Salt marshes in the silica budget of the North Sea

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A B S T R A C T

Local scale studies reported the silica recycling of salt marshes to substantially attenuate the dissolved silica (DSi) limitation in coastal waters during summer. To assess the importance of salt marshes in the silica budget of the North Sea, we extrapolate reported DSi exports by local scale studies to salt marsh areas adjacent to the North Sea. The resulting annual average contribution of salt marshes to the DSi budget of the North Sea is estimated to 0.8% of the annual river DSi export. During summer, this contribution may reach 2.4%. Thus, salt marshes likely impact the annual dissolved silica budget of the North Sea only weakly. However, for regions with favorable geographic conditions of low river DSi exports and large marsh areas, salt marsh DSi exports may substantially contribute to coastal DSi budgets. In the English Channel, salt marsh DSi exports are estimated to 16% of river DSi export in summer. However, the low data density calls for additional field research to improve extrapolations and the evaluation of the contribution of salt marsh DSi export to the coastal DSi budgets.

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1. Introduction

Dissolved silica (DSi) is an important nutrient for coastal marine ecosystems (Schelske and Stoermer, 1971; Officer and Ryther, 1980). It ultimately originates from chemical weathering of silicate rocks and is delivered to the coasts by rivers (Treguer et al., 1995; Laruelle et al., 2009; Dürr et al., 2011). Silica can be retained and remobilized in rivers and lakes (Lauerwald et al., 2013) before reaching estuaries, which filter the DSi and also shift the seasonal distribution of DSi inputs into the oceans (e.g. Arndt et al., 2009). Particularly during the main growing season, when river DSi export declines because of increased primary production (e.g. in the Rhine: Hartmann et al., 2007, 2011), the limitation of DSi in the coastal zone may lead to harmful blooms of non-diatom algae (Smayda, 1990; Hallegraeff, 1993). Salt marshes (which are after Adam (1990) defined as areas vegetated by herbs, grasses or shrubs, bordering saline water bodies) have been hypothesized to buffer the seasonal DSi limitation in coastal marine environments by recycling biogenic Si and net-exports of DSi (Hackney et al., 2000). Local studies support that hypothesis (Dankers et al., 1984; Struyf et al., 2005, 2006; Vieillard et al., 2011; Müller et al., 2013; Weiss et al., 2013). A biogenic silica (BSi) pool is built up during the growth of marsh vegetation and diatoms, and by the trapping of suspended particles containing BSi, which rapidly redissolves. The resulting recycled DSi accumulates in the pore water, and leaves the marsh via diffusive exchange during high water and most importantly by advective drainage through the tidal creeks during low water (Struyf et al., 2005). For example, the tidal marsh areas of the Scheldt estuary, Belgium, are reportedly able to deliver the total monthly summer DSi river export in only a few days (Struyf et al., 2005).

Continental to global scale studies on terrestrial DSi mobilization (Hartmann et al., 2010; Jansen et al., 2010; Moosdorf et al., 2011) or input into coastal waters (Beusen et al., 2009; Dürr et al., 2011; Tréguer and De La Rocha, 2013), as well as silica budgets of regional seas (Proctor et al., 2003) neglect the effect of DSi exports from tidal marshes. Until now, no study quantifies the salt marsh DSi exports to coastal waters at the regional scale. This study provides a first estimate for the North Sea and highlights areas where salt marshes could particularly impact the regional DSi budget.

2. Materials and methods

Four salt marshes around the North Sea (including the English Channel) with quantified area specific DSi exports are known to the
These were used for upscaling to the salt marsh area around the North Sea coast (Table 1). The named studies calculated DSi export from discharge and DSi concentration measurements in tidal creeks over up to 26 tidal cycles. From the salt marsh DSi export values by Dankers et al. (1984), four tidal cycles were omitted because of very

Table 1

<table>
<thead>
<tr>
<th>References</th>
<th>Location</th>
<th>Average flux (Mmol km⁻² a⁻¹)</th>
<th>Number of tidal cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dankers et al. (1984)</td>
<td>Ems-Dollard Estuary, The Netherlands</td>
<td>0.11</td>
<td>26</td>
</tr>
<tr>
<td>Struyf et al. (2006)</td>
<td>Carmel Polder, France</td>
<td>0.33</td>
<td>6</td>
</tr>
<tr>
<td>Müller et al. (2013)</td>
<td>Söhnke-Nissen Koog, Germany</td>
<td>0.09</td>
<td>4</td>
</tr>
<tr>
<td>Müller et al. (2013)</td>
<td>Dieksanderkoog, Germany</td>
<td>0.05</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Box Nr</th>
<th>Name/definition</th>
<th>Area (km²)</th>
<th>Average water depth (m ASL)</th>
<th>Salt marsh area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Northern North Sea between 57.758 N and north of the Dogger Bank</td>
<td>166,000</td>
<td>-76</td>
<td>150</td>
</tr>
<tr>
<td>2</td>
<td>Waters around the Dogger Bank: between Box 1 (North), tidal front (South), and coastal area (East)</td>
<td>92,900</td>
<td>-42</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Southern North Sea</td>
<td>67,000</td>
<td>-23</td>
<td>218</td>
</tr>
<tr>
<td>4</td>
<td>German Bight</td>
<td>35,100</td>
<td>-19</td>
<td>275</td>
</tr>
<tr>
<td>5</td>
<td>English Channel</td>
<td>71,700</td>
<td>-44</td>
<td>162</td>
</tr>
</tbody>
</table>

