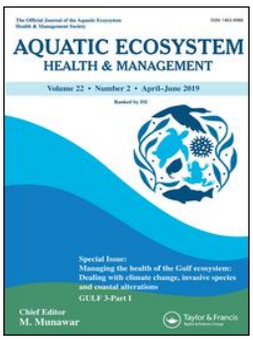

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Nutritive effect of dust on microbial biodiversity and productivity of the Arabian Gulf

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Abstract

The Arabian Gulf is exposed to intensive dust storms during summer until early winter. We investigated the nutritive effect of the dust on microbial biodiversity of the water column and the productivity of the Gulf. We collected samples from three sites in a transect perpendicular to the shore in March (before the strong dust storms) and in October (after the dust season) in 2013. At the three sites, we sampled the water column at three depths, and see-floor sediments using a HAPS corer. We also sampled the sand dunes that are the source of the dust. We analyzed the samples for pigments, microbial community composition using a 16S rRNA analysis, and nutrients. Our results showed that species richness and biodiversity were higher in October than in March. The relative abundances of key-player microorganisms were strongly pronounced in October. We assume that the dust rapidly sinks to the seafloor where the nutrients Fe and P are liberated through iron reduction. Assuming that all phosphate diffusing from the seafloor originates from the dust particles after deposition, we estimated a contribution of minimum 30,000 tons of fish produced every year in the Gulf. We found no close temporal coupling between dust storms and productivity. This is because nutrient liberation from the seafloor is slow and its transport from the seafloor to the photic zone by circulation processes is irregular. This study highlights the importance of dust as a source of nutrients in the Gulf ecosystem..

Introduction

The Arabian/Persian Gulf is a bowl- shaped semi-enclosed water body with a total volume of around 900 km3 (Alosairi et al., 2011), with well-constrained element budgets, which makes it ideal for testing ecological hypotheses on large scale. It is connected to the Gulf of Oman from the south through a narrow (i.e., 33 Km wide) marine passage called the Strait of Hormuz. The average depth of the Gulf ~ 30 m, and the depth gradually increases from the strait seaward toward the Arabian Sea and the Indian Ocean (Kämpf and Sadrinasab, 2006). The organic material content of the Gulf is relatively high, which mainly originates from biological productivity (Al-Ghadban et al., 1994; Sheppard et al., 2010). Similar to other ecosystems driven by light energy such as coral reefs (Hochberg and Atkinson, 2008), rain forests (Sand-Jensen, 1997) and microbial mats (Al-Najjar et al., 2014; Al-Thani et al., 2014), the availability of

nutrients and the light energy from the sun determine the productivity of this ecosystem. Light that is trapped by photosynthetic microorganisms will be used to fix CO2 only when essential nutrients are available. Part of the fixed carbon and the stored energy will be transferred to the higher level in the food web of the ecosystem. The excreted exudates, the dissolved and the particulate organic matter will be further degraded by heterotrophic microorganisms releasing the inorganic nutrients again to the ecosystem. This so-called " microbial loop" (Buchan et al., 2014) controls the cycling of elements and thereby sustains the productivity of the ecosystem. However, unavoidable losses must be compensated by external nutrient supply to maintain the very high productivity of the Gulf. Several interesting studies measured nutrients in the Gulf and followed their spatial and temporal distribution (Al-Said et al., 2018; Michael Reynolds, 1993), However, exactly how nutrient input occurs and how essential nutrients become bioavailable is not fully understood.

In the Gulf region, sunlight is not limiting, because the sun shines almost every day and on an average of 10 h day^{-1} (Al Mahdi et al., 1992). The Gulf has very limited river discharges, which provides an important source of nutrients for other seas (Ludwig et al., 2009). The only river supply for the Gulf comes from the northern and the north-eastern part of the Gulf, represented by The Shatt Al Arab River (North) and three rivers from the Iranian side: the Hendijan, the Hilleh and the Mand (Michael Reynolds, 1993; Munawar, 2009). Other sources of fresh water that supply nutrients to the Gulf are rain and the submarine springs, but their contributions are negligible (< 0.15 m $year^{-1}$ per unit surface area; (Fairbridge, 1982; Johns et al., 2003; M. Farzin, 2017). Organic material is also obtained from human discharges from oil production and transportation, municipal, and petrochemical industries (Monazami Tehrani et al., 2014). The effect of these resources is more prominent in the coastal areas than off shore water, as their disposal occurs close to the shore. Water circulation is an important controlling factor for exchanging nutrients between different water bodies (from Gulf of Oman and Arab Sea to the Gulf), and between different layers within the Gulf (Alosairi et al., 2011; Kämpf and Sadrinasab, 2006). Water circulation in the Arabian Gulf is driven by wind, salinity, high evaporation rates and high temperatures.

Dust may represent an important source of nutrient that support the productivity of the Gulf. Most commonly, marine primary production is limited by nitrogen, iron and phosphate (Elser et al., 2007; Mills et al., 2004). Whereas nitrogen is provided by N-fixation, iron and phosphate can well be supplied by dust, as it is rich in Fe(III) that forms complexes with phosphate.. The Arabian Peninsula is considered one of the major sources of dust, characterized by high dust storm intensities, because it is one of the largest desert areas in the world (Goudie and Middleton, 2001; Hamza et al., 2011; Miller et al., 2008; Sissakian et al., 2013). Dust storms are caused by the presence of many sand dunes, arid conditions, and monsoon winds during spring and summer seasons (April-August). Substantial quantities of the sand are carried by dust storms to the Arabian Gulf basin and the Gulf of Oman (Alobaidi et al., 2017; Foda et al., 1985; Hamza et al., 2011). The dust input is so large that it elevates the Gulf floor by 1-2 mm $year^{-1}$

The studies on the dust in the Gulf region have concentrated—so far—on the physical and chemical influences, and on the factors affecting the transport of the dust from the source to the sink (examples (Hamza et al., 2011; Miller et al., 2008; Sissakian et al., 2013). Except for a laboratory scale experiment at the UAE (Hamza, 2008), there is no work that investigated the effect of dust on the microbial biodiversity and the productivity of the Arabian Gulf. We expect that dust will sink too fast to the sea-bottom for effective uptake by phytoplankton. That is a complex process, as iron oxides are insoluble. After a microbial reduction the iron and phosphate that is bound to the iron oxides become biologically available (Jilbert and Slomp, 2013). Such a reduction process is well possible in the anoxic zones of the sediments.

