

Assessing the long-term carbon-sequestration potential of the semi-natural salt marshes in the European Wadden Sea

PETER MUELLER ^{1,†} NILS LADIGES,² ALEXANDER JACK,² GERHARD SCHMIEDL,³ LARS KUTZBACH,² KAI JENSEN,¹ AND STEFANIE NOLTE¹

¹*Plant Ecology, Institute of Plant Science and Microbiology, Universität Hamburg, Ohnhorststr. 18, 22609 Hamburg Germany*

²*Center for Earth System Research and Sustainability, Institute of Soil Science, Universität Hamburg, Allende-Platz 2, 20146 Hamburg Germany*

³*Center for Earth System Research and Sustainability, Institute for Geology, Universität Hamburg, Bundesstr. 55, 20146 Hamburg Germany*

Citation: Mueller, P., N. Ladiges, A. Jack, G. Schmiedl, L. Kutzbach, K. Jensen, and S. Nolte. 2019. Assessing the long-term carbon-sequestration potential of the semi-natural salt marshes in the European Wadden Sea. *Ecosphere* 10(1):e02556. 10.1002/ecs2.2556

Abstract. Salt marshes and other blue carbon ecosystems have been increasingly recognized for their carbon (C)-sink function. Yet, an improved assessment of organic carbon (OC) stocks and C-sequestration rates is still required to include blue C in C-crediting programs. Particularly, factors inducing variability in the permanence of sequestration and allochthonous contributions to soil OC stocks require an improved understanding. This study evaluates the potential for long-term C sequestration in the semi-natural salt marshes of the European Wadden Sea (WS), conducting deep (1.3 m) down-core OC-density assessments in sites with known site histories and accretion records. Because these young marshes have developed from tidal-flat ecosystems and have undergone rapid succession during the last 80–120 yr, the identification of different ecosystem stages down-core was crucial to interpret possible changes in OC density. This was conducted based on the down-core distribution of different foraminiferal taxa and grain sizes. Comparisons of historic and recent accretion rates were conducted to understand possible effects of accretion rate on down-core changes in OC density. $\delta^{13}\text{C}$ in OC was used to assess the origin of accumulated OC (autochthonous vs. allochthonous sources). We show that large amounts of short-term accumulated OC are lost down-core in the well-aerated marsh soils of the WS region and thus emphasize the importance of deep sampling to avoid overestimation of C sequestration. Despite steep declines in OC-density down-core, minimum values of OC density in the salt-marsh soils were considerably higher than those of the former tidal-flat sediments that the marshes were converted from, illustrating the greater C-sequestration potential of the vegetated ecosystem. However, our data also suggest that marine-derived allochthonous OC makes up a large fraction of the effectively, long-term preserved OC stock, whereas atmospheric CO_2 removal by marsh vegetation contributes relatively little. The implication of this finding for C-crediting approaches in blue C ecosystems has yet to be clarified.

Key words: allochthonous; autochthonous; blue carbon; carbon density; constructed wetlands; drainage; minerogenic; tidal flats; tidal wetlands.

Received 28 November 2018; **accepted** 4 December 2018. Corresponding Editor: Debra P. C. Peters.

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† **E-mail:** peter.mueller@uni-hamburg.de

INTRODUCTION

Salt marshes and other vegetated coastal ecosystems, such as mangroves and seagrass beds, have

been increasingly recognized for their carbon (C)-sink function in recent years. In these blue C ecosystems, rates of C sequestration exceed those of most other ecosystem types because slow rates

of organic matter decomposition co-occur with high rates of organic matter input, through both autochthonous primary production and import of allochthonous organic matter (Duarte et al. 2005, Bridgham et al. 2006, Mcleod et al. 2011). The important role of blue C ecosystems in the global C cycle caused great interest to include their protection, restoration, and even construction as greenhouse-gas-offset activities in C-crediting programs and climate-change policy (Herr et al. 2011).

The present study represents the first approach to describe the C-sequestration potential of the semi-natural salt marshes along the mainland coast of the European Wadden Sea (WS) UNESCO World Heritage site. The salt marshes of the WS region account for ~20% of the European salt-marsh area (Doody 2008). Among these, the salt marshes of the mainland coast make up by far the largest part of the total WS salt-marsh area. They are almost exclusively man-made, semi-natural systems that have been constructed for means of land reclamation via conversion of tidal-flat ecosystems during the late 19th and early 20th century (Hofstede 2003, Esselink et al. 2009). Estimates of C sequestration for semi-natural systems such as constructed or restored tidal wetlands are scarce because most of these systems are simply too young for long-term assessments (Craft et al. 1999, 2003, Callaway et al. 2012, Balantine and Schneider 2014). The century-long development of the WS salt marshes, however, might suffice to estimate the potential of this type of coastal engineering for C sequestration over decennial and potentially longer timescales.

The C-sequestration rate of blue C ecosystems is described by the product of vertical accretion rate and soil or sediment organic carbon (OC) density. The mainland marshes of the WS region are fast accreting systems (mean rate >9 mm/yr; Esselink et al. 2017) and may therefore yield a high potential for C sequestration. However, it is reasonable to assume that OC densities are comparatively low in the soils of WS marshes, thereby counterbalancing the positive effect of high accretion on C sequestration. The main reason for this assumption is that soil conditions are highly oxidizing in the WS marshes, thus likely sustaining high rates of mineralization and consequently OC loss from the system (Erchinger et al. 1996, Mueller et al. 2017).

The WS marshes are minerogenic ecosystems (Allen 2000). In contrast to organogenic marshes, minerogenic marshes do not primarily rely on the preservation of organic matter under anoxic soil conditions to generate soil volume and thus develop with rising sea level (Allen 2000, Kirwan and Megonigal 2013). Indeed, recent studies conducted in minerogenic marshes often showed strong declines in OC density with soil depth (e.g., Livesley and Andrusiak 2012, Saintilan et al. 2013, Kelleway et al. 2016, Schile et al. 2017), which are likely due to the low preservation of organic matter in soils (Schile et al. 2017, Van de Broek et al. 2018). In such cases, the distinction between short-term C accumulation (based on topsoil OC densities) and long-term C sequestration (based on sub-soil OC densities) is necessary, however, surprisingly often left unconsidered (Choi and Wang 2004, Van de Broek et al. 2018). Furthermore, minerogenic marshes often experience considerable inputs of sedimentary allochthonous organic matter contributing to the marsh OC stock (Middelburg et al. 1997, Craft 2007, Spohn et al. 2013). The distinction between allochthonous and autochthonous contributions to the total OC pool is relevant for C-crediting approaches because allochthonous OC burial does not represent in situ atmospheric CO₂ sequestration by the marsh ecosystem, and the alternative fate of the allochthonous OC (i.e., if it had not accumulated in the wetland soil) is unclear.

