

Aerobic respiration in a high-energy sandy beach



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ABSTRACT

Wave and tide dominated beaches are composed of medium to coarse sandy sediments depleted in organic matter. In these sediments, the availability of organic matter limits benthic heterotrophic respiration processes. This study shows that oxygen consumption linked with nutrient recycling occurs in sands and that the intensity of this process follows a seasonal pattern. Furthermore, substantial seawater exchange occurs through intertidal sandy sediments during each tide. During floods, seawater penetrates sandy sediments, filling the pore spaces with dissolved oxygen and marine organic matter. Water expelled from the sediment during ebb is depleted in oxygen and enriched in nitrate. In order to quantify the extent of respiration processes, we collected pore waters at low tide on tidal cross-shore transects on the Truc Vert beach (France) every two weeks over 20 months. Temperature, salinity and oxygen saturation were recorded in situ and nutrient concentrations were determined from collected samples. The seasonal monitoring showed that aerobic respiration occurred in sands. Organic matter supplied by the seawater entering the pore spaces during floods was trapped long enough to be mineralized. An efficient recycling of nutrients was thus found to occur in tidal sandy beaches. The intensity of the respiration processes varied seasonally. The strongest oxygen depletions occurred in spring, when planktonic organic matter was abundant, as well as in summer when we observed occasional denitrification. Nitrate concentration of recycled seeping seawater reached values up to 40 μM . According to our calculations, the 240-km-long Aquitanian beach recycles 3500 t of carbon and releases 600 t of N-nitrate to the adjacent coastal zone each year. Since phosphorus is readily adsorbed on particles, the N:P ratio of recycled nutrients released to the seawater was much higher than the Redfield ratio.

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1. Introduction

Sediments have a major effect on the function of coastal ecosystems. Respiration and N regeneration in sediments account for >80% of total shelf ecosystem metabolic activity in shallow sediments and about 10% at the shelf break (Middelburg and Soetaert, 2004). Sandy sediments are dominant on continental shelves and act as filter beds that remove particles from the water column. At depths shallower than 50 m, tide and waves promote water circulation near the bottom and thus seawater filtration through permeable sediments at the seafloor. Both the benthic and pelagic biogeochemical cycles are affected by this filtration process. Sand traps organic matter and enhances its mineralization (Riedl and Macmahon, 1969; Riedl and Machan, 1972; McLachlan et al., 1985; McLachlan and Turner, 1994; Huettel et al., 1996). Boudreau et al. (2001) suggested that the low organic matter content of permeable sediments reflects the efficiency of oxidation processes linked to the advective flow of seawater. Consequently, biogeochemical fluxes from sandy sediments should not be neglected (Shum and Sundby, 1996; Rush et al., 2006; Rocha, 2008; Anschutz et al., 2009; Riedel et al., 2011). The intertidal zone is located on the upper part of the continental shelf, at the interface between continental waters and

the ocean. Intertidal sandy beaches are commonly found in association with coastal dunes and occur along approximately 20% of the world's coasts (Masselink and Kroon, 2009). Generally, wave-dominated and high-energy tidal beaches consist of medium to coarse sand sediments. The role of these sediments in biogeochemical cycles has, until recently, been considered unimportant because they are usually characterised by very low content in organic matter and associated reactive compounds (Boudreau et al., 2001; Rocha, 2008). Most recent studies on sandy beaches have focused on submarine groundwater discharges (SGDs) and the interactions between seawater and coastal aquifers within permeable sediment in so-called subterranean estuaries (Moore, 1999; Charette et al., 2005; Charette and Sholkovitz, 2006; Burnett et al., 2006; Robinson et al., 2007; Xin et al., 2010; De Sieyes et al., 2011). As a widespread phenomenon, SGDs play a significant role in the water cycle and in the global geochemical cycles of some elements, such as carbon, nitrogen and phosphorus (Slomp and Van Cappellen, 2004; Moore, 2006; Swarzenski et al., 2006). Nevertheless, recent studies focusing on processes in the tidal zone have shown that sands also act as biogeochemical reactors as a result of enhanced filtering of seawater due to tidal pumping at each cycle (Anschutz et al., 2009). Seawater brings dissolved oxygen and marine organic matter as it enters the sand during floods. It mixes with the underlying pore waters and some of these pore waters are flushed to the ocean during ebb (Bakhtyar et al., 2012; Chassagne et al., 2012). The residence

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time of water in the pore space of intertidal beaches can be several tidal cycles, during which organic matter can be degraded by respiration processes (Anschutz et al., 2009). Previous field studies have been carried out over limited time periods and mostly in winter (Anschutz et al., 2009). Here, we present the results of a two-year monitoring programme of pore water and seeping water composition on a high-energy tidal beach to determine the evolution and intensity of heterotrophic processes. The sampling rate was selected to enable us to best quantify the organic carbon respiration and subsequent nutrient release from this high-energy environment.

2. Materials and methods

2.1. Study area

The Aquitanian coast (SW France) is a 240-km-long straight sandy coastline between the Gironde and the Adour estuaries and is bordered by high aeolian dunes. This coast comprises double bar beaches subjected to high-energy conditions (Castelle et al., 2007). The Truc Vert beach is located a few kilometres north of the Cap Ferret sand spit (Fig. 1a). It is representative of the Aquitaine coast and preserved from human disturbance because of difficult access. Sediment consists of medium quartz sand with mean grain size ranging from 300 to 400 μm (Pedreiros et al., 1996). The tide is a meso-macro-type with an average tidal range of 3.2 m, extending up to 5 m during spring tides, and mean wave amplitude of 1.5 m that can reach up to 10 m during winter storms. A ridge and runnel system develops more or less in relation with meteorological conditions (Michel and Howa, 1999; Castelle et al., 2007). The intertidal zone extends across an 80–200-m-long cross-shore beach depending on topographical variations. At the upper beach and at low tide, the sand is only saturated with water below more than 1 m depth. This indicates that a significant volume

of pore water is flushed towards the seashore during ebb. The lower beach surface sediment is wet at low tide and water seeps out of the sediment. The seepage zone generally corresponds to a 10–50 m band of the lower beach.

2.2. Sampling

Seawater and pore water chemistry was monitored from February 2011 to November 2012. Sampling was conducted at low tide at noon every two weeks during spring tides. The use of permanently installed piezometric wells to collect pore water samples was ruled out because of the high-energy conditions. Attempts made to collect water by this means were a failure, because the piezometres were broken or buried in the sand, sometimes after just one tidal cycle. Therefore, only pore waters at the top of the water-saturated zone were sampled in the intertidal zone of the beach. For that, holes were dug every 10 m along a cross-shore transect from the low-tide swash zone to the high-tide watermark (Fig. 1b). Thirty seven profiles were obtained during the 22 months of monitoring. Parallel cross-shore profiles were also carried out three times in 2012 to assess spatial patchiness. For that purpose, a grid of six profiles separated by 10 m allowed us to collect pore water samples in 40 to 50 holes. Sampling holes were deep enough to reach the top of the water-saturated zone of the sediment. The saturated zone was reached with one shovelful in the lower beach, whereas we had to dig holes more than 1.5 m deep in the upper beach. The first water that filled the bottom of the hole was removed with a polypropylene beaker. Due to the high permeability of sand, the hole refilled immediately and the measurements were performed on this water. Temperature, salinity and dissolved oxygen saturation were directly recorded in the waters of the excavated holes within 1 min using WTW probes. The probes were calibrated before and after each field campaign using an oxygen-free solution and an aerated solution

