Continental Shelf Research 82 (2014) 31–36

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Salt marshes in the silica budget of the North Sea

Nils Moosdorf[a,*], Andreas Weiss[a], Frauke Müller[b], Ronny Lauerwald[a,c,d], Jens Hartmann[a], Fred Worrall[e]

[a] Institute for Geology, Center for Earth System Research and Sustainability (CEN), University of Hamburg, Bundesstraße 55, D-20146 Hamburg, Germany
[b] Department of Biology, University of Hamburg, Hamburg, Germany
[c] Department of Earth and Environmental Sciences, Univeristé Libre de Bruxelles, Bruxelles, Belgium
[d] Institut Pierre-Simon Laplace, CNRS—FR636, 78280 Guyancourt Cedex, France
[e] Department of Geological Sciences, Science Laboratories, University of Durham, Durham, United Kingdom

ARTICLE INFO

Article history:
Received 17 December 2013
Received in revised form
4 April 2014
Accepted 7 April 2014
Available online 24 April 2014

Keywords:
Silica
Salt marsh
Estuary
Coastal sea
North Sea

ABSTRACT

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.

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 into 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

* Corresponding author. Tel.: +49 40 428386683.
E-mail addresses: nils_sci@moosdorf.de, nils.moosdorf@zmaw.de (N. Moosdorf).

http://dx.doi.org/10.1016/j.csr.2014.04.009
0278-4343/

authors (Dankers et al., 1984; Struyf et al., 2006; Müller et al., 2013). 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
Literature values of dissolved silica fluxes from salt marshes used in this study. Average DSi fluxes and the number of sampled tidal cycles are provided.

References	Location	Average flux (Mmol km^{-2} a^{-1})	Number of tidal cycles
Dankers et al. (1984)	Ems-Dollard Estuary, The Netherlands	0.11	26
Struyf et al. (2006)	Carmel Polder, France	0.33	6
Müller et al. (2013)	Söhnke-Nissen Koog, Germany	0.09	4
Müller et al. (2013)	Dieksanderkoog, Germany	0.05	4

Table 2
The here used "Boxes" of the North Sea (after Proctor et al., 2003), their surface area, water depth (after GEBCO, 2009) and salt marsh area (based on 2005 and 2006 CORINE land cover data).

Box Nr	Name/definition Proctor et al. (2003)	Area (km^2)	Average water depth (m ASL)	Salt marsh area (km^2)
1	Northern North Sea between 57.758 N and north of the Dogger Bank	166,000	−76	150
2	Waters around the Dogger Bank: between Box 1 (North), tidal front (South), and coastal area (East)	92,900	−42	5
3	Southern North Sea	67,000	−23	218
4	German Bight	35,100	−19	275
5	English Channel	71,700	−44	162

