1-1-2020

Role of vegetated coastal ecosystems as nitrogen and phosphorous filters and sinks in the coasts of Saudi Arabia

V. Saderne

M. Cusack

Oscar Serrano
Edith Cowan University

H. Almahasheer

P. K. Krishnakumar

See next page for additional authors

10.1088/1748-9326/ab76da
Saderne, V., Cusack, M., Serrano, O., Almahasheer, H., Krishnakumar, P. K., Rabaoui, L., ... Duarte, C. M. (2020). Role of vegetated coastal ecosystems as nitrogen and phosphorous filters and sinks in the coasts of Saudi Arabia. *Environmental Research Letters, 15*(3), Article 034058. https://doi.org/10.1088/1748-9326/ab76da

Authors

V. Saderne, M. Cusack, Oscar Serrano, H. Almahasheer, P. K. Krishnakumar, L. Rabaoui, M. A. Qurban, and C. M. Duarte

Environmental Research Letters

LETTER • OPEN ACCESS

Role of vegetated coastal ecosystems as nitrogen and phosphorous filters and sinks in the coasts of Saudi Arabia

To cite this article: V Saderne *et al* 2020 *Environ. Res. Lett.* **15** 034058

IOP Publishing Environ. Res. Lett. 15 (2020) 034058 https://doi.org/10.1088/1748-9326/ab76da

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
9 January 2019

REVISED
16 February 2020

ACCEPTED FOR PUBLICATION
17 February 2020

PUBLISHED
6 March 2020

LETTER

Role of vegetated coastal ecosystems as nitrogen and phosphorous filters and sinks in the coasts of Saudi Arabia

V Saderne[1], M Cusack[1], O Serrano[2], H Almahasheer[3], P K Krishnakumar[4,5], L Rabaoui[4,5], M A Qurban[4,5] and C M Duarte[1]

[1] King Abdullah University of Science and Technology, Red Sea Research Centre, Thuwal 23955-6900, Saudi Arabia
[2] School of Science & Centre for Marine Ecosystems Research, Edith Cowan University, 270 Joondalup Drive, Joondalup WA 6027, Australia
[3] Department of Biology, College of Science, Imam Abdulrahman Bin Faisal University (IAU), Dammam 31441-1982, Saudi Arabia
[4] Marine Studies section, Center for Environment and Water, Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), P. B. No. 391, Dhahran 31261, Saudi Arabia
[5] Geosciences Department, The College of Petroleum Engineering & Geosciences, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia

E-mail: vincent.saderne@kaust.edu.sa

Keywords: blue carbon, nitrogen, phosphorus, mangrove, seagrass, Red Sea, Arabian Gulf

Supplementary material for this article is available online

Abstract

Vegetated coastal ecosystems along the Red Sea and Arabian Gulf coasts of Saudi Arabia thrive in an extremely arid and oligotrophic environment, with high seawater temperatures and salinity. Mangrove, seagrass and saltmarsh ecosystems have been shown to act as efficient sinks of sediment organic carbon, earning these vegetated ecosystems the moniker 'blue carbon' ecosystems. However, their role as nitrogen and phosphorus (N and P) sinks remains poorly understood. In this study, we examine the capacity of blue carbon ecosystems to trap and store nitrogen and phosphorous in their sediments in the central Red Sea and Arabian Gulf. We estimated the N and P stocks (in 0.2 m thick-sediments) and accumulation rates (for the last century based on ^{210}Pb and for the last millennia based on ^{14}C) in mangrove, seagrass and saltmarsh sediments from eight locations along the coast of Saudi Arabia (81 cores in total). The N and P stocks contained in the top 20 cm sediments ranged from 61 g N m^{-2} in Red Sea seagrass to 265 g N m^{-2} in the Gulf saltmarshes and from 70 g P m^{-2} in Red Sea seagrass meadows and mangroves to 58 g P m^{-2} in the Gulf saltmarshes. The short-term N and P accumulation rates ranged from 0.09 mg N cm^{-2} yr^{-1} in Red Sea seagrass to 0.38 mg N cm^{-2} yr^{-1} in Gulf mangrove, and from 0.027 mg P cm^{-2} yr^{-1} in the Gulf seagrass to 0.092 mg P cm^{-2} yr^{-1} in Red Sea mangroves. Short-term N and P accumulation rates were up to 10-fold higher than long-term accumulation rates, highlighting increasing sequestration of N and P over the past century, likely due to anthropogenic activities such as coastal development and wastewater inputs.

Introduction

Vegetated coastal habitats offer myriad vital services that support coastal communities. Mangroves, seagrass meadows and saltmarshes can protect coasts from storm surges and rising sea levels (Duarte *et al* 2013) and provide essential habitats for fisheries and wildlife (Mumby *et al* 2004, Aburto-Oropeza *et al* 2008). They are also very effective at trapping and storing sediment, organic matter, anthropogenic pollutants and nutrients from surrounding waters (Jordan *et al* 2003, Alongi and McKinnon 2005, Rabaoui *et al* 2019). Special attention has been paid in recent years to the capacity of these vegetated coastal habitats to sequester carbon in their sediments efficiently. The high productivity and sedimentation rates, and their ability to vertically accrete sediment combined with the low oxygen availability, means these habitats can store carbon for millennia in their sediments (Donato *et al* 2011, Mcleod *et al* 2011,

Duarte *et al* 2013, Atwood *et al* 2017). The capacity of mangroves, seagrasses and saltmarshes, collectively known as 'blue carbon' habitats, to trap and bury organic carbon (C_{org}) may also make them effective at removing excess nutrients from the surrounding environment. Nutrients are stoichiometrically linked to carbon in organic matter sequestered in sediments (Redfield ratio). Nutrient densities (mg m^{-3}) and stocks (mg m^{-2} over a certain sediment depth) of nitrogen (N) and phosphorus (P) have been already assessed in seagrass (e.g. Fourqurean *et al* 2012, McGlathery *et al* 2012, Eyre *et al* 2016, Kindeberg *et al* 2018), mangroves (e.g. Breithaupt *et al* 2014, Feng *et al* 2017) and saltmarshes (e.g. Zwolsman *et al* 1993, Spencer *et al* 2003, Hopkinson and Giblin 2008, Covelli *et al* 2012, Ruiz-Fernández *et al* 2018, Noll *et al* 2019). Data on accumulation rates (mg N or P cm^{-2} yr^{-1}) in those ecosystems, however, remain scarce (e.g. Breithaupt *et al* 2014, Noll *et al* 2019) as the measurement of nutrient densities and overall sediment accretion rates (cm yr^{-1}, or mass accretion rates in g cm yr^{-1}) is required. The most traditional way to obtain sediment accretion rates is through radiometric dating of the sediment, by measuring the activity of ^{137}Cs for the most recent decades, ^{210}Pb for the last 100 years, and ^{14}C for centennial- to millennial-scale (Breithaupt *et al* 2018, Arias-Ortiz *et al* 2018a, 2018b).

Here, we assess N and P stocks and accumulation rates in the sediments of seagrass meadows and mangroves along the Saudi coast in the Red Sea, as well as in those of seagrasses, mangroves and saltmarshes along the Saudi coast in the Gulf. We measured the N and P stocks in 0.2 m sediment cores, and, calculated the short- and long-term accumulation rates using the ^{210}Pb and ^{14}C sediment accretion rates reported for the same cores by Cusack *et al* (2018) and Saderne *et al* (2018). We use the changes in accumulation rates to hypothesize on changes in ecosystem functioning in the coastal ecosystems over the past millennia to centuries.