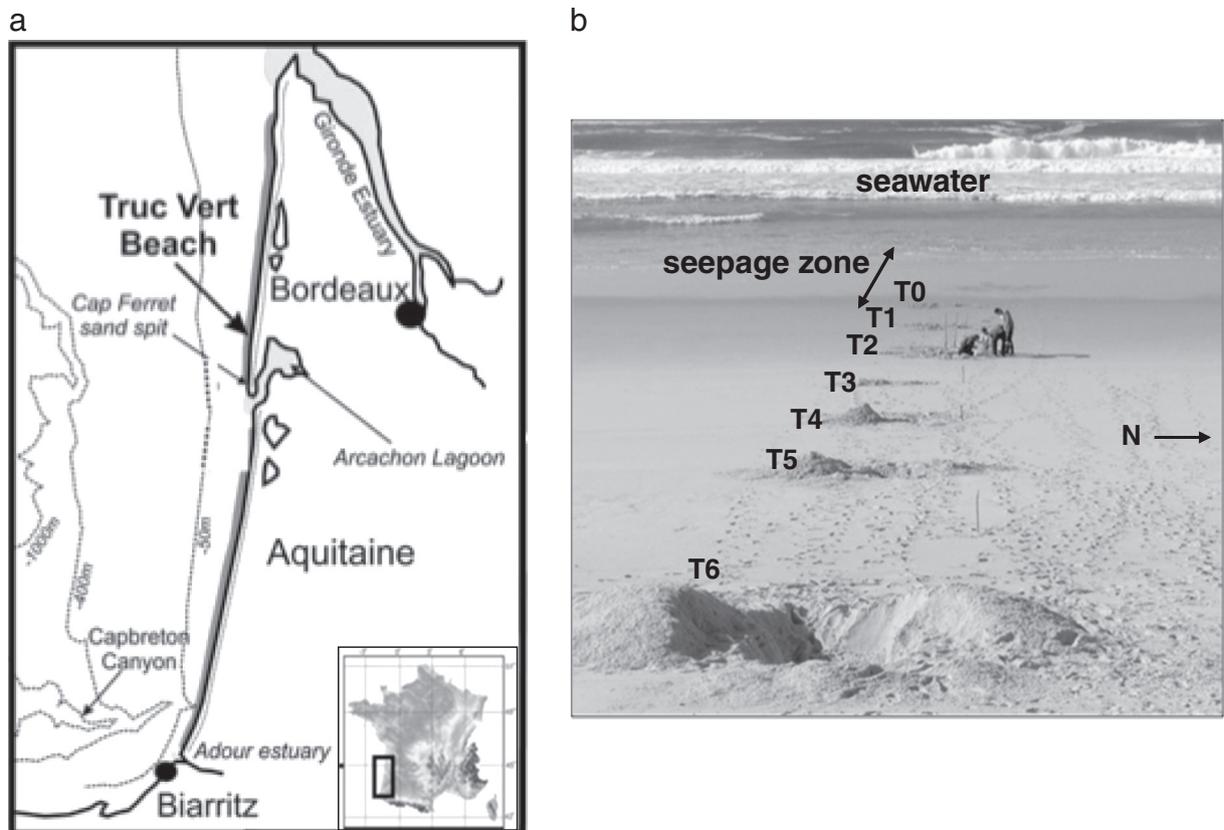


Fig. 1. a) Map of the south-western part of France and location of the study area; b) view of the Truc Vert beach at low tide and location of the pore water sampling sites (T0–T6) on February 8th, 2011.

(100% saturation) for the oxygen saturation, and with IAPSO standard seawater and deionized water for the salinity. Oxygen and salinity probes were compensated automatically for in situ temperature. The salinity influence on oxygen saturation was recalculated for each measurement. Contamination of O₂-depleted pore waters by atmospheric oxygen due to re-equilibration could not, therefore, be excluded. Nevertheless, the measurement was done in the holes immediately after having reached the water table. The water depth in the holes was between 10 and 15 cm. The oxygen sensor was placed at the bottom of the puddle, so that contact with the atmosphere was avoided. After several minutes of immersion of the probe in the water, no significant evolution of O₂ saturation was observed. In summer 2011, we detected anoxic waters (0% O₂ saturation). This observation indicates that atmospheric oxygen contamination was negligible and that the measurements were fast enough to be representative of in-situ saturation within the uncertainty of the instrument. The digging operation, in-situ measurements and samplings took from 5 to 20 min per hole. At selected periods, autonomous Aanderaa optodes and NKE data loggers were buried directly into the sediment (data not shown). The in-situ variations of oxygen concentration of the water table were always lower than 5% at low tide, when the beach was left exposed, and serve to validate our sampling procedure. Waters were sampled using a 50-mL syringe and filtered through a 0.45 µm cellulose acetate syringe-membrane. One subsample was acidified with a 1% equivalent volume of concentrated HNO₃ for later analysis of dissolved inorganic phosphorus (DIP); another subsample was frozen until later analyses of other dissolved nutrients. To determine the chlorophyll-a concentrations, 1 L of surface seawater was filtered through GF/F filters, which were stored in the dark at -80 °C until analysis. Cross-shore topography and sampling location were obtained for each sampling date with a kinematic GPS Trimble 5700, with a centimetre to decimetre accuracy in the X, Y, Z, planes. The positions of piezometric levels at low tide were also recorded for each hole. The instantaneous porosity corresponds to the relative volume of the interstitial environment, in which water and air could be exchanged during a tidal cycle. We measured it in autumn 2012 and winter 2013. A known volume (152 cm³) of undisturbed sand was collected with a beaker at low tide at different depths in the walls of the dug holes. The sand was placed in a graduated test tube and 100 cm³ of water was added. The difference between the initial volume of sediment plus water (252 cm³) and the final measured volume was the volume of interstitial air, considered as the exchangeable volume that defines the instantaneous porosity. Several samples of the solid fraction from the holes of the cross-shore transect were sampled in October 2012 in order to measure particulate phosphorus concentrations. For that purpose, 1 g of crushed bulk sediment was leached with a 1 N HCl solution to extract phosphorus sorbed on particles and adsorbed or co-precipitated with iron oxides and calcium carbonates. These reactive particles only represent a minor fraction in comparison with sandy quartz. They are concentrated in the fine fraction. Hence, pore waters were filtered and fine particles (<100 µm) were collected on filters. HCl leaching was performed on these filters and also on shell debris picked up on the beach in order to obtain the phosphorus concentration extracted with 1 N HCl on the fine fraction and the biogenic carbonate. A sub-sample of crushed sand was used to measure the inorganic carbon content. The analytical methods are compiled in the Table 1.

3. Results

3.1. Topography

The cross-shore topography changed according to the swell, tidal regime and meteorology. At a given position, we sometimes observed accretion or erosion of more than 1 m height of sand between two successive measurements (Fig. 2). This highly dynamic system is characteristic of the meso-macrotidal high-energy Aquitanian double-bar

beach system (Bernie et al., 2009; Senechal et al., 2011). A berm and an inner bar build up during periods of lower energy. Longshore migration of the ridge and runnel system also explains the evolution of the profile (De Melo Apoluceno et al., 2002; Lafon et al., 2004). The beach profile became linear with a smooth slope after storms and high waves. From February 2011 to November 2012, 37 cross-shore profiles were carried out, taking water samples at the surface of the water table at a distance of 30–190 m from the dune. The top of the water-saturated zone of the sediment was very close to the air–sand interface of even surfaces in the lower beach. The water table was deeper (>1 m depth) in the upper beach. The diversity of the beach topographic profiles (Fig. 2) explains why the cross-shore profiles of pore water sampling were not always located exactly at the same place. The instantaneous porosity of the sand represents the maximal volume of pore waters that can be flushed to the coastal ocean during low tide. We measured an instantaneous porosity of 40% in dry sand located more than 40 cm above the water table. The instantaneous porosity was about 10% in wet sand directly above the water table and it was intermediate in humid sediment located 20–40 cm above the water table (Fig. 3). This volume is filled with seawater during flood tide when the seawater mixes with the underlying pore waters. Hence, at every tide, seawater is exchanged between the intertidal sediment and the coastal ocean.

3.2. Water chemistry

3.2.1. Surface seawater

Surface seawater salinity was close to 35 and oxygen saturation close to 100% throughout the year. Nitrate, ammonia and dissolved silica concentrations were almost always less than 8 µM and DIP concentrations were below 0.6 µM. Only temperature displayed a seasonal trend with values ranging from 8.0–13.9 °C in winter, to 11.3–18.9 °C in spring, 18.4–21.9 °C in summer and 14.1–20.1 °C in autumn. Chlorophyll-a concentrations ranged from 0.4–16.0 µg/L with maximum values in spring and autumn (Table 2).