In the shallow Gulf, most of the remineralization will take place in the sediments. The organic matter supplies electrons for iron reduction, leading to release of Fe2+ and phosphate. The liberated nutrients, partially complexed by organics, can be transported to the upper surface by water column circulation. To test our hypothesis, we investigated the microbial biodiversity, sediment biogeochemistry and productivity before and during the dust season.

Materials and Methods

Sites of sampling

The marine samples were collected from three sites in a transect perpendicular to the shore (Fig.1), starting from close to shore (S1; N251802.3 E514542.0), the middle (S2; N255308.8 E521055.6), and the off-shore (S3; N 253744.7 E520008.9). At each location we sampled 3 depths in the water column (0.5m below sea surface, at 10m, and 0.5m above sediment surface), and the sea floor sediment. The sampling was done during a cruise in March (3rd & 4th), and in October (30th & 31st) of 2013 using the research vessels "Janan" and "Mukhtaber Albihar", respectively.

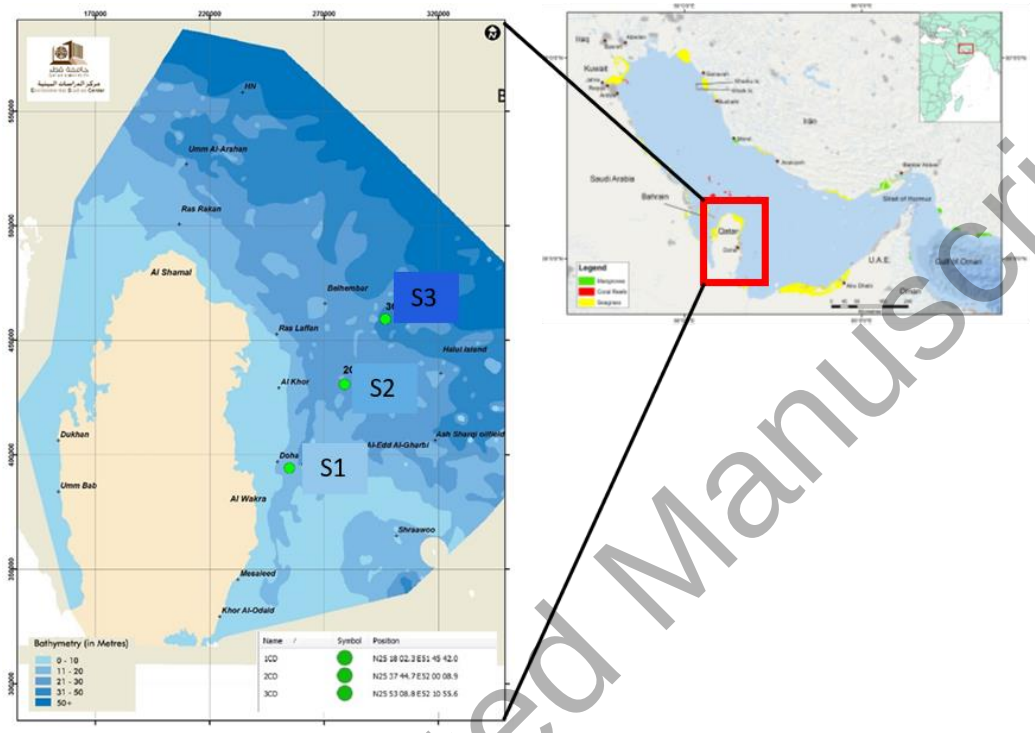

Figure 1. The map depicts the three sampling locations starting from the site closest to the shore (S1: N251802.3 E514542.0), in the middle (S2: N255308.8 E521055.6), and the off-shore site (S3: N 253744.7 E520008.9).

Sampling for Pigment analysis and DNA extraction

For DNA extraction and photopigment harvesting from the water column, we filtered 2L of seawater with 0.2 µm polycarbonate filter membrane (47 mm diameter, Millipore). After filtration, the filters were wrapped in aluminum foil –stored at -20° C. From the sediment, the top ~0.5 cm of sediments that was sampled by a HAPS corer were stored in 15 ml Falcon tubes distributed equally between two tubes; one for pigment analysis and the second one for DNA extraction. The tools were sterilized using 70% ethanol before and after each sample. The samples for pigment analysis from the water column and from the sediment were shipped to Max-Planck Institute-Germany in dry ice for further analysis using the HPLC.

Pigment analysis

Sample preparation for pigment extraction was done as described in Al-Thani et al., (2014). Pigments were separated according to the method described by (Wright et al., 1991). Identification and

quantification were done by comparing the retention time and absorption spectrum of the eluents with those of pigment standards. The pigment standards were from DHI Water and Environment, Denmark.