Methods

Ecosystem descriptions

The Arabian Peninsula is an especially arid region of the globe, with most of the peninsula receiving very little rainfall on an annual basis (Almazroui *et al* 2012). This low precipitation results in minimal fluvial input of sediments anywhere along the coasts of the Red Sea or the Gulf coast. The Red Sea does not have any permanent rivers. The Arabian Gulf, on the other hand, receives water from the Shatt al Arab River in the north, which itself is a result of the confluence of the Tigris and Euphrates Rivers. The sediments of the Red Sea and Arabian Gulf originate mainly from carbonate deposits from seawater and deposited airborne sediment of terrestrial origin, which is reported to comprise up to one-third of Gulf sediments (Sugden 1963, Saderne *et al* 2018). Dust deposition from frequent dust storms originating in the Sahara and the Arabian Peninsula is believed to be one of the primary sources of nutrients to the Red Sea and the Gulf (Acosta *et al* 2013, Engelbrecht *et al* 2017).

The Red Sea is oligotrophic, with P and N sea surface concentrations estimated, in its central part, at 0.05–0.1 μmol kg^{-1} and 0.03–0.2 μmol kg^{-1}, respectively (Weikert 1987, Wafar *et al* 2016). Saderne *et al* (2018) measured surface water concentrations of P and N, in a seagrass (Khor Almasena'a) and mangrove area, from the same study zone, and reported annual mean ($\pm$SD) records of 0.8 $\pm$ 0.4 μmol P kg^{-1} and 1.3 $\pm$ 0.5 μmol N kg^{-1}, and 2.3 $\pm$ 0.5 μmol P kg^{-1} and 0.9 $\pm$ 0.2 μmol N kg^{-1}, respectively. The chemical oceanography of the Arabian Gulf has been largely understudied, with only five sampling expeditions since 1965 (although substantial gray literature exists) (Al-Yamani and Naqvi 2019). The most recent published data for the Saudi coast of the Arabian Gulf are from 1993 to 1994 (Hashimoto *et al* 1998). Concentrations of phosphates between 0.2 and 0.4 μM and of nitrates from $<$0.09 to 0.2 μM were reported (Brewer and Dyrssen 1985, Hashimoto *et al* 1998). Annual mean ($\pm$SE) concentrations of nitrates and phosphates measured in 2011–2012 in seagrass beds of the Saudi coasts of the Gulf ranged between 0.4 $\pm$ 0.14 μM and 0.3 $\pm$ 0.03 μM, respectively (KFUPM 2011).

This study was conducted in the Central Red Sea and along the Gulf coast of Saudi Arabia (figure 1). The study area of the Red Sea comprised four sites encompassing about 80 km of the coastline: Al Taweelah Island (22°16′ N, 39°05′ E), in front of the traditional fisherman urbanization of Thuwal, whose coastline has been modified drastically over the past ten years; Khor Almesena'a lagoon (22°22′ N, 39°07′ E), which has seen the development of King Abdullah Economic City to its north and King Abdullah University of Science and Technology to its south in the past decade; Khor Al-Baqila lagoon, whose entire southern side was converted into a large petrochemical terminal in 1981; and Khor Al-Kharrar lagoon (22°57′ N, 38°51′ E), which is relatively undeveloped.

The study area in the Saudi Gulf coast spanned 400 km along the Saudi coast. The southernmost site, Uqair (25°43′ N, 50°13′ E), has undergone negligible development. The Ras Tanura/Safwa site (26°41′ N, 50°00′ E) is an embayment north of the city of Dammam. Now a natural park, this area have been subjected to significant urban and industrial development since 1950. The site of Abu Ali Island (27°17 N, 49°33′ E) is now also part of a natural park, but has seen development due to the petrochemical industry and extensive modification of the area's hydrography due to the construction of dikes. The northernmost site, Ras Safanya (27°58 N, 48°46′ E), is a site of extensive petrochemical and oil extraction activities on the

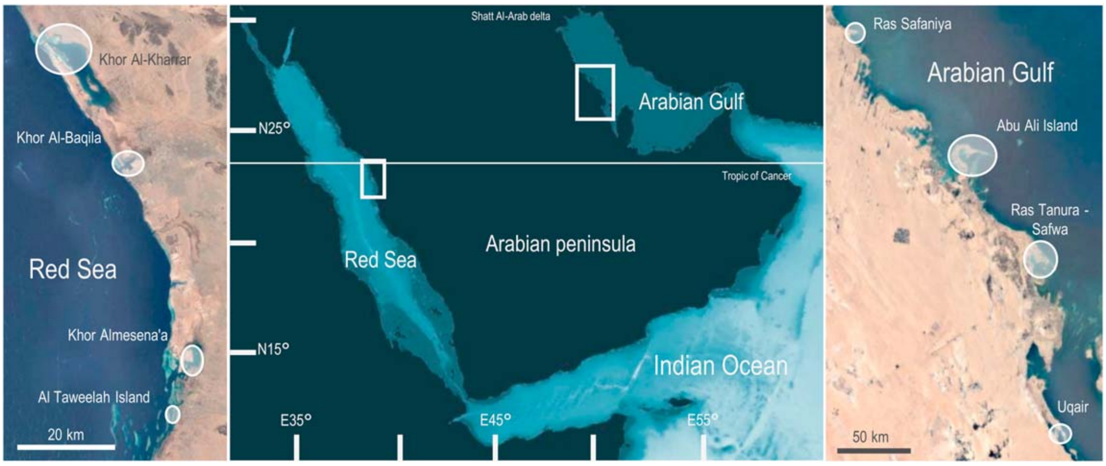

Figure 1. Locations of the blue carbon ecosystems sampled along the Saudi coasts in the Central Red Sea (left) and Arabian Gulf (right). Images Landsat/Copernicus.

Safaniya oil field, one of the largest offshore oil fields in the world.

The mangrove ecosystems sampled on both coastlines were very similar, formed by mono-specific stands of *Avicennia marina* of less than 2 m height (Anton *et al* submitted). Seagrass species found in the Red Sea include *Halophila stipulacea, Thalassia hemprichii, Enhalus acoroides, Thalassodendrum ciliatum, and Halodule uninervis*. In the Gulf, the dominant seagrass species are *H. uninervis* (most widely distributed), *H. stipulacea* and *H. ovalis* (less common). Seagrass meadows across the Gulf occur at 46% of the coastal areas and 30% of offshore sites of the Gulf (Erftemeijer and Shuail 2012), and are under threat due to local dredging activities, land reclamation and associated changes in hydrology, together with pressures derived from climate change and marine pollution (Almahasheer *et al* 2013, Almahasheer 2018). Finally, saltmarshes of the Gulf coast are dominated by salt-tolerant or halophytic perennial grasses such as *Aleuropus lagopoides* and *Bienertia cycloptera,* conforming an ecosystem known locally as Sabkahs.

Sediment sampling

The sediments were sampled using manual percussion and rotation of PVC pipes (Red Sea samples: internal diameter 60 mm. Gulf samples: 110 mm). A total of 27 and 29 cores were collected from seagrass and mangrove ecosystems in the Red Sea, respectively, while in the Gulf, a total of 12, 7, and 6 cores were collected in seagrass, mangrove and saltmarsh ecosystems, respectively. At each site, cores were sampled within 1–10 km^2. The sediment cores in the present study are the same as those described in Cusack *et al* (2018) and Saderne *et al* (2018).

In the Red Sea, two types of cores were sampled; plain PVC pipes and PVC pipes with pre-drilled sampling ports (Howard *et al* 2014) of 3 cm diameter at 6 cm apart along the length of the core. The sediments of the port cores were sampled in the field using modified plastic syringes (i.e. cut open to allow subsampling the ports). The regular cores were opened lengthwise and cut into 1 cm thick slices in the laboratory. All samples were dried at 60 °C until constant weight was reached to estimate dry bulk density (DBD), and subsamples were milled for nutrient analysis. In the Red Sea cores, N concentrations were measured in every slice (1 cm thick) down to a depth of 20 cm (compressed) and then every second cm down to the bottom of the core in mangroves, and every cm from top to bottom in the seagrass cores. In the port cores, N concentrations were measured in every sample, and P concentrations were measured in every port sample down to 27 cm. In the Red Sea cores, P concentrations were measured every 5 cm in the whole core down to 20 cm (compressed), while in the Arabian Gulf cores, N and P were measured every 5 cm down to approx. 20 cm (compressed). All data presented here are corrected for compression effects during coring, following the procedure in Howard *et al* (2014). The difference between the length of the core barrel inserted in the sediment and the length of the core retrieved was measured and the difference distributed uniformly throughout the length of the core.

