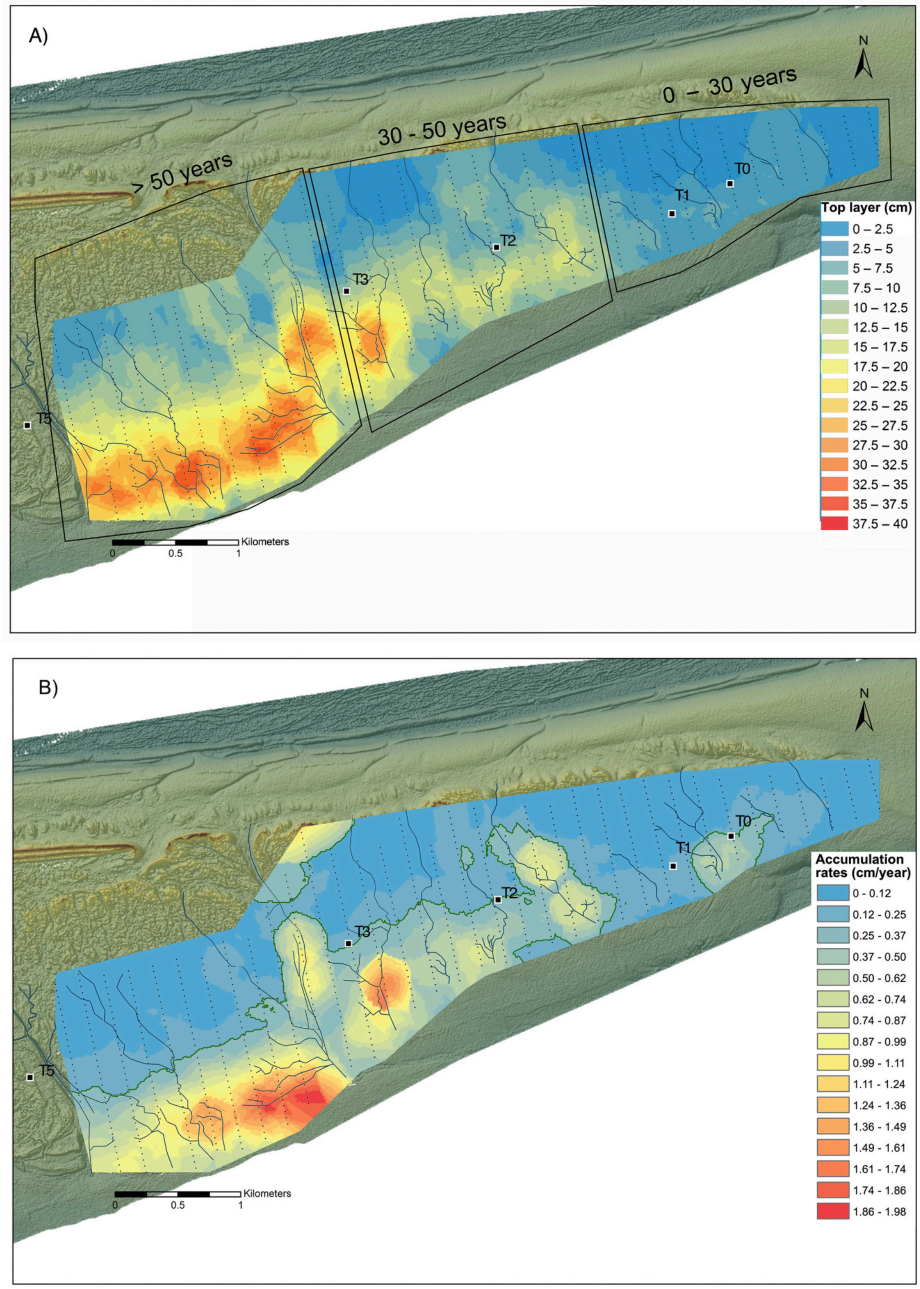


**Fig. 3.** A) Interpolated thickness of the top layer (cm) deposited on top of the sand base on the eastern part of the back-barrier marsh of Schiermonnikoog in 2010. Every dot indicates each of the 820 measuring points, and the squares indicate the location of the transects T0 – T5 (online version in colour). B) Interpolated accumulation rates (cm/year) calculated since the start of vegetation establishment. The green contour line shows the rate of 0.25 cm/year, corresponding to the local rate of sea-level rise. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thickness of the top layer by the age to obtain accretion rates in cm/yr. Thus, these values represent sediment accumulation rates since the beginning of salt-marsh formation. An ordinary kriging interpolation was carried out in ArcMap version 10.7.1 using a Gaussian semivariogram model, to obtain a raster map of accretion rates with cell size of 13 m × 13 m.

Sediment accumulation in the short transects over decades was measured by comparing the thickness of the top layer in 1992, 2001, 2005 and 2009. The short transects are far enough away from creeks and intertidal flats to not have experienced erosion, and their positions have not changed since their establishment in 1992 (Olff et al., 1997). Duration of the top-layer accumulation on these transects by 2009 was estimated to be 14 years (transect 0, T0), 27 years (transect 1, T1), 35 years (transect 2, T2), 45 years (transect 3, T3), 115 years (transect 5, T5) and 150 years (transect 7, T7), respectively. T0 was measured for the first time in 2001, as it was still bare soil in 1992 (Fig. 4). T7 was excluded from cattle grazing since 1972, whereas it was previously grazed, being nearest to the village. The other transects more eastward have never been grazed by livestock (Bakker, 1989). The chronosequence resulting from the succession and dynamics of the island provides a space for time substitute (Olff et al., 1997). Such a chronosequence allows studying accretion over a time-span of centuries (Walker et al., 2010).

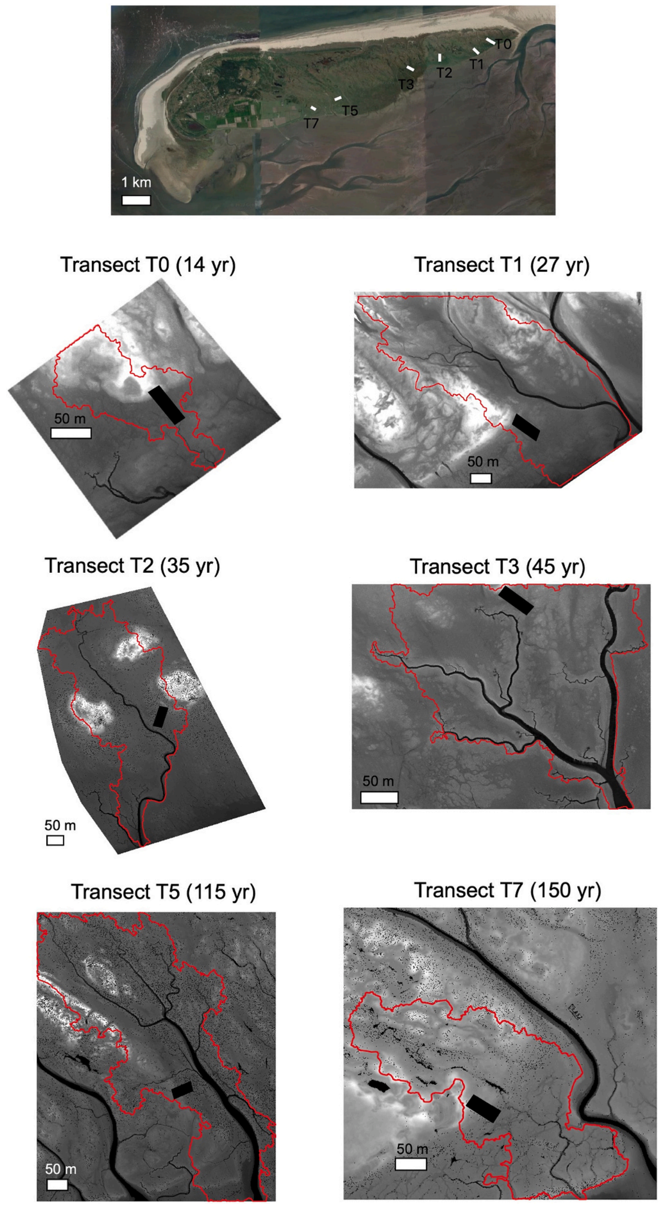


**Fig. 4.** Location of short transects in Schiermonnikoog (indicated by a black rectangle) and maps of the DTM sections used to calculate the creek network structure within the limits of the drainage basin indicated in red (online version in colour). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 2.6. Inundation frequencies and Standardized Water Level Index