A recent study conducted in the salt marshes of the Scheldt estuary ~200 km south of the WS region provides important biogeochemical insight into soil OC dynamics that might be useful to understand the OC-density distribution in our study system—the WS salt marshes. Van de Broek et al. (2018) showed that, despite large plant-biomass and topsoil OC stocks, only a small fraction of autochthonous OC remains preserved with soil depth, thus contributing to long-term C sequestration. They furthermore show that the effectively, long-term preserved OC at greater depth is predominantly of allochthonous origin.

In order to assess the potential for long-term C sequestration of the young, semi-natural mainland marshes of the WS region and thus provide a first estimate of the C value that the conversion of tidal flat to salt marsh may generate, the present study investigates (1) if decomposition

causes OC densities to markedly decline with soil depth and level out at stable value that can be interpreted as effectively preserved; (2) if the OC density of the effectively preserved OC stock is higher than that of the un-vegetated tidal-flat sediment that the marsh system has been converted from; and (3) if allochthonous OC represents a relevant fraction of the effectively preserved OC stock.

METHODS

Selection of study sites

The young age of the WS marshes poses some challenges to our investigation of down-core OC densities: The salt marshes could build only shallow soil bodies over tidal-flat sediments, which necessitates the distinction of salt-marsh

soils from tidal-flat sediments in a down-core OC-density assessment. Furthermore, accretion and sedimentation rates may have varied considerably during ecosystem development with potential effects on OC density (Ruiz-Fernández et al. 2018). Thus, knowledge on accretion rates during early marsh development and their relation to accretion rates of the mature ecosystem is needed to interpret potential down-core changes in OC density. The present study is therefore focused on a targeted assessment of the OC-density distribution in three marsh sites with known site histories, including records of historic and recent accretion rates and vegetation composition.

The study was conducted in three semi-natural mainland salt marshes along the German WS coast in the WS National Park of Schleswig-Holstein (Fig. 1). The early development of semi-natural

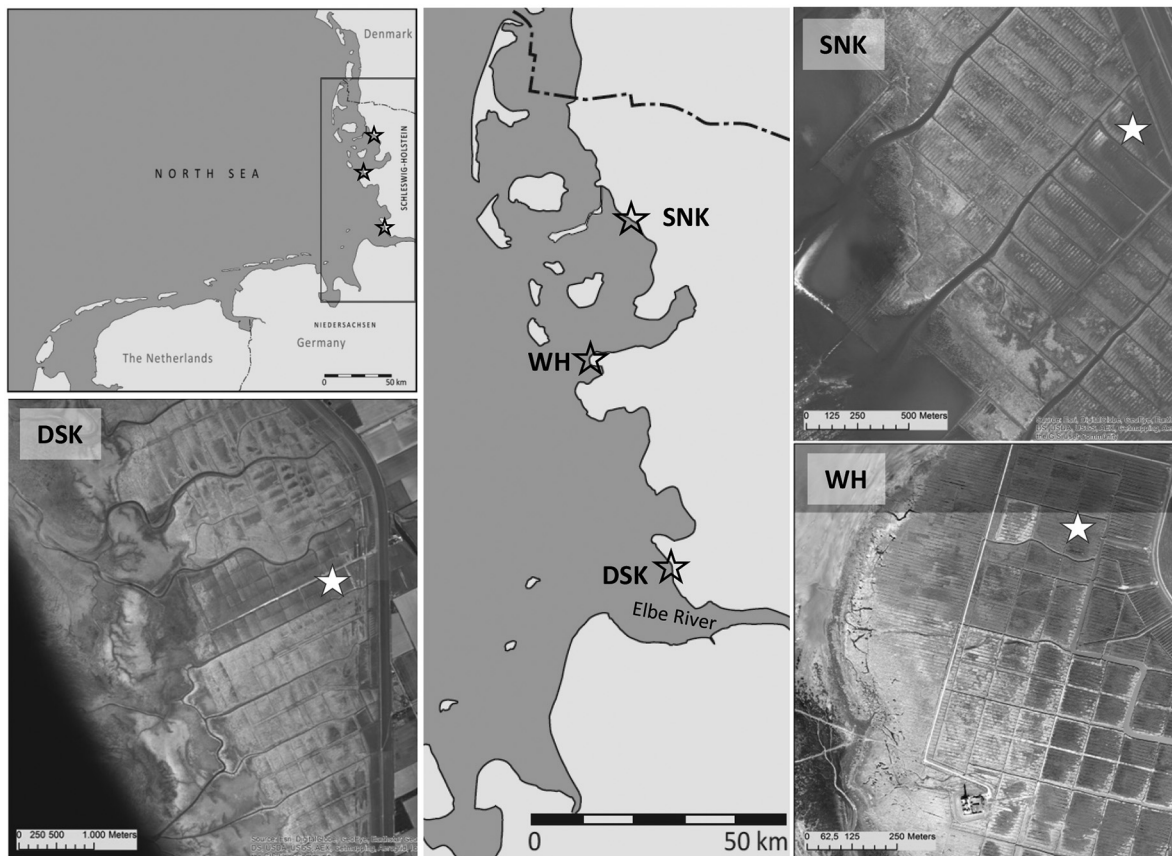


Fig. 1. Sampling positions (star symbols) in the three semi-natural mainland marsh sites Dieksanderkoog (DSK), Westerhever (WH), and Sönke-Nissen-Koog (SNK). Aerial photographs source: Esri, DigitalGlobe, GeoEye, EarthStar Geographics, CNES/Airbus CS USDA, USGS, AEX, GetMapping, AeroGRID, IGN, IGP, swisstopo, and the GIS User Community.

WS marshes relies on accretion-enhancement techniques (Hofstede 2003). Accretion enhancement is achieved indirectly through drainage leading to increased soil aeration, which promotes vegetation development. The deposition of sediment from the ditches onto the marsh does generally not directly affect vertical accretion rates (Esselink et al. 2009 and references therein). Additionally, construction of brushwood groynes reduces wave energy and creates an artificial low-energy environment that increases sedimentation in the tidal flats and stabilizes existing marshes (Hofstede 2003). Like >90% of the WS marshes before establishment of the WS national parks in the late 1980s/early 1990s, the three marsh sites of this study have traditionally been used for livestock grazing. All three sites still include grazed areas, which allowed to sample soil profiles that have developed under the same land use or management (i.e., livestock grazing) over time. Furthermore, sites include areas that were dominated by the same vegetation type in 1988 (Stock et al. 2005) and 2016 when sampling was conducted. This allowed for sampling in areas that were in a relatively stable ecosystem state (i.e., negligible succession) during the past three decades.

The Dieksanderkoog marsh (DSK) is situated at the outer mouth of the Elbe estuary. The adjacent seawall was built in 1935 for land reclamation, and construction of brushwood groynes and ditching in the tidal flat led to high sedimentation rates and a rapid growth of the salt marsh that today extends approx. 2 km from the seawall to the tidal flats. The marsh elevation ranges from 1.2 to 2.8 m NHN (Normalhöhennull; German standard ordnance datum [i.e., sea level]). Tidal range in the area is 3.0 m with a mean high tide at 1.6 m (BSH 2011, Müller et al. 2013).