3.2.2. Pore waters

Irrespective of the season, pore waters collected at the surface of the beach water table had a salinity close to that of seawater, with 80% of samples having a salinity between 34 and 36 (Fig. 4). Nevertheless, several samples had salinities as low as 30. These samples were located in the lower beach. They probably were a mixture of seawater and continental fresh groundwater (Robinson et al., 2007). Only 3 out of the 340 samples collected during this study had a salinity below 30, with the lowest value being 11. The latter was sampled in April 2012 in the upper beach at 160 cm depth, one of the deepest hole we dug. We probably reached the upstream part of the seawater wedge on that day. Temperature in pore waters varied throughout the year with values ranging from 4.4–15.2 °C in winter, to 11.4–22.9 °C in spring, 18.3–22.4 °C in summer and 12.5–21.5 °C in autumn. Ammonium concentrations showed no particular trend along the cross-shore profile, with low values (<10 µM) everywhere on the beach (Fig. 5). Dissolved O₂, nitrate, silica and inorganic phosphorus showed variations along the cross-shore profile and throughout the year. In the upper beach, between 30 and 70 m from the base of the dunes, pore water characteristics were close to those of seawater. With one exception, dissolved oxygen saturations were always between 100% and 80%, nitrate and dissolved silica concentrations less than 10 µM and DIP concentrations less than 0.6 µM (Fig. 5). In the lower beach, pore waters were generally depleted in oxygen and enriched in nitrate and dissolved silica. Pore water concentrations along the cross-shore profile varied throughout the year: the minimum values observed for oxygen saturation ranged from 22% (which corresponds to 56 µM at the in situ salinity and temperature) to 86% (218 µM) in winter (average value of 57%, or 148 µM), from 3% (8 µM) to 50% (124 µM) in spring (average value of 31%, or 73 µM), from 0% (0 µM) to 58% (127 µM) in summer (average

Table 1
Summary of the analytical methods.

Studied element	Reference	Method	Standard deviation	Detection limit
Dissolved nitrate ($\Sigma\text{NO}_3^- = \text{NO}_3^- + \text{NO}_2^-$)	Anderson (1979)	Colorimetric by FIA	<10%	0.5 μM
Dissolved silica	Strickland and Parsons (1972)	Colorimetric	<15%	1 μM
Dissolved inorganic phosphate	Murphy and Riley (1962)	Colorimetric	<5%	0.05 μM
Ammonia	Koroleff (1976)	Colorimetric	<5%	1 μM
Chlorophyll-a	Strickland and Parsons (1972)	Fluorescence after 90% acetone extraction	15%	0.1 $\mu\text{g/L}$
HCl extracted phosphorus	Deborde et al. (2007)	Colorimetric after HCl extraction	15%	0.1 $\mu\text{mol/g}$
HCl extracted iron	Deborde et al. (2007)	Colorimetric after HCl extraction	15%	1 $\mu\text{mol/g}$
Particulate inorganic carbon		Volumetric after 6 N HCl attack	10%	1 wt.% CaCO_3

value of 21%, or 50 μM) and from 9% (20 μM) to 72% (170 μM) in autumn (average value of 46%, or 102 μM). Nitrate enrichment also varied seasonally and nitrate concentrations of the most oxygen-depleted pore waters ranged from 12.1 to 29.2 μM in winter (average value of 19 μM), 20.0–40.0 μM in spring (average value of 28 μM), 1.7–33.1 μM in summer (average value of 16.6 μM) and 6.2–50.0 μM in autumn (average value of 23.3 μM) (Fig. 5). Throughout the year, dissolved silica also showed enrichment along the cross-shore profile with average values in the lower beach of about 9.3 μM in winter, 8.0 μM in spring, 11.3 μM in summer and 15.2 μM in autumn. Similar spring values were reported by Anschutz et al. (2009), which studied biogeochemistry of the Truc Vert beach between January and March 2007. DIP concentrations were almost always lower than 0.6 μM with no particular trend along the cross-shore profile (Figs. 4 and 5). Only one profile (August 1st, 2011) showed DIP concentrations higher than 1 μM in the upper beach. The same samples also had the highest ammonium concentrations (up to 27 μM).

Samples collected on the six parallel profiles at different seasons showed limited longshore patchiness within the 60-m-long grid (Fig. 6); cross-shore variations were much higher than longshore variations. As observed with the seasonal monitoring, pore water oxygen depletion in the lower beach was associated with nitrate enrichment. In November 2012, the local impact of some slightly brackish waters ($S = 31$), possibly related to a local change in topography, was observed in the lower beach with nitrate concentrations reaching 20 μM , higher than nitrate concentrations of other pore waters at the same cross-shore distance (from 10 to 15 μM). In April 2012, the formation of a ridge at the lower beach limited the seeping of old and oxygen-depleted pore waters. Waters seeping from the ridge accumulated in the runnel formed behind the ridge. Therefore, the runnel was fed with water coming from the seaside, and not from the upper beach. We thus observed high oxygen and low nitrate concentrations in these waters, similar to seawater. This observation illustrated the influence of topographic variations on the pore water chemistry at the metre

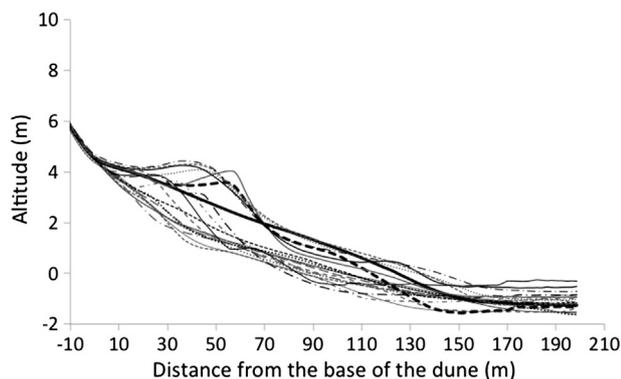


Fig. 2. Evolution of the topography (cross-shore sections) of the Truc Vert beach in 2011. Each line corresponds to a given measuring day and represents an averaged profile of several cross-shore profiles realised on a 500-m longshore beach portion centred on the pore water sampling site. Fourteen or fifteen days separate each line. The two bold lines identify an example of contrasting successive situations: September 14th (solid line) and September 28th (dotted line).

scale, which overlapped with the general influence observed at the cross-shore scale (~100 m).

3.3. Leaching of sand

HCl-leaching of the sand yielded phosphorus concentrations of about 0.5 $\mu\text{mol/g}$. With one exception, this value was nearly invariant (± 0.1 $\mu\text{mol/g}$) with the location of samples along the beach profile and the carbonate content, which ranged from 0.8% to 3.7%. An HCl leach of the fine particles gave phosphorus concentrations ranging from 0.9 to 5.4 $\mu\text{mol/g}$. These were correlated with the extract iron concentration that ranged from 9.4 to 62.5 $\mu\text{mol/g}$ (Fig. 7). Shell debris had a low iron (<4 $\mu\text{mol/g}$) but variable phosphorus content (0.5–6.5 $\mu\text{mol/g}$); the highest value being found in oyster shell debris.

4. Discussion

4.1. Hydrology of the beach

Our sampling is located in the upper saline plume formed by the hydraulic turnover of seawater driven by the tide and swash (Fig. 8). With the exception of a few samples, we observe that changes in oxygen and nutrient concentrations are not related to salinity changes. Therefore, pore water composition cannot be explained by conservative or non-conservative mixing of seawater and fresh groundwater end-members. This suggests that recirculation of seawater due to tidal pumping is the major driver of biogeochemical reactions at our study site. For example, we observe that pore waters that have exactly the same salinity as seawater display a range of nitrate concentrations (0 to 35 μM), whereas seawater nitrate concentrations ranged from 0 to 5 μM (Fig. 4). Therefore, differences in chemical composition between surface seawater and pore waters are most likely to be the result of biogeochemical processes occurring in the sands.