N concentrations in each sediment sample were determined from 200 mg samples contained in a pre-combusted aluminum case using a FLASH 2000 CHNS Elemental Analyzer. P concentrations were determined by inductively coupled plasma-optical emission spectrometry (Varian Inc. model 720-ES). 200 mg of sediment were acid digested in 5 ml of concentrated HCl and a few drops of H_2O_2 in a Digi PREP digestion system in three temperature steps: 30 °C for 30 min, 50 °C for 30 min and 75 °C for 45 min. The digested samples were then cooled, diluted to 25 ml with Mili-Q water and analyzed for P concentrations. Standard reference materials from the US National Institute of Standards and Technology were employed

to verify the accuracy of P measurements. For N concentrations, a standard reference material (BBOT) and calibration standard (Sulfanilamide) were used to ensure the accuracy of results.

The N and P contents were calculated in each slice by multiplying the sediment DBD (g cm^{-3}) by the nutrient concentration. In each core, the nutrient stocks in g m^{-2} integrated over the top 20 cm was estimated by building a continuous depth profile of N and P content by linear interpolation. The nutrient accumulation rates (mg m^{-2} yr^{-1}) were calculated by multiplying the nutrient content by the sediment accumulation rates (mass m^{-2} yr^{-1}) derived from ^{14}C and ^{210}Pb age-depth models (where successfully measured) and published in Cusack *et al* (2018) and Saderne *et al* (2018) for the same cores used in this study. The changes in accumulation rates of N and P were calculated for different periods by averaging the burial rates across each habitat type for the periods provided by ^{210}Pb dating. Nutrient ratios are reported as atomic ratios (mol/mol). All standard errors presented include error propagation for the calculation of accumulation rates from elemental contents and sediment accretion rates, and the calculation of averages within sites, ecosystems and regions.

General linear models (GLMs) were used to test differences in the variables studied between regions, among habitat types, and among habitat types within regions. Differences in soil P and N accumulation rates among long-term periods (based on ^{14}C), and three periods over the last century (1850–1930, 1930–1980 and Modern (1980–2016); based on ^{210}Pb) for Red Sea mangrove habitats, and Arabian Gulf seagrass, mangrove and saltmarsh habitats were also tested with a GLM. Region (Red Sea versus Arabian Gulf), habitat type (saltmarsh, seagrass and mangrove) and periods (1850–1930, 1930–1980 and Modern: 1980–2016) were treated as fixed factors in all statistical models (probability distribution: normal; link function: identity).

Results

The average (±SE) N concentration in mangrove and seagrass sediments from the Red Sea were similar, at 0.03 ± 0.09% DW and 0.03 ± 0.02% DW, respectively. In the Gulf, N concentrations for mangrove, seagrass, and saltmarsh sediments were at least twice those of Red Sea sediments at 0.017 ± 0.003%, 0.09 ± 0.03% and 0.10 ± 0.08%, respectively (table 1). The highest sediment N density was in Gulf saltmarsh sediments, specifically in Ras Tanura, Arabian Gulf (1.68 ± 1.13 mg N cm^{-3}) and the lowest N density was recorded in seagrass sediments of Al-Baqila, Red Sea (0.015 ± 0.03 mg N cm^{-3}). The average P concentrations were 0.043 ± 0.007 and 0.03 ± 0.02 %DW in Red Sea seagrass and mangrove sediments (table 1). They were 0.019 ± 0.004, 0.076 ± 0.015 and 0.022 ± 0.003 %DW in the Gulf seagrass, mangrove and saltmarsh sediments (table 1). The highest sediment P density was measured in seagrass sediments of Al Taweelah Island, Red Sea (0.6 ± 0.05 mg P cm^{-3}), while the lowest was recorded in seagrass sediments of Ras Tanura, Arabian Gulf (0.19 ± 0.02 mg P cm^{-3}). The variability of N and P %DW with sediment depth for Red Sea and Arabian Gulf habitats are provided in the supplementary material. A marked increasing trend in N concentrations (%DW) towards surface sediments is visible across all Red Sea habitats (supp. figure 1, available online at stacks.iop.org/ERL/15/034058/mmedia) except for seagrass sediments in Al-Baqila, Red Sea (supp. figure 1). In contrast, P concentrations (% DW) do not appear to undergo any discernible trend between shallow and deeper sediments, except in Khor Al-Kharrar mangrove sediments (sup. figure 1). Measurements of N and P for Gulf sediments were performed to a maximum depth of 20 cm, and the variability of N and P %DW with sediment depth are shown in supp. figure 1. Concentrations in the top 20 cm do not show any obvious increasing trend toward shallower sediments.

Stocks of N were 61 ± 32 and 99 ± 47 mg N cm^{-2} in seagrass and mangrove ecosystems of the Red Sea. Stocks of N in each habitat were at least three-fold higher for the Arabian Gulf, with 223 ± 110, 209 ± 96 and 265 ± 93 mg N cm^{-2} in seagrass, mangrove and saltmarsh sediments (figure 2(a); table 2). In contrast, stocks of P were more similar across the Red Sea and Gulf habitats with 70 ± 57 and 70 ± 15 mg P cm^{-2} in seagrass and mangrove sediments of the Red Sea, and 33 ± 11, 47 ± 16 and 58 ± 23 mg P cm^{-2} in seagrass, mangrove and saltmarsh sediments of the Gulf (figure 2(a); table 2). The highest N stocks were found in Gulf saltmarsh sediments at 265 ± 93 mg N cm^{-2} and the highest P stocks were recorded in Red Sea ecosystems at 70 ± 57 and 70 ± 15 mg P cm^{-2} in seagrass and mangroves, respectively, closely followed by Gulf saltmarshes (58 ± 23 mg P cm^{-2}; table 2).

Long-term sediment accretion rates, as determined by ^{14}C dating, varied from a minimum of 0.04 ± 0.04 and 0.04 ± 0.01 cm yr^{-1} in Arabian Gulf mangroves and saltmarshes to a maximum of 0.2 ± 0.1 cm yr^{-1} in Arabian Gulf seagrass meadows. The elevated accretion rate in Gulf seagrasses resulted in a very high long-term N accumulation rate of 0.3 ± 0.2 mg N cm^{-2} yr^{-1} (table 2; figure 2(b)). However, although sediment accretion rates in Gulf seagrass sediments were high, long-term accumulation rates of P remained low (0.036 ± 0.027 mg P m^{-2} yr^{-1}), comparable to that in seagrass sediments in the Red Sea (0.052 ± 0.036 mg P cm^{-2} yr^{-1}; figure 2(b)).

The short-term N accumulation rates in mangroves averaged 0.093 ± 0.062 mg N cm^{-2} yr^{-1} in the Red Sea and 0.38 ± 0.16 mg N cm^{-2} yr^{-1} in the Gulf (figure 2(b)), with remarkably high N accumulation rates in mangrove stands at Ras Tanura in the Gulf

Table 1. The mean (± SE) sediment N and P density (mg cm^{-3}) and % dry weight (DW) and atomic stoichiometric ratios for each site and habitat for the Central Red Sea and the Gulf.