The Westerhever marsh (WH) is situated on the peninsula of Eiderstedt. It is part of a larger marsh complex in the Tümlau Bay. In 1897, a small patch of naturally developed salt marsh of approx. 3 ha, separated from the mainland by a tidal creek, was accessed through dam construction. Damming and ditching activities led to a rapid increase in salt-marsh area to at least 161 ha until 1909. Today, the marsh extends approx. 1 km from the seawall to the tidal flats and covers an area of ~250 ha. The marsh elevation ranges from 1.5 to 2.4 m NHN at a tidal

range of ~3 m with mean high tide at 1.5 m NHN (Peiter 2002, BSH 2011).

The Sönke-Nissen-Koog marsh (SNK) is situated in the north of the WS region. The adjacent seawall was built in 1924, and the salt marsh began to develop. Today, the marsh extends ~1 km from the seawall to the tidal flats and has an elevation between 0.9 and 2.6 m NHN at a tidal range of 3.4 m with mean high tide at 1.6 m NHN (BSH 2011, Müller et al. 2013).

In all three marsh sites, annual measurements of surface elevation are conducted using sedimentation erosion bars (SEBs; Nolte et al. 2013a) since 2006 at DSK and SNK and since 2008 at WH (Stock 2012), allowing calculation of recent accretion rates. For historic accretion rates at DSK and SNK, we used the data provided in Nolte et al. (2013b), who conducted ^{137}Cs dating in deep soil cores that were taken directly next to the SEB positions in 2006. The available historic accretion data for WH are based on ^{137}Cs dating of a soil core taken in an adjacent marsh patch of the Tümlau Bay in 2013 (Müller-Navarra 2018). In all soil cores, ^{137}Cs peaks of two historic events could be identified: an upper peak caused by the Chernobyl disaster of 1986 and a deeper peak caused by nuclear bomb tests during the 1960s that had their maximum in 1963 (Kirchner and Ehlers 1998).

Sampling and OC analyses

Duplicate soil cores of 130 cm depth were taken in areas of each site that showed the same vegetation type in 1988 and 2016 in order to sample soils that developed under relatively little vegetation succession during the last three decades. The aim of the deep-coring procedure was to sample the entire salt-marsh soil as well as sections of the underlying tidal-flat sediment that the marsh soil developed on. Cores were taken in April 2016 within 2 m of SEB positions. We used an Eijkelkamp peat sampler with a 50 cm long, 500-cm³ shuttle head for our mineral-dominated marsh soils. As the peat sampler cuts sidewise into the soil profile, the technique allowed for uncompacted and undisturbed sampling (Jowsey 1966). Soil cores were sliced into eight increments of 5 cm (top 40 cm), 5 × 10 cm (40–90 cm), and 2 × 20 cm (90–130 cm). For potential reference analyses, we additionally sampled 40-cm cores in two randomly chosen

positions of the tidal flats directly in front of each marsh site (in the following referred to as reference tidal-flat cores).

Bulk density and OC content were determined to calculate OC density (product of bulk density and OC content). Samples were dried at 105°C for 72 h and weighed to determine bulk density. Organic carbon contents were determined using a total carbon analyzer (liquiTOC II, Elementar, Hanau, Germany).

We determined $\delta^{13}\text{C}$ to assess the origin of OC (autochthonous vs. allochthonous sources). $\delta^{13}\text{C}$ of OC was analyzed using an isotope-ratio mass spectrometer (Nu Horizon, Nu Instruments, Wrexham, UK). Inorganic C was removed prior analysis via sample acidification (Mueller et al. 2017). Results are given in δ -notation vs. Vienna Pee Dee Belemnite (VPDB), and measurements were calibrated using the international standard caffeine. $\delta^{13}\text{C}$ was assessed in one core per site.

Down-core identification of ecosystem stages

We utilized the down-core distribution of foraminifera to distinguish salt-marsh soils from underlying tidal-flat sediments because their abundance and species composition exhibit a distinct vertical zonation in salt marshes relative to the tidal frame (Scott and Medioli 1978, Edwards et al. 2004). Between 3.0 and 3.5 g dry sediment/soil was washed over a 63- μm sieve, and the residue $>63\ \mu\text{m}$ was dried and inspected for benthic foraminifera under a stereo microscope. Drying of samples may result in the destruction of fragile agglutinated tests (Scott and Medioli 1980); however, the frequent occurrence of fragile tests of *Jadammina macrescens* in the studied samples indicated a reasonable representation of agglutinating taxa. If present, between 50 and 100 individuals were counted, which provides a confident estimate of environmental changes based on the overall low diversity of tidal-flat and salt-marsh foraminiferal assemblages (Fatela and Taborda 2002). Species designation to ecosystem stages was based on Müller-Navarra et al. (2016) and Gehrels and Newman (2004).

Grain-size distribution was used as an additional indicator for the transition from tidal flat to salt marsh, because this transition is typically associated with an increase in the relative amount of finer grains (i.e., clay or silt vs. sand) in the WS region (Elschot et al. 2015, Müller-Navarra

et al. 2016). Grain-size fractions $<63\ \mu\text{m}$ (silt fractions and clay) were determined on an automated sedimentation analyzer system (Sedimat 4-12, UGT, Müncheberg, Germany). Sand fractions were determined on a sieve shaker (Retsch, Haan, Germany).

Data analysis

Down-core interpretation of OC density.—Stable minimum OC-density values in the salt-marsh soil sections of the sampled cores were assessed visually to determine the OC density of what we consider here the effectively preserved OC stock: OC density was considered stable when data from at least three successive depth steps showed no or a positive slope and subsequent depth steps showed no deviation from this trend (illustrated in Fig. 3).

To assess whether down-core changes in OC density are driven by changes in accretion during ecosystem development, we compared mean OC density and mean annual accretion of three defined quantification periods: (1) recent (\sim past 5 yr), (2) 30 yr (1986–2016), and (3) 53 yr (1963–2016). Recent accretion is based on the 5-yr mean of yearly SEB assessments, whereas mean accretion for the 30- and 53-yr periods is based on ^{137}Cs -peak depths below the soil surface divided by the number of years since 1986 and 1963, respectively. We consider the OC density of the uppermost soil section (0–5 cm) as the recent OC density. Thirty- and 53-yr OC densities are based on the mean OC density of soil sections above the reported ^{137}Cs -peaks for the years 1986 and 1963, respectively, calculated dividing the total amount of OC [g] by the volume of the core [cm^3] above the respective peak.

