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The effects of short-term increases in turbidity on sandflat microphytobenthic productivity and nutrient fluxes

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ABSTRACT

Turbidity is a major limiting factor of benthic primary production and nutrient uptake on estuarine intertidal sandflats. Estuaries exhibit a wide range of suspended sediment concentrations (SSCs), however, few studies have quantified the effects of increasing SSC on ecosystem functioning. Here, we report on an *in situ* experiment examining the effects of short-term increases in SSC on intertidal sandflat benthic primary production and nutrient fluxes. Fine sediments (<63 μm) were added to sunlit and darkened benthic chambers (0.25 m^2) at concentrations ranging from 16 to 157 mg L^{-1} and kept in suspension for a 4–5 h incubation period. In addition to solute fluxes we also measured sediment chlorophyll-*a* content and physical properties as covariables. In sunlit chambers, we observed a three-fold reduction in net primary production (NPP) with increasing SSC (NPP, $R^2 = 0.36$, $p = 0.01$) and stronger reductions when NPP was standardised by sediment chlorophyll-*a* content (i.e., photosynthetic efficiency, $NPP_{chl\text{-}a}$, $R^2 = 0.62$, $p < 0.01$). Concurrent with reductions in photosynthetic efficiency, there was a four-fold increase in nutrient efflux from the sediment to the water column (NH_4^+, $R^2 = 0.44$, $p < 0.01$). SSC had no effect on solute fluxes in darkened chambers. NPP was correlated with SSC and light intensity, whilst NH_4^+ efflux was solely correlated to SSC. The results of this study imply that increased exposure to SSC associated with the tidal exchange of sediments from far-field sources may severely impair benthic primary productivity and increase the flux of inorganic nutrients from benthic to pelagic systems.

1. Introduction

Estuaries are highly dynamic ecosystems with large variations in salinity, nutrients, sediment loads and light availability over time scales ranging from tidal cycles to years. Fluctuations in the light environment occur as a function of cloud cover, tidal height, depth and turbidity (reviewed in Kirk, 2011) and light is a primary driver of photoautotrophic production and nutrient exchange. Suspended sediments can generate up to 80% of the variation in light availability (Anthony et al., 2004). Different scenarios of increased suspended sediment concentrations (SSCs) depend on underlying climatic and hydrodynamic processes. For example, SSC can be elevated due to local wind/wave driven resuspension but can also fluctuate with the tidal exchange of sediments eroded from one location (e.g. the muddy banks of tidal creeks) to impact another (e.g., the middle and upper flats) (Green and Coco, 2007; Talke and Stacey, 2008). Wave orbital motions can be sufficient to retard the settling of particles without causing local resuspension and this is a commonly observed process in New Zealand's estuaries (e.g. Green and Coco, 2007). In microtidal estuaries, SSC typically range between 1 and 100 mg L^{-1} during calm, fair-weather conditions, but can easily exceed 200 mg L^{-1} with higher sediment loads associated with freshwater run-off during episodic climate events (Green and Hancock, 2012; Uncles et al., 2002). Primary productivity is constrained by the reduction in light availability associated with SSC and can become severely limited when SSC exceeds 30–50 mg L^{-1} (Cloern, 1987; Colijn, 1982; Gameiro et al., 2011; Kromkamp et al., 1995).

In shallow coastal and estuarine systems, microphytobenthos (MPB) are highly productive; contributing up to 50% of the total primary production (Cahoon, 1999; Underwood and Kromkamp, 1999) and a significant proportion of this biomass is exported to adjacent ecosystems (Duarte and Cebrian, 1996). MPB production constitutes an important source of labile organic material fuelling benthic food webs (e.g. Kang et al., 2003; Middleburg et al., 2000), playing a key role in nutrient cycling (Sundbäck et al., 2000) and sediment stabilising processes (Lelieveld et al., 2003; Yallop et al., 1994). Therefore, major changes in the functioning of MPB are likely to have widespread implications for the ecological performance of estuaries. MPB regulate the flux of nutrients remineralised in sediments to the water column, directly through uptake during photosynthesis and via microbial nitrification–denitrification processes through photosynthetic oxygenation of sediments (Sundbäck et al., 2000; Thornton et al., 1999). Experimental studies have shown that rates of nutrient uptake in benthic sediments can be c. 50% lower in darkened conditions (Longphuirt et al., 2009; Thornton et al., 1999). The effects of variable light conditions are a strong component in the