The ability of beach sands to filter large volumes of seawater was demonstrated by McLachlan et al. (1985). The influence of topography on the pore water circulation and thus, on the transport of redox compounds, is well documented at the centimetre scale (Huettel et al., 1996, 1998; Cook et al., 2007; Cardenas et al., 2008; Rocha, 2008) but less so at the plurimetric scale of exposed beaches (Chassagne et al., 2012). Swell and tidal intensity influence advective flow of water and fluxes of material entering or leaving the sediments (Robinson et al., 2007; Xin et al., 2010; Chassagne et al., 2012). These processes explain the variability of pore water chemistries observed at the Truc Vert beach during any given season. Results of studies that focused on the influence of tidal forcing on coastal pore water flow in sandy beaches (e.g., Nielsen, 1990; Turner, 1993; Li et al., 1997; Ataie-Ashtiani et al., 1999; Boufadel, 2000; Wilson and Gardner, 2006; de Drézigué et al., 2009; Chassagne et al., 2012) indicate that, when the tide begins to fall, the upper part of the beach system begins to empty. The velocity vectors along the seepage zone are parallel to the beach slope and directed towards the seashore. They are directed out of the sediment just below the swash zone level. The flow vectors reach their maximum value during the falling tide, as much as 0.50 m h^{-1} at the Truc Vert

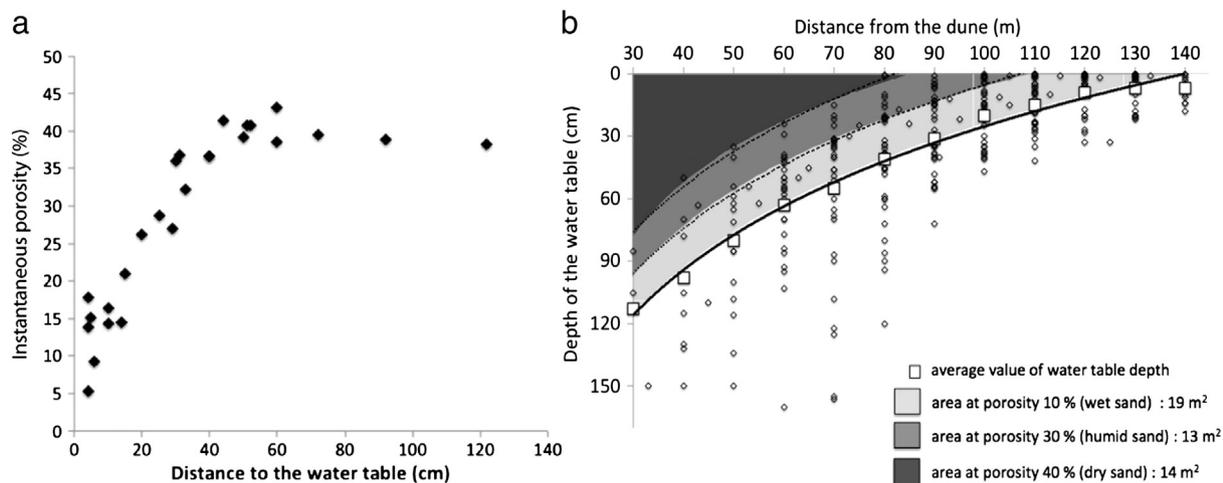


Fig. 3. a) Instantaneous porosity measured at different distances above the water table in November 2012 and January 2013; b) depth of the water table vs. position on the beach relative to the dune. Each point corresponds to a given sampling day in 2011 and 2012. The grey areas represent a 46 m² surface area, which corresponds to the averaged measured under-saturated sand wedge at low spring tide.

beach (Chassagne et al., 2012). During the rising tide, velocity vectors become oriented towards the top of the beach and seawater penetrates into the unsaturated part of the sediment. In fact, observations in the field show that the swash, which has not been modelled in the studies

cited above, plays a major role in rapidly filling the unsaturated sand during flood. In summary, pictures of the field of velocity vectors during a tidal cycle indicate that the pore waters we sampled at low tide at the top of the water table originate from the last high tide in the upper beach. Pore waters that seep out on the lower beach are older because they originate from water that percolated through the sand from the upper beach to the lower beach. This pathway requires at least one tidal cycle or more, depending on the slope. This might explain why pore waters sampled in the upper beach have properties close to those of surface seawater and the seeping waters on the lower beach are significantly modified.

The volume of water that is exchanged at each tidal cycle corresponds to the volume of the pore environment that is replaced with air at low tide and becomes saturated with water at high tide. Our field observations, based on beach topography and the depth of the water table at low spring tides, show that the average volume of under-saturated sand in the intertidal beach corresponds approximately to a 46 m³ wedges by metre of longshore distance. Considering that the instantaneous porosity depends on the elevation above the water table, we calculated that 11.4 m³ of water can be exchanged

Table 2

Temperature, salinity, concentrations of dissolved O₂, nitrate, silicic acid, DIP, ammonia and chlorophyll a, in surface seawater of the Truc Vert beach from February 2011 to November 2012.

Date	T °C	S	O ₂ (%)	NO ₃ ⁻ (μM)	H ₄ SiO ₄ (μM)	DIP (μM)	NH ₄ ⁺ (μM)	Chl a (μg/L)
02/08/11	11.2	35.1	101	3.8	3.1	0.1	0.5	0.9
02/22/11	11.6	34.9	92	3.3	3.2	0.2	0.2	5.0
03/08/11	11.1	35.2	102	0.8	2.0	0.2	1.8	0.9
03/22/11	11.8	34.2	98	4.3	5.9	0.2	1.3	0.4
04/05/11	16.3	34.2	99	3.8	4.9	0.2	1.4	2.0
04/19/11	15.2	34.7	97	3.5	4.7	0.1	2.8	2.4
05/05/11	16.7	35.4	94	1.4	1.3	0.1	2.2	1.8
05/19/11	14.1	35.5	92	0.8	0.2	0.1	0.5	8.1
06/06/11	18.9	35.4	98	0.7	1.7	0.2	0.4	3.3
06/17/11	19.3	35.3	96	0.7	2.1	0.0	5.9	0.9
07/01/11	18.4	35.6	95	1.4	2.6	0.2	1.0	3.0
07/17/11	18.6	35.2	95	2.4	2.5	0.2	0.3	3.4
08/01/11	21.0	35.3	94	2.3	3.2	0.0	1.1	1.6
08/31/11	21.1	35.4	98	0.4	0.0	0.0	0.0	0.6
09/13/11	21.9	35.3	107	0.5	1.1	0.0	0.6	4.0
09/27/11	20.1	35.6	107	0.0	1.0	0.0	0.5	6.6
10/13/11	18.4	35.5	101	0.8	0.7	0.1	0.6	16.0
10/27/11	16.1	35.7	107	0.2	0.2	0.0	0.6	10.0
11/10/11	16.0	35.6	103	1.9	5.0	0.6	1.1	5.2
11/24/11	14.1	35.3	99	3.0	0.6	0.3	1.1	4.9
12/13/11	13.9	35.4	102	2.7	1.6	0.2	0.7	5.9
01/13/12	9.8	34.9	98	7.8	8.0	0.4	0.1	4.5
01/24/12	11.8	34.9	99	7.8	5.9	0.2	0.4	4.7
02/09/12	8.0	34.9	97	2.6	2.7	0.3	0.7	12.7
03/08/12	10.1	35.0	100	4.2	1.9	0.0	1.3	1.9
04/04/12	11.3	35.1	95	4.4	1.7	0.0	1.7	1.5
05/09/12	17.8	33.8	99	4.2	3.0	0.1	3.3	0.8
05/22/12	14.3	35.1	99	1.6	2.1	0.0	1.1	4.4
06/21/12	20.4	35.0	103	2.1	3.0	0.1	4.0	1.6
07/23/12	20.1	35.2	87	1.2	1.9	0.1	2.3	0.8
08/02/12	21.0	34.8	89	0.9	1.2	0.1	1.1	0.9
08/31/12	19.3	34.8	98	5.2	9.7	0.3	4.0	1.0
09/17/12	19.9	35.4	97	1.3	3.2	0.1	4.8	0.8
10/02/12	18.4	35.4	97	1.5	2.7	0.1	1.5	0.8
10/30/12	15.2	35.1	100	3.7	4.2	0.2	2.9	–
11/14/12	14.6	35.4	97	1.6	2.6	0.1	0.1	–
11/29/12	12.1	35.1	94	3.6	6.3	0.4	0.8	–

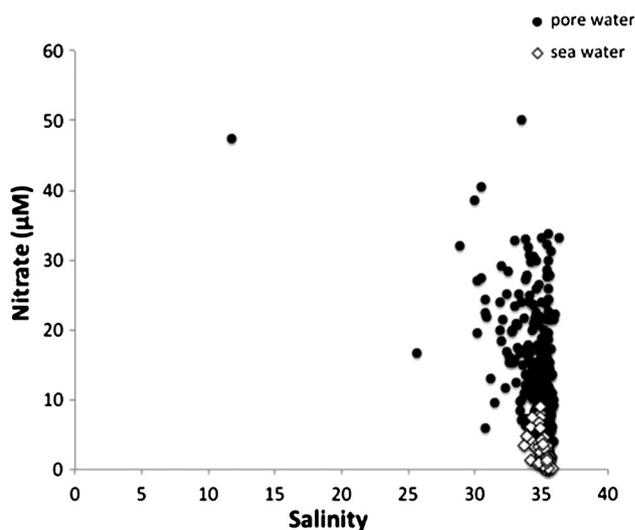


Fig. 4. Nitrate concentration vs. salinity in pore water (black circles) and surface seawater (white diamonds).