	Location	Species	No. of cores	Sediment N density (mg N cm^{-3})	% N (DW)	Sediment P density (mg P cm^{-3})	% P (DW)	C:N	N:P
Red Sea Seagrass	Al Taweelah Isl.	*H. stipulacea*	3	0.239 ± 0.034	0.020 ± 0.002	0.599 ± 0.05	0.054 ± 0.001	33:1	0.7:1
		T. hempreichii	10	0.365 ± 0.097	0.046 ± 0.016	0.23 ± 0.055	0.029 ± 0.004	27:1	3.8:1
	Khor Almesena'a	*E. acoroides*							
		T. ciliatum							
	Khor Al-Baqila	*T. ciliatum*	4	0.015 ± 0.032	0.015 ± 0.004	0.519 ± 0.068	0.053 ± 0.002	52:1	0.6:1
	Khor Al-Kharrar	*H. stipulacea*	10	0.346 ± 0.083	0.038 ± 0.012	0.314 ± 0.085	0.035 ± 0.005	26:1	2.9:1
		H. uninervis							
Red Sea Mangrove	Al Taweelah Isl.	*A. marina*	8	0.262 ± 0.091	0.019 ± 0.006	0.348 ± 0.134	0.025 ± 0.006	39:1	2.6:1
	Khor Almesena'a	*A. marina*	8	0.328 ± 0.059	0.027 ± 0.006	0.323 ± 0.059	0.028 ± 0.003	40:1	3.1:1
	Khor Al-Baqila	*A. marina*	6	0.253 ± 0.071	0.019 ± 0.008	0.426 ± 0.089	0.035 ± 0.004	33:1	1.9:1
	Khor Al-Kharrar	*A. marina*	7	0.49 ± 0.226	0.073 ± 0.086	0.278 ± 0.061	0.035 ± 0.018	41:1	9:1
Arabian Gulf Seagrass	Safaniya	*H. uninervis*	3	1.57 ± 0.296	0.073 ± 0.02	0.196 ± 0.016	0.019 ± 0.002	18:1	19:1
	Abu-Ali Island	*H. uninervis*	3	1.583 ± 0.088	0.148 ± 0.011	0.179 ± 0.032	0.017 ± 0.003	18:1	12:1
	Ras Tanura	*H. uninervis*	3	1.354 ± 0.329	0.111 ± 0.012	0.192 ± 0.025	0.021 ± 0.002	22:1	14:1
	Uqair	*H. uninervis*	3	1.659 ± 0.085	0.064 ± 0.007	0.203 ± 0.013	0.018 ± 0.001	24:1	19:1
Arabian Gulf Mangrove	Abu-Ali Island	*A. marina*	3	0.833 ± 0.141	0.016 ± 0.002	0.224 ± 0.031	0.060 ± 0.008	19:1	9:1
	Ras Tanura	*A. marina*	4	1.243 ± 0.176	0.018 ± 0.002	0.249 ± 0.038	0.092 ± 0.013	22:1	11:1
Arabian Gulf Saltmarsh	Abu-Ali Island	*Undetermined*	3	1.027 ± 0.434	0.082 ± 0.033	0.257 ± 0.047	0.020 ± 0.003	23:1	10:1
	Ras Tanura	*Undetermined*	3	1.684 ± 1.129	0.123 ± 0.074	0.327 ± 0.028	0.024 ± 0.002	19:1	12:1
				Sediment N Density (mg N cm^{-3})	% N (DW)	Sediment P Density (mg P cm^{-3})	% P (DW)	C:N	N:P
Habitat Averages	Red Sea Seagrass		27	0.241 ± 0.136	0.030 ± 0.021	0.416 ± 0.132	0.043 ± 0.007	34:1	2:1
	Red Sea Mangrove		29	0.333 ± 0.261	0.035 ± 0.087	0.344 ± 0.182	0.03 ± 0.02	38:1	4:1
	Arabian Gulf Seagrass		12	1.542 ± 0.46	0.099 ± 0.026	0.192 ± 0.046	0.019 ± 0.004	21:1	10:1
	Arabian Gulf Mangrove		7	1.038 ± 0.225	0.017 ± 0.003	0.236 ± 0.049	0.076 ± 0.015	21:1	10:1
	Arabian Gulf Saltmarsh		6	1.355 ± 1.209	0.103 ± 0.081	0.292 ± 0.054	0.022 ± 0.003	21:1	11:1

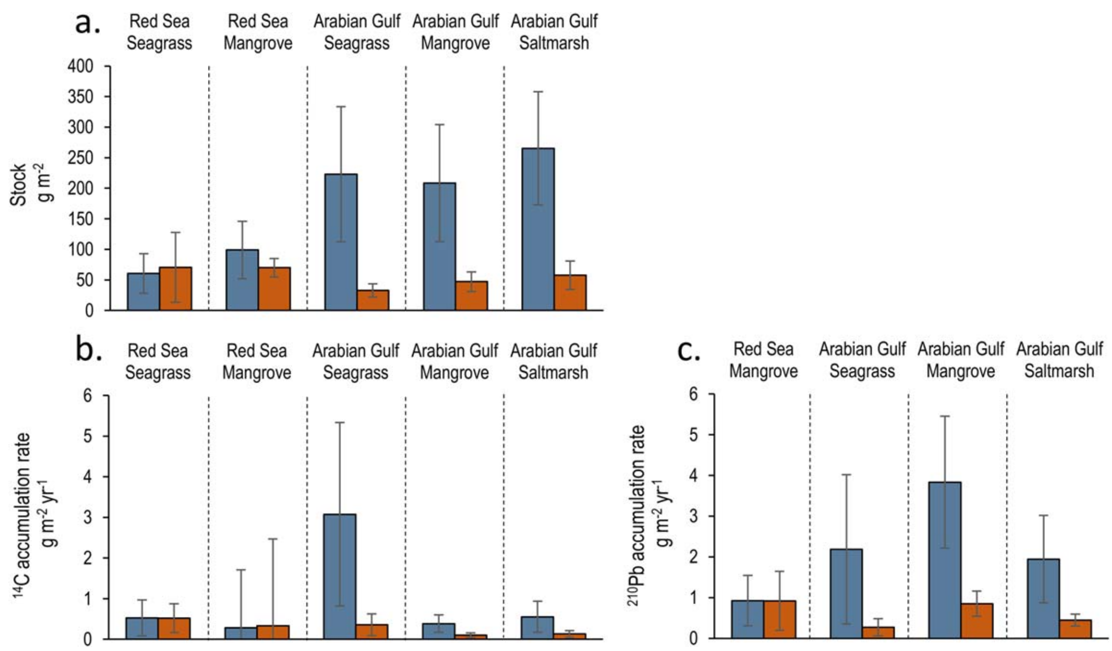

Figure 2. (a) Stocks of N in blue and P in orange (g m^{-2} in 0.2 m thick sediments), (b) long-term accumulation of N and P derived from ^{14}C dating (g m^{-2} yr^{-1}) and (c) short-term accumulation of N and P derived from ^{210}Pb dating (g m^{-2} yr^{-1}) from Cusack *et al* (2018) and Saderne *et al* (2018) for each habitat in the Red Sea and Arabian Gulf. Values are mean ± SE.

(table 2). The short-term P and N accumulation rates in Red Sea mangroves were found to be similar (0.092 ± 0.073 mg P cm^{-2} yr^{-1} and 0.093 ± 0.062 mg N cm^{-2} yr^{-1}). In contrast, in the Gulf ecosystems the P accumulation rates were one order of magnitude lower than the N accumulation rates in (figure 2(c)).

Changes in N and P accumulation over specific periods are presented in figure 3 and supplementary table 1: 1850–1930 (pre-oil discovery), 1930–1980 (oil discovery and exploitation) and Modern (1980—present-day). Mean N accumulation rates across all habitats for the pre-oil discovery period (0.104 mg N cm^{-2} yr^{-1}) were significantly lower than in modern times (0.147 mg N cm^{-2} yr^{-1}; $P < 0.001$; figure 3, supplementary table 1). N accumulation in Red Sea mangroves doubled between the pre-oil era and the present day (0.074–0.144 mg N cm^{-2} yr^{-1}). However, N accumulation rates in the Gulf peaked in all three habitat types during 1930–1980, followed by a slight decrease in the modern era. The highest accumulation rates across all habitats were for Gulf mangroves, which also underwent the largest increase in accumulation rates from the pre-oil era (0.13 mg N cm^{-2} yr^{-1}) to the post-oil era (0.24 mg N cm^{-2} yr^{-1}). P accumulation rates were relatively flat across the three periods in both the Red Sea and Gulf, except for Gulf mangroves, which did show an increasing trend in P accumulation rates from the pre-oil era (0.03 mg P cm^{-2} yr^{-1}) to the modern era (0.06 mg P cm^{-2} yr^{-1}).