DNA extraction and 454-pyrosequencing

DNA was extracted from the sediment (0.3 gram) and the whole filters and purified using the UltraClean soil DNA isolation kit (MO BIO Laboratories, Inc., Carlsbad, CA, USA) according to the manufacturer's instructions. The extracted DNA was then analyzed by 454 pyrosequencing for Bacterial diversity. Primer sets (27Fmod AGRGTTTGATCMTGGCTCAG and 519Rmodbio GTNTTACNGCGGCKGCTG) were used for Bacterial sequences. Pyrosequencing was done by Research and Testing Laboratories, Lubbock, Texas, using a Roche 454 FLX Genome Sequencer system as previously described (Dowd et al., 2008)(2008).
Sequence processing was performed using the software "mothur v1.34" (Schloss et al., 2009). Sequences were curated for quality, length and denoising using parameters recommended in (Schloss and Westcott, 2011). Sequences were aligned and classified using the SILVA reference alignment v119 (downloaded from http://www.mothur.org/wiki/Silva_reference_alignment). Diversity indices and Non-Metric Multidimensional Scaling (NMDS) axes were calculated in mothur. NMDS was calculated using the Bray-Curtis algorithm and plotted using PAST3 (Hammer et al., 2001).

Iron bio-availability

Samples from several sand dunes were collected on the main land of Qatar near the border with Kingdom of Saudi Arabia and along the eastern coast of the peninsula. To determine the availability of iron for biota in the Gulf, after deposition of the aeolian sediments, a sequential-leaching experiment was set up. We exposed the dry- and wet sediments that were collected on land and from the Gulf to solutions of NH4Cl (2M), ascorbic acid (0.11 M at pH 8.0), and Nitric acid (1M at pH 0) to measure the bioavailable iron and the accumulative iron according to (Kostka and Luther, 1994). After each reaction, the residue was measured using an ICP-MS, to determine how much of each element was leached by the respective solution. NH4Cl was used to leach adsorbed elements, ascorbic acid was used to leach the amorphous oxides, and Nitric acid was used to leach Calcium Carbonates. All reactions were conditioned at room temperature and took place in 50ml Falcon tubes.

Pore-water analysis

Porewater was extracted through pre-drilled holes in the core liners in 2 cm intervals using Rhizons (pore size <0.2 µm, Rhizosphere Research Products). One subsample of the porewater was frozen for phosphate analyses using standard methods (Grasshoff et al., 1983). Another subsample was fixed with concentrated HCl and total Fe concentrations were determined using the Ferrozine method (Viollier et al., 2000).

Chamber incubations

Flux incubations were performed to quantify organic matter remineralization and the release of nutrients into the water. For this sediment cores (8 cm in diameter) and overlying water were incubated in gas tight chambers. The water was stirred at 10 rpm by a suspended stirring bar, driven by an external magnet. The chambers were incubated in aquaria submerged in water from the respective site to allow for water exchange. After a pre-incubation time of one hour, the chamber lids were closed and cores were incubated for approximately four hours in dark and at a constant temperature, 24 °C. At the beginning water samples were taken from each aquarium and at the end from each core. Water samples were analyzed for oxygen using a fast-responding Clark-type oxygen microsensor (tip diameter ~30 µm; Revsbech, 1989) and for nutrients using standard procedures. The flux of analytes was calculated from the difference between end and start concentrations, respecting incubation time and sediment surface area.

Results

Microbial community analysis

In total, we analyzed 246,272 good bacterial sequences (Table 1). In general, the number of sequences in the water column samples were much higher than those in the sediment samples and in sand dunes. The coverage in the water samples was more than 98%, while it ranged between 70-78% in the sediment samples. Species richness indices (sob, Chao, and Ace) showed higher species richness in the sediment samples compared to those collected from the water column. When considering the time of sampling, species richness was higher in the samples collected in October than the samples collected in March. Similarly, the sediment samples were more diverse (> 290, compared to maximum 9; based on inverted Simpson index) than the samples collected from the water column. The water samples collected in October were considerably more diverse than those collected in March. Conversely, the sediment sample showed a much higher diversity in March than in October.

Table1. Number of sequences (N. seq.), coverage, species richness [the total number of Species Observed in a Sample (sobs); Chao; Abundance-based Coverage Estimator (Ace)], and biodiversity index (inverted Simpson) carried for both March and October samples. Each sample is named after the time of collection (March or October abbreviated as "Mar" or "Oct", respectively), followed by the year "2013", followed by station number abbreviated as "S1, S2, & S3), and ended with the depth measured from the surface water. For the sediment samples, "sed" was added instead of the depth. The samples collected from the Dunes were only from the first cruise (March 2013)

Samples	N seq	Coverage %	Sobs	Chao	Ace	Inv. Simpson
Dunes	934.0	91.6	177.0	302.1	271.7	32.2
Mar13S1-50cm	5579.0	99.1	161.0	208.0	209.3	5.0
Mar13S1-10m	5712.0	98.8	187.0	267.5	272.9	3.6
Mar13S1-18m	22669.0	98.7	524.0	1106.2	1574.3	3.8
Mar13S1_Sed	8713.0	77.9	3168.0	6423.6	9941.8	292.8
Mar13S2_50cm	6361.0	99.0	170.0	237.3	289.8	3.9
Mar13S2_10m	13071.0	99.4	196.0	297.3	381.7	3.3
Mar13S2_24m	10874.0	99.2	210.0	321.6	318.1	2.7
Mar13S2_Sed	6644.0	72.4	2903.0	6358.2	9523.8	719.9
Mar13S3_50cm	10213.0	99.2	203.0	351.8	395.3	3.7
Mar13S3_10m	9930.0	99.2	211.0	314.8	360.4	3.7
Mar13S3_35m	5595.0	98.8	199.0	264.1	269.5	3.4
Mar13S3_Sed	6799.0	71.7	2998.0	6720.4	10239.9	892.2
Oct13S1_50cm	6719.0	98.8	236.0	333.2	321.6	3.4
Oct13S1_10m	6305.0	98.9	195.0	272.5	273.7	2.5
Oct13S1_18m	7212.0	97.8	396.0	624.4	588.8	6.5
Oct13S1_Sed	4940.0	70.7	2238.0	5077.0	7515.3	418.4
Oct13S2_50cm	9560.0	99.0	286.0	371.9	393.5	6.4
Oct13S2_10m	19403.0	98.8	512.0	827.1	1104.1	6.2
Oct13S2_24m	8600.0	98.1	409.0	592.4	614.2	9.4
Oct13S2_Sed	6247.0	73.6	2642.0	5816.4	8573.3	724.0
Oct13S3_50cm	10237.0	99.0	263.0	390.0	398.0	4.0
Oct13S3_10m	6197.0	98.8	211.0	302.4	356.2	5.1
Oct13S3_35m	11104.0	98.9	319.0	454.4	450.2	3.9
Oct13S3_Sed	5784.0	75.0	2383.0	4899.5	7087.8	699.4