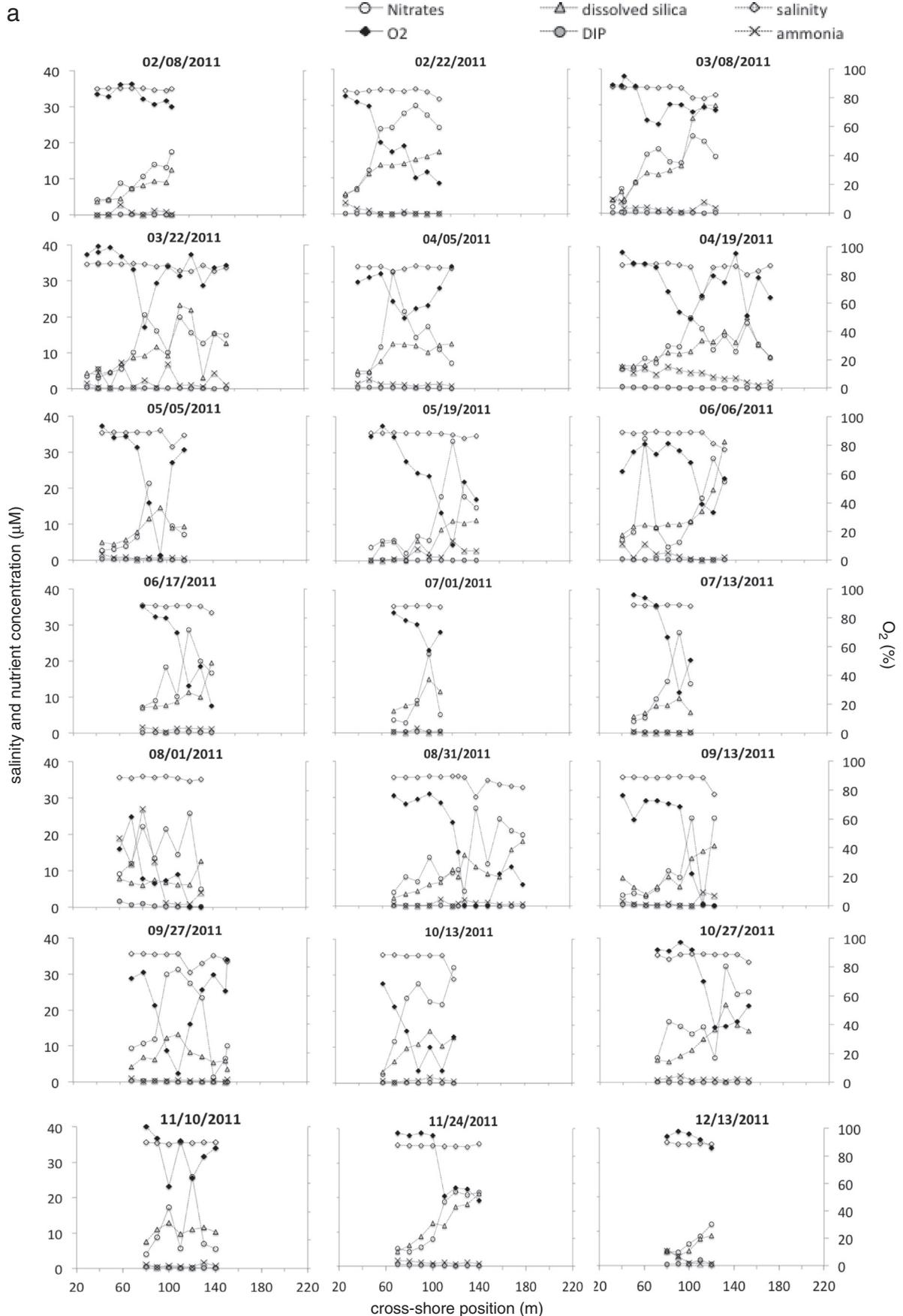


Fig. 5. Concentrations of dissolved O₂, nitrate, dissolved silica, DIP, ammonia and salinity in pore waters of the Truc Vert beach in 2011 (a) and 2012 (b). The position 0 m corresponds to the base of the dune.

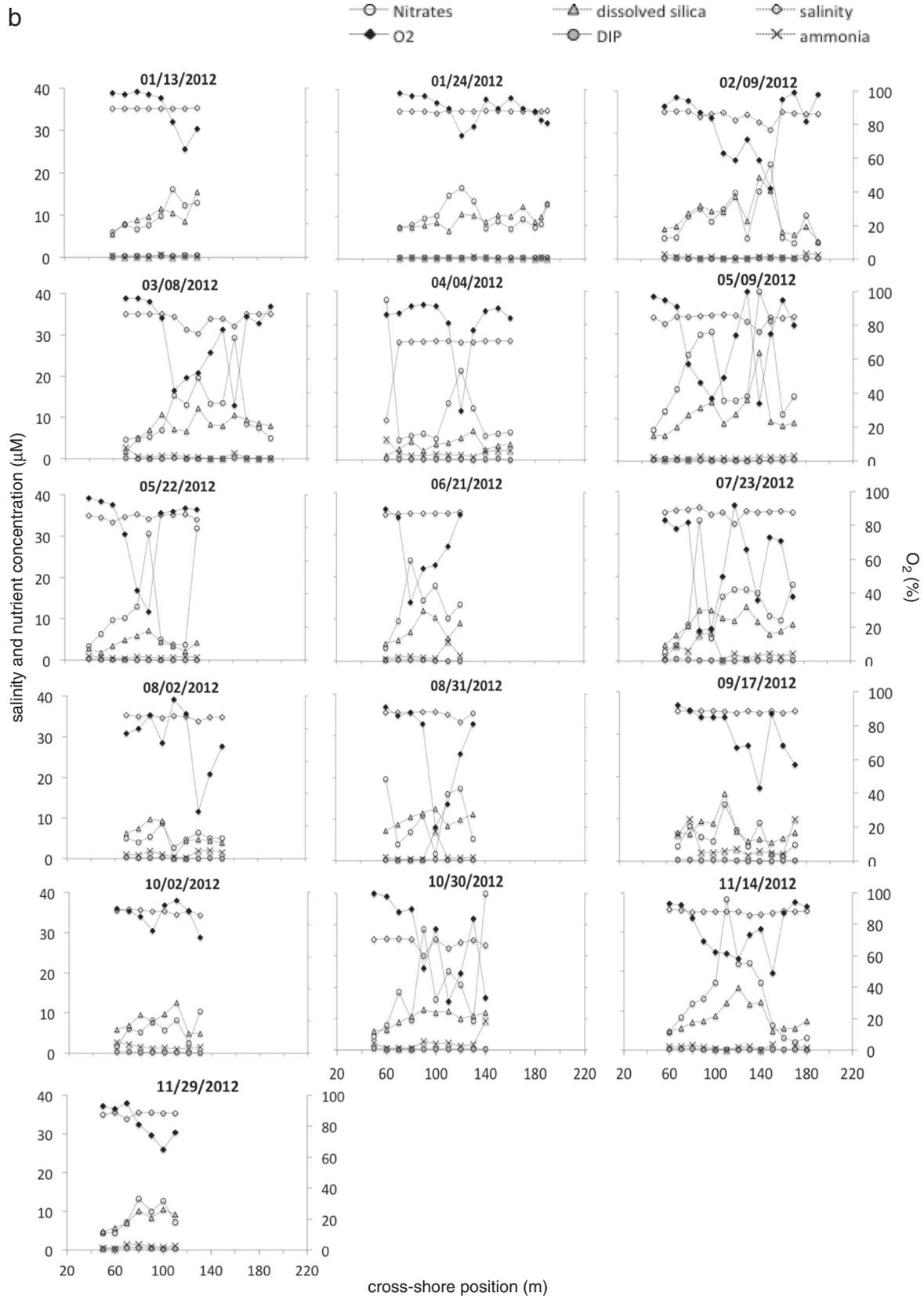


Fig. 5 (continued).