Nutrient ratios varied widely not only geographically but also within habitats. The contrast in N and P distribution is reflected in the nutrient atomic ratios in the sediments, with a cross-habitat average N:P of 1:1 in the Red Sea, whereas in the Arabian Gulf this ratio was 5:1 (table 1). Furthermore, C:N ratios in mangroves sediments of the Red Sea were more than twice those of Gulf (table 1). We measured N:P ratios in seagrass sediments in the Red Sea ranging five-fold from 0.3:1 to 1.4:1, and in Red Sea mangrove sediments ranging three-fold from 0.5:1 to 1.6:1. In the Arabian Gulf sediments, N was much more abundant relative to P, with ratios ranging from a minimum of 4:1 in mangrove to a maximum of 8:1 in seagrass sediments in Abu Ali Island (table 1).

Discussion

The N and P stocks were quite comparable within blue carbon ecosystems of the Red Sea and the Gulf (figure 2(a)). On average, N stocks were at least twofold higher in the Gulf compared to the Red Sea, while P stocks were only a maximum of 1.2 times higher in Red Sea vegetated coastal habitats.

Owing to the negligible rainfall and minimal fluvial inputs of terrestrial material to the Red Sea and Gulf, desert dust deposition is believed to be one of the main sources of nutrients N, P and Fe to both marine environments (Acosta *et al* 2013). Engelbrecht *et al* (2017) reported that deposited desert dust for the same region of the Red Sea coastline as this study, contained on average 0.8% NO_3^- and 0.3% PO_4^{3-}. Assuming that 6 Mt and 5.5 Mt of mineral dust is deposited into the Red Sea and the Gulf every year, respectively (Hamza *et al* 2011, Jish Prakash *et al* 2015), which would be equivalent to ~21 000 and ~11 000 tonnes of N and P

Table 2. Sediment stocks of N and P (g m^{-2}) to 0.2 m sediment depth, and short-term sediment accretion and N and P accumulation rates as determined by ^{210}Pb analysis, and long-term accumulation rates as determined by ^{14}C from Cusack *et al* (2018) and Saderne *et al* (2018). Values are mean ± SE of each site.

	Location	N Stock (g N m^{-2})	P Stock (g P m^{-2})	^{210}Pb sediment accretion rate (cm yr^{-1})	^{210}Pb N accumulation rate (mg N cm^{-2} yr^{-1})	^{210}Pb P accumulation rate (mg P cm^{-2} yr^{-1})	^{14}C sediment accretion rate (cm yr^{-1})	^{14}C N accumulation rate (mg N cm^{-2} yr^{-1})	^{14}C P accumulation rate (mg P cm^{-2} yr^{-1})
Red Sea Seagrass	Al Taweelah Isl.	42.6 ± 6.8	92.1 ± 49.9	N/A	N/A	N/A	0.26 ± 0.15	0.064 ± 0.026	0.086 ± 0.015
	Khor Almesena'a	95.1 ± 23.6	53.0 ± 21.9	N/A	N/A	N/A	0.12 ± 0.12	0.047 ± 0.025	0.028 ± 0.019
	Khor Al-Baqila	23.1 ± 6.0	77.0 ± 11.8	N/A	N/A	N/A	N/A	N/A	N/A
	Khor Al-Kharrar	82.0 ± 20.2	59.4 ± 12.4	N/A	N/A	N/A	0.13 ± 0.07	0.047 ± 0.026	0.042 ± 0.026
	Mean	60.7 ± 32.3	70.4 ± 57.2	N/A	N/A	N/A	0.17 ± 0.11	0.053 ± 0.044	0.052 ± 0.036
Red Sea Mangrove	Al Taweelah Isl.	81.7 ± 13.0	70.8 ± 8.2	0.21 ± 0.07	0.065 ± 0.022	0.055 ± 0.019	0.2 ± 0.4	0.05 ± 0.137	0.079 ± 0.213
	Khor Almesena'a	88.3 ± 8.8	65.8 ± 5.1	N/A	N/A	N/A	0.04 ± 0.01	0.014 ± 0.009	0.014 ± 0.008
	Khor Al-Baqila	46.6 ± 12.2	89.0 ± 9.3	0.38 ± 0.16	0.115 ± 0.048	0.153 ± 0.065	0.06 ± 0.02	0.016 ± 0.004	0.023 ± 0.008
	Khor Al-Kharrar	181.4 ± 42.7	55.3 ± 6.5	0.22 ± 0.22	0.097 ± 0.032	0.067 ± 0.027	0.06 ± 0.06	0.033 ± 0.039	0.015 ± 0.011
	Mean	99.0 ± 47.0	70.0 ± 15.0	0.27 ± 0.22	0.093 ± 0.062	0.092 ± 0.073	0.08 ± 0.17	0.028 ± 0.142	0.033 ± 0.214
Arabian Gulf Seagrass	Safaniya	185.0 ± 73.4	29.2 ± 3.6	0.21 ± 0.05	0.321 ± 0.09	0.041 ± 0.008	0.06 ± 0.02	0.096 ± 0.024	0.012 ± 0.002
	Abu-Ali Island	319.9 ± 51.2	37.5 ± 2.9	0.13 ± 0.06	0.209 ± 0.092	0.023 ± 0.01	0.3 ± 0.2	0.442 ± 0.22	0.052 ± 0.026
	Ras Tanura	259.3 ± 64.3	48.6 ± 8.6	0.07 ± 0.03	0.133 ± 0.061	0.019 ± 0.008	0.11 ± 0.02	0.149 ± 0.042	0.018 ± 0.006
	Uqair	127.9 ± 8.3	15.9 ± 4.6	0.13 ± 0.04	0.211 ± 0.115	0.026 ± 0.014	0.3 ± 0.001	0.543 ± 0.019	0.061 ± 0.003
	Mean	223.0 ± 110.5	32.8 ± 10.8	0.13 ± 0.05	0.218 ± 0.183	0.027 ± 0.021	0.2 ± 0.1	0.308 ± 0.226	0.036 ± 0.027
Arabian Gulf Mangrove	Abu-Ali Island	168.1 ± 24.2	45.0 ± 11.5	0.18 ± 0.07	0.157 ± 0.037	0.043 ± 0.009	0.07 ± 0.04	0.065 ± 0.021	0.018 ± 0.006
	Ras Tanura	249.2 ± 92.5	49.4 ± 10.8	0.25 ± 0.09	0.61 ± 0.157	0.127 ± 0.03	0.01 ± 0.001	0.011 ± 0.003	0.002 ± 0.001
	Mean	208.6 ± 95.6	47.2 ± 15.8	0.21 ± 0.09	0.383 ± 0.162	0.085 ± 0.031	0.04 ± 0.04	0.038 ± 0.022	0.01 ± 0.006
Arabian Gulf Saltmarsh	Abu-Ali Island	212.2 ± 72.0	50.7 ± 13.6	0.10 ± 0.02	0.111 ± 0.056	0.027 ± 0.007	0.05 ± 0.02	0.054 ± 0.027	0.013 ± 0.006
	Ras Tanura	318.5 ± 58.3	64.8 ± 18.8	0.09 ± 0.03	0.278 ± 0.091	0.062 ± 0.013	0.03 ± 0.01	0.057 ± 0.027	0.013 ± 0.006
	Mean	265.4 ± 92.6	57.8 ± 23.2	0.10 ± 0.01	0.195 ± 0.107	0.045 ± 0.014	0.04 ± 0.01	0.055 ± 0.038	0.013 ± 0.008