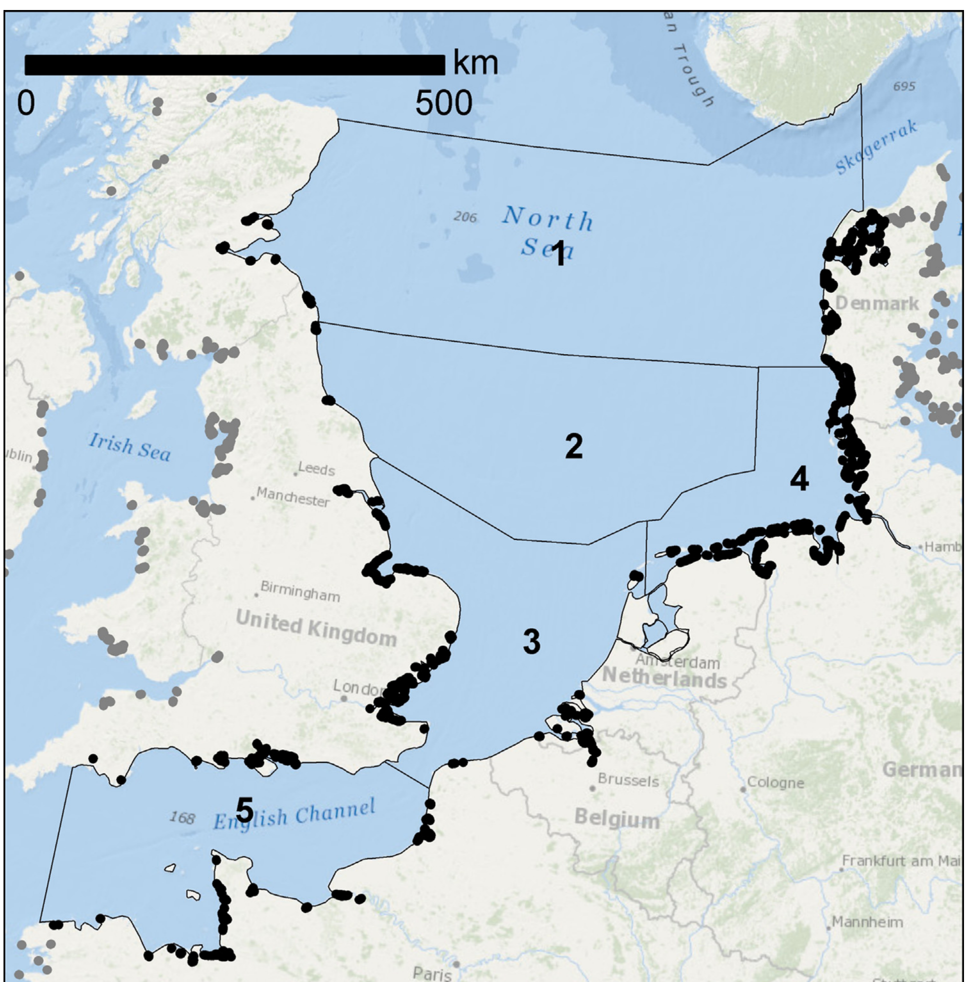

Fig. 1. Location of salt marshes and boxes defined by Proctor et al. (2003). The boxes are explained in Table 2. Salt marshes around the North Sea and English Channel are highlighted in black, salt marshes outside that area are marked in grey (salt marsh locations are from CORINE land cover data). The figure exaggerates the area of the salt marshes for visibility reasons. Base map is the "Oceans Basemap" by ESRI® 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), which represents advective flux in the ocean, benthic flux, river export and internal fluxes in five "boxes" of the North Sea and the English Channel. The boxes were defined by Proctor et al. (2003) as regions with similar hydrodynamic behavior (Fig. 1, Table 2).

The land cover class 37 "salt marshes" from the European EEA CORINE land cover 2006 database represents the salt marsh areas used in this study. Data for Great Britain were derived from CORINE land cover 2005 data (CLC2000 100 × 100 m version 8/2005). No data on salt marshes were available for Norway. However, due to the relatively short and predominantly steep Norwegian shoreline (Lundberg, 1996), the resulting underestimation of salt-marsh derived DSi in Box 1 should be minor. The salt marshes were manually attributed to the boxes of Proctor et al. (2003) using the software ArcGIS 10 (ESRI®). In total, the salt marshes in the North Sea tributary area and the English Channel extend to 809 km².

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

$$SF_{BoxNr} = FDSi_{min}/FDSi_{avg}$$

where SF_{BoxNr} is the seasonality factor for each box, $FDSi_{min}$ is the minimum monthly DSi export of the river dataset representing that box and $FDSi_{avg}$ is the dataset's annual average monthly DSi export. For the North Sea, the average SF of all three datasets was used.

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). 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.