$\delta^{13}\text{C}$ mixing-model calculations.—To estimate whether allochthonous OC represents an important fraction of the effectively preserved OC stock, we exemplarily estimated its contribution for two of our sites (DSK and SNK), for which we have a comprehensive dataset on the $\delta^{13}\text{C}$ of sedimentary OC and plant materials (Mueller et al. 2017). The allochthonous OC contribution to the effectively preserved OC stock was calculated using two-end-member mixing models (sensu Middelburg et al. 1997). We used the $\delta^{13}\text{C}$ of the tidal-flat OC below the salt-marsh soil as

the allochthonous $\delta^{13}\text{C}$ end-member. We used $\delta^{13}\text{C}$ of belowground plant litter as the autochthonous end-member because aboveground-litter accumulation is negligible in the studied grazed systems (Mueller et al. 2017). As the $\delta^{13}\text{C}$ of old tidal-flat OC in our cores is close to the $\delta^{13}\text{C}$ of recent sedimentary allochthonous OC (Mueller et al. 2017), we assume no substantial post-depositional ^{13}C fractionation in allochthonous OC. Because we cannot exclude this for autochthonous OC, we base our calculations on different end-member assumptions (sensu Mueller et al. 2016): (1) no post-depositional ^{13}C fractionation in autochthonous OC and (2) ^{13}C enrichment of $+2\text{‰}$, based on reports from terrestrial systems and representing high fractionation from litter to soil organic matter (Boström et al. 2007, Menichetti et al. 2014). Assumption 2 thus provides the more conservative estimate for the contribution of allochthonous OC to the effectively preserved OC stock.

Statistics.—We used one-tailed paired *t*-tests (paired by site) to compare OC densities and OC- $\delta^{13}\text{C}$ values between different sections of the 130-cm cores and also to compare OC densities of the tidal-flat underlying the salt marsh and the reference tidal flat in front of the marsh. Friedman's test was used to test for effects of quantification period (i.e., recent vs. 30 yr vs. 53 yr) on mean OC density and mean accretion rate. Analyses were conducted using Statistica 13 (Dell Software, Round Rock, Texas, USA).

RESULTS

Identification of ecosystem stages

High percentages of the hyaline species *Ammونيا batava*, *Elphidium williamsoni*, *Haynesina germanica*, and *Elphidium excavatum* indicate the depth zone of the former tidal flat in all three profiles (Fig. 2). In turn, high percentages of the agglutinating species *Balticammina pseudomacrescens*, *Jadammina macrescens*, and *Trochammina inflata* are indicators for the vegetated, salt-marsh system (Fig. 2). Between these clearly identifiable zones, a zone of 10–30 cm with intermediate abundances of both groups indicates the transition from tidal flat to the salt marsh.

High sand and low clay contributions were also useful indicators of the former tidal flat and the

early developing marsh ecosystem. Specifically, relative clay contents clearly reflect the patterns observed in the foraminiferal record (Fig. 2). Based on agglutinating-taxa abundance and clay contents, we consider all depths below 50 cm at DSK, below 110 cm at WH, and below 90 cm at SNK as former tidal-flat sediments. We consider the soils above 35 cm at DSK, 80 cm at WH, and 60 cm at SNK as the zone of the salt-marsh ecosystem (Fig. 2).

OC-density distribution and origin

Organic carbon density decreased considerably with depth in all three sites (Fig. 3). Yet, in the profiles of WH and SNK, sections of stable OC density in the salt-marsh soil are clearly discernible: In the WH profile, OC density stabilized between 40 and 80 cm depth (mean \pm SD: $0.018 \pm 0.002 \text{ g/cm}^3$). In the SNK profile, OC density stabilized between 25 and 60 cm depth ($0.022 \pm 0.001 \text{ g/cm}^3$). The salt-marsh soil of the DSK profile is shallow compared to WH and SNK. Still, within this shallow section of the profile, OC density stabilized at 20 cm down to 35 cm (mean \pm SD: $0.015 \pm 0.001 \text{ g/cm}^3$). Mean stable OC density of the three sites assessed was $0.018 \pm 0.003 \text{ g/cm}^3$ (Figs. 3, 4).

On average, OC density decreased by 55% from the topsoil ($0.040 \pm 0.006 \text{ g/cm}^3$; 0–5 cm) to a minimum stable value in the salt-marsh soil (Figs. 3, 4). Yet, stable OC density of the salt-marsh soil was 36–73% higher than the OC density of the former tidal flat ($0.012 \pm 0.004 \text{ g/cm}^3$; $P = 0.005$; Fig. 4). Organic carbon density of the reference tidal-flat cores ($0.003 \pm 0.002 \text{ g/cm}^3$) sampled in front of each marsh site was 75% lower than in the tidal-flat zone underlying the marsh core ($P = 0.04$).

$\delta^{13}\text{C}$ of the accumulated OC decreased strongly with soil depth (Fig. 5). $\delta^{13}\text{C}$ of the stable OC-density sections was strongly enriched compared to $\delta^{13}\text{C}$ values of the topsoil ($\Delta\delta^{13}\text{C} = 2.1\text{‰}$; $P < 0.001$; Fig. 4). By contrast, $\delta^{13}\text{C}$ of the OC accumulated in the former tidal flat was only slightly enriched compared to $\delta^{13}\text{C}$ values of the stable OC-density sections of the salt-marsh soil ($\Delta\delta^{13}\text{C} = 0.4\text{‰}$; $P = 0.07$; Fig. 4). Mixing-model calculations for the DSK and SNK site yield allochthonous OC contributions to the stable OC-density sections of the marsh soils of 79% and 86%, respectively, assuming no ^{13}C