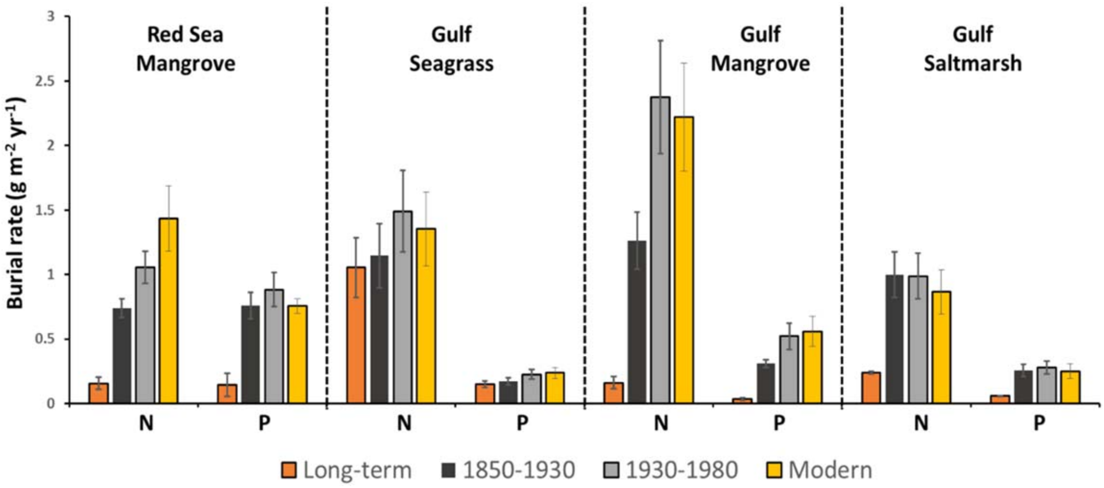

Figure 3. Accumulation rates of P and N (g m^{-2} yr^{-1} ± SE) for long-term (^{14}C dating) and periods 1850–1930, 1930–1980 and Modern (1980–2016) from ^{210}Pb for Red Sea mangrove habitats, and Arabian Gulf seagrass, mangrove and saltmarsh habitats. The ^{210}Pb and ^{14}C sediment accretion rates used for calculations are from Cusack *et al* (2018) and Saderne *et al* (2018).

in both the Red Sea and the Gulf, we estimate that blue carbon habitats of Saudi Arabia could potentially accumulate between 0.3% and 0.8% of annually deposited nutrients by dust deposition.

The ratios of N:P in our sediments, ranging from 0.3:1 to 8:1 (table 1), highlight that vegetated coastal habitats along the Saudi coast are severely N limited, based on the Redfield ratio, which states that molar ratios of N:P <16:1 are N limited (Redfield 1960, Downing 1997). This hypothesis is further reinforced if we consider the ratio of 30:1 for vegetated benthic ecosystems of Atkinson and Smith (1983). Red Sea sediments are more severely N limited relative to Gulf ecosystems (table 1). This low ratio in the benthic habitats of the Gulf contrasts with the ratio in open waters that approaches the Redfield ratio (Hashimoto *et al* 1998, Al-Yamani and Naqvi 2019). This ratio is, however, consistent with the low ratio found in the water column above seagrass beds of the Saudi coast of the Gulf, at 1.6 ± 2.1 (mean ± SD) (KFUPM 2011). A higher ratio has been reported in a seagrass and mangrove ecosystem of the central Red Sea with 8.1 ± 9.6 and 4.9 ± 5.6, respectively (mean ± SD; calculated from Saderne *et al* 2019).

In contrast to P, N accumulation rates exhibit higher spatial and temporal variability, respectively. Short-term N accumulation rates (figure 2(c)) have increased between 1.3 and 15-fold relative to long-term accumulation rates (figure 2(b)). Comparing modern-day N accumulation rates to those of the pre-oil discovery period (figure 3), there has been a significant rise in accumulation rates in Red Sea and Gulf mangroves, which is possibly a result of large-scale N mobilization from anthropogenic activities. In the case of Red Sea mangroves, N accumulation rates have increased steadily since the pre-oil discovery period until the modern-day (figure 3). Almahasheer *et al* (2016b), who also described sediment accretion rates and C_{org} accumulation for the same locations of the Red Sea as this study (Almahasheer *et al* 2017), suggested that high values of $\delta^{15}N$ in mangrove sediments of the Central Red Sea was indicative of sewage and fertilizer sources, thus indicating a possible local source of anthropogenic N. Unfortunately, the Red Sea and the Gulf suffer from a lack of data on seawater chemistry, spatial and temporal, that would allow to correlate the increase of nutrients in the sediments to a potential increase in the water column (Al-Yamani and Naqvi 2019). We note however, that the apparent reduction of N and P accumulation rates in deep sediments could also be due to remobilization of labile N and P from deep to surface sediments.

The capacity of vegetated coastal ecosystems of the Arabian Peninsula to sequester nutrients is significant. Whereas the area coverage of seagrass meadows in the Red Sea and the Gulf remains poorly constrained, mangrove coverage has been accurately mapped for the Red Sea (135 km^2; Almahasheer *et al* 2016a) and the Gulf (165 km^2; Almahasheer 2018). The extrapolation of mangrove N and P stocks measured in this study to the entire Red Sea and Gulf, suggest that mangrove sediments hold 13 365 ± 6345 tons of N and 9450 ± 2025 tons of P in the Red Sea, and 34 485 ± 15 840 tons of N and 7755 ± 2640 tons of P in the Gulf within the top 0.2 m of sediments. Based on our average short-term sediment accumulation rates of N and P (table 2), mangrove sequester 125 ± 83 Mg yr^{-1} of N and 124 ± 98 Mg yr^{-1} of P in the Red Sea, and 518 ± 218 Mg yr^{-1} of N and 115 ± 42 Mg $yr^{-1}$of P in the Gulf. Furthermore, at characteristic concentrations of about 2 mmol m^{-3} nitrate and 0.2 mmol m^{-3} phosphate in surface waters of the highly oligotrophic Red Sea, the average stock in one square meter of the top 0.2 m of mangrove sediments contain the equivalent in N and P of 13 700 m^3 and 102 000 m^3 of Red Sea surface waters, respectively. For

seagrass sediments, this represents the equivalent of 8200 m^3 and 102 000 m^3 of Red Sea surface waters for N and P, respectively, which highlights the role of vegetated coastal ecosystems as massive sinks and reservoirs for nutrients in the oligotrophic Red Sea.

Published data on nutrient accumulation rates in blue carbon ecosystems are rather scarce. Breithaupt *et al* (2014) presented a short review of the available accumulation rates for mangroves, mostly obtained using the ^{210}Pb dating technique, and found a global mean/median of 1.25/0.89 mg N cm^{-2} yr^{-1} and 0.65/0.07 mg P cm^{-2} yr^{-1}. In comparison, the accumulation rates of N in the Red Sea and Gulf mangroves (table 2) range among the lowest, while the accumulation rates of P are within the global median (with the mean being strongly influenced by high accumulation rates reported in the Jiulongjiang Estuary in China). The low short-term N accumulation rates found in our study are mainly due to low N densities because sediment accumulation rates in our Red Sea and Gulf cores are within the global average (see discussion in Saderne *et al* 2018. For example, Breithaupt *et al* 2014 found N and P densities in mangrove sediments of 2.5 ± 0.9 and 0.21 ± 0.06 mg cm^{-3} in the Everglades (Florida, USA), which is higher than our N densities (0.33 ± 0.26 and 1.04 ± 0.22 mg N cm^{-3} in the Red Sea and Gulf), but comparable in terms of P densities 0.34 ± 0.18 and 0.24 ± 0.05 mg P cm^{-3} for the Red Sea and Gulf) (table 1).