at each spring tide (Fig. 3). The wedge of sand that is alternately filled and under-saturated with water extends landward below the sand dune beyond the upper beach. This part of the oscillating groundwater table could not be sampled directly. The position of the water table can

be detected with geophysical tools, such as electrical resistivity profiling (e.g., Swarzenski and Izbicki, 2009). Our team plans to deploy similar instrumentation in the near future (Canton et al., 2010). Nevertheless, modelling of the Truc Vert beach water circulation has allowed to assess

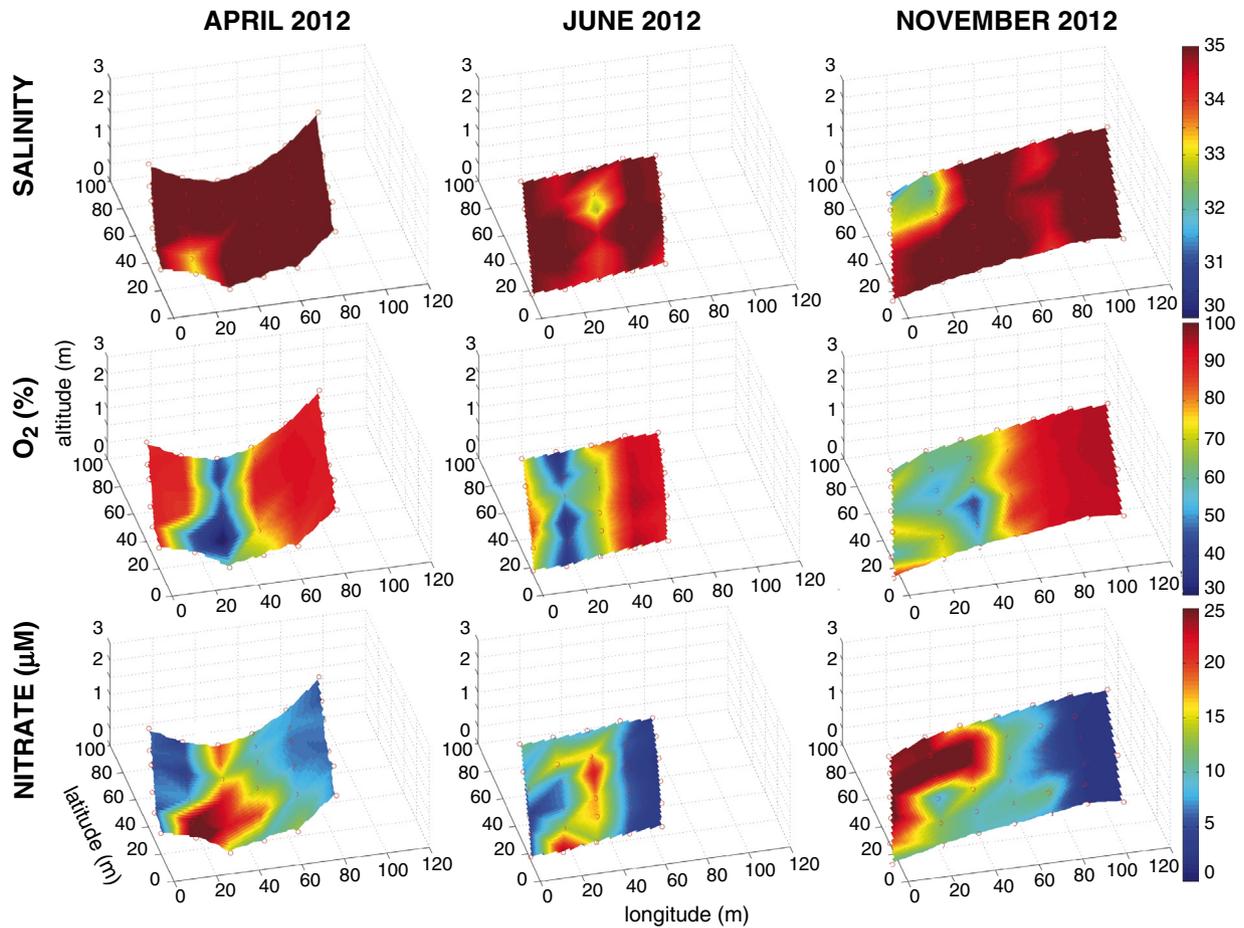


Fig. 6. Salinity (top), oxygen saturation (middle, in %) and nitrate concentration (bottom, in µM) in pore water along a 60-m-long grid in April (left), June (middle) and November (right) 2012. The upper beach is on the right, the lower beach on the left. The 3D relief corresponds to the geometry (longitude X, latitude Y, altitude Z) of the top of the water table. Red circles correspond to sampling locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the whole volume of sediment affected by the tidally oscillating water table (Chassagne et al., 2012). The part that extends below the dune increased twofold the volume that we measured in the tidal beach (Fig. 3b), making a total volume of water exchanged during spring tides of 22.8 m³. This is a maximum value because the mean tides have an amplitude corresponding to 2/3 of the mean spring tides, implying that the averaged water exchange is 15.2 m³ per tidal cycle. This value is the volume of sediment that can be filled with water during high tide (or by air during low tide), but it is not the total volume of water that can be filtered through the beach, because water and air exchanges at the time scale of individual waves are not considered.

4.2. The Truc Vert beach as an efficient heterotrophic environment

Recycling of organic matter and nutrient mineralization in exposed sandy beaches has been recognised in recent studies (Avery et al., 2008; Rauch and Denis, 2008; Rauch et al., 2008; Rocha, 2008; Dugan et al., 2011). Anschutz et al. (2009) showed that oxygen consumption occurred in the very high-energy sandy beach of the Truc Vert, where they measured, in winter, a 20% depletion of the oxygen saturation relative to the inflowing surface waters. The present study gives a more complete view of the seasonal evolution of organic matter recycling. To our knowledge, this is the first time that results of a long-term

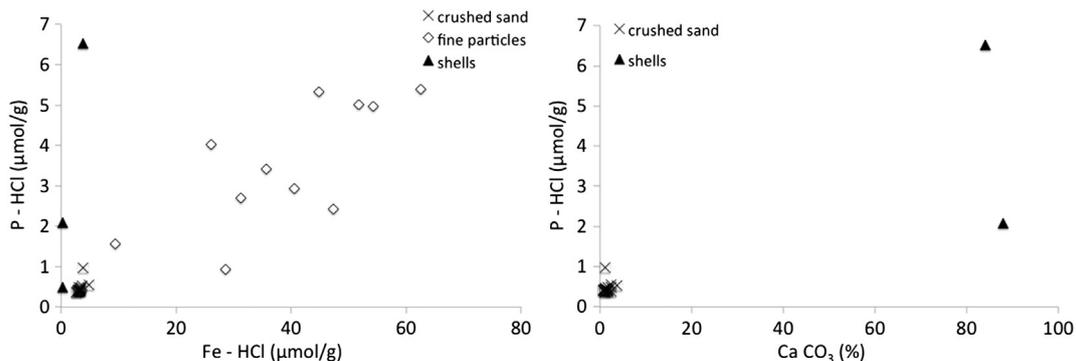


Fig. 7. a) Phosphorus and iron from the 1 N HCl extraction of crushed sand (black crosses), fine particles collected by filtering pore waters (white diamonds) and shell debris picked up on the beach (black triangles); b) HCl-extracted phosphorus and carbonate content on crushed sand (black crosses) and shell debris (black triangles).