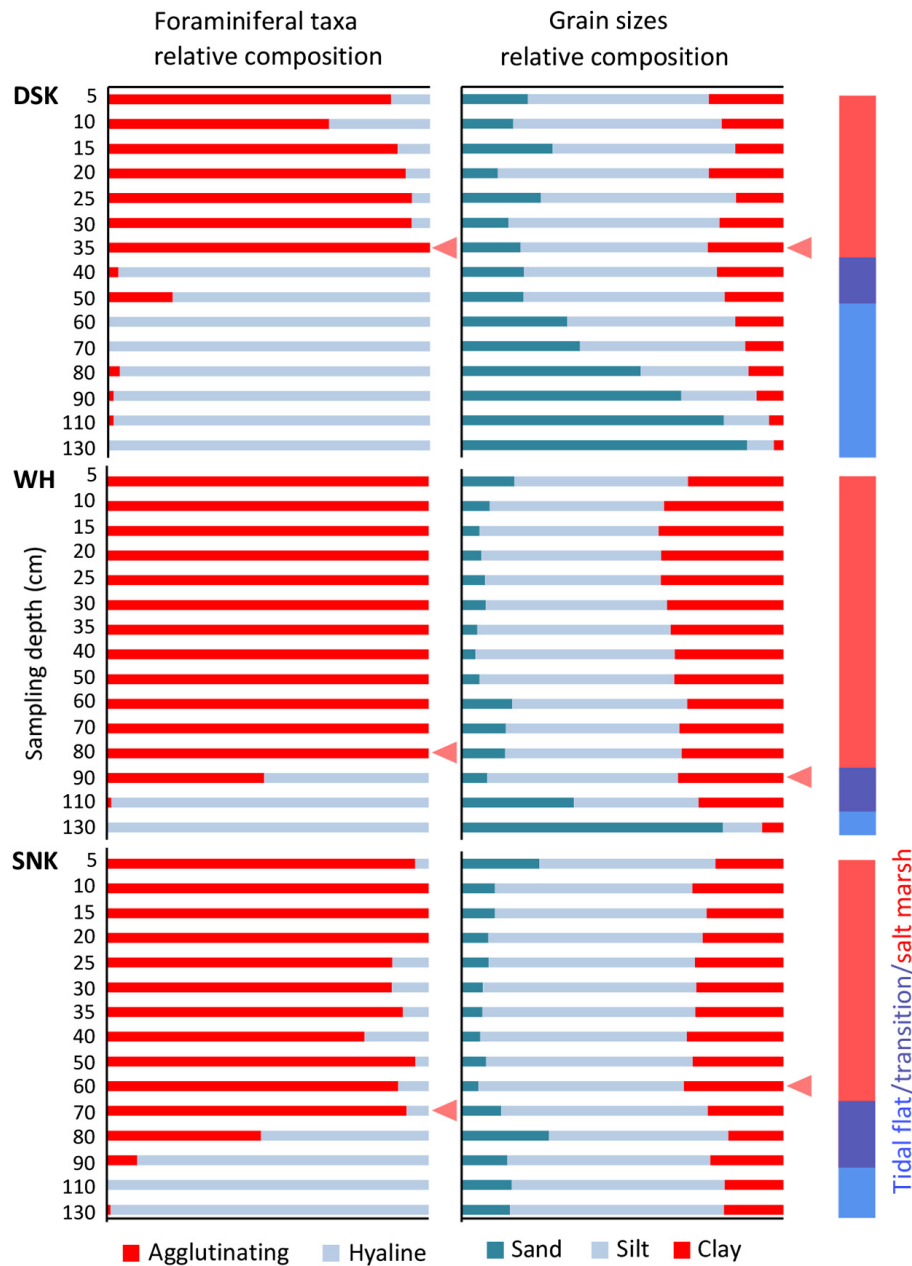


Fig. 2. Relative abundance of agglutinating and hyaline foraminiferal taxa (left panels) and relative contributions of sand, silt, and clay (right panels) with soil/sediment depth in three semi-natural Wadden Sea salt-marsh sites: Dieksanderkoog (DSK), Westerhever (WH), and Sönke-Nissen-Koog (SNK). *Data interpretation:* Triangles on the right indicate the estimated maximum depth of the salt-marsh soils based on the indicators relative abundance of agglutinating taxa and relative clay content. We first assessed the depth of the salt-marsh soil based on the dominance of agglutinating taxa. We then assessed whether the classification based on the foraminiferal distributions is also supported by grain-size distributions. In all cores, distinct gradual increases and subsequent peaking in clay contents occur within 10 cm of the deepest soil section classified as salt marsh based on agglutinating species dominance. Color bars on the right indicate the resulting estimated depth zones of the former tidal flats, transition zones (i.e., pioneer zones, initial marsh development), and salt marsh.

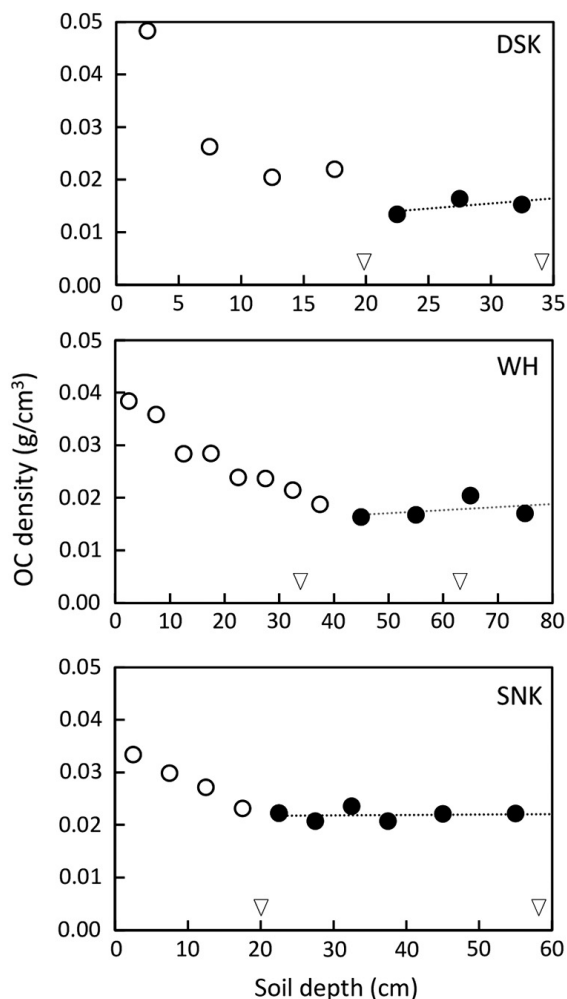


Fig. 3. Organic carbon density (g/cm^3) with soil depth in three semi-natural Wadden Sea salt-marsh sites: Dieksanderkoog (DSK), Westerhever (WH), and Sönke-Nissen-Koog (SNK). Triangles on the x -axis indicate ^{137}Cs -peak depths of the years 1986 and 1963 taken from Nolte et al. (2013b) and Müller-Navarra (2018). Only data of the identified salt-marsh zones of the 130-cm profiles are included (i.e., excluding data of the tidal-flat and transition zones; compare Fig. 2). Filled circles indicate stable sections of OC-density down-core: OC density was considered stable when data from at least three successive depth steps showed no or a positive slope and subsequent depth steps showed no deviation from this trend. Linear trend-lines are included.

enrichment during diagenesis from litter to effective preservation at depth, and 71% and 72%, respectively, assuming a ^{13}C enrichment of $+2\text{‰}$ in autochthonous OC.

OC density vs. accretion during ecosystem development

Organic carbon density decreased significantly with the quantification period and showed consistent decline patterns across sites (Fig. 6). Organic carbon density integrated over 30 yr ($0.029 \pm <0.001 \text{ g}/\text{cm}^3$) was reduced by 28% compared to topsoil OC density and showed considerably less variability (Fig. 6). Integrating over a period of 53 yr, mean OC density decreased again to $0.024 \pm <0.001 \text{ g}/\text{cm}^3$ and showed similarly low variability (Fig. 6). In contrast to the changes in OC density over time, accretion rate for the three time periods considered showed large variation across sites and no significant change depending on quantification period (Fig. 6). Thus, the constant decrease in OC density and the consistent patterns across sites were independent of accretion rate: Specifically, while the DSK experienced a slight, but constant increase in accretion rate from 0.64 cm/yr over a 53-yr period, 0.65 cm/yr over 30 yr, to recently 0.85 cm/yr, the opposite is true for the WH site. Here, accretion over 53 yr is 1.2 cm/yr; however, the rate strongly slowed down during the last two decades to only 0.4 cm/yr as the recent rate. The SNK also showed highest mean accretion of 1.1 cm/yr over 53 yr, whereas accretion over 30 yr and recent accretion are comparable to rates at DSK (Fig. 6).