Microbial biodiversity in the water column and in the sediment

All the water column samples were dominated by bacteria belonging to the class cyanobacteria (relative abundance reaching to > 70%) and a group of "Unclassified" bacteria (up to 60%) (Fig.2). The relative abundances of the groups belonging to the classes Flavobacteria, Gamma-proteobacteria, and Bacteriodetes were considerably lower, but may reached up to 10% like the samples collected in October from station 2. In general, all the samples collected in October showed higher relative abundances of the most abundant bacterial classes, they also showed higher diversity (see Table 1) compared to those collected in March.

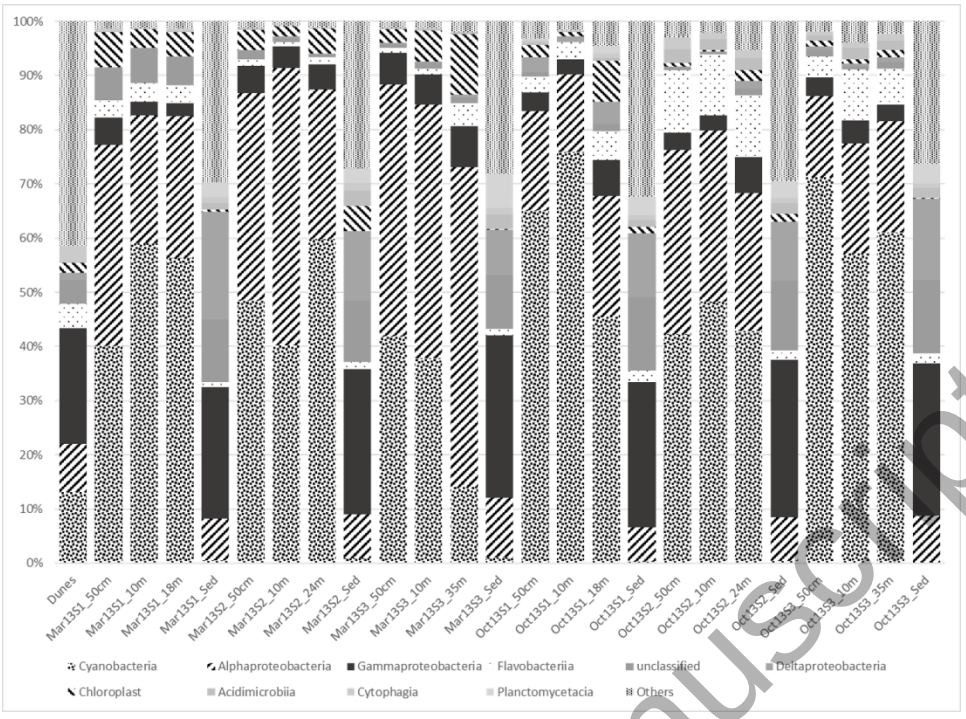

Figure 2. Relative abundance (relative to the total identified bacterial sequences) of different bacterialclasses in different samples of the water column. Each sample is named after the time of collection (March or October abbreviated as "Mar" or "Oct", respectively), followed by the year "2013", followed by station number abbreviated as "S1, S2, & S3), and ended with the depth measured from the surface water.

While the dunes sample showed more diverse microbial community composition, all the sediment samples represented similar trends when it comes to the relative abundance of bacteria at the "class' level (Fig. 2). We analyzed the sequencing data of the sediment in more depth to investigate the distribution of specific functional bacteria by specifically targeting sulfate reducing bacteria, and Fe/Mn reducing bacteria. Our data showed that the total number of sequences belonging to Desulfobacteraceae (Sulfate reducing bacteria) was 599 sequences, with relatively equal distribution across the different sediment samples (47 - 154 seq/sample; Appendix, Fig SI.1). Our data has 580 sequences belonging to the family Desulfobulbaceae most of them were present in the sediment sample of S1 collected in March 2013.

The shared Operational Taxonomic Units (OTUs) in the samples collected in March were higher than those collected in October (78% in March compared to 65% in October). This indicates the appearance of new species in the October samples (Fig. SI.2). When considering the depth, the deeper samples showed more unique OTUs than the uppermost water column layer in all the stations (Fig. SI.2). This was even more pronounced for the samples collected in October than those collected in March.

Our NMDS and factorial analysis (Fig. 3) illustrated that the samples collected in the same season were closer to each other according to the Euclidean distance. On the contrary, samples collected in different seasons were further apart from one another. The main environmental factor that contributes to the grouping of the samples collected in March is Nitrate, while O2, silicate and phosphate control the distribution behavior of the samples collected in October (Fig. 3).