Inundation frequencies along the elevation gradient were calculated using tidal data recorded at the station of Schiermonnikoog (53°28′05.6"N, 6°12′06.4″E). The water height measurements were collected at 10-min intervals between 1997 and 2009, and obtained from Rijkswaterstaat Waterinfo (https://www.rijkswaterstaat.nl/formulieren/contactformulier-rijkswaterstaat-waterinfo-vraag-over-geleverde-data-download-meer-data.aspx). The inundation frequency for each elevation was then calculated in R Statistical Software (v4.2.1; R Core Team, 2021) using the 'IF' function in the package 'Tides' (Cox and Schepers, 2018).

To facilitate comparison of our data with other studies on sites with different tidal ranges, the elevation of each sample is provided both in m +MHT and in a standardized form (Table 1), by reconstructing it as a standardized water level index (SWLI) following the equation in Horton and Edwards (2006):

$$\mathrm{SWLI} = \left[\frac{\mathrm{Elev} - \mathrm{MLWS}}{\mathrm{MHWS} - \mathrm{MLWS}}\right] \times 100$$

Where *Elev* is the elevation of the sample (in m +NAP), *MLWS* is the mean low water spring tide level (m +NAP) at the site, and *MHWS* is the mean high water spring tide (m +NAP). MLWS and MHWS were calculated from the previously mentioned water height measurements between 1997 and 2009. Through this conversion, a SWLI value of 0 indicates that the observed elevation equals MLWS. Conversely, a SWLI of 100 indicates that the observed elevation equals MHWS.

### 2.7. Sediment supply routes

The properties of the drainage basin and its creeks in which each short transect was located (Fig. 4) were derived from Digital Terrain Models (DTM), obtained from airborne laser altimetry (LIDAR) data. The Actueel Hoogtebestand Nederland (AHN) dataset was used in this study, selecting the latest series of data acquired between 2014 and 2019 (AHN3, openly accessible from https://app.pdok.nl/ahn3-downloadpage/). The DTMs were selected with a pixel size of 0.5 m × 0.5 m and had a vertical accuracy of 0.1 m. The AHN3 DTM ground level raster is specifically processed to represent the bare-soil surface, by filtering surface objects such as vegetation or buildings.

To extract the channel network properties, the DTMs were analyzed in Python using an open-source GIS software package called Whitebox Geospatial Analysis Tools (Whitebox GAT) (Lindsay, 2016). The Whitebox Toolbox was used to calculate the flow direction in each grid cell (flow pointer) and to create a flow accumulation raster (indicating the drainage basin area each grid cell belongs to). The flow accumulation raster was used to delineate the stream skeleton (i.e., the centreline of each channel), where a threshold of 25 $m^2$ was used as the minimal drainage area needed to be defined as a channel. The flow pointer was used to delineate the drainage basins, and the creek network properties were calculated for the basin in which a transect was located. Creek complexity can be expressed in terms of stream order, which indicates the sequence of increasingly smaller side channels branching from the main channels (Chirol et al., 2018). To express such complexity and branching of the creek network, the flow pointer and stream skeleton were then combined to classify the creeks, following Hack's stream ordering system (Hack, 1957), where the main channel is given an order of 1 and the terminal channels have the highest order. Based on the stream ordering raster, each creek segment was identified. The total number of creek segments and the total creek length are used as a measure of the complexity of the creek system. The distance to creeks was calculated for each cell in the DTM as the downslope distance to the nearest creek and was then averaged to a single value across the marsh platform. The distance from each transect to the intertidal flats (edge of the salt marsh) was measured in GIS as the straight-line distance from the middle point of each transect. At the landscape scale, the shapefiles representing the creeks (extracted with the method above) were subdivided into sections (every 50 m) and the number of features were counted to obtain the total creek number. Moreover, the maximum creek order in each subsection was recorded.

### 2.8. Data analyses

The landscape scale grid data of 820 points sampled in 2010 were separated in three sections, based on salt-marsh age: up to 30 years ($n$ = 173), 30 to 50 years ($n$ = 276) and >50 years ($n$ = 371). Afterwards, within each section, the points were averaged according to distance from the salt-marsh edge (every 50 m). The parameters calculated were the average base elevation (m +MHT), top-layer thickness (cm), total number of creeks and maximum Hack stream order (as measures of creek complexity).

Samples of thicknesses of the top layer along the short transects elevation gradient of 0.3–0.9 m +MHT were lumped in 20 cm surface elevation classes, each class including 100–150 samples depending on the slope of the gradient. The surface elevation class was determined anew for each measurement year between 1992 and 2009. As a result, some data points may have shifted between elevation classes over the study period due to changes in surface elevation. This approach may increase the variability and change the sample size within elevation classes, however it can better capture the dynamic elevation changes and reflect the temporal variability and evolution of the system. Medium-term accumulation was calculated from comparison of top-layer thickness between 1992 and 2009 in transects with varying age. Long-term accumulation was estimated by dividing thickness of the top layer in 2009 by the age of each transect.

For the landscape scale grid data, spatial regression was used to estimate the impact of age, elevation and sediment supply sources on sediment accumulation rates. The response variable was sedimentation rate (since the beginning of vegetation development) and the explanatory variables were marsh age, base elevation, distance to the intertidal flat and distance to the nearest creek. This analysis was carried out in Python 3.7 using the libraries 'libpysal' and 'spreg' from the PySAL suite for spatial analysis. A classical Ordinary Least Squares Regression revealed strong spatial autocorrelation of the residuals (Moran's $I = 11.3$; $p < 0.0001$), indicating spatial dependence of the model. Thus, a spatial lag model with maximum likelihood estimation was used to account for spatial autocorrelation in the data. We constructed a spatial weights matrix to model the spatial relationships among observations. The matrix was generated using the 'DistanceBand' method from 'libpysal.weights', with a threshold distance determined through an exploratory analysis of the distribution of pairwise distances among all observation points. This threshold was set at 149.255 m to ensure that each observation had an adequate number of neighbors while maintaining meaningful spatial relationships. The model was fitted using the ML_Lag class from the spreg module, which implements Maximum Likelihood estimation for spatial lag models.

For the short elevation transects, stepwise regression was used to estimate the relative contribution of age and distance to the sediment supply route to sediment accumulation. The response variable was top-layer accumulation rate per transect and the explanatory variables were marsh age in 2009, distance to the intertidal flat, number of creek segments and mean distance to creeks in the drainage basin.