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theoretical framework of MPB productivity (Underwood and Kromkamp, 1999). However, attempts to empirically measure the effects of elevated SSC on primary production and nutrient release from sediments in the field are rare.

In intertidal areas, MPB production is often considered to be limited to the low tide period, particularly in turbid mudflat systems (Colijn, 1982; Guarini et al., 2002; Migné et al., 2009). Yet high rates of primary production measured in shallow, clear coastal areas (Billerbeck et al., 2007; Sundbäck and Jönsson, 1988) and in numerous estuarine sandflats in the North Island of New Zealand (Jones et al., 2011; Lohrer et al., 2011; Needham et al., 2011; Rodil et al., 2011) suggest that significant productivity can occur during the tidal immersion period. Photo-adaptive mechanisms including up-regulation of photopigments (to increase light harvesting (Jesus et al., 2009)) and vertical migration (Underwood et al., 2005) have been described, which may help sustain productivity in light limited environments. Furthermore, New Zealand's, warm-temperate climate and the ozone hole can equate to high light, UV-B, temperature and desiccation stress during low tides on sunny days, all of which can impair photosynthetic efficiency (Blanchard et al., 1997; Coelho et al., 2009; Rijstenbil, 2003). Taken together, MPB production during the tidal immersion period is likely to contribute significantly to overall system production, therefore the impacts of water column turbidity on light attenuation and benthic primary production are important to characterise.

In this study, we manipulated SSC in benthic incubation chambers to examine the effects of elevated turbidity on rates of benthic primary production and nutrient exchange in Tauranga Harbour, New Zealand. Our aim was to determine the effects of SSC advected from far-field sources (e.g. resuspension in tidal creeks, terrestrial runoff) that is mediated by climate patterns. The experiment relates to the short-term (one tidal cycle) effects of this process and does not directly reflect the effects of SSC due to local sediment resuspension. In calm conditions, mean SSC in the estuary ranges between 37 and 52 mg L^{-1} (Hewitt and Pilditch, 2004), but is likely to be higher during an episodic climate event. Based on our knowledge of MPB–light interactions, we predict that increases in SSC will reduce primary productivity and increase the rate of nutrient efflux to the water column, particularly at SSC levels > 50 mg L^{-1}. The major advantage of the approach used in our study (in-situ manipulation of SSC in enclosed chambers) is the inclusion of the complex interactions occurring between SSC and the benthic community as a whole. For example increases in sediment loads can stimulate the growth of bacterial cells (Goosen et al., 1999) and invoke behavioural and physiological responses in large, biomass dominant macrofauna species in sandflats (Hewitt and Norkko, 2007; Woodin et al., 2012) that may further affect sediment biogeochemical processes.

2. Material and methods

2.1. Study site and experimental design

Tauranga Harbour (located in the North Island of New Zealand) is a large (200 km^2), shallow (mean depth 2.1 m) barrier enclosed lagoon. The estuary is tidally dominated (mean tidal range = 1.6 m) with extensive intertidal sandflats (66% of the area) and is connected to the Pacific Ocean by a northern and a southern entrance. SSC was manipulated in-situ at a mid-intertidal site (approx. 40 × 30 m^{-2}) in the Tuapiro sub-estuary, which is located in the northern arm of the Harbour (37° 29.450′ S; 175° 57.050′ E). Sedimentary conditions at the site (median grain size, 180 μm; silt/clay content, 6.5%) are typical of many intertidal sandflats in New Zealand and therefore ideal to test the effects of temporary elevations in turbidity on ecological processes in sandflat systems.