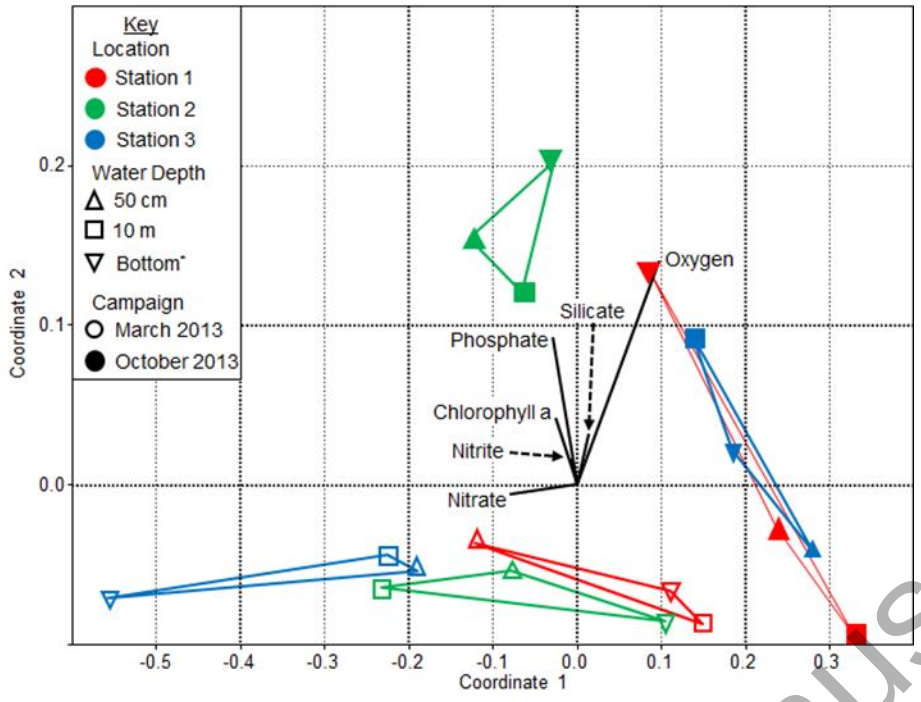

Figure 3. Non-metric multidimensional scaling and the factorial analysis of the samples collected in March and in October considering OTUs and the environmental conditions.

In March, the maximum relative abundance of cyanobacteria reached 5% in the surface water of station 2 (S2). The relative abundance of bacteria belonging to the class Flavobacteria reached ~ 4% in the deepest layer of the samples collected from S3. The relative abundances of members belonging to the other classes (cytophagia and Acidomicrobia) were negligible. The Chl a concentration was around 0.02 mg.L-1 g-1 dry weight for the most samples collected in March, except for the water column samples from the deepest water of S2 and the deepest water from S3 (Fig. 4). For the latter, fucoxanthin concentrations were also high suggesting the dominance of diatoms as the main photosynthetic organism. The deepest water of S2 and S3 also showed high concentrations of nitrate and silicate, which supports the assumption that at these depths dominant photosynthetic microorganism are diatoms. The water column samples collected in October were much more diverse than those collected in March. The relative abundance of cyanobacteria was considerably elevated and reached 17% of the total microbial community composition of the surface water collected from S3. The relative abundances of members of the three other classes (cytophagia, acidomicrobia, and flavobacteria) notably increased in October compared to March, especially for the samples collected from the second station (S2). This coincided with the elevation of the measured nutrients (nitrate, silicate, and phosphate) (Fig. 4).

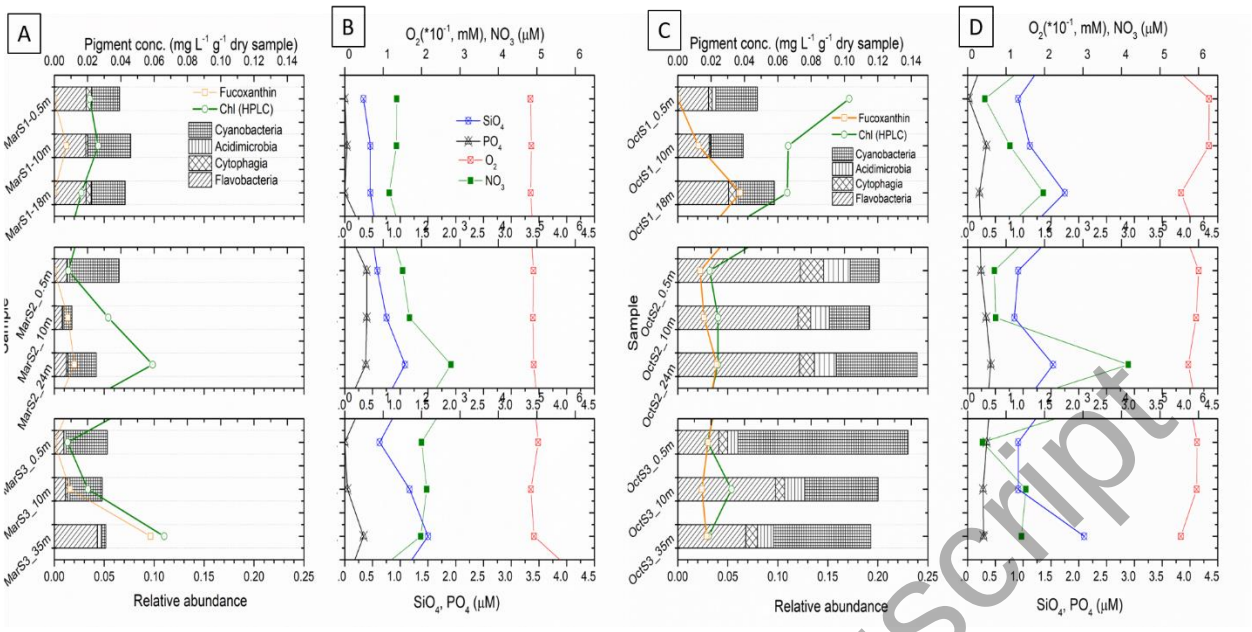

Figure 4. Vertical distribution of the relative abundances of the classes Cyanobacteria, Cytophagia, Acidomicrobia, and Flavobacteria in samples collected in March (A), and in October (C) along with the vertical distribution of key photosynthetic pigments such as Chl a and fucoxanthin, where the samples closer to the shore (S1) are in the uppermost panel followed by the S2 and the most distant samples (S3) are in the deepest most layer. The panels B & D shows the vertical distribution of silicate, phosphate, nitrate and oxygen for water column in March and in October, respectively.