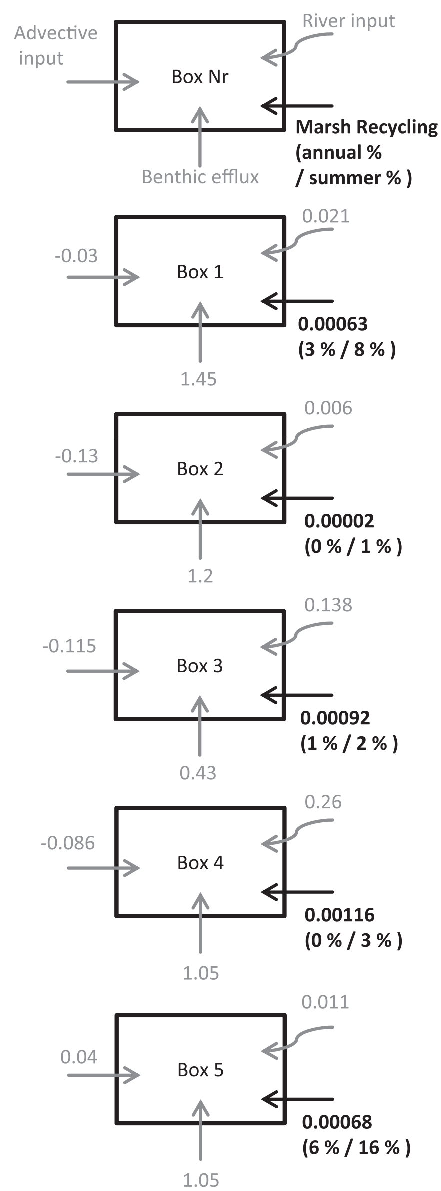

Fig. 2. DSi fluxes (Mt Si a^{-1}) from salt marshes compared to advective input, benthic efflux and river input taken from Proctor et al. (2003). The percentage equals marsh DSi export divided by river DSi export annually/in summer. The extent of the individual boxes is provided in Fig. 1. Only the bold black DSi fluxes from salt marshes are results from this study; the grey DSi fluxes were quantified by Proctor et al. (2003).

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 (Triplett 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

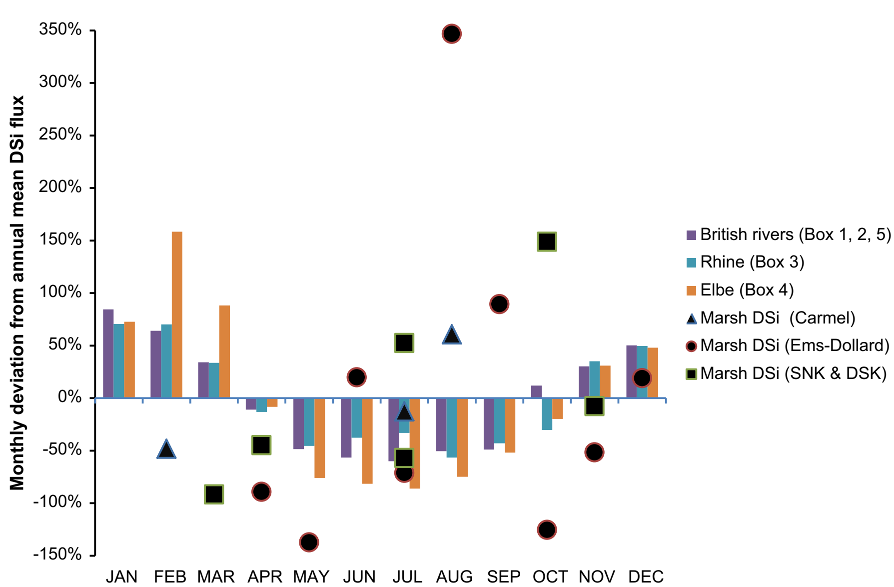

Fig. 3. Deviation of monthly average DSi export from annual average DSi export from rivers (bars, based on the used river chemistry database) and salt marshes (point markers). In brackets, the corresponding boxes (after Proctor et al., 2003) are provided, as well as the salt marshes from which the DSi is exported: Carmel Polder (Struyf et al., 2006), the Ems-Dollard estuary (Dankers et al., 1984) and the Söhnke-Nissen Koog (SNK) and Dieksander Koog (DSK) from Müller et al. (2013). For the salt marshes, all available months were taken as annual average, despite representing only an incomplete annual cycle.

historic land use change (Struyf et al., 2010), the embankment could have substantially decreased the seasonal DSi supply to the coastal waters if the specific salt marsh DSi export followed the same patterns as today.

4. Conclusions

For the North Sea as a whole, we estimate the contribution of salt marsh DSi exports to 0.8% and 2.4% of river DSi exports annually and in summer, respectively. However, in regions where small river exports meet large salt marsh areas, as the English Channel, the summer salt marsh DSi exports may amount to 16% of the river DSi export, leaving salt marshes a seasonally relevant source of DSi to coastal waters. This suggests that at least studies resolving individual coastal segments ("COSCATS"—Meybeck et al., 2006; Beusen et al., 2009; Garnier et al., 2010) would benefit from considering salt marsh DSi export when representing the seasonality of DSi supply in coastal waters.

Only few data of specific salt marsh DSi exports around the North Sea are available. This of course leaves large uncertainties in our extrapolation. In addition, the North Sea may be unrepresentative globally. More field research is needed to identify the factors governing salt marsh DSi export, which currently are only poorly understood.

Acknowledgements

Nils Moosdorf and Jens Hartmann are funded by the DFG Cluster of Excellence 'CliSAP' (EXC177). Andreas Weiss has been funded by ESTRADE (Estuary and Wetland Research Graduate School Hamburg as member of LExI (State Excellence Initiative) and by the DFG Cluster of Excellence 'CliSAP' (EXC177). Frauke Müller was funded by ESTRADE and the Bauer-Hollman Foundation (research project BASSIA). Ronny Lauerwald was funded by the EU project GEOCARBON (Grant agreement number: U4603EUU1104) and by the French National Research Agency ("Investissement d'Avenir", n°ANR-10-LABX-0018").