## 3. Results

### 3.1. Top-layer thickness, accumulation, total sediment volume and sediment supply routes at the landscape scale

The elevation on the landscape scale of the grid of 820 points varied between 0 and 1 m +MHT, with increasing elevation further from the intertidal flats, and a less steep gradient in the older part (Fig. 5). The top-layer thickness showed a positive correlation with age of the salt marsh, exhibiting variations based on the distance from the intertidal flats. In the age section up to 30 years, the thickest layer of 8 cm was found at 150 m from the intertidal flats. In the age section ranging from 30 to 50 years, the thickest layer of 20 cm was measured at a distance of 250 m. In the age section over 50 years, the thickest layer of 35 cm was found at a distance of 350 m from the intertidal flats (Fig. 3, 6; Fig. S1). A positive correspondence between the top-layer thickness and the total creek number could be observed in the older part of the marsh. Total creek number and maximum creek order increased with age of the

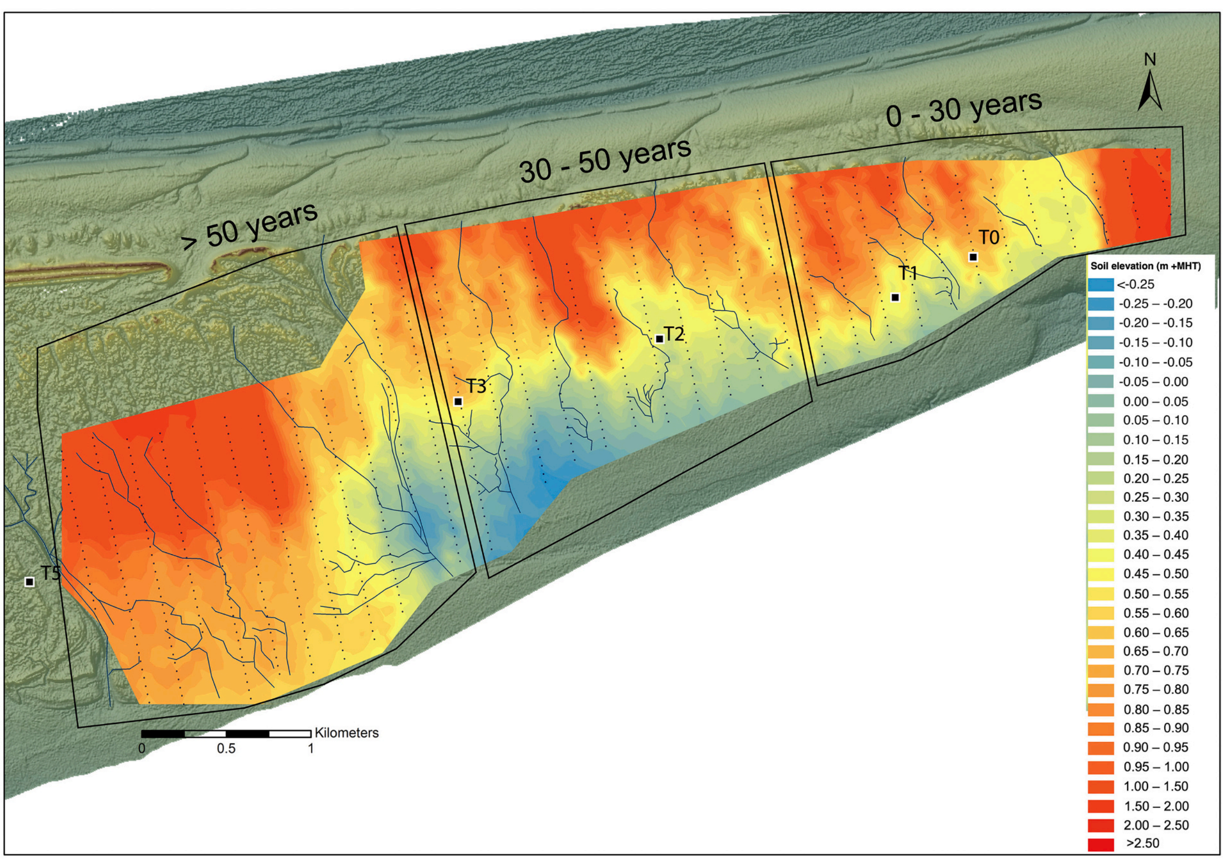


**Fig. 5.** Elevation (m +MHT) of marsh soil surface of the eastern part of the back-barrier marsh of Schiermonnikoog in 2010. Every dot indicates each of the 820 measuring points of the landscape-scale grid, and the squares indicate the location of the transects T0 – T5. The blocks outline the three sections in which the landscape scale grid data were separated, based on salt-marsh age: up to 30 years, 30 to 50 years and >50 years (online version in colour).

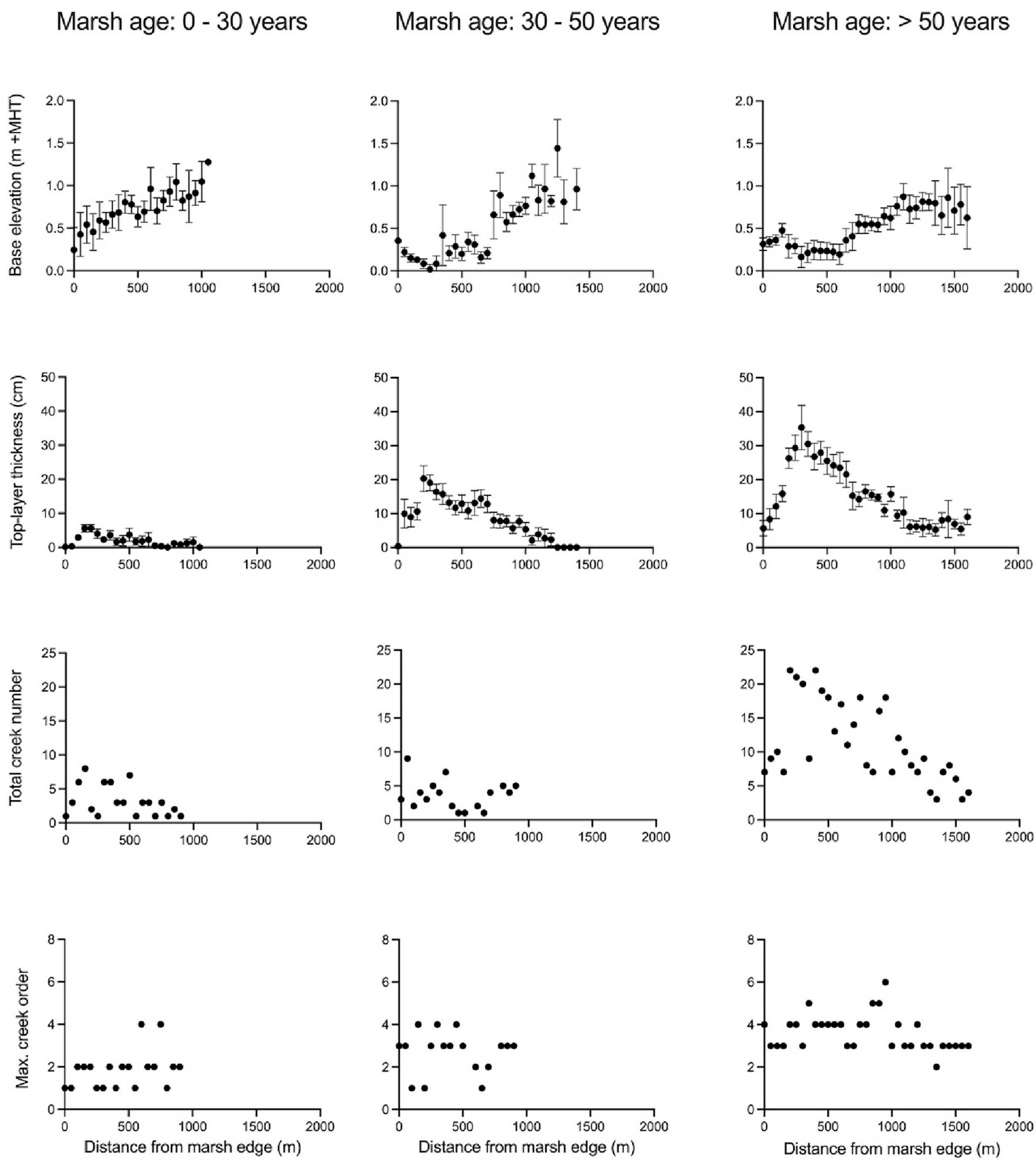


**Fig. 6.** Average base elevation (m +MHT), top-layer thickness (cm), total number of creeks and maximum Hack stream order (as measures of creek complexity) calculated at increasing distances from the marsh edge (m) based on the grid data of 820 points at the landscape scale. The grid data were separated in three sections, based on salt marsh age: up to 30 years ($n$ = 173), 30 to 50 years ($n$ = 276) and >50 years ($n$ = 371).

