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A model to assess microphytobenthic primary production in tidal systems using satellite remote sensing

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ABSTRACT

Quantifying spatial variability in intertidal benthic productivity is necessary to guide management of estuaries and to understand estuarine ecological processes, including the amount of benthic organic carbon available for grazing, burial and transport to the pelagic zone.

We developed a model to assess microphytobenthic (MPB) primary production using (1) remotely sensed information on MPB biomass and remotely sensed information on sediment mud content, (2) surface irradiance and ambient temperature (both from local meteorological observations), (3) directly-measured photosynthetic parameters and (4) a tidal model. MPB biomass was estimated using the normalized-difference vegetation index (NDVI) and mud content was predicted using surface reflectance in the blue and near-infrared, both from Landsat 8 satellite imagery. The photosynthetic capacity (maximum photosynthesis rate normalized to MPB chl-*a*) was estimated from ambient temperature, while photosynthetic efficiency and the light saturation parameter were derived from *in situ* fluorometry-based production measurements (PAM). The influence of tides (submergence by turbid water) on MPB production was accounted for in the model. The method was validated on several locations in two temperate tidal basins in the Netherlands (Oosterschelde and Westerschelde). Model based production rates ($mg\,C\,m^{-2}\,h^{-1}$) matched well with an independent set of *in situ* (PAM) measurement based production rates (Oosterschelde: RMSE = 9.7, mean error = 1.5, $\chi = 0.57$; Westerschelde: RMSE = 46.7, mean error = −17.6, $\chi = 0.9$). The relationship between photosynthetic capacity and temperature shows considerable variation and may be improved by using sediment surface temperature instead of ambient temperature. A sensitivity analysis revealed that emersion duration and mud content determine most of the variability in MPB production. Our results demonstrate that it is possible to derive a satellite remote sensing-based overview of average hourly and daily MPB primary production rates at the macro scale. As the proposed model is generic, the model can be applied to other tidal systems to assess spatial variability in MPB primary production at the macro scale after calibration at the site of interest. Model calibration, results and possible applications for regular monitoring of MPB production are discussed below.

1. Introduction

Estuarine intertidal zones rank among the most productive and potentially economically valuable ecosystems in the world (Costanza et al., 1997; Heip et al., 1995; Schelske and Odum, 1962). Microphytobenthos (MPB), consisting of microalgae and photosynthesizing bacteria, are the main primary producers in intertidal ecosystems depending on the total surface area of intertidal flats present (McLusky, 1989; Underwood and Kromkamp, 1999). MPB primary production rates on intertidal flats are typically in the range of $100\,g\,C\,m^{-2}\,y^{-1}$ (Underwood and Kromkamp, 1999) but can exceed $300\,g\,C\,m^{-2}\,y^{-1}$ (MacIntyre et al., 1996).

Production in terms of carbon assimilation can be several orders of magnitude higher in benthic sediments than in the water column (Guarini et al., 2008) and benthic primary productivity provides a main food source for the majority of macrofaunal species in intertidal ecosystems (Christianen et al., 2017). The global annual productivity of MPB is estimated to be in the order of 500 million tons of carbon (Cahoon, 1999). MPB are therefore expected to play an important role in the global carbon cycle.

Due to the high ecological and economic importance of intertidal ecosystems and their current deterioration as a result of human

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activities (Barbier et al., 2011; Lotze et al., 2006), *in situ* sampling campaigns are needed. Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management) has monitored MPB biomass in the Westerschelde (The Netherlands) from 1987 until 2013 and some project-based sampling campaigns have been conducted worldwide (*e.g.* Colijn and de Jonge, 1984; Lomas et al., 2002; Santos et al., 1997; Yamaguchi et al., 2007). Overall, microphytobenthos monitoring campaigns are very scarce. *In situ* sampling is costly and only provides limited spatial information on large scale ecosystem dynamics. Satellite remote sensing provides the opportunity to upscale *in situ* measurements to the entire estuary and provide further insight into large scale intertidal ecosystem structure and dynamics.

MPB primary production rates on intertidal flats are strongly influenced by the tidal cycle (Pratt et al., 2013; Serôdio and Catarino, 1999). In ecosystems with high water turbidity (which limits light penetration trough the water column), benthic primary production mainly occurs during daytime low tides (Colijn, 1982; Serôdio and Catarino, 2000). In muddy sediments, MPB biomass is mostly concentrated at the sediment surface and decreases exponentially with depth (de Brouwer and Stal, 2001; Kelly et al., 2001). Light attenuation is strong in these sediments (Forster and Kromkamp, 2004) and resuspension rates are low (Herman et al., 1999). MPB biomass in sandy sediments shows a more homogeneous distribution with depth, a result of sediment mixing by tidal currents and bioturbation, and light penetrates deeper (Kühl and Jorgensen, 1994). Generally, resuspension rates are higher in sandy sediments (Jesus et al., 2006; Yallop et al., 1994).