This extrapolation relies on data from CORINE, whose publisher, the European Environmental Agency (EEA), is acknowledged for providing the data free of charge. In addition, the authors acknowledge the important work of the colleagues who generated and shared the DSi field data which were aggregated in the presented extrapolation. We acknowledge three anonymous reviewers, whose thoughtful and constructive comments helped to improve the manuscript.

References

Adam, P., 1990. Saltmarsh Ecology. Cambridge University Press, Cambridge; New York.
Amann, T., Weiss, A., Hartmann, J., 2014. Silica fluxes in the inner Elbe estuary, Germany. Biogeochemistry, 1–24, http://dx.doi.org/10.1007/s10533-013-9940-3.
Anderson, G.F., 1986. Silica, diatoms and a freshwater productivity maximum in Atlantic Coastal Plain estuaries, Chesapeake Bay. Estuarine Coastal Shelf Sci. 22, 183–197, http://dx.doi.org/10.1016/0272-7714(86)90112-5.
Arndt, S., Regnier, P., Vanderborght, J.P., 2009. Seasonally-resolved nutrient export fluxes and filtering capacities in a macrotidal estuary. J. Mar. Syst. 78, 42–58, http://dx.doi.org/10.1016/j.jmarsys.2009.02.008.
Beusen, A.H.W., Bouwman, A.F., Dürr, H.H., Dekkers, A.L.M., Hartmann, J., 2009. Global patterns of dissolved silica export to the coastal zone: results from a spatially explicit global model. Global Biogeochem. Cycles 23, GB0A02, http://dx.doi.org/10.1029/2008gb003281.
Carbonnel, V., Lionard, M., Muylaert, K., Chou, L., 2009. Dynamics of dissolved and biogenic silica in the freshwater reaches of a macrotidal estuary (The Scheldt, Belgium). Biogeochemistry 96, 49–72, http://dx.doi.org/10.1007/s10533-009-9344-6.
Conley, D.J., 1997. Riverine contribution of biogenic silica to the oceanic silica budget. Limnol. Oceanogr. 42, 774–777.
Daly, M.A., Mathieson, A.C., 1981. Nutrient fluxes within a small north temperate salt-marsh. Mar. Biol. 61, 337–344.
Dankers, N., Binsbergen, M., Zegers, K., Laane, R., Vanderloeff, M.R., 1984. Transportation of water, particulate and dissolved organic and inorganic matter between a salt-marsh and the Ems-Dollard estuary, the Netherlands. Estuarine Coastal Shelf Sci. 19, 143–165.
Deutsche Kommission zur Reinhaltung des Rheins (DK Rhein), 2008. Zahlentafeln der chemisch-physikalischen Untersuchungen 2006. DK Rhein, Worms.
Dürr, H.H., Meybeck, M., Hartmann, J., Laruelle, G.G., Roubeix, V., 2011. Global spatial distribution of natural riverine silica inputs to the coastal zone. Biogeosciences 8, 597–620, http://dx.doi.org/10.5194/bg-8-597-2011.
Garnier, J., Beusen, A., Thieu, V., Billen, G., Bouwman, L., 2010. N:P:Si nutrient export ratios and ecological consequences in coastal seas evaluated by the ICEP approach. Global Biogeochem. Cycles 24, http://dx.doi.org/10.1029/2009gb003583.
GEBCO, 2009. General bathymetric chart of the oceans: The GEBCO_08 Grid, version 20091120, British Oceanographic Data Centre.
Gehlen, M., Malschaert, H., Vanraaphorst, W.R., 1995. Spatial and temporal variability of benthic silica fluxes in the Southeastern North-Sea. Cont. Shelf Res. 15, 1675–1696, http://dx.doi.org/10.1016/0278-4343(95)00012-P.
Grunwald, M., Dellwig, O., Kohlmeier, C., Kowalski, N., Beck, M., Badewien, T.H., Kotzur, S., Liebezeit, G., Brumsack, H.J., 2010. Nutrient dynamics in a back barrier tidal basin of the southern North Sea: time-series, model simulations, and budget estimates. J. Sea Res. 64, 199–212, http://dx.doi.org/10.1016/j.seares.2010.02.008.
Hackney, C.T., Cahoon, L.B., Preziosi, C., Norris, A., 2000. Silicon is the link between tidal marshes and estuarine fisheries: a new paradigm. Concepts and Controversies Tidal Marsh Ecol., 543–552.
Hallegraeff, G.M., 1993. A review of harmful algal blooms and their apparent global increase. Phycologia 32, 79–99, http://dx.doi.org/10.2216/i0031-8884-32-2-79.1.
Hartmann, J., Jansen, N., Dürr, H.H., Harashima, A., Okubo, K., Kempe, S., 2010. Predicting riverine dissolved silica fluxes to coastal zones from a hyperactive region and analysis of their first-order controls. Int. J. Earth Sci. 99, 207–230, http://dx.doi.org/10.1007/s00531-008-0381-5.