Regarding seagrass, Eyre *et al* (2016) reported short-term N accumulation rates ranging from 0.82 to 0.13 mg N cm^{-2} yr^{-1} in three estuarine systems of New South Wales (Australia), which are similar to those reported here for the Gulf (0.22 mg N cm^{-2} yr^{-1}; table 2). Similarly, in the coastal bays of the Delmarva Peninsula (Virginia, USA) Aoki *et al* (2019) found N accumulation rates of 0.35 mg N cm^{-2} yr^{-1}. We could not find other direct reports of N and P accumulation rates in seagrass meadows. However, we estimated N and P accumulation rates in Florida Bay (Cheng *et al* 2012) and Shark Bay (Western Australia, Arias-Ortiz *et al* 2018a, 2018b) based on separate reports of nutrients densities and ^{210}Pb sediment accretion rates (0.08 mg P cm^{-2} yr^{-1} and 0.025 mg P cm^{-2} yr^{-1} for Florida Bay and Shark Bay, respectively), which are comparable to the rates estimated for the Gulf (0.027 mg P cm^{-2} yr^{-1}). For Shark Bay, we estimated an N accumulation rate of 0.29 mg N cm^{-2} yr^{-1}, which is comparable to the rate found in the Gulf.

To our knowledge, our study is the first report of N and P accumulation rates in sediments of arid saltmarshes (short-term: 0.195 ± 0.107 and 0.045 ± 0.014 mg cm^{-2} yr^{-1} respectively). Overall, the only study reporting such data was from Cape Fear River in North Carolina (USA), with mean (±SE) N and P accumulation rates based on ^{210}Pb of 0.49 ± 0.22 mg N cm^{-2} yr^{-1} and 0.05 ± 0.03 mg P cm^{-2} yr^{-1} (Noll *et al* 2019). For comparative reasons, we estimated short-term N and P accumulation rates separately from four different studies. In the tropical saltmarshes of Mexico and El Salvador, we calculated rates ranging from 0.08 mg N cm^{-2} yr^{-1} to 1.4 mg N cm^{-2} yr^{-1}, with an estimated mean of 0.46 mg N cm^{-2} yr^{-1} from the data in Ruiz-Fernández *et al* (2018). In a North Mediterranean saltmarsh (Marano lagoon, Italy, Adratic Sea). Covelli *et al* (2012) reported N accumulation rates ranging from 0.3 to 1 g N cm^{-2} yr^{-1}. Regarding P, short-term accumulation rates ranging from 4.5 to 6 mg P cm^{-2} yr^{-1} were reported for temperate saltmarshes of the Scheldt estuary (the Netherlands; Zwolsman *et al* 1993), i.e. 100 times higher than the rates in the Gulf. These high burial rates are, however, explained by sediment accretion rates 9–13 times higher than in our cores, rather than differences in nutrient concentrations. In comparison, Spencer *et al* (2003) found P accumulation rates of 0.12 mg P cm^{-2} yr^{-1} in a saltmarsh of the Medway river estuary (UK). Overall, although comparisons between such different types of saltmarshes are somewhat difficult, it seems that the rates found in the Gulf range among the lowest reported anywhere.

Conclusion

Vegetated coastal ecosystems such as mangroves, seagrass meadows and saltmarshes provide a range of essential services to coastal communities, such as protection against sea-level rise, fish nurseries, and trapping of carbon and sediment. However, their role as possible sinks for nutrients has received comparatively little attention, despite the massive mobilization of nutrients, especially N and P, into the environment on a massive scale over the past century. Here, we measured the below-ground sediment stocks of N and P at several locations in the central Red Sea and along the Gulf coast of Saudi Arabia to determine that these habitats are major sinks for N and P. Indeed, the accumulation rate of these nutrients has increased over time, quite possibly because of human activities leading to the major mobilization of these nutrients. Our results provide evidence for a hitherto understudied but valuable ecosystem service that is, on a local scale, as important as their capacity to sequester carbon, and provides further impetus for the conservation of these habitats.

Acknowledgments

This research was supported by a project funded by base-line funding from King Abdullah University of Science and Technology (KAUST). OS was supported by an ARC DECRA (DE170101524). We thank R Lindo, R Magalles, P Bacquiran, S Ibrahim and M Lopez, at the Marine Studies section of the Center for Environment and Water of King Fahd University of Petroleum and Minerals and Z Batang and staff from

the Coastal and Marine Resources core lab at KAUST for help with sampling. We thank I Schulz, N Geraldi, K Rowe, S Roth, M Ennasri, D Prabowo and I Mendia for help with laboratory analyses. We wish to thank the two anonymous reviewers, as well as the editor for their precious comments/suggestions that improved the manuscript.

Any data that support the findings of this study are included within the article.

ORCID iDs

V Saderne https://orcid.org/0000-0003-3968-2718
M Cusack https://orcid.org/0000-0002-9804-2641
O Serrano https://orcid.org/0000-0002-5973-0046
H Almahasheer https://orcid.org/0000-0002-7696-7707
L Rabaoui https://orcid.org/0000-0003-2068-692X
C M Duarte https://orcid.org/0000-0002-1213-1361

References

Aburto-Oropeza O, Ezcurra E, Danemann G, Valdez V, Murray J and Sala E 2008 Mangroves in the Gulf of California increase fishery yields *Proc. Natl. Acad. Sci.* **105** 10456–9

Acosta F, Ngugi D K and Stingl U 2013 Diversity of picoeukaryotes at an oligotrophic site off the Northeastern Red Sea Coast *Aquat. Biosyst.* **9** 16

Almahasheer H 2018 Spatial coverage of mangrove communities in the Arabian Gulf *Environ. Monit. Assess.* **190** 85

Almahasheer H, Aljowair A, Duarte C M and Irigoien X 2016a Decadal stability of Red Sea mangroves *Estuar. Coast. Shelf Sci.* **169** 164–72

Almahasheer H, Al-Taisan W and Mohamed M K 2013 Mangrove deterioration in tarut bay on the eastern province of the Kingdom of Saudi Arabia Pakhtunkhwa *J. Life Sci.* **01** 49–59

Almahasheer H, Duarte C M and Irigoien X 2016b Nutrient limitation in central Red Sea mangroves *Frontiers Mar. Sci.* **3** 271

Almahasheer H, Serrano O, Duarte C M, Arias-Ortiz A, Masque P and Irigoien X 2017 Low carbon sink capacity of Red Sea mangroves *Sci. Rep.* **7** 1–10

Almazroui M, Islam M N, Jones P D, Athar H and Rahman M A 2012 Recent climate change in the Arabian Peninsula: seasonal rainfall and temperature climatology of Saudi Arabia for 1979–2009 *Atmos. Res.* **111** 29–45

Alongi D M and McKinnon A D 2005 The cycling and fate of terrestrially-derived sediments and nutrients in the coastal zone of the Great Barrier Reef shelf *Mar. Pollut. Bull.* **51** 239–52

Al-Yamani F and Naqvi S W A 2019 Chemical oceanography of the Arabian Gulf *Deep. Res.* II **161** 72–80

Anton A *et al* Dwarfed mangrove trees in the oligotrophic Red Sea. Unpublished

Aoki L R, McGlathery K J and Oreska M P J 2019 Seagrass restoration reestablishes the coastal nitrogen filter through enhanced burial *Limnol. Oceanogr.* **65** 1–12

Arias-Ortiz A, Masqué P, Garcia-Orellana J, Serrano O, Mazarrasa I, Marbá N, Lovelock C E, Lavery P S and Duarte C M 2018a Reviews and syntheses: ^{210}Pb-derived sediment and carbon accumulation rates in vegetated coastal ecosystems - setting the record straight *Biogeosciences* **15** 6791–818

Arias-Ortiz A *et al* 2018b A marine heatwave drives massive losses from the world's largest seagrass carbon stocks *Nat. Clim. Chang.* **8** 1–7

Atkinson M J and Smith S V 1983 C:N:P ratios of benthic marine plants1 *Limnol. Oceanogr.* **28** 568–74

Atwood T B *et al* 2017 Global patterns in mangrove soil carbon stocks and losses *Nat. Clim. Change* **7** 523–8