Suspended sediment concentrations (SSCs) were experimentally enhanced from natural levels in benthic incubation chambers (35 L volume of seawater enclosed over a 0.25 m^2 area of sediment). A range of treatments were applied to different chambers by addition of approximately 2, 4, 8, 16, 24 and 36 g dry weight sediment and compared to a control (0 g sediment addition). These sediment doses were selected to achieve a gradient in SSC between 0 and 200 mg L^{-1}, recognising from preliminary laboratory trials that 40–80% of these sediments would settle out during the first hour of incubation. We used a clay/silt mixture (<63 μm) of muddy surficial sediments collected near the site to increase the SSC within the chambers, as fine sediments stay in suspension longer and form the bulk of the SSC in estuaries. The muddy sediments we collected were wet-sieved through a 63 μm mesh and fractionated by settling velocity (Day, 1965). All experimental treatments were established from a homogenous slurry comprised of 21% clay (<3.9 μm) and 79% silt (3.9–63 μm) with a 0.6% organic content (determined by loss on ignition). Aliquots of sediment slurry were mixed with 50 mL of artificial seawater and pre-loaded into capped Luer-lock syringes for injection into the chambers.

Within the study area, a benthic chamber was placed on each of sixteen experimental plots (0.25 m^{-2}), which were spaced approximately 3 m apart. We included two replicates of treatments 2, 4, 8, 16 and 24 g and three replicates of treatments 0 and 36 g. To minimise the potential influence of small-scale heterogeneity in ambient sediment conditions, SSC treatments were randomly allocated to chambers ensuring the distribution of low to high SSC treatments across the site. The biogeochemical response of the sandflat system to experimental elevations in SSC was determined from dissolved O_2 and nutrient fluxes across the sediment–water interface. These were measured in the presence and absence of photosynthetic activity by MPB using sunlit and darkened benthic chambers, respectively. Light and dark chambers were separately deployed on the first and second days of the experiment, respectively. On the second day, treatment plots were positioned in areas adjacent to those used on the previous day to prevent the resampling of sediments. The experiment was conducted on 3- and 4-November-2011 with similar light (mean surface PAR = 1960 μmol photons m^{-2} s^{-1} measured with a LiCOR sensor deployed at the shoreline) and ambient water temperature (21 ± 2 °C) conditions on both days. Weather conditions were generally sunny and calm and measurements coincided with the mid-day high tide to ensure an adequate incubation period (c. 4 h) during the time of the day with the highest incident light.

2.2. SSC manipulation and solute flux measurement

Benthic incubation chambers consisted of a square base with a perspex dome lid (described in Lohrer et al., 2012). Recirculating pumps (SBE 5M-1, Sea-Bird Electronics Inc., Washington, USA) were used to stir the water enclosed within each chamber and to keep suspended particles from settling whilst minimising disturbance to the bed. Pumps were powered by battery and operated from a separate circuit board to control pump flow rate, set at 40 mL s^{-1}. Variation in light intensity (lux) as a function of SSC was monitored in 8 of the 16 chambers using HOBO data loggers (Onset Computer, Corporation, Bourne, Massachusetts, USA), placed approximately 2 cm from the sediment surface and logging at 5 min intervals. Measures of light intensity in control chambers were used to account for the effects of cloud cover, ambient water column turbidity and the potential effect of the chamber dome on the light intensity within the chambers. Note that lux measurements provide a relative measure of light availability but cannot be directly compared with photosynthetically-active radiation (PAR). HOBO data loggers were also used to determine chamber water temperature, since variability in both temperature and light can strongly affect sediment O_2 and nutrient exchange by altering the rates of biological and physico-chemical processes.

At low tide, chamber bases were placed into the sediment and pumps were fitted to the interior rim of the base. On the incoming tide when the plots were covered by c. 0.5 m of water, chamber lids were carefully fixed onto the bases to ensure no air bubbles were