marsh, and were highest in the older part of the marsh with decreasing numbers at higher elevation (Fig. 6). The total sediment volume, calculated from the interpolation of the large grid points, was $1.1 \times 10^6$ $m^3$ over the entire salt marsh. In the section of the marsh aged 0–30 years, the total volume was $5.5 \times 10^4$ $m^3$; in the section of 30–50 years, it was $3.2 \times 10^5$ $m^3$, and in the section older than 50 years, it was $7.4 \times 10^5$ $m^3$. While the average top-layer height in each section increased with marsh age, the area covered also increased, resulting in a larger volume. The volume per square meter (reflecting the average top-layer height) is 0.025 $m^3/m^2$, 0.087 $m^3/m^2$ and 0.155 $m^3/m^2$, respectively for the three sections (0–30, 30–50, and > 50 years), showing an increase of sediment volume with the progression of salt-marsh age.

The accretion rate map on the landscape-scale grid (Fig. 3B), which presents rates calculated since the beginning of salt-marsh formation, showed higher accretion rates along marsh edges and creeks, but these differences were not as apparent in the young marsh to the east (section <30 years in Fig. 3B). Lower accretion rates were observed in older marsh sections to the west, although similarly low rates were also found in some young marsh areas to the east. Accretion rates increased with age from east to west across the marsh, but decreased from the intertidal flats to the higher, older areas (Fig. 1B), particularly in the section>50 years in Fig. 3B.

Spatial regression was used to investigate the factors influencing sedimentation rates at the landscape scale. The analysis revealed that salt-marsh age, proximity to creeks and base elevation are significant factors influencing sedimentation dynamics in the study site, whereas distance to tidal flats does not appear to have a significant impact (Table 3; Table S1). Regression results indicated that the model explained approximately 30 % of the variance in accretion rates (Pseudo $R^2 = 0.3009$). Age had a significant negative effect on accretion rates ($z = -5.296$, $p < 0.001$), suggesting that older marshes tend to have lower accretion rates. Similarly, base elevation had a significant negative effect ($z = -2.809$, $p < 0.01$), likely reflecting the decrease in inundation frequency at higher elevations. Distance to creeks also had a significant inverse relationship with accretion rates ($z = -3.239$, $p < 0.01$), showing the importance of tidal creeks as sediment supply routes. Conversely, distance to intertidal flats was not statistically significant ($z = -0.238$, $p = 0.8$). The spatial lag coefficient was 0.38 and highly significant ($z = 10.209$, $p < 0.0001$), pointing to substantial spatial autocorrelation in the data, suggesting that areas with high accretion rates tend to be surrounded by areas with similarly high rates.

### 3.2. Top-layer thickness and accumulation in short transects

In the short transects, thickness of the top layer increased down the elevation gradient from 0.9 to 0.3 m +MHT, as well as over the two survey decades, irrespective of the age of the salt marsh (Fig. 7; Fig. S2). This is consistent with the increase in inundation frequency from 1.3 % to 21.1 % (Table 1). However, the increase in top-layer thickness across all elevations between the first (1992) and last (2009) survey year slowed down with increasing marsh age in the chronosequence (Fig. 8).

The pattern of sediment accumulation rates along each elevation gradient varied between transects. Transects T3 and T5 displayed the highest rates in the middle of the gradient, in the younger transects (T0, T1 and T2) the rates decreased with increasing elevation, and transect T7 exhibited the highest rates at the highest elevation (Fig. 9). However, at elevation above 1 m +MHT, no accumulation was found (Fig. S2). Overall, the average top-layer thickness along the elevation gradient increased between the first and last survey year in all transects. Younger marshes showed a continuous increase in thickness with time, as opposed to the initial increase and later decrease in older marshes (Fig. S3A). The rate of top-layer thickness accumulation, calculated as the slope of the relationship between top-layer thickness and survey time, showed an exponential decline with increasing marsh age in the chronosequence (Fig. S3B).

Between 1992 and 2009, at the low end of the gradient (0.3 m +MHT), sediment accumulation rates decreased from 0.56 cm/yr to 0.12 cm/yr with increasing age of the salt marsh. At the high end of the

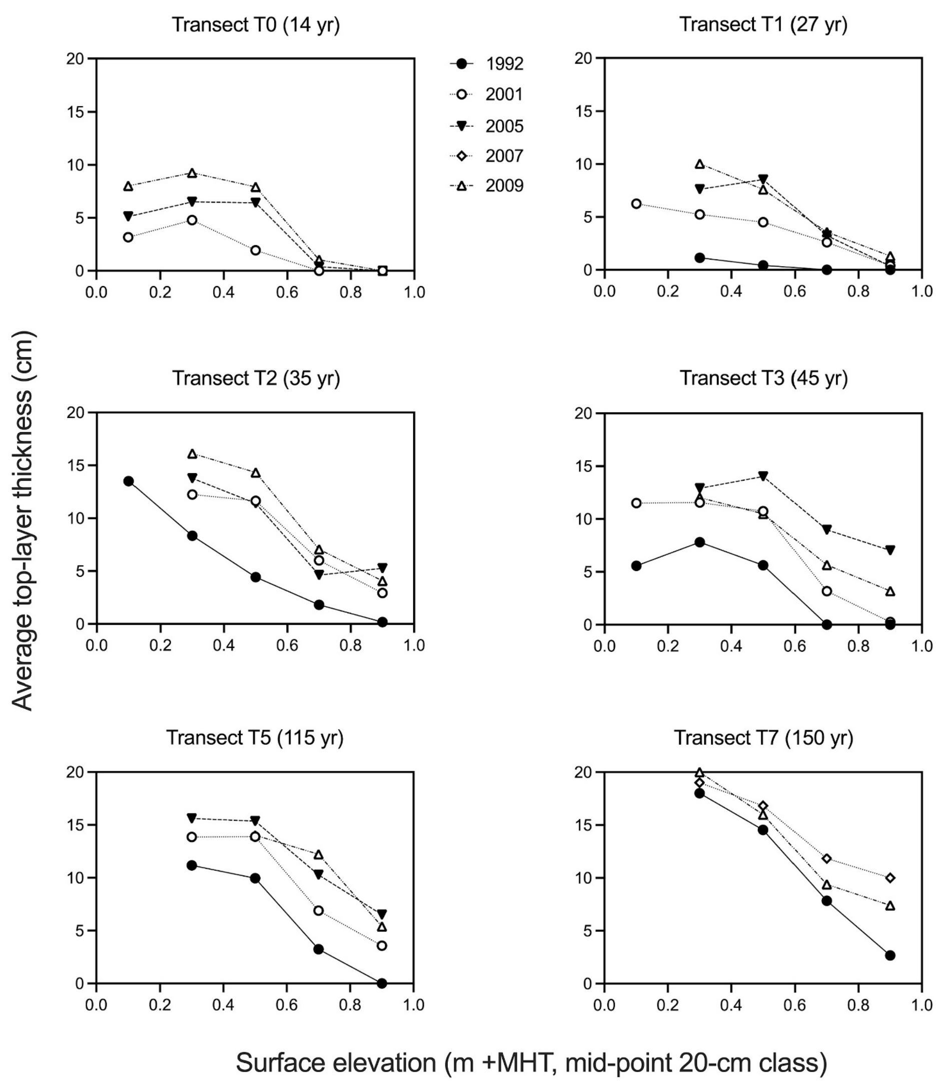


**Fig. 7.** Relationship between average top-layer thickness (cm, vertically) over 1992 and 2009 and surface elevation class (horizontally) along the small-scale elevation gradient (m +MHT in 20-cm classes) in short transects.