Hartmann, J., Jansen, N., Kempe, S., Dürr, H.H., 2007. Geochemistry of the river rhine and the upper danube: recent trends and lithological influence on baselines. J. Environ. Sci. Sustainable Soc. 1, 39–46, http://dx.doi.org/10.3107/jesss.1.39.
Hartmann, J., Levy, J.K., Kempe, S., 2011. Increasing dissolved silica trends in the Rhine River: an effect of recovery from high P loads? Limnology 12, 63–73.
Imberger, J., Berman, T., Christian, R.R., Sherr, E.B., Whitney, D.E., Pomeroy, L.R., Wiegert, R.G., Wiebe, W.J., 1983. The influence of water motion on the distribution and transport of materials in a salt-marsh estuary. Limnol. Oceanogr. 28, 201–214.
Jansen, N., Hartmann, J., Lauerwald, R., Dürr, H.H., Kempe, S., Loos, S., Middelkoop, H., 2010. Dissolved silica mobilization in the conterminous USA. Chem. Geol. 270, 90–109, http://dx.doi.org/10.1016/j.chemgeo.2009.11.008.
Krinitz, J., 2000. Stoffkonzentrationen in mittels Hubschrauber entnommenen Elbewasserproben: (1979 bis 1998); allgemeine Gewässergüte, biologische Kenngroßen, Schwermetalle und Arsen, organische Schadstoffe. Arbeitsgemeinschaft für die Reinhaltung der Elbe, Potsdam.
Laruelle, G.G., Roubeix, V., Sferratore, A., Brodherr, B., Ciuffa, D., Conley, D.J., Durr, H. H., Garnier, J., Lancelot, C., Phuong, Q.L.T., Meunier, J.D., Meybeck, M., Michalopoulos, P., Moriceau, B., Longphuirt, S.N., Loucaides, S., Papush, L., Presti, M., Ragueneau, O., Regnier, P., Saccone, L., Slomp, C.P., Spiteri, C., Van Cappellen, P., 2009. Anthropogenic perturbations of the silicon cycle at the global scale: key role of the land-ocean transition. Global Biogeochem. Cycles 23, GB4031, http://dx.doi.org/10.1029/2008gb003267.
Lauerwald, R., Hartmann, J., Moosdorf, N., Dürr, H.H., Kempe, S., 2013. Retention of dissolved silica within the fluvial system of the conterminous USA. Biogeochemistry 112, 637–659, http://dx.doi.org/10.1007/s10533-012-9754-8.
Lundberg, A., 1996. Environmental change and nature management in Norway. Nor. Geografisk Tidsskr.—Norw. J. Geogr. 50, 143–156, http://dx.doi.org/10.1080/00291959608622036.
McLusky, D.S., 2001. North sea estuaries. Senck. Marit. 31, 177–186.
Meybeck, M., Dürr, H.H., Vorosmarty, C.J., 2006. Global coastal segmentation and its river catchment contributors: a new look at land-ocean linkage. Global Biogeochem. Cycles 20, GB1S90, http://dx.doi.org/10.1029/2005gb002540.
Moosdorf, N., Hartmann, J., Lauerwald, R., 2011. Changes in dissolved silica mobilization into river systems draining North America until the period 2081–2100. J. Geochem. Explor. 110, 31–39, http://dx.doi.org/10.1016/j.gexplo.2010.09.001.
Müller, F., Struyf, E., Hartmann, J., Weiss, A., Jensen, K., 2013. Impact of grazing management on silica export dynamics of Wadden Sea saltmarshes. Estuarine Coastal Shelf Sci. 127, 1–11, http://dx.doi.org/10.1016/j.ecss.2013.03.010.
Officer, C.B., Ryther, J.H., 1980. The possible importance of silicon in marine eutrophication. Mar. Ecol. Prog. Ser. 3, 83–91.
Poulin, P., Pelletier, E., Koutitonski, V.G., Neumeier, U., 2009. Seasonal nutrient fluxes variability of northern salt marshes: examples from the lower St. Lawrence Estuary. Wetlands Ecol. Manage. 17, 655–673, http://dx.doi.org/10.1007/s11273-009-9141-y.
Proctor, R., Holt, J.T., Allen, J.I., Blackford, J., 2003. Nutrient fluxes and budgets for the North West European Shelf from a three-dimensional model. Sci. Total Environ. 314, 769–785, http://dx.doi.org/10.1016/S0048-9697(03)00083-4.
Reise, K., 2005. Coast of change: habitat loss and transformations in the Wadden Sea. Helgol. Mar. Res. 59, 9–21, http://dx.doi.org/10.1007/s10152-004-0202-6.
Roubeix, V., Rousseau, V., Lancelot, C., 2008. Diatom succession and silicon removal from freshwater in estuarine mixing zones: from experiment to modelling. Estuarine Coastal Shelf Sci. 78, 14–26, http://dx.doi.org/10.1016/j.ecss.2007.11.007.