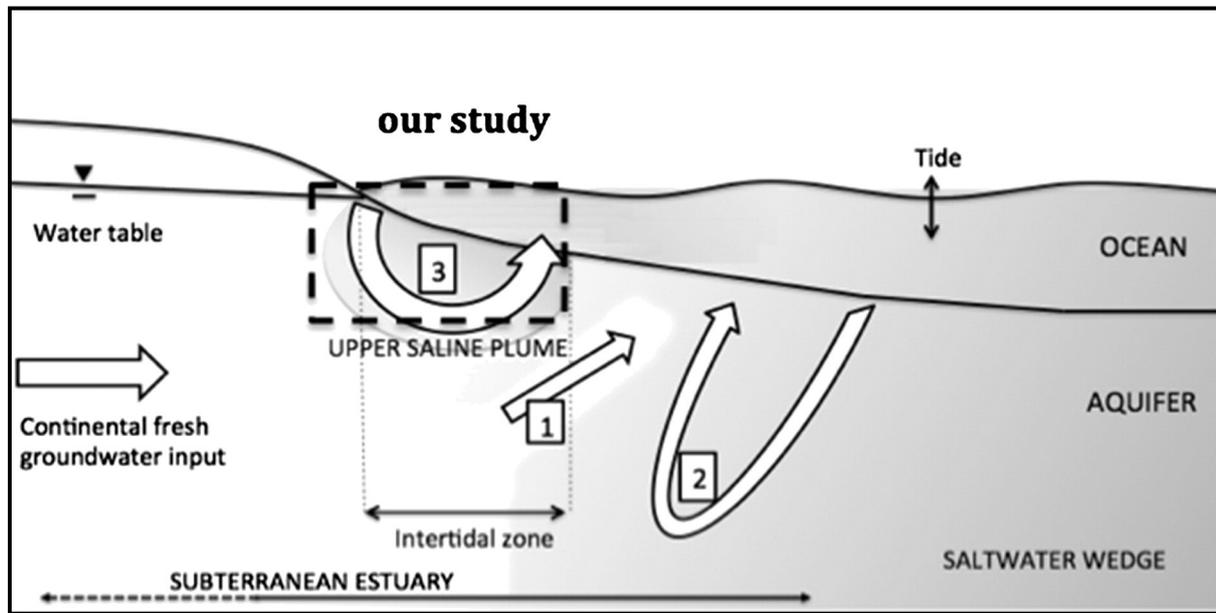


Fig. 8. Conceptual diagram of subterranean estuary, including major nearshore flow processes: (1) freshwater discharge, (2) density-driven recirculation and (3) seawater recirculation induced by wave set-up, tide and wave-bed form interactions. Modified from Robinson et al. (2007).

monitoring have been presented for a high-energy tidal beach where permeable sandy sediments are continuously moving.

Pore waters collected in the lower beach were always depleted in oxygen relative to seawater. Pore waters even became anoxic during summer. Oxygen depletion, coupled with an increase in nitrate concentration (Figs. 5 and 6) downslope on the cross-shore profile, reflects the occurrence of aerobic respiration processes in sandy sediments of the Truc Vert beach during the tidally-induced recirculation of seawater. Organic matter mineralization should convert organic nitrogen and phosphorus into dissolved inorganic forms. Pore water accumulated nitrate, but DIP concentrations showed low values. DIP decreased slightly between the upper beach and the lower beach (Fig. 5), most likely as it was adsorbed onto sand grain surfaces and onto fine particles and/or shell debris (Fig. 7). HCl-leachable iron accounted for up to $5 \mu\text{mol g}^{-1}$ of the bulk sand, and up to $60 \mu\text{mol g}^{-1}$ of the fine fraction, probably present in the form of iron oxides or clay coatings. Fe and Mn (hydr)oxides can precipitate in subterranean estuaries, when anoxic, fresh continental groundwater mixes with seawater, forming an “iron curtain” that traps dissolved elements such as P, Th and Ba (Charette and Sholkovitz, 2002; Charette et al., 2005; Spiteri et al., 2006). Hence, the Fe phase detected here probably trapped a large part of the DIP.

In the lower beach, concentrations of dissolved silica were higher than in the surface seawater, but were identical to the surface seawater in the upper beach. Dissolved silica originated from two main processes: the dissolutions of biogenic silica and quartz, of which the sand is composed. When we consider only the second process, we can estimate the residence time of pore waters in the sand from the enrichment in dissolved silica and the kinetics of quartz dissolution. Quartz dissolution kinetic data (Dove, 1994; Anschutz et al., 2009) indicate that this process can modify significantly the dissolved silica concentration within a few days, because seawater and pore waters of the Truc Vert beach remain far below saturation with respect to quartz (the expected equilibrium value is $115 \mu\text{M}$ and $155 \mu\text{M}$ of dissolved silica at 10°C and 20°C , respectively). A 20 days-long flow-through experiment conducted with Truc Vert beach sediment and local surface water at 20°C showed that the concentration of dissolved silica increased linearly by $1.4 \mu\text{M d}^{-1}$ from the starting concentration found in seawater ($2.9 \pm 2.1 \mu\text{M}$; Table 2). Therefore, the increase in dissolved silica that we observed downslope on the cross-shore profiles is consistent with the ageing of pore waters as they percolate from the upper beach to the lower beach. However,

because of lack of data, we cannot assess the contribution of biogenic silica dissolution (e.g., from diatom frustules), which has a higher solubility than quartz, as a source of the silicic acid found in the pore water.

4.3. Seasonal variability of aerobic respiration

Spatial patchiness indicates that lateral changes in measured cross-shore profiles are much lower than seasonal changes. Therefore, the evolution with time of profiles actually is due to seasonal variations of biogeochemical processes along the studied beach. Seasonal data, obtained between February 2011 and November 2012, show a temporal variability in the intensity of aerobic respiration processes in sandy sediments of the Truc Vert beach. Oxygen depletion and associated nitrate enrichment observed in pore waters of the lower beach were much stronger in summer than in winter (Fig. 5). In spring and autumn, respiration processes were moderate and average dissolved oxygen and nitrate concentrations were intermediate to those observed in winter and summer. In summer 2011, the intensity of respiration processes reached a maximum; oxygen saturation in pore waters of the lower beach fell to 0% for several weeks (Fig. 4). For some of these dysoxic or anoxic pore waters, nitrate concentrations were very low, suggesting that nitrate was consumed by denitrification processes (Fig. 9). This seasonal variability of organic matter mineralization pathways seems to be linked to the availability of organic matter in the studied environment. Oxygen depletion was elevated during spring, when phytoplanktonic blooms occurred, as inferred from the high chlorophyll-a concentration in surface seawater (Fig. 10). During that period, the sandy sediment of the studied beach probably acted as a filter that retained and concentrated marine particulate organic matter, including phytoplankton cells, as observed in other permeable sediment environments (Mclachlan et al., 1985; Huettel et al., 1996; Huettel and Rusch, 2000; Ehrenhauss et al., 2004). During the summer, concentrations of chlorophyll-a in surface seawater were low, although significant oxygen consumption occurred, suggesting that the source of the organic matter mineralized in the sands was not dominated by phytoplankton. One alternative source of organic matter in summer could be microphytobenthos. This kind of benthic production has not been studied on the Truc Vert beach, but it can represent a significant source of organic carbon for temperate tidal beaches (Spilmont et al., 2005). High temperature

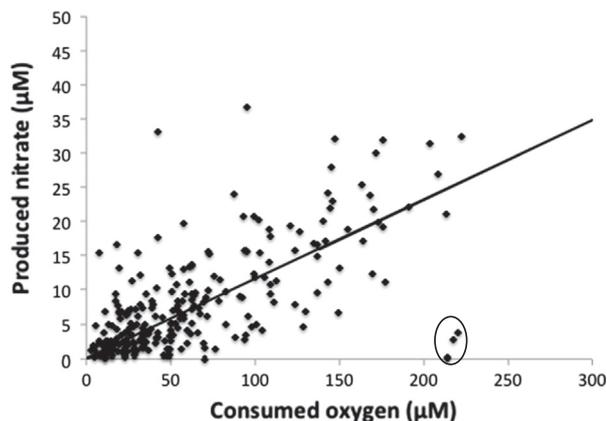


Fig. 9. Consumed oxygen and produced nitrate in pore waters at salinity close to 35, from February 2011 to November 2012. Each point corresponds to a pore water sampling point along the cross-shore transect of the Truc Vert beach. Circled data correspond to dysoxic or anoxic pore waters with low nitrate concentrations. Values of consumed oxygen and produced nitrate are obtained by differences between surface seawater and pore water concentrations. The straight line has a slope of 138/16 corresponding to the aerobic respiration of Redfield-type organic matter.