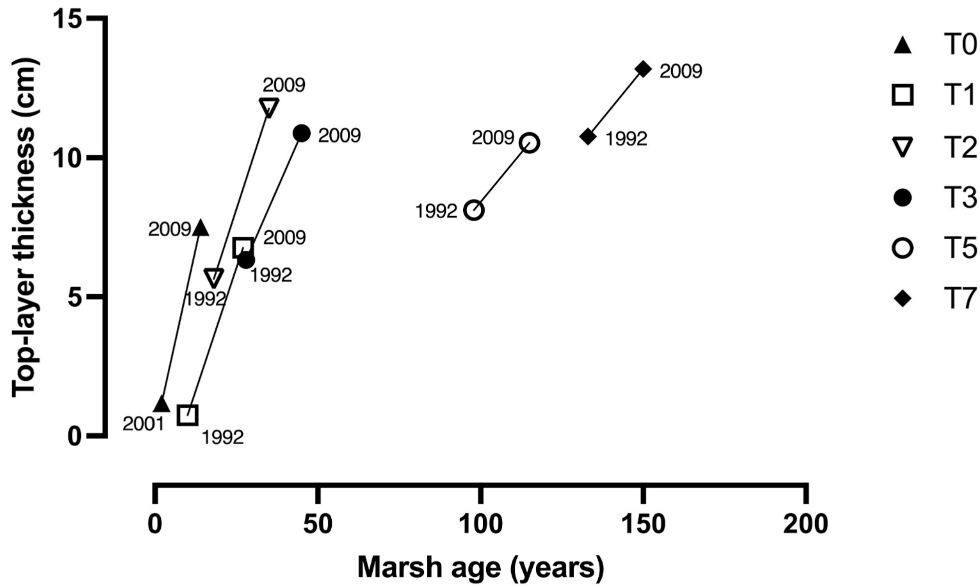


**Fig. 8.** Average top-layer thickness in relation to marsh age between the first (1992 or 2001) and last (2009) survey year. Each point represents the average value for that year across the entire short transects.

gradient (0.9 m +MHT), the rates remained relatively stable at around 0.25 cm/yr, with the exception of the two youngest transects (Table 2). To determine the average rate of accumulation since the beginning of salt-marsh formation, we divided the thickness of the top layer in 2009 by the estimated age of the salt marsh. At the lower end of the gradient, the rates ranged from 0.66 to 0.12 cm/yr and consistently decreased with salt marsh age. In contrast, the higher end of the gradient exhibited an irregular pattern, with most values falling below 0.06 cm/yr (Table 2). Moreover, the accretion rates exhibited a non-linear pattern over time, as the rates observed between 1992 and 2009 are higher than those estimated since the beginning of salt marsh formation, consistent with Fig. S3.

Comparing the larger grid to the short transects, the thickness of top layers in 2010 at the landscape scale (over a surface elevation 0.3–1.0 m + MHT) ranged from 0 to 10 cm in sites younger than 30 years, 0–20 cm in sites between 30 and 50 years, and 5–35 cm in sites over 50 years (Fig. 6). In 2009, thickness of top layers in the short transects (deliberately established 0.3–0.9 m + MHT for comparison from low dune towards salt marsh) ranged from 0 to 10 cm, 5–13 cm, and 5–15 cm, respectively (Fig. 7).

### 3.3. Sediment supply routes for short transects

The accumulation rate of the top layer was negatively related to the age of the salt marsh (Fig. 10). Comparing the accumulation rate with the sediment supply routes, we found a negative relationship with distance to the intertidal flats up to 400 m. It was also negatively related to the mean distance to creeks up to 140 m, and to the total creek length up to 2 km. Moreover, it was negatively related to the number of creeks segments up to 150 segments, and to the highest order of the creek system up to the fourth order. These relationships remained consistent for transects of increasing age up to approximately 50 years, after which the older transects displayed stabilization. Notably, the oldest transect, estimated to be around 150 years old, appeared to be an outlier in the analysis. (Fig. 10A–F).

The small-scale analysis of the factors affecting sediment accumulation rates revealed that marsh age (which is correlated with surface elevation) had the largest negative impact on these rates, accounting for 71.8 % of the variability in the response variable. The distance to the intertidal flat also had a notable effect, although small, explaining 12.7 % of the variability. Additionally, the number of creek segments showed a negative effect on accumulation rates, accounting for 11.6 % of the variability, while the mean distance to creeks contributed 3.8 % (Table 3). Creek network structure parameters, such as distance to creek, total creek length, highest order of creek system and number of creek segments, were positively correlated with each other (Table S2; Fig. S4). Overall, the analysis highlighted the substantial impact of marsh age on sediment accumulation rates, followed by a smaller and nearly equal influence of the two main sediment supply routes (distance to the intertidal flats and to tidal creeks).

### 3.4. Accretion rates in relation to sea-level rise

To evaluate salt-marsh resilience to SLR, we compared marsh accretion rates at both the landscape scale and in the short transects to the local SLR rate (0.25 cm/yr, reported in Vermeersen et al., 2018), for different elevations and salt-marsh ages (Fig. 3B; Table 2). At the landscape scale, accretion rates in the eastern region (section 0–30 years in Fig. 3B) were mostly below 0.12 cm/yr, lower than the rate of SLR. In the central and western part of the marsh (sections 30–50 years and > 50 years), accretion rates increased from higher elevations to the intertidal flats, and exceeded SLR rates in the lower half of the marsh, reaching values up to 1.98 cm/yr. Higher accretion rates were found along creeks in all zones, with increasing rates from east to west. This aligns with the results in Table 3, showing that creeks accounted for 17.5 % of the variability in landscape-scale accumulation rates.

In the short transects at the low end of the gradient (0.3 m + MHT), the younger salt marsh areas (T0 of 14 and T1 of 27 years old) displayed accretion rates of 0.56 and 0.52 cm/yr, respectively, largely outpacing SLR (Table 2). Similarly, the 35-year-old marsh at transect T2 maintained a rate of 0.46 cm/yr, still exceeding the rate of SLR. For the 45-year-old marsh at T3, accretion rate dropped to exactly match the sea-level rise rate at 0.25 cm/yr. This decreasing trend continued in the older marshes with the 115-year-old marsh (T5) recording an accretion rate just below SLR (0.24 cm/yr), and the 150-year-old marsh (T7) displaying an accretion rate of 0.12 cm/yr, half of the rate of SLR. Hence, when compared at the same low elevation, marshes that formed earlier (i.e., older marshes) accreted less than younger ones, a difference that can be partly attributed to the autocompaction of sediment over time.