Schelske, C.L., Stoermer, E.F., 1971. Eutrophication, silica depletion, and predicted changes in algal quality in Lake Michigan. Science 173, 423–424, http://dx.doi.org/10.1126/science.173.3995.423.

Scudlark, J.R., Church, T.M., 1989. The sedimentary flux of nutrients at a Delaware salt-marsh site—a geochemical perspective. Biogeochemistry 7, 55–75.

Smayda, T.J., 1990. Novel and nuisance phytoplankton blooms in the sea: evidence for a global epidemic. In: Granéli, E., Sundström, B., Edler, L., Anderson, D.M. (Eds.), Toxic Marine Phytoplankton: Proceedings of the Fourth International Conference on Toxic Marine Phytoplankton held June 26–30 in Lund, Sweden. Elsevier, New York, pp. 29–40.

Struyf, E., Dausse, A., Van Damme, S., Bal, K., Gribsholt, B., Boschker, H.T.S., Middelburg, J.J., Meire, P., 2006. Tidal marshes and biogenic silica recycling at the land-sea interface. Limnol. Oceanogr. 51, 838–846.

Struyf, E., Smis, A., Van Damme, S., Garnier, J., Govers, G., Van Wesemael, B., Conley, D.J., Batelaan, O., Frot, E., Clymans, W., Vandevenne, F., Lancelot, C., Goos, P., Meire, P., 2010. Historical land use change has lowered terrestrial silica mobilization. Nat. Commun. 1, 129, http://dx.doi.org/10.1038/ncomms1128.

Struyf, E., Van Damme, S., Gribsholt, B., Meire, P., 2005. Freshwater marshes as dissolved silica recyclers in an estuarine environment (Schelde estuary, Belgium). Hydrobiologia 540, 69–77, http://dx.doi.org/10.1007/s10750-004-7104-0.

Treguer, P., Nelson, D.M., Vanbennekom, A.J., Demaster, D.J., Leynaert, A., Queguiner, B., 1995. The silica balance in the world ocean—a reestimate. Science 268, 375–379.

Tréguer, P.J., De La Rocha, C.L., 2013. The world ocean silica cycle. Ann. Rev. Mar. Sci. 5, 477–501, http://dx.doi.org/10.1146/annurev-marine-121211-172346.

Triplett, L.D., Engstrom, D.R., Conley, D.J., Schellhaass, S.M., 2008. Silica fluxes and trapping in two contrasting natural impoundments of the upper Mississippi River. Biogeochemistry 87, 217–230, http://dx.doi.org/10.1007/s10533-008-9178-7.

Vieillard, A.M., Fulweiler, R.W., Hughes, Z.J., Carey, J.C., 2011. The ebb and flood of Silica: quantifying dissolved and biogenic silica fluxes from a temperate salt marsh. Estuarine Coastal Shelf Sci. 95, 415–423, http://dx.doi.org/10.1016/j.ecss.2011.10.012.

Weiss, A., Amann, T., Hartmann, J., 2013. Silica dynamics of tidal marshes in the inner Elbe estuary, Germany. Silicon 5, 75–89, http://dx.doi.org/10.1007/s12633-012-9131-1.

Yamada, S.S., D'elia, C.F., 1984. Silicic-acid regeneration from estuarine sediment cores. Mar. Ecol. Prog. Ser. 18, 113–118.