Several 1D models have been developed to calculate MPB primary production in intertidal areas (Barranguet et al., 1998; Blackford, 2002; Brotas et al., 1995; Forster et al., 2006; Forster and Kromkamp, 2006; Forster and Kromkamp, 2004; Serôdio and Catarino, 2000). Some of these models aim to describe the vertical movement of MPB within the sediment as a function of tidal phase and/or irradiance (Pinckney and Zingmark, 1993; Serôdio and Catarino, 2000), while others use a sediment-optical model to calculate areal primary production rates (Barranguet and Kromkamp, 2000; Barranguet et al., 1998; Forster and Kromkamp, 2006). However, few studies have focused on mapping and monitoring of large scale spatial variability in MPB production. Guarini et al. (2002) made a spatial primary production model by combining measurements of photosynthesis-irradiance curves with a deterministic model of tidal elevation and ambient irradiance to calculate daily aerial production rates for intertidal mud flats. However, spatial variation in mud content and chlorophyll-*a* (chl-*a*) concentrations and their effect on primary production rates were not taken into account in this study. Remote sensing studies have mainly focussed on quantifying the MPB biomass standing stock (Kazemipour et al., 2012; Meleder et al., 2003a; Van der Wal et al., 2010) and not on production. Remote sensing has also been used to assess the grain-size characteristics of the sediment, such as mud content (Rainey et al., 2003; Van der Wal and Herman, 2007), which can support spatial estimates of primary production. Several methods have been developed to retrieve sediment properties from hyperspectral *in situ* remote sensing (Adam et al., 2011; Hakvoort et al., 1997), hyperspectral airborne remote sensing (Adam et al., 2006; Rainey et al., 2003) and multispectral satellite remote sensing (Ryu et al., 2004; Van der Wal and Herman, 2007).

The aim of this study is to develop a generic method to assess MPB primary production rates at the estuary scale using optical remote sensing. The model is applied to two intertidal ecosystems in the Netherlands (the Oosterschelde and Westerschelde) and is validated with *in situ* measurements on muddy and sandy sediments on intertidal flats in these systems. We performed a sensitivity analysis that provides insight in the model response to variation in chl-*a* concentration, mud content, ambient irradiance, emersion duration and photosynthetic parameters (photosynthetic efficiency (α) and capacity (P_s)).

2. Methodology

2.1. Study area

The proposed model was tested in two shallow tidal basins located in the southwestern part of the Netherlands: the relatively clear, mesotrophic tide-dominated Oosterschelde (E 4°00′, N 51°35′, Van der Wal et al., 2010) and the eutrophic turbid, tide-dominated Westerschelde estuary (E 3°50′, N 51°20′, Van der Wal et al., 2010). Both basins are part of the Dutch delta system where the Scheldt, Meuse and Rhine rivers flow into the North Sea. In the Oosterschelde, the construction of dams and a storm surge barrier resulted in a tidal basin with a reduced tidal range and little freshwater input (Nienhuis and Smaal, 1994). The tidal basin is polyhaline and consists of relatively clear water (Secchi depth: 3.3 ± 0.9 m; k_d: 1.3 ± 1.2 m^{-1}, spring 2011–2016, NIOO/NIOZ monitoring data, unpublished results). The spring tidal range is around 3 m (Van der Wal et al., 2010).The surface area of the intertidal zone in Oosterschelde is approximately 50 km^2 (Van der Wal et al., 2010). The Westerschelde estuary is about 60 km long and 5 km wide at the mouth. The estuary is well-mixed and has a clear salinity gradient, varying from mesohaline at the Dutch-Belgium border to polyhaline at the mouth. The estuary is macrotidal and has a spring tidal range varying from 4.5 m on springs at the mouth, and 5.5 m on springs at the transition of the polyhaline and mesohaline zone (water height data from 2012; Rijkswaterstaat, 2017). The intertidal zone of the Westerschelde has a surface area of approximately 70 km^2 (Van der Wal et al., 2010). The sediments in the Westerschelde consist of coarse to fine sands and mud. The Westerschelde is relatively clear at the mouth (Secchi depth: 0.86 ± 0.38; k_d: 2.8 ± 0.9, spring 2011–2016, NIOO/NIOZ monitoring data, unpublished results) and more turbid in the mesohaline zone (Secchi depth: 0.34 ± 0.08; k_d: 4.9 ± 1.9, unpublished results).

2.2. Model overview

The goal of the proposed model is to retrieve average daily estimates of MPB primary production for intertidal coastal areas. The model describes spatial variability in MPB primary production using remotely sensed information on MPB biomass and sediment type (mud content, % < 63 μm) as input. The model was subdivided into a primary production module and a tide module (Fig. 1). In the primary production module, MPB primary production is calculated for the photic zone within the sediment. Sediment-optical relationships and the vertical distribution of MPB biomass within the sediment are accounted for and depend on mud content and MPB biomass, which were derived from *in situ* sediment characteristics and surface reflectance in specific wavelengths using multiple linear regression (described in detail in Section 2.4). Earlier studies have shown that the photosynthetic capacity (maximum photosynthesis rate) depends on temperature (Blanchard et al., 1997; Blanchard et al., 1996; Morris and Kromkamp, 2003). We have used the formulation of Blanchard et al. (1996) to calculate variations in the photosynthetic capacity as function of ambient temperature over time, which is described in detail in Section 2.4.4.2. Other photosynthetic parameters (photosynthetic efficiency α and optimal light intensity E_{opt}) necessary to calculate primary production rates were measured in the field. The primary production module was applied to a Landsat 8 OLI image taken at the same time period as a series of *in situ* fluorometry-based production measurements, to validate the calculation of instantaneous hourly MPB primary production rates from satellite remote sensing. Subsequently, the primary production module was combined with a tide module to account for variation in MPB production over time associated with emersion *versus* immersion of the tidal flats and vertical migration of MPB within the sediment. The combined modules were applied to the intertidal areas of the Oosterschelde and Westerschelde to identify potential spatial variability in daily MPB production rates.