Our pore-water measurements (Fig.5) showed a gradient of phosphate and total iron inside the sediment, with clear efflux directed from inside the sediment to the water column. Phosphate concentration at different depths of the three investigated sediments ranged between 0.14 µM at the surface of the sediment to ~12.5 µM at 6 cm in the sediment of the S2 and S3. With respect to the total iron, the highest concentration was detected under the surface of the sediment in S1 for the samples collected in March and in October with a directed flux towards the water column. From the phosphate profiles in the sediment collected in October, we calculated from the phosphate profiles in the sediment collected in October, we calculated a diffusional flux of 1.5 µmol m-2 day-1 using Fick's law (J=D.dc/dx) (Graca et al., 2006). In the chamber incubation experiments, phosphate flux towards water column was ~ one order of magnitude higher than the flux calculated from the pore-water measurements (~19 compared to 1.5 µmolP m-2 day-1) (Fig 5 C&D), possibly due to advectional exchange. Oxygen consumption rate ranged between 20 and 30 mmol m-2 d-1, typical for coastal regions. Except for S2 in March that took up Si, sediments at all stations showed high silicate release rates ranging between 500 and 2300 µmol m-2 d-1. Nitrate fluxes followed a similar pattern as phosphorus, but with high variability (Fig. 5 C, D).

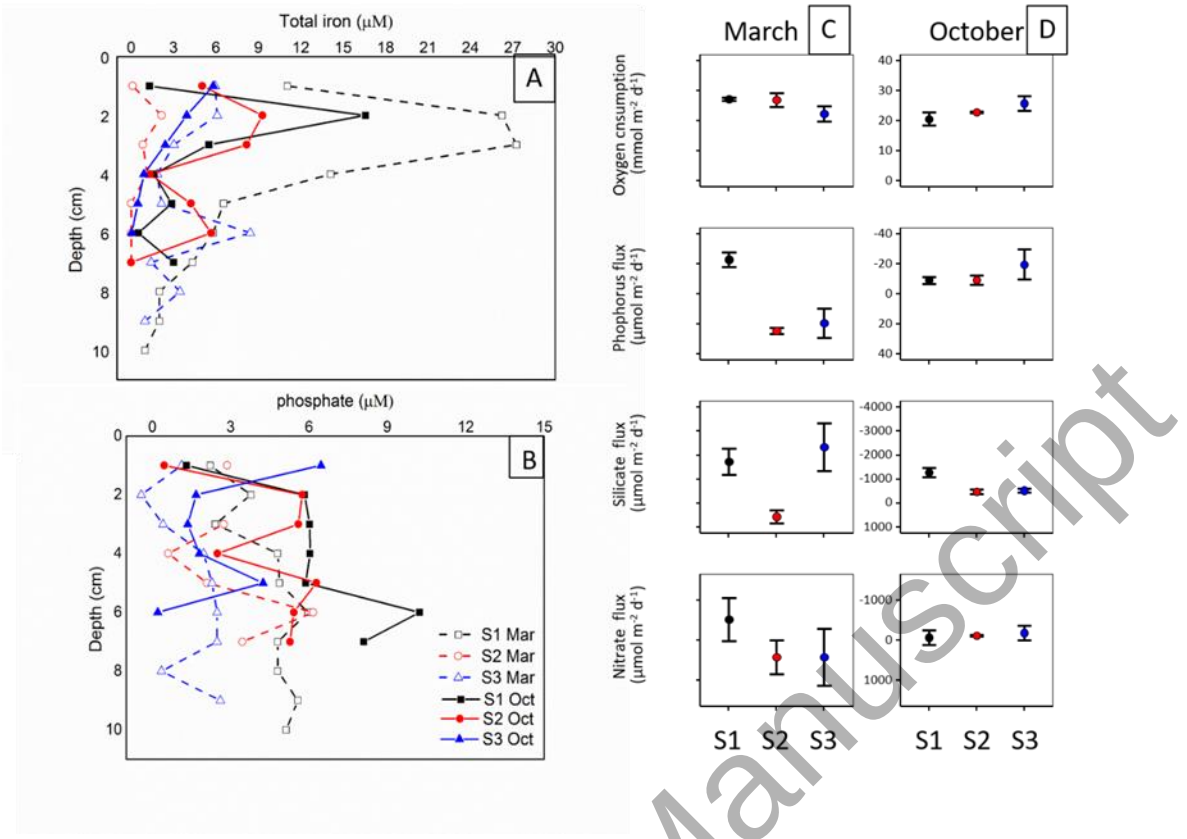

Figure 5. Pore-water profiles in the sediments collected in March (hollow symbols, dashed line) and in October (solid symbols, solid line) showing total iron concentration (A) and the phosphate concentration (B) for the three locations S1, S2, and S3. The panels C & D represent calculated nutrients fluxes (oxygen, silicate, nitrate and phosphate) from chamber incubation experiment.