DISCUSSION

Decline patterns of OC density with soil depth

The present study shows steep declines in OC content and density with soil depth in three salt-marsh sites of the European Wadden Sea (Figs. 3, 5) and thereby adds to a growing number of reports from blue C ecosystems illustrating markedly lower OC density at depth than in the topsoil (e.g., Choi and Wang 2004, Livesley and Andrusiak 2012, Kelleway et al. 2016, Schile et al. 2017). The implications of such findings on C-sequestration assessments, however, depend on the underlying mechanisms causing the observed phenomenon in the respective ecosystem and have rarely been assessed.

We argue that a substantial amount of the OC accumulating in the topsoil is lost down-core through sustained decomposition with soil depth. Other mechanisms potentially affecting

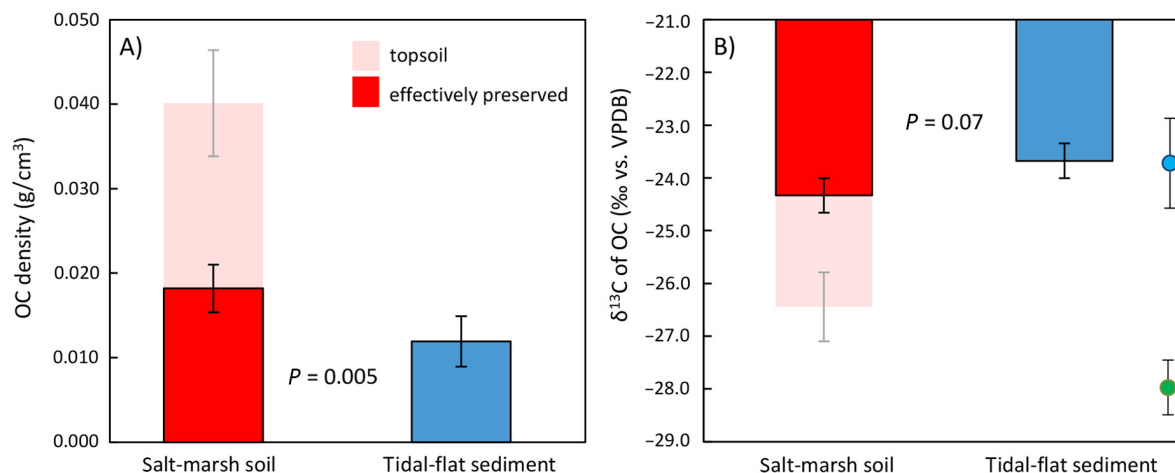


Fig. 4. (A) Organic carbon density (g/cm^3) and (B) $\delta^{13}\text{C}$ of salt-marsh soils and underlying tidal-flat sediments. Data for salt-marsh soils are divided in topsoil (5 cm) and the section of the effectively preserved OC stock. Shown are mean values \pm SD; P -values refer to paired t -tests. Green/blue circles in panel B indicate mean $\delta^{13}\text{C}$ values of belowground plant litter and sedimentary OC, respectively, determined in the sites DSK and SNK. Error bars indicate the two site means (sediment $\delta^{13}\text{C}$ data taken from Mueller et al. 2017).

OC density include shifts in plant species composition (and thus differences in net primary production) and changes in sedimentation rate during ecosystem development. Shifts in species composition during succession can lead to substantial differences in soil OC input via primary production (Elschot et al. 2015), which could be reflected in the down-core OC-density distribution. Likewise, sedimentation rates can be higher during early ecosystem development and successively slow down (Van Wijnen and Bakker 2001, Butzeck et al. 2014). Thus, declines in OC density with depth could also reflect decreasing dilution of autochthonous OC with mineral sediments during ecosystem development (Ruiz-Fernández et al. 2018). However, these two mechanisms are unlikely the primary drivers of the OC-density pattern observed here: More than 50% of the decline in OC content and density occurs within the top 20 cm of the soil profiles, which developed under the same vegetation type in the respective sites, indicating that succession and concomitant changes in net primary production were irrelevant. Furthermore, our data give no indication that accretion or sedimentation rates were consistently higher during early ecosystem development than during later stages. While accretion at WH indeed slowed down in the course of ecosystem development,

the opposite was true for the DSK site (Fig. 6). The consistent decline in OC content and density with soil depth in all three sites is therefore independent of changes in sedimentation rate during ecosystem development.

The WS salt marshes are situated relatively high in the tidal frame, leading to oxidizing soil conditions (Erchinger et al. 1996, Mueller et al. 2017). Continuous records of soil redox in the low-marsh zone of DSK show frequent oxic conditions at least down to 15 cm, and occasional oxic events down to 30 cm occur during periods of low precipitation and low water levels (Appendix S1: Fig. S1). This demonstrates that aerobic microbial metabolism is enabled deep in the soil profile, even in this low elevated and relatively frequently flooded zone of the site. We therefore argue that the key driver of organic matter preservation in wetland ecosystems—anoxia induced by water-logging—is less relevant in the soils of the WS salt marshes. Instead, factors controlling organic matter preservation or stabilization in terrestrial soils, including microbial C-use efficiency, formation of organo-mineral complexes, and physical protection (i.e., Prescott 2010, Schmidt et al. 2011, Cotrufo et al. 2013), may possibly be more relevant here. However, the importance of factors other than oxygen availability (in combination with