Breithaupt J L, Smoak J M, Byrne R H, Waters M N, Moyer R P and Sanders C J 2018 Avoiding timescale bias in assessments of coastal wetland vertical change *Limnol. Oceanogr.* **63** S477–95

Breithaupt J L, Smoak J M, Smith T J and Sanders C J 2014 Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades *J. Geophys. Res.* G **119** 2032–48

Brewer P G and Dyrssen D 1985 Chemical oceanography of the Persian Gulf *Prog. Oceanogr.* **14** 41–55

Cheng J, Collins L S and Holmes C 2012 Four thousand years of habitat change in Florida bay, as indicated by benthic foraminifera *J. Foraminifer. Res.* **42** 3–17

Covelli S, Langone L, Acquavita A, Piani R and Emili A 2012 Historical flux of mercury associated with mining and industrial sources in the Marano and Grado Lagoon (northern Adriatic Sea) *Estuar. Coast. Shelf Sci.* **113** 7–19

Cusack M *et al* 2018 Organic carbon sequestration and storage in vegetated coastal habitats along the western coast of the Arabian Gulf *Environ. Res. Lett.* **13** 074007

Donato D C, Kauffman J B, Murdiyarso D, Kurnianto S, Stidham M and Kanninen M 2011 Mangroves among the most carbon-rich forests in the tropics *Nat. Geosci.* **4** 293–7

Downing J 1997 Marine nitrogen: phosphorus stoichiometry and the global N:P cycle *Biogeochemistry* **37** 237–52

Duarte C M, Losada I J, Hendriks I E, Mazarrasa I and Marbà N 2013 The role of coastal plant communities for climate change mitigation and adaptation *Nat. Clim. Change* **3** 961–8

Engelbrecht J, Stenchikov G, Prakash P J, Anisimov A and Shevchenko I 2017 Physical and chemical properties of deposited airborne particulates over the Arabian Red Sea coastal plain *Atmos. Chem. Phys. Discuss.* **17** 11467–90

Erftemeijer P L A and Shuail D A 2012 Seagrass habitats in the arabian gulf: distribution, tolerance thresholds and threats *Aquat. Ecosyst. Heal. Manag.* **15** 73–83

Eyre B D, Maher D T and Sanders C 2016 The contribution of denitrification and burial to the nitrogen budgets of three geomorphically distinct Australian estuaries: importance of seagrass habitats *Limnol. Oceanogr.* **61** 1144–56

Feng J, Zhou J, Wang L, Cui X, Ning C, Wu H, Zhu X and Lin G 2017 Effects of short-term invasion of Spartina alterniflora and the subsequent restoration of native mangroves on the soil organic carbon, nitrogen and phosphorus stock *Chemosphere* **184** 774–83

Fourqurean J W, Kendrick G A, Collins L S, Chambers R M and Vanderklift M A 2012 Carbon, nitrogen and phosphorus storage in subtropical seagrass meadows: examples from Florida Bay and Shark Bay *Mar. Freshw. Res.* **63** 967–83

Hamza W, Enan M R, Al-Hassini H, Stuut J B and De-Beer D 2011 Dust storms over the Arabian Gulf: a possible indicator of climate changes consequences *Aquat. Ecosyst. Heal. Manage.* **14** 260–8

Hashimoto S, Tsujimoto R, Maeda M, Ishimaru T, Yoshida J, Takasu Y, Koike Y, Kamatani A and Otsuki A 1998 *Distribution of nutrients, nitrous Oxide, and Chlorophyll a of RSA: Extremly High Ratios of nitrite to nitrate in whole water column Offshore Environment of the ROPME Sea Area After the War-Related Oil Spill—Results of the 1993–94 Umitaka-Maru Cruises* ed R M Otsuki *et al* (Tokyo: Terra Scientific Publishing Company (Terrapub)) pp 99–124

Hopkinson C S and Giblin A E 2008 *Nitrogen Dynamics of Coastal Salt Marshes Nitrogen in the Marine Environment* ed E J C Douglas *et al* 2nd edn (Amsterdam: Elsevier) pp 991–1036

Howard J, Hoyt S, Isensee K, Pidgeon E and Telszewski M 2014 Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International

Union for Conservation of Nature, Arlington, VA, USA 1–180

Jish Prakash P, Stenchikov G, Kalenderski S, Osipov S and Bangalath H 2015 The impact of dust storms on the Arabian Peninsula and the Red Sea *Atmos. Chem. Phys.* **15** 199–222

Jordan T E, Whigham D F, Hofmockel K H and Pittek M A 2003 Nutrient and sediment removal by a restored wetland receiving agricultural runoff *J. Environ. Qual.* **32** 1534

KFUPM/RI 2011 Annual Report: sustaining research project—marine environmental studies *Phase V. Prepared for Saudi Aramco by the Center for Environment and Water* Report Project No. CEW2344 Research Institute, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

Kindeberg T, Ørberg S B, Röhr M E, Holmer M and Krause-Jensen D 2018 Sediment stocks of carbon, nitrogen, and phosphorus in Danish eelgrass meadows *Frontiers Mar. Sci.* **5** 1–14

McGlathery K J, Reynolds L K, Cole L W, Orth R J, Marion S R and Schwarzschild A 2012 Recovery trajectories during state change from bare sediment to eelgrass dominance *Mar. Ecol. Prog. Ser.* **448** 209–21

McLeod E, Chmura G L, Bouillon S, Salm R, Björk M, Duarte C M, Lovelock C E, Schlesinger W H and Silliman B R 2011 A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2 *Frontiers Ecol. Environ.* **9** 552–60

Mumby P J *et al* 2004 Mangroves enhance the biomass of coral reef fish communities in the Caribbean *Nature* **427** 533–6

Noll A, Mobilian C and Craft C 2019 Five decades of wetland soil development of a constructed Tidal Salt Marsh, North Carolina, USA *Ecol. Restor.* **37** 163–70

Rabaoui L *et al* 2019 Anthropogenic-induced acceleration of elemental burial rates in blue carbon repositories of the Arabian Gulf *Sci. Total Environ.* 135177 at press

Redfield A C 1960 The biological control of chemical factors in the environment *Sci. Prog.* **11** 150–70

Ruiz-Fernández A C *et al* 2018 Carbon burial and storage in tropical salt Marshes under the influence of sea level rise *Sci. Total Environ.* **630** 1628–40

Saderne V, Baldry K, Anton A, Agustí S and Duarte C M 2019 Characterization of the CO_2 system in a coral reef, a seagrass meadow, and a mangrove forest in the Central Red Sea *J. Geophys. Res. Ocean.* **2** 1–16

Saderne V, Cusack M, Almahasheer H, Serrano O, Masqué P, Arias-Ortiz A, Krishnakumar P K, Rabaoui L, Qurban M A and Duarte C M 2018 Accumulation of carbonates contributes to coastal vegetated ecosystems keeping pace with sea level rise in an arid region (Arabian peninsula) *J. Geophys. Res. Biogeosciences* **123** 1498–510

Spencer K L, Cundy A B and Croudace I W 2003 Heavy metal distribution and early-diagenesis in salt Marsh sediments from the Medway Estuary, Kent, UK *Estuar. Coast. Shelf Sci.* **57** 43–54

Sugden W 1963 Some aspects of sedimentation in the Persian Gulf *SEPM J. Sedim. Res.* **33** 355–64

Wafar M, Qurban M A, Ashraf M, Manikandan K P, Flandez A V and Balala A C 2016 Patterns of distribution of inorganic nutrients in Red Sea and their implications to primary production *J. Mar. Syst.* **156** 86–98

Weikert H 1987 *Plankton and the Pelagic Environment Red Sea* (Amsterdam: Elsevier) pp 90–111

Zwolsman J J G, Berger G W and Van Eck G T M 1993 Sediment accumulation rates, historical input, postdepositional mobility and retention of major elements and trace metals in salt march sediments of the Scheldt estuary, SW Netherlands *Mar. Chem.* **44** 73–94