Iron Bioavailability

The bio-availability is defined as the fraction that can be leached using ascorbic acid. Interestingly, the bioavailable iron, extracted by ascorbic acid, from the sand dunes (source of the dust) is <2% of the metal iron (Fig. 6A), while the bioavailable iron from the marine sediment is 2-2.5 times higher than that extracted from the sand dunes (Fig. 6B). Thus the biogeochemical processes in the sediment can increase the concentration of the bioavailable iron that can be used to support the primary productivity in the water column.

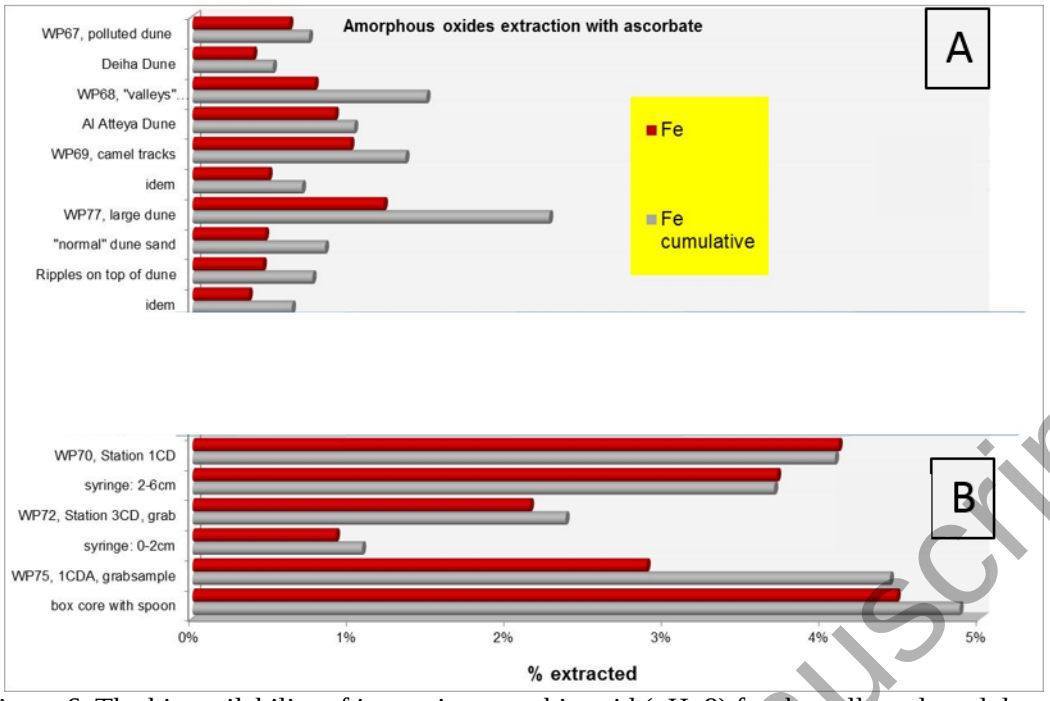

Figure 6. The bioavailability of iron using ascorbic acid (pH. 8) for the collected sand dunes from Qatar desert (source of the dust) in panel (A) and for the sediment in panel B).

Discussion

For any marine ecosystem to sustain, it should be provided continuously by nutrients from several sources. The nutrients are needed to support the primary production at the photic zone, which will then supply the food web with the energy and carbon source for biomass production. The nutrient supply coming from rivers and from rain is very low owing to the limited number of rivers with low discharges and to the scarcity of annual precipitation. This study considers another valuable source of nutrients that enhances the productivity of the Gulf, which is mineral dust. We were able to connect the measured biogeochemical process enhanced by the dust input with the microbial diversity of key players in the food web of marine ecosystems. The cruises were planned in March and in October to measure the effect of non-dust season and dust season, respectively, because it is well documented that the dust storms extend from summer until December annually (Alobaidi et al., 2017; Rao et al., 2001).

Primary producers and hHeterotrophic bacteria

The raised concentrations of key nutrients (silicate and nitrate) in the water column of the samples collected in October (Fig. 4) triggered the emergence of high relative abundance of cyanobacteria (up to 35 times higher). Although our data doesn't show the relative abundances of important primary produces such as diatoms, fucoxanthin indicated the appearance of diatoms (Peeken, 1997) indicated the appearance of diatoms in S1 and S2 of the samples collected in October. Another logical cause for increasing numbers of diatoms in October is the availability of higher concentrations of silicate compared to the samples collected in March, as silicate is an important component of the frustule of diatoms (Milligan and Morel, 2002). As expected, the increase in relative abundances of the primary producers stimulates the flourishment of heterotrophic bacteria that grow on the exudates of the photosynthetic microorganisms such as exopolymeric substances (EPS) (Engel et al., 2004; Hassler et al., 2011).
In our case, we documented a synchronized blooming of three main heterotrophic groups (namely; cytophagia, Acidomicrobia, and flavobacteria) with the prospering of cyanobacteria. Members of

cytophagia influence the carbon cycle through the degradation of organic carbon compounds (Kirchman, 2002). The Cytophaga-Flavobacterium group also flourishes in the coastal water, offshore water, sediments, hydrothermal vents, and the polar region. In these niches, they can be found free living, attached to organic compounds and associated with marine plankton and animals (Fernández-Gomez et al., 2013). The Cytophaga-Flavobacterium group can degrade cell wall, cellulose, cellobiose, carboxymethylcellulose, chitin, starch, inulin, keratin, xylan, pectin, pectate, agarpectin, agar, laminarin, lipids, DNA, and RNA (Kirchman, 2002). These activities contribute significantly in microbial loops in the water column and subsequently in the nutrients cycling (Buchan et al., 2014) resulting in increasing the productivity of the ecosystem.