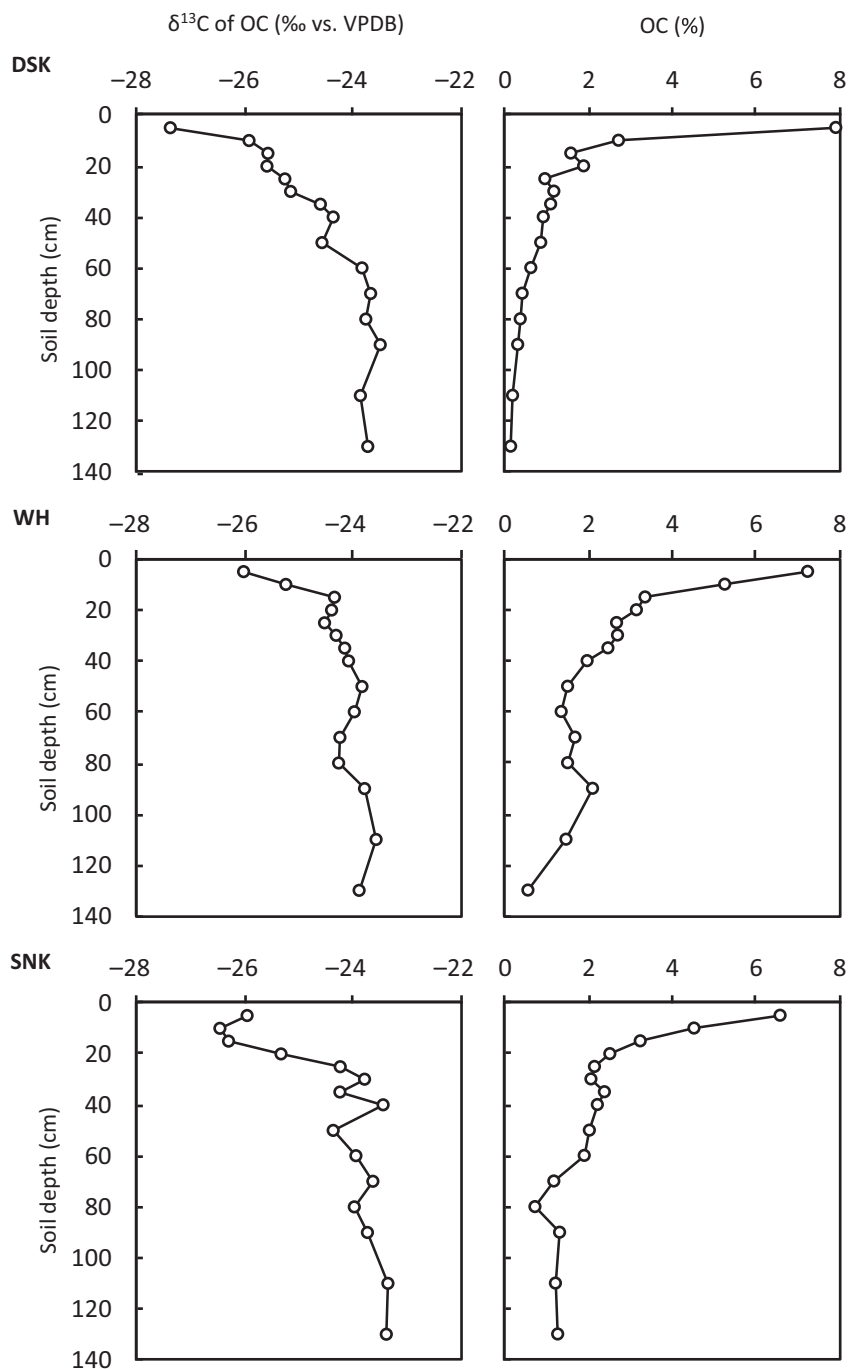


Fig. 5. $\delta^{13}\text{C}$ signatures of OC and OC contents with soil/sediment depth in three semi-natural Wadden Sea salt-marsh sites Dieksanderkoog (DSK), Westerhever (WH), and Sönke-Nissen-Koog (SNK).

substrate recalcitrance) for organic matter preservation in tidal wetlands is poorly considered in the literature (Kirwan and Megonigal 2013).

Effectively preserved OC and long-term C-sequestration potential

Topsoil OC densities are 120% higher than minimum stable OC densities within the marsh

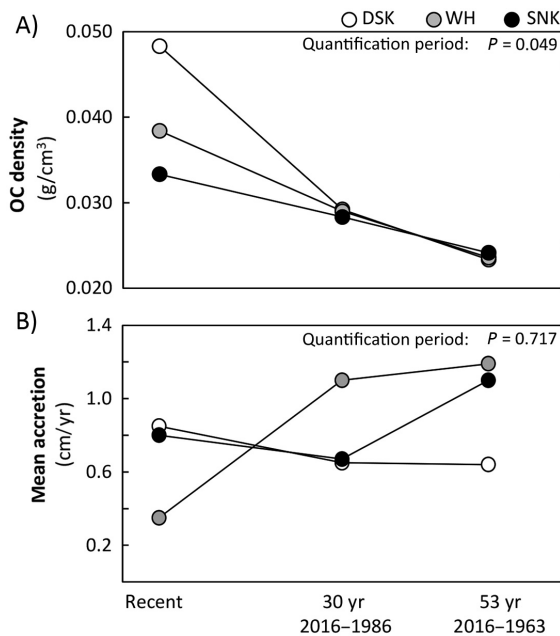


Fig. 6. (A) Mean OC density and (B) accretion determined for three quantification periods: recent (based on OC density of the topsoil (5 cm) and recent (SEB based) accretion rates), 30 yr (soil depth based on ¹³⁷Cs dating back to 1986), and 53 yr (soil depth based on ¹³⁷Cs dating back to 1963). Data points are colored by site. P-values are based on Friedman’s test and indicate the effect of quantification period on (A) OC density and (B) accretion. Recent accretion data for WH site taken from Stock (2012); historic accretion calculated from ¹³⁷Cs data given in Müller-Navarra (2018) and Nolte et al. (2013b).

soil OC stock that is here considered as effectively preserved (Fig. 4). Assessments and models of long-term C sequestration for the WS region therefore should not be based on shallow topsoil investigations. However, despite considerable declines in OC density down-core within the salt-marsh soil, OC density of the effectively preserved OC stock is approx. 60% higher than the OC density of the underlying tidal flat (Fig. 4). Given that accretion of the marsh system is at least equal to that of the un-vegetated tidal flats, the here reported OC-density values illustrate the greater capacity of the vegetated ecosystem to sequester OC. It needs to be noted here that OC densities of tidal flats that develop naturally outside of brushwood-fenced sedimentation fields are likely even lower than of those directly

underlying the marsh soils sampled here due to the higher contribution of fine-grained particles settling in sedimentation fields (Erchinger et al. 1996, Hofstede 2003) and the tight association of organic matter with fine-grained mineral particles in tidal-flat sediments of the region (Volkman et al. 2000). In support of this notion, surface (0–40 cm) OC densities of the reference tidal-flat sediments sampled in front of the three investigated marsh sites (outside of closed sedimentation fields) are 75% lower than in the tidal-flat sediments sampled below the marsh soils. This suggests that the here reported increase in OC density (and with that the higher C-sequestration potential) generated by the conversion of tidal flat to salt marsh likely represents a conservative approximation.

Interestingly, our data show increasingly constrained OC densities in the course of ecosystem development (Fig. 6). That is, despite large differences in topsoil OC density (range: 0.016 g/cm³; Fig. 4), recent and historic accretion rate (range: 8.4 mm; Fig. 6), and grain-size distribution (Fig. 2) between our three sites, OC density integrated over few decades show a surprisingly small range (0.001 g/cm³ for quantification periods between 30 and ~50 yr; Fig. 6). Likewise, OC density of the effectively preserved OC stock shows relatively low variability (range: 0.007; Fig. 4). We therefore argue that variability in C-sequestration rate (the product of accretion rate and OC density) over decennial and potentially longer timescales is primarily determined by the variability in accretion rate and to a far lesser degree by variability in OC density. This yields valuable information for estimating and upscaling C-sequestration rates for the WS region.