Fig. 1. Location of salt marshes and boxes defined by Proctor et al. (2003). The boxes are explained in Table 2. Salt marshes around the North Sea and English Channel are highlighted in black, salt marshes outside that area are marked in grey (salt marsh locations are from CORINE land cover data). The figure exaggerates the area of the salt marshes for visibility reasons. Base map is the “Oceans Basemap” by ESRI’s ArcGIS Online, updated January 2013.
high flux uncertainties during storm flood events. To derive a DSI export for extrapolation, first, one arithmetic average DSI export was calculated for each of the marsh areas assessed in the input studies (Table 2). From those values, the arithmetic average was calculated; it amounts to 0.15 Mmol km\(^{-2}\) a\(^{-1}\) (= 4.23 t Si km\(^{-2}\) a\(^{-1}\), Table 1).

Other works that report salt marsh DSI exports around the North Sea were discarded from this selection because the salt marsh signal was blurred by external DSI inputs to the marsh areas (Daly and Mathieson, 1981; Imberger et al., 1983). Influxes by streams or groundwater render the salt marsh area unrepresentative for the reported DSI flux and thus unusable in this study. Further, a study quantifying diffusive DSI flux (Scudlark and Church, 1989) was disregarded, because diffusive flux does not represent total DSI export (Struyf et al., 2005). Two more studies report DSI exports from North American salt marshes (Poulin et al., 2009; Vieillard et al., 2011). However, these studies could not be included here, as the North American marshes show significantly different characteristics, e.g. vegetation and tidal amplitude, than those bordering the North Sea. The reported DSI fluxes of all studies which were explicitly not used here remain below the smallest DSI export included in the average used here. This hints to that the values used here might represent an upper estimate of the expected salt marsh DSI exports.

The average specific DSI export of the included studies was linearly extrapolated to the salt marsh area tributary to the North Sea. Because the few available field studies do not allow the quantification of factors controlling the salt marsh DSI export, a simple linear extrapolation based on an average observed DSI export seemed the most robust technique to use. Of course, this technique assumes implicitly that the average DSI export from the four salt marshes used here represents the regional average DSI export of salt marsh areas in the extrapolation area. The estimated salt marsh DSI export was included into an existing DSI budget of the North Sea (Proctor et al., 2003). While the DSI exported from salt marshes is mostly “recycled” silica redissolved from previously sedimented BSI, the riverine exports are new additions to the coastal system.

3. Results and discussion

Extrapolating the specific DSI export to the salt marshes adjacent to the North Sea results in a total estimated annual export of 121 Mmol Si a\(^{-1}\) (3400 t Si a\(^{-1}\)). This equals 0.8% of the annual river DSI export to the North Sea (river DSI export from Proctor et al., 2003). To quantify the relative contribution of salt marshes to the DSI budget in coastal waters in summer, we analyzed monthly riverine DSI exports using data from the GLORICH river chemistry database (containing published data from the DEFRA Monitoring Scheme and published studies (Krinitz, 2000; Deutsche Kommission zur Reinhaltung des Rheins (DK Rhein), 2008)). In total, 65 rivers were included in the seasonality analyses (63 British rivers, the Elbe River and Rhine River). Only sampling locations close to the river mouths were included. To assess the seasonality of individual boxes, the annual average river DSI exports of Proctor et al. (2003) were corrected by a seasonality factor based on the river dataset that was considered representative for the individual boxes (English rivers: Box 1, 2, 5; Rhine: Box 3; Elbe: Box 4). The seasonality factor was calculated as

\[ SF_{\text{BoxN}} = \frac{\text{DSI}_{\text{min}}}{\text{DSI}_{\text{avg}}} \]

where \(SF_{\text{BoxN}}\) is the seasonality factor for each box, \(\text{DSI}_{\text{min}}\) is the minimum monthly DSI export of the river dataset representing that box and \(\text{DSI}_{\text{avg}}\) is the dataset’s annual average monthly DSI export. For the North Sea, the average SF of all three datasets was used.