Contribution of dust to the productivity of the Gulf

The shallow depth of the Gulf (averaged 30 m), combined with the short travel distance of the mineral-dust particles ensures a very rapid settling of the dust particles. After reaching the sediments on the sea floor, anoxic biogeochemical processes such as Iron and sulfate reduction help in releasing nutrients such as iron and phosphate to the water column. Due to efficient water circulation (Kämpf and Sadrinasab, 2006), the released nutrients reach the photic zone fast, which will subsequently be fixed by the primary producers (cyanobacteria, diatoms and algae). Additionally, dust could provide the Gulf marine ecosystem with important groups of microorganisms that might enrich the ecosystem (Fig. 4). Although it is well documented that dust can travel thousands of kilometers (Griffin et al., 2002), we think that effect of the distal dust compared to the proximal dust, the is negligible; both in particle size as well as in mass/flux. In fact, we do know the particle-size distribution of the dust being deposited into the Arabian Gulf, is large in size (data not published). This is because across such small distance, transported dust is very coarse-grained and thus will sink to the sea floor almost instantaneously. Van der Does and his colleagues (2016) investigated the particle-size distributions of Saharan dust deposited into the Atlantic Ocean, which was collected with sediment traps. They showed that there is a large drop in particle size from East (proximal) to West (distal), keeping in mind that the easternmost trap was located about 700km from the coast and probably ~ 1000km from the dust sources. Comparing this to the less-than-100km distance between source and sink in the Arabian Gulf, we expect to have coarse sediment, which was the case indeed.

The contribution of the dust to the total productivity of the Gulf can be estimated from the calculated phosphate fluxes from phosphate profiles (Fig. 5), which was 1.37 µmol P m-2day-1. First, the total flux of carbon was calculated using the Red Field ratio (116 C:16N:1P) (Geider and La Roche, 2002), which resulted in 159 µmolCm-2day-1. Second, considering the total volume of the Arabian Gulf (900 Km3; (Alosairi et al., 2011), and the total amount of dust that falls annually on the Gulf, ~10,330 ton. Km-3 (Al-Dousari et al., 2017), the total rate of carbon that can be formed in the Gulf would be 477 ton C. day-1, supposing that all the phosphate that is in the sediment originated from the dust. Third, assuming that all this carbon will be used to form biomass in primary productivity, the amount of C that could be fixed in photosynthesis is 3*106 ton biomass year-1. One tenth of this amount will be transferred to fish biomass (since the fish are in the third trophic level), which will end up of having 30,000 tons fish year-1 (2.3 tons of fish m-2 year-1, surface area) originated from the dust that precipitated on the Gulf. From the phosphate flux calculated from the chamber incubation experiment (Fig. 5 C&D), the fish production could even be an order of magnitude higher. However, the advectional flux may in chambers well be higher than in situ. Using the diffusional flux a conservative number estimate is obtained, and the real effect may be in between both extremes.

Contrary to the several reports on the negative effects of dust on human health (Griffin, 2007), on transportations (Al-Hemoud et al., 2017) and on economics and tourism (Ai and Polenske, 2008), our results emphasize the positive contribution of it to the health of marine ecosystem. Although the contribution of the fish biomass originated from dust is relatively low (~ 1.5%) compared to that estimated as a yearly produced in the Gulf (2M tons; (Moffitt and Cajas-Cano, 2014), dust enhances the

microbial biodiversity in general (Fig. 2, Table 1) and increased the abundances of key players in the microbial loops (Fig. 4).

With satellite images (Appendix, Fig. SI.3), we were able to detect much more dust events during September and October compared to February and March (20 days with dust events in September compared to 7 in February). The raised number of dust events in September and October coincided with the measured increase in relative abundance of cyanobacteria from the samples collected in October than those collected in March (Fig. 1 & Fig.4). Additionally, it was reflected on the emergence of new OTUs that were not found in the samples collected in March from the same sites (Fig. 2). However, the satellite images do not show an obvious connection between the appearance and the disappearance of algal blooms and the occurrence of dust storms. This could be due to the delay between a dust storm and its fertilizing effect but the more likely factor is the irregular mixing of deep and shallow water. When considering the depth, the deeper the water column the more likelihood for new OTUs for the samples collected in October (Appendix Fig SI. 2). The appearance of more OTUs in October can be explained by mixing communities from deeper layers. Also, the increased mixing brings nutrients from deeper water to the stronger illuminated surface water, leading to enhanced primary productivity. This vertical mixing is an irregular phenomenon, determined by the normal circulation plus the occurrence of wind. Relatively small changes in wind direction and strength will affect the vertical exchange over a distance of less than 40 m. Our data on iron bioavailability support our hypothesis that the biogeochemical cycling in the sediment is responsible for leaching the nutrients to the water column. Nutrient availability enhances the biodiversity when the water column is vertically mixed. Indeed upwelling currents that bring nutrients to the surface are well documented (Kämpf and Sadrinasab, 2006).

In conclusion, in addition to the reported negative effects of dust on human health, we propose that dust has also a positive effect on the microbial biodiversity and productivity of the Gulf. Iron reduction in the sediments is mandatory for the bioavailability of at least iron and probably also for phosphate, that is bound to Fe(III). Therefore, dust should be considered as a source of nutrients for sustaining the Gulf's ecosystem, especially because of absence of alternative nutrient input. Even in the shallow Gulf, hydrodynamics are crucial in bringing the nutrients to the photic zone, where primary productivity occurs. Due to this transport step, dust input is not tightly connected to blooms. Our study emphasizes the ecological importance of dust in the marine ecosystems. More research is still required to study the effect of dust on different locations of the Gulf In relation to the local hydrodynamics.

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