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Permeability of intertidal sandflats: Impact of temporal variability on sediment metabolism

E. Zetsche [a,b,*,1], M.T. Bulling [a,c], U. Witte [a]

[a] Oceanlab, University of Aberdeen, Main Street, Newburgh AB41 6AA, United Kingdom
[b] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, United Kingdom
[c] Department of Biology and Forensic Science, University of Derby, Kedleston Road, Derby DE22 1GB, United Kingdom

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ABSTRACT

The effects of sediment permeability on sediment oxygen consumption (SOC) in an intertidal permeable sandflat were studied over a 1-year period. Our study demonstrates that temporal variation in sediment metabolism was not only driven by temperature, but also changes in sediment permeability and total carbon content over time. High SOC rates in the summer months (seasonal mean 36.5 mmol m^{-2} d^{-1}) could be attributed to high temperatures affecting metabolic processes, the rapid turnover of labile organic material and the presence of large amounts of microphytobenthos and their exudates in interstitial pore spaces. The resultant clogging of pores lowered sediment permeabilities and led to the observation of increasing SOC rates at decreasing permeabilities. Despite higher permeabilities, oxygen consumption rates in winter (seasonal mean 17.3 mmol m^{-2} d^{-1}) were less than half those measured in the summer, reflecting the presence of more persistent refractory material and lower temperatures. During the winter, a major storm event reworked the sediment and significantly changed the permeability, affecting SOC rates. As sediment permeability rose by ~25%, SOC rates were increased by ~35% in the month after the event compared to the previous month. Our results show that temporal variation, not only in temperature and carbon content, but also in sediment permeability, affects sediment metabolism and that resuspension and storm events are necessary to unclog systems and maintain high remineralisation rates in organically poor permeable sands.

1. Introduction

Benthic remineralization rates of organic matter are often quantified by measuring the consumption of oxygen or the production of total carbon dioxide by the sediment (Cook et al., 2007). In sandy sediments, organic matter is degraded generally by two main pathways—oxic respiration and sulphate reduction. Whether aerobic pathways or sulphate reduction dominate can be highly variable in sands, depending on a range of factors such as temperature, availability of organic matter, sediment topography, boundary layer flow velocity and sediment permeability (Cook et al., 2007). In certain other environments, metabolic pathways such as denitrification and dissimilatory iron reduction may also be important (Canfield et al., 2005). However, in permeable sands, advective transport mechanisms enhance the penetration depth of oxygen (Forster et al., 1996; Ziebis et al., 1996; De Beer et al., 2005) and tend to shift organic matter degradation towards aerobic processes (D'Andrea et al., 2002).

Porewater advection in permeable sands is driven by gradients in pressure caused by changes in density or by the interaction of waves and currents with sediment topography. The magnitude of boundary currents, ripple slope and height, wave height and length and sediment permeability, all contribute to velocity, direction and depth of advective porewater flow in sands (Huettel and Webster, 2001). It exceeds diffusive transport by several orders of magnitude (Boudreau et al., 2001; Precht and Huettel, 2004) and enables permeable sands to function as biocatalytic filters (Boudreau et al., 2001; Rusch et al., 2006). Recent work has shown that rates of organic matter remineralization in permeable sands can be comparable or even higher than those found in cohesive sediments (Glud, 2008). Advection not only enhances oxygen penetration but also transports dissolved and particulate organic material into the sediment (e.g. Huettel and Rusch, 2000; Ehrenhauss and Huettel, 2004), and, at the same time, potentially inhibitory mineralisation end-products are efficiently removed (Werner et al., 2006).

* Corresponding author at: Laboratory of Analytical and Environmental Chemistry, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium.
Tel.: +31 113 577 322; fax: +31 113 573 616.
E-mail addresses: eva-maria.zetsche@nioz.nl (E. Zetsche), M.Bulling@derby.ac.uk (M.T. Bulling), u.witte@abdn.ac.uk (U. Witte).
[1] Present address: Laboratory of Analytical and Environmental Chemistry, Earth System Science Department, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium.

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A key factor in making advective transport possible in sands is their generally high sediment permeability ($>10^{-12}$ m^2) (Huettel and Gust, 1992a). Experiments where advective transport processes have been accounted for in the experimental design, have confirmed that sediment oxygen consumption (SOC) of a sediment is directly linked to permeability—the higher the permeability, the higher SOC (Ehrenhauss and Huettel, 2004; Janssen et al., 2005). However, these studies have generally been undertaken at one point in time and assumed permeability to remain constant. Yet, a variety of physical as well as biological factors which tend to show strong temporal variation, influence permeability. For example, the build-up of microbial biomass and extracellular polymeric substances (EPS) from the presence of microphytobenthos (Pilditch and Miller, 2006; Thullner, 2009) and the physical clogging of pore spaces by algal cells and fine particles (Huettel and Gust, 1992b; Forster et al., 2003) can lead to reductions in sediment permeability. For our study site, temporal changes in sediment permeability were identified and could be linked to the clogging by EPS rather than by fine-grained material (silts and clays) (Zetsche et al., 2011a), suggesting that the sediment's filtering capacity will have been impacted. If high permeability and mineralisation rates are to be maintained in the long term, flushing events, particularly during strong tidal or storm events, can effectively rework the sediment and unclog pore spaces.