![Fig. 2. DSI fluxes (Mt Si a\(^{-1}\)) from salt marshes compared to advective input, benthic efflux and river input taken from Proctor et al. (2003). The percentage equals marsh DSI export divided by river DSI export annually/in summer. The extent of the individual boxes is provided in Fig. 1. Only the bold black DSI fluxes from salt marshes are results from this study; the grey DSI fluxes were quantified by Proctor et al. (2003).](image-url)
Rivers are used for reference because local studies reported river DSi export and tidal marshes of the same magnitude on the scale of single estuaries (Struyf et al., 2005, 2006; Vieillard et al., 2011). However, riverine silica fluxes are often altered in estuaries before reaching the coastal sea (Carbonnel et al., 2009; Amann et al., 2014), and estuarine area comprises less than 2% of the total North Sea (Mclusky, 2001). Thus, results on the regional sea scale which is addressed here do not contradict different findings at the estuarine scale elsewhere. From the distinguished regions of the North Sea, the Boxes 4 and 3, the German Bight and the well mixed waters of the southern North Sea, have the largest salt marsh areas (Table 2) and consequently the largest total salt marsh DSi exports (Fig. 2). However, because they also receive the most DSi from riverine export, the estimated relative salt marsh DSi export compared to rivers remains at 0% and 1% in Box 4 and Box 3, respectively (Fig. 2). The estimated relative contributions of annual salt marsh DSi export rise to 3% and 6% in the Boxes 1 and 5, the stratified water north of the Dogger Bank and the English Channel, which have smaller river contributions (Fig. 2). Box 2, the water around the Dogger Bank, has the smallest river contributions but also only 4.5 km² of mapped salt marsh area, resulting in very low DSi exports. The estimated annual average contribution of salt marsh areas to the DSi fluxes is small for the North Sea and remains at 6% of river exports even under the favorable geographic conditions in the English Channel.

Although the annual DSi exports presented in the previous paragraph are of interest for budget calculations, for DSi consuming marine organisms (e.g. diatoms), Si exports during summer, when silica is usually scarce, are likely more important than annual averages. Based on the GloRiCh data regional scale riverine DSi exports in summer months are on average reduced to 32% of their annual average monthly export (Fig. 3). A seasonal behavior of salt marsh DSi exports cannot be clearly identified based on the studies analyzed here (Fig. 3). The exports were reported to decline (Müller et al., 2013), stay constant (Poulin et al., 2009), or even double (Scudlark and Church, 1989; Struyf et al., 2006) in summer. Based on the ambiguous findings, salt marsh DSi exports are here assumed as constant throughout the year. Thus, with assumed constant DSi exports and the river export decrease, the proportion of DSi from salt marshes is estimated to 2.4% of the river DSi exports to the North Sea in summer. In addition, the summer decrease of riverine DSi is accompanied by an increase of exported BSi (Conley, 1997; Roubeix et al., 2008), of which a substantial proportion may redissolve in the coastal zone (Yamada and D’elia, 1984: Anderson, 1986). Dissolving BSi would increase DSi concentrations in the coastal zone and thus reduce the relative seasonal buffering effect of salt marsh DSi exports. However, in favorable regions like the English Channel (Box 5), where small river exports meet large salt-marsh areas, salt marsh DSi export may account for up to 16% of the riverine exports during summer.

This study compares the two land-based DSi fluxes into the coastal ocean. However, the North Sea is not a river dominated system. In the North Sea, the benthic component is of course the most important recycling based system (Fig. 2). Benthic DSi fluxes are tightly coupled to the siliceous water column primary production (Grunwald et al., 2010), i.e. the fluxes are highest after deposition of fresh diatom frustules (Gehlen et al., 1995). The salt marsh DSi exports on the other hand are controlled by different factors than the water column primary production. Thus, in other marine areas, the importance of land based DSi fluxes may be higher than in the North Sea.

Although the estimated total salt marsh DSi export is small compared to river DSi export at the regional scale, specific export from salt marshes (regarding the area) is high. For comparison, the assumed specific salt marsh DSi export amounts to 2.7 and 4.0 times the average specific DSi fluxes from the continents (Dürr et al., 2011) or into North American rivers (Moosdorf et al., 2011), respectively. The used salt marsh DSi export is in the same range as e.g. 0.18–0.35 Mmol Si km⁻² a⁻¹ identified as benthic silica recycling rates in two North American lakes (Tripplett et al., 2008). These numbers suggest that the export rates used in this study are reasonable.

In the North Sea tributary area, the average specific river DSi export was estimated to 0.04 Mmol DSi km⁻² a⁻¹ (Dürr et al., 2011); the assumed specific salt marsh DSi export is 3.8 times higher. This can be linked to environmental aspects of the historic coastal engineering of the southern North Sea, because the salt marsh area along the Wadden Sea before embankment of tidal areas was about ten-fold larger than today (Reise, 2005). Thus, similar to the reduction of silica mobilization on land due to
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