At the high end of the gradient (0.9 m + MHT), the two youngest short transects showed no or little accretion rates: 0.0 cm/yr for the 14-year-old marsh (T0) and 0.08 cm/yr for the 27-year-old marsh (T1). This

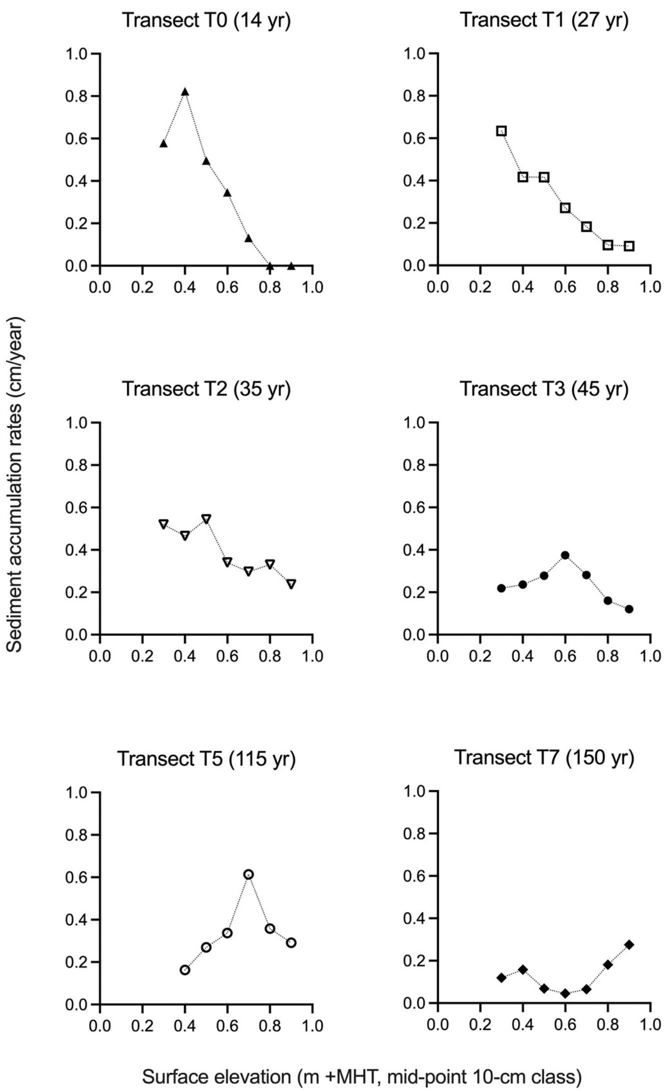


**Fig. 9.** Sediment accumulation rates (cm/yr) along the elevation gradient over the survey years (1992–2009) as a function of the 1992 elevation (m +MHT, in 10-cm classes) for each short transect.

indicated that the higher parts of the younger salt-marsh areas might not be keeping pace with rising sea levels. A similar trend was observed for the 35-year-old and 45-year-old marshes (T2 and T3), with accretion rates of 0.23 cm/yr and 0.19 cm/yr respectively, slightly below the local rate of SLR. In contrast, older marshes had accretion rates exceeding the SLR rate: 0.32 cm/yr for the 115-year-old marsh and 0.28 cm/yr for the 150-year-old marsh (T5 and T7).

## 4. Discussion

This study explored the variation in top-layer thickness and accumulation rates within a single salt marsh and from landscape scale to short transects. At the landscape scale, top-layer thickness generally increased from younger to older marshes, and from near to further away from the sediment source, i.e. the intertidal flats. Closest to the intertidal flats, however, low top-layer thickness was found, which can be explained by the low base elevation with pioneer vegetation that traps little sediment. Creeks are the second sediment source, and their total number and maximum creek order increased with marsh age.

Repeated measurements in short transects allowed focusing on changes over short spatial and temporal scales within the chronosequence, which spans centuries. At low elevations, the younger marshes had higher accumulation rates than the local rate of SLR, while the older marshes maintained an equilibrium. Net sediment accumulation was lower in the older salt marsh due to the possible role of ongoing autocompaction in thicker and older top layers. Older marshes, particularly at lower elevations, as well as younger marshes at higher elevations and far away from intertidal flats (the primary sediment source), may be at increased risk of flooding due to their limited ability to keep pace with SLR. Contrary to the transect data, which suggested higher accretion rates in the younger part of the marsh, the landscape-scale findings showed that accretion rates were higher along creeks across the entire marsh. This indicates that sediment supply routes can have varying effects on sedimentation rates depending on the spatial scale considered.

### 4.1. Accumulation of sediment

Esselink et al. (2017) reported an average surface elevation change rate of 0.27 cm/yr across 12 back-barrier salt marsh sites in the international Wadden Sea, varying between 0.04 and 0.37 cm/yr. Our study helps to explain the large range, finding similar ranges already within a single site. Sediment accumulation rates ranged from 0.56 to 0.12 cm/yr at an elevation of 0.3 m + MHT, and were related to marsh age ranging from 14 to 150 years. At 0.9 m + MHT, accumulation rate was approximately 0.25 cm/yr, but not clearly related to marsh age. Esselink et al. (2017) reported an increase in MHT since the 1980s (0.2–0.3 cm/yr) along the barrier-connected salt marshes in the Wadden Sea. It appears that accumulation initially exceeds the increase in MHT during the initial stages of salt-marsh formation, until it reaches equilibrium in older salt marshes, where it keeps pace with SLR. This pattern aligns with previous findings and theoretical models of salt-marsh growth (Allen, 2000; French, 1993; Fagherazzi et al., 2006; Mudd et al., 2009).

**Table 2**
Top-layer thickness (cm) in the last survey year and sediment accumulation rates (cm/yr) between first (1992) and last (2009) survey year at the low end (0.3 m + MHT) and high end of the elevation gradient (0.9 m + MHT), for each transect in the chronosequence. * data of T5 from the low end of 0.5 m + MHT. Sediment accumulation measured by Van Wijnen and Bakker, 2001 and Van Dobben et al. (2022) from Sedimentation Erosion Bars at the transect locations.

| Transect (age in 2009) | Top-layer thickness in last survey year 2009 (cm) | | Sediment accumulation rates between 1992 and 2009 (cm/yr) | | Sediment accumulation from the beginning of salt-marsh formation (cm/yr) | | Sediment accumulation rate at 0.4 m + MHT between 1995 and 2011 (cm/yr) (Van Wijnen and Bakker, 2001; Van Dobben et al., 2022) |
|---|---|---|---|---|---|---|---|
| | Low end of the gradient (0.3 m + MHT) | High end of the gradient (0.9 m + MHT) | Low end of the gradient (0.3 m + MHT) | High end of the gradient (0.9 m + MHT) | Low end of the gradient (0.3 m + MHT) | High end of the gradient (0.9 m + MHT) | |
| T0 14 yr | 9.25 | 0.00 | 0.56 | 0.00 | 0.66 | 0.00 | 0.41 |
| T1 27 yr | 10.04 | 1.31 | 0.52 | 0.08 | 0.37 | 0.05 | 0.40 |
| T2 35 yr | 16.12 | 4.08 | 0.46 | 0.23 | 0.46 | 0.12 | 0.33 |
| T3 45 yr | 12.02 | 3.19 | 0.25 | 0.19 | 0.27 | 0.07 | 0.30 |
| T5 115 yr | 14.02* | 5.39 | 0.24* | 0.32 | 0.12* | 0.05 | 0.22 |
| T7 150 yr | 20.00 | 7.40 | 0.12 | 0.28 | 0.13 | 0.05 | N/A |