Estimates of C sequestration based on our small number of OC-density observations and the reported mean accretion value of 6.2 mm/yr for the northern part of the WS region (Schleswig-Holstein sector) that our three sites are located in (Suchrow et al. 2012) result in values for mid-term (over 50 yr) and potential long-term (based on the OC-density of the effectively preserved OC stock) C sequestration of 149 and 112 g·m⁻²·yr⁻¹, respectively. Future research will need to refine these initial estimates by conducting a larger-scale deep-core OC-density assessment throughout the WS region in order to complement the available comprehensive

accretion record (Esselink et al. 2009). The preliminary values reported here are approx. 50% lower than the current global mean value for long-term C sequestration of $218 \text{ g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ reported for salt marshes (Mcleod et al. 2011). However, it needs to be noted that part of the data used for the calculation of global means in meta-analyses (i.e., Chmura et al. 2003, Mcleod et al. 2011, Duarte et al. 2013) are based on shallow topsoil assessments of OC density and might therefore provide overestimated C-sequestration rates, following the conclusions of the present study and others (e.g., Choi and Wang 2004, Van de Broek et al. 2018).

Organic-C sources

The distinction between allochthonous and autochthonous OC to the total OC pool is relevant for C-crediting approaches because the alternative fate of the allochthonous OC (i.e., if it had not accumulated in the wetland soil) is unclear. Quantifying the contributions of different OC sources to the total soil OC pool is commonly conducted by means of ^{13}C natural abundance and simple mixing-model calculations (Middelburg et al. 1997, Bouillon et al. 2003). In terrestrial ecosystems, aging and repeated cycling of the organic material can complicate an accurate separation of OC sources because it induces ^{13}C enrichment with soil depth (typical range: 1–3‰ over entire soil profiles) (Boström et al. 2007, Menichetti et al. 2014, Kohl et al. 2015). It is, however, unclear if such fractionation processes also occur in tidal-wetland soils to a degree that mixing-model calculations would be considerably biased (Kelleway et al. 2018 and references therein). In the present study, we demonstrate steep increases in $\delta^{13}\text{C}$ with soil depth in all three sites (Fig. 5). Compared to ^{13}C fractionation curves described for terrestrial soil profiles (e.g., Menichetti et al. 2014), the slopes of ^{13}C increase found for our sites occur to be too steep and abrupt to be solely driven by gradual ^{13}C enrichment via repeated microbial cycling of the total OC pool. Instead, our data suggest preferential decomposition of autochthonous vs. allochthonous OC with depth to be primarily responsible for ^{13}C enrichment. In support of this notion, Van de Broek et al. (2018) demonstrated that allochthonous OC of marine origin is the main component of OC that

is long-term preserved in the soils of salt marshes on the Scheldt estuary, The Netherlands. This may occur surprising, considering the higher decomposability of marine-derived allochthonous vs. autochthonous organic matter both in terms of relative N contents and structural components (i.e., lignin). However, the authors argue that the allochthonous material contributing to C sequestration is not fresh, but has been deposited and stabilized elsewhere before transported to the marsh. Particularly, sediment deposits during winter contained old OC due to the general absence of estuarine phytoplankton production (Van de Broek et al. 2018 and references therein). Also in the marsh sites of the present study, sediment deposition on the high marsh almost exclusively occurs during winter (Müller et al. 2013) and may therefore carry predominantly aged and pre-stabilized organic material.

$\delta^{13}\text{C}$ of the effectively preserved OC stocks of our three investigated sites are clearly closer to the $\delta^{13}\text{C}$ of the former tidal-flat sediments underneath the marsh soils (Fig. 4). Although our data do not suffice to provide accurate values of the contribution of allochthonous OC to the effectively preserved OC stock, we can assess whether it represents the primary source for this stock based on mixing-model calculations with conservative end-member assumptions (i.e., assuming fractionation; Mueller et al. 2016). Even under the assumption of high fractionation from autochthonous litter to stable soil organic matter (+2‰; Boström et al. 2007, Menichetti et al. 2014), the contribution of allochthonous OC to the effectively preserved OC stock is ~70% in the two sites we conducted the calculations for. Our data therefore suggest that allochthonous OC represents a large fraction of the long-term, effectively preserved OC in the mainland marshes of the studied systems, whereas atmospheric CO_2 removal by marsh vegetation contributes comparably little.

Conclusions and perspective

Large amounts of short-term accumulated OC are lost with soil depth in the well-aerated marsh soils of the WS region. We therefore emphasize the importance of deep sampling in combination with long-term accretion records and knowledge on ecosystem development to avoid overestimation of C sequestration and OC stocks in blue C

ecosystems with decomposition maintained deep in the soil profile. It is important to note that stable minimum OC-density values of the marsh soils are considerably higher than those of the tidal flats the marshes were converted from, illustrating the greater potential for C sequestration of the man-made vegetated ecosystems. At the same time, however, our study supports a recent report highlighting the importance of allochthonous OC contributions for long-term C sequestration in salt marshes of NW Europe (Van de Broek et al. 2018). As the alternative fate of the allochthonous OC (i.e., if it had not accumulated in the wetland soil is unclear), future research will need to clarify the implications of such findings for C-crediting approaches in blue C ecosystems.

Despite large differences in accretion during ecosystem development, we demonstrate remarkably similar mean OC densities across sites after few decades of ecosystem development. We therefore argue that variability in mid-term and potential long-term C sequestration of the WS marshes is primarily driven by variability in accretion rate and to a lesser degree by variability in OC density, yielding valuable information for estimating and upscaling C-sequestration rates in the region. Future research will need to refine our first estimates of C sequestration provided for the WS mainland marshes by conducting a larger-scale deep-core OC-density assessment throughout the region in order to complement the available comprehensive accretion record (Esselink et al. 2009).

ACKNOWLEDGMENTS

Katharina Müller-Navarra is thanked for discussion and providing information on accretion rates in the Westerhever salt marsh. Likewise, Sigrid Suchrow, Peter Esselink, and Pat Megonigal are thanked for discussion. Many thanks go to Birgit Grabellus for providing support in the laboratory of the Institute of Soil Science. Finally, we thank Martin Stock and all project partners of the Wadden Sea National Park Schleswig-Holstein for their cooperation. N. Ladiges and L. Kutzbach were supported through the Cluster of Excellence "CliSAP" (EXC177), Universität Hamburg, funded by the German Research Foundation (DFG). P. Mueller and S. Nolte were supported by the Bauer-Hollmann Stiftung in the framework of the research project INTERFACE (Interaction of fish, plants, carbon &

sediment: management and ecosystem functions of Wadden Sea salt marshes).

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