The purpose of this study was therefore to assess whether and how these temporal variations in the permeability would influence the metabolism of the intertidal sandflat. Through a combination of stirred benthic chamber incubations to measure SOC and measurements of sediment characteristics on retrieved cores over a one-year period, we (a) determined whether sediment metabolism varies seasonally, and (b) identified possible drivers of oxygen consumption rates using predictive statistical modelling techniques.

2. Materials and methods

2.1. Study area and sampling site

The Ythan Estuary extends for approximately 10 km from its mouth to the town of Ellon on the north-eastern coast of Scotland, United Kingdom (Fig. 1), about 20 km north of Aberdeen. Leach (1969) classified it as a shallow well-mixed estuary with diurnal tides dictating water flow. Flushing time for the estuary ranges from 1.15 tidal cycles (Leach, 1971) to 5–12 days (Balls, 1994). The investigated intertidal sandflat is located in the middle reaches of the Ythan Estuary, is exposed during low tide, and depending on the tides and weather, immersed by an overlying water column of 1–2 m depth at high tide. The site represents an area of permeable well-sorted medium sand sediment (median grain size 336 μm) with a fairly uniform porosity (0.40). Sediment ripples were observed across the study site throughout the year suggesting that advective transport processes were active. Three representative positions were randomly located with the constraint of being far enough apart to be considered independent (at least 35 m apart), and marked with wooden poles. Samples associated with each location were treated as replicates. The samples were taken from random positions within a 2-m radius of each pole twice per month over a 1-yr period from May 2007 to May 2008 allowing seasonal changes to be investigated. However, in the Scottish climate the seasonal boundaries are shifted as a long winter period prevails (Harrison et al., 1999). Based on the analysis of collected data from temperature and light loggers (Onset HOBO® Pendant Temp/Light Data Logger) that had been fixed to the poles, the seasons' boundaries were adapted. Spring extends from the middle of April to the end of June, summer from July to mid-September, autumn from mid-September to mid-November and the long winter dictates the time between mid-November and mid-April.

2.2. Sediment oxygen consumption (SOC) rates

A total of six undisturbed cores of 25 cm inner diameter (two at each pole) were taken with 32 cm long acrylic tubes at low tide during each sampling occasion. Cores were inserted approximately 10 cm into the sediment, carefully dug out and sealed from the bottom before their immediate return to the laboratory. Here cores were carefully replenished with UV-filtered seawater (0.5 μm filter) and kept aerated for at least 12 h in a cold room at in situ temperature (± 1.5 °C). Following this, the cores were sealed off, avoiding all air bubbles, and stirred benthic chamber flux incubations initiated. The chambers used are described in detail in Ehrenhauss and Huettel (2004). Briefly, a horizontal disc (15 cm diameter) rotated approx. 8 cm above the sediment surface, the space between the lid and sediment surface being on average 13.7 cm. Once sealed, each chamber thus held a water volume of approximately 5.8 L which was continuously stirred at 60 rpm. Stirring was kept constant throughout the study period. Temperature of the overlying water in each of the incubated cores was recorded. Chambers were covered in foil to exclude light and incubated in the cold room for 4 h with samples being taken at the beginning and every hour thereafter. Syringes (60 ml) were used to sample the water column with the volume of water removed being replaced at the same time via a separate port on the chamber lids. Duplicate measurements for dissolved oxygen concentration were taken from each syringe using 10 ml Winkler bottles. Samples were also taken from the replacement water at each time interval. Over the course of the incubation, dissolved oxygen concentrations generally did not decline by more than 20%. Dissolved oxygen concentration was determined using the Winkler titration technique (Grasshoff et al., 1999). Linear regression applied to the measurements of dissolved oxygen concentration allowed the calculation of sediment oxygen consumption (SOC) (mmol m^{-2} d^{-1}) across the sediment–water interface as a function of incubation time, water volume and surface area. Corrections were applied for the addition of replacement water during each sampling.

2.3. Sediment properties

During each sampling occasion throughout the 1-yr period, cores (inner diameter 3.6 cm; sampling depth 15–20 cm) were collected at each of the three stations to determine various sediment properties. One core at each station was taken at low tide for estimating algal biomass and were extruded in 1 cm intervals to 15 cm and frozen immediately. For their analysis with a spectrophotometer (Hitachi U-2001), duplicate measurements of 0.5 g sediment from these slices were extracted in 5 ml of 90% acetone, shaken and left in the dark at 4 °C over 24 h. Chl *a* and phaeopigment content (μg g^{-1}) was calculated for each section according to standard equations (Parsons et al., 1984) using absorbance readings taken at 665 and 750 nm before and after acidification (2 M HCl). Further cores were taken for the determination of water content and grain size (data not shown), and were subsequently pooled, dried, milled, and vertical depth profiles of total carbon content (TC) and total nitrogen content (TN) determined with a NA1500 NCS Elemental analyser (Fisons Instruments). Measurements from each sediment slice for each of these parameters were averaged over the full 15 cm core. The conversion factor to calculate total organic carbon (TOC) for the study site is 0.99 ± 0.06 (S.E.) (E. Zetsche, unpublished), demonstrating the minor importance of inorganic carbon in the system.