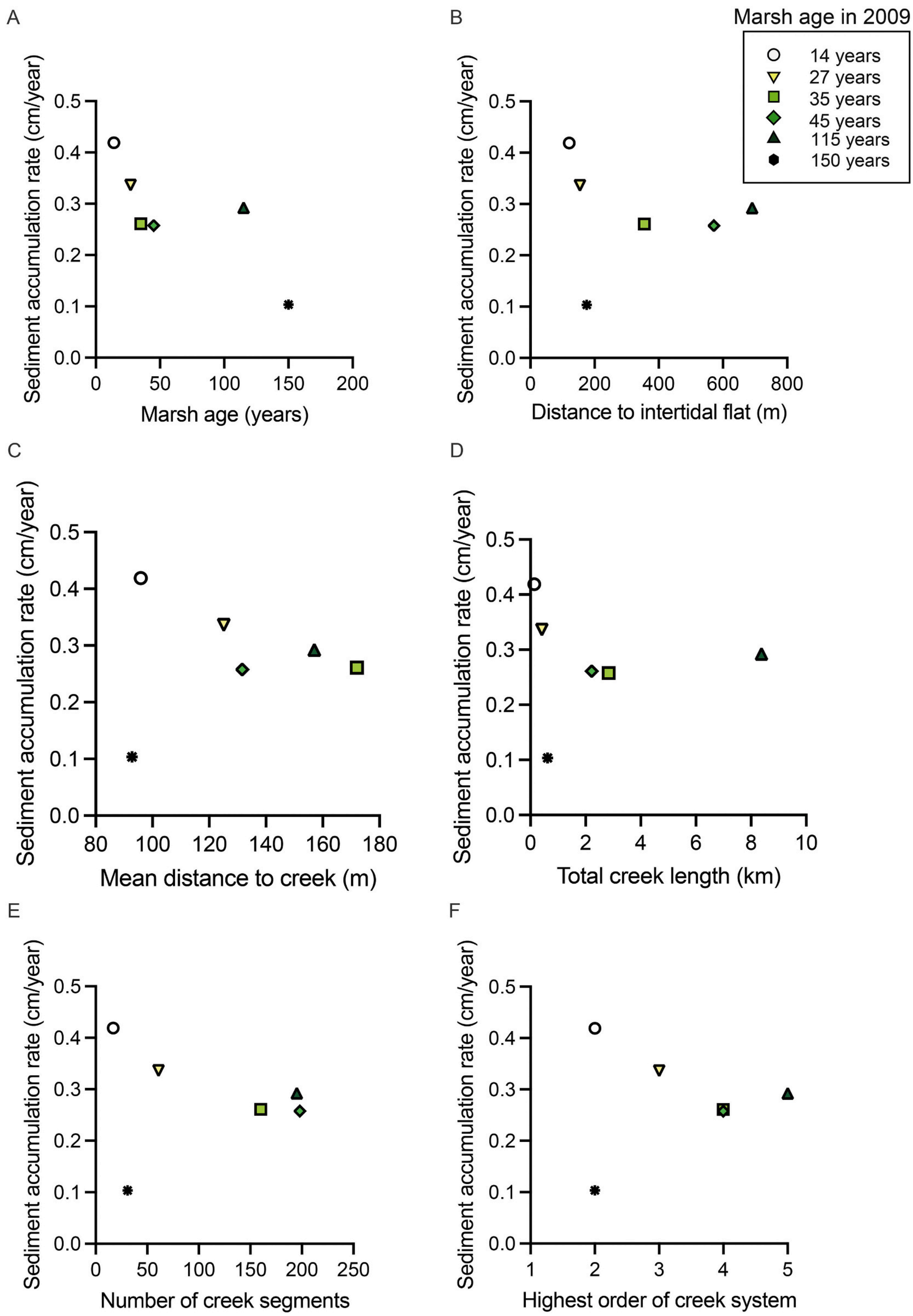


**Fig. 10.** Sediment accumulation rate (cm/yr) in short transects between 1992 and 2009 in relation to (A) marsh age and creek network structure: (B) distance to intertidal flats along the age gradient, (C) mean distance to creek, (D) total creek length, (E) number of creek segments, and (F) highest order of creek system) (online version in colour).

The mean background rate of SLR during 1994–2012 near Schiermonnikoog was 0.25 ± 0.009 cm/yr (Vermeersen et al., 2018). Based on the conditions observed in our study area, sediment accumulation and SLR would then be in equilibrium when the marsh is 100 years old. This time-frame could potentially vary significantly between various marshes depending on factors such as sediment supply, vegetation dynamics, and other site-specific dynamics. However, in our oldest marsh (approximately 150 years), the top-layer thickness seems lower than could be expected from the aforementioned equilibrium time (Table 2). This discrepancy may be related to the long-term changes in MHT, as indicated by historical data from the Eastern Wadden Sea at Delfzijl (45 km from Schiermonnikoog), namely, a slight decrease of 0.1 cm/yr between

**Table 3**
Factors as relative contributions to sediment accumulation rates for the landscape-scale grid, and the small-scale short elevation transects. Relative contributions for the landscape scale were calculated by comparing the changes in $R^2$ after removing each independent variable.

| Factor | Landscape-scale grid | Short transects |
|---|---|---|
| Age | 69.8 | 71.8 |
| Distance to sediment source (intertidal flats) | 1.0 | 12.7 |
| N. of creek segments | N/A | 11.6 |
| Distance to sediment source (creeks) | 17.5 | 3.8 |
| Base elevation | 11.6 | N/A |

1840 and 1890, followed by an increase of 0.2 cm/yr between 1890 and 2000 (Esselink et al., 2011). These data suggest that there was no accumulation during most of the first century of the oldest marsh, thus explaining the low accumulation of T7. A similar relationship between sediment accumulation and MHT has been observed in the salt marshes of the Scheldt estuary, in the Netherlands and Belgium: recently established marshes accumulated sediment rapidly compared to MHT rise, but accumulation slowed down over time and the marshes maintained their equilibrium level relative to MHT (Temmerman et al., 2004).

At our study site, sediment accumulation rates measured over the short- and long-term decreased with marsh age, potentially indicating equilibrium with MHT. Also, autocompaction likely contributed to reducing the differences in accumulation rates with thicker top layers. Consolidation causes the bulk dry density to vary from the top layer downwards as a logarithmic increasing function (Bartholdy et al., 2010b). Bartholdy et al. (2010b) therefore suggest not to judge salt-marsh accumulation by the change in elevation and thickness of the top layer alone. Their study on the Skallingen back-barrier marsh in the Danish Wadden Sea showed that sediment accumulation was rapid during the initial stages of salt-marsh formation, but reduced to half its initial value within about 70 years. Our data suggest a similar stronger rate of autocompaction with high rates in the older marsh with the thickest top layer (Table 2). Trampling by herbivores may further reduce accumulation rates as it increases the bulk density of the fine-grained top layer (Marin-Diaz et al., 2021). Long-term experiments along the chronosequence of Schiermonnikoog revealed that grazing by livestock, hare and geese led to thinner top layers and lower surface elevation in grazed areas compared to ungrazed ones (Elschot et al., 2013).

### *4.2. Sediment supply routes*

In the short transects, we observed a decrease in accretion rates with increasing distance to sediment supply routes, namely intertidal flats and creeks. This aligns with the deposition model proposed for the back-barrier salt marsh of Skallingen, Denmark, suggesting spatial variation in deposition patterns, extending up to 100 m from the salt-marsh edge, up to 500 m from the edge along creeks, and up to 50 m from individual creeks (Bartholdy et al., 2010a). Notably, in the back-barrier salt marsh of Ameland, the Netherlands, natural gas extraction since 1986 caused deep subsidence, totaling about 25 cm including relative SLR after 25 years (Dijkema et al., 2011; Van Dobben et al., 2022). While accretion compensated for subsidence near the salt-marsh edge, a location further from the edge experienced minimal accretion and a negative SEC, despite its higher initial elevation (Dijkema et al., 2011). The case of Ameland confirms the interaction between surface elevation and distance to sediment supply routes within a single marsh.

Our short transects had been established at different distances from the intertidal flats, where distance increased with age of the salt marsh, except for the oldest transect T7, which has become closer due to cliff erosion (Fig. 10). As a result, sediment accumulation seemed to be lower in older transects, in part due to their greater distance from the intertidal flats, as the grid data across the entire salt marsh show (Fig. 6). The small negative effect of distance to the intertidal flats on accumulation rates might be due to the non-linear form of the relationship, with lower thickness both near and far from the intertidal flats, and higher thickness at intermediate distances. Low thickness along the intertidal flats may be due to the presence of pioneer vegetation that typically traps less sediment. If distances within the first 200 m from the intertidal flats are excluded (Fig. S1), a significant negative relationship emerges indeed, showcasing the effect of sediment supply routes.