in summer probably enhanced the mineralization of organic matter that remained refractory in cooler periods of the year. On the 1st of August 2011, marine organic debris washed up on the Truc Vert beach, including thousands of small dead mussels. The pore water profile obtained on this date showed the largest concentrations of ammonia and DIP in the upper beach. Previous studies have reported relationships between pore water nutrient concentration and the amount of organic material advected on intertidal beaches. This includes the accumulation of phaeocystis foam on an English Channel beach (Rauch et al., 2008), kelp macroalgae from the Santa Barbara channel (Dugan et al., 2011), sea grasses and, in some systems, carrion (Colombani and Chelazzi, 2003). This strong input of organic matter and the elevated temperatures in August could explain the intensity of respiration processes in pore waters during summer, leading to anoxia. The Truc Vert beach is a very dynamic system, in which marine organic matter can be efficiently mineralized by respiration and denitrification processes, the intensity of which varies seasonally. Although significant seasonality can be observed from our data set, some variability of dissolved oxygen and nitrate concentrations is observed within a single season. This is especially true in spring and autumn, when oxygen saturations in the lower beach ranged from 3% to 72%. This variability reflects the very dynamic nature of the system, particularly in terms of beach morphology. The tides influence the volume of water entering or leaving the sediment and sand migration

along the beach. Waves also impact circulation of pore waters and sand and thus, the biogeochemical processes. The impact of the wave regime was not investigated in this study, but wave height and frequency probably influence the rate of pore water renewal. The latter could be assessed by high-resolution temporal O_2 measurements, which could only be performed in-situ.

4.4. Up-scaling

Our data set allows us to estimate the amount of organic carbon that is mineralized on the Truc Vert beach and the mean flux of nitrate to the ocean. The mean deficit in dissolved oxygen of the seeping waters is 149.8 μM , as deduced from the difference between dissolved oxygen concentration at 100% saturation and values measured in the lower beach pore waters. Assuming that oxygen consumption is due to aerobic mineralization of Redfield-type organic matter, the amount of oxidised organic carbon would be 115.1 μM (106/138) and the related production of nitrate would be 17.4 μM (16/138). If the latter is added to nitrate initially present in seawater that enters the porous sediment (3 μM ; Table 2), a mean concentration of 20.4 μM is obtained. This is very close to the mean nitrate concentration (21.6 μM) measured in the seeping waters with a salinity of 35. As indicated above, we estimated the average volume of recirculating seawater in sand at 15.2 m^3 per tidal cycle for each longshore metre of beach. Given that the Aquitanian beach is 240-km-long, about 2.5 km^3 of seawater is filtered through the sand each year by tidal pump. Therefore, the 240-km-long Aquitanian beach recycles $290 \cdot 10^6$ mol (3500 t) of carbon and releases $44 \cdot 10^6$ mol (609 t) of N-nitrate each year to the adjacent coastal zone. Even if these fluxes should be viewed as upper limits, the nitrate flux is similar to that of the watershed that feeds the Arcachon lagoon located on the same coast (Canton et al., 2012; Fig. 11). Fresh groundwater constitutes an additional source of nitrate for the coastal ocean. Only a few samples of brackish pore waters were sampled during our monitoring. They reveal that the fresh groundwater end-member has a nitrate concentration of about 60 μM (Fig. 4), but our data set is not suitable to estimate the flux of nutrient from this end-member.

5. Conclusions

The Truc Vert beach is an ideal place to observe the effects of seawater recirculation in sands on benthic biogeochemical processes, because little or no fresh continental groundwater mixes with seawater in the intertidal zone. Our seasonal monitoring of surface seawater and pore water chemistry reveals active organic matter mineralization processes in intertidal sandy sediments. The nature and intensity of these processes vary seasonally with strong oxygen consumption in

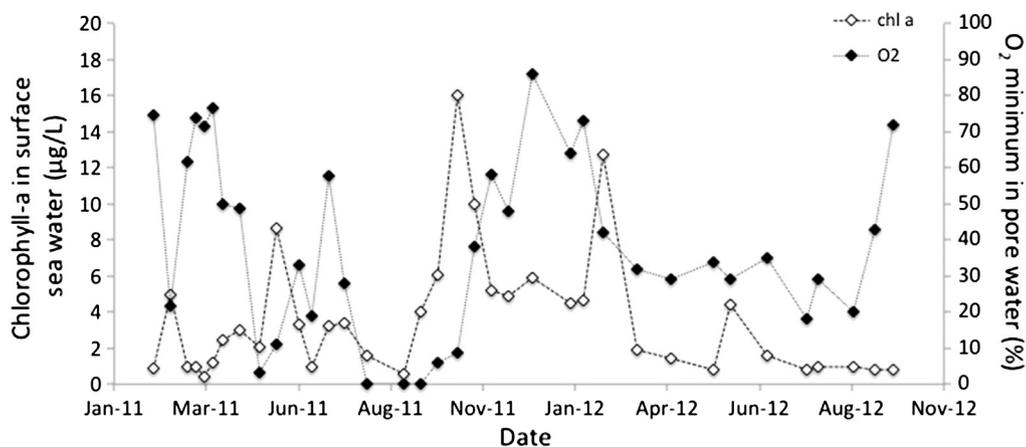


Fig. 10. O_2 minimum (% saturation) in pore waters and chlorophyll-a ($\mu\text{g/L}$) in surface seawater from February 2011 to October 2012, in the Truc Vert beach.

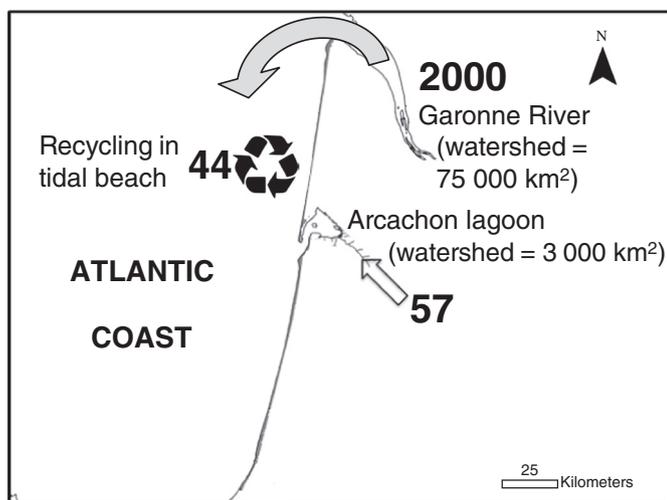


Fig. 11. Estimated fluxes of N-nitrate (in 10^6 mol/year) from the Garonne and Leyre Rivers and recycling in tidal beach along the 240-km-long Aquitanian coast (SW France).

spring, during phytoplankton blooms and in summer. In summer, respiration can be intense enough that pore waters of the lower beach become dysoxic or anoxic for several weeks. Some results suggest that denitrification occurs in such environments, which is unexpected given that the Truc Vert beach is considered as an extreme example of a ventilated coastal soft sediment. Moreover, the Truc Vert beach is bathed with mesotrophic coastal waters. Therefore, dysoxic or anoxic conditions in surface pore waters of lower tidal beaches in summer are probably the rule in all coastal zones, even if the waters are not eutrophic. Intertidal sandy sediments might be the site of intense organic matter mineralization processes and nutrient recycling. Some intra-seasonal variability is observed, particularly during spring and autumn, which show transitional situations between the two very contrasting pore water oxygenation regimes of winter and summer. Short-term variability is due to the strong hydrodynamic characteristics of the system, which affect pore water circulation in the sands, particularly through abrupt topographic changes. Additional field studies are needed to understand this variability and improve the coupled physical–biogeochemical models.

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