The channel patterns we observed, where older sections of the marsh show a larger number of creeks, align with existing literature on creek development (Redfield, 1972; Steel and Pye, 1997; Chirol et al., 2018). As vegetation establishes and the marsh grows vertically, the steeper elevation gradient promotes water flow in the creeks, deepening them and leading to the formation of higher-order channels (D'Alpaos, 2005; Temmerman et al., 2007). However, the aforementioned negative change of MHT during the first century of the oldest marsh may have caused the deviating creek pattern in the drainage basin of T7, compared to the other sections.

### *4.3. Salt-marsh resilience to sea-level rise*

Comparing the results at the low end of the gradient (0.3 m + MHT) with the sediment accumulation rates at 0.4 m + MHT between 1995 and 2011 using SEB-measurements reported by Van Dobben et al. (2022), we observed similar trends (Table 2). The sediment accumulation rates at 0.4 m + MHT ranged from 0.41 cm/yr to 0.22 cm/yr during that time period and displayed a gradual decline with increasing marsh age (Van Dobben et al., 2022), a pattern that is consistent with our results for marshes situated at 0.3 m + MHT. The study by Van Dobben et al. (2022) did not incorporate measurements at higher elevations, therefore a complete comparison of our results with theirs is not feasible. They found a mean accretion rate of 0.33 cm/yr across all salt-marsh ages, which exceeds the local rate of SLR (0.25 cm/yr) (Vermeersen et al., 2018; Nicholls et al., 2021). In our study, the mean accretion rate at the low end of the gradient (0.3 m + MHT) was slightly higher at 0.36 cm/yr. Thus, both methods indicate that the lower parts of the marsh can keep up with sea-level rise. Only T7 was an outlier with a much lower accretion rate at 0.12 cm/yr. At higher elevations, accretion rates in younger marshes are much lower than the rate of SLR. Despite their current elevation advantage, with these accretion rates we can expect that the higher parts of the younger marshes will be vulnerable to increased flooding over time. This might lead to a change in vegetation composition, favoring species more characteristic of lower salt-marsh environments, but alternatively may receive extra sediment input because of higher flooding frequencies. However, both the results of Van Dobben et al. (2022) and our study (Table 3) indicate that their distance to the tidal flats may be a limiting factor in sediment supply. Overall, our findings reveal different trajectories in terms of adaptation to SLR when both elevation and age are included as factors. The downward trend of accretion emphasizes the potential vulnerability of older marshes to rising sea levels (Cahoon et al., 2006).

### *4.4. Generalisation*

We expect that our findings on sediment accumulation can be applied to other barrier-island salt marshes in the International Wadden Sea region (Bartholdy et al., 2010a) and England (Stoddart et al., 1989; French and Spencer, 1993), due to comparable elevation gradients, creek systems, vegetation types and geomorphic development. However, the results might be less broadly applicable to naturally-formed foreland-type and estuarine marshes. There, the initial topography is typically shaped by sediments deposited within the marsh environment, rather than by pre-existing variation in sandy subsoil (Temmerman et al., 2004; Hartmann and Stock, 2019). Also, creek patterns in natural foreland and estuarine marshes can be significantly influenced by the development of vegetation patterns (e.g. Temmerman et al., 2007; van de Vijsel et al., 2023), although the effect of creeks as sediment transport routes would be similar.

Differences in sedimentation patterns may arise in marshes with distinct vegetation types, especially in the pioneer zone, which in our site is dominated by annual species such as *Salicornia* spp., *Suaeda maritima* and low-statured perennial species such as *Limonium vulgare* and *Puccinellia maritima*. In salt marshes colonized by different species, such as perennial stiff tall grass *Spartina anglica* in Europe or *Spartina* spp. elsewhere, sedimentation rates in the pioneer zone tend to be higher (Temmerman et al., 2003; Ma et al., 2014) and do not result in the low accumulation we found near the intertidal flats. Also, sedimentation rates may be much more dominated by organic deposition, such as in marshes found in North America, so that distance from the sediment source is less of a determining factor. Organogenic back-barrier salt marshes along the Virginian coast, with vertical accretion of <0.07 cm/yr, are more vulnerable to the redistribution of coastal sand reservoirs and SLR (Fitzgerald et al., 2018) compared to those along the coast of the Wadden Sea, with vertical accretion rates around 0.3 cm/yr (Esselink et al., 2017).

Moreover, foreland salt marshes in the Wadden Sea, where marsh formation is facilitated by man-made sedimentation fields with brushwood groynes and overdimensioned artificial ditches, tend to show a more regular spatial pattern in sediment accumulation (Esselink et al., 1998) than natural marshes with meandering creeks. Cliff erosion, as observed in our older marsh location at T7 and often present in older estuarine marshes (Allen, 2000), can also impact sedimentation dynamics as part of the low marsh disappears and sediment from the cliff may be redistributed onto the marsh surface.

## 5. Conclusions

This study reports on the large variation in top-layer thickness and accumulation rates within a single salt marsh over decades to centuries, and from landscape scale to small-scale short transects. At both large and small scales, top-layer thickness showed a positive relation with salt-marsh age. However, the effect of the sediment supply routes (intertidal flats and the creek network) on top-layer thickness and accumulation depended on the scale of investigation: at the landscape scale, sediment accumulation rates were higher along creeks but not significantly influenced by proximity to intertidal flats. Conversely, in the short transects within individual drainage basins, distance to intertidal flats had a larger impact on sediment accumulation than distance to creeks. By comparing our medium-term observations with prior studies, our results confirmed earlier findings that accretion rates in the back-barrier salt marsh of Schiermonnikoog are generally higher than the local rate of SLR. However, this does not hold true for all ages and elevations. Our results point to the vulnerability of lower-elevation older marshes and higher-elevation younger marshes far from sediment supply sources (intertidal flats or creeks), where accretion rates were lower than the local rate of SLR. Taken together, these findings demonstrate that both methods are complementary to understand the evolution of a salt marsh. While the short transects provide detailed information about specific locations and elevation over decades, they do not cover the entire marsh, and particularly not the intertidal flat. Conversely, the grid data provide a broader overview of the entire salt marsh over centuries, but with less detailed information with respect to elevation.

## CRediT authorship contribution statement

**L. Cornacchia:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **J.P. Bakker:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **E.C. Koppenaal:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **A. V. de Groot:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **H. Olff:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **J. van de Koppel:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **D. van der Wal:** Writing – review & editing, Validation, Supervision, Conceptualization. **T.J. Bouma:** Writing – review & editing, Validation, Supervision, Conceptualization.

## Declaration of competing interest

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

## Data availability

The data supporting the findings of this study are available at the 4TU.Research Data repository: https://doi.org/10.4121/c62db524-db8d-45d6-8fe4-673857d4bd8c

## Acknowledgements

Collecting the data for this paper was a joint effort of many people and we wish to thank Harm van Wijnen, Roos Veeneklaas, Dries Kuijper, and many students and field assistants. Vereniging Natuurmonumenten is acknowledged for allowing access to the National Park Schiermonnikoog. Loreta Cornacchia was supported by the project "Coping with deltas in transition" within the Programme of Strategic Scientific Alliances between China and the Netherlands (PSA), financed by the Chinese Ministry of Science and Technology (MOST), Project no. 2016YFE0133700, and Royal Netherlands Academy of Arts and Sciences (KNAW), Project no. PSA-SA-E-02. We acknowledge the constructive comments from reviewers and editor.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